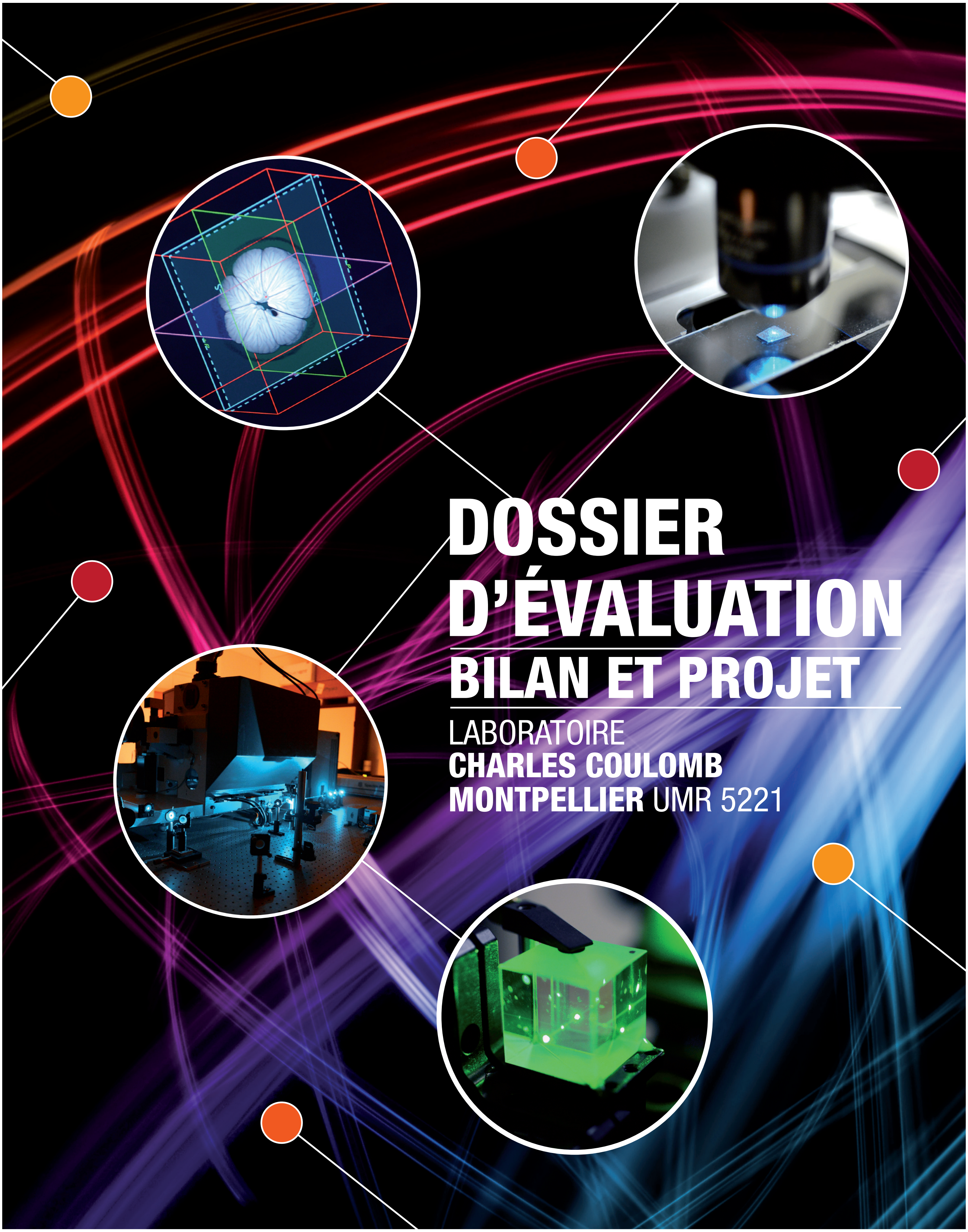

DOSSIER D'ÉVALUATION

BILAN ET PROJET

LABORATOIRE
CHARLES COULOMB
MONTPELLIER UMR 5221

LABORATOIRE CHARLES COULOMB MONTPELLIER

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SCIENCES ET TECHNIQUES

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SCIENTIFIC REPORT

of the “Laboratoire Charles Coulomb”

agence d'évaluation de la recherche et de l'enseignement supérieur

Dossier d'évaluation d'une unité de recherche

Vague E : campagne d'évaluation 2013-2014

Nom de l'unité : Laboratoire Charles Coulomb
Acronyme : L2C, UMR5221
Nom du directeur pour le contrat en cours : Jean-Louis SAUVAJOL
Nom du directeur pour le contrat à venir : Pierre LEFEBVRE

Type de demande :

Renouvellement à l'identique ☐	Restructuration X	Création ex nihilo ☐

Choix de l'évaluation interdisciplinaire de l'unité de recherche :

Oui ☐	Non X

1. Presentation of the laboratory

Following a recommendation from “Institut de Physique” of the CNRS and “Université Montpellier 2”, on July 2009, the “Laboratoire Charles Coulomb” (L2C, UMR5221) was founded on January, 1st 2011. This laboratory is the result of a merger between three well-established physics units in Montpellier, namely: the “Laboratoire des Colloïdes, Verres et Nanomatériaux (LCVN, UMR5587)”, the “Groupe d'Etude des Semi-conducteurs (GES, UMR5650)”, and the major part of the theory group of the “Laboratoire de Physique Théorique et Astroparticules (LPTA, UMR5207)”. In a first stage, each of the three parent physics units was transformed in a “Department” of the new laboratory, respectively:

- *“Colloids, Glasses and Nanomaterials” Department*
- *“Semi-conductors, Materials and Sensors” Department*
- *“Theoretical Physics” Department*

The first two Departments, *“Colloids, Glasses and Nano materials” and “Semi-conductors, Materials and Sensors”,* develop mainly experimental activities on the primary research fields of the laboratory, namely: Condensed matter including semiconductors, glasses and nanomaterials (quantum dots, carbon nanotubes and graphene), soft matter including biophysics, and research at the interface with life sciences.

From 2011 to 2012, only the theoretical physics group of the former LPTA was in the "*Theoretical Physics*" Department. Since January 2013, this Department gathers the majority of the theoreticians of the laboratory. Beyond its own theoretical activities such as: mathematical physics and field theory, fundamental interactions and cosmology, non-linearity and complex systems, statistical physics, some of the activities of this Department contribute to a better understanding of experimental results obtained in the other two Departments, especially in the physics of 2D semiconducting nanostructures, that of complex materials (glasses, soft matter), and biophysics.

The "Laboratoire Charles Coulomb" (L2C) is localized in the University Montpellier 2. It occupies some parts of four separate buildings in the "Campus Triolet" of the University Montpellier 2. The delocalization of the L2C is an open problem that has to be solved in the future. As already noticed in the previous report in 2009, the localization in a same building is a key point for the success of our lab. This project was a priority for the University in 2009 and it still is, according to the new University management.

Due to its history and current composition, **one of the strengths and specificity of the L2C is to develop a wide range of activities of basic research in physics: from theoretical physics to biophysics, with emphasis on condensed matter physics, including nanophysics and soft matter.**

Another feature of the L2C is the presence of a large number of experimental platforms, in particular an extended park of optical spectroscopy facilities. These platforms exhibit a state-of-art and often unique level of performance.

Since the laboratory was created on January 1st, 2011, we will give in this summary report the information regarding the organization of the lab, its financial and human resources, and its scientific policy since this date. However, because all the scientific teams of the L2C already existed in the three parent units, the scientific activities of each team, and consequently those of the lab, in terms of scientific production, highlights, distinctions etc, will be reported from January 2008 to June 2013.

Scientific Policy

Our aim during the last years can be summarized as: "**To keep and to improve our skills in the "core" of our fundamental activities in physics while at the same time working at the interface with others disciplines**".

As previously claimed, one of the strengths of the L2C is the development of a wide range of research activities in physics: from theoretical physics to biophysics, a large part of these being dedicated to the physics of condensed matter and soft matter, and to nanosciences.

Concerning the scientific organization of the laboratory, each Department is divided in several teams or topics.

-The Department "**Theoretical Physics**" is currently divided in four topics:

"*Mathematical Physics and Field Theory*": The activities of the group concern mainly the study of non perturbative effects in quantum field theory using various mathematical techniques.

"*Fundamental Interactions and Cosmology*"**:** The activities of this group are spanning relatively large domains, from topics close to field theory to others linked to on-going experiments in high energy collider particle physics (e.g. LHC), or in astroparticle and cosmology**.**

"*Complex systems and nonlinear physics*"**:** The group has a strong tradition in theoretical modeling of complex systems arising in different fields of physics and at its interfaces with other sciences. The breadth of its application interests ranges from nanophysics to fluid dynamics, interfaces with biology, medicine, environment, and color science.

"*Statistical physics*": The research done in the group encompasses the studies of many different physical systems, ranging from complex states of matter like glasses or granular media, to out-of-equilibrium phenomena such as transport on biological networks. The concepts and tools are those of statistical physics and stochastic processes, and are implemented either by numerical or analytical methods. Its research interests involve the development of new theoretical methods based on statistical physics which can furthermore be used to understand in greater depth the outcome of experiments.

-The Department "**Colloids, Glasses and Nanomaterials**" is currently divided in four teams:

The "*Nanostructure*" group is mainly interested in the understanding the properties of carbon-based nanostructures: carbon nanotubes and graphene, including the synthesis of these nanostructures and their studies at the individual level.

The "*Soft Matter*" group studies the structure and dynamics of soft condensed matter systems like surfactants, polymers, liquid crystals, colloidal and biomimetic systems. Experimental research activities are currently focused on complex interfaces, jammed and glassy matter, biological systems, soft composites, and mechanical instabilities of complex fluids.

The "**Physics of the glassy state**" group focuses its research activity on the fundamental properties of the glass state and more generally on the disorder-induced effects on material properties. The topics currently addressed by the group encompass structure, vibrations and relaxations in glasses, nanocomposites, relaxors and ferroelectric nanoceramics as well as nanoscale mechanical response of glasses. A special effort is devoted to the development of innovative instruments.

The "**BioNanoNMRI**" group develops the performances of the instrumentation in NMR spectroscopy and imaging and explore different topics in agronomy, biology and health, in close collaboration with well established groups from Montpellier.

-The Department "**Semi-conductors, Materials and Sensors**" is currently divided in three teams:

The "**Materials, Devices and Sensors**" group brings together complementary expertise in the field of material science, sensors and nanostructures, combining experimentation and modeling. Research activities are dedicated to the elaboration of materials (photovoltaic structures, ultraporous materials, glasses, graphene) and to the fundamental research on semiconductors and related nanostructures. Device and sensors physics is especially addressed.

The "*Physics of Exciton, Photon and Spin*" group is mainly interested in radiation-matter coupling, either tailored to get new optical functionalities such as in metamaterials, or used as a tool to study different systems such as wide bandgap semiconductor nanostructures, carbon nanotubes, spins in semiconductors, but also biological cells. Magnetic properties of diluted magnetic semiconductors or other magnetic materials are also actively studied.

The "**Terahertz Spectroscopy and Quantum Metrology**" group is studying collective quantum excitations in semiconductor nanostructures using infrared (Terahertz and MIR) magneto-optics and magneto-transport methods with special accent on graphene and graphene-like nanostructures and devices.

Beyond the Departments, in order to develop common research between teams of different departments, "Transverse projects" were created and actively supported by the lab. These projects involve an emerging research field and researches at the interfaces with biology and life sciences.

-Transverse Project **on "Graphene**": This project merges teams of the "**Colloids, Glasses and Nanomaterials**" and "**Semi-conductors, Materials and Sensors"** Departments. This project focuses on the synthesis, by different methods, and the understanding of the properties (optics, electronics, and transport) of this new and exciting material. The main results obtained in the framework of this transverse project are reported in the reports of the associated teams.

-Transverse Project on **"Physics and Life Science":** researchers of the "**Theoretical Physics**" Department and those of the "Soft Matter" group of the "**Colloids, Glasses and Nanomaterials**" Department are involved in this project. The common objective is to explain, interpret and model specific biological mechanisms occurring at the cellular scale and experimentally observed in our laboratory. This tranverse project focus on:

-"Egress from red blood cells and motility for invasion by Plasmodium Falciparum (malaria parasite)", in collaboration with the "Laboratoire de Biologie (DIMNP)" and the Hospital "Saint-Eloi", Montpellier.

-"Delivering on Networks: From specific Systems to general Principles of Transport Processes".

-Transverse project on "**Multiscale Bioimaging**": researchers of the Department "**Semi-conductors, Materials and Sensors**" and those of the "BioNanoNMRI" group of the Department "**Colloids, Glasses and Nanomaterials**" are involved. The objective is to develop new methods in advanced imaging techniques permitting fast and precise diagnosis. This transverse project is associated to the creation of the “BioNanoNMRI User Facility” (highlight of the University in 2012).

The scientific quality of the laboratory is illustrated, among others, by its participation to two national Labex (Laboratoire d’Excellence), concerning the core physics research of the lab, in collaboration with French laboratories:

1-L2C participates to the labex **OCEVU** "Origins, Constituents and Evolution of the Universe", a collaborative structure involving 6 laboratories from the Marseille, Montpellier and Toulouse universities, connected with the 3 CNRS physics institutes (IN2P3, INSU, INP) and having a multidisciplinary approach ranging from cosmology to high-energy particle physics and astrophysics.

2-L2C is involved in the Labex **GaNeX**, coordinated by J.Y. Duboz (director of CRHEA-Valbonne, UPR 10). The Labex GaNeX gathers all French industrial and academic partners working on nitride semiconductors. Six thematic axes are identified within GaNeX: LEDs and lighting, lasers and coherent sources, power devices, high frequency electronics, sensors, photovoltaic and energy converters, the seventh non-thematic axis being focused on Education.

Beyond its own and well established research in basic science and with regards to its large spectrum of activities, the Charles Coulomb Laboratory is well positioned to develop studies at the interfaces with the other disciplines, including strong actions towards chemistry, biology and life science. During the last years, research groups in the different Departments have been strongly encouraged to develop such interdisciplinary topics.

First signatures of the interface activities are the strong implications of the L2C in two Labex (Laboratoire d’Excellence) of Montpellier site.

1-Different teams of L2C are involved in the labex **NUMEV** *“Numerical and Material Solutions, and Modeling for the Environment and Life Sciences”* which merges researchers in mathematics, physics, electronics, mechanics and computer science. It must be emphasized that transverse activities within the lab and with colleagues from other disciplines have been significantly enhanced via this Labex. Several ongoing projects of the L2C (PhD grants, post-docs, equipments) at the interface with the environment and life sciences have been supported by the Labex NUMEV.

2-A team of the L2C participates in the Labex **CheMISyst** in collaboration with the chemistry Institutes and laboratories of the Montpellier area. Common projects (PhDs) have been initiated.

Other significant signatures of our interface activities are the following:

1-"Four research teams from all Departments of the L2C participate in the Interdisciplinary Research Axis of the "Pôle Biosanté Rabelais" unifying Languedoc-Roussillon research potential in the field of Biology and Medicine".

2-"Physical Modeling in Biology and Life Sciences is one of the main directions of the L2C interaction with the labs in the Biology/Health sector traditionally strong in Montpellier. The activity in this field is now demonstrated by a whole series of common publications and research projects and, by the double affiliation of one professor and two assistant professors with biology labs, namely with the “Institut de Génomique Fonctionnelle” and the “Laboratoire de Dynamique des Interactions Membranaires Normales et Pathologiques".

3- A team of the L2C is the leader of the project concerning the development of a “NMR User Facility” dedicated to the study of living systems, in particular one can cited: spinal cord injuries, Alzheimer's disease, fruit and plant modelling...The opening of this platform, also supported by CNRS, was considered as one of the highlights (“Opération phare”) of the Montpellier University in 2012. This activity is transverse with several units of of INSERM, EPHE, INRA, UM1 and CHU of Montpellier and Nîmes. A few years ago, in order to promote this activity, two professors of medicine, one researcher in biology and one research engineer in electronics have been integrated into the L2C.

4-L2C is the leader in a transverse project on the “Physics of blood” (La physique du Sang). This project merges the activities of physicists and mathematicians of the University and also industrial companies such as Horiba, and the research units of some hospitals of Montpellier.

5-Montpellier is one of the most important academic Centers of researchers in Agronomy and Environmental science in Europe. Encouraged by our University, we have developped a new scientific activity at the interface between physics and agronomy and environmental science. This has resulted in the recruitment of a young assistant professor in the field of soft matter for agronomy, and the supervision of two PhD theses, in collaboration with both INRA and the international company “Solvay”.

Profile of activities

The implication of each team in the four different items: “Academic research, Interactions with the environment, Support for research, and Training by research”, is summarized in the table below.

Team	Academic research	Interactions with the environment	Support for research	Training by research
L2C	65	12	11	12
Theoretical Physics	70	7	10	13
Soft Matter	70	10	10	10
Nanostructures	65	10	15	10
Physics of the glassy state	65	10	10	15
BioNanoNMRI	65	5	20	10
Materials, Devices and Sensors	50	30	10	10
Physics of Exciton, Photon and Spin	70	5	10	15
Terahertz Spectroscopy and Quantum Metrology	68	16	0	16

Obviously, this table evidences that basic research is the main activity in our lab. The significant part of the activity in Research and Development of the “Materials, Devices and Sensors” team can be underlined. Finally, all the teams are involved in the development and administration of teaching activities.

Organization of the laboratory

The staff and its evolution

The L2C has currently 223 members. It has 100 researchers (63 university staff and 37 CNRS), 8 emeritus, 46 technicians (17 university staff and 29 CNRS), and 69 non-permanent positions (47 PhD students, and 22 postdocs and long-time visitors).

From January 1st, 2011 to June 30th, 2013 the composition of the laboratory evolved as follows:
-3 young assistant-professors, 1 professor and 3 young CNRS researchers have been recruited.
-3 CNRS researchers, 2 assistant-professors and 1 professor have integrated the L2C during the same period.
-1 administrative CNRS agent and 1 research engineer (IR) CNRS have been recruited.
-The number of PhD students has increased during the reference period: from 40 to 52.
-The large numbers of visitors, and post docs, 16 by year, during the same period should be noticed.

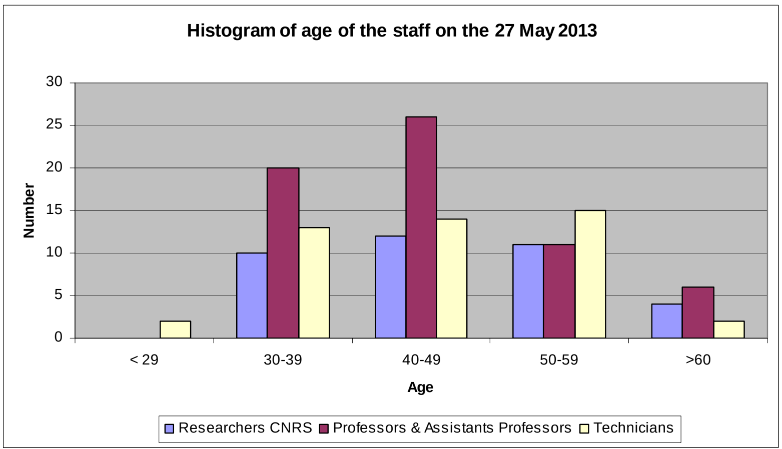
All these data indicate that L2C is a highly attractive and internationally competitive research center.

During the same period, 1 CNRS researcher has changed laboratory, 1 DR of CNRS became emeritus, 2 IE CNRS retired, one IR left the CNRS, and unfortunately, one professor passed away in 2011.

The table below summarizes the evolution of the lab from January 2011 to June 2013.

	Position	January 1st, 2011	January 1st, 2012	June 30th, 2013
Permanent positions	Professors	**28**	**27**	**29**
	Assistant-professors	**31**	**34**	**36**
	Directeurs de Recherche (CNRS)	**16**	**17**	**19**
	Chargés de recherche (CNRS)	**23**	**21**	**18**
Emeritus	Professors	**4**	**4**	**3**
	Directeurs de Recherche (CNRS)	**4**	**4**	**5**
	Engineers/Technicians	**31 CNRS+17 UM2**	**31 CNRS+17 UM2**	**29 CNRS+17 UM2**
Non-permanent positions	Long-term visitors (more than 3 months), Post-docs, and ATERs (Adjoint temporaire d'enseignement)	**18**	**12**	**16**
	PhD students	**40**	**46**	**52**
	Engineers/Technicians	**1**		
Total		**213**	**213**	**224**

The age histogram of the staff (permanent positions only) on June 2013 clearly shows that young CNRS researchers, assistant-professors and professors represent a significant part of the staff. This histogram also shows that few retirements are expected in the next years.

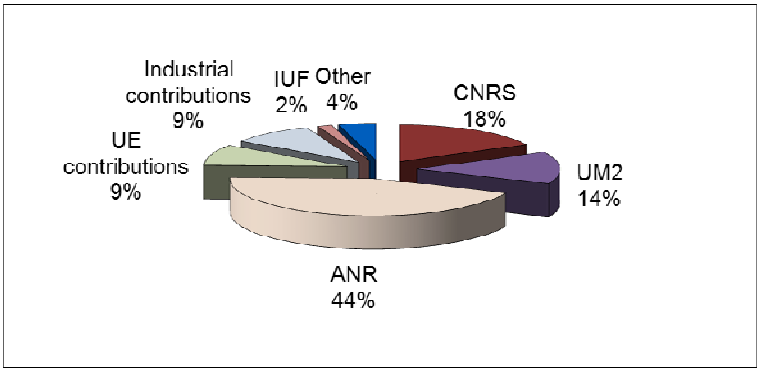


The financial resources and their evolution

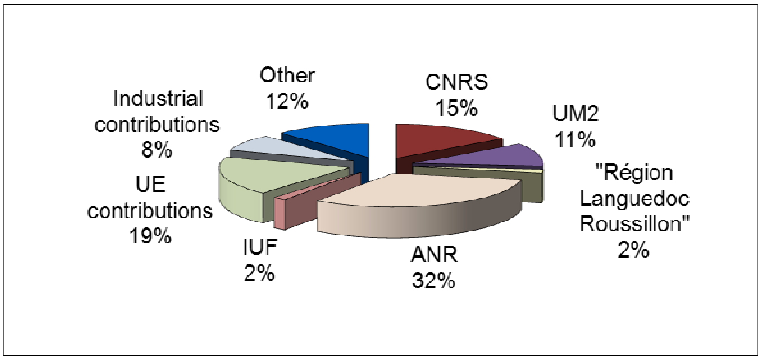
The average budget of L2C (salary excluded) is around 2 300 k€/year (average of the financial resources from 2011 to 2013). It is financed at the level of around 370K€/year by the CNRS and 295k€/year from the University. 70 % of the financial resources come from different projects: ANR projects (880k€/year), European programs (272k€/year), contracts with different industries (199k€/year), other financial resources: (national programs, Region Languedoc-Roussillon...) 140 k€/year. A table in the appendix gives the details of the financial resources.

The above diagram shows the origin of the financial resources (in %) of the L2C in 2011 and 2012. It points out that the majority of the financial resources of L2C (around 70%) are provided by projects and contracts, especially ANR projects (average 38%).

2011



2012



Financial impulse of the scientific policy of the lab: It must be emphasized that, in order to implement the scientific policy both at the Laboratory and Department level, a 12% share was deducted from the financial resources earned through projects and contracts in each Department (excluding salaries). 30% of this deduction was allocated to the common budget of the laboratory, and 70% of it was managed in the Departments.

Organization chart

As previously indicated, the three parent physics units have been transformed into a scientific Department of the lab:

- *Colloids, Glasses and Nano materials (CVN)*
- *Semi-conductors, Materials and Sensors (SMC)*
- *Theoretical Physics (PTh)*

It must be emphasized that the composition of the "Theoretical Physics" Department evolved since 2011. The team "Theory and Simulation", which was initially in the CVN Department, moved in 2013 to the PTh Department. This reorganization is a first step of the complete reorganization of the laboratory which will occur in the next contract (see the part "Strategy and Perspectives" of this report).

Concerning the scientific animation inside the lab, four actions can be emphasized:

1-The research pursued within the laboratory covers a wide range of topics. Consequently, in order to encourage the interactions between the three Departments and a better knowledge and understanding by the lab's community of the different topics pursued in each Department, regular general conferences, named Colloquia, were organized. To deliver such seminars, we selected high level researchers (from France and abroad). Each seminar had always to contain a "state-of-art" part which had to be accessible to non-experts. The frequency of Colloquium is once a month or less. From 2011 to June 2013, 45 Colloquia were organized.

From 2011 to June 2013, in addition to the Colloquium, about 250 regular seminars on specific topics (physics-biology interface, spectroscopies of nanostructures, semi-conducting, soft matter, glassy state, and theoretical physics), or on new (exotic) topics were organized by the different teams of the lab.

2-Each year, a meeting of the PhD students of the lab is organized. In front of the lab's community, all the PhD students report their main results, their objectives and answer to questions regarding their research project. The scientific organization of this meeting (program, schedule) is done by the PhD students.

3-A L2C meeting was organized on July 2012. Each topic pursued in the lab was presented by an expert of the lab. The aim of this meeting was to improve the knowledge between all the members of the lab and to identify possible new interactions between the teams. Another objective of this meeting was to start the discussion about the future organization of the lab on the basis of scientific arguments.

4-Following the L2C meeting, a commission 'Future Organisation du Laboratoire" has been created. The role of this commission was to propose, after discussions and exchanges with all the members of the lab, a new scientific and administrative organization of the lab (see the "Strategy and Perspectives" part in this report).

Concerning the management of the lab, **e**ach Department is independent as far as financial and organizational administration and decision-making is concerned. The Director of a Department is a Deputy-Director of the lab. Each Director of a Department is assisted by a deputy-director.

The L2C is currently managed by the Director and the three deputy Directors.

To help the Director in his decision-making, three consultative assemblies are regularly consulted.

The Directory: Current matters and the preparation of documents, i.e. budget, recruitment in CNRS and University researchers and technicians, applications for equipment etc., are handled at weekly meetings by the so-called Directory. The Directory is composed of the Director, the deputy Directors, the assistant deputy director of each Department. The responsible of the financial service and the management secretary also participate to the directory. These meetings encourage informal and open discussions and thus facilitate reaching a general agreement on many of the proposals presented in the directory and on the decisions taken by the management. All issues discussed in the directory are shared with the members of the lab via minutes sent by e-mail after each meeting.

The Laboratory council: Important proposals concerning the functioning of the lab are presented and debated in the laboratory council. This council is composed of elected members (7 scientists, 5 technical or administrative agents, 1 PhD student), and 5 members appointed by the management (the director and the three deputy directors). At the beginning, the council meetings took place on average four times a year. Since 2013, in order to improve the exchange between the management and the lab, the council meetings take place once a month. The minutes of these meetings are available on the L2C intranet.

The General Assembly: At the beginning of each year, a “General Assembly” of all the members of the lab is organized especially to present the summary of the last year in terms of: how the financial resources were used, the evolution of the staff, the scientific highlights, the scientific events organized by members of the lab, etc. On the other hand, information about the financial and human resources expected for the current year as well as the events organized in the lab are reported and discussed. During the last period, additional general assemblies were organized to debate on specific questions. For instance, a general assembly on the future organization of the laboratory took place in March 2013.

The information about the organization is summarized in the organization chart, and the rules and directives concerning the functioning of the lab are described in detail in the “Réglement intérieur”.

Administrative and Technical Services

The scientific research activity pursued at L2C could not exist without the substantial support of highly competent administrative and technical services. These services are organized as follow:

Administrative service: J.-C. Art, D. Auger, M. Camps, M. Delpond, P. Ejarque, C. Eve, A. Gabillard, I. Lafon, D. Mesnard, R. Pauzat and T. Rabeharivelo.

An administrative cell, working under solely the responsibility of the director of the lab was created. It consists of the executive secretary, the person in charge of the financial resource of the lab and the person in charge of the human resources of the lab. This cell has in charge the management of the lab in its different aspects (administrative, financial and human resources).

In parallel, an administrative and financial cell is located in each Department (see organigram).

Technical Services

Computing service: D. Caron, S. Layssac, J. Leyzat and K. Steuckardt

The L2C is localized in four buildings. This required the implementation of a data processing system suited to the laboratory's size. It consisted particularly in creating an Internet domain and adapting the network infrastructure, implementing new server architecture and expanding the network services. A “**Computing Information**” cell of the L2C was created to this end. It is composed of three engineers and one technician. In particular, the website and intranet were developed and are continuously improved by the “Computing Information” cell of the L2C. More generally, this computing cell manages and develops all the laboratory's information resources.

The other technical services have cells located and managed in the Departments (see organigram).

Mechanics service: J. Barbat, A. Bertrand, and P. Martinez (CVN); H. Domergue and C. L’Hénoret (SMC).
Electronics service: R. Jélinek (CVN), P. Solignac and [redacted] (SMC).
Vacuum and Cryogenics service: E. Alibert (CVN).
*Maintenance service***:** A. Charbit, P. Gamet (CVN); L. Rigal (SMC).
Design and fabrication of new equipements service: S. Clément, J.-M. Fromental, G. Prévot, and R. Vialla (CVN); P. Buzatu (SMC).

Experimental physics is the main vocation of CVN and SMC Departments. In both Departments, the researchers are supported by technical services such as Mechanics, Electronics, Vacuum and Cryogenic techniques, Design and fabrication of new equipment. These technical services embody a number of different competences which are all indispensable to these Departments. The activities of these services are focused on the design, fabrication of new instruments and the maintenance of experimental set ups. The skills of these services range from sample environment in extreme conditions (high pressure, low and high temperatures), to computing software development for the control of experimental devices, metrology, and mechanical engineering.

Chemistry service: R. Aznar, C. Dupas, T. Phou and S. Tahir (CVN)

A large part of the activities of the CVN department is the synthesis of new materials. The Chemistry service activities are mainly centered on syntheses (including nanomaterials) and purifications following established protocols. The service also makes sure that the Departments are fully equipped with all necessary chemicals.

Theoretical Physics Library: F. Duceau, G. Moultaka (PTh)

The L2C possesses a collection of scientific books in the field of theoretical and mathematical physics of about 4000 volumes. This heritage is maintained in a secure room dedicated to the library of the Theoretical Physics Department. Its listing is computerized.

Technical platforms

Instrumental development constitutes one of the important skills of the L2C. L2C manages a large number of experimental platforms with high and often unique performance, in particular a large park of optical spectroscopies. The L2C is in charge of the following platforms: "**Pôle THz" (**N. Diakonova); "**Rhéologie"** (J.-M. Fromental); "**IR et Spectroscopie Raman sous conditions extrêmes"** (D. Maurin); **Bio-Imagerie** (C. Gergely); "**Spectroscopie IR" (**N. Diakonova) and "**Spectroscopie UV"** (P. Valvin and S. Rousset); "**Nanoélectronique et Métrologie"** (C. Consejo).

This strong technical and engineering activity of L2C is especially visible through instrumental platforms which are recognized by the "Région Languedoc-Roussillon" as GPTR ("**Grand Plateau technique pour la Recherche**"). At this time, L2C has (or has been) during the reference period in charge of two such technical platforms:

*X-Ray and Gamma platform***:** This platform is devoted to diffraction and small angle X-ray scattering techniques which include three experimental set-ups located at the L2C. This platform is under the responsibility of Ph. Dieudonné.

OMEGA platform: This platform brings together the instruments involving the measurement of vibrations in solids and liquids. It constitutes six set-ups in four areas, namely: Brillouin scattering, Raman scattering, Hyper-Raman scattering, and infrared spectrometers. The scientific responsible for this platform is Prof. B. Hehlen, and two engineers, D. Maurin and G. Prevot, are responsible for the technical part.

Finally, the L2C is the leader of the project concerning the development of a "*BioNanoNMRI platform*" dedicated to the study of the traumas of the spinal cord (experimentation with small animals). A building was specifically constructed by the University to house this platform. The scientific responsibles for this platform are Dr. C. Goze-Bac (DR CNRS) and C. Coillot (IR CNRS), both members of the L2C.The opening of this platform in 2012 was considered as a highlight ("Opération phare") of the University.

Common Cells

Four common Cells have been created in order to take in charge different important aspects regarding the life of the lab.

Communication: D. Cassagne, C. Eve, M. In, J. Dorignac

The communication of L2C is supported by a communication cell consisting of a communication officer, a responsible of scientific communication and correspondents in each department. Its most important activity in the last four years has been to construct an "identity" (visual identity, awareness, etc.) for the Laboratoire Charles Coulomb, following the creation of the new laboratory. This has required several steps, among which: the creation of a logo, a new website, signs at the entrance of buildings, writing materials (letterhead, business cards, etc.) and an institutional brochure. A library of 500 photos taken by a professional photographer has been established. Various events to raise awareness on the new laboratory were organized, including the inauguration of L2C, but also the 13t^{h} Condensed Matter Days of the Société Française de Physique. Its organization by the Laboratoire Charles Coulomb, with about 650 participants in Montpellier, increased the awareness of the laboratory at the national level. The communication of scientific news (awards, highlights) is done in coordination with institutional partners (UM2, INP, CNRS DR13). News and articles were published in the local press (Midi Libre and MontpellierPlus), the Journal of CNRS, News of INP, CNRS Hebdo and the Journal of UM2. On the website, all seminars are advertised, and automatically connected to Twitter and Facebook accounts to give a presence on social networks.

Health and safety: E. Alibert, R. Aznar, G. Prevot, S. Rousset

Health and safety services are essential in a research lab as safety risks are inherent to many research activities. The potential dangers in the lab have been identified as follows: Electrical danger, chemical dangers, synthesis and manipulations/handling of nanoparticles, laser radiation, x-rays, UV radiation, strong magnetic fields, machines, instruments under pressure, high temperature ovens, cryogenics, and waste handling.

In order to improve the security related to these risks, four dedicated members of the lab, called APs ("Agents de prevention") have been appointed by the management. The APs can request the head of a research group to put health and safety issues on the council agenda, and they are invited to assist the meeting where these issues are addressed. The APs have introduced the following procedures:

-A list of the different types of risks and personnel having expertise on these (the 'risk owners') is available to all members and posted in each department. This list gives the names, office and phone numbers of the APs, and of the experts on laser equipment, radioprotection, electrical qualification...

-Organization of one (at least) annual meeting gathering the lab management, the APs, the group and platform leaders, regional safety engineers, medical services, in order to discuss novelties, problems, and new measures.

-Since 2013, two presentations of risks and security measures organized by the APs are mandatory for all new members of the lab. The first one deals with general risks (emergency phone numbers, …), and the second one with risks of specific instruments or manipulations (chemistry, laser, etc) for those concerned by these risks.

-Training sessions for fire alarm and laser security have been organized.

-In the past years, the information concerning risks has been considerably improved. Now signboards with persons to contact and news are posted in the corridors, risks are indicated at the entry of each experimental area, a registry keeps track of procedures and problems, and the intranet has been completed.

-Other specific actions: **(a)** The setting up of "DOCUNIC"; **(b)** The creation of a Health and Safety page on the L2C intranet.

-In the near future, we plan to equip all the buildings with an automatic defibrillator, and install security showers at the entry of each chemistry lab.

Research and Development: F. Geniet, J. Oberdisse, P. Etienne

In order to offer a common entry point for both L2C-scientists and potential industrial partners, a specific cell ("cellule valorization") has been put in place. Its role is to identify and to promote technology transfer between the lab and industrial companies, in close collaboration with the specialized services of University Montpellier 2 and CNRS, as well as Transfer LR of the region. For this purpose, meetings have been organized between L2C researchers and the above mentioned services.

Training: J.-M. Fromental, R. Pauzat, F. Terki

This cell collects and identifies all the requests of training of all the administrative and technical agents. Each year, a "plan de formation" that contains the list of requested trainings, their interest for the lab and the number of involved agents for each is sent to the 'Direction Régionale" of CNRS. In this list, the priorities of the lab in terms of training are also indicated. On the other hand, this cell regularly transfers to the agents the possibilities of formations offered by CNRS, the Universities and other organisms.

The organization chart of the lab and the one of each Department is given in Appendix 4.

Highlights of L2C

A large number of important and original scientific results were obtained in the lab during the last period. These results are commented in detail in the report of each team. Here are given some general highlights of the lab from its creation (January 1st 2011):

1-Many distinctions have been obtained by members of the lab: Ludovic Berthier: ERC Starting Grant (2012), Walter Kob: "Varshneya Award" of American Ceramic Society" (2012), Manouk Abkarian: Médaille de bronze du CNRS (section 11) (2012). Guillaume Cassabois : Membre junior de l'IUF (2012), Bernard Gil: Professeur Honoris Causa de l'Université de St Pétersbourg (2012), Vladimir Fateev : Prix scientifique franco-allemand Gay-Lussac – Humboldt (2011). Walter Kob : Prix Ivan Peychès de l'Académie des Sciences (2011). Walter Kob Membre sénior de l'IUF (2011), Didier Felbacq Membre junior de l'IUF (2011). Guillaume Cassabois et Manouk Abkarian, "Chercheurs d'Avenir" of the "Région Languedoc-Roussillon" (2011). Mauro Antezza (Membre junior IUF, 2013).

2-The number and the quality of the scientific productions can be underlined. From January 1st 2011 to June 30th 2013: 430 peer-reviewed publications and 220 invited conferences. Among these publications, one can emphasized 11 % of publications in journals with impact factor >7, 44 % in journals with impact factor >3.5.

3-Many conferences and workshops were organized by the lab such as : Summer school on the Physics of Nitrures (June 23-28 2013), "International School "Fundamental Problems in Statistical Physics XIII", (June 16-29

2013)", International Workshop "MIRO" (May 13-16 2013); Workshop en l'Honneur de Lev Pitaevsk (May 4 2012), Rencontre des Physiciens des Particules (May 14-16 2012), Workshop on Glasses: Formation, Structure, and Strength (July 2-6 2012), 15th International Conference on High Pressure in Semiconductor Physics, HPSP'15 (July, 25 au 27 2012), "13èmeJournées Matière Condensée de la Société Française de Physique, JMC13" (August 27-31 2012), Workshop Cosmology (December 2011, October 2012), New Horizons of Colloidal Science: Fundamentals and Applications (October 17-20 2012), International Workshop "Physical Virology" (September 24-28 2012), European workshop on Nanocomposites and Polymer Dynamics (2008 and 2011); School on EXAFS (July 2011 and 2012).

4-Despite the fundamental character of its research activities, it mus be emphasized that L2C has submitted 20 patents.

5- Almost all the PhD students trained in the L2C found an employment: permanent positions or post-docs (see appendix 7).

2. Réalisations

Thanks to the strong efforts of its members, the L2C has become in two and half years a high profile laboratory with a strong national and international visibility.

In the following, are described in detail the research groups' activities of each Department. Because all the teams of L2C existed before the creation of the lab, the summary report of each team presents its scientific activities and results from January, 1st 2008 to June, 30th 2013, with a particular emphasis on outstanding achievements over the last five years.

3. Implication of the laboratory in training by research

L2C belongs to the "Ecole Doctorale" "Information, Structure et Systèmes (I2S)". V. Lorman (PREC) was the coordinator of the Doctoral Specialty "Physics" of the "Ecole Doctorale I2S until 2010. Since 2011, A. A. Zahab, (PR1), has taken over this task.

From 2008 to 2013, 75 students have prepared (or still are preparing) their PhD in the lab, and the list of the thesis is given in appendix 7. The current employment status of each PhD student is also indicated on this list.

Scientific teaching, training and dissemination are essential parts of the L2C activity. 24 professors and 37 assistant-professors ("Maîtres de Conférences") are directly involved in teaching at UM2 mostly at the "Faculté des Sciences", but also at the Polytech'school and at the IUTs in Nîmes, Sète and Montpellier.

11 CNRS researchers and 4 CNRS engineers are involved in teaching activities, mostly at the Master level.

Several professors and assistant-professors of the lab have taken important responsabilities in the management of teaching: Salam Charar: Director of the "IUT de Nîmes"; Maurizio Nobili: deputy-director of the "Faculté des Sciences"; Eric Anglaret, head of the Materials department at the Polytech school (2009-2012); Annelise Faivre head of the Materials department at Polytech school (2013-); Thierry Bretagnon: Director of the "Département Enseignement de Physique" at the "Faculté des Sciences"; Vladimir Lorman: Director of the Master "Physique"; Brahim Guizal: Director of the "Etudes Licence de Physique"; Marie Foret: Director of the "Etudes Licence de Physique-Chimie"; Ferial Terki is responsible of the International Relations at the "Faculté des Sciences" in charge of the EURASMUS MUNDUS et CREPUC programs; David Cassagne is project leader of TICE.

The professors and assistant-professors of the lab are strongly involved in introducing new courses and managing exiting ones at the University and some of them are the coordinators of about master courses and doctoral courses. In particular, they manages the following "parcours" of Master and Licence:

Masters:

Mention "Physique" – Spécialité "Physique et Ingénierie"

"NanoPhysique"
"Physique de la Matière Molle et des Systèmes Vitreux"
"Physique et Ingénierie du vivant"
"Physique Informatique"
"Physique Ingénierie des Matériaux pour la Microélectronique et les Nanosciences"
"Cosmo, Champs et Particules"
Master "STIC-Santé" - Spécialité "Physique Biomédical"
Licence :
"L2-L3, Physique Fondamentale"
"L2-L3, Physique et Applications"
"L2-L3, Physique et Chimie"
"L2-L3, Licence Pro Couleur"

It must be pointed out that, since two years, the L2C is strongly engaged in the development of the cursus "**Master en Ingénierie**". The aim of this cursus is to prepare engineers with a good knowledge of the methods and the topics of fundamental research. The long-terme goal is to enhance the connections between research and teaching activities and the industry.

Training by research is actively pursued at L2C, which hosts an average of 45 "stagiaires" per year at a Master and Licence levels, in addition of the PhD student. We strongly believe that research in the lab should be an essential part of a student's curriculum since his/her early years: accordingly, we have proposed and organized on a volunteer basis short research projects for bachelor students, the so-called "ManipLab" project.

Members of the "Theoretical Physics" Department regularly supervised internships of the students from University of Pisa (Italy), University Aix Marseille, Landau Institute, Moscow (Russia), University of St. Petersburg (Russia), NYU, New York (U.S.A.), Cornell University (U.S.A.).

Some members of the lab organize schools, mostly at the PhD level, in which specific teachings are given:

National schools: Jean-Louis Bantignies: school on "Spectroscopie Raman des nanostructures carbonées" (July 2013); Jean-Louis Bantignies: summer school on EXAFS (in June, since 2009); Anne-Caroline Genix and Julian Oberdisse: Organization of a four-day school "Neutrons et matière molle" in 2009; Sandrine Juillaguet: Summer school and ESR Training in the ITN Marie Curie Projects (2012); Sandrine Juillaguet: course on semiconductor physics at the "Union des Professeurs de Physique et Chimie"» (October 2011), Julian Oberdisse: school in relation with the labex ChemiSyst (2012).

International schools: Guillaume Cassabois: organizer of a summer school on "The physics and applications of nitrides" (23-28 June 2013); Julian Oberdisse: organization of the European school, "Bombannes Sumer school on scattering" (2008, 2010, 2012); Bernard Hehlen: Organization of the yearly Montpellier Summer School "Workshop for new researchers in glass science and Technology". Organization of international schools in Morocco in 2011 (Jean-louis Bantignies) and Venezuela (E. Anglaret) in 2011 and 2013.

Some researchers of L2C are regularly invited to give teaching lectures in French and foreign Universities. Somme examples: Mathieu George: Lecture at the National CNRS training action in "Forum de Microscopie à Sonde Locale" (2011); Sandrine Juillaguet: "Functionalized Materials and Nanosciences" and "Chemical Physics of Materials" at the Lebanon University; Jean-Louis Bantignies, Bernard Hehlen and Jean-Louis Sauvajol: "Spectroscopie Raman" at Sousse (Tunisie) (December 2012). W. Kob and J. Oberdisse "Simulation numérique", Fes (Maroc), 2011.

Since 2013, a team of L2C (Terahertz and quantum metrology) is involved in the master degree of the University of Hanoi (Vietnam), which is linked to our university.

Members of the "Theoretical Physics" Department gave dozens of lectures at different "Ecoles Thématiques du CNRS", "Ecoles d'Eté", "Ecoles d'Hiver", including several Cargèse and Les Houches Schools, (International Summer and Winter Schools).

agence d'évaluation de la recherche et de l'enseignement supérieur

Présentation synthétique de l'entité

Unité de recherche

Vague E : campagne d'évaluation 2013-2014

Charles Coulomb laboratory

Intitulé de l'unité : Laboratoire Charles Coulomb

Nom du directeur de l'unité : Jean-Louis SAUVAJOL

Effectifs de l'entité au 1er janvier 2011

UM2: 28 professors and 31 assistant-professors and 4 emeritus, 17 Engineers and Technicians; **CNRS**: 16 Director of Research, 23 "Chargé de recherche (CR)" and 4 emeritus and 31 Engineers and Technicians; 40 PhD students; 18 Post-docs and long-time visitors.

Personnels ayant quitté l'entité pendant le contrat en cours (et nombre de mois cumulés passés dans l'entité au cours de la période 2011-2013.

1 Professor (2 months), 2 CNRS researchers (32 months); 3 IT CNRS (55 months) ; 26 PhD students (314 months); 25 post-docs (181months).

Nombre de recrutements réalisés au cours de la période considérée et origine des personnels

1 professor (from another lab of the Univ. Montpellier), 3 assistant-professors (from Univ. Paris, Univ. Bordeaux, Univ. Madrid); 2 DR CNRS (from Toulouse and ENS Paris), 4 CR CNRS (from Univ. Grenoble, Univ. Trieste, and post-doc Berlin), 1 IT (from the "Délégation Régionale Languedoc-Roussillon"); 36 PhDs students, 10 Post-docs.

Production scientifique au cours de la période écoulée (2011-2013)

The scientific productions of each team are reported in their "Fiche synthétique". Below, are summarized the main fields of activities of the lab:

1-Theoretical physics including mathematical physics and field theory, fundamental interactions and cosmology, non-linearity and complex systems including biophysics, statistical physics.

2-Physics of soft matter (complex interfaces, jamming, plasticity, material failure, biological systems), glassy state and disordered condensed matter (disorder-induced effects on material properties).

3-Physics of low-dimensional nanostructures: quantum semiconductor nanostructures, metamaterials, carbon nanotubes, graphene

4-Applied physics: Sources and Detectors of THz radiations; Devices and Sensors.

5- Interfaces with the other disciplines, including strong actions towards chemistry, biology and life science.

Bilan quantitatif des publications de l'entité (2011-2013)

430 Publications in peer-reviewed journals and **220** invited conferences

Publications majeures de l'entité (2011-2013)

The most important publications of each team are reported in their "Fiche synthétique". Among these publications, one can emphasize:

-11 % of publications in journals with impact factor >7, 44 % in journals with impact factor >3.5.

-8 articles in Journals of Nature group.

-34 articles in Physical Review Letters.

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5 documents majeurs produits par l'entité (2011-2013)

1-Despite the fundamental character of its research activities, L2C has submitted 14 patents such as: "Laser device for emitting waves in the THz range" (Patent number: WO2012143410) and "Peptide derivatives for biofunctionalisation of silicon for sensing and other application" European Patent n° IB 2011051999.
2- Productions of softwares such as: Free Public Software 'SuSpect' devoted to calculations of properties in different supersymmetric models. This code is widely used by the international community of high-energy physics.
3- Numerous members of L2C are consulted on regular basis as experts in ANR and European projects, AERES Committees...

Indiquer **au maximum 5 faits illustrant le rayonnement ou l'attractivité académiques (2011-2013)**

1-Many distinctions have been obtained by members of the lab such as: Ludovic Berthier: ERC Starting Grant (2012), Walter Kob: "Varshneya Award" of American Ceramic Society" (2012); Manouk Abkarian: Médaille de bronze du CNRS (section 11) (2012); Bernard Gil: Professeur Honoris Causa de l'Université de St Pétersbourg (2012), Vladimir Fateev : Prix scientifique franco-allemand Gay-Lussac – Humboldt (2011) ; Walter Kob : Prix Ivan Peychès de l'Académie des Sciences (2011), Didier Felbacq Membre junior de l'IUF (2011) ; Guillaume Cassabois et Manouk Abkarian, "Chercheurs d'Avenir" of the "Région Languedoc-Roussillon" (2011).
2-Five members of the lab are members of the "Institut Universitaire de France" : W. Kob, L. Cipelletti, G. Cassabois, D. Felbacq, M. Antezza.
3-Many conferences and workshops were organized by the lab such as: Summer school on the Physics of Nitrures (June 23-28 2013), "International School "Fundamental Problems in Statistical Physics XIII", (2013)", International Workshop "MIRO" (2013); Workshop en l'Honneur de Lev Pitaevsk (May 4 2012), Rencontre des Physiciens des Particules (2012), Workshop on Glasses: Formation, Structure, and Strength (2012), 15th International Conference on High Pressure in Semiconductor Physics, HPSP'15 (2012), "13èmeJournées Matière Condensée de la Société Française de Physique, JMC13" (2012), Workshop Cosmology (2012), New Horizons of Colloidal Science: Fundamentals and Applications (2012), International Workshop "Physical Virology" (September 24-28 2012), School on EXAFS (2011, 2012)…
4-The L2C is involved in 4 Labex: OCEVU, GANEX, NUMEV, CheMISyst
5- 32 ANRs in progress in L2C during the 2011-2013 period (12 obtained from 2011).

Indiquer **au maximum 5 faits illustrant les interactions de l'entité avec son environnement socio-économique ou culturel (2011-2013)**

1) L2C has submitted 14 patents.
2) 19 contracts with industries (EADS, CANON, SIEMENS, ST microelectronics, Essilor international, Michelin, Rhodia..). 4 contracts CIFRE (Rhodia/Solvay, Michelin (2), Essilor).
3) L2C participated in 8 European projects.
4) Strong investment of members of L2C for scientific Culture: "Agora des Savoirs", "Université du Tiers Temps". "Association Kyklos" (History-Philosophy of sciences), organization of events at "Fête de la science", "Bar des sciences", one general public conference at the "Palais de la découverte" in Paris, lectures at the "Université du Tiers Temps", traveling exhibitions in schools.
5-Members of the lab are, or were, involved in administrative and scientific Committees of the University Montpellier and as members of CNRS scientific committees and "Conseil National des Universités (CNU)".

Principales contributions de l'entité à des actions de formation (2011-2013)

Several professors and assistant-professors of L2C have important responsibilities in the management of teaching:
1-Deputy-director of "Faculté des Sciences (FDS)"; Director of "Département Enseignement de Physique" of FDS, Head of the Materials Department at the "Polytech" school, Director of IUT de Nîmes; Director of the "Etudes Licence de Physique" and Director of the "Etudes Licence de Physique-Chimie".
2-Coordinator of the Doctoral Specialty "Physics" of the "Ecole Doctorale I2S.
3-Responsible of the 6 "parcours" within Master Mention "Physique"- Spécialité "Physique et Ingénierie".
4-L2C hosts an average of 45 trainees per year at Master and Licence levels
5-Organization of 5 international schools and 6 national schools, and regularly invitations of members of the lab to give teaching lectures in French and foreign Universities.

SCIENTIFIC REPORT

of the Teams

Team: “Theoretical Physics”

Team: "Theoretical Physics"

Topic 1: *Mathematical Physics / Field Theory*

Participants: S.Alexandrov (CR1), E.Buffenoir (DR2), C.Contou-Carrère (PR1), N.Crampé (CR1), V.Fateev (DR1), P.K.Mitter (DREM), A.Neveu (DREM), Ph.Roche (DR2), S.Belliard (ATER).

The activities of the group concern mainly the study of nonperturbative effects in quantum field theory using various mathematical techniques. The group has also an activity in developing mathematics connected to physics. The group has developed in the past an expertise in Conformal Field theories, Integrable systems (Integrable spin chain as well as integrable two dimensional field theory), String theory, Quantum Gravity in the canonical approach and rigorous results in statistical mechanics. The mathematical activities are centered on algebraic groups and dynamical quantum groups.

Two dimensional field theories are studied in our group by **V.Fateev**, **A.Neveu** and **S.Ribault**. The correlations of the Z_N models perturbed by the thermal operator have been computed from the point of view of perturbed conformal field theory and from the point of view of form factors. One of the most interesting two dimensional field theories is Yang Mills theory SU (N) with massive quarks in the fundamental representation. The t'Hooft equation, which enables to compute the spectrum of mesons, has been studied with the techniques of integrable systems and an algorithm computing the spectrum of mesons to arbitrary order has been constructed. Recently an important conjecture by AGT (2009) stipulates that there is a correspondence between the instantons expansion of N=2 gauge theory SU(2), and the expansion of conformal blocks in the conformal field theory of Liouville. This conjecture has been proved by **V.Fateev** and Al.Litvinov in different cases. It has been obtained in the case where there is only one massive supermultiplet in the adjoint representation and further generalized to arbitrary massive supermultiplet. AGT conjecture has a further generalization to SU(n), linking n=2 Yang mills theory SU(n) to conformal Toda theory SU(n). In this case also, AGT conjecture has been proved and a combinatorial expansion of conformal blocks of Toda theory has been obtained. More complicated configurations of instantons arise in the case of Yang mills theory on ALE space. The corresponding conformal field theory is the Zn parafermionic CFT and all 3 points functions in this CFT have been computed.

Conformal field theories with boundaries have been analyzed by **S.Ribault** and **V.Fateev** In particular Conformal Toda theories with boundaries has been analyzed (which is important for obtaining the previous results on AGT) and it has been shown that in the sigma model on the space H3+ one can construct a boundary term such that one can reproduce the results of the conformal bootstrap. **A.Neveu** has obtained with **V.Fateev** new results in the exact computation of 4 points conformal blocks in Liouville Theory. By relating certain types of four points conformal blocks to a Schrödinger equation with a potential expressed as an elliptic function, these types of conformal blocks can be expressed exactly in term of integral representation. The explicit conformal bootstrap can be checked in these cases.

Bethe ansatz techniques are important tools to study the exact spectrum of integrable system. Generalized coordinates and matricial Bethe Ansatz have been developed in the group by **N.Crampé**. These techniques are essential for solving integrable systems with the presence of boundaries breaking the symmetry of the system. These techniques can also be applied to compute the fluctuation of the current in off equilibrium system. Ising model on a Y topology has been shown to be not equivalent to free fermions on the same topology and it has been shown that this is equivalent to a Kondo impurity in a free fermion gas. It is well known that such impurity can modify drastically the physics of the system, one obtains that in such a simple system as Ising model, the modification of the local topology modifies global physical properties. **S.Belliard** has studied the form factors of quantum integrable systems with SU(3) symmetry using algebraic Bethe Ansatz. He has also studied the different realizations of coideals in various integrable systems with boundaries. These coideals are important for the study of the energy and correlation functions when the algebraic Bethe Ansatz cannot be applied.

String theory is developed mainly by **S.Alexandrov**, he has developed the twistor approach to quaternionic geometries which has then been applied to the problem of non-perturbative description of the low-energy effective action in string compactifications with N=2 supersymmetry. This allowed to obtain numerous results including the exact from of D-instanton corrections to the geometry of the hypermultiplet moduli space, realization of mirror symmetry and S-duality in the presence of these non-perturbative effects, approximate description of NS5-brane instantons, relations of non-perturbative hypermultiplet geometry to topological strings and integrable structures, such as thermodynamical Bethe ansatz, duality map to heterotic string vacua.

Works on **quantum gravity** have focalized on spin foam models of quantum gravity. Clarifications of the crucial role played by projected spin networks have been obtained and it has been shown that the standard approach to quantization based on the implementation of simplicity constraints on quantum BF theory is inconsistent with canonical quantization. A Physics Report paper on a critical review of loop and spin foam models has been written. Instead alternative quantization procedure inspired by canonical approach and new general formula for the vertex amplitude have been proposed. Canonical analysis of several modified theories of gravity including generalized Plebanski theories and a chiral formulation of massive bi-gravity have been performed. In the former case, it was found that the theory describes 8 degrees of freedom in contrast to the usual general relativity, whereas for the latter it was proven that it does not contain the scalar ghost and thus describes massive and massless gravitons.

Rigorous results in statistical mechanics are developed by **P.K.Mitter**. Wilson Renormalization group relies on multiscale expansion of Gaussian measures in statistical mechanics. Existence of new types of multi scale expansion with the property of short scale fluctuations has been obtained. In the case of lattice system this gives a powerful alternative to block-spins transformations. These methods have been applied first to continuous system with long range interaction and have provided an analysis of the infrared fixed point. The supersymmetric version on a lattice in 3 dimensions has been studied and enabled to study the Green functions of self-avoiding Levi random walk. The critical subvariety has been analyzed and it has been shown that the theory is not Gaussian.

The mathematics results obtained in the group are of two types, those which are physically motivated and those which are still remote from physics. A result of the first type of problem is the construction of the universal Baxter transformation for quantum affine algebras. It generalizes previously universal results obtained by our group in the case of finite dimensional simple Lie algebras and explain the connection between the universal coboundary and non-trivial quantum characters. The second type of results is in the realm of algebraic geometry and algebraic groups. There are three main results. The first is the extensive study of a relative duality formula on a scheme known as the Contou-Carrère symbol. This is a now well-known concept but there were previously no extensive study of it. **Contou-Carrère** has published an extensive work on this notion. The second is a huge monograph on the study of buildings and Schubert schemes. It contains the explicit construction of birational resolutions of singularities for Schubert varieties of any reductive groups. The construction of the desingularisations only involves explicit combinatorial data and therefore is valid for an arbitrary field. The third obtained by **Ph.Roche** and I.Badulescu of the Math department of Montpellier, is the proof of an explicit Langlands correspondence, known as Jacquet-Langlands correspondence, between automorphic representations of two inner form of GL(n) in positive characteristic. The proof of this correspondence uses as a central tool Arthur-Lafforgue trace formula.

Topics 2: *Statistical Physics*

Participants: L. Berthier (DR2), I. Campbell (DREM), M. Clusel (CR2), D. Coslovich (MCF), S. Ispas (MCF), N. Kern (MCF), W. Kob (PREX), E.Pitard (CR1).

The research done in the group encompasses the studies of many different physical systems, ranging from complex states of matter like glasses or granular media, to out-of-equilibrium phenomena such as transport on biological networks. The concepts and tools are those of statistical physics and stochastic processes, and are implemented either by numerical or analytical methods.

Numerical simulations of glasses and other disordered systems is developed by S. Ispas, W. Kob, D. Coslovich, L. Berthier and I. Campbell.

The research made by **S. Ispas** focuses on two topics that are intrinsically linked, and whose implementation require the use of supercomputers: 1) the **study of oxide glasses** by means of first-principles and classical molecular-dynamics simulations, in order to get more insight into their structural and dynamic properties (silica, alkali glasses, aluminosilicates, germanium dioxide). First-principles simulations represent a reliable approach but they are very time consuming, and to circumvent the CPU, and consequently we have developed a methodology of extracting simple classical force-fields based only upon ab initio calculations. 2) the **modeling of experimental spectra** (NMR, IR, inelastic neutron scattering): if the first topic is dedicated to obtaining a rather complete characterization of the structural disorder in oxide glasses, the aim of the second is to understand how the structural arrangement of the constituent particles and the interactions between them determine the macroscopic properties.

The main focus of **W. Kob**'s research is the investigation of the **static and dynamical properties of disordered systems**, such as simple liquids, structural glasses, polymers, etc. by means of computer simulations and other statistical mechanics methods. In addition he is also interested in optimization algorithms, such as genetic algorithms. In the last few years he has shown that the relaxation dynamics of glass-forming systems changes qualitatively at the so-called mode-coupling temperature and that there are in fact two relevant length scales that govern the dynamics, in contrast to popular belief that there is only one. Furthermore computer simulations were used to investigate the presence of an ideal liquid to glass transition in *equilibrium*. The obtained results indicate that this transition is of first order type and compatible with the scenario proposed by the random-first-order-transition theory. Finally he worked on the development of efficient optimization algorithm that could allow to solve problems that have before been considered as intractable.

The research of **D. Coslovich** has mostly focused on the **theoretical modeling and numerical simulation of supercooled liquids**. In particular, the relationship between the slow dynamics of these systems and their local structure has been investigated through numerical simulations: it has been shown that such a connection can only be established at the level of high-order static correlations. As probes of such non-trivial correlations, various forms of confinement (e.g., particles pinning, boundary conditions) have also been used, borrowing tools and ideas from previous studies on fluids in porous media. These results have provided guidelines to analyze low-activity, glassy states generated by biasing the particle mobility (Speck et al. PRL 2012) and the ultra-stable glasses obtained by vapor deposition techniques (Singh et al., Nature Mat. 2013). A recent extension concerns the physical properties of so-called ultrasoft colloids. This is a peculiar class of soft matter systems formed by highly branched macromolecules, such as dendrimers, which can easily interpenetrate. The phase behavior and the dynamic properties of two models of ultrasoft colloids were analyzed: (i) a new primitive model of polyelectrolyte chains, modeled as quenched Gaussian charge distributions. ; (ii) dense assemblies of repulsive, ultrasoft particles that form "cluster phases". In this latter case, an anomalous dynamic and structural behavior was predicted, as well as formation of a novel "cluster glass" phase.

L. Berthier uses statistical mechanics tools and computer simulations to understand the **structure and dynamics of** a variety of **disordered materials**, ranging from glass-forming liquids to soft materials (gels, colloids) and granular media. This resulted in a number of achievements: (i) several review articles and a book about the glass transition of viscous liquids and dynamic heterogeneity in disordered materials.(ii) the definition and measurements of new types of static correlation lengthscales in supercooled liquids, role of quenched disorder on glassy liquids, and observation of equilibrium phase transition between liquid and glass. (iii) the theoretical study of interplay between gelation and glass transition in soft colloids, prediction and numerical observation of exotic glassy phenomena in ultrasoft colloids.(iv) the theoretical study of the jamming transition in athermal particle systems using replica calculations, numerical investigations of jamming transition in soft repulsive particles, and its relation to the glass transition.

I. Campbell is an emeritus researcher since 2004. Collaborations are active with Per Lundow (Stockholm) and others. His research is focused on **numerical simulations of ferromagnets and spin glasses**. The main results concern the validation of correct scaling laws ((T-T_c)/T in ferromagnets and (T^2-T_g^2)/T^2 in spin glasses), the study of the link overlap at criticality, the universality laws in spin glasses. Moreover emphasis is put on chiral interactions (Kawamura mechanism) for the study of Heisenberg spin glasses.

Physics of out-of-equilibrium phenomena in simple model systems using analytical and numerical tools is studied in the group, with applications to glassy dynamics, transport, condensed matter theory and biological physics ; it is developed by **Pitard**, **Clusel** and **Kern** in different contexts.

E.Pitard is interested in the **statistical physics description of out-of-equilibrium systems**, both for glassy systems and for forced systems. A main achievement has been the study of large-deviation functions of time-extensive quantities, such as the activity and the integrated current: the signature of glassy nature of the dynamics of a given model has been shown to rely on the existence of a first-order transition in such a large deviation function. The study of large deviation functions has also been performed in the case of dissipative simple solvable models. The role of kinetic constraints has been shown to be of major importance for forced systems, both for local and global properties. Finally, one-dimensional models of transport with a dynamical constraint are developed with an application to the transport of ribosomes on messenger RNAs during the protein production in the cell.

The research activities developed by **M. Clusel** during the period 2008-2012 cover various aspects of statistical physics, from **exact solutions of statistical models** to **application in condensed matter physics**, with a particular emphasis on systems exhibiting abnormal behaviors. While essentially theoretical, the research is characterized by strong interaction with experimental physics. A number of results have been obtained in the 2008-2012 period :(i)a statistical model to understand the influence of polydispersity on random packing of spheres. (ii) the Influence of non-Markovian environment on a quantum open system driven through a Landau-Zeener transition. (iii) the origin of generalized extreme value distributions and link with sum of correlated random variables. Since he joined the Laboratoire Charles Coulomb in 2010, he has been working on three new independent projects: (i) Extreme value statistics for correlated random variables, in collaboration with J.-Y. Fortin (IJL Nancy),(ii) Stochastic thermodynamics for driven quantum open systems, in collaboration with P. Degiovanni (ENS Lyon) and A. Auffèves (Institut Néel Grenoble), (iii) Physics of the dense phase of active particles.

The main research topic developed by **N. Kern** is transport and regulation on networks, in a context of biologically inspired statistical physics. The stochastic transmission on complex networks is explored based on the Totally Asymmetric Simple Exclusion Process, with a view towards modelling cytoskeletal transport (collaboration with A. Parmeggiani). A strategy to treat large-scale complex networks has given access to studying how out-of-equilibrium inhomogeneities can be maintained and regulated, for example via the attachment/detachment rates when coupling to a bulk volume. A more refined representation of the dynamics at junctions is under investigation. A complementary project in collaboration with plant biologists in Montpellier (ANR, c/o L.Lejay, A. Gojon, S. Ruffel, BMPM Montpellier) aims to explore modelling strategies in support of ongoing experimental work on gene regulation networks.

Topics 3: *Complex Systems and Non-linear Phenomena (SCPN)*

Participants: F.Geniet (MCFHC), A.Callan-Jones (MCF), J.Dorignac (MCF), M.Dyakonov (PREM), A.Kavokin (CDD), V.Lorman (PREX), M.Manna (PR1), F.Molino (MCF), J.Palmeri (DR2), A.Parmeggiani (PR2)

The group has a strong tradition in theoretical modeling of complex systems arising in different fields of physics and at its interfaces with other sciences. It therefore has a long history of collaborations with other groups of the L2C, many other labs and institutes in Montpellier, in France and worldwide. The approach developed by the group is based mainly on analytical asymptotic methods (perturbation theory, group theory, statistical methods, etc.) with supporting numerical modeling. The breadth of its application interests ranges from nanophysics to fluid dynamics, interfaces with biology, medicine, environment, and color science. The vast majority of its members consists of university professors ("enseignants-chercheurs"). The recent recruitment of new permanent members has allowed the group to focus an important part of its research efforts at the interface between Physics and Biology.

Electronic Properties in Condensed Matter and Nanophysics, Physics of Spins, Excitons and Photons

This direction is represented by **Michel Dyakonov**, an internationally renowned physicist, presently Emeritus professor. Among other well-known works on electronic properties of solids, his works on Spin Physics with V.I. Perel are considered to be the starting point of the field of "Spintronics". They have also predicted the Spin Hall Effect. He has developed a close collaboration with experimentalists from the L2C, particularly with the group of Denis Scalbert on spin physics, and with the group of Wojciech Knap who is working with great success in the realization of some of Dyakonov's ideas for generating and detecting Terahertz radiations in nanometric transistors. These collaborations are in a very active phase, and have given birth to many publications and in a recent patent. The works of M. Dyakonov have been honored by many prizes, notably the APS Beller Lectureship award in 2009, and the SFP Robin prize also in 2009.

To reinforce the collaboration with the experimental groups of the L2C, our group has recruited as a DR for 3 years (starting from October, 2010) **Alexey Kavokin**, a well-known specialist in theory of light-matter interaction in semiconducting hetero-structures. Together with the groups of D. Scalbert and B. Gil he developed a new activity on exciton spin dynamics (which gave rise to an important common European project "INDEX"), on exciton-plasmon coupling in ZnO and GaN wells, and on cold exciton dynamics in coupled quantum wells and bosonic cascade lasers. This activity resulted in a number of papers in high-impact reviews (PRL, Nature Photonics, etc.) and invited lectures in international conferences. These works together with the new direction on optical properties of BN material for optoelectronic applications are at the origin of the new European project demand expressed together with the experimental groups of the L2C.

Nonlinear Physics: Propagation in model systems, and applications to nonlinear optics

In this field **Jerome Leon** (member of the group deceased in 2011) discovered with **F. Geniet** the nonlinear supratransmission phenomenon (NST) which typically occurs in nonlinear media possessing a forbidden band gap: driving one boundary at a frequency lying within the gap generates gap solitons provided a *driving amplitude threshold* is met. NST has since been observed in many different systems like Bragg media or coupled-wave-guide arrays. With the impulse given by the arrival of **Jérome Dorignac** and **P. Anghel-Vasilescu** they have shown that an asymptotic expansion of the evanescent wave profile generated by the suitable generalization of the NST concept, allow a long-sought-after evaluation of the amplitude threshold manifold in *multi-component* models. In particular, these results have been successfully applied to a model of second harmonic generation in birefringent media (Editors' Suggestion in PRL). Recently, they have devised an *ultra-discrete* approach to NST where a mere set of driven *monomers* replaces the full set of coupled PDEs. This enables a simple analytical determination of the amplitude threshold in systems for which accurate asymptotic expansion is out of reach.

Fluids dynamics, complex fluids and active fluids, charged fluids at interfaces

Miguel Manna investigations have been focused on constructing simple, but realistic, mathematical models in order to study highly nonlinear, dispersive and dissipative physical phenomena. This activity was mainly focused on three major topics: (A) electromagnetic propagation in ferromagnetics, (B) viscoelastic instabilities in non-Newtonian fluids and (C) winds generating near shore ocean waves. The main results in each one of these topics were: (A) Unstable line solitons (propagating in a ferromagnetic slab) can decay into stable two-dimensional solitary waves. (B) The Saffman-Taylor theory of viscous fingers pattern formation was extended to non-Newtonian fluids. We have shown that blow-up of fingers are related to the very common observed fractures in viscoelastic fluids. (C) The Miles' theory of wave generation by wind limited to the deep-water wave context was extended to the finite depth domain. The theory provides a valuable insight about the physical mechanism responsible for growth rate evolution of wind waves. This will be useful in theoretical forecast of rogue waves in near shore regions.

In connection with his teaching activities **Frederic Geniet** has applied concepts of the radiative transfer theory to the modeling of pearlescent and aluminum paints. This activity is conducted in relation with GPC/Colorinnov, a SME working in applied color science, and has resulted in the production of commercial software and a patent.

Andrew Callan-Jones has contributed to the hydrodynamics of the cytoskeleton and cell motility. In collaboration with F. Jülicher (MPI-PKS Dresden), he developed a theory of active gels that describes out-of-equilibrium flows in the cytoskeletal network. This theory provides a framework to understand current experiments that probe the active behaviors involved in cell mechanics. In the second part of this project, in collaboration with R. Voituriez (UPMC, Paris) he constructed a simplified model of cells migrating in confined three-dimensional geometries and applied it to amoeboid cell motility.

François Molino was working on the theory of complex fluid flows, namely the flow of foams. A new continuous model incorporating non-linear elasticity at large deformations was proposed, and tested on the example of behavior under shear of these materials. A new explanation of a spectacular banding phenomenon in the direction of shear has been proposed.

In collaboration with colleagues in Toulouse and Montpellier, **John Palmeri** has been using the tools of theoretical physics to study electrolyte transport near **interfaces** and through charged **nanopores** by combining molecular modeling, theory, and experiment. For ionic transport near interfaces and through nanopores, they have used a variational field theory at the mesoscopic level and all-atom molecular dynamics simulations at the microscopic one. At the mesoscopic scale they have shown that an electrolyte confined to a cylindrical nanopore traversing a low dielectric membrane exhibits a first-order ionic liquid-vapor phase-transition. Their work on nanopores has practical applications: their commercial modeling software, *NanoFlux*, is used in the technologically important area of membrane nanofiltration (for the production of potable water and the treatment of industrial wastewater). The work on *NanoFlux* recently led to articles in *CNRS le Journal* and *CNRS International Magazine.*

Interface physics/biology and Theoretical physics of living systems:

Vladimir Lorman has focused his research on **Landau-Ginzburg theory** and its **applications to Physics of Living Systems** and **Physics of Biological and Bio-mimetic Matter**. Original results have been obtained in following domains: 1) Theoretical study of fluctuational mechanics of lipid nanotubules, their elastic instabilities and their interaction with proteins involved in the formation of intra-cellular and inter-cellular tubular structures, and in endocytosis. 2) Models of physical processes during Malaria parasites egress from infected red blood cells (coupled non-linear elasto-hydrodynamical phenomena which result in outward curling dynamics of the cell membrane, followed by an elastic instability and parasite propulsion in the extra-cellular medium). 3) Possible solution of the problem of relations « topological constraints apoptosis in non-proliferative epithelial tissues. The evidence of global order in cell positioning of an oocyte and its role in the optimization of the massive apoptosis process was demonstrated. 4) Most interesting results were obtained in the emerging field of **Physical Virology**: New physical principles were proposed for the virus self-assembly and organization. Principles of virus maturation process were formulated for the Flavivirus family of human viruses. The relation between quasicrystalline order and structures of Papilloma and Polyoma viruses was also shown. The last result generated « derivative » papers in the field of quasicrystals in metallic alloys.

All these papers in the field of Physics/Biology Interface have been selected for "Virtual Journal of Biological Physics Research". Some of them have been also selected for "Virtual Journal of Nanoscale Science and Technology" and in PRL as Editors' Suggestions. A "Research Highlight" has been proposed by Nature Nanotechnology.

Andrew Callan-Jones In collaboration with **V. Lorman,** G. Massiera, and M. Abkarian (L2C), developed a model of the membrane dynamics occurring during release of malaria parasites from red blood cells. Their model captures the importance of the axisymmetry in the problem a balance between elastic energy release due to parasite-induced membrane spontaneous curvature and viscous dissipation in lipid flows in the membrane. Furthermore, a physical model of curling on the example of the long times dynamics of a flattened elastica has been developed. This work has resulted in a PRL Editors' Suggestion, and an APS Physics Focus. In collaboration with the group of P.

Bassereau (Institut Curie), he also developed a model of spatial distribution of proteins in cell membranes to explain bio-mimetic experiments on vesicles containing proteins from the N-BAR family. These results provide a quantitative basis for biological studies on the role of N-BAR proteins as “timers” that mediate endocytosis.

New member of the group **François Molino** is at the same time a member of a neurophysiology lab at the Institut de Génomique Fonctionnelle in Montpellier. He develops **quantitative models in the neurophysiology field**. With the biology team he is working on the question of neurohormonal rhythms, from the scale of a single cell to the whole organism (lactotroph and growth hormone rhythms). The principal results of this interaction are: (1) the identification of memory effects in the pituitary gland using quantitative data extraction from images and network theory analysis (2) the unraveling of physical mechanisms of transport across the blood/parenchyma barrier in the neuroendocrine system through the use of a PDEs model compared to *in vivo* images of fluorescent probes (3) the complete mapping of the pituitary gland at cellular resolution using new microscope (coupled to a slicer and designed with Zeiss) data and an intensive image reconstruction algorithm, coupled to structural analysis tools.

Andrea Parmeggiani has a double affiliation to the L2C and to the DIMNP laboratory of biology. His activity focuses on the study of the **physical principles** of organization and dynamics **of active biological matter**. Theoretical methods that he develops issue from statistical mechanics, stochastic processes theory and non-linear physics. Among systems studied, considerable progress has been made in describing: i) cytoskeletal transport driven by motor proteins (collaboration with **N. Kern**) and ii) protein-membrane interactions under mechanical constraints (with **V. Lorman**). 1) A multiscale approach chosen was able to describe motor protein transport on small and large scale networks (comparable to the whole cytoskeleton of a cell), from a single motor properties and up to the global network topology. This approach allows understanding how density heterogeneities of motor proteins form along the cytoskeleton, and can build gradient of matter in the cytoplasm. 2) A new theory for tubular membrane instability under a mechanical tension and a pressure gradient applied to the membrane has been produced. Such an approach allows formulating a completely new mechanism for the nucleation of domains of protein adsorbing at the membrane. 3) In parallel with these works, collaborations with experimental biologists have been set up on the study of protein delivery and protein localization and regulation in cancer studies. Results have been matter of publications of high scientific impact for physics and biology communities. A. Parmeggiani is now involving a larger community of theorists and experimentalists, national and international partners to model systems such as the neuritis and the endoplasmic reticulum, to study the **physics of the genome** and its connections with protein translation and regulatory mechanisms.

John Palmeri and his collaborators have studied the structural changes undergone by fluctuating **DNA** in response to an increase in temperature or to an applied force. To do so they have developed a coupled “Discrete Wormlike Chain-Ising” model that links in a nonlinear way internal base-pair “opening and closing” to the molecular conformational fluctuations. This model has been used to investigate in a unified way both the thermal denaturation and force-induced stretching transitions, thereby shedding light on the nature of the stretched DNA states (an object of considerable current controversy). Their work, which recently led to an EPJE highlight, could potentially help to understand how DNA performs certain biological functions, via its interactions with proteins and its packaging in viruses.

Topics 4: *Fundamental interactions, Astroparticles and Cosmology (IFAC)*
Participants: J.-L.Kneur (DR2), M.Frigerio (CR2), G.Moultaka (CR1), D.Polarski (PR1)

Important preliminary remark: the IFAC group is actually transverse to the two physics laboratories of the UM2, the L2C and the LUPM, as a by-product of the fission/fusion of the ex-LPTA after 2010: there is thus by definition a common part in the introductory presentation of interests and activities.

IFAC activities are spanning relatively large domains, from topics close to field theory to others linked to on-going experiments in high energy collider particle physics (e.g. LHC), or in astroparticle and cosmology (Planck etc.). One may describe the activities during the relevant period along the following sub-topics:

Theory and phenomenology beyond Standard Model: Minimal Supersymmetric (SUSY) Standard Model (MSSM) or its extensions; supersymmetry breaking models (super-gravity or others). Computation of particle spectrum, dedicated public codes (SuSpect, NMHDecay); reconstruction of basic MSSM parameters from collider data (LHC, ILC); theoretical and experimental constraints. Grand Unification models, flavor models (neutrinos, leptogenesis), composite Higgs models. After the major July 2012 event of the discovery of the scalar boson resonance of mass ~125 GeV at the LHC, this is evidently driving a large part of our next future projects.

Astroparticles/Dark Matter: supersymmetric dark matter candidates (neutralinos, gravitinos, etc.) or others (e.g. from composite Higgs models). Relic density calculation, theoretical analysis for direct and indirect detection, study of collider signatures. Other constraints (e.g. Big Bang Nucleosynthesis).

Cosmology and dark energy: study of dark energy models, to possibly explain the present phase of accelerated expansion of the universe; predictions confronted with present or future data. Inflationary models; study of the universe expansion and growth of perturbations. Modified gravity models (e.g. scalar-tensor models and models of the f(R) type).

Non-perturbative QCD and Hadron physics: study of nonperturbative Quantum Chromodynamics (QCD) phenomena related to the dynamical properties of hadrons (spectra and decays) using, in particular, the QCD spectral sum rule approach. This method is among the very few analytical ones which use the fundamental QCD parameters (alpha_s, quark masses, quark and gluon condensates,...) and is a robust alternative to lattice numerical simulations.

Other activities: other non-perturbative approach (variationally optimized perturbation, resummations, renormalization group) in field theories and condensed matter: applications in QCD and low energy hadron physics; studies of phase transitions at finite temperature and density.

We shortly describe below some selected highlights on IFAC results, concentrating on activities of the present L2C members of the group. Some of these works were done in collaboration between IFAC members without distinction of laboratory membership, and the group was part of a unique laboratory (LPTA) until end 2010. Collaborations beyond IFAC exist also inside the L2C theory department, with the mathematical physics and field theory (PMTC) team, as well as many others national and international collaborations.

Highlights in Theory and phenomenology beyond Standard Model

Some of the team members have been active since long ago in developing public codes to calculate the mass spectrum and related properties in a variety of supersymmetric models. The 'SuSpect' code initiated in 1997 (A. Djouadi, J-L Kneur, G. Moultaka) is largely used internationally by the SUSY community. Another public code developed for the NMSSM extension of the MSSM by C. Hugonie and U. Ellwanger (LPT Orsay) is also largely used internationally. Besides, the recent recruitment of M. Frigerio brings new and complementary 'beyond standard model' topics in flavor physics (neutrino mass models, leptogenesis,...) as well as alternative to SUSY, composite Higgs or other strongly interacting models of electroweak symmetry breaking.

SuSpect public code upgrade to C++: Over the last two years J-L. Kneur, G. Moultaka with D. Zerwas (LAL) and M. Ughetto (PhD student) undertook a major upgrade of the code rewritten in C++ language. Beyond the more convenient C++ language for the community the main aim is an opportunity to make it more flexible for easy inclusion of various new models/options thanks to the object-oriented architecture. The first release of this upgrade version is foreseen for late spring 2013.

'no-scale' supergravity model revisited: J-L. Kneur, G. Moultaka, A. Benhenni (PhD student) and S. Bailly (Postdoc) reconsidered 'noscale' type models for a dynamical determination of soft SUSY breaking parameters and the related gravitino mass. This study reemphasizes, in an up-to-date SUSY spectrum calculation context, the non trivial minimization of the MSSM effective potential, with the important role of the vacuum energy contribution. Phenomenologically the recent LHC sparticle exclusion limits put strong constraints on such scenario, with a gravitino LSP that can account for the observed dark matter relic density.

Lepton flavor and neutrino mass models: M. Frigerio and collaborators discovered a new source of leptogenesis in a class of Grand Unification Theories based on SO (10), in which neutrino masses are controlled by the same parameters controlling leptogenesis. The scenario is necessarily supersymmetric and they studied the associated lepton flavor violation effects that provide important constraints. Michele Frigerio, Albert Villanova del Moral and collaborators analyzed discrete family symmetry in the light of recent neutrino oscillation results. In the context of SO(10) unification, they studied the predictions of the symmetry A4 for quark and lepton masses and mixing. After the measurement of the 1-3 lepton mixing, they pointed out that a generic prediction of simple flavor models is a deviation from maximal 2-3 lepton mixing, as recently suggested by experiments.

Higgs boson decay into 2 photons in the type II see-saw model: G. Moultaka and external collaborators studied the two-photon decay channel of Standard Model-like CP-even Higgs bosons present in the type II Seesaw Model. They found significantly enhanced cross-sections in parts of the parameter space, due to the (doubly-)charged Higgs bosons H++(--) virtual contributions, which can account for the reported ATLAS excess in this channel, if confirmed in the future, or else put stringent lower bounds on the H++ mass.

Highlights in Astroparticles and Dark Matter

It is well-known that the lightest supersymmetric particles (LSP) constitute (assuming R-parity conservation) excellent dark matter candidates, and the study of the different facets of SUSY dark matter is also a tradition of our group, with a complementary view at both collider and indirect and direct detection experiments.

Gravitino Dark matter and Lithium abundances: K. Jedamzik, G. Moultaka, and S. Bailly (PhD student) have analyzed scenarios with a gravitino LSP and a next-to-LSP decaying to the gravitino during Big Bang nucleosynthesis, and showed it to be a possible solution to the "Li7 problem" overproduction in standard BBN. NLSP staus decays to light gravitinos may also lead to significant Li6 (and Be9) abundances, whereas NLSP neutralinos decaying into light gravitinos may solve the Li7 problem.

Non-supersymmetric DM candidates: M. Frigerio and collaborators proposed some new well-motivated dark matter (DM) candidates, alternative to the traditional SUSY ones. These are either fermion DM motivated by SO(10) unification models, or scalar DM, in models with spontaneous breaking of lepton flavor symmetries, or other scalar DM motivated in a class of composite Higgs models providing an alternative solution to the hierarchy problem.

Highlights in Cosmology and dark energy

These topics are developed by D. Polarski and PhD students and various external collaborators. Dark energy models aim to explain the present phase of accelerated expansion of the universe. Like with inflationary models, a wealth of observationally viable models exists. It is thus crucial to be able to select models using their precise predictions when these are confronted with present or future data. For this purpose it is necessary to study both the universe expansion, as well as the growth of perturbations. A modification of gravitation could be one of the keys to this major problem in cosmology, well-known examples being scalar-tensor models and models of the f(R) type. Surprisingly, it was shown that many f(R) models are in fact producing a non-viable expansion. Moreover a detailed study of the growth of perturbations in viable f(R) type models shows that perturbations in these models have a specific signature allowing to clearly differentiate them from the 'LambdaCDM' model and this was also shown for some scalar-tensor models. Similar results were obtained for chameleon models. The background dynamics of running vacuum energy models was studied, best-fit models undistinguishable from LCDM and some interesting conceptual problems were exhibited. Finally the crossing of future soft-singularities was studied for a class of tachyon models.

Highlights in nonperturbative method for QCD and other models

Since several years, J.-L. Kneur, A. Neveu (PMTC team) and external collaborators (M. Pinto, R. Ramos, Brazil) have developed a non-perturbative approach based on a variationally modified optimized perturbative expansion. Recently JLK and AN have shown that renormalization group properties uniquely fix the variational mass interpolation in terms of anomalous dimensions, which drastically improves the empirical convergence properties of the series. They have also provided generic cures to previous problems, principally the generally non-real optimized solutions beyond lowest order. The method has been recently applied to calculate the nonperturbative basic scale Lambda_QCD from the pion decay constant, deriving a new independent rather precise prediction of alpha_s(mZ) in good agreement with experimental values and recent lattice simulations.

Rayonnement et attractivité académiques

Topic 1: *Mathematical Physics / Field Theory*

Prix et distinctions: V.Fateev was awarded with **Gay-Lussac Humboldt Research Award 2011**.

Réseaux scientifiques: V.Fateev participated to the projects **PICS**-09-02-91064 and **PICS**-09-02-93106-CNRS Landau Institute and ITEP (Moscow, Russia). N.Crampé participated with E.Ragoucy (LAPTH UMR5108) to the project **PEPS** "Physique théorique et ses Interfaces".

Attractivité nationale et internationale (recrutement, chercheurs invités…) : The group recruited 1 CR CNRS (N.Crampé) and 1 ATER (S.Belliard). The group recruited 1 post-doc V.Belavin.

Following foreign researchers were invited by the group for research stays: A.Belavin (Landau Institute), G.Jona-Lasinio (U. Roma « Sapienza »), R.Ramakrishnan (ICTP, Trieste), E.Onofri (U. Parma), E. Ragoucy (LAPTH, Annecy), P. Le Doussal and K. Wise (ENS Paris), C.Thorn (U. Florida), L.Brink (U. Uppsala), P. Ramond (U. Florida), P.West (King's College), M.Halpern (UC Berkeley).

V.Fateev was invited several times as invited professor or invited research scientist to U. Parma (Italy), Brookhaven National Lab (U.S.A.), Rutgers University (U.S.A.), Landau Institute (Russia), DESI Hamburg (Germany), U. Bonn (Germany). P.K.Mitter was invited as research scientist to U. Roma « Sapienza » (Italy). S.Alexandrov was invited as research scientist to Perimeter Institute (Canada).

Expertise : V.Fateev participated to the « **comité d'évaluation** de l'Institut de Physique Théorique de Saclay » in 2011. V.Fateev is a member of '**Advisory Board** of Annual International Parma School in Theoretical Physics. A.Neveu is a member of "**jury du Programme Blanc de l'ANR** (2011-2013) » Member of « **comité de visite AERES** du Laboratoire de Physique Théorique de l'Ecole Normale Supérieure de Paris ». Ph.Roche is an expert for **ANR** projects. S.Alexandrov has been an expert for **ANR** projects and for the program « Retour post-doctorants 2009 ».

Contrats institutionnels sur financement public (ANR, PCRD...): The group members participated to 2 **ANR** projects, as well as to PEPS and PICS projects (voir l'annexe 6)

Topics 2: *Statistical Physics*

Prix et distinctions : I.Campbell was awarded with **"Grand Prix Ampère 2009"** de l'Académie des Sciences . W.Kob was awarded with: 1) **Darshana and Arun Varshneya Frontiers of Glass Science Lecture Award** 2013 by the American Ceramic Society; 2) **Prix Ivan Peyches** de l'Académie des Sciences in 2011. W.Kob is a senior member of the Institut Universitaire de France since 2010.

Réseaux scientifiques: All members of the group participate to the activities of the GDR Phenix (statistical and non-linear physics). E. Pitard is a member of its **scientific committee** since 2010. S.Ispas, D.Coslovich, W.Kob participate to GDR Verres, GDR Modélisation Matériaux, GDR Matinex. W.Kob participates to **GPS** (scientific committee) of the **Labex Numev**. E.Pitard participates to "Réseau National des Systèmes Complexes"

Attractivité nationale et internationale: The group recruited 1 CR CNRS (M.Clusel) and 1 Maître de Conférence (D.Coslovich) The group recruited following post-docs: I. Neri (Sept 2010-2013), ANR project; A.Ikeda (since April 2011), Region Languedoc-Roussillon contract; D. Levis (since November 2012), ERC contract; T. Kawasaki (since April 2013) ERC contract; M. Matsubara (2007/2008, 22 months), ANR project; L. Pedesseau (2009/2011, 18 months), ANR project.

The group has invited following foreign researchers: A.Moreno, Donostia International Physics Center, San Sebastian (Spain), February 2011; P.Ziherl, Jozef Stefan Institute, Ljulbljana (Slovenia), November 2011; G.Szamel, Colorado State University (USA), April-July 2009; E.I.Corwin, Department of Physics, University of Oregon (USA), January-February 2012; J.Horbach, University of Dusseldorf, December 2009; P.Chaudhuri, January-April 2008; I. Plans, June 2008-November 2009; S.Roldan-Vargas, January-April 2009; Lorenzo Rovigatti, March-April 2009

Members of the group were invited as invited professors or invited scientists: M.Clusel: University of Oregon (USA), August-October 2011; M.Clusel: New York University (USA), June-July 2010 W. Kob: June 2010 (1 month): Visiting scientist at the Kavli Institute of Theoretical Physics in Santa Barbara (USA) W. Kob: June 2012 (1 month): Invited professor at the Department of Physics at University of Rome "La Sapienza"

Organisation de manifestations scientifiques: E. Pitard organized 1 workshop « Network Dynamics » March 2013, Montpellier. D.Coslovich co-organized the workshop: CECAM workshop, "Complex dynamics of fluids in disordered and crowded environments" with V. Krakoviack (Lyon) and G. Kahl (Vienna), June 28th 2010 - July 1st 2010, Lyon. S. Ispas co-organized the workshop: SiMaDes3 avec P. Jund (Institut Charles Gerhardt), (2009) Montpellier.

Expertises: W.Kob was a member of evaluation committee of the Institute of Material Physics in Space at the German Aerospace Laboratory. W. Kob is the Chair of « Review Panel Commission on Soft Condensed Matter at the Linac Coherent Light Source at Stanford University » since 2010. E. Pitard is an ANR expert. M. Clusel is an expert for the Israel Science Foundation. S. Ispas: Expert of the GENCI (Grand Equipement National de Calcul Intensif) and ANR expert. S. Ispas is a member of the "comité de pilotage du centre de calcul haute performance HPC@LR".

Contrats institutionnels sur financement public (ANR, PCRD...) : Members of the group participate (as members or coordinators) in **7 ANR contracts**, as well as in contracts PEPS, PHC Alliance France - Grande Bretagne, and RNSC financial support (voir l'annexe 6). L. Berthier is the recipient of the **ERC Starting Grant** and of the Grant "Chercheur d'avenir", Languedoc-Roussillon Region.

Topics 3: *Complex Systems and Non-linear Phenomena (SCPN)*

Prix et distinctions: M.Dyakonov was awarded with: 1) "**Prix Félix Robin"** de la Société Française de Physique (2009) » ; 2) **"Beller Lectureship Award"** of the American Physical Society (2009).

Réseaux scientifiques: M.Dyakonov is the Scientific Coordinator d'un Collaborative research project between UMII and Italian enterprises NTT (New Tera Technology). A.Kavokin is the coordinator of the Collaborative research project with the Rome University "Tor Vergata". A.Kavokin is the co-coordinator of the Collaborative research project with the University of Sao Paulo, Campinas, Brazil. A.Kavokin is the Scientific Director of **Mediterranean Institute of Fundamental Physics** created in 2010 in Italy with participants from the United States, Canada, Great Britain, France, Sweden, Greece, Italy, Germany, Russia, and Brazil. V.Lorman and A.Parmeggiani are members of the International Network **"IPOLS : International Physics of Living Systems"** established by the NSF (U.S.A.) and the CNRS. Members of the network : U. Princeton, U. Harvard, U. Yale, UCSD, U. Rice, GeorgiaTech, U. Illinois, Institut Curie, with the participation of U. Cambridge (U.K.), U. Heidelberg (Germany), and U. Tel Aviv (Israel). « Kick-off meeting » was organized in à Montpellier in 2012. V.Lorman is a member of the **GPS** (scientific committee) of the **LabEx "NUMEV"** (Solutions Numériques, Matérielles et Modélisation de l'Environnement et du Vivant). V.Lorman is the French coordinator (member of the Management Committee) of the **COST Action** "Integrating devices and materials: a challenge for new instrumentation in ICT" (2013-1017). J.Dorignac is a member of the administration council of the

International Consortium EINSTEIN (Italy, France, Russia, Great Britain), focused on the Non-linear Physics. A.Parmeggini is a member of the "Comité d'Organisation et de Pilotage du Réseau Régional **ModSysC2020** (Systèmes Complexes, CNRS, INRA, INRIA, CIRAD, IRD, UM1, UM2, UM3)". V.Lorman participates to this network. A.Parmeggini is a member of the « Comité de Pilotage du Programme Interdisciplinaire du CS de l'UM2 "Modélisation du Vivant".

V.Lorman et A.Parmeggiani are members of the "Groupe de Recherche Interdisciplinaire sur les Systèmes Biologique (**GRISBI**)" which links physicists of the physics/biology interface with the researchers of 11 labs of the Pôle Biologie/Santé, Pôle Biologie/Environnement and Pôle Chimie on Montpellier site. A.Parmeggiani participates to the research network with biology and experimental biophysics groups (CRLC Val D'Aurelle-Montpellier, IGMM-Montpellier, BPMP-INRA-Montpellier, DIMNP-Montpellier, CBS-Montpellier, Raman Institute-Bangalore, India). J.Palmeri participates to the « Groupement d'Intérêt Scientifique : Modélisation et traitement de l'Information pour Biologie Systémique (**GIS MIBS**) ». V.Lorman, A.Parmeggiani, A.Callan-Jones, F.Molino, J.Palmeri are members of the GDR 3070 « Physique de la cellule aux tissus ». A.Parmeggiani participates to the GDR 2588 « Imagerie Fonctionnelle du Vivant ». V.Lorman and A.Parmeggiani participate to the "Axe interdisciplinaire" of the Pôle Bio/Santé Rabelais. A.Parmeggiani and F.Molino participate to the activities of the LabEx "EpiGenMed". A.Parmeggiani, V.Lorman, M.Manna and J.Palmeri participate to the activities of the du LabEx "NUMEV"**.** J.Palmeri participates to the activities of the LabEx "CHEMISYST".

Attractivité nationale et internationale : The group recruited 1 Professor (A.Parmeggiani) and 1 Maître de Conférences (A.Callan-Jones). In addition, 1 Maître de Conférences (F.Molino) joined the group by change of affiliation procedure and 1 DR CNRS (J.Palmeri) joined the group by mutation procedure to reinforce the activity at the Physics/Biology Interface. The group recruited as temporary DR (CDD de 3 ans) the well-known specialist in the light-matter coupling domain (A.Kavokin) to reinforce the collaboration with experimental groups on spin physics, exciton and photon physics on nanometer scale. The group benefited from the invitation of the Nobel Prize 2003 winner Prof. Antony Leggett (2012). The group benefited from the research stays of S.Rochal (Southern Federal University, Russia, Interface physics/biology) and R.Kraenkel (Fluid Mechanics, Universidade Estadual Paulista (UNESP), Sao Paulo, Brazil). The group recruited following post-docs: M.Lifshits (Physics of spin) 2009-2012 ANR project; K.Romanov in the field of TeraHertz physics (2011-2013) ANR project; S.Buyukdagli (charged fluids) 2008-2010 ANR project; S.Noubissié in the field of fluid mechanics, 2008-2009, international grant ; L.Ciandrini (physics/biology interface) 2013-2014, European Molecular Biology Organization (EMBO) grant; J.-C.Walter (physics/biology interface) 2013, LabEx NUMEV financial support;

During the period 2008-2013 M.Dyakonov was several times invited as an invited professor or invited scientist to Argonne National Lab (U.S.A.), University of Minnesota (U.S.A.), University of Wurzburg (Germany), University of Regensburg Germany), Max Planck Institute, Stuttgart Germany), Data Storage Institute (Singapore), Ioffe Institute Russian Academy of Sciences, St. Petersburg (Russia), Warsaw University (Poland). M.Manna was several times invited as an invited professor or invited scientist to Universidade Estadual Paulista (UNESP), Sao Paulo (Brazil). V.Lorman was several times invited as an invited professor or invited scientist to University of Ljubljana (Slovenia), Saarland University (Germany), Universidade de Sao Paulo (Brazil), EPFL, Lausanne (Switzerland). J.Palmeri was invited as an invited professor to Boston University (Boston, USA), (2010)

Expertises: M.Dyakonov is an expert responsible for attribution of "Grants of the Government of the Russian Federation". V.Lorman is an expert for scientific programs, research projects and « research professor » applications for Southern Federal University (Russia), Ghent University (Belgium), University of Ljubljana (Slovenia), Dublin Institute of Technology (Ireland). V.Lorman is an expert at 'AERES. J.Palmeri is an expert for Program ANR *PRODUCTION DURABLE ET TECHNOLOGIES DE L'ENVIRONNEMENT* (2010) J.Dorignac is an elected member of the 29 CNU section.

Organisation de manifestations scientifiques: M.Dyakonov is the organizer of the International Workshop "MIRO and all that", May 2013, Montpellier. A.Parmeggiani is the co-president and V.Lorman is a member of the organizing committee of the "Journées d'Etude du Groupe de Recherche Interdisciplinaire sur les Systèmes Biologiques", Montpellier, 2010 V.Lorman is the co-president of the organizing committee of the International Conference « Physical Virology », International Centre for Theoretical Physics (ICTP), Trieste, Italy, September 2012. A.Parmeggiani is the co-president of the organizing committee of the International Summer School "Fundamental Problems in Statistical Physics XIII", Leuven, Belgium, June 2013. A.Parmeggiani is the co-president of the organizing committee of the workshops "Modélisation et Simulation du Vivant et de l'Environnement" (sponsored by the CS of the UM2) (2009-2011). J.Palmeri is the co-organizer of the « From Quantum Foundations to Quantum Fluids » in honor of Prof. A.J. Leggett, Nobel Prize 2003 winner, Toulouse, April 2012. J.Dorignac and F.Geniet are the organizers of the international workshop "Non-linear Physics" in memory of J. Léon, Montpellier, November 2011. A.Kavokin is the co-president of the organizing committee of the International Conference « Physics of Light Matter Coupling in Nanostructures », Montpellier, 2014

Contrats institutionnels sur financement public (ANR, PCRD...) : Members of the group participate (as members or coordinators) in **3 European contracts**, **11 ANR** contracts, **2 contracts CNRS interdisciplinary program** « Interface physics-chemistry-biology », 3 contracts of the Labex NUMEV, as well as PEPS contracts, and contracts of the interdisciplinary program "Modélisation du Vivant", (voir l'annexe 6).

Topic 4: *Fundamental interactions, Astroparticles and Cosmology (IFAC)*

Réseaux scientifiques : All group members participate to the GDR "Terascale" (2008-2012) and (2013-2017). J-L.Kneur was the convene of the **GDR** "Terascale" (2008-2012). G. Moultaka is the **co-director** of the **GDR** 'Terascale' (2013-2017). Network "Theory LHC France" (IN2P3 financial support) (2008-2012). PEPS CNRS (INP-IN2P3) with ATLAS CPPM Marseille members (2010-2011). Integrated action AI n° MA/08/186 (2008 -2011), Hubert Curien program 'Volubilis', France/Morocco (French leader: G. Moultaka). LIA-ILCP, **International Laboratory for Collider Physics**, France/Morocco/Sweden (2009-2013). M. Frigerio is a member of the European Network "ITN Invisibles" (started in 2012). All group members participate to the activities of the LABEX "OCEVU" (origines, constituants, évolution de l'univers). G.Moultaka is a member of **Executive Committee of the LABEX "OCEVU"**.

Attractivité nationale et internationale (recrutement, chercheurs invités…): The group recruited 1 CR CNRS (Michele Frigerio) and 1 ATER (David Gherson). The group recruited following post-docs : A.Jokinen (2008); David Gherson, 2008-2009; Albert Villanova del Moral (postdoc IN2P3) 2009-2012.

Regular invitations/collaborations: M. Kuroda (Univ. Meiji Gakuin, Japan); T. Hambye (ULB Brussels),A. Starobinsky, Landau Institute, Moscow, Russia; S. Tsujikawa, Tokyo University of Science, Japan; D. Mota, Oslo University, Norway S. Kamenshchik, Bologna University, Italy

Expertises: J-L Kneur: 1) nominated member of CNRS national committee section 2 (theoretical physics) 2008-2012 ; 2) member of the AERES committee for LPT Orsay evaluation (December 2008). G. Moultaka : 1) ANR referee; 2) Scientific Council member of IPN-Lyon (2012-2016) ; 3) Member of the OCEVU Labex executive committee.

Organisation de manifestations scientifiques: Annual Meetings of the GDR Terascale. **International Conference** 'Identification of Dark Matter' (IDM2010) (July 2010 Montpellier) organized by the members of the IFAC group. 'Rencontres Physique des Particules' (Montpellier Mai 2012) organized by the members of the IFAC group Yearly 'Cosmology workshop' (Montpellier): organized by D. Polarski. Alexei Smirnov Fest within the workshop "What's nu?" (Florence June 2012) co- organized by M. Frigerio

Contrats institutionnels sur financement public (ANR, PCRD...) : Members of the group participate (as members or coordinators) in **1 contrat International Laboratory**, **1 contrat européen, 1 contrat ANR**, 1 Action Intégrée ainsi que dans les contrats PEPS (voir l'annexe 6).

Interactions avec l'environnement social, économique et culturel

A.Neveu gave 2 "conférences grand public": 1) May 2011: Invited Conference in Moscow on the LHC and quark-gluon plasma on the occasion of Andrei Sakharov 90th anniversary, with simultaneous translation; 2) April 2013 : 2 "conférences grand public" at the "Université du Tiers Temps" in Montpellier: "Les premiers instants de l'Univers en laboratoire" and "Qu'est-ce qu'une particule élémentaire?".

E.Pitard participated to: 1) "journée d'échange" with high-school (lycée) students '"Pour les femmes et la science'", l'Oréal- Unesco-Académie des sciences, November 2008, Palais de la Découverte, Paris, 2) Days '"Découverte des métiers scientifiques au féminin" for high-school (lycée) students, 3) conference for the association ConnaiSciences, January 2011, Ecole des Mines d'Alès, Nîmes. E.Pitard is the co-editor and et the coordinator of the collective "grand public" book: "Panorama des Systèmes Complexes" (éditions Belin), to be published in 2013. W.Kob gave "conférence grand public": « Le verre : un solide mystérieux... qui coule », Mars 2009, Montpellier, Délégation Régionale du CNRS.

A.Neveu was a member of the Scientific Committee of the University Montpellier 2 and the 1st Vice-President of the UM2 during 2008-2012 E.Buffenoir was the Vice-President of the Administration Council of the University Montpellier 2 during 2008-2012 has focused his activities on this duty. E.Pitard was a member of the Scientific Committee of the University Montpellier 2 during 2008-2010 ; member of its bureau, organizer with A. Parmeggiani and B. Godelle of the pluridisciplinary program "Modélisation et Simulation du Vivant et de l'Environnement". V.Lorman was a member of the Administration Council of the University Montpellier 2 (2008). A.Parmeggiani was a member of the CEVU Council of the University Montpellier 2 during 2008-2012.

M.Dyakonov gave 2 "conférences grand public": "La foudre", Conférence SFP Grand Public, Nice, 30 mars 2010, and "Conférence Grand Public" of the University Montpellier 2, 2009. F.Molino gave 4 "conférences grand public" : at Ladislav Tauc Conference Paris 2010 ; and at "Maison de l'école polytechnique", Paris 2011 ; at Colloque "Darwin 2011", Paris 2011 and in the frame of 'ED CPBS, Montpellier 2012. F.Geniet gave **11 "conférences grand**

public" focused on the themes "Science et Musique", "La couleur et sa mesure", and "A quelle vitesse passe le temps ?" : at different high-schools (lycées), secondary schools (collèges) and primary schools (écoles) of the Languedoc-Roussillon region; at the "Université du Tiers Temps"» ; at "Bar des Sciences", in the frame of the "Conférences grand public (TAKTIK)" network ; at the student Association "Quanta", at "Journées Portes Ouvertes de l'UM2".

Members of the group IFAC participated several times to the activities of the scientific culture dissemination, namely « Fêtes de Science » ; Members of the IFAC group gave several lectures at high-schools (lycées) (including "conférences Nepal"), "conférences grand public" at the Bar des Sciences, at the Planétarium Galilée Montpellier-Agglomération, for associations; Members of the IFAC group organized the « Exposition grand public 'le LHC et la physique des particules' » (May 2009); Members of the IFAC group participated to debates and gave interviews to local press (Midi Libre, L'Hérault du jour and radios, namely after the announcement of the scalar boson discovery in July 2012).

Implication de l'équipe dans la formation par la recherche

-The Team contributes significantly to the Doctoral Specialty « Physics » of the Doctoral School (ED) I2S. V.Lorman was the **coordinator of this Doctoral Specialty** until 2010. V.Lorman is the director of the **Mention « Physique » du Master** of the University Montpellier 2. A.Parmeggiani is the **co-responsible of the parcours** « Physique et Ingénierie du Vivant » of this Master.

-Members of the Team are coordinators of a big number of M2 courses (unités d'enseignement) of the "Master Physique". In the parcours "Cosmos, Champs et Particules ", "Physique Informatique", "Physique et Ingénierie du Vivant"; members of the Team constitute the basic part of the coordination and pedagogical team. They coordinate also M2 course in the parcours "PhyMaTech".

-Members of the Team supervised a whole series of Ph.D. theses in the frame of the Doctoral Specialty "Physics" of the ED I2S and internships of the "Master Physique" of the UM2. They also supervised internships of the students from University of Pisa (Italy), University Aix Marseille, Landau Institute, Moscow (Russia), University of St. Petersburg (Russia), NYU, New York (U.S.A.), Cornell University (U.S.A.), and ENS Cachan.

-Members of the Team gave dozens of lectures at different « Ecoles Thématiques du CNRS", "Ecoles d'Eté", "Ecoles d'Hiver", including several Cargèse and Les Houches Schools, International Summer Schools and International Winter Schools all over the world.

agence d'évaluation de la recherche et de l'enseignement supérieur

Présentation synthétique de l'entité
Unité de recherche
Vague E : campagne d'évaluation 2013-2014

Team "Theoretical Physics"

Intitulé de l'unité : Laboratoire Charles Coulomb, L2C, UMR 5221

Nom du directeur de l'unité : Jean-Louis SAUVAJOL

Nom du responsable de l'équipe (le cas échéant) : Vladimir LORMAN

Effectifs de l'équipe. 13 University professors (EC) + 1 Emeritus Professor; 12 CNRS researchers (C) + 3 DR CNRS Emeritus + 1 contract DR (CDD); 3 technicians, engineers and other staff members; 13 post-docs and Ph.D. students.
Personnels ayant quitté l'entité pendant le contrat en cours (et nombre de mois cumulés passés dans l'entité au cours de cette période). 2 Statutory members (83 months) : 1 CR (S.Ribault, 45 months) ; 1 PR (J.Léon, deceased, 38 months) ; 10 Ph.D. students (287 months) ; post-doc (158 months) : including PMTC: post-docs (16 months); PhSt : Ph.D. students (72 months), post-docs (40 months) ; SCPN : Ph.D. students (68 months), post-docs (56 months); IFAC : Ph.D. students (147 months), post-docs (46 months).
Nombre de recrutements réalisés au cours de la période considérée et origine des personnels. 6 recruitments: 1 PR (A.Parmeggiani, MCF at DIMNP, Montpellier) ; 2 MCF (A.Callan-Jones, Post-doc, Institut Curie, Paris ; D.Coslovich, post-doc, University of Vienna, Austria); 3 CR CNRS (N.Crampé, post-doc, SISSA, Trieste, Italy ; M.Cluzel, post-doc, New York University, USA ; M.Frigerio, post-doc, Autonoma University of Barcelona, Spain)
2 Team members joined the Team by the change of affiliation procedure 1 MCF (F.Molino, IGF, Montpellier), and 1 DR CNRS (J.Palmeri, LPT, Toulouse).

Production scientifique au cours de la période écoulée (1er janvier 2008 - 30 juin 2013) :
1) "On AGT conjecture", V.A. Fateev, A.V. Litvinov, JHEP 1002 (2010) 014. In these notes we consider relation between conformal blocks and the Nekrasov partition function of certain N=2 SYM theories proposed recently by Alday, Gaiotto and Tachikawa. We concentrate on N=2* theory, which is the simplest example of AGT relation. **2**) "A "granocentric" model for random packing of jammed emulsions", M. Clusel, E.I. Corwin, A.E.O Siemens and J. Brujic, Nature 460 (2009), 611-615. We developed a statistical model for the random packing of frictionless polydisperse spheres by considering the « granocentric » point of view of a single particle in the bulk. The model gives access to the microscopic distributions of nearest neighbours and contacts, the local density fluctuations as well as the global density of the packing. **3**) "Chiral Quasicrystalline Order and Dodecahedral Geometry in Exceptional Families of Viruses", O.V. Konevtsova, S.B. Rochal, V.L. Lorman, Phys. Rev. Lett. 108 (2012) 038102; We show a new type of matter organization in exceptional families of viruses, with regions with quasicrystalline order of protein positions arranged in a structure commensurate with the spherical topology and dodecahedral geometry. **4**) "On the growth of linear perturbations", D. Polarski, R. Gannouji, Phys. Lett. B660 (2008) 439-443. In order to pinpoint the nature of dark energy, in particular of its gravitational sector, one can use the growth "index" of the matter perturbations. We have shown that a quasi-constant "index" as in LCDM arises generically in non-interacting smooth dark energy models inside General Relativity.

Bilan quantitatif des publications : Articles in the international peer review journals : **310**, including PMTC: 70; PhSt: 118; SCPN: 89; IFAC: 33; **Invited Conferences**: **159**, including PMTC: 36 ; PhSt :79; SCPN: 23; IFAC: 21 **Conferences**: **50**, including PhSt : 39 ; SCPN : 11.

Indiquer les **5 publications majeures: 1)** PMTC : 'On AGT conjecture', V.A. Fateev, A.V. Litvinov, JHEP 1002 (2010) 014; **2)** PhSt : 'Theoretical perspective on the glass transition and amorphous materials', L. Berthier, G. Biroli, Reviews of Modern Physics 83 (2011), 587; **3)** SCPN : 'Chiral Quasicrystalline Order and Dodecahedral Geometry in Exceptional Families of Viruses', O.V. Konevtsova, S.B. Rochal, V.L. Lorman, Phys. Rev. Lett. 108 (2012) 038102; **4)** IFAC : 'On the growth of linear perturbations', D. Polarski, R. Gannouji, Phys. Lett. B660 (2008) 439-443; **5)** 'Gravitino Dark Matter and the Cosmic Lithium Abundances', S. Bailly, K. Jedamzik, G. Moultaka, Phys. Rev. D80 (2009) 063509.

Indiquer **au maximum 5 documents majeurs : 1)** Free Public Software 'SuSpect' (authors: A.Djouadi, J-L.Kneur, G.Moultaka): Calculation of the masse spectrum and related properties in different supersymmetric models **(Comput.Phys.Commun. 176 (2007) 426-455)** last version 2.41 (08/2008); major update in spring 2013. This code is widely used by the international community of high-energy physics (>580 citations so far). **2)** A.Neveu produced expertise reports du « Jury du Programme Blanc de l'ANR (2011-2013) »

Indiquer **au maximum 5 faits illustrant le rayonnement ou l'attractivité académiques:** 1) Members of the Team were awarded with **6 major scientific prizes** : a) I.Campbell : **Grand Prix Ampère** de l'Académie des Sciences (2009) ; b) M.Dyakonov: **Prix Félix Robin** de la Société Française de Physique (2009) c) **M.**Dyakonov: **« Beller Lectureship Award »** of the American Physical Society (2009) ; d) W.Kob: **Prix Ivan Peyches** de l'Académie des Sciences (2011) ; e) V.Fateev: **Gay-Lussac Humboldt Research Award 2011 (2012) ;** f) W.Kob: **Darshana and Arun Varshneya Frontiers of Glass Science Lecture Award** of the American Ceramic Society (2013).

2) M.Dyakonov was invited to give a **Plenary Lecture at the APS March Meeting** (2009); members of the team gave more than 140 invited lectures at national and international conferences.

3) Team members participate actively in GDRs: GDR 'Terascale', convener (J-L.Kneur, 2008-2012), co-director (G.Moultaka, since 2013); GDR Phenix, member of Scientific Committee (E.Pitard); GDR Verres; GDR Modélisation Matériaux; GDR Matinex; GDR Physique de la cellule aux tissus; GDR Imagerie Fonctionnelle du Vivant; The Team participates in international collaborative networks : CNRS - Landau Institute - ITEP (Moscow); IPOLS - International Physics of Living Systems (NSF-CNRS) with Harvard, Princeton, Yale, Rice, UCSD, etc.; Mediterranean Institute of Fundamental Physics; International Consortium EINSTEIN; LIA-ILCP, International Laboratory for Collider Physics, France/Morocco/Sweden; European Network 'ITN Invisibles', and many national networks.

4) Team members organized national and international conferences: « Network Dynamics », March 2013, Montpellier; CECAM workshop « Complex dynamics of fluids in disordered and crowded environments », June-July 2010, Lyon; International Workshop « MIRO and all that », May 2013, Montpellier; International Workshop « Non-linear Physics » in memory of J. Léon, November 2011, Montpellier; International Conference « Physical Virology », September 2012, ICTP Trieste, Italy; International Summer School « Fundamental Problems in Statistical Physics XIII », June 2013, Leuven, Belgium; and others.

Indiquer **au maximum 5 faits illustrant les interactions de l'entité avec son environnement socio-économique ou culturel**

1) Organization and participation to « Exposition grand public « le LHC et la physique des particules » » (May 2009)

2) Interviews with local press (Midi Libre, L'Hérault du jour) and radio stations after scalar boson discovery announcement by LHC in July 2012

3) More than 40 "conférences grand public" at high-schools (lycées) of the Region, at secondary and elementary schools, at the Bar des Sciences, at the Planétarium Galilée Montpellier-Agglomération, for several associations, at the « Université du Tiers Temps », at "Journées Portes Ouvertes de l'UM2"; at the International Conference on the occasion of Andrei Sakharov 90th anniversary in Moscow

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Indiquer **les principales contributions de l'entité à des actions de formation**: Members of the Team supervised **23 Ph.D. theses** (13 are already defended and 10 are currently in progress) V.Lorman is the director of the mention « Physique » of the UM2 Master; A.Parmeggiani is the co-responsible of the parcours « Physique et Ingénierie du Vivant » of the Master. Several members participate actively in coordination of the parcours "Cosmos, Champs et Particules" and in the parcours "Physique Informatique" of the Master. Members of the Team are the coordinators of about 15 Master courses and Doctoral courses. V.Lorman was the coordinator of the Doctoral Specialty « Physics » of the UM2 until 2010.

Team: “Soft Matter”

Team: "Soft Matter"

The activities of the group cover a large spectrum of experimental studies of the structure and dynamics of soft condensed matter. All classical systems of soft matter are in some way or the other present in our labs, like surfactants, polymers, colloids, liquid crystals, and biophysical systems. In parallel, we innovate by creating new systems, like colloids at structured interfaces, composites, or specific protein assemblies. All of them are studied by scattering techniques, different types of microscopy, rheological or mechanical experiments, may they be in standard or home-made geometries. In this overview of the results obtained since 2008, we have chosen to highlight five research activities: complex interfaces, glassy and jammed soft matter, biological systems, mechanical instabilities of complex fluids, and soft composites.

Topic: *Complex interfaces*

Physics of interfaces have enjoyed a renewed interest thanks to the introduction of new experimental tools and theoretical concepts able to design and rationalize interfaces with large degree of complexity. In this context, the main results of the group concern: A) the characterization of static and dynamic properties of liquid crystal interfaces presenting correlated quenched disorder and B) the design and characterization of liquid interfaces presenting complex morphologies and order and their coupling with colloidal particles trapped on them. We have received funding by a French-Ukrainian program and Marie-Curie fellowships.

A) Disorder and dynamics at liquid crystal/solid interfaces (C. Blanc (CR1), M. Nobili (PR1), M. Nespoulous (PhD), K. Slyussarenko (PhD), E. Angot(BSc), K. Antonova (visiting scientist), Y. Reznikov (IOP, Kiev Ukraine)).

Quenched disorder is ubiquitous in condensed matter. It refers to a disorder that is frozen; i.e., it does not change in time. In systems with orientational degrees of freedom like ferromagnets, ferroelectrics, and liquid crystals, it profoundly affects the out-of-equilibrium dynamics. In crystals, disorder measurements are difficult to realize due to the typical microscopic length scale of the heterogeneities. In this respect, a nematic liquid crystal is a system of choice as the quenched heterogeneities scale up to easily accessible optical scales. We measured the orientational quenched disorder and its spatial correlations by direct imaging of the surface orientations of a nematic liquid crystal [*PRL* 097801, **2010**]. A formal analogy with the Langevin equation proves unequivocally the correlated character of the measured disorder. The origin of this correlation is still subjected to debate but the substrate morphology and the liquid crystal adsorption on the substrate play certainly important roles.

This measured surface orientational disorder could eventually couple with the orientation degrees of freedom of the liquid crystal and be a source of rotational solid friction. This kind of friction is analogous to the solid static friction force between two sliding bodies given by the Coulomb's law where pinning by disordered asperities of the contacts play an important role. In simple fluids, solid friction is not possible as a force applied to the fluid induces viscous friction. Surprisingly in complex fluids, as liquid crystals, a solid friction may appears as the orientational elasticity can convey this surface force to the bulk as in solids. We have measured the orientational dynamics through macroscopic liquid crystal defects moving on surface having well characterized quenched disorder [*PRL* 127801, **2010**]. Quantitative analysis (see Figure 1) unambiguously reveals the presence of solid friction forces on the defects, which are equivalent to a solid friction torque for the surface director. Led by the analogy with the solid-solid friction, sensitive to both interface disorder and plastic mechanisms, we have discussed the respective roles of the easy-axis disorder and the ''plastic'' memorization on the measured dynamics.

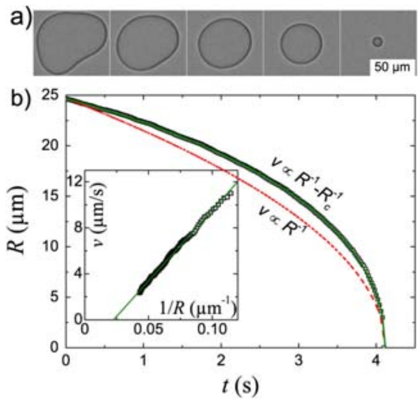

Fig-1: a) Evolution of a π-wall loop in a nematic cell. B)The analysis of the dynamics reveals the existence of a pinning force due to the substrate.

Note finally that when the substrate is softer (polymer layers), we have evidenced [*PRE* 050701(R), **2011**] more complex behaviours where the liquid crystal rotation strongly modifies the mechanical properties of the anchoring layers and strongly influences its temporal evolution.

B) Colloidal physics at liquid interfaces (M. In (DR2), M. Abkarian (CR1), M. Gross (DR2), C. Blanc (CR1), M. Nobili (PR1), M. Gharbi (PhD), D. Federenko (post-doc), T.Lopez Leon (post-doc)).

The interface between two fluids is extremely efficient to trap particles ranging from nanometer to millimeter sizes. For spherical particles trapped at planar interfaces, this strong confinement has been used to address fundamental problems of 2D condensed matter physics. However, in real systems, the particles are not always spherical, the interface could be curved [*PRL*, accepted] or the liquids could be structured [*Soft Matter* 1467, **2011**, and **2013**].]. In the framework of the ANR Surfoids, we have explored such complex trappings and how to use them to create new soft matter organizations. Main achievements concern: a) The measurements of the extremely tiny lateral capillary forces down to femto-Newton acting on a spherical colloids placed on a curved fluid interface of arbitrary shape. Measurements agree well with a theory relating the capillary force to the gradient of Gaussian curvature and to the mean curvature of the interface [*PRL,* accepted]. b) The discovery of new colloidal organisations at nematic liquid crystal/air interfaces resulting from the delicate competition between nematic elasticity and molecular anchoring at the particles surface [*Soft Matter* 1467, **2011**]. Future focus will concern an <u>increase of complexity in surface profile and how lateral forces arise</u>, coupling with particle morphologies beyond the spherical one, and with particles activity.

C) Liquid crystal emulsions (M. Nobili (PR1), C. Blanc (CR1), M. Gharbi (PhD), T.Lopez Leon (post-doc))

Competition between elasticity and interface tension might also produce complex shapes in liquid crystals emulsions. Using surfactants design [*JPCB* Lett 4157, **2008**] and microfluidics techniques [*PRL* 247802, **2011**; *J Phys: Cond Mat* 284122, **2012**; *PRE* 020705(R),**2012**], we obtained several original systems such as nematic filaments or smectic shells (see Figure 2) and explained the underlying mechanisms that control their shape and textures. On one of these controlled interfaces namely nematic shells, we have also shown that the position of trapped particles could be easily controlled through capillarity effects. In future work, these phenomena could be used to create microspheres with tunable valences and directionalities [*Soft Matter* **2013**].

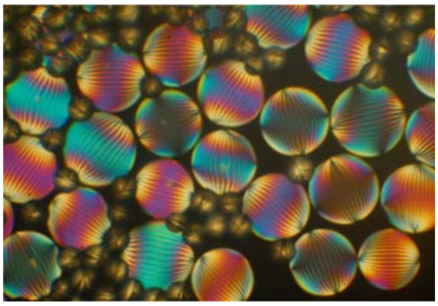

Fig-2: Textural instability in smectic shells

Topic: *Glassy and jammed soft matter*

Participants: L. Cipelletti (PR1), L. Ramos (DR2), L. Berthier (DR2, L2C Theoretical Physics), M. Ciccotti (L2C Glasses, CR1), S. Mazoyer (PhD), D. El Masri (PhD), G. Brambilla (PhD), M. Perno (Post-doc), S. Maccarrone (Post-doc).

Most soft materials that exhibit a predominantly solid-like mechanical behavior also exhibit complex slow dynamics at a microscopic level. These dynamics are actively investigated because some of these systems may be regarded as model systems to tackle long-standing problems in condensed matter (e.g. colloidal hard spheres, HS, for the glass transition), and because slow dynamics play an important role in shaping the material properties for systems of industrial interest. In recent years, this field has been further propelled by the availability of new experimental methods (confocal microscopy, space- and time-resolved light scattering…). Our activity has covered five topics (space-resolved DLS, dynamical heterogeneity, glass transition of HS, sedimentation, and supra-diffusive slow dynamics), for which the main achievements are detailed below. We have received funding from ANR DynHet, CNES, Languedoc-Roussillon region, and EU MCRTN Arrested Matter. Collaborations within the lab and internationally (R. Piazza, Milano, and V. Trappe, Fribourg) have been vital for our activity. Part of our activity has been performed as preliminary ground experiments in view of experiments to be performed on board the International Space Station, in the framework of a program sponsored by CNES and ESA.

A) *Space-resolved dynamic light scattering* **(PCI).** Using a CCD-detector and an ad-hoc optical layout, we combine imaging and light scattering to obtain a spatial map of the dynamical activity of a sample [*PRL* 085702, **2009**]. As an extension to this new method we have patented [Patent 1000133058, **2011**] a method to measure both the mesoscopic drift in a sample (*e.g.* due to sedimentation or internal/applied stress) and its microscopic dynamics.

B) *Dynamical heterogeneity***.** We have shown that unexpectedly long-ranged spatial correlations of the dynamics are ubiquitous in jammed soft matter [*PRL* 085702, **2009**; *Soft Matter* 5514, **2010**], and that temporal heterogeneity surprisingly drops on approaching the jamming transition [*Nature Phys* 550, **2008**]. Recent work on dynamical heterogeneity has been reviewed in a book that we have co-edited [Book Dynamical Heterogeneities, **2011**].

C) *Glass transition of colloidal HS***.** We have shown that colloidal HS do not undergo a glass transition "à la mode coupling theory" at a volume fraction φ_c~ 0.58, but rather cross over to an activated dynamics regime above φ_c [*PRL* 085703, **2009**; *JSTAT*, 07015, **2009**]. This unexpected result has stirred a lively scientific debate [*PRL* 199605, **2010**; *PRL* 169602, **2010**].

D) *Sedimentation and microscopic dynamics in colloidal gels***.**

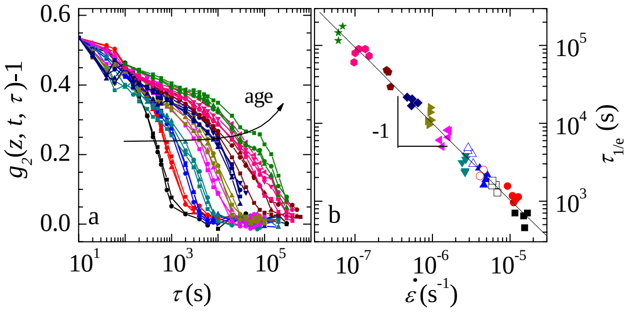

Fig-3: a) Squared dynamic structure factor measured at different heights (same color) and ages during the settling of a gel. b) The structural relaxation time scales as the inverse compressive strain rate: both the microscopic dynamics and the macroscopic settling are ruled by the same parameter.

We use PCI to fully characterize the temporal and spatial evolution of network-forming colloidal gels that settle under the gravitational stress, a problem relevant for the stability of many industrial products. While previous studies could only monitor the evolution of the total height of the gel, using PCI we measure the time dependent concentration profile, sedimentation velocity profile and the local microscopic dynamics. We find that the gel settling can be accurately reproduced using the "poroelastic" model [*J Phys: Cond Mat* 284103, **2012**]. Surprisingly, both the macroscopic settling and the microscopic dynamics are ruled by the same parameter, a time-dependent compressive strain rate [*PRL* 118302, **2011**], in analogy with strained polymer glass formers.

E) *Supra-diffusive slow dynamics in jammed and glassy systems***.** In the past, we and others have reported anomalous supra-diffusive dynamics that were ascribed to internal stress relaxation. Using PCI to measure the temporal evolution of the strain field within an actin network [*Nat Mat* 236, **2011**], we have been able to demonstrate the very existence and evolution of internal stress in a jammed system. While these anomalous dynamics were observed so far only in soft matter systems, we have recently shown that a metallic glass former also exhibits the same behavior [*PRL* 165701, **2012**].

In the future we will focus on driven glassy or jammed systems. In particular we plan to investigate plasticity, dynamical precursors in material failure, sedimentation in complex fluids. Thus the "slow dynamics" and "fracture" themes of the soft matter team will merge into a common activity.

Topic: *Physics of biological systems*

A part of the Soft Matter team activities is dedicated to the application of soft matter physics to biological systems. Our strategy is either to use conceptual tools from soft matter physics in order to explain and interpret some specific biological mechanisms occurring at the cellular scale and observed in our laboratory using videomicroscopy; or to develop biomimetic models to answer specific questions in biology or on the specific functioning or dynamics of some proteins. Here we highlight work done on actin networks, Malaria parasites, sickle cell anemia, cytoskeleton/membrane coupling, and interface crossing encapsulation. We have several collaborations in France and abroad. We benefited from funding by two ANR projects, by the UM2 scientific council (2), by the region ("chercheur d'avenir"), and by Labex Numev.

A) Actin networks (L. Cipelletti (PR1), G. Brambilla (PhD, post-doc)): We have used space-resolved light scattering to investigate the role of internal stress in the dynamics of actin networks (see "Slow dynamics in glassy and jammed soft matter" for more details) [*Nature Mat* 236, **2011**]. We are currently investigating the dynamics of active actin networks containing molecular motors.

B) Malaria parasites (M. Abkarian (CR1), G. Massiera (MdC), O.E.A. Arriagada (PhD), N. Casanova-Morales (PhD))

Egress from red blood cells and motility for invasion - Malaria is caused by a unicellular parasite, *Plasmodium Falciparum*, transmitted to the human during a mosquito meal. At the red blood cell stage, the parasite has 48 hours during which it sequentially invades a red blood cell, multiplies and is released to invade other cells. Our work is focused on the invasion and evasion steps, each lasting a very short time, which implies highly synchronized cell cultures and high-speed imaging.

-Parasite Motility: Invasion of red blood cells requires a reorientation of the apical part of the parasite towards the red blood cell membrane, without the aid of cilia, flagella or deformations. To understand how the parasite is able to move and reorient on a red blood cell membrane, we performed a detailed analysis of the parasite trajectories and orientation firstly on rigid substrates. We observe that the substrate-attached parasite explores all degrees of freedom with in-plane rotation, translation and flipping. Three types of transitory trajectories have been identified: confined, directed and circular. These trajectories and motions are characterized using correlation analysis and possible mechanisms that could explain these peculiar trajectories. It is proposed to take the cell adhesion on the substrate and the shape of the parasite into account. Finally, we also investigate the role of the cytoskeleton components in the parasite motion by affecting specific structures such as the actin filaments and the microtubules. Concerning the perspectives of this work, a numerical approach is currently developed to compare trajectories obtained to various proposed models of motion generation.

-Parasite egress and membrane curling: Parasite egress from infected red blood cells is a multi-step process occurring in a split second. Using high-speed videomicroscopy, we showed that a curling of the red blood cell membrane is following the cell swelling and the formation of a pore [Blood 4118, **2011**]. Our work is focused on determining the biological actor of the inverted curvature of the membrane leading to its outward curling, and to the study of its curling kinetics. We developed theoretical and physical models to go further in the interpretation of this phenomenon based on elasticity theories [Biophys J 2475, **2012**]. In particular, we study both experimentally and theoretically the dynamical curling and rolling of naturally curved ribbons for high Reynolds numbers (Re) as a preliminary for future studies at small Re. Our theoretical and experimental approaches allow us to distinguish the respective roles of elasticity, gravity and dissipation from inertia and emphasize the fundamental differences between the curling of a naturally curved ribbon and a classical rod. In the future, we plan to investigate the biological origin and physical consequences of the presence of the spontaneous curvature in the membrane of the Malaria-infected red blood cells.

C) Reconstitution of ezrin mediated cytoskeleton/membrane coupling (L. Ramos (DR2), K. Carvalho (PhD), N. Khalifat (post-doc))

The plasma membrane–cytoskeleton interface is a dynamic structure participating in a variety of cellular events. Moesin and ezrin, proteins from the ezrin/radixin/moesin family, provide a direct linkage between the cytoskeleton and the membrane via their interaction with phosphatidylinositol 4,5-bisphosphate (PIP2). The aim of this project was to understand the interactions between these proteins and PIP2 using in vitro simplified systems containing PIP2. We have shown that PIP2 induced a conformational change in ezrin and the formation of ezrin oligomers [*Biochemistry* 9318, **2010**]. Using confocal imaging with labeled proteins and lipids, we have quantitatively showed comparable behaviors for the interaction of moesin and ezrin to giant unilamellar vesicles (GUVs) containing PIP2, in agreement with our measurements using biochemical approaches [*BiophysBiochim Acta* 2839, **2012**]. Finally, thanks to zeta-potential measurements, we have demonstrated the effective incorporation of PIP2 in the membrane of GUVs [*Biophys* J 4348, **2008**]. This was the first time a zeta-potential measurement was used to quantify the incorporation of charged molecules in the membrane of GUVs.

D) Continuous interface crossing encapsulation (M. In (DR2), M. Abkarian (CR1), G. Massiera (MdC), E. Loiseau (PhD), C. Claudet (post-Doc), T. Lopez-Leon (post-Doc))

Vesicles are spherical lipid bilayers which enclose an internal volume, there are thus used in many applications such as encapsulation, vectorisation or design of biomimetic systems. We developed and patented [Patent FR0955035, **2009**] an original simple method called continuous Droplet Interface Crossing Encapsulation (cDICE), to produce vesicles and more generally capsules controlled in size and content. This method allows the production of vesicles in the range 5-70 μm in diameter and to encapsulate solutions as diverse as micrometric colloids, proteins, cells, viscous solutions (40 mPa.s) or saline solutions (>300 mOsm) [Soft Matter 4610, **2011**]. Hemoglobin S (HbS), purified from sickled cell anemia patients can be encapsulated and led to the HbS polymerization at low O_2 partial pressure (Figure 4). Vesicles are produced continuously at high frequency (> 150 Hz). We showed that this method allows producing vesicles with membranes composed of an asymmetric bilayer, of lipid mixtures or of copolymers. We are also studying the mechanism of interface crossing by imaging and exploring the role of the lipid in oil composition and structure. For future applications, cDICE has a great potential as a tool for academic research using a biomimetic approach and also for industrial use. Collaborative projects are currently developed in these two directions.

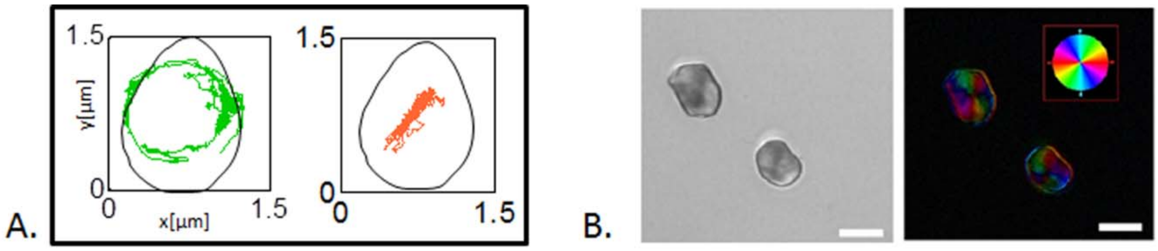

Fig-4: A. Trajectories of the Malaria parasites on glass, represented together with the parasite profile for size comparison. Two types of trajectories are observed: circular (green), directed (orange). The parasite transiently explores both types of motion. B. Phospholipid vesicles encapsulating hemoglobin S (HbS), purified from red blood cells of sickled cell anemia patients, obtained using the cDICE (Continuous Droplet Interface Crossing Encapsulation) method. In absence of oxygen, HbS crystallization is obtained as evidenced by the birefringence level color coded in the left picture.

E) Sickle Cell Anemia (G. Massiera (MdC), M. Abkarian (C1R), E. Loiseau (PhD)):

This term refers to a genetic disease which results in vaso-occlusive crisis of the blood circulation. Microfluidic channels designed to mimic physiological conditions (flow velocity, oxygen concentration, hematocrit...) of the microcirculation were used to carry out a biomimetic study at the cellular scale of sickle cell vaso-occlusion. This study has shown that flow geometry, oxygen concentration, white blood cells and free hemoglobin S are essential in the formation of cell aggregates which could play a role in the vaso-occlusion events. In the future, we will focus on the onset of the aggregation as well as the effect of aggregate failure on clogging of the flow.

Topic: *Mechanical instabilities of complex fluids*

Among the materials that can withstand large deformations before rupture, many model systems originating from Soft Matter Science are of particular interest especially as many of their mechanical properties (elasticity, plasticity, brittleness, ductility, etc.) are shared by a wide variety of materials. To study the behavior of materials subjected to large deformations, we have combined our expertise in the formulation of well-defined supramolecular systems with original and home-designed devices allowing the control of the strain or the stress imposed to the samples. The major asset of this research is a precise control of the properties of the synthesized materials, which is made possible by **(i)** a thorough study of the physical-chemistry and the chemistry of these materials (including relying on the chemistry service of the laboratory), **(ii)** a detailed characterization of the structures of the materials in particular by scattering techniques, **(iii)** a precise characterization of the constitutive rheological laws of the materials, obtained by taking advantage of the rheology platform of L2C and IES (created in 2010). We have received funding from two ANR projects.

Through this approach and using these tools, we have investigated, and in some cases highlighted several mechanical instabilities occurring at large deformations where the elasticity plays a key role.

A) Wrinkle-to-fold transition (M. Abkarian (CR1))

Using a two-layer polymeric system under biaxial compressive stress, we have shown that a repetitive wrinkle-to-fold transition generates a hierarchical network of folds during reorganization of the stress field. The folds delineate individual domains, and each domain subdivides into smaller ones over multiple generations. By modifying the boundary conditions and geometry, we have demonstrated control over the final network morphology [*Nat Mat* 952, **2011**]. These ideas should find applications in the many situations where stress impacts two-dimensional pattern formation. For future work, we will investigate the effect of the thickness of the film on the wrinkle-to-fold transition, in particular in the limit of vanishing thickness.

B) Capillarity of soft solids (M. Abkarian (CR1), S. Mora (MdC), H. Tabuteau (post-doc))

We have shown that Biot's instability can be observed under homogeneous uniaxial compression: creases appear at the surface of a soft gel for deformations larger that a critical value. We have demonstrated the critical role that both the finite thickness and the elasto-capillary length (defined as the ratio of the surface tension to the elastic shear modulus) play in the problem. Their ratio determines the value of the instability threshold. The smaller this ratio the larger the critical deformation for the instability to appear. The wave length of the instability is equal to the thickness of the material, when the thickness is larger than the elasto-capillary length and larger otherwise [*Soft Matter* 10612, **2011**]. We have also evidenced that the elasto-capillary length dramatically impacts the macroscopic equilibrium shape of an elastic body, for instance the Plateau instability of a thin filament of a solid gel [*PRL* 214301, **2010**]. We are now investigating surface tension effects of solids for other geometries.

C) Saffman-Taylor instability (S. Mora (MdC), L. Cipelletti (PR1), F. Lechenault (post-doc), A. Delbos (post-doc), D. Truzzolillo (post-doc))

The role of elastic forces on other instabilities has been investigated, for example regarding the Saffman-Taylor one when a fluid is viscoelastic, or in the case of cornstarch suspensions [*PRE* 106308, **2009**; *PRE* 026305, **2010**; *J Non-Newt Fluid Mech* 30, **2012**]. We have also studied the nucleation and the propagation of fractures in model viscoelastic fluids, where large elastic deformations and viscous dissipation become crucial. In the future, we will investigate such instabilities and fractures in colloidal glasses.

D) Brittle fracture in model transient networks (L. Ramos (DR2), S. Mora (MdC), C. Ligoure (PR1), G. Foyart (PhD), H. Tabuteau (post-doc))

We have revealed several important findings about fracture of a model system consisting in a model transient network made from oil in water microemulsion droplets reversibly linked together by triblock copolymers. The comparison between the measured stress threshold and the model of the thermally activated fracture clearly indicates that the nucleation occurs in a brittle manner [*Prg Theo Phys* 47, **2008**; *PRL* 155501, **2009**]. Using high speed videomicroscopy, we have tracked the fracture propagation and found that it is purely elastic without any significant bulk and interfacial viscous dissipation. This brittle behavior is well explained by a hyperelastic generalization of the viscoelastic trumpet model of de Gennes [*Soft Matter* 9474, **2011**].

E) Brittle-to-ductile transition (C. Ligoure (PR1), L. Ramos (DR2), S. Mora (MdC), A. Laperrousaz (Master), G. Foyart (PhD), H. Tabuteau (post-doc), T. Tixier (post-doc))

To extend our results on brittle fracture toward a possible brittle-to-ducile transition for transient networks, a new class of transient networks, made of surfactant micelles of tunable morphology (from spheres, to rodlike to wormlike) reversibly linked by telechelic polymers has been designed and investigated [*J Rheol* 359, **2008**; *Langmuir* 2467, **2009**; *Soft Matter* 2699, **2010**]. Coupling rheology and time-resolved structural measurements using synchrotron radiation, we have shown that the emergence of strong fluctuations of the degree of alignment of the micelles evidences a structural probe of a fracture process under shear [*PRL* 148302, **2011**]. In order to obtain quantitative evidences of a brittle-to-ductile transition in the fracture of self-assembled networks, we are now investigating the fracture patterns when transient networks with tunable anisotropy are confined in 2D Hele-Shaw cell (see Figure 5 below) and pushed by a low viscosity oil.

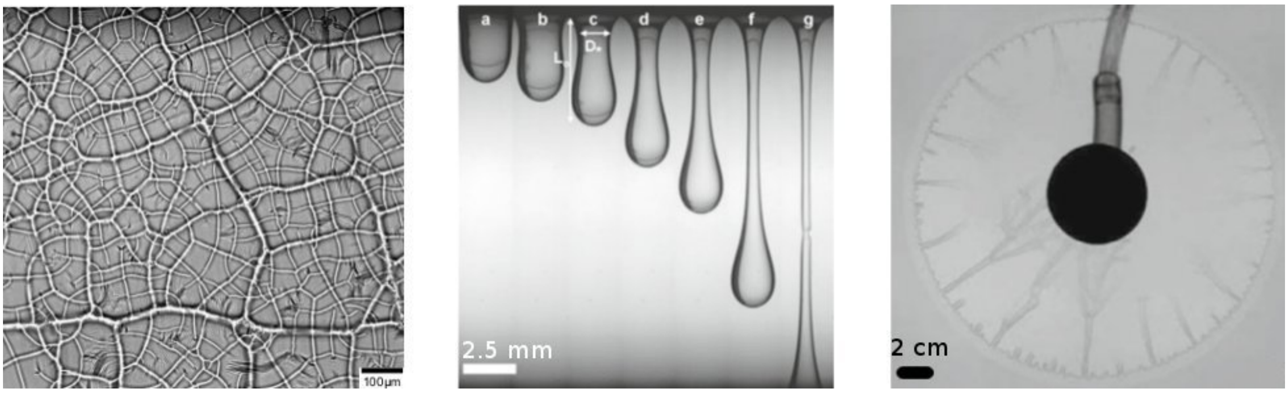

Fig-5: from left to right: Folds in a two-layer polymeric system under biaxial compressive stress. Sequence of images of the fall of a pendant drop of a viscoelastic fluid. A fracture is appearing on image (g). Fracture-like pattern during the aspiration of a viscoelastic fluid from the central hole of a radial Hele-Shaw cell.

Topic: *Soft composites*

Soft composite materials, comprising nanoparticles dispersed in a matrix, are of great interest, since the nanoparticles can enhance the matrix properties or impart new functionalities and because the matrix can act as a template that structures the particles at the nanoscopic level. In this context, the main contributions of our group are detailed characterizations and a deep understanding of the complex structure of soft composite. Three topics are described below, where the matrix is a polymer melt, a block-polymer micellar crystal, or a liquid crystal. We have received funding by the Languedoc-Roussillon region, two ANR projects, the LabEx ChemiSyst, ILL (Grenoble), Michelin, and a joint Ukrainian-French project for exchange of researchers.

A) Nanocomposite structure and the reinforcement effect (A. Banc (MdC), A.C. Genix (MdC, L2C Glasses), J. Oberdisse (DR2), C. Dupas (AI), M. Tatou (PhD), G. Baeza (PhD), C. Schmitt (PhD, LabEx, chemistry with H. Mutin (ICGM), M. Chirat (post-doc))

By adding nanoparticles to polymer melts, nanocomposites with improved mechanical properties are obtained, which are of particular importance for applications like car tires. We have performed structural analysis of those materials, leading the way to a fundamental understanding of mechanical properties of the nanocomposites. The reinforcement of soft polymer matrices by hard filler particles is based on three contributions: (i) The hydrodynamic influence of the nanoparticles or aggregates (up to percolation), (ii) chain stretching, and (iii) changes in the dynamics of the chains close to particle surfaces. We have set up the synthesis (using a grant by the region to install a nanolatex reactor) and formulation of several silica-filled systems to study these effects. In model nanocomposites, filler nanoparticles are added as a rather monodisperse colloidal suspension, e.g. following the latex route and casting. In such systems, we have evidenced an 'aggregation diagram' of the nanoparticles [*Macromol* 9029, **2011**], allowing for a continuous triggering of the average aggregation number. We have also studied the polymer chain structure in these hard environments using isotopic substitution and SANS (cf. L2C Glasses), finding that chains keep their Gaussian conformation [*Macromol* 1663, **2012**]. In these samples, a slowing down of the dynamics was observed, which could be related to the formation of glassy layers on the nanoparticle surface, as found in another system [*Soft Matter* 4090, **2012**]. In future work, we will focus on the segmental dynamics, and develop new model systems, with innovative phosphonate chemistry.

Progress in the formulation of industrial nanocomposites has been obtained in the framework of a CIFRE-PhD with Michelin. It is important to realize the large number of ingredients in real materials, and we have therefore formulated a simplified industrial nanocomposite made by mixing of polymer and silica pellets with coating agent only. The structural and rheological analysis has led to a cover paper in Macromolecules [*Macromol* 317, **2013**]. It is based on a combination of a statistical TEM analysis (see Figure 6), numerical simulations of structure factors, and SAXS. The multi-scale structure of small silica beads (≈10 nm), aggregated in clusters (R≈40 nm) of compacity 35%, and building up a fractal superstructure, has been characterized as a function of silica concentration, and found to agree with the mechanical properties. This approach will be generalized in the future to understand the impact of matrix composition, in particular in presence of grafting polymer units.

B) Aligning and structuring nanocomposites with liquid crystals (E. Anglaret (PR1, L2C Nanostructures), M. Nobili (PR1), C. Blanc (CR1), N. Ould-Moussa (post-doc))

Anisotropic nanoparticles (spindle-like, rod-like...) might have very interesting individual anisotropic characteristics (magnetic, optical ones ...). The translation of these properties to a macroscopic material requires a good control of the orientation of the particles. For such a task, we have explored how to use intermediate liquid crystalline states during the design of nanocomposites (see Figure 6). A substantial part of our work has been focused on the realization of functional single wall carbon nanotubes composites and films; it is detailed in the activity "films and composites" (L2C Nanostructures) and reviewed in [*Phil Trans A*, 20120499, **2013**]. The introduction of a small amount of nanoparticles can also drastically change the properties of the resulting liquid crystal. The photoluminescence properties [*Liq cryst* **2013**] or the magnetic properties [*Mol Cryst Liq Cryst* 104, **2010**] of liquid crystals composites have thus been strongly enhanced. The underlying phenomena strongly depend on the correlation between the orientation of the doping nanoparticles and the orientation of the liquid crystal molecules, but also on their respective orientational order parameters, whose evolution is still debated when mixing different anisotropic particles/molecules. We have developed techniques based on optical and Raman spectroscopies in the case of single wall carbon nanotubes to measure independently the order parameter of the LC matrix and the one of the particles [*Liq cryst* **2013**, PRL 247801, **2012**].

C) Colloidal metallurgy: crystallization process and structure of colloidal analog of metallic alloys (L. Cipelletti (PR1), J. Oberdisse (DR2), L. Ramos (DR2), A. Louichi (master), E. Tamborini (PhD), N. Ghofraniha (post-doc))

Virtually all real-life crystalline materials have defects. In particular, most metals and ceramics are aggregates of crystalline grains. Grain-boundaries (GBs), the two-dimensional lattice defects that separate the different grains of a crystal, control the mechanical properties of polycrystalline materials. Although GB motion is known to play important roles in plastic deformation, the microscopic origin of the plasticity of polycrystalline materials is still largely unknown, because of the limitations of available experimental tools to record, during deformation, the dynamics of the process with a nanometer resolution. To overcome these limitations, we have proposed to use a colloidal analog of atomic polycrystals.

We have used a soft nanocomposite material obtained by dispersing small quantities of nanoparticles (at most 2%) in a colloidal crystalline matrix composed of thermosensitive micelles. The volume fraction of the micelles increases with temperature *T*, until crystallization occurs due to entropic reasons, as in hard sphere colloidal systems. Hence our system allows crystallization to be induced at the desired rate simply by varying *T*. Nanoparticles act as impurities, and as such, they segregate in the grain boundaries of the colloidal polycrystal, allowing their visualization, by light and confocal microscopy (see Figure 6), and by scattering techniques [*Langmuir* 8562, **2012**]. We have shown by confocal imaging that the microstructure of the polycrystal can be tuned by varying the nanoparticle volume fraction and the crystallization rate and have rationalized our findings using standard models for the nucleation and growth of crystalline materials [*Soft Matter* 6214, **2012**; PRE 032306, **2013**]. The models have been adapted to account for the peculiarities of our experiments: the presence of nanoparticles that are expelled in the grain boundaries and the steady increase of *T* and, hence, of the effective volume fraction of micelles during the experiments.

We are currently investigating the plasticity of our colloidal polycrystals, by performing multispeckle time-resolved dynamic light scattering measurements on the samples submitted to cyclic shear deformations using a novel light scattering apparatus specifically designed to access the dynamics of the network of GBs [*Rev Sci Instr* 093106, **2012**]. In future work, we will apply this technique in combination with rheology to investigate plasticity and material failure in polycrystalline systems.

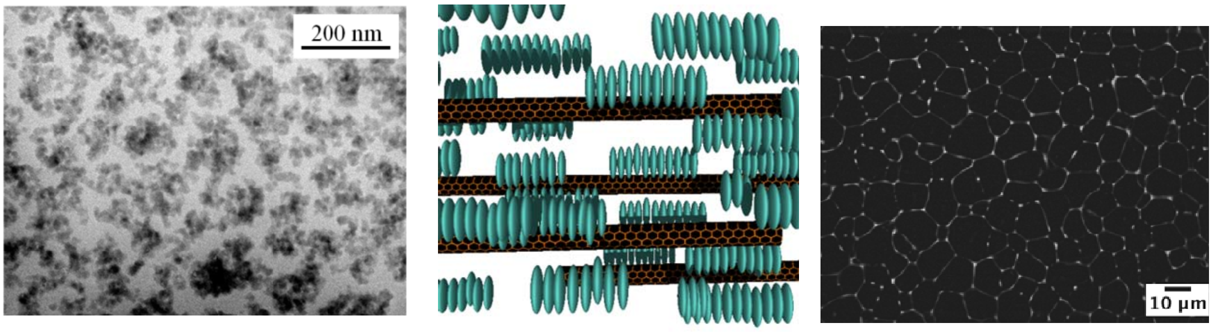

Fig-6: from left to right: electron microscopy of silica nanocomposite, carbon nanotubes in liquid crystals, and confocal microscopy of a network of grain boundaries.

Rayonnement et attractivité académiques

Invited conferences and awards: Recognition of the soft matter team by its community can be first assessed by the numbers of invited talks which amounts to 52 for international conferences and to 7 for national events. Recent results from the team lead to several awards at the regional as well as at the national level: J. Oberdisse and M. Abkarian were awarded a “chercheur d’avenir“ price from the Region Languedoc Roussillon. In 2008 J. Oberdisse was awarded the polymer physics price from the Groupe Français des Polymères and the French Physical Society (SFP). In 2012, the “bronze medal” was attributed to M. Abkarian by the section 11 of CNRS.

Organization of scientific events: Such recognition allowed the team to organize several well attended conferences: Two European workshop on Nanocomposites and Polymer Dynamics were held in Montpellier in 2008 and 2011 under the supervision of the Soft Matter team of L2C. In 2012, the conference “New horizons of colloidal science 2012”has been organized in Sète by the Soft Matter team in collaboration with the Physics Institute of Ukraine. With the European Space Agency a workshop on Time resolved correlation has been organized at the European Space Research and Technology Centre in the Netherlands. In 2013, the soft matter team co-organized with Solvay and the Ecole de Physique des Houches, a conference on Macromolecules in Constrained Environments. Finally the Soft Matter team actively contributed to the organization of the Journées de la Matière Condensée (SFP), supervising one (resp. one and three) sessions in 2008 in Strasbourg (resp. 2010 in Troyes, and 2012 in Montpellier). We have also participated in the local organization in Montpellier.

Expertise and membership in councils: Expertise of the soft matter team members is also well recognized as suggested by the number of commissions they belong to: the team keeps on the tradition of having an elected member of the commission 11 of the National Comity of Scientific Research. The team is also present in the board of the Liquids section of the European Physical Society. Members of the team have been elected or nominated at several scientific councils: University Montpellier 2, European Spallation Source and have been hired as experts by the Netherlands Foundation for Fundamental Research on Matter, by the Université Catholique de Louvain, the fond de recherche du Quebec, and by several large instruments facilities (Jülich Center of Neutron Science, NIST et Soleil). They are also members of the editorial board of Journal of Statistical Mechanics and of the annual review of the CNRS “Images de la Physique”. They served as experts in AERES, BMBF and Helmholtz Association comities (Germany).

Invited researcher and recruitment: The soft matter team benefitted of 3 invited professors during the last years: Pr. R. Piazza (Politecnico di Milano, twice), Pr. F. Melo (Santiago de Chile), Pr. S. Faetti (University of Pisa). One may also note that three CNRS researchers have obtained a promotion to ‘directeur de recherche’ in the last few years. Finally the soft matter team attracts every year young scientists seeking for an academic position: in the last period, an associate professor (A. Banc) and a CNRS researcher (A. Stocco) have been hired in the team. Moreover a senior CNRS fellow, M. Gross from Laboratoire Kastler Brossel (ENS Paris) has joined the group in 2010 and will bring his expertise in holography to various projects. D. Alexandre, a CNRS researcher in biology from a Montpellier lab, is currently a visitor in our team.

Interactions avec l’environnement social, économique et culturel

In spite of the strong academic commitment of the soft matter group, we do have long-lasting interactions with industrial partners. We also participate regularly in local or national cultural events, playing our role in spreading scientific knowledge.

In the past years, we have started two collaborations with multinational companies, Solvay, and Michelin. These companies finance two PhD-projects in our lab (CIFRE), together with an accompanying contract. One project deals with the control of the size distribution of droplets of complex fluids in sprays for agronomical applications. Here the company needed expertise in the non linear rheology and break-up of sheets and filaments of dilute complex fluids. The other is focused on the structure and rheology of simplified industrial nanocomposites, as a model system for car tires. Here the industrial partner was looking for expertise in scattering experiments and data analysis for structural characterization at the nano-level.

We also have several other contracts with companies. MedesisPharma for instance is a local start-up setting up delivery systems based on soft matter, like emulsions or microemulsions. We have participated in elucidating the structure of their carrier system, and proposed a rationalization of their approach. Unilever has paid a postdoc for the study of time- and space resolved dynamics of skin. Our contracts with Amatsi and Caragum are in the field of particle size characterization, whereas Flamel is interested in our expertise in the characterization of gels formed of sticky particles. LambdaX, finally, is a manufacturer of scientific instruments, and the soft matter group participates in the design of light scattering instruments.

Some of our work in the group leads to patents. In one of them, we report on a continuous droplet interface crossing encapsulation (cDICE) technique producing vesicles tunable in size and content with an unprecedented high-yield [Patent FR0955035, **2009**]. Overcoming some of the current techniques limitations, our setup has a great potential in various fields from encapsulation to the design of biomimetic cells used in many of our studies of pathophysiological flows. Concerning measurement methods in colloid science, one describes a new method for analyzing Taylor dispersion data, in order to retrieve the full size distribution of a colloidal suspension or a polymer solution [Patent FR1256050, 2012]. Another one protects a new method for analyzing speckle patterns generated by a soft matter sample illuminated by a laser beam [Patent 1000133058, **2011**]. The method allows one to calculate coarse-grained drift maps (e.g. for a sedimenting sample or a sample submitted to an external or internal stress) and to measure the microscopic dynamics (relative motion of scatterers) without the contribution of the drift motion. These calculations were implemented in a software [Analysis, logiciel deposé **2011**], which also allows more generally to process speckle images issued from light scattering experiments on soft matter.

Concerning networking, at the campus level, the soft matter team is member of the LabEx NUMEV (‘Solutions Numériques, Matérielles et Modélisation pour l’Environnement et le Vivant’) and is also partner of the LabEx CheMISyst (‘Chimie des systems moléculaires et interfaciaux’) coordinated by the chemist of the Pôle Balard of Montpellier. Over the past eight years, the team has been member of the European network of excellence SOFTCOMP, and this year a new European project in the field of supramolecular assembly of polymeric structures (‘Supolen’) is about to start.

The soft matter group is also quite active in promoting science and spreading scientific expertise. Every year, we hold a booth at the traditional ‘Fête de la science’, with hands-on soft matter experiments. We have also participated in local events, like the ‘Agora des savoirs’ organized by the city of Montpellier, or the ‘Bar des sciences’ on “seeing the invisible”. Members of the group have given talks on colloids or rheology of complex fluids in ‘Université du Tiers Temps’, or even in a conference of local wine producers. On a national level, a conference for the general public on “ça coule et ça casse: lorsque liquides et solides s’imitent” has been given at the Palais de la découverte in Paris, and a contribution to an itinerating exposition “Ruptures: les matériaux roulent les mécaniques” (E. Guyon and T. Rouxel) has been designed.

Implication de l’équipe dans la formation par la recherche

Our teachers are involved in the creation and responsibility of the “parcours” Physique et Ingénierie du Vivant (since 2009) and « Physique de la Matière molle et des Systèmes Vitreux » (2009-2012) within the « Master de Physique » de l'UM2. They carry the responsibility of 5 UE’s at a Master level. Moreover, one of us is deputy director of the Faculté des Sciences. Concerning teaching at the research level, we have co-organized several European schools (‘Bombannes summer school on scattering ’), 2008, 2010, 2012, a national school (2012, Labex Chemisyst), as well as the ‘Journées de la diffusion neutronique’, with the four-day school ‘Neutrons et matière molle’(2009) and a book issued from this school. We are currently mentoring 9 PhD students, and 11 PhD theses have been defended since January 2008.

Conclusions

Over the past five years, the group has evolved considerably. Two highly visible people retired in January 2009 (G. Porte and F. Larché). Since then, we have recruited two young scientists, A. Banc (MdC) and A. Stocco (CNRS), both giving a new impetus to our activities. A. Stocco brings in his expertise for colloids and nanoparticles at complex interfaces, and in particular analysis of motion of active particles at interfaces. He combines ellipsometry and DLS, and has already set up an evanescent dynamic light scattering instrument for fluid interfaces. A. Banc drives the establishment of a new topic, ‘physics for agro-sciences’. In order to elucidate the mechanisms at play in the structuration of proteins under shear, she has set-up collaboration with a team of INRA. We investigate the gelation and structural properties of model systems comprising proteins purified from gluten. Moreover, to go further into the understanding of such elastomeric proteins, we plan to study the assembly of model peptides with hydration. These peptides inspired from repetitive sequences of gluten and other elastomeric proteins will be investigated using a microfluidic tool.

In addition to this, two senior researchers (both CNRS) have joint us. M. Gross from ENS Paris is an expert in holography, and he is currently setting up experiments for the analysis of the dynamics of colloidal and biophysical systems. D. Alexandre has already joint us as a visitor in the past months. As a biologist, he will reinforce our biophysical activities.

aeres
agence d'évaluation de la recherche
et de l'enseignement supérieur

Présentation synthétique de l'entité
Unité de recherche
Vague E : campagne d'évaluation 2013-2014

Team "Soft Matter"

Intitulé de l'unité: Laboratoire Charles Coulomb

Nom du directeur de l'unité: Jean-Louis SAUVAJOL

Nom du responsable de l'équipe (le cas échéant): Julian OBERDISSE

Effectifs de l'entité (since january 2008)
6 professors and assistant-professors; 6 researchers ; 1 post-doc and 8 PhDs.

Personnels ayant quitté l'entité, (since january 2008)
2 statutaires (24 months) ; 12 PhDs (329 months) ; 14 post-docs (203 months).
Retirement : G. Porte and F. Larché (december 2008).

Nombre de recrutements réalisés au cours de la période considérée (since january 2008) et origine des personnels
M. Gross, DR CNRS, LKB, ENS Paris (2010); A. Banc, MdC UM2, post-doc L2C (2011) ; A. Stocco, CR CNRS, post-doc HZB (2011). Recruitment of 13 PhD and 15 post-docs.

Production scientifique au cours de la période écoulée (1er janvier 2008 – 30 juin 2013) :

1) Colloïdal particles trapped at complex fluid interfaces: we have computed and measured new lateral colloidal forces due to the Gaussian curvature [PRL058302, 2013], nematic elasticity has been used to organize particles at liquid crystal/air interfaces [Soft Matter, 1467, 2011], we have fabricated new types of liquid crystal emulsions and controlled their valency by using topological defects and trapped microspheres [PRL 247802, 2011; Soft Matter, 6911, 2013].
2) Colloidal metallurgy: we have designed a colloidal analog of metallic alloys by doping a micellar crystal with a small amount of nanoparticles (NPs) populating grain boundaries [*Langmuir* 8562, **2012]**. We have shown that the microstructure of the polycrystals can be tuned by the amount of NPs and the crystallization rate and have modeled our findings using models for the nucleation and growth of crystalline materials [*Soft Matter* 6214 ,**2012**].
3) Mechanics of complex fluids and soft solids: Fracture nucleation and propagation has been studied in various geometries in complex fluids using self-assembled transient networks [*Rheol Acta* 91, **2013**]. In soft elastic solids, we have revealed that the surface tension plays a key role in the determination of equilibrium shape, once a characteristic length becomes comparable to the capillary length, i.e. the ratio of the surface tension to Young's modulus [*PRL* 214301, **2010**; *Soft Matter* 10612, **2011**].
4) Structure of soft composites: A multi-scale description of filler and chain structure in model and industrial nanocomposites based on a combination of TEM, SAXS, and numerical simulations has been achieved and linked with rheological properties [*Macromolecules* 9029, **2011**; 1663, **2012**; 317, **2013**].
5) New light scattering method: A measurement of the mesoscopic displacement field and the microscopic dynamics [Patent 1000133058, 2011] has been used to investigate samples under internal or external stress, including actin networks [*Nature Mat* 236, **2011**] and colloidal gels settling under their own weight [*PRL* 118302, **2011**]. It is shown in particular for gels that both the microscopic dynamics and the macroscopic compression are ruled by a single parameter, the compressive strain rate.

Bilan quantitatif des publications de l'entité.

139 articles in peer-reviewed journals, 59% of which in journals with impact factor > 4. In particular: 13 in Physical Review Letters, 22 in Soft Matter, 3 in Nature Physics, Materials and Communications, 9 in Macromolecules. The articles published by the soft matter team after 2008 are currently cited about 400 times per year (ISI).

Indiquer les **5 publications majeures** de l'entité:
1) Structural Signature of a Brittle-to-Ductile Transition in Self-Assembled Networks L. Ramos, A. Laperrousaz, P. Dieudonné, C. Ligoure, *Phys. Rev. Lett.* 107, 148302 (**2011**)
2) Grain refinement and partitioning of impurities in the grain boundaries of a colloidal polycrystal, N. Ghofraniha, E.Tamborini, J. Oberdisse, L. Cipelletti, L. Ramos, *Soft Matter*, 8, p.6214 (**2012**). Front cover article.
3) A novel mechanism for egress of malarial parasites from red blood cells, M. Abkarian, G. Massiera, B. Laurence, M. Roques, C. Braun-Breton, *BMC Blood Disorders*, 117, 4118 (**2011**)
4) Multiscale Filler Structure in Simplified Industrial Nanocomposite Silica/SBR Systems Studied by SAXS and TEM, G. BAEZA, A.C. GENIX, C. Degrandcourt, L. Petitjean, J. Gummel, M. Couty, Oberdisse J., *Macromolecules*, 46, 317 (**2013**). Front cover article.
5) Capillary force on a micrometric sphere trapped at a fluid interface exhibiting arbitrary curvature gradients, Ch. Blanc, D. Fedorenko, M. Gross, M. In, M. Abkarian, M. A. Gharbi, M. Nobili, et al, *Phys. Rev. Lett*. 111, 058302 (**2013**)

Indiquer **au maximum 5 documents majeurs** (autres que publications) produits par l'entité.
1) To protect innovative instrumentation and data analysis in colloid science, two patents and one software have been deposited: i) size distribution analysis of colloidal suspensions or polymer solutions in Taylor dispersion data [Patent FR1256050, **2012**]; ii) a new speckle analysis method to determine coarse-grained drift maps (e.g. in sedimentation) and microscopic dynamics [Patent 1000133058, **2011**], with its software implementation ["Analysis",registered **2011**].
2) We have patented a high-yield method [Patent FR0955035, **2009**] to produce monodisperse capsules tunable in size and content, using a continuous droplet interface crossing encapsulation (cDICE) principle. This process has a great potential in various fields from encapsulation to the design of biomimetic cells and tissues and provides an important tool to study pathophysiological flows.

Indiquer **au maximum 5 faits illustrant le rayonnement ou l'attractivité académiques** de l'entité.
1) 58 invitations to international conferences, 8 invitations to national conferences.
2) Organization of 5 international conferences and workshops: New horizons of colloidal science 2012 (Sète), Macromolecules in constrained environments 2013 (co-organization, Houches, Solvay), Time resolved correlation 2012 (co-organization, Estec, ESA), Nanocomposites 2008 and 2011 (Montpellier). Co-organization of Journées de la matière condensée (JMC13), Montpellier 2012; co-organization of 4 mini-colloques (1 at JMC11, 3 at JMC13), inter-UMR meeting (Gulliver, 2010). Participation in the organization of "Matériaux 2014" in Montpellier (>1000 participants).
3) Recruitment: one CR CNRS, one MdC. Incoming CNRS transfers: one CR (mid-2013) and one DR CNRS. Invited professors: R. Piazza (Milano), F. Melo (USACH Chili), S. Faetti (Pisa).
4) Expertise: Comité national (CNRS); ANR; CNU 28; scientific council ESS and UM2 ; peer review Jülich Center of Neutron Science, NIST and Soleil; members of AERES and Helmholtz committees; experts for: committee 'Grands instruments BMBF' (Germany), Netherlands Foundation for Fundamental Research on Matter, Université Catholique de Louvain, Fond de recherche du Quebec; editors for JSTAT and 'Images de la physique'; Liquid Matter Board (EPS).
5) Bronze medalist CNRS 2012 (M. Abkarian), Prize 'Physique des polymères' SFP/GFP 2008 (J.Oberdisse), prize "Chercheur d'avenir" Languedoc Roussillon 2009 (J. Oberdisse) and 2011 (M. Abkarian).

Indiquer **au maximum 5 faits illustrant les interactions de l'entité avec son environnement socio-économique ou culturel**.
1) 2 contracts CIFRE (PhD funding) with Michelin and Rhodia/Solvay.
2) 8 contracts (counseling, sample characterization, research): Médesis Pharma, Amatsi, Caragum, Flamel, LambdaX, Michelin, Rhodia/Solvay, Unilever.
3) Outreach activities: Fête de la science, Agora des savoirs, Bar des sciences, lectures at the « Université du Tiers Temps », scientific exhibit 'Ruptures: les matériaux roulent la mécanique' (with E. Guyon and T. Rouxel), one general public conference at the Palais de la découverte in Paris.

Indiquer **les principales contributions de l'entité à des actions de formation**.
1) Creation and responsibility of the "parcours" Physique et Ingénierie du Vivant (since 2009) and Physique de la Matière molle et des Systèmes Vitreux (2009-2012) within the Master de Physique de l'UM2. Responsibility of 5 UE's at a Master level.
2) Deputy-director of the Faculté des Sciences.
3) Co-organization of: i) a European school ('Bombannes summer school on scattering '), 2008, 2010, 2012; ii) a national school (2012, Labex Chemisyst). Organization of the 'Journées de la diffusion neutronique', with the four-day school 'Neutrons et matière molle'(2009), editor of a book issued from this school.
4) Currently mentoring of 9 PhD students; 11 PhD theses defended since January 2008.

Team: “Physics of the Glassy State”

Team: "Physics of the Glassy State"

The group has a strong experimental activity in the field of glass science, research that is now conducted by 6 University researchers and 2 emeritus. C. Weigel, a new assistant professor has been hired in 2009 and M. Ciccotti promoted professor at the ESPCI has left the group in 2010.

During the last years, the combined use of innovative optical time- and spectral-domain spectroscopy has led to significant advances in the understanding of the elastic and vibrational properties of glasses and their relationship with the disorder at the molecular scale and at the nanoscale. New projects have allowed extending our expertise to vibrational spectroscopy under extreme conditions (high temperatures and high pressures), to structure-property relationships in ferroelectric relaxors and in reinforced polymer matrices. In parallel, cutting-edge technical developments of an AFM coupled to state-of-the-art multi-scale finite element calculations have given rise to new and extremely relevant results about mechanisms ruling stress corrosion in oxide glasses at the nanoscale. This expertise is now directed towards polymer glasses, which present a brittle fracture behavior at ambient temperature. It is worth noting that a significant part of the success in developing original instruments relies on the synergy between the researchers and the engineers of the "Instrument Design" Group.

In the following we give a non-exhaustive summary for the main achievements obtained in the two areas of research: "G*lasses under high-stress conditions"* and "*Structure, vibrations and relaxations in disordered materials*".

Topic: *Glasses under high-stress conditions*

Slow crack propagation mechanisms acting at the nanoscale in vitreous materials (M. Ciccotti (CR1), A.-C. Genix (MCF), M. George (MCF); A. Grimaldi, G. Pallares, Y. Nziakou (PhDs); F. Lechenault, M. Flemming (Post-docs))

An innovative experimental set-up allowing for the in situ observation by atomic force microscope (AFM) of slow crack propagation in controlled environment has been developed. We combined advanced investigation techniques at the nanoscale, optical interferometry measurements at the mesoscale and multi-scale finite element calculations to relate accurately the observed mechanisms to the global loading condition and get over the classical phenomenological models. This activity was supported by the ANR project *CorCoSil* managed by our laboratory in collaboration with CEA (Saclay) and LPMCN (Lyon).

Firstly devoted to the study of the stress corrosion of oxide glasses, our research have led to several fundamental results for the research community working in glass damaging. We shed light on different aspects of the subtle role of water in sub-critical propagation of cracks. Through AFM phase imaging, we were able to visualize and study capillary condensation at the crack tip between the fresh fracture surfaces. We established thus clearly the environment local conditions and clarified the relative contributions of surface corrosion phenomena and volume damaging induced by water diffusion [*PRL* 165505 **2008**]. This should pave the way to advanced physical chemistry studies on multi-components glasses. Mechanical effect of capillary forces has also been quantified. It should be noted that capillary condensation at the crack tip can moreover be combined to AFM measurements of wetting properties, also developed in our team, to investigate in a novel way the fundaments of capillary action at very small scale.

New development of digital correlation techniques to AFM pictures whose size can reach 200 nm2 allowed us to measure precisely the strain field around the crack tip and to show that the linear elastic theory was still valid at very small distance of this tip (10 nm). This was a major experimental point to relate to the debated size of a process zone in oxide glasses [*PRL* 025502 **2010**, *EPL* 66003 **2010**].

The experimental technique and multi-scale analysis is nowadays adapted to the study of vitreous polymers, which presents a brittle fracture behavior at ambient temperature, such as poly-methyl-methacrylate (PMMA). We currently investigate plasticity mechanisms acting in a micrometric sized process zone, in relation with structural relaxation driven by macromolecules movements. Controlled crack propagation in PMMA has been reached and first multi-scale analysis of the strain-stress field in progress. This activity is supported by the ANR project *ProMorph*. In a new collaboration with LMGC (Montpellier) and IATE (INRA, Montpellier), through a PhD, AFM abrasion test have been performed and analyzed to reach for the first time local mechanical properties of important bio-polymers.

Funding: ANR Blanc *CorCoSil* (2007-2010), in Coll. with CEA Saclay (E. Bouchaud), LPMCN Lyon (E. Charlaix); ANR Mat&Pro *Promorph* (2012-2015) in Coll. with ESPCI Paris (M. Ciccotti), IMP Lyon, LMT ENS Cachan (S. Roux), GEM Ecole Centrale Nantes, EADS and ARKEMA.

Small scale mechanical response of silicate glasses (E. Courtens (PREM), M. Foret (PR1), B. Hehlen (PR2), B. Rufflé (PR2), R. Vacher (DREM), C. Weigel (MCF); S. Ayrinhac, H. Tran, M. Kint (PhDs); E. Gouirand, W. Zhou (Post-Doc))

The plastic deformation of glasses is not well known, because it occurs at very small length scales, below the micrometer scale. However, it controls the occurrence of surface damage and is certainly involved as local initiator for crack propagation. In this way, the plastic deformation strongly impacts the practical strength of glasses. Amorphous silicates form an excellent playground to study the mechanisms of plastic deformation in amorphous solids because they exhibit a wide range of plastic behaviours as a function of composition, such as a densification or not upon high local pressure. In a previous ANR project (PlastiGlass 2005-2008) we pioneered the use of spatially resolved Brillouin scattering technique to study the small scale mechanical response of silica and complex silicates [*JAP* 094903 **2010**, *APL* 231901 **2012**]. In parallel we revisited the vitreous silica mechanical response to a hydrostatic stress up to 10 GPa. The dissipation coefficient exhibits a sharp maximum located at 2 GPa, which appears to coincide with the well-known anomalous maximum in the compressibility [*PRB* 024201 **2011**]. We are currently pursuing this activity through a new ANR project (*MecaSil*) which combines high performance spectroscopic measurements under advanced loadings and atomistic numerical simulations to identify the small scale response of model amorphous materials (silicate glasses), and develop if possible in situ predictive tools for plastic deformation and crack initiation in these materials.

Recently we also demonstrated that the acoustic Bulk modulus of vitreous silica immersed in pressurized fluid helium is less than half the static Bulk modulus which can be derived from the volume variation of the silica sample with pressure [*PRL* 245504 **2012**], see Figure 1. This large difference in compressibilities must relate to the open structure of the glass allowing He to distend the network, suggesting that silica glass behaves unexpectedly as a poroelastic material at the sub-nanometric scale. In that picture, the amount of gas which penetrates into the network is much larger than that which is initially allowed by the free volume. From our measurements we have indeed estimated a huge He solubility, amounting to about 1 mol He/mol SiO_2 at 6 GPa. We are investing much effort into the understanding of this surprising poromechanical behavior. To that effect, we have submitted a new ANR project in collaboration with MSE[2], a recently created joint CNRS/MIT Department unit (MIT Cambridge, USA), IMPMC (Paris), and ICG (Montpellier).

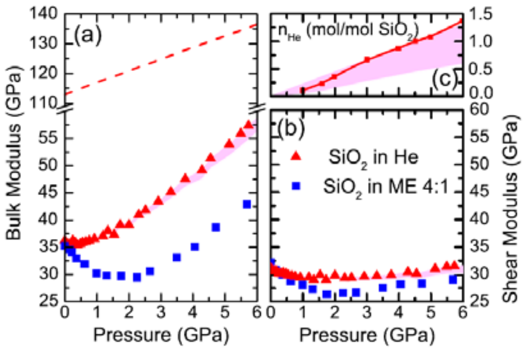

Figure 1 : Elastic moduli of v-SiO_2 in a nonpenetrating pressurizing medium (blue squares) and in He (red triangles): (a) bulk modulus, (b) shear modulus. The red dashed line in (a) is the bulk modulus derived from the sample volume variation. (c) The relative He concentration (red line).

Funding: ANR Blanc *MecaSil* (2012-2015), in Coll. with LPMCN Lyon (A. Tanguy), ESPCI Paris (D. Vandembroucq), SVI Saint Gobain Aubervilliers (E. Barthel), LPCML Lyon (D. de Ligny)

Topic: *Structure, vibrations and relaxations in disordered materials*

Sub-THz Phonons in glasses (E. Courtens (PREM), M. Foret (PR1), B. Hehlen (PR2), B. Rufflé (PR2), R. Vacher (DREM); S. Ayrinhac (PhD))

A challenging project is to obtain direct evidences for the expected dramatic decrease of acoustic phonons mean free path of wavelength in the mesoscopic length scale domain or sub-THz frequencies region in some important model glasses. A crossover to such a strong acoustic damping mechanism should become rapidly effective at very high frequencies in relation with the emergence of the boson peak [*PRL* 015501 **2008**, *PRL* 067402 **2010**, *APL* 246101 **2011**]. The acoustic modes of some nanometres in wavelength or more (mesoscopic length scale) have remained mainly inaccessible in glasses by light, neutron or x-ray spectroscopies [*PRB* 132201 **2011**]. Pump-probe optical techniques (POT) now offer a possible approach to access vibrational modes in this region. The general idea is to generate a hypersound pulse by the absorption of a femtosecond optical pulse, the pump, and to follow its evolution by a second optical pulse, the probe, delayed in time. Within the *GlassPhon* ANR project, successful POT measurements of longitudinal acoustic phonons up to 300 GHz were performed at IEMN owing to a new scheme involving silica glass layer deposited on silicon (111) substrate. Our remarkably precise acoustic attenuation results were found to follow rather well our pioneering POT data [*PRB* 100201 **2008**], and a model combining anharmonicity and thermally activated relaxations [*PRB* 014204 **2011**]. The challenge is now to reach the sub-terahertz frequency region using GaAs/AlAs super-lattices as efficient generators and detectors of coherent acoustic waves.

Funding: ANR Blanc "GlassPhon" (2011-2014), in Coll. with INSP Paris (B. Perrin), IEMN Lille (A. Devos). Programme Hubert Curien (2009) in coll. with S. Elliott (Cambridge, UK)

Vibrations and glass structure in oxide glasses (B. Hehlen (PR2), B. Rufflé (PR2); H. Harker, O. Noguera (Post-docs))

The investigations focused on the relation between the vibrational response and the local structure of simple oxide glasses. We developed a spectral analysis method which enables, from the Raman response, to obtain the distribution and the value of the Si-O-Si angle in the network as well as in the threefold and fourfold rings in silica, silica under pressure, and alkali-doped silicas [*JPCM* 025401 **2010**]. The concentration of small rings could also be quantitatively estimated, revealing for example a cascade effect from large structures toward 4-fold then 3-fold rings upon density in *v*-SiO_2 [*PRB* 184203 **2008**]. Raman scattering associated to hyper-Raman yields to the concentration ratio of $[BO_3]/[BO_4]$ units in boron oxide glasses [*JPCM* 155103 **2008**]. It was also found that hyper-Raman is sensitive to the coherence length of the modes. We used this very interesting specificity to show that contrary to all other vibrations, the lowest transverse optic mode of *v*-SiO_2 involves highly cooperative Si-O-Si motions, a behavior quite unique in glasses [*JRS* 1941 **2012**].

Funding: ANR Mat&Pro "*Postre*" (2008-2012), in Coll. with Saint-Gobain Recherches Aubervillier (O. Dargaud), IMPMC Paris (G. Calas), CEMHTI Orléans (P. Etchegut) and Statistical Physics Group L2C (W. Kob/S. Ispas).

Self-assembled nanostructures: emergence of confinement effects (A.-C. Genix (MCF); Collaboration: A. Arbe, J. Colmenero, San Sebastian, Spain and D. Richter, Jülich, Germany)

The structural and dynamical properties of 'comb-like' polymers with increasing length of the side groups have been investigated using different experimental techniques, dielectric spectroscopy, calorimetry, and a variety of neutron scattering methods [*Soft Matter* 1792 **2008**, *Macromol* 2522 **2012**]. These, together with the help of molecular dynamics simulations, have allowed evidencing the nanosegregation of alkyl side groups and main chains. Our results point toward a confined character of the side-groups dynamics [*Macromol* 3107 **2010**, *ibid.* 4394 **2012**].

Nanocomposite structure and the reinforcement effect (A.-C. Genix (MCF); C. Dupas (AI); M. Tatou (PhD), G. Baeza (co-directed PhD); Collaboration: J. Oberdisse (L2C Soft Matter Group, doctoral advisor))

Different silica-filled systems have been developed in order to study the reinforcement of soft polymer matrices by hard filler particles. In model nanocomposites following the latex route and casting, we have evidenced an 'aggregation diagram' of the well-defined nanoparticles, allowing for a continuous triggering of the aggregation state [*Macromol* 9029 **2011**]. We have also studied the polymer chain structure in these hard environments using isotopic substitution and SANS. Sophisticated modeling based on a combination of 'dissolving' latex beads described by a Pedersen model, and a Random Phase Approximation description of the free chains (in absence of solvent) has been proposed [*Macromol* 1663 **2012**]. The key result characterizing the evolution during annealing (nanocomposite film formation) towards complete molecular chain dispersion is shown in Figure 2. After annealing, we have successfully measured the chain conformation for different silica loading finding that chains keep their Gaussian conformation.

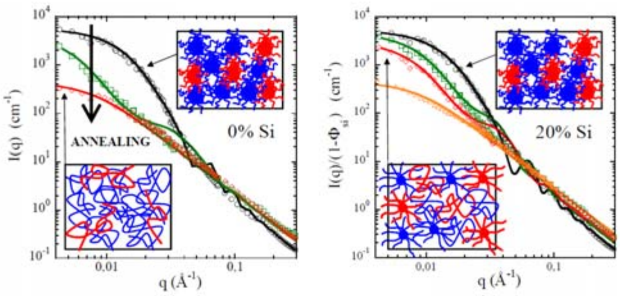

Figure 2: Modeling of the structural evolution of the polymer chains in nanocomposites.

In these samples, a slowing down of the dynamics was observed, which could be related to the formation of glassy layers on the nanoparticle surface. This topic has fueled a large debate in the literature, and we have started investigations in order to evidence the immobilized/glassy polymer layers in our systems. For this purpose, we collaborate with leading European laboratories on broadband dielectric spectroscopy (A. Alegria - San Sebastian) and Double-Quantum NMR (K. Saalwächter - Halle-Saale, C. Lorthioir - Thiais). In parallel, progress in the structural characterization of industrial nanocomposites has been obtained in the framework of a CIFRE-PhD with Michelin using simplified systems (polymer, silica and coating agent only). We have used the combination of a statistical TEM analysis, numerical simulations of polydisperse structure factors, and SAXS. It has led to a cover paper in

Macromolecules [*Macromol* 317 **2013**], and a 'JCJC' ANR project has been submitted in 2013 by A.-C. Genix. This ongoing work is a close collaboration with J. Oberdisse from the "Soft Matter" Group.

Relaxors and ferroelectric nanoceramics (B. Hehlen (PR2); A. Al-Zein, M. Al-Sabbagh (PhDs); Collaboration: J. Hlinka, Prague, Czech Republic, J.-M. Kiat, Ecole Centrale Paris)

Locally disordered ferroelectric crystals exhibit giant dielectric and piezoelectric properties and are therefore widely used in industry. They also constitute an interesting playground for understanding **i)** the effect of disorder at nanoscale on the lattice vibrations of macroscopically ordered crystals (relaxors) and **ii)** the vibrations in confined media (nanopowders and nanoceramics). For example, hyper-Raman scattering performed in the prototypical relaxor system $PbMg_{1/3}Nb_{2/3}O_3$ (PMN) led to a much more detailed understanding of the vibrations than previously reported [*PRB* 134113 **2008**, *JAP* 124114 **2011**]. In particular the soft mode exhibits a doublet structure whose lowest frequency component is found to be responsible for the Curie-Weiss behavior of the dielectric constant [*PRL* 017601 **2010**]. A confocal microscope recently implemented on the hyper-Raman setup opened the spectroscopy to ceramics. In $SrTiO_3$ we highlighted a strong broadening of the soft mode when reducing the grain size down to nanometer scale. This effect is related to the reduction of its lifetime due to confinement. Interestingly, we also observed a non-linear coupling between two order parameters, a behavior not accounted for by the standard Landau-Ginzburg theory and likely originating from the strong strain field the outer shell (or grain boundary) imposes to the core grain [*PRB* 014303 **2013**, *PRB* 024106 **2013**]. An ANR project has been submitted in 2013 to financially support this activity in collaboration with LSPMS Ecole Centrale (Paris), LLB Saclay and ESRF Grenoble.

Funding: PICS Franco-Tchèque (2013-2016), in Coll. with J. Hlinka, dielectric department, ASCR-Prague

Rayonnement et attractivité académiques

Organization of scientific events: M. Ciccotti organized an International Expert Meeting on *Glass Surfaces* in 2009, Montpellier. B. Hehlen organized an International Expert Meeting on *Structure and vibrations of oxide glasses* in 2011, Montpellier. A.-C. Genix participated to the organization of two European Workshops on Nanocomposites & Polymer Dynamics (2008 & 2011). A.-C. Genix organized with J. Oberdisse the 17th *Journées de la Diffusion Neutronique* in 2009, La Grande Motte. B. Hehlen organized five editions of the yearly Montpellier Summer School *Workshop for new researchers in glass science and technology*, 2009-2013. M. Foret and B. Rufflé have organized with A. Pradel from ICG Montpellier the French annual meeting USTV-GDR Verres in 2012, Montpellier. M. George participated to the local organization of the 13th *Jounées de la Matière Condensée* (SFP) in 2012 and C. Weigel co-organized a session on glasses.

Expertise, membership in councils and scientific networks: The group nourishes strong ties with the International Commission on Glass, and especially three Technical Committees: M. Foret and B. Rufflé are expert members of TC26 *Glass Structure and Vibrations* chaired by B. Hehlen. B. Rufflé is expert member of TC08 *Glass Transition including Relaxations* chaired by L. Wondraczek. TC09 *Glass Nanomechanics* was chaired by M. Ciccotti until 2011. R. Vacher is chairman of the *Coordinating Technical Committee*. All members of the group participate to the activities of the GDR Verres. R. Vacher is member of its scientific council. B. Rufflé participated to the project PEPS "*Physique théorique et ses interfaces*" chaired by A. Tanguy (LPMCN, Lyon). M. Foret, B. Hehlen and B. Rufflé are experts for ANR projects. B. Rufflé has been an expert for the Austrian Science Fund. M. George is a steering committee member of ReMiSol "*réseau des microscopies à sonde locale*" (MRCT) since 2009.

Public contracts and Funding: The group members participated to 6 ANR projects (two as coordinator, *CorCoSil* and *GlassPhon*). R. Vacher coordinated a European Coordination Action (*European Forum On New Glass Applications*) ending in 2009. B. Hehlen is chairman of the Omega Platform (Grand Plateau Technique pour la Recherche) significantly supported by the Languedoc-Roussillon regional council. B. Hehlen research activities have been supported by a PHC grant in collaboration with S. Elliott (Cambridge, UK) in 2009 and now by a PICS grant (2013-2016) in Collaboration with J. Hlinka (ASCR-Prague, CZ).

Recruitment: the group recruited 1 associate professor (C. Weigel, University of Bayreuth) and the following post-docs: H. Harker, University of California Berkeley; F. Lechenault, North Carolina State University; M. Flemming, Fraunhofer Institute Jena; O. Noguera, SPCTS Limoges; W. Zhou, Virginia Polytechnic Institute; E. Gouirand, TU Darmstadt.

Interactions avec l'environnement social, économique et culturel

We have long-lasting interactions with the industrial R&D Research Center of Saint Gobain Aubervilliers through ANR projects; a Mat&Pro Program entitled "*Understanding optical and structural properties of glass melts and glass* *fibers of industrial interest: energy saving and reduction of CO_2 emission*", and two "Blue-sky" Programs on "Mechanical properties of oxide glasses". More recently we developed a partnership with EADS and Arkema Companies through an ANR Mat&Pro Program "*Composite materials with controlled morphology: from the macromolecule to the mesoscopic properties*". A.-C. Genix is co-advisor of a CIFRE PhD student hired by Michelin Company (advisor: J. Oberdisse Soft Matter Group). The work focuses on "*Study of the Structure/Properties correlations in SBR-Silica Nanocomposites for Tires application*". M. Foret is member of the Administration Council of the USTV (*Union pour la Science et la Technologie Verrière*). M. Ciccotti, M. Foret, M. George and B. Rufflé have been scientific consultants for SAGEM Company (Argenteuil France) on "*Minimisation des pertes mécaniques de résonateurs en silice causées par l'endommagement de surface"* in (2009). The group has been the driving force behind the creation of the High Pressure Facility of the Lab (Resp. S. Clément) which is now used by a large number of researchers forming the *Montpellier High Pressure Science and Technology Group*, coordinated by C. Levelut (L2C) and J. Haines (ICGM).

Implication de l'équipe dans la formation par la recherche

The group was involved in the creation of the Master "Master *Physique de la Matière Molle et des Systèmes Vitreux*" (2009-2012) co-directed by B. Hehlen and M. Nobili (Soft Matter group). New training modules were developed by M. Foret, B. Hehlen, and B. Rufflé. Since 2012, B. Hehlen is co-responsible for the new Master "*NanoPhysique".* M. George has been responsible for a core training experimental module in Master 1 till 2012. M. Foret created and manages the undergraduate degree programs in physics and chemistry sciences. As mentioned above, a Summer School for new researchers in glass science and technology is organized each year since 2009 by B. Hehlen in Montpellier. Several lectures were given by M. Ciccotti, B. Hehlen, M. George and R. Vacher. A.-C. Genix organized with J. Oberdisse (Soft Matter Group) a four-day school *Neutrons et matière molle* in 2009 in La Grande Motte. M. George gave a lecture at the National CNRS training action *Forum de Microscopie à Sonde Locale* in 2011. We have supervised 5 PhD between 2008-2013 in the frame of the Doctoral Specialty « Physics » of the ED I2S and 4 PhD (2 co-directed) are in progress.

agence d'évaluation de la recherche et de l'enseignement supérieur

Présentation synthétique de l'entité

Unité de recherche

Vague E : campagne d'évaluation 2013-2014

Team "Physics of Glass"

Intitulé de l'unité : Laboratoire Charles Coulomb

Nom du directeur de l'unité : Jean-Louis SAUVAJOL

Nom du responsable de l'équipe (le cas échéant) : Benoît RUFFLE

Effectifs de l'entité au 1er janvier 2008

5 professors and assistant-professors and 1 emeritus; 1 researcher and 1 emeritus; 5 PhD students; 1 Post-doc

Personnels ayant quitté l'entité pendant le contrat en cours (et nombre de mois cumulés passés dans l'entité au cours de cette période).

1 researcher (32 months); 6 PhDs (204 months); 6 post-docs (68 months).

Nombre de recrutements réalisés au cours de la période considérée et origine des personnels

1 assistant-professor (C. Weigel, Univ. Bayreuth) ; 5 PhD students (A. Amouri, Tunisie ; M. Kint, UM2 ; M. Al Majzoub Al Sabbagh, Liban ; G. Baeza, UM2 ; Y. Nziakou, Paris) ; 5 post-docs (F. Lechenault, North Carolina State University ; M. Flemming, Fraunhofer Institute Jena; O. Noguera, SPCTS Limoges ; W. Zhou, Virginia Polytechnic Institute ; E. Gouirand, TU Darmstadt).

Production scientifique au cours de la période écoulée (1er janvier 2008 - 30 juin 2013) :

1) An innovative method of quantitative analysis for the multi-scale structure of industrial nanocomposites has been recently established. It is based on the combination of statistical TEM analysis, small angle scattering and numerical simulations
2) Evidence for an unexpected huge solubility of rare gas atoms in silica glass from extended Brillouin scattering experiments. An analysis of the associated poroelastic behavior at the sub-nanometric scale is under development in collaboration with the recently created joint CNRS/MIT Department unit MSE^2
3) Hyper-Raman spectroscopy is sensitive to vibrations that are inaccessible otherwise. This opens up new avenues of research. This has been shown in glasses, and more recently in a prototypical relaxor system were the soft mode responsible for the peculiar behavior of its dielectric constant has been observed
4) Breakthrough in accurate sound-attenuation coefficient measurements thanks to picosecond optical techniques: application to sub-terahertz phonons in glasses
5) Set-up of an unique experimental analyze technique which allows at the same time in situ observation of mechanisms activated during sub-critical crack propagation in vitreous materials and measurements of associated strain/stress fields from macroscopic to nanometric scales

Bilan quantitatif des publications de l'entité.

52 Publications in Peer-reviewed journals

Indiquer les 5 publications majeures de l'entité

1. *Multiscale Filler Structure in Simplified Industrial Nanocomposite Silica/SBR Systems Studied by SAXS and TEM;* Baeza G., Genix A.-C., Degrandcourt C., Petitjean L., Gummel J., Couty M., Oberdisse J.; **Macromolecules** 46, 317 (2013) – **Cover Article**
2. *Vitreous silica distends in helium gas: acoustic vs. static compressibilities* Weigel C., Polian A., Kint A., Rufflé B., Foret M., Vacher R. **Physical Review Letters** 109, 245504 (2012).
3. *Soft Mode Doublet in PbMg1/3Nb2/3O3 Relaxor Investigated with Hyper-Raman Scattering* Al-zein A., Hlinka J., Rouquette J., Hehlen B. **Physical Review Letters** 105, 017601 (2010)
4. *Scaling the Temperature-Dependent Boson Peak of Vitreous Silica with the High-Frequency Bulk Modulus Derived from Brillouin Scattering Data* Rufflé B., Ayrinhac S., Courtens E., Vacher R., Foret M., Wischnewski A., Buchenau U. **Physical Review Letters** 104, 067402 (2010)
5. *Effects of Finite Probe Size on Self-Affine Roughness Measurements* Lechenault F., Pallares G., George M., Rountree C., Bouchaud E., Ciccotti M. **Physical Review Letters** 104, 025502 (2010)

Indiquer **au maximum 5 faits illustrant le rayonnement ou l'attractivité académiques**

1. Organization of two European Workshops on *Nanocomposites* (2008 & 2011, A.-C. Genix) and two Expert Meetings on *Glass surfaces* (2009, M. Ciccotti) and on *Structure and vibrations of oxide glasses* (2011, B. Hehlen)
2. 6 ANR grants during the 2008-2012 period establishing formal collaborations with about 15 groups in glass science
3. Strong involvement in the International Commission on Glass (B. Hehlen, chairman of TC26 *Structure & Vibrations*; M. Ciccotti, chairman of TC09 *Glass Nanomechanics*; R. Vacher chairman of the *Coordinating Technical Committee*)
4. Organization of the yearly Montpellier Summer School: *Workshop for new researchers in glass science and technology* (~25 students), chaired by B. Hehlen, 5th edition in July 2013
5. 26 Invited Talks in International and National Conferences or Workshops covering most of the topics addressed by the group

Indiquer **au maximum 5 faits illustrant les interactions de l'entité avec son environnement socio-économique ou culturel**

1. Scientific consulting partnership with SAGEM Company (Argenteuil France) on "*Minimisation des pertes mécaniques de résonateurs en silice causées par l'endommagement de surface*", (2009)
2. Partnership with EADS and Arkema Companies through an ANR project (Mat&Pro Program, *Promorph* 2012-2015) entitled "Composite materials with controlled morphology: from the macromolecule to the mesoscopic properties"
3. Partnership with the industrial R&D Research Center of Saint Gobain Aubervilliers through an ANR project (Mat&Pro Program, *Postre* 2008-2012) entitled "Understanding optical and structural properties of glass melts and glass fibers of industrial interest: energy saving and reduction of CO_2 emission"
4. CIFRE PhD grant with Michelin Company (Advisor J. Oberdisse, Co-advisor A.-C. Genix) "Study of the Structure/Properties correlations in SBR-Silica Nanocomposites for Tires application" (2010-2013)
5. Partnership with the CNRS/Saint Gobain joint Unit SVI through ANR projects (Blue-sky Programs, PlastiGlass 2005-2008 & MecaSil 2012-2015) on "Mechanical Properties of Silica-based Glasses"

Indiquer **les principales contributions de l'entité à des actions de formation**

1. Co-direction of the Master *Physique de la Matière Molle et des Systèmes Vitreux* and Co-direction of the Master *NanoPhysique* (2012-), B. Hehlen. Development of training modules specific to the Physics of Glasses (2009-2012), M. Foret, B. Hehlen, and B. Rufflé. Responsible for a core training experimental module in Master 1, M. George
2. Organization of the yearly Montpellier Summer School: *Workshop for new researchers in glass science and technology* (~25 PhD students or young researchers), B. Hehlen
3. Organization of a four-day school *Neutrons et matière molle* in 2009 together with J. Oberdisse (Soft Matter Group I2C) and publication of the lectures, A.-C. Genix
4. Lecture at the National CNRS training action *Forum de Microscopie à Sonde Locale 2011*, (~140 participants), M. George
5. Manager of the undergraduate degree programs in physics and chemistry sciences, M. Foret

Team: “Nanostructures”

Team: "Nanostructures"

The "nanostructures" team is involved in a wide range of topics that cover the growth mechanisms and structural properties of nanostructures, the development of optical setups, as well as fundamental and applied work on the physical properties of nanostructures at the individual and macroscopic level. Long standing research on the properties of carbon nanostructures has been pursued. Within the last years, the investigation on the physical properties of individual nanotubes has been extended to the optical properties of graphene. New projects allowed us to extend the group expertise to nanomaterials under extreme conditions and hybrid nanostructures. Our main achievements are detailed below.

Topic: *Individual Carbon Nanostructures*

Raman spectroscopy of individual carbon nanotubes

Participants: V. Jourdain (MCF), T. Michel (MCF), M. Paillet (CR1), J-L Sauvajol (DR1), A. Zahab (PR1), D. Levshov (PhD), R. Parret (PhD), X-T. Than (PhD), D. Nakabayashi (PostDoc)

Our objective is to address the intrinsic properties of individual isolated single-walled (SWNT), double-walled (DWNT) and triple-walled (TWNT) carbon nanotubes. The overall approach involves the synthesis of suspended individual carbon nanotubes and the study of their intrinsic properties by combining, on the same suspended nanotube, resonance Raman spectroscopy experiments and structural characterizations such as electron diffraction (ED) and high resolution electron microscopy (HRTEM). These latter characterizations were performed in the framework of various collaborations (INA at the University of Zaragoza, Max Planck Institute at Stuttgart, LEM at ONERA).

Since 2005, this original approach, mainly applied to SWNT, led to an extensive comprehension of their vibrational and optical properties enabling the building up of precise Raman criteria to identify the (n,m) atomic structure from Raman spectroscopy only [Phys. Rev. B. **80** (2009) 245416].

In the last period, an intensive work has been dedicated to understand the Raman spectra of DWNTs. Figure 1 displays the low-frequency Raman spectra of an individual (12,8)@(16,14) DWNT (indices derived from ED) at two laser excitation energies. These Raman spectra cannot be directly interpreted as the sum of the two constituting SWNTs: (i) the observed frequencies cannot be connected to inner and outer layer diameters by means of the 1/d power law (d= diameter of the nanotube) widely used for the radial-breathing mode (RBM) of SWNT. In agreement with theory, radial vibrations of the two layers behave as coupled oscillators giving rise to collective modes of both layers: the radial breathing-like Modes (RBLM). The two peaks are thus associated to in-phase (133 cm^{-1}) and counter-phase (186 cm^{-1}) radial vibrations. (ii) Comparing with the RBM of SWNTs, the resonance conditions to observe the collective RBLM are also different. From our experimental resonance chart (not shown) we evidence that only the inner (resp. outer) layer is in resonance at 2.41 eV (resp. 1.96 eV). Thus, for the first time our results qualitatively explain the observation of RBLM Raman lines, whenever only one of the layers (inner and/or outer) is resonant with the laser energy [Nano Lett. **11** (2011) 4800].

Other important and specific behaviors, in particular regarding G modes in DWNT, were also evidenced in our studies. This pioneer work highlights the important role played by layer coupling on the properties of DWNT.

To complete our knowledge on this aspect, we are also interested in the Raman spectra of TWNTs. Optimization of the synthesis has made possible this unique and on-going study. An example is given in figure 2. The RBLM and tangential modes of a suspended structure-identified as TWNT are reported for the first time.

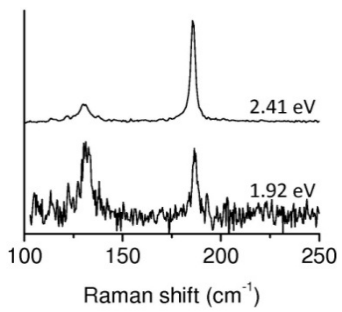

Fig-1: low-frequency Raman spectra of an individual (12,8)@(16,14) DWNT measured at two laser excitation energies as indicated in the text.

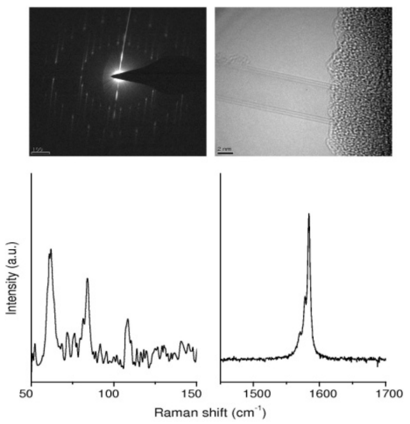

Fig-2: Top: ED pattern (left) and HRTEM image (right, scale bar 2 nm) of an individual TWNT. Bottom: Raman spectrum excited at 2.18 eV of the same TWNT.

It must be emphasized that our combined approach is presently the most suitable one to derive accurate understanding of Raman responses of such complex systems.

Optical characterization of graphene and graphene-based materials

These studies are performed in the framework of the group of spectroscopy of the "**Axe transverse graphene**". This axe merges researchers of the "**Nanostructures team**": T. Michel (MCF), M. Paillet (CR1), J-L Sauvajol (DR1), A. Zahab (PR1), R. Parret (PhD); H-N. Tran (PhD), D. Nakabayashi (PostDoc)) and researchers of the "**Materials, Devices and Sensors team**": J.R Huntzinger (MCF), A. Tiberj (MCF), P. Landois (MCF), S. Contreras (CR1).

The group of spectroscopy of the "Axe transverse graphene" has developed in the recent years a unique expertise in terms of characterization of single-layer graphene (SLG) and multi-layer graphene (MLG). This know-how is based on instrumental developments (including the combined used of local Raman, transmission and reflection measurements), as well as the development of data treatment and interpretation tools. These skills are used for the study of various samples elaborated at L2C (SLG/MLG exfoliated on Si/SiO_2 or glass) or obtained through collaboration: SLG/MLG on SiC (F. Duclairoir, INAC, CEA Grenoble) or suspended graphene (E. Dujardin, CEMES, Toulouse). A reliable tool for counting the number of layers of any kind of graphene samples is now available. The simultaneous use of Raman and optical measurements permitted to demonstrate that some commonly used criteria in the field, such as the width of the 2D band for instance, are not fully relevant for this purpose, especially in the case of misoriented, doped or strained SLG/MLG. We are currently studying strategies of Raman data treatment that would allow separating the effects of charges and strain.

On-going studies are mainly focused on fundamental optical and thermal properties of SLG/MLG and on the influence of environmental perturbations.

1-In situ Raman probing of graphene over a broad doping range upon Rb vapor exposure

Building on the experience of our team in the study of alkali-doping of carbon nanotubes, we developed an experimental set-up to investigate in situ the evolution of graphene Raman modes upon rubidium vapor exposure [ACS Nano **7** (2013) 165]. Such experiments have been carried out mainly on single and bilayer graphene samples. Alkali doping presents the advantage to probe an extended doping range as compared to the most commonly used electrostatic gating method. The estimation of the injected charge density is however not as straightforward. Nevertheless, we have shown in this study that by comparison with experimental data available in the literature as well as with theoretical calculations, it is possible to establish a relationship between the Rb vapor exposure time and the injected electron density in graphene.

On SLG, the maximal charge density attained is above 10^{14} electrons/cm^2, which corresponds to a Fermi level displacement of about 1 eV. We studied the G-band frequency variation as a function of the electron density and observed three different regimes: a continuous upshift followed by a plateau and a downshift (figure 3). This behavior is interpreted as the signature of the competition between dynamic and adiabatic effects upon n-doping. Indeed, for n-type doping, the former induce a strengthening of the G-band frequency while the latter tend to soften it. Since the variation laws as a function of electron density are different, this experimental inversion of tendency is expected theoretically (cf. M. Lazzeri, F. Mauri, Phys. Rev. Lett 97 (2006) 266407). Comparison of the obtained results with theoretical predictions indicates however that a substrate pinning effect occurs and inhibits charge-induced lattice expansion of SLG. Accounting for this effect together with the GW DFT evaluation of the electron-phonon coupling for the G band (cf. M. Lazzeri et al., PRB 78 (2008) 081406) leads to a good agreement with experimental data. In particular, the maximum upshift experimentally measured is well reproduced.

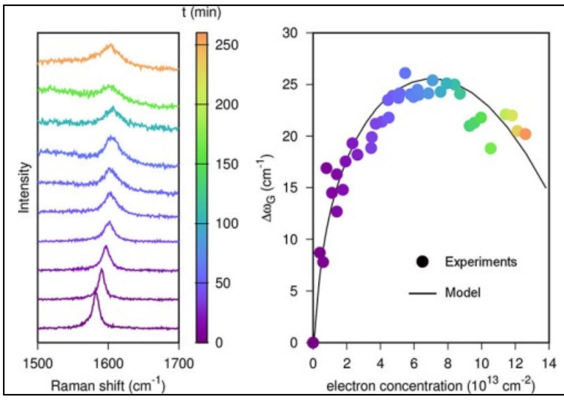

Fig-3: Selected Raman spectra in the G-band (left panel) region of SLG at different doping times. Right panel: comparison between experimental and theoretical evolution of the G band shift as a function of electron concentration

For BLG, the added electrons are shown to be first confined in the top layer, but the system evolves with time toward a more symmetric repartition of the added electrons in both layers. The results obtained on BLG also confirm that the slope of the phonon dispersion close to the K point tends to be slightly reduced at low doping but suggest the occurrence of an unexpected increase of the phonon dispersion slope at higher electron concentration.

2-Graphene functionalization through photo-active molecule absorption

In the framework of the ANR project “Grafonics”, we studied the functionalization of graphene through immersion in solutions of acceptor or donor molecular systems. The objective is to modify graphene electrical properties and to bring new functionalities. The more advanced study concerns the Co-phthalocyanine (Copc)/graphene system. We have shown by optical, Raman and AFM measurements that the molecules are preferentially absorbed on SLG/BLG as compared to MLG and that they are lying flat on the surface without preferential orientation in this plane. The optical absorption bands of the CoPc are observed to be significantly redshifted when the molecules are in interaction with graphene. The investigation of the effect of such functionalizations on graphene properties is under progress.

This ANR project funded the new Raman experiment we developed specifically for graphene studies taking advantages of the long time experience of our team on the spectroscopy of carbon nanostructures and on the combination of Raman spectroscopy and reflectivity and transmission measurements developed in “Materials, Devices and Sensors team” to analyse accurately epitaxial graphene on SiC. In this project epitaxial graphene on SiC, exfoliated graphene on SiO_2/Si substrates and suspended graphene are investigated to secure the graphene samples supply.

3-Reversible photo-doping of graphene

Finally, in collaboration with CEMES, we demonstrated that the charge carrier density of graphene exfoliated on a SiO_2/Si substrate can be finely and reversibly tuned between electron and hole doping with visible photons [A. Tiberj *et al.*, arXiv:1304.4418]. This photo-induced doping happens under moderate laser power conditions but is significantly affected by the substrate cleaning method. In particular, it is found to require hydrophilic substrates and to vanish in suspended graphene. These findings suggest that optically gated graphene devices operating with a sub-second time scale can be envisioned but also that Raman spectroscopy is not always as non-invasive as generally assumed.

Topic: *Confinement*

There are two main motivations behind this research. First, endohedral filling of specific species into the hollow core of single walled carbon nanotubes (CNTs) can provide a powerful method to tailor their physical properties or to elaborate new hybrid systems for fundamental and applied goals. Second, highly porous carbon nanostructures represent particularly attractive materials for high and reversible energy storage.

Endohedral filling

Participants: L. Alvarez (MCF), R. Le Parc (MCF), J-L. Sauvajol (DR1), J-L. Bantignies (PR2), T. Michel (MCF), Yann Almadori (PhD), Anouar Belhboub(PhD)

This project is a fundamental research on 1D nano-hybrid systems consisting mainly in photo-active molecules (organic and organometallic chromophores) encapsulated into the 1D cavity of single wall carbon nanotubes. Our objective is the understanding of the physical interactions taking place between the photo-active molecules confined in the hollow core of the host nanotubes and their consequences on the physical properties of the hybrid material. The final objective is to control the opto-electronic properties of the 1D hybrid system.

We have elaborated model systems to study the confinement effect. The confined phase behavior can differ significantly from the bulk phases. In particular, the 1D character of nanotubes can give rise to very specific quantum effects on the confined species. The nanotubes can also be used as nano-reactor to create new polymorphic structures of the encapsulated species. Finally, nanotubes, particularly chemically inert, can protect relatively unstable species under normal conditions and thus allow the study of new systems whose access has been limited.

To modulate the optical and/or electronic properties of the CNTs, different compounds have been encapsulated:

- Oligothiophene molecules (oTh) which display strong absorption in the 350-500 nm range. They were also chosen because they display finely tunable optical properties with respect to their chain length and end-capped functionalized substituents.
- Phthalocyanine molecules (Pc) which display a remarkably high extinction coefficient in the 650-720 nm region which corresponds to an important part of the solar spectrum.
- Iodine species (I_n^-) which are known to improve significantly the conductivity of CNTs.

Most significant results concerning this topic are detailed below:

Our studies on the **confinement of oligothiophene** derivatives into single-walled nanotubes of different diameters (oTh@NT) evidenced a strong interaction between both species [JPCC, **115**, 11898 (2011), Phys. Status Solidi B **248**, 560 (2011)]. Indeed, infrared results are consistent with a permanent charge transfer between both materials. A resonant Raman process is clearly observed on the oTh signal (1450 cm^{-1}) with respect to the nanotubes G-band (1590 cm^{-1}) (figure 4). The Raman responses of oTh@NT for low excitation wavelengths (514.5, 488 and 458 nm) lead to the vanishing of the RBM and to a G band shift (from 1 to 3 cm^{-1}), in good agreement with a significant photo-induced charge transfer.

The Raman spectra of **zinc phthalocyanine molecules** (Zn-Pc) either in their bulk phase or confined into NTs are rather close to each other, suggesting that the encapsulated molecule behaves as the one in the bulk phase. By contrast, for Zn-Pc localized at the outer surface of the NTs, the Raman measurements display significant differences, consistent with a strong interaction involving mainly the zinc central atom of the molecule. [J. Nanoelectron. Optoelectron. 8, 28-35 (2013)]

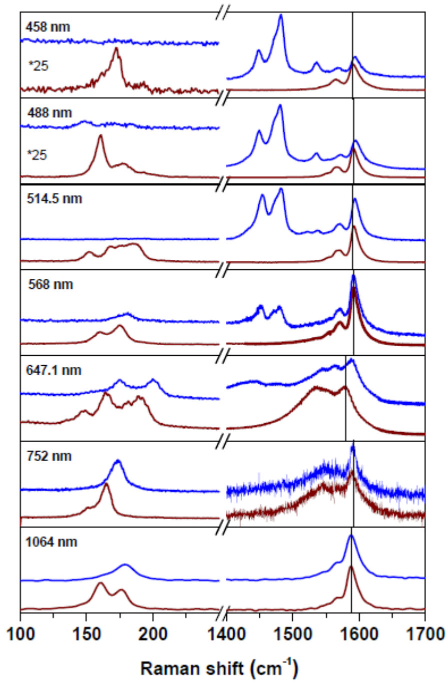

Fig-4: *Raman spectra of raw (wine) NT and oTh@NT (blue)*

Using X-ray Absorption spectroscopy (SOLEIL and ESRF synchrotrons), we have also performed a detailed study of the structure of **polyiodide chains** confined inside carbon nanotubes as a function of the nanotube diameter [Carbon, **52** (2013) 100 –108]. We identify experimentally for the first time the 1D signal of linear polyiodide chains confined inside the hollow core of CNT thanks to X-ray and electron diffraction. EXAFS experiments allow assessing the dependence of the length and charge of the confined polyanions with the tube diameter. A critical diameter Φc around 1 nm is identified. Below Φc, long I_n^- polyanions (n >> 5) with subsequent weak charge transfer are obtained. For diameter above Φc, significant shortening of the polyanions leading to a more important charge transfer is shown in agreement with Raman results. From a fundamental point of view, the electronic properties of such atomic system can be defined according to a Peierls model of electrons delocalized on a one dimensional lattice of atoms. Thus, ideal 1D lattice is expected to disappear at low temperature with a pairing of the atoms known as the Peierls transition. This transition leads to switching from a metallic behavior to a semi conducting one by opening a band gap in the electronic structure.

Numerical study of H_2 and CH_4 storage in nanoporous carbons

L.Firlej (PR1)

One of potential perspectives for clean fueling of cars is the use of hydrogen-powered fuel cells. A major challenge in the massif implementation of hydrogen-fuelled vehicles consists in designing hydrogen storage systems that are reversible, light, cheap and able of delivering a driving range of few hundreds of kilometers. Between the possible hydrogen adsorbents carbon porous structures remain the most promising ones. However, we have shown [Carbon 48, 223-231 (2010)] that it is not possible to increase hydrogen storage capacity by modification of slit width only, without simultaneous increase of the H_2 binding energy [J.Chem.Phys. 131, 164702 (2009)] and the adsorbent specific surface [Carbon 53, 208-215 (2013)].

Therefore, we have recently proposed a class of high-surface-area carbons [JACS **134,** 15130–15137 (2012)] which goes beyond the traditional model of parallel graphite sheet hosting layers of physisorbed hydrogen in slit-shaped nanopores. We call them Open Carbon Frameworks, OCF (Fig-5). The structures are ordered, and have low density architecture required for effective applications for mobile storage. Theoretically they may have the specific surfaces exceeding 6000 m^2/g.

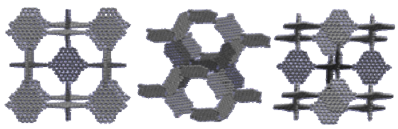

Fig-5: Schematic structure of open carbon frameworks

From the analysis of the computer simulations of adsorption properties of the new structures, a rich spectrum of relations between structural characteristics of OCFs and ensuing hydrogen adsorption (structure-function relations) emerges: (i) storage capacities higher than in slit-shaped pores can be obtained by fragmentation/truncation of graphene sheets, which creates additional surface areas (with respect to infinite graphene sheets), carried mainly by edge sites; ii) for OCFs with a ratio of in-plane to edge sites approximately equal 1 and surface areas of 3800-6500 m^2/g, we found at 77 K record storage capacity of 100-260 g H_2/kg C (at 100 bar); (iii) additional increase of hydrogen uptake could potentially be achieved by chemical substitution and/or intercalation of OCF structures, in order to increase the energy of adsorption. In consequence we conclude that OCF structures, if synthesized, will allow the hydrogen uptake at the level required for vehicular applications

Topic: Films and composites

Catalytic chemical vapor decomposition (CCVD) is the most used technique to grow single-walled carbon nanotubes (SWNTs). While growing nanotubes with a controlled structure and a high crystalline quality are key points for the development of SWNT-based applications in electronics and opto-electronics, an important issue is that CCVD generally yields SWNTs presenting a broad diameter distribution and a low crystalline quality.

On the other hand, SWNTs present exceptional, but very anisotropic, properties at the nanometric scale. In order to take advantage of these properties in composites, one needs to control both the dispersion and the orientation of the nanotubes in different kinds of matrices.

CCVD Growth

Participants: V. Jourdain (MCF), E. Anglaret (PR1), Mathieu Picher (PhD) H. Navas (PhD), H. Navas (Post-doc)

Our approach to probe CCVD growth mechanisms and products is based on a systematic Raman analysis of SWNTs grown by CCVD using different carbons precursors and in various conditions of temperature and precursor pressure. The radial breathing modes (RBM) are used to monitor the evolution of the diameter distribution while the D-band allows assessing the density and type of defects. The main advantages of in situ Raman studies of CCVD growth are its high throughput and the possibility to perform dedicated experiments monitored by Raman spectroscopy and in a controlled gas environment. The main disadvantage is the lack of information at the individual nanotube level and about the catalyst, which imposes to use complementary *ex situ* characterizations such as TEM and XPS which we performed in the collaborative framework of the ANR project SOS Nanotubes.

Our systematic Raman studies notably revealed two parameter domains with opposite influences of the temperature and precursor pressure on the diameter distribution (Fig. 6) [ACS Nano **5**, 2118 (2011)]. Thanks to specially-designed experiments made of two successive growths, three processes influencing the diameter distribution were identified: i) at low precursor pressure, nanotube nucleation is thermodynamically impeded on the smallest catalyst particles; ii) at low temperature and high precursor pressure, small catalyst particles are encapsulated by disordered carbon; iii) at high temperature, catalyst coarsening causes the disappearance of the smallest catalyst particles.

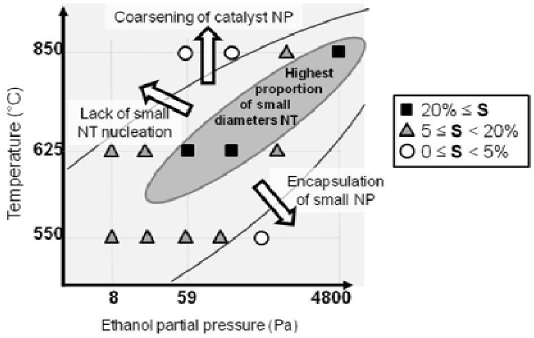

Fig-6. Processes influencing the diameter distribution of SWNTs grown by CCVD. The small-diameter index S is the intensity ratio of small- over large-diameter RBM.

Anisotropic nano-composites

Participants: E. Anglaret (PR), C. Blanc (CR), M. Nobili (PR), R. Metz (MCF), C. Zamora-Ledezma (PhD), C. Zamora-Ledezma (Postdoc), Nawel Ould-Moussa (Postdoc), Fernando Torres-Canas (PhD), Julien Stein (PhD))

We prepare and study the physical properties of various anisotropic nanotube-based composites : i) nematic aqueous suspensions of nanotubes which can be homogeneously oriented by shearing between two glass plates, and subsequently dried to prepare anisotropic thin films, ii) mixtures nanotubes/liquid crystals which can be homogeneously oriented in thin cells using alignment layers, iii) nanotubes/polymer composite films, which can be oriented by stretching above the glass transition temperature of the matrix.

One major result was the preparation of series of nanotube/polymer composites with various concentrations and orientations [Phys. Rev. B **80**, 113407 (2009), J. Phys. Chem. C **116**, 13760 (2012)]. We proposed a simple way to measure the order parameter from polarized Raman measurements assuming one single non-zero value in the (resonant) Raman polarizability tensors. This hypothesis was validated by checking that spectra measured in different polarization conditions can be superimposed by a simple multiplication factor.

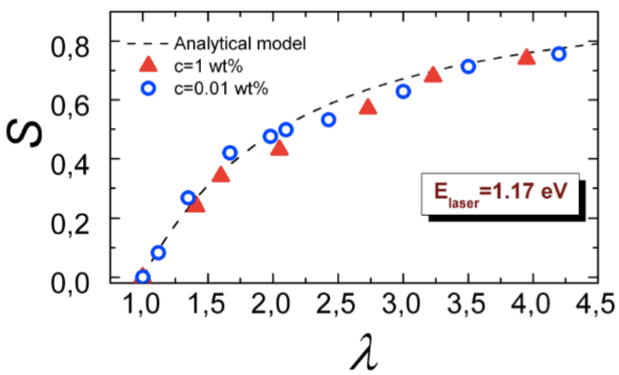

Fig-7. Order parameter of nanotubes dispersed in polymer matrices (PVA). Symbols: experiments, dotted line: analytical model.

Furthermore, we found a good agreement between the measurements and a simple analytical model assuming uniaxial deformation at constant volume. The measured orientations of well-dispersed nanotubes in the polymer matrix do not depend on their concentration, providing that absorption anisotropy is taken into account for concentrated composites (fig. 7). Our validated spectroscopic method to describe the orientation of nanotubes in composites was then used to show that length and entanglement of the nanotubes were key parameters to control the orientational order in anisotropic thin films due to limitation of orientation via elasticity and topological defects [Nanoletters **8**, 4103 (2008), J. Phys. Chem. C. **115**, 3272 (2011]. The main advantages of optical spectroscopic studies of the orientation and optical properties of SWNT-based composites are accurate and easy measurements on various kinds of samples.

On the other hand, we reported an excellent alignment of the nanotubes dispersed in nematic lyotropic liquid crystals which opens up the possibility of orientational switching of the nanotubes in the field of the nematic [Liq. Cryst., **DOI:** 10.1080/02678292.2013.772254 (2013)].

Topic: *Beyond carbon nanomaterials*

In the last four years, the team has been active in a wide range of subjects involving its vibrational spectroscopy expertise. The development of new optical setups has been performed to study the structuring mechanisms of nanomaterials and investigate the physical properties of electrode materials and nanostructured materials under extreme conditions.

Self-assembly of hybrid organic inorganic nanomaterials

Participants: J-L. Bantignies (PR), R. Le Parc (MCF), Ph. Dieudonné (IR2), C. Blanc (CR1), G. Creff (PhD)

Nanostructured hybrid silica (NSHS) obtained by the sol-gel synthesis combines the properties of the organic moieties with those of the silica matrix. Organic groups act as internal structuring agents due to non covalent intermolecular interactions during the sol-gel hydrolysis-condensation of the molecular precursors. The self-structuring mechanism is still not fundamentally understood. Our objective is to establish the mechanistic pathways that contribute to the structuring of these solids. We have developed a novel experimental approach in order to elucidate the mechanisms which control the evolution of the organised solid from such sol-gel processing: self-assembly, hydrolysis, polycondensation of precursor molecules, and nucleation and growth of the hybrid solid in solution. We have combined *in-situ* infra-red spectroscopy, *in-situ* polarizing optical microscopy and *in-situ* light scattering to monitor the different stages of the self-organization process.

We showed that a long range structuring exists within the organic fragments with the transcription of the DDAA (Donor-Donor-Acceptor-Acceptor) H-bonding array from precursor to material [PCCP 2012].

A mechanism describing the formation of the organized NSHS has been proposed, based on our *in-situ* microscopic and spectroscopic studies [Small 2009; Langmuir 2013]. The highlight of this activity is the synergy between the skills in chemical nano engineering of our colleagues from the Institute Charles Gerhardt of Montpellier 2 University and our experimental expertise in condensed matter physics.

Self-assembly of 2D adsorbed monolayers

People: L.Firlej (PR1)

We have numerically analyzed thermodynamic properties of alkanes physisorbed on graphite. From the practical point of view, interfacial properties of n-alkanes are relevant for many widespread applications (e.g., lubrication, adhesion, catalysis etc.). Alkanes can be also considered as simplified model materials that help us understanding similar but larger systems such as polymers, lipids and proteins. We have shown that the melting mechanism of alkanes' monolayers self-assembled on graphite is correlated with internal degrees of freedom for long molecules (e.g., tetracosane [Langmuir 24, 12392-12397 (2008)], whereas for short molecules (e.g., hexane, [Langmuir 25, 6596–6598 (2009)] it occurs as a proliferation of small domains reorienting within low temperature lamellar structure. Recently we extended the analysis of self-organized systems on 2D molecular sieves, consisting in molecularly engineered alkanes-based host matrices self-assembled at solid(graphite)/liquid interfaces. We analyse the thermal stability of such structures, the size and shape selectivity of adsorption, dynamics and surface diffusion of the guest molecules within 2D porous structure.

Nanomaterials under extreme conditions

Participants: C. Levelut (DR2), J-L. Bantignies (PR1), P. Hermet (post-doc), J. Catafesta (post-doc)

Our aim is to investigate pressure-induced amorphization (PIA) in materials displaying negative thermal expansion (NTE). NTE has been linked to thermally-excited rigid unit vibrational modes. These materials exhibit unusual behavior upon compression due to the softening of a large number of these modes leading to pressure-induced amorphization. Both NTE and PIA confer unique physical properties to these materials for technical applications in optical components and shock wave absorption. Our study is focused on two classes of materials with open structures exhibiting the highest known degree of negative thermal expansion: zeolites and cyanide compounds.

We have used a multi-scale approach under pressure and temperature, including in situ EXAFS measurements (SOLEIL, ESRF), the total neutron scattering (ILL, ISIS) and x-ray scattering (SOLEIL, ESRF SPRING 8). The measurements are coupled to ab Initio (Patrick Hermet) and Monte Carlo (Benoit Coasne, ICG) calculations. We try to understand the dynamic origin and structural consequences of negative thermal expansion and amorphization pressure [*Phys. Rev.Lett.(2012)* **109**, 035701; *Nature Mat*. 2013, **12**, 212-216] .

Instrumental developments were required for far infrared measurements under pressure: original results were obtained in hydrated faujasite 13X under pressure providing a direct evidence of local depressurization (related to a transition to a denser phase). Incorporation of species (Ar, CO2) in the pores of the Silicalite-1OH is shown to prevent amorphization under pressure. In this case, the compression mechanisms are modified and the amorphization mechanism is disabled. The incorporation of the species is a mean of stabilizing other porous materials, including some MOFs and cyanides, up to very high pressures. Partially filling pores modify the physical properties of these materials. By heating the system silicalite-1OH/CO_2 pressure, a chemical reaction has been observed producing a new amorphous SiO_2-CO_2 mixed compound (*JACS, 2010,* **132**(26), 8860, *PCCP.2011* **13**, 20096).

Electrode materials

Participants: F. Henn (PR1), J-L. Bantignies (PR2), T. Michel (MCF), L. Gourrier (PhD)

The *β*-form of nickel hydroxide [Ni(OH)2] is the active mass of many rechargeable alkaline batteries. $Ni(OH)_2$ electrode efficiency relies on its ability to exchange a proton and an electron. Due to defects and of heterogeneities throughout the electrode, the exact conditions corresponding to the detrimental semiconductor-insulating transition that occurs upon reduction of Ni(OOH) toward $Ni(OH)_2$ is not known. We have explored relationships between the structural properties of the active material, the transport mechanisms governing mobility of the charge carriers within the solid material and the electrochemical performance of the electrode. "Pseudo-single" crystals of β-nickel hydroxide constituted by extremely well ordered hexagonal nanocrystallites were synthesized. They appear to be a unique model material for investigating the fundamental β-$Ni(OH)_2$ redox behavior and exhibit a potentially highly efficient active mass for rechargeable batteries (*J. Phys.Chem C (2011)* **115**, 15067). We perform a complete study of their structural, electronic, magnetic, dynamical, and elastic properties coupling experimental and DFT calculations (*Phys. Rev. B (2011)* **84**(23), 235211).

Our expertise, which is rather unique in that field, relies on our capability to study both the electrochemical and vibrational properties of this solid. Since the Ni(OOH)/$Ni(OH)_2$ redox reaction is associated to complex structural change at the local and non-local scales, the use of vibrational spectroscopy (IR and µRaman) is of great relevance for obtaining more insights into the electrochemical mechanisms involved. Our weakness is that we have no competence for developing new synthesis routes of this material. We, therefore, need to collaborate with solid-state chemists and, hence, are dependent on the progress that can be achieved regarding synthesis. For that purpose, we have recently established a new cooperation with Dr. Valeriy Kotok from the Ukrainian State University of Chemical Technology at Dniepopretrovsk. This international cooperation is in addition to those we have already established for many years with our Montpellier colleagues: Dr.Stefano Deabate of the European Institute of Membranes and Prof. A. Medhi of the Institute Charles Gerhardt.

The future of this research project is rather well defined. First of all, we need to develop in-situ µ-Raman characterization upon electrochemical test. A first series of experiments has been carried out (Laure Gourrier's PhD) but significant improvements are requested. Secondly, investigation of the electrochemical/vibrational properties of "pseudo-single" crystals of $Ni(OH)_2$ doped with Co and Zn will be necessary since it is well known that these dopants increase the electrochemical performances of this compound. Finally, characteristics of the structural changes induced by high current density redox reaction will be studied since it turns out the "Pseudo-single" crystals of $Ni(OH)_2$ could exhibit interesting performance for application in super-capacitor.

Rayonnement et attractivité académiques

Organization of scientific conferences: The members of the team are strongly involved in the organization of national and international scientific conferences, schools and workshops:

2008: chairman of NT08: "Ninth International Conference on the Science and Application of Nanotubes", Montpellier, France (June 29 - July 4 2008).

2009: Organization committee of the international conference: "Vie, vivant, vital: vitalisme", (Montpellier, June 24-27, 2009); Co-organizer of the "Nanoscience's School 2009 (ENANO2009)", Caracas/Choroni, Vénézuela (November 2009); Organization committee of "Carbon 2009", Biarritz, (June 14-19, 2009).

2010: Scientific committee of NT10 and APS 2010; Local organization committee of "MOLMAT 2010", scientific committee Workshop on Organic Electronics and Nanophotonics 2010

2011 : Chairman du 14^{e} International Symposium on Electrets (ISE14/ conference IEEE) ; Montpellier, (August 28-31); Scientific committee of the "Workshop on Organic Electronics and Nanophotonics 2011"; Organization committee of the topic "History of philosophically neglected, marginalized and recently emergent disciplines" of the European Science Fundation, Montpellier (November 18-19); Co-organizer of the "Nanosciences School 2011 (ENANO2011)", in Vénézuela (October 2011-February 2012); Organizer of symposium A31 (Carbon nanotubes and graphene) in conference EUROMAT2011, Montpellier (September 2011)

2012: Organizer of "13ème Journées de la Matière Condensée", Montpellier, August, 27 –31; Scientific committee of the international conference NT12; Co-organisation of the "Ecole franco Maghbenine de spectroscopie Raman", Sousse (Tunisie), December 10 –14, 2012

2013: Scientific committee of the "Workshop on Organic Electronics and Nanophotonics 2013"; Organizer of topic A3 symposium A31 (Carbon nanotubes and graphene) in conférence EUROMAT 2013, Sevilla, Spain (September 2013); Co-organizer of the "School Nanosciences 2013 (ENANO2013)", *Choroni, Vénézuela (January 2013).

Thematic Schools: Our group attaches a great importance in spreading its knowledge by organizing national thematic schools every year. The important recognition of our expertise makes these schools very successful according to the growing attendance.

- Organizer of "Ecole d'initiation à la diffusion Raman pour l'étude de nanostructures à base de carbone", Montpellier, (01-05 Juillet 2013),
- Organizer of "Ecole d'initiation à la spectroscopie d'absorption des rayons X", Montpellier, 2012,2013 ; - Co-Organizer of the "Ecole d'initiation à la spectroscopie d'absorption des rayons X", Montpellier, 2009, 2010, 2011.
- Organization of the Lavoisier workshop on "Spectroscopies du Graphène ", (2011).

International and national academic and industrial projects: The recognized expertise of the group allows developing an important coordination network leading to the participation to different national and international academic projects.

ANR dedicated to carbon nanomaterials : ANR "T-NICE" (2007 – 2009), ANR "NATALI" (2007-2010), ANR "Excitubes" (2009 – 2012), ANR "TRICOTRA" (2007 – 2009), ANR "GRAFONICS" (2010 -2013), , ANR "SOS Nanotube" (2009 – 2013) ANR "TRANSION" (2013-2015), ANR "Nanophoresis" (2013-2016)

ANR dedicated to non carbon nanomaterials : ANR "ANZAS"(2008 – 2011), ANR "PRESENT" (2009 – 2013), ANR "Matisse" (2012-2015), ANR "chalmemory" (2006- 2009).

International collaborations **:** Projet CNRS /CNRST Maroc, Egide (2009-2012), PICS franco-russe (2009-2012), US air force contract (2012 – 2015), PCP Nanomatériaux France-Vénézuela, (2011-2014),PICS COMPANINA France-Vénézuela, (2011-2013), PREFALC NANO^2, (2011-2012), PHC Tassili-CMEP, PESSOA Egide (2011 – 2013), PHC Ulysse (2009-2011), LUSO Egide (2011–2013), US Department of Energy (DOE) Grant under award No. DE-FG02-07ER46411 and DOE/EERE Grant No. DE-FG36-08GO18142.

Expertize and Networking: Expertise of the nanostructure group team is recognized through the commissions they are involved in:

1-we are strongly involved in international and national networks as the "Graphene and Nanotubes: science and applications" ("GNT") group which is a national research group (GDR 3217) and an international coordination network (GDR-I) cross-linking research on nanotubes and graphène (co-director: J-L. Sauvajol (2008-2012) ; National committee J-L. Bantignies (since 2012) .

2-We are partner of the European project COST COINAPO (2010-14) (Laurent Alvarez).

3-At the national level, the group assumed the direction of the C-NANO – GSO Région LR (2008 and 2009) and is member of the national committee GFEC (Vincent Jourdain, since 2008) and C-NANO GSO (Jean-Louis Sauvajol).

4-At the local level, our team participates at the Labex NUMEV ('Solutions Numériques, Matérielles et Modélisation pour l'Environnement et le Vivant').

Membership in councils of the University. We have been deeply involved at the local scale in the management of the University: Vice president for the international relations (F. Henn 2012-13); CEVU Members (A. Zahab, F.Henn 2008-12); Scientific committee members (R. LeParc, F. Henn, 2012 – 13); Direction of laboratory (J-L. Sauvajol , LCVN (2009-2010) and L2C (2011-2014)); National expertizes ANR, AFSAPS, CNU 31ème section.

Interactions avec l'environnement social, économique et culturel

Our team is significantly active in promoting **scientific culture**. At the local scale, we are significantly involved in "Université du Tiers Temps" (F. Henn president 2009-12), Agora des savoirs (president F. Henn 2009-12) and association Kyklos-Histoire et Philosophie des sciences (vice-president F. Henn). We also participate to scientific vulgarisation events such as: Fête de la science and Bar des sciences in Montpellier, Vulgarisation Conference: J-L. Bantignies and F. Henn "Université du Temps Libre"; R. Almairac and J.l. Sauvajol "trainings on Nanoscience" in elementary and high schools of the "Région Languedoc-Roussillon".

Industrial collaborations: Our research activities exhibit mainly a fundamental character. However, our group provides significant efforts to create an industrial network, leading to several joint-projects. At the national scale, we have a collaboration agreement with the company Global Technology (Vincent Jourdain, 2011-2014). At the International level, our group has two industrial contracts ''Nanostructured conductive inks for printing metallic circuits'', Atotech Berlin, (2010-2012) and another one on ''Nanotubes-metal composites'', EADS Munich (30000 €, 2009-2011).

Implication de l'équipe dans la formation par la recherche

In the Materials department of the school Polytech'Montpellier, member of the team have been carrying responsibilities such as: (1) the direction of the department from 2008 to 2012, (2) the administration of the 4th year from 2008, 3) the recruitment of students from 2008 to 2011, 4) the implementation of environmental management at the scale of the school and through new teaching units from 2010. At the faculté des sciences, the team investment was illustrated through the direction of the physics department of the "faculté des sciences" (2008-2010), creation and coordination of new teaching units (experimental physics for Licence level, 1200 students, 2008-2009; sustainability and aging of materials for master level, ..). We are also participant in the IUT of Chemistry in Sète, notably responsible for coordinating the internship of the students since 2010.

At the research level, the team is annually organizing one week school on X-ray absorption techniques and organized in July 2013, a school on "Raman spectroscopy for nanostructures materials". The team members have also been lecturing in the frame of international schools in Morocco and Venezuela in 2011 and 2013.

The involvement in doctoral formation is also significant: Ahmed Zahab is responsible of the physics section in the "Ecole Doctorale: Informations, Structures et Systèmes, I2S".

Since January 2008, the team has been mentoring 15 PhD students from the University of Montpellier and 10 theses have been defended.

In addition, about 2 PhD students per year came for long stays in the frame of international collaborations. Every year, about 10 engineer student internships, 2 IUT internships and 3 master internships are supervised by members of the team.

Conclusions

During the last five years, the team achieved balanced activities between research focused on the physical properties of carbon nanostructures both as individual objects and nanomaterials and of non carbon nanomaterials.

We have a visibility and recognition through our participation to several ANR and international projects. Our attractiveness manifests itself through an international recruitment of PhDs, post-docs and invited researchers.

The group is strongly involved in international and national networks dedicated to carbon nanomaterials.

At the local scale, we have developed the interdisciplinary character of our research. Different instrumental developments have been performed allowing the emergence of collaboration at the interface between the physics and chemistry community. Our instrumental skills are recognized through participation in various regional platforms.

We also participate very significantly in teaching and science management at different levels. Our investment has been significant for the organization of national and international scientific events. Our expertise in Raman spectroscopy for carbon nanostructures and X-ray absorption spectroscopy has given rise to the organization of thematic schools.

agence d'évaluation de la recherche et de l'enseignement supérieur

Présentation synthétique de l'entité
Unité de recherche
Vague E : campagne d'évaluation 2013-2014

Team "Nanostructures"

Intitulé de l'unité : Laboratoire Charles Coulomb, L2C, UMR 5221

Nom du directeur de l'unité : Jean-Louis SAUVAJOL

Nom du responsable de l'équipe (le cas échéant) : Jean-Louis BANTIGNIES

Effectifs de l'entité (au début du contrat en cours, janvier 2008).
8 professors and assistant professors; 3 researchers; 0 technicians, 1 engineer; 2 PhD students (M. Picher, G. Creff)
Personnels ayant quitté l'entité pendant le contrat en cours (et nombre de mois cumulés passés dans l'entité au cours de cette période).
Assistant professor and researcher (24 months) ; PhD students (324 months) ; post-docs (90 months).
Nombre de recrutements réalisés au cours de la période considérée et origine des personnels
4 permanent positions : M. Paillet (CR2, Oct 2008), T. Michel (MdC, Sept 2008), F. Henn (PR1, Dec. 2010), ICG UM2) ; R. Metz (McF, Janv 2013 , Univ. Lyon 1), Said Tahir (Technician) ; 15 PhD students ; 7 post-docs.

Production scientifique au cours de la période écoulée (1er janvier 2008 – 30 juin 2013) :
1) Instrumental developments for Individual carbon nanostructures: include the combined used of local Raman, transmission and reflection measurements, as well as data treatment and interpretation tools. we have developed an experimental set-up to investigate *in situ* the graphene Raman modes evolution upon rubidium vapor exposure. We establish a relationship between the Rb vapor exposure time and the injected electron density in graphene. (ACS Nano 2013, Scient. Report 2013). **2) Individual carbon nanotubes :** Our work was dedicated to understand Double walled carbon nanotubes's (DWNT) Raman spectra. Our work highlights the important role played by layer coupling on the properties of Double walled carbon nanotubes (Nano. Lett. 2011). **3) CCVD growth mechanisms of nanotubes :** We developed an approach based on a in situ systematic Raman analysis of SWNTs grown by CCVD using different carbons precursors and in various conditions of temperature and precursor pressure. Our systematic Raman studies notably revealed two parameter domains with opposite influences of the temperature and precursor pressure on the diameter distribution (ACS Nano 2011). **4) Anisotropic nanotube-based composites :** We established a simple way to measure the order parameter from polarized Raman measurements assuming one single non-zero value in the (resonant) Raman polarizability tensors. Our validated spectroscopic method to describe the orientation of nanotubes in composites was then used to show that length and entanglement of the nanotubes were key parameters to control the orientational order in anisotropic thin films due to limitation of orientation via elasticity and topological defects [Nanolett. 2008, J. Phys. Chem. C 2011]. **5) Beyond carbon nanomaterials : Self-assembly of hybrid organic inorganic nanomaterials :** A self-structuring mechanism describing the formation of organized Nano structured hybrid silica has been proposed, based on our *in-situ* microscopic and spectroscopic studies (Small 2009 and Langmuir 2013).

Bilan quantitatif des publications de l'entité (depuis janvier 2008).
Articles: 122 ; Invited conferences: 46 ; proceedings: 18 – Communications : 114 – HDR : 1 ; PhD thesis : 10

Indiquer les **5 publications majeures** de l'équipe :
1) Raman doping profiles of polyelectrolyte singlewall carbon nnotubes in solution, F. Dragin, A. Pénicaud, M. Iurlo, M. Marcaccio, F. Paolucci, E. Anglaret, R. Martel, *ACS Nano* 5, 9892 (2011). **2) Exprimental evidence of a mechanical coupling between layers in an individual double-walled carbon nanotubes** D. I. Levshov, T. Than, R. Arenal, V.N. Popov, R. Parret, M. Paillet, V. Jourdain, A . A. Zahab, T. Michel, Yu. I. Yuzyuk, and J.-L. Sauvajol, , Nano. Lett. 11 (11), 4800–4804 (2011). **3) In situ Raman probing of graphene over a broad doping range upon Rb vapor exposure**, R. Parret, M. Paillet, J.-R. Huntzinger, D. Nakabayashi, T. Michel, A. Tiberj, J.-L. Sauvajol and AA. Zahab, In situ Raman probing of graphene over a broad doping range upon Rb vapor exposure, ACS Nano 7, 165 (2013)
4) "Processes controlling the diameter distribution of single-walled carbon nanotubes during catalytic chemical vapor deposition" Picher, M., Arenal, R., Anglaret, E. and Jourdain, V *ACS Nano* 5(3), 2011, pp. 2118-2125.
5) 'Self-Assembly of Bridged Silsesquioxanes: Modulating Structural Evolution via Cooperative Covalent and Non-covalent Interactions',Creff, G.; Pichon, B. P.; Blanc, C.; Maurin, D.; Sauvajol, J.-L.; Carcel, C.; Moreau, J.; Roy, P.; Bartlett, J. R.; Wong Chi Man, M. & Bantignies, J.-L. (2013), *Langmuir* 29, 5581

Indiquer au maximum 5 documents majeurs produits par l'équipe :
1) AFNOR document (experimental standart) on "Caractérisation de nanotubes de carbone monofeuillet en utilisant la spectroscopie de photoluminescence dans le proche infrarouge" (J-L. Sauvajol, 2011).
2) Development of CCVD industrial reactor in collaboration with a French company (Contract Global Technologies)

Indiquer **au maximum 5 faits illustrant le rayonnement ou l'attractivité académiques de l'équipe :**
1) Participation to International academic projects : (13) **et national academic projects** (11 ANR).
2) Organization of international conferences et workshops (total 15) :**chairman** (NT08, ISE14/ conference IEEE), **Co-organization** (ENANO 2009,CARBON 2009, EUROMAT11, ENANO 2011, EFMSR12, EUROMAT 2013, ENANO 2013 scientific committee. (NT10, NT12, Workshop on Organic Electronics and Nanophotonics (2010, 2011 and 2013)
3) Organization national conferences and workshops (total 9) : **Organization thematic schools** (SAX 2008, SAX 2009, SAX 2010, SAX 2011, SAX 2012, Raman2013, SAX2013), **Chairman** (JMC13) ; **co-organization mini-workshops** (JMC11,JMC13), scientific organization committee (conference Molmat 2010, Discussions. Lavoisier "S. Graphène 2011)
4) Invited **conférences : 47**
5) Committees: Vice-président in charge of the international relations (F. Henn université Montpellier 2) ; ANR scientific committee (6 people); CNU 31 (F. Henn); scientific council members of University Montpellier 2 (R. LeParc, F. Henn) ; Council studies an university life – University Montepllier 2 (A. Zahab, F. Henn, 2008-2012) AFSSET Expert (J-L. Bantignies)
6) Network: Co-direction GDR/GDRI nanotubes and graphene (**J-L. Sauvajol,** 2008-12), member of national board of this GDR / GDRI (**J-L. Bantignies** 2012-13), Direction C-NANO GSO district LR (**J-L. Sauvajol**, (2008-2009), member of the national committee GFEC (V. Jourdain 2008-13), member of the steering committee C-NANO (J-L. Sauvajol), Partner Action COST (Projet Européen « COINAPO » (composites of inorganic nanotubes and polymers) (L. Alvarez 2010-2014)

Indiquer les interactions de l'entité avec son environnement socio-économique ou culturel
1) International industrial contracts : ATOTECH Berlin (2011-13) et EADS Munich (2009-11); 2 PhD grant CIFRE with EADS and Atotech companies ; national industrial contract (Global technologies 2011-2014). **2) Investment for scientific Culture :** président Université du tiers temps, Président of Agora des Savoirs, Vice-président association Kyklos (History-Philosophy of sciences. **3) Participation in extension activities** : Fête de la science, Agora des savoirs, Bar des sciences, Public Conferences on the nanosciences and Energy (University du temps libre de Lattes), Conferences at the University du Temps Libre, traveling exhibitions in schools.

Les principales contributions de l'entité à des actions de formation
Teaching responsibilities: 1) Direction department "materials" engineer school Polytech (2008-2012). **2)** Creation and coordination of an experimental physics course (first university year – 1200 students - 2008-2009) **3)** Head 4th year department materials engineer Polytech Montpellier (2008-) **4)** Recruitment manager department materials engineer Polytech Montpellier (2008- 2011). **5)** Responsible of training IUT Sète (2010-13) **6)**, Responsibility of the specialty physics of the graduate school I2S (A. Zahab 2011-13). **7)** Head of the sustainable development mission for the engineer school Polytech (2010-13). **8)** Implantation and responsibility of a master 2 teaching course: sustainability and material aging (Master Materials, University Montpellier 2), responsibility carbon based nanostructures course (master 2 physics, University Montpellier 2).
Organisation of national thematic schools (7) (SAX 2008, SAX 2009, SAX 2010, SAX 2011, SAX 2012, Raman2013, SAX2013)

Team: “Materials, Devices and Sensors”

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The **“Materials, Devices and Sensors”** team has been set up in order to bring together the complementary expertise of researchers in the field of material science and nanostructures with a possible opening towards physical-biology interface. However, the biophysics group soon found that their activity was more connected to another team and in 2010 they left our team to join another one, their projects are thus transfered to the PEPS team.

The research activities of our Team are based on two main areas:

Growth and Structured Materials - in which efforts are dedicated to the elaboration of structured materials and growth of mismatched epitaxial systems. The Hybrid and Nanostructured Materials group works principally on functionalized organic-inorganic hybrids and inorganic glasses. The photovoltaic group originates from the reconversion of the Nitride Growth group towards renewable energy which research theme is supported by our University. Moreover, the growth of Graphene onto SiC substrates is being actively developed, with a new furnace installed in April 2013.

Devices and Sensors - in which fundamental research on materials and nanostructures contributes to the development of sensors or devices. Research activities of this group are based on optical and transport expertise on III-V compounds and wide band gap semiconductors such GaN and SiC. The knowledge on SiC has conducted to the emergence of a graphene research activity which has attracted very much attention and was a federative theme of the laboratory since it is a transverse axis between two departments.

A part of our team was during 12 years a Technological Research Team of the University. This label was the recognition of an advanced technological research which requires a high level fundamental research and a strong industrial support. That’s why our activity was developed on the basis of various research contracts with industrial and/or academic partners. Our research activities are organized through the collaborative efforts with national and international institutions and are validated by the financial support from national and European projects.

Topic: *Growth and Structured Materials*

1-Hybrid and Nanostructured Materials

Participants : Pascal Etienne (PR1), Sylvie Etienne (MCF), Annelise Faivre (PR2), Nathalie Olivi-Tran (CR1), Florence Despetis (MCF), Laurent Bonnet (AI), Rémi Courson (PhD), Rémi Girard (PhD), Saly Yaacoub (PhD)

The activity of the group may be divided into four parts where the last one is transversal (modeling and simulations of the materials we are working on).

The first activity is dedicated to ultraporous materials. In particular, we studied the porosity effect on thermal properties in order to build up super insulating materials as well as the condensation/evaporation processes as a function of the strength of disorder in aerogels.

During the last decade, an active policy of research and development of new high-performance thermal insulation materials called super insulating materials was engaged internationally. Presently, most of the work focused on nanostructured silica, high-performance materials but mechanically very brittle. The NANOCEL project worked to develop a nanostructured super insulating cellulose matrix of low cost and of low environmental impact, also adapted to be used for the mechanical reinforcement of silica super insulator without compromising their very low thermal conductivity. Two approaches have been studied with the cellulose or its derivatives. The first method relies on regeneration of cellulose solutions. The second one is to synthesize, by a sol-gel process a gel of cellulose acetate by chemical crosslinking with an isocyanate. These gels were then dried in a stream of supercritical CO_2 to keep part or all of their original morphology while avoiding the occurrence of capillary stress. The materials are then finally characterized in thermal physicochemical angles (structure, texture...), (thermal conductivity, specific heat...) and water (sorption, aging...). The project is ending and objectives are achieved: the levels of thermal conductivity achieved under ambient conditions for these materials are in the range of those ultraporous silica between 15 and 20 mW/mK for matrices based on cellulose acetate and slightly higher for matrices of pure cellulose. This project was followed by a work which aimed to develop at laboratory scale materials mechanically more viable than "conventional" thermal superinsulating silica aerogels (Silica Cell project). For this, it was decided to reinforce mechanically the silica aerogels with cellulose. Two approaches have been adopted: the impregnation of ultraporous matrices cellulosic and dispersion of cellulosic fillers in mineral soil. This work has been planned on the basis of "composite" (organic and inorganic phases without chemical interactions) to the "hybrid" (two covalently linked matrices).

At the same time, we worked on the HEVEPORE project. The objectives were the study of the condensation/evaporation processes as a function of the strength of the disorder, disorder which was controlled by the aerogel porosity. For example, 4He has been confined in a 95% porosity silica aerogel in the vicinity of the bulk liquid gas critical point. Both thermodynamic measurements and light scattering experiments were performed to probe the effect of a quenched disorder on the liquid gas transition.

The second scientific activity concerns glasses.

First, the effect of alumina on the sub-critical crack growth was investigated on a set of calcium aluminophosphate glasses of molar composition 50% P_2O_5–(50 x)% CaO–x% Al_2O_3 (0% 6 x 6 10%). The crack propagation was operated using the double-cleavage-drilled-compression (DCDC) method. In this test, the sample is loaded in compression with a mechanical testing machine in an environmentally controlled chamber (both temperature and water vapor pressure). The crack velocity is plotted as a function of stress intensity factor. Regions I and II are characterized by a dependence of crack velocity on the amount of alumina content in the glass. When the alumina content increases, glass shows, as expected, a trend less sensitive to the stress corrosion correlated to the slope of the crack growth curves, but in the same time, these curves are shifted toward higher crack velocity values. For different compositions, an unexpected behavior is also observed with temperature and water vapor pressure. We assume the formation of a 'gel-like product' on fresh fracture surfaces which modifies the reactivity at the crack tip.

The effect of ionic implantation on the structure of silica and borosilicate glasses was also studied. These structural changes, probed by IR micro-reflectance spectroscopy, Raman spectroscopy and Gi-SAXS, as well as the changes in mechanical properties probed by micro-indentation were compared to the consequences of glass thermal quenching. Results indicate that a comparison can be drawn between fictive temperature and irradiation effects.

Moreover, we worked on room temperature micro-plastic phenomena in alumina-phosphate glasse. Micro-plasticity was attributed to combined effects of densification and shear flow, the origin of which remains however speculative. Using AFM imaging to analyse the imprints topology created by micro-indentation in mixed alkali alumino-phosphate glasses, we show that the amount of matter displaced at the surface is correlated with the alkali mobility. These results lead to the conclusion that mobile alkali assist shear flow processes produced by indentation at room temperature and that these processes rather correspond to plastic than viscous flow.

Finally, we looked for the Influence of water on crack self-healing in soda-lime silicate glass.The self-healing behaviour of radial cracks generated by Vickers indentation in floatglass has been analysed when heat treated at 620°C under various atmospheres. Results evidence that two main driving forces influence radial crack evolution: release of residual stresses induced by initial indentation and capillary forces due to surface energy minimization. Depending on the viscosity level, viscous flow allows crack morphological changes driven by capillarity forces or not. Our results evidence that at 620°C, the viscosity of the glass surrounding cracks can be significantly reduced by water diffusion and glass hydrolysis, or increased by glass des-hydration, as a function of the humidity level of the furnace atmosphere. Hydration and des-hydration of glass are shown to play a major role in the crack morphology changes during healing, respectively favouring or impeding morphological changes driven by capillarity forces.

The third activity is about organic-inorganic materials used as layers for the fabrication of integrated optical circuits or to make a permanent micro pattern on a substrate.

3D optical waveguides are the basis of the fabrication of integrated optical circuits. We have already used an organic-inorganic material where the silica matrix is obtained by means of the sol-gel process and the organic network by cationic polymerization under UV radiation through a mask or with the laser writing. However, obtained results showed some weakness such as an important contribution of OH and aliphatic CH groups to the attenuation at 1550 nm wavelength and low conversion rate of organic polymerization involving poor mechanical properties. To overcome theses drawbacks, we worked a new generation of hybrid materials with a very high reactivity and low amount of groups involved in the attenuation. We have chosen vinyl ether function as reactive organic part for her highest polymerization rate via cationic way. The alkoxide function is separate from the vinyl ether one by a phenyl group containing only unsatured CH groups which induce no attenuation at 1550nm wavelength. By studying the synthesis conditions, we defined a simple compromise between the highest reactive multifunctional oligomers and the lowest residual silanol groups, necessary in the film adhesion process on silicon substrate.

At the same time, we studied Micro-patterned layers on an organic substrate. This work is part of the pixelized optical project supported by Essilor, the world leader in the field of ophthalmic optics. This collaboration has given birth to a new generation of optical systems affixed directly on the ophthalmic lens. This system consists of microtanks filled with another material which may be different from one tank to another. This results in pixelation surface for innovative optical phenomena.

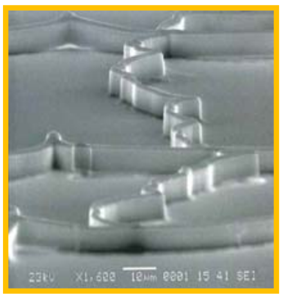


Figure 1: Micro-patterned layers on an organic substrate.

The first part of this work is devoted to the synthesis and characterization of hybrid organic-inorganic photosensitive resins operating at different wavelengths from UV to Visible domains. The goal is to create, by a photolithography process or high speed laser writing (Mosahyc Project), the microcavities which rigidity is such that the walls can resist to the filling of a liquid. Mineral and organic polymerization of these resins have been studied from a structural (infrared and NMR spectroscopy), mechanical (nanoindentation technique) and textural point of view (absorption-desorption of gas). Results of this research are protected with two international patents.

The last part is a transversal one and deals with modelling and simulations in material physics. During these 5 years, an exact calculation of the random close packing in 2 dimensions [Adv. Stud. Theo. Phys. 2, 975,2008] has been published by the group: this is of main importance in the topic of vitreous materials as it is a first step towards the understanding of how a simple packing of spherical particles is distributed geometrically speaking; i.e. the simplest model of glass. Another publication on the topic of glass [Physica B 404, 2289, 2009]showed that in a Lennard Jones model of glass, the geometrical structure of the surface is different from the bulk. Two other studies [J. of Polymers and the Env. 17, 187 (2009), J. of Non-Cryst. Sol. 356 ; 287,2010] about hybrid materials show that one can link the well-known tight binding model to macroscopic features of these materials. Indeed, we showed that the structure of a given hybrid material was amorphous (or was more stable in the amorphous state with respect to crystalline structures). This was possible by modifying the tight binding model by introducing hybridization in the covalent electronic bonds. This modification allowed us also to reproduce previous experimental work on the toughness of hybrid materials: this means that, although toughness is a macroscopic characteristic, its origin comes from the electronic bonds between the atoms. Finally, another numerical modeling [J. of Non-Cryst. Sol. 358 , 1180, 2012] lead to the numerical reconstruction in three dimensions of base-catalyzed aerogels, from their MET images. Other publications dealing with modeling have been written in the group between 2008 and 2009: they concerned the modeling of thin films of yttria stabilized zirconia obtained by sol-gel [Phys. Rev. B 79 , 035413, 2009][J.of Luminescence129, 1767,2009]|FRACTALS16, 361, 2008], graphene theory[Physica B 405 , 2749, 2010], mechanics of glass beads and simulations of fullerenes[Eur. Phys. J. D , 50, 153 ,2008]. Finally, the theoretician of the group holds 12 other publications in topics which do not deal with material science (i.e.: neurophysics, cosmology and particle physics [Adv. Stud. Theor. Phys from 2008 to 2013]).

2-Photovoltaic structures

Participants: Roger Aulombard (PREX), Olivier Briot (DR2), Matthieu Moret (IR), Yoann Robin (PhD), Sandra Ruffenach (IR)

This is a new theme, introduced in our team to replace the activity previously pursued on InN growth. Let us first summarize the work done between 2008 and 2010, since it corresponds to the beginning of the reporting period.

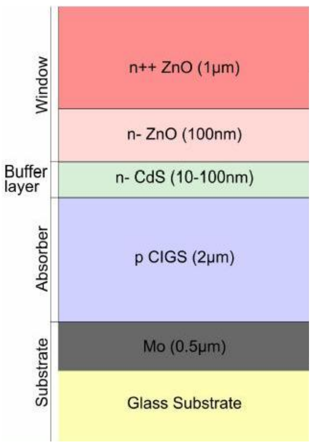


Figure 2 : Typical Structure of a CIGS solar

Back in 2008, we have been involved, since 2002, in the epitaxy and physics of the InN nitride semiconductor. We had established a know-how that led us to supply many teams and research centers in Europe with samples, and to sched light on the growth mechanisms of this poorly known semiconductor. As a result, we were invited at many conferences and workshops, and produced numerous papers. In the 2008-2010 period, we established a striking fact: hydrogen, which is present in the growth environment of InN in MOCVD, is incoporated in the materials and acts as a shallow donor. The process is reversible, as hydrogen can be extracted from the semiconductor by annealing. This is a good part of the explanation of the high residual doping level (n-type), always observed in InN. This major result led to several papers in journals and invitations to conferences, and led to a strong collaboration with the University of Lingkoping, Sweden.

During this period, we were aware that the main problems limiting the use of InN in devices (surface conductivity, residual doping, p-type doping, …) were not to be overcomed soon, after a decade of efforts, and particularly using the MOCVD technique. Since our University was supporting research activities dedicated towards renewable energy, we decided to turn to the study of photovoltaic devices, with an emphasis on chalcopyrite materials, like CuIn(Ga)Se2. A survey of the literature and participation at selected conferences convinced us that the community involved in this research was wide, but with a minor participation of solid-state physicists. Thus we were convinced that we could bring useful knowledge and efforts in understanding the basic growth and physics of these materials, which, despite their industrial use, are poorly understood.

Although its material quality and purity is rather low, $CuIn(Ga)Se_2$ (CIGS) has led to demonstrator cells with an efficiency of 20 %, overtaking monocrystalline solar cells. It can reasonably be expected that improving the understanding of the material synthesis, as well as the physical phenomena at work will lead to efficiency improvements.

We started with the goal of setting up in the laboratory the necessary know-how to build a complete solar cell based on CIGS. The typical structure is, from bottom to top : Glass (substrate)/Mo(contact)/CIGS(p-layer)/CdS(n-layer)/undoped ZnO(transparent electrode/doped ZnO(contact layer).

CIGS is elaborated by co-evaporation in a MBE system. The typical process involves a 3 step process with successive co-evaporations (In + Ga + Se)/(Cu + Se)/ (In + Se). Although widely used in the industry, this process is poorly understood.

We have established that $(In,Ga)_2Se_3$ is formed in the first step, which constitutes a pseudo-ternary alloy involving "ordered" vacancies. During the second step, copper diffuses through the pre-existing $(In,Ga)_2Se_3$ layer to form the CIGS quaternary. The third step allow for the elimination of the excess copper, which is detrimental (formation of a top CuSe, Cu_2Se layer) to the photovoltaic cell.

Then we implemented the CBD technology (Chemical bath deposition) to realize the CdS layer, which forms the n-type of the diode heterostructure. We investigated the deposition parameters and studied, with x-ray diffraction , photoluminescence and transmission, the material quality. We demonstrated that CdS is deposited into its cubic form at the low temperatures (80°C) involved in the CBD process, which is not optimal. We then performed annealing studies and observed that a complete conversion to the hexagonal form (the stable one) could be easily obtained at moderate temperatures. We plan to apply this thermal process to full photovoltaic structures to study its impact on efficiencies.

Third, we developed the deposition of ZnO (both undoped and aluminum doped) by electrodeposition. ZnO was deposited on various substrates, in particular on transparent conducting FTO layers, in order to be able to study transmission of the material, which is used a conductive transparent window in the solar cell. Growth kinetics, transport and optical properties have been studied in relation with deposition parameters. It is quite surprising that ZnO deposited by this technique at low temperature (80°C) could lead to material exhibiting excitonic luminescence!

Finally, all these building blocks are now assembled to produce full solar cell devices, and we are starting to perform detailed electrical measurements on the devices, benefiting from the experience of the team, whose members are involved in transport measurement and device studies.

With the support of the laboratory, we have bought a solar light simulator in order to realize an experimental setup to accurately measure efficiencies. Our aim for the next future will be to correlate device efficiencies with individual layers structures and quality, to better analyze the impact of each layer on the whole cell efficiency, and to understand the physical mechanisms involved. Up to now, our efforts were mainly targeted at setting up the necessary « toolbox », comprised of a set of techniques and processes to produce all the necessary samples to investigate the physics of this class of devices. This base work is the subject of the Ph.D thesis of one of our students, Yoann Robin.

We also envision to extend our efforts to related materials, such as kesterites ($Cu_2ZnSn(S,Se)_4$) , which are interesting due to the fact that they are indium free, and that indium resources may become constrained at some point in the future.

3-Graphene growth

These studies are performed in the framework of the "Axe transverse graphene". This axe merges researchers of the "**Nanostructures team**": T. Michel (MCF), M. Paillet (CR), J-L Sauvajol (DR), A. Zahab (PR), R. Parret (PhD), H-N. Tran (PhD), D. Nakabayashi (PostDoc) and researchers of the "**Materials, Devices, Sensors team**": Jean Camassel (DR), Nicolas Camara (ATER), Sylvie Contreras (CR), Wilfried Desrat (MCF), Jean-Roch Huntzinger (MCF), Bilal Jabakhanji (PhD, PostDoc), Benoit Jouault (CR), Sandrine Juillaguet (MCF), Leszek Konczewicz (MCF), Périne Landois (MCF), Antoine Tiberj (MCF).

In 2010, we planned to strengthen our emerging graphene research activity by developing a local graphene sample supply. We decided to develop the graphene growth on SiC to get large-scale, homogeneous and high quality graphene to study its transport properties on semi-insulating substrates. During the evaluated period, we hired an assistant professor to develop the growth either by sublimation or CVD techniques. A specific resistive graphite furnace was purchased with support from the State-Region Plan (175k€). 40k€ were funded by the team, the L2C laboratory and the university to refurbish the room and fit with the security rules. Unfortunately, the delay imposed by the provider for this prototype prevents us to present first results in this report. The furnace was indeed delivered in April 2013.

Thanks to the ANR Grafonics (2010-2013) funding (150k€), a dedicated Raman experiment was developed to analyze precisely and quickly the grown samples. The design, results and performances of this home-made setup will be detailed in the following sections.

Topic: Devices and Sensors

At the beginning of the evaluated period, one of our main activities was to solve an industrial problem: the thermal drift cancellation of the magnetic sensitivity of Hall sensors used for electricity metering by ITRON Company. It was the main purpose of our last ERT contract (ERT: Equipe de Recherche Technologique interne, ERT-4 : Matériaux-µCapteurs-µSystèmes (2007-2010)). For that, we have focused on physics and nanophysics of III-V compounds combined with applied physics actions validated by the financial support of industrial contract (ITRON 2006-2009) and ANR project (MagMap 2009-2013).

At the same moment, our second main activity was based on wide band gap semiconductors (GaN, SiC). The GaN activity has led to the creation of an European Associated Laboratory (LEA NodLab- collaboration with UNIPRESS in Warsaw and IKZ in Berlin), a number of bilateral cooperations as well as our participation in the national network LabeX Ganex. Concerning silicon carbide, always well positioned for electronic power device applications, challenges depend of polytypes. During the last seven years we were involved in ANR contract and two different European Networks devoted for the first one (MRTN-MANSiC 2007-2010) to the 3C-SiC polytype and for the second one (ITN-Marie Curie NETFISiC network 2011-2015) to the crucial role of surface and interfaces in SiC.

Our SiC expertise leads to the emergence of a graphene research activity in our group in 2007. This activity was first focused on Raman spectroscopy and transport properties of epitaxial graphene on SiC, while the Nanostructure team of the CVN department was also studying exfoliated graphene by Raman spectroscopy. From the beginning, collaboration between our two teams was initiated and resulted in the creation of the inter-department project "Graphene". This activity was funded by 3 ANR projects (GraphSiC 2008-2011, Graphonics 2010-2013 and Metrograph 2011-2014), the GDR C-Nano GSO and also supported by NetFiSiC network.

1-Sensors based on micro and nanotechnologies- Physics and Application

Participants: Laure Bouguen (PdD), Sylvie Contreras (CR1), Wilfried Desrat (MCF), Benoit Jouault (CR1), Leszek Konczewicz (MCF)

Zero-thermal drift Hall Sensor for electricity metering (ITRON Industrial Contrat n°4 634).

The thermal drift cancellation of the magnetic sensitivity of Hall sensors used for electricity metering was the purpose of an industrial contract with ITRON-France and the main purpose of the ERT project. We demonstrated that applying a voltage feedback onto a Schottky gate on top of a Hall device based on GaAs/GaInAs/GaAlAs pseudomorphic heterostructures, it is possible to cancel the thermal drift of the magnetic sensitivity. In addition, tailoring the gate shape and/or the gate biasing scheme, we could adjust the Hall sensor bias current value for which the thermal drift vanishes.

A useful tool was the finite element method (FEM) analysis. Using FEM, we have calculated the Hall voltage of gated Hall sensors in the temperature range -55 °C, +125 °C. We investigated how both the sensor shape and the external connections influence the Hall voltage and its thermal drift. Combining altogether the FEM analysis and the experimental data, we concluded that FEM gives remarkable results for this problem: numerical results are in excellent agreement with the experimental measurements. FEM allows estimation a priori of the sensor characteristics with a limited choice of parameters or even without adjustable parameter. It is found that the thermal drift in the Hall voltage can be cancelled for a current of the order of 300 µA, a much higher value than that predicted by the corresponding analytical calculations (Thesis: L. Bouguen (2009)).

Improvements acquired in terms of thermal drift constituted one of the elements among others, taken into account by ITRON to introduce on the market a new generation of meters programmed from 2008. An operating agreement was concluded between ITRON, CNRS and UM2.

Hall sensor Application in Micromagnetometry (MagMap-ANR- 09-BLAN-0042)

Hall sensors previously developed for electricity metering can be used for metrological and microscopic applications. We used a microscopic Hall-probe for developing scanning magnetometers dedicated to Earth and planetary sciences in the MagMap ANR project. Partners intend to develop 3 complementary instruments: a scanning magnetic microscope based on the Giant Magneto Resistance technology, a magnetic microscopy system using the magneto-optical Faraday Effect, and a micro magnetometer using micro Hall probe. Complementariness between all these systems is in the sensitivity, spatial resolution, sensor-to-sample distance, type of measurement are different from one instrument to another.

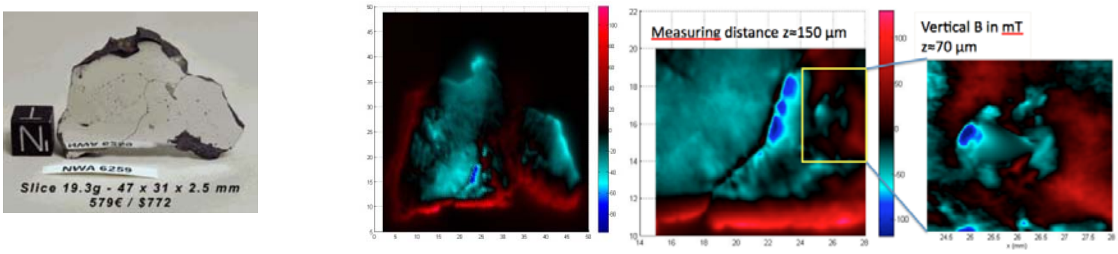


Figure 3: Mapping of a thick meteorite slice using a Hall probe (10µm width) positioned at 150 and 70 µm from the surface.

Concerning the Hall sensor, a scanning system was developed. Magnetic field maps were obtained on a 3 mm thick slice of a meteorite provided by CEREGE laboratory using this microHall probe scanning system (10 µm square sensor measuring vertical component of the magnetic field at 150 and 70 µm distance from sample surface). Measured magnetic fields, in the range ±120 mT, point toward heterogeneous remanent magnetizations and strong coercivity. These results contribute to a better understanding of oriented magnetic rocks.

InAs/GaSb superlattice for photodiodes

InAs/GaSb strain layer superlattices (SLS) emerge as an attractive system for MWIR : mid-wavelength infrared detection devices. The material fabrication by molecular beam epitaxy is now quite mature, and simulation of the SLS band-gap has been achieved using different methods. Despite these impressive progresses, basic studies of the SLS material are still needed, in particular to get a better understanding of the carrier transport in such a structure. A key parameter of a sensor is the doping of the absorption zone. Most of the mechanisms of generation and non-radiative recombination are largely related to the number of carriers. To characterize the epitaxial layers conventional electrical transport parameters: conductivity, carrier concentration and mobility of the carriers can be used. Our expertise in electrical measurements in extreme conditions (high pressure / high magnetic field) gives us a particularly useful tool for the study of multicarrier conduction in InAs/GaSb SLS case. Mastering the method of the Quantitative Spectrum Mobility Analysis (QSMA) allows us the detailed analysis of electrical transport measurements results. The QSMA algorithm converts experimentally measured resistivity and Hall coefficient data into carrier mobility spectra in which the different type of carriers (heavy and light holes and electrons) could be identify as a taking part in the conduction process. InAs/GaSb SLS study is developed in the frame of informal collaboration with IES Laboratory from University of Montpellier 2.

2-Materials and processes: Physical Properties

Participants: Jean Camassel (DREM), Nicolas Camara (ATER), Sylvie Contreras (CR1), Wilfried Desrat (MCF), Jean-Roch Huntzinger (MCF), Bilal Jabakhanji (PhD, PostDoc), Benoit Jouault (CR1), Sandrine Juillaguet (MCF), Leszek Konczewicz (MCF), Périne Landois (MCF), Hervé Peyre (MCF), Teddy Robert (PhD), Jianwu Sun (PostDoc), Antoine Tiberj (MCF), Pawel Kwasnicki (PhD), Georgio Zoulis (PhD)

Silicon Carbide (ANR BLAN08-3_344560 VHVD-SiC (2009-2011) - (MRTN-CT-2006-°35735 Marie-Curie MANSIC 2007-2010; PITN-GA-2010-264613 Marie Curie NETFISiC)

Silicon carbide (SiC) is positioned as a promising material for electronic power device applications. Challenges are i) the control of the doping level, ii) the understanding of stacking faults associated to the degradation problem of the forward I-V characteristics in 4H-SiC high voltage diodes, iii) the role of the surfaces and the interfaces for devices. These points were our research activity on SiC during the evaluated period.

The aim of the ANR-SiC VHVD was the design, the realization of silicon carbide high-voltage, 10 kV and with a final target of 15 kV type converters, compact, reliable and economically attractive. This project addressed the market for electrical distribution components with SiC. Recognizing the impact on sustainable development, this project fits into the new networks for decentralized energy generation, taking into account renewable energy. Thick epitaxial layers (with a typical thickness of 100µm) have been conducted to realize high voltage components on 4 inch wafers. Cartographies of the doping level of these 4'' wafers were done by optical measurement to check the homogeneity and the presence of the defects as staking faults. Diodes and bipolar transistors were made with innovative protective VLS layers for devices in Lyon with the company Novasic.

It's well known that the faults change the stacking sequence of the 4H polytype and result in quantum wells of a different polytype, for example cubic polytype (3C-SiC), a few nanometers, in a matrix of 4H-SiC. Optical techniques (low temperature photoluminescence (LTPL), LT-micro-Photoluminescence and micro-Raman) have been combined to highlight and explore the SFs in 4H-SiC samples. For the first time, the screening of the internal electric field by free carriers has been identified. More recently, high-resolution transmission electronic microscopy (HR-TEM) measurements (Aristotle University of Thessaloniki) confirmed the structure and size of these nano-defects. The experimental results are correlated with theoretical calculations and developed in the thesis of Robert Teddy (2006-2009).

Stability problem in the 4H-SiC polytype make 3C-SiC very attractive and justified the consolidation of the scientific community in the Marie Curie RTN network: "MANSIC". The main objective was to develop a line of components in 3C-SiC substrate components, one being the technological development of crystal size and quality compatible with the needs of the microelectronics especially in 3C-SiC. The spectroscopy measurements (LTPL and Raman) have revealed the polytype, doping and thickness of the first 3C-SiC materials developed on hexagonal substrates, according to the different growth techniques used by different partners network of 3C-SiC on ▫-SiC substrates A qualitative analysis of the quality of the samples was done using both the observation of the structural defects and the information from the optical characterisation techniques. We were able to acquire information about physical parameters of 3C-SiC like the binding energy of Ga and Al, the Al bound exciton fine structure and the Al-N and Ga-N donor acceptor pair fine structure. (Thesis G. Zoulis (2007-2010), Postdoc J. Sun).

The role of surfaces and interfaces especially when the components are used in harsh environments and under extreme conditions is crucial. In 2011 a new project called NETFiSiC has started. The main scientific objective of NetFISiC is to provide SiC material (of various polytypes) with improved and adequate functional interfaces for getting a step forward in electronic devices performance. Targeted applications are high temperatures sensors, high power and/or high voltage devices, in addition to more innovating devices based on other polytypes than the usual 4H ones (3C, 15R), which need specific material development. (Thesis P. Kwasnicki)

Specific shared trainings were organized with partners of the European networks for students: joint training activities as schools, workshops, tutorial days, common courses. In this context, between 2008 and 2012, seven students (ESR) have been trained on optical measurements in the laboratory.

GaN and related compounds (L.E.A. NODLab (2005-2010)- PHC Polonium (2009-2010) - LaBeX GANEX 2012-2022)

First, in the framework of our collaboration with Unipress laboratory in Warsaw (NODLab and Polonium contracts), we have focused on two fundamental subjects: (i) heavily doped p-type materials (ii) semi-isolating thin layer structures and bulk material.

The p-type doping of GaN and other wide band gap III-V nitrides is the key for producing short-wavelength optical devices as well as high-power and high frequency electronics. So far the magnesium is the only acceptor dopant which generates sufficient p-type conductivity in a reproducible manner. However, in the case of the MOVPE growth process, the Mg acceptor is electrically inactive in as-grown material and an additional annealing procedure is required. Our study of the annealing process by in-situ measurements of electrical transport properties of material in the temperature range 20-600°C has allowed the optimization of activation temperature of acceptors in magnesium-doped in GaN layer and AlxGa1-xN/GaN superlattices.

The development of low-cost GaN-based high-power and high-frequency electronics is limited due to a lack of suitable semi-isolating substrates for structures growing. The homoepitaxial growth on the truly bulk GaN substrates would be an ideal solution. The crystallization of GaN by High Nitrogen Pressure Solution method in multi-feed-seed (MFS) configuration and ammonothermal method are the key technologies of bulk GaN substrates manufacturing. Addition of magnesium into the growth solution causes strong compensation of free electrons in the crystals and highly resistive GaN crystals can be grown. Due to the very high sample resistance, the electrical parameters of material of became measurable at temperatures above 300°C. Our study of resistivity and Hall Effect in the temperature range 300-900°C allows to characterize the material and to observe the conductivity process activated via a deep state with energy of ~1 eV.

Second, we are a partner of the national network GANEX. This Labex, which began in February 2012, focuses on the development of devices based on gallium nitride (GaN) and its alloys. Within this context, we measure the electrical properties of high electron mobility transistors (HEMTs) provided by CRHEA laboratory.

Recently, we dealt with two-conduction layer samples, which consist of a 2D electron gas in parallel with a buried "polarization doped" 3D electron slab, arising from an aluminum gradient layer. We reported an unexpected non-linear behavior of the Hall resistivity, indicating a fake hole transport, likely due to the contact misplacement in this complex structure. Also, HEMTs present intrinsic high densities due to the large spontaneous and piezo-electric polarizations (n>1×1017m-2), which become interesting under illumination by a LED, as they exhibit double subband occupation at low temperature. The determination of the quantum and transport scattering times has highlighted the role of magneto-intersubband scattering between each subband.

Graphene (ANR GraphSiC 2008-2011, ANR Graphonics 2010-2013, ANR Metrograph 2011-2014, GDR C-Nano GSO and also supported by NetFiSiC network)

These studies are performed in the framework of the “Axe transverse graphene”. This axe merges researchers of the “**Nanostructures team**”: T. Michel (MCF), M. Paillet (CR), J-L Sauvajol (DR), A. Zahab (PR), R. Parret (PhD), H-N. Tran (PhD), D. Nakabayashi (PostDoc) and researchers of the “**Materials, Devices, Sensors team**”: Jean Camassel (DR), Nicolas Camara (ATER), Sylvie Contreras (CR), Wilfried Desrat (MCF), Jean-Roch Huntzinger (MCF), Bilal Jabakhanji (PhD, PostDoc), Benoit Jouault (CR), Sandrine Juillaguet (MCF), Leszek Konczewicz (MCF), Périne Landois (MCF), Antoine Tiberj (MCF).

The graphene research activity in our team started in June 2007 by performing Raman spectroscopy and AFM on exfoliated graphene on SiC with the Nanostructure team. The first epitaxial graphene samples were studied in the framework of the Graphsic ANR project with Institut Néel, Soleil and CEA-SIMA. In the meantime, we also studied sublimated graphene coming from different partners: Center National of Microelectronics (CNM in Barcelona), CNR-INM in Catania (Italy) and the Linköping University in Sweden.

In collaboration with CNM, we evidenced that graphene can be selectively grown on a « prepatterned » SiC surface [Appl. Phys. Lett. 93, 123503 (2008)]. We also showed that the early stage of the graphene growth is mainly extrinsic. It is driven and occurs around defects like dislocations [Appl. Phys. Lett. 93, 263102 (2008)]. Finally we investigated the influence of the SiC polytype (6H, 4H, 3C) and its orientation on the graphene growth. The size and shape of the graphene domains depends mainly on the surface orientation according to the c axis (0001) [Mat. Sci. Forum **615-617**, 203 (2009)]. Recently, we demonstrated that graphene ribbons can be grown on the C face of 6H-SiC surfaces. These ribbons have an excellent uniformity. They are made of mainly mono and bilayers of graphene and are 300 µm long and 5 µm large [Phys. Rev. B 80, 125410 (2009)].

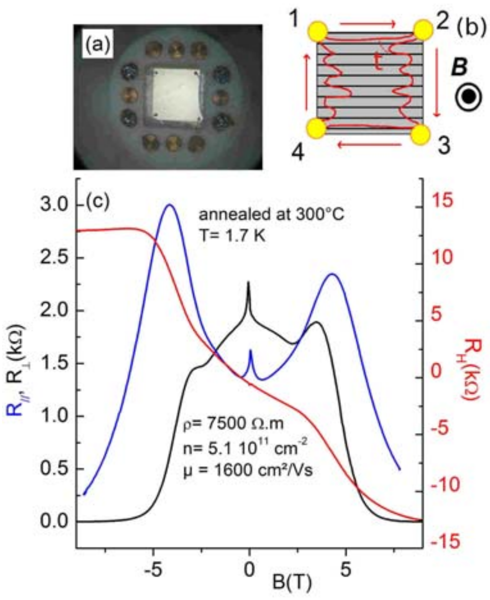


Figure 4: (a) Top view of a 6 mm x 6 mm graphene sample. (b) Sketch of the sample connections, with respect to the SiC steps. Contacts are indicated in by yellow circles, edge states by a red solid line, SiC steps by horizontal lines. Edge state scattering (dashed red line) is sketched in the vicinity of contact 2. (c) Magnetoresistances of the sample at T=1.6 K. The sample was prepared by a first heating at 300°C, followed by a period of several hours in a wet atmosphere. Blue line: $R_{//}(B)= R_{32,12}$, black line: $R_{perp}= R_{23,14}$, red line: $R_H= R_{13,42}$, showing that the quantum regime specific to graphene has been reached. The R_H (B) asymmetry at high field is possibly explained by scatterings close to some contacts, as sketched in (b).

To perform these first studies, we improved our Raman setup to measure simultaneously the Raman spectrum of graphene sheets and their transmission. This combination is the only method to determine without any ambiguity the number of graphene sheets (and their stacking order) which was grown during the sublimation of the SiC surfaces. This experiment was further improved by adding reflectivity measurements, to increase the S/N ratio and to measure graphene on nontransparent substrate (for instance SiO_2/Si, Cu …). It is now measuring simultaneously Raman spectra with the incident laser the reflected and transmitted power and the temperatures in several room locations. This design has led to the development of a home-made Raman experiment dedicated to graphene research in the framework of the Grafonics ANR project. This experimental development was made in the framework of the”Axe transverse graphene”.

A detailed modelling of the Raman scattering and optical properties of graphene is developed to understand and interpret our experimental findings. For instance, the reflectivity, transmission and Raman scattering intensity of graphene on any kind of multilayered substrate can be predicted. These predictions enable to measure accurately the graphene thickness and to study the optical properties of graphene on a wide set of substrates: SiC, Cu, AlN/Si, SiO_2/Si, suspended graphene …

This know-how has been used to optimize the graphene growth of several partners: the SiC sublimation developed by the CNM, CVD growth of CRHEA on the Si face of SiC, and finally the SiC sublimation of CEA-INAC in the framework of the Grafonics ANR project. These growth optimization studies help us to improve our Raman spectroscopy experiments and will speed up our own graphene growth process development. The high quality of the graphene produced by the CNM and the CRHEA are now assessed by studying their transport properties by magnetotransport experiments.

While the optical properties of the ribbons grown on the C-face were investigated, we also planned to measure them electrically. To this end, we bought a new helium cryostat, with a 9 T superconducting magnet, in which either a variable temperature inset or a He3 inset can be introduced. It is possible to work in a wide temperature range: 1.5K-300K with the variable temperature inset, 300mK-4K with the He3 inset. An air-lock system, on top of the cryostat, has been installed for sample preparation. The samples can be heated up to 150°C under primary vacuum before measurements at low temperatures.

In parallel, we developed our own lithography methods, using the electron-beam lithography at disposal in the clean room of the CTM.

We first focussed on epitaxial multilayer graphene on SiC(0001), which exhibits a stepped surface with regular terraces and step edges. We observed an anisotropic behavior in the magnetoresistance [PRB82, 85438]. We attributed this effect to macroscopic inhomogeneities in the graphene, close to the step edges. We extracted the cyclotron mass from the transport measurements and demonstrated that the system behaves electrically as an n-doped graphene bilayer, in the presence of a strong perpendicular electric field. In these systems, the current flows mainly in the first graphene layers, which are immediately above the SiC surface and have a Bernal stacking. The electric field which induces the confinement is generated by a strongly doped interface carbon layer (the so-called buffer layer or zero buffer layer) between the SiC and the first graphene layer. When a strong magnetic field is applied perpendicularly to the graphene plane, the well-known Quantum Hall effect can be observed in graphene, as in other two dimensional systems. This effect is expected to be remarkably robust in graphene, both in current and temperature. However, the observation of the Hall plateau can only be done if low carrier density are achieved, which is not the case on graphene on SiC(0001) where the doping is typically $n \sim 10^{13}$ cm^{-2}.

To overcome this problem, we focused on epitaxial monolayer graphene on SiC(000-1) from CNM. On this face (carbon face), the growth is not as homogeneous as on the Si face, but there is no buffer layer and a much lower carrier density was expected. We connected monolayer graphene on the carbon face of SiC substrates (samples from CNM) and we indeed observed half-integer quantum Hall effect, at reasonably low magnetic fields B~10 T[APL97,93107]. Moreover, the growth conditions were chosen in order to obtain rather large and long ribbons. Ribbons as large as 50µm were obtained by this method. The size is an important parameter, because larger currents can flow in the graphene, allowing more precise measurements of the quantum Hall plateaus.

Approximately in the same period, in the UK, a relative precision of 10^{-9} was achieved in epitaxial graphene devices for the measurement of the R_K constant, evidencing how graphene can be a serious challenger of GaAs-based devices when metrology and Ohm standards are in consideration. This justified to study in more details the stability of the quantum Hall effect in our devices and we proposed the Metrograph projet (ANR Grant), who started in November, 2011.

For this project, a better understanding of the transport properties of graphene (type of scatterings in particular) is also required. We investigated transport mechanisms at low magnetic fields and we found that not only weak localization and weak antilocalization are present; a contribution due to electron-electron interaction is also responsible of a negative parabolic magnetoresistance, whose curvature is strongly dependant on temperature. This temperature dependence indicates that e-e interaction is reduced by the chiral nature of the particles[PRB83, 195417].

In order to control more efficiently the carrier density, we also investigated bottom-gated devices on the carbon face [APL100, 52102]. The bottom gate was realized by nitrogen implantation. In such devices, the better control of the carrier density, associated with high magnetic fields provided by Grenoble High Magnetic fields Laboratory, allowed us to observe a very large plateau in the Hall resistance: more than 20 Tesla. With respect to what is observed on the Si face, it seems unlikely that this plateau could have been stabilized by charge transfer between graphene and an unknown electron reservoir. Such a charge transfer cannot explain the behaviour of the Hall plateau when the injected current is increased.

On the whole, QHE is now observed in most samples we realize on the C-face, but the quantum plateaus are easily destroyed by moderate currents, probably because of still imperfect cleanings.

To solve this problem, a special attention was devoted to identify new and best graphene sources. To increase the current, larger graphene sample can be realized. Therefore, we also investigated graphene grown on the Si face. As already said, on this face, the whole SiC surface can be covered by a single layer graphene, which simplifies the lithography process. However, the graphene grows occurs on a step bunched surface, and the samples are usually n-doped with a too high concentration to observe the quantum Hall plateaus. Nevertheless, detailed optical analysis of graphene samples from CHREA, reinforced by recent ARPES measurements, confirmed the good overall quality of this graphene. More surprinsingly, electrical measurements on these samples revealed QHE at the centimeter scale at moderate magnetic fields [submitted, see Fig. 4], as doping by water (or other molecules) deposited at the graphene surface can dramatically reduce the carrier concentration. New devices are currently under measurements and/or fabrication in LPN/L2C.

Remarkably, CRHEA samples can be doped either with electrons, or with holes, depending on the sample preparation. In fact, depending on the growth condition, the SiC/Graphene interface differs, and, in particular, can be hydrogenated. Hydrogenation is known to decouple the graphene to the substrate; in hydrogenated samples, a (low) p-doping can be recovered. The control of the carrier density would be a major breakthrough for epitaxial graphene. Therefore, we plan to study the role of the interface in great details in a near future.

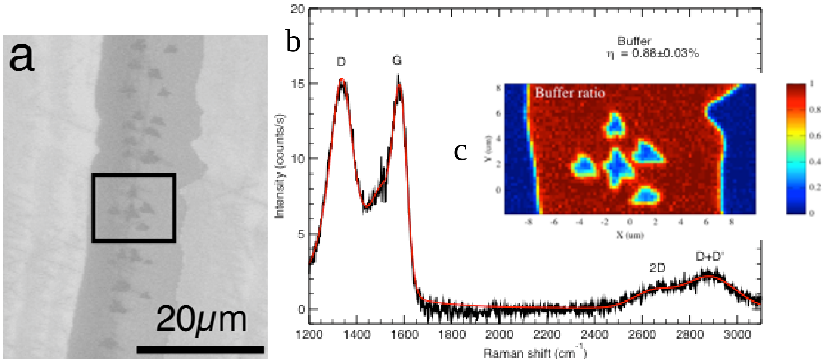


Figure 5: a) SEM pictures of a partly graphitized surface. Three areas can be distinguished. The light grey in the left and right hand-side of the image corresponds to bare SiC, the mid grey area corresponds to a large SiC surface fully covered by the buffer layer (~ 10μm large step). On top of this buffer layer, darker flakes appear and correspond to graphene monolayers on top of the buffer layer. b) Raman spectrum of the buffer layer obtained after SiC spectrum substraction. Notice the large and broad D and G bands. This spectrum does not exhibit any sharp 2D-band, but only broad 2D and D+D' overtones extending from 2400 to 3000 cm−1. The relative extinction value $\eta = 0.88\%$ is extracted from micro-transmission measurements. c) Combined micro-Raman spectroscopy and micro-transmission mapping of the area shown in a) were performed. On the buffer ratio map, we can clearly distinguished three areas: bare SiC substrate in blue with no buffer signal, the reconstructed SiC surface step covered by the buffer layer in red and finally the graphene monolayers flakes in blue with a Raman buffer signal divided by 3.

A major concern for epitaxial graphene on SiC (EG/SiC) is the interface structure between the first graphene layer and the underlying SiC substrate. For usual (0001) SiC wafer orientation, it depends strongly on the growth conditions and orientation (Si vs C face) on which graphene is grown. On the Si face, large homogeneous graphene monolayers (MLs) and bilayers (BLs) can be obtained on top of a $6\sqrt{3}\times6\sqrt{3}$ R30 SiC surface reconstruction. These graphene planes are Bernal (AB) stacked and the interface between the first graphene plane and the SiC is made of an intermediate C-rich layer (called buffer layer) which has covalent bonds with Si atoms of the substrate. On the C face, the situation is completely different. There is no buffer layer anymore. The interaction between the first graphene layer and the C atoms of the SiC-C face is reduced.

Recently, we have analysed the buffer layer by combined micro-Raman and microtransmission experiments. The Raman spectrum of the buffer layer corresponds to those observed for graphene layers with a significant percentage of sp3 bonds. Its relative extinction $\eta = 0.88\pm0.03\%$ corresponds, approximately, to 2/3 of the graphene one. The Raman spectrum of the buffer layer remains visible after the growth of one monolayer on top. This buffer layer background will bias usual evaluations of the crystalline quality of graphene based on domain sizes estimation from the D/G integrated intensities ratio. These studies also confirm the strong coupling existing between the graphene monolayer and the buffer layer: i) the monolayers grown on top of the buffer layer are highly compressively strained ($-0.60\% < \varepsilon < -0.42\%$). The graphene layers are indeed pinned by the buffer layer which prevents wrinkles formation and therefore the strain relaxation ii) despite the relatively low absorption coefficient of graphene, the Raman intensity of the buffer layer is strongly reduced, it is divided by 3. A plausible explanation is related to the strong coupling existing between graphene and the buffer layer. This coupling could decrease the polarizabilities fluctuations of the buffer layer and therefore its Raman intensity.

This strong coupling could also explain the disappointingly low mobility of carriers on the Si face (usually few thousands cm2.V−1.s−1) compared to exfoliated graphene or epitaxial graphene on the C face (between 10000 to 27000 cm2.V−1.s−1). The buffer layer acts as a primary source of carrier doping and scattering. The corresponding (residual) n-type doping is around 1013 cm−2, pinning the Fermi level energy at about 420 meV above the Dirac point.

As a consequence, to improve the transport properties, it is needed to avoid or remove the buffer layer. This has been done by passivating the Si dangling bonds either by post-growth hydrogen annealing [Ref] or by in-situ hydrogenation of graphene during the propane CVD growth developed by CRHEA [Ref]. We can easily detect the presence of the buffer layer and its crystalline reconstruction upon different annealing conditions with our optical techniques and compare and correlate the transport properties probed by magnetotransport. ARPES performed at synchrotron SOLEIL shows that the interface between graphene and the Si face can be continuously tuned from the classical $6\sqrt{3}\times6\sqrt{3}$ R30 SiC surface reconstruction (with a buffer layer) to a fully hydrogenated interface yielding to "free standing" graphene with a continuous evolution of the carrier density, mobility and strain.

Finally, in the framework of the ANR project Grafonics, we are investigating another way to tune the graphene transport properties: functionnalization. This project corresponds to a real merging of the graphene research activities that are developed in the Nanostructure team and our team. This ANR project funded the new Raman experiment we developed specifically for graphene studies taking advantages of the long time experience of the nanostructure team on the spectroscopy of carbon nanostructures and on the combination of Raman spectroscopy and reflectivity and transmission measurements developed to analyse accurately epitaxial graphene on SiC. In this project both epitaxial graphene on SiC and exfoliated graphene on SiO_2/Si substrates and suspended graphene are investigated to secure the graphene samples supply. Our contribution in this project was first to help CEA-INAC to develop the SiC sublimation process. The first non-covalent functionalization studies show that charge transfer may occur but need to be confirmed by transport measurements on devices. For the moment, only Raman spectroscopy and optical characterizations evidence the molecule grafting. In collaboration with CEMES, we demonstrated that the charge carrier density of graphene exfoliated on a SiO2/Si substrate can be finely and reversibly tuned between electron and hole doping with visible photons. This photo-induced doping happens under moderate laser power conditions but is significantly affected by the substrate cleaning method. In particular, it is found to require hydrophilic substrates and to vanish in suspended graphene. These findings suggest that optically gated graphene devices operating with a sub-second time scale can be envisioned but also that Raman spectroscopy is not always as non-invasive as generally assumed.

Rayonnement et attractivité académiques

Recruitment: We have recruited an assistant professor to develop the graphene growth by sublimation and/or CVD techniques.

Invited conferences: We have presented 14 invited talks in different international conferences.

Organization of scientific events: We have organized two international Conferences in Montpellier : ISGN3–July 4-7 2010 and HPSP15, July 25-27 2012. We have participated, as the co-organizator of HeteroSiC & WASMPE conferences in Tours (2011) and in Nice (2013).

Collaborative Network and ANR Contracts: Our research activities are organized through collaborations with national and international institutions and are validated by the financial support from national and European projects. During the evaluated period, we participated (as member or coordinator) in : 2 Marie Curie RTN networks federating the SiC scientific community; 2 Post-Graduated Cooperation Programs with Venezuela; 2 Hubert Curien Partnerships "PHC-Polonium"; 2 LabEx "GANEX" and NUMEV; 1 Associated European Laboratory (LEA) "NODLab" as well as 10 ANR contracts.

Interactions avec l'environnement social, économique et culturel

Advanced technological research requires both the fundamental research bases and the strong industrial support. That's why we have long term collaboration with industrial partners.

During the past years, we had several Industrial contracts with ESSILOR, on new generation of active ophthalmic lenses (till 2008). We also obtained the MOSAHYC Project via a « Fond Unique Interministériel » (2010-2012) and a STREP EC contract with three industrials companies: AIXTRON (Germany), EPICHEM (U.K.) and SAES Getters (Italy) (2005-2008). The improvements acquired in terms of thermal drift constituted one of the important elements, taken into account by ITRON Society to introduce on the market a new generation of meters since 2008. For this reason, on the basics of our experience, the industrial contract with ITRON-France on Hall sensors used for electricity metering (2006-2009) led to an operating agreement between ITRON/CNRS/UM2.

During 12 years period, our activity on Hall sensors have been recognized by the label "Technological Research Team" of the University (ERT-4 -Matériaux-µCapteurs-µSystèmes) (1998-2010).

We have participated regularly in local events which contribute to the spreading scientific knowledge.

Implication de l'équipe dans la formation par la recherche

Our university teaching staff is involved in the responsibility of different teaching units: IUT (University Institute of Technology), Lpro (bachelor's degree – professional formation), L3 (bachelor's degree), Masters and Cursus Master en Ingéniérie (CMI). Concerning teaching at the research level, we participated to masters lectures of the

Lebanon University, to the organization of European Summer Schools and ESR Training in the ITN Marie Curie Projects, to the national school on “The physics and applications of nitrides” in the Labex GANEX (2013). In our training mission, we held a lecture on semiconductor physics at the « Union des Professeurs de Physique et Chimie » (2011) and we have presented technological seminars in industrial companies. We follow up 11 PhD students during the evaluated period.

agence d'évaluation de la recherche et de l'enseignement supérieur

Présentation synthétique de l'entité

Unité de recherche

Vague E : campagne d'évaluation 2013-2014

Team "Materials, Devices and Sensors"

Intitulé de l'unité : Charles Coulomb-UMR5221/Département SMC/Equipe « Matériaux, Composants et Capteurs »

Nom du directeur de l'unité : Jean-Louis SAUVAJOL

Nom du responsable de l'équipe (le cas échéant) : Sylvie CONTRERAS

Effectifs de l'entité (au début du contrat en cours ; préciser si l'entité a été créée au cours de la période d'évaluation).

11 professors and assistant-professors ; 4 researchers ; 4 technicians and engineers; 3 post-docs et PhD.

Personnels ayant quitté l'entité pendant le contrat en cours (et nombre de mois cumulés passés dans l'entité au cours de cette période).

8 PhDs (218 months) ; 4 post-docs (77 months).

Nombre de recrutements réalisés au cours de la période considérée et origine des personnels

- 1 CNRS researcher(CR) from mutation (LPMCN, Université de Lyon 1)
- 1 assistant-professor (MdC): post-doc collaboration between le "Laboratoire de Physique des Solides", UMR 8502 Université Paris Sud, Orsay" and the "laboratoire Francis Perrin, URA 2453, CEA Saclay".

Production scientifique au cours de la période écoulée (1er janvier 2008 – 30 juin 2013) :

1) The thermal drift cancellation of the magnetic sensitivity of Hall sensors used for electricity metering was the purpose of an industrial contract with ITRON-France.
2) Our knowledge on SiC has conducted to the emergence of a graphene research activity which has attracted very much attention.
3) Organic and Inorganic vitreous bulk materials: cracks healing on oxide glasses, super insolating properties as a function of the structure and the texture of ultra-porous systems such as silica, cellulose and silica/cellulose nanocomposites.
4) Organic-inorganic hybrid vitreous coatings: works on layers stacked on substrate to build 3D structures such as optical waveguide or micro tanks.
5) Development of the full know-how allowing for the growth of solar cells demonstrators based on chalcopyrite semiconductors (Cu,(In,Ga),Se2).

Bilan quantitatif des publications de l'entité.

120 publications (71 Articles, 49 Proceedings) and 14 Invited Conferences, 4 Patents, 8 PhD Thesis, 1 HDR, 12 oral communications without proceeding, 10 poster communications without proceeding

Indiquer les **5 publications majeures** de l'entité

1) N. Camara, J.-R. Huntzinger, G. Rius, A. Tiberj, N. Mestres, F. Perez-Murano, P. Godignon, J. Camassel Anisotropic growth of long isolated graphene ribbons on the C face of graphite-capped 6H-SiC Physical Review B 80, 125410 (2009)
2) Jouault, B., Jabakhanji, B., Camara, N., Desrat, W., Tiberj, A., Huntzinger, J.-R., Consejo, C., Caboni, A., Godignon, P., Kopelevich, Y. and Camassel, J. "Probing the electrical anisotropy of multilayer graphene on the Si face of 6H-SiC", Physical Review B 82, 2010, pp. 085438.
3) Girard R., Faivre A., Despetis F., Journal of the American Ceramic Society, vol. 94 (2011) p.2402-2407
4) Biver C. ,Etienne S., Cano J-P, Courson R., Etienne P. "*Elément optique comprenant un aérogel sans fissure*", Brevet: #WO 2012/080658 A1, (2012).
5) Ruffenach, S., Moret, M., Briot, O. and Gil, B. "*Ammonia: A source of hydrogen dopant for InN layers grown by metal organic vapor phase epitaxy*", Applied Physics Letters 95, 2009, pp. 042102.

Indiquer **au maximum 5 documents majeurs**

1) Operating agreement between ITRON/CNRS/UM2: Improvements acquired in terms of thermal drift constituted one of the elements among others, taken into account by ITRON to introduce on the market a new generation of meters programmed from 2008.

Indiquer **au maximum 5 faits illustrant le rayonnement ou l'attractivité académiques** de l'entité

1) 14 Invited Conferences
2) Organization of two international Conferences-Montpellier : ISGN3–July 4-7 2010 and HPSP 2012, July 25-27 2012.
3) Collaborative Networks: Marie Curie RTN networks federating the SiC scientific community: "MANSIC"(2006-2010) and "NetFiSiC" (2011-2015); PCP with Venezuela (2008-2011 et 2012-2015); Hubert Curien Partnerships "PHC-Polonium" (2009-2010) and (2011-2012); LabEx "GANEX"(2012-2022) and NUMEV (2012-2022).
4) Associated European Laboratory (LEA) "NODLab" between L2C/UNIPRESS-Poland/IKZ-Germany (2005-2009).
5) ANR type Cofinancement : 10 contrats [GRAPHONICS (2010-2013), METROGRAPH (2011-2013), MAGMAP (2009-2012), VHVD (2009-2012), SONGES (2007-2009), HEVEPORE (2007-2011), NANOCEL (2010-2013), SILICACEL (2012-2014), SIROCO (2012-2014), SICX (2013-2015)].

Indiquer **au maximum 5 faits illustrant les interactions de l'entité avec son environnement socio-économique ou culturel**

1) Several Industrial contracts with ESSILOR : Work on new generation of active ophthalmic lenses (2008-)
2) MOSAHYC Project via a "Fond Unique Interministériel" (2010-2012)
3) Industrial contract with ITRON-France on Hall sensors used for electricity metering (2006-2009).
4) Technological Research Team of the University :ERT-4 - Matériaux-µCapteurs-µSystèmes (2007-2010)
5) STREP EC contract with three industrials : AIXTRON (Germany), EPICHEM (U.K.), SAES Getters (Italy) (2005-2008).

Indiquer les **principales contributions de l'entité à des actions de formation**

1) Lecture to masters 2 « Functionalized Materials & Nanosciences » and « Chemical Physics of Materials » of the Lebanon University (15h), supervision of 3 Lebanon M2 students.
2) Leadership of teaching units: L3, Lpro, IUT, CMI.
3) Follow up of 11 PhD students.
4) Summer school and ESR Training in the ITN Marie Curie Projects.
5) Training : Course on semiconductor physics at the « Union des Professeurs de Physique et Chimie » October 2011 and et technological seminar to industrial companies.

Team: "Terahertz Spectroscopy and Quantum Metrology"

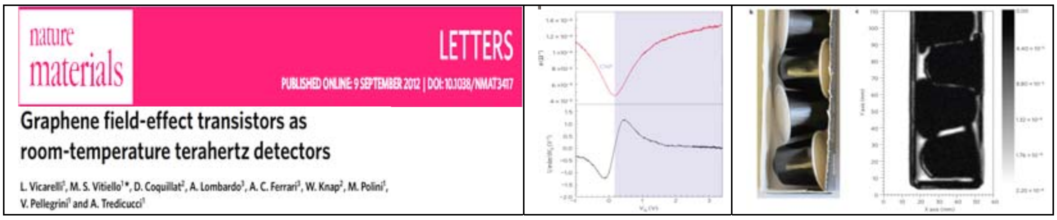
Team: "Terahertz Spectroscopy and Quantum Metrology"

Participants: Nina Diakonova (IR), Dominique Coquillat (DR), Petre Buzatu (IE), Pierre Solignac (IE), Boris Chenaud (MCF), Christophe Chaubet (PR), Frédéric Teppe (CR), Wojciech Knap (DR).

Our research concentrated on terahertz plasma excitations in nanometer size devices. Below we present a few examples selected in a way to stress some new physical aspects and developments rather than purely technological or engineering improvements. We studied the basic physics related problems like power and dependence of the plasma rectification, and helicity sensitive THz rectification. We also present results from THz detection by nanowires and grapheme transistors.

Until now, most of the work on plasma oscillations considered mainly THz imaging applications. We show the progress in overcoming the loading problems and demonstrate first results on the application of plasma rectification by nanotransistors as detectors in wireless communication with signal modulated in the GHz frequency range. These and other results were presented in review articles in Nanotechnology (Nanotechnology 24 2013) and as book chapter (*Handbook of terahertz technology for imaging, sensing and communications*, Cambridge, Woodhead Publishing, 121-155(2013)). Our research has also a basic physics axis in which we study the fundamental transport phenomena such as QSHE in Topological Insulators, Spin Hall Effect (SHE), QHE, transport in nanotubes, nanowires and in Graphene structures. Except the traditional cryogenic transport measurements we are also interested by THz radiation induced modification of the quantum effects. A good example is Quantum Conductance Fluctuations (QCF) in Graphene which were observed in standard transport and THz rectified photovoltage signal.

THz rectification by plasma oscillations in graphene: We describe our scientific activity by the most recent results. They concern Terahertz rectification by Graphene top gate transistors. Owing to its high carrier mobility, gapless spectrum, and frequency independent absorption, graphene is very promising material for the development of detectors and modulators operating in the terahertz region of the electromagnetic spectrum, still severely lacking in terms of solid-state devices. Indeed, we have demonstrated in collaboration with the "Scuola Normale Superiore (SNS) di Pisa", and Cambridge University THz detectors based on graphene FETs.

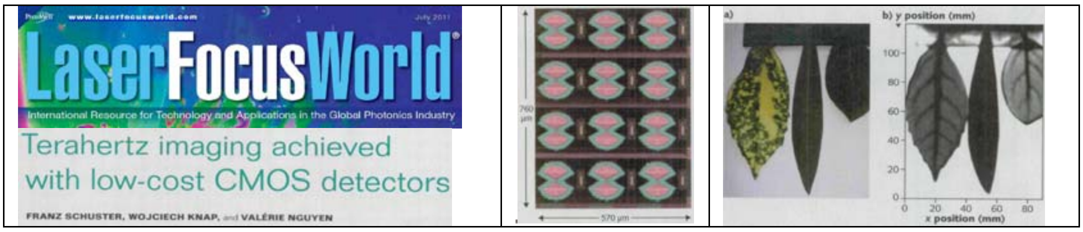


We have demonstrated room temperature THz rectification at 0.3 THz, showing that unusual change of the sign of the rectified signal is due to change of the conduction type (electrons/holes) in the Dirac point of Graphene transistors. This work was published in [Nature Materials, 11, 865-871 (2012)]. Semiconductor nanowires are also offering a wealth of new approaches for unidimensional (1D) plasma modes and the development of a future generation of nanoelectronic devices. Together with SNS-Pise team, we have demonstrated that plasma oscillations in semiconductor nanowires can be used for THz rectification and that nanowires can be used as building blocks for the realization of high-sensitivity THz detectors. In order to take advantage of the low effective mass and high mobilities achievable in III-V compounds, we have used InAs nanowires. This work was published in [Nano-Lett., 12, 96-101 (2012)].

New Graphene-like semiconductor nanostructures: As written earlier, the THz energy range also corresponds to the Landau energies encountered in QHE and QSHE. This is the reason why our research has logically a basic physics axis in which we study the fundamental phenomena such as QSHE. Indeed, a new class of topological insulators was experimentally demonstrated in materials with band inversion. In collaboration with Grenoble LNCMI and with Russian colleagues in Nizhny Novgorod and Novosibirsk, we have experimentally studied THz Landau level (LL) transitions spectra under magnetic field in a series of HgTe-based heterostructures. We have confirmed the observation of the anti-crossing of the zero-mode LLs caused by the breaking of time-reversal symmetry, expected in two dimensional topological insulators. We have also shown the linear dispersion of the 2D massless Dirac fermions in HgTe QW structures [Phys. Rev. B **86**, 205420 (2012)].

Quantum effects and metrology: In more standard heterostructures such as GaAs/GaAlAs heterojunctions, we have demonstrated, in collaboration with the "Laboratoire de Photonique et Nanostructures" (LPN) and the Polish Academy of Science, two new quantum effects in the QHE regime: the thaw down and the boil off of electrons on bound acceptors states created by the quantizing magnetic field (Phys. Rev. B, 2012). On those structures, we have worked also on nano Hall bars, with the aim to design and process efficient Hall sensors. The technological process made at LPN could guarantee a very low contact resistivity even in ultra-small devices (JAP, 2011) which is a key result to diminish at most the thermal noise. Besides, we have recently characterized the noise in the Hall configuration in order to obtain the smallest detectable magnetic field with those sensors, found to be 50 nano-Tesla. When depositing a gate on those sensors we have also shown that we obtain a direct image of the local density of states by measuring the longitudinal conductivity in quantizing magnetic field, as a function of the gate voltage.

Plasma oscillations for THZ imaging and wireless communication: While novel applications using THz radiation are developed, there is an increased demand for sensitive THz detectors, passive and real-time active camera systems. New concepts such as plasma wave excitation of submicron FETs allow our team to develop a new generation of solid state THz efficient and non-resonant or resonant detectors. These ideas were verified since 2008 through a number of detection experiments. One of the most important realizations is the MOS-transistor-based pixel allowing for room temperature ,world record sensitivity at 300 GHz. This result obtained in collaboration with "CEA-LETI" was published in [*Laser Focus World* **47**(7), 37 (2011)]. Also recently, we have demonstrated in collaboration with Osaka University and IES, THz wireless communication using a GaAs FET detector at a carrier frequency of 310 GHz for a error-free data rate of up to 8.3 Gbit/s. This wireless data transfer has already a much higher frequency than used by Wi-Fi or 3G. It is the first time that high-speed wireless data transfer using a FET was demonstrated.



Rayonnement et attractivité académiques

The team is coordinatinig the (last 8 years) GDR, GDR-E and GDR-I projects "*Semiconductor sources and detectors of THz frequencies"* including Japan and twelve European countries. This way the team participates in structurization of national and international research related to Terahertz science and technology. International Workshops and meetings are organized every year in collaboration with LMPQ lab in Paris and with, IPM of Nizhniy Novgorod in Russia. The team organized also a consortium on the use of THz radiations for medical, biological and physical purposes in form of a regional technical platform"Terahertz Platform" strongly supported by the Region of Languedoc-Roussillon. The work of the team was also participated in ANR program TeraGaN to study the possibility of using GaN High Electron Mobility Transistors as efficient THz sources with special geometries and architectures. The team worked also with the CEA-LETI through the "THz imaging on Si-MOSFTEs" project. This project has the goal to fabricate and to study a new architecture of transistors, amplifiers and antennas to obtain the best single pixel for THz detection focal plane arrays. Since almost 3 years, the team coordinates French efforts in ANR and JST French-Japanese project on the wireless Terahertz telecommunication with plasma wave devices as THz detectors/emitters. This program is one of the most important ,(worldwide) in the field of data transfer in the THz frequency range. The JSPS International Fellowship Program for Research in Japan founded bilateral exchange of a few students and post-docs. Three joint Egide French-Lithuanian, French-Polish and French-Japanese research programs ("Gilibert", "Polonium" and "Sakura", respectively) were granted to the team helping in development of scientific relations and acces to specific experimental facilities with these countries. The team is linked since 2 years with the TeHo team of the "Institut d'Electronique du Sud" (IES) via the "Groupement d'Interet Scientifique" (GIS) named **Teralab** and steered by L. Varani and W. Knap. This GIS Teralab is an excellent opportunity to reinforce significantly the synergy between the two teams and to create a "pole of excellence" in the research on the frontier between physics and electronics. Our team participate as cofounder and active member of the European Union project COST - MP1024 TERA-MIR that has as a purpose to find/stimulate/organize synergy in EU research in Terahertz and Mid Infrared range. It is worth also to mention bilateral collaborations with national laboratories of nanofabrication and metrology (LPN, IEMN, and LNE). We also have active collaborations with the Polish Academy of Science, UNIPRESS Poland, the Rensselaer Polytechnic Institute, NY, USA, the Universidad de los Andes in Bogota, Colombia, and many more. Our team was granted by the "Institut de Physique de Montpellier" for upgrading the Plateform "nanoelectronics and metrology", and obtained two grants from the Conseil Scientifique of UM2 for the "magneton", and the "nanotubes for THz detection" projects.

Interactions avec l'environnement social, économique et culturel

Independently of the research activity the team works on the technology transfer and patents. We have proposed together with Tohoku University (Sendai, Japan) an original 2D-plasmon-resonant micro-chip emitter as a new THz source. The structure is based on a HEMT and featured with interdigitated dual-grating gates. The dual grating gates can alternately modulate the 2D electron densities to periodically distribute the plasmonic cavities along the channel, acting as an antenna. Before writing the first publication, the idea of asymmetric multigrating gate structures for THz emission, mixing and detection, was patented together with our Japanese colleagues [Japanese Patent PCT/JP2010/007074 (2010)]. With the University of Regensburg, we have also measured a THz helicity sensitive photoresponse in plasma wave FETs. The results provide the basis for a new sensitive, all-electric, room-temperature, and fast measurements of all polarization parameters of THz radiation. That is the reason why before publishing the results we wrote an European patent together with our German colleagues [French patent n° 1161615, International Patent PCT n° EP2012074375]. Moreover, the work of the team is supported since 5 years by the French Embassy in Moscow, providing funds for PhD cotutelles and exchanges of researchers. In the frame of this project our team, in collaboration with Lebedev Institute in Moscow has also patented a transportable, compact and tunable Terahertz laser based on p-Ge crystals [Patent number: WO2012143410 (A1) (2011)]. Because transistor based structures are able to interact efficiently with THz waves, it is now possible to think of large applications to THz physics. STMicroelectronics was the strongest industrial partner of the team with the "Nano2012" program which was based on the study of ballistic effect and plasma wave effect in last generation of Silicon technology devices. The intention was to create at the end a complete device for THz real time imaging at room temperature. The team was also supported by the Italian Company "New Terahertz Technologies" during the last few years. Since 2012, our team is supported by collaboration with Canon France Industry to study THz communication systems for close environment and especially intra system communication. On the base of the different patents described above, our team is involved in a start-up creation since a year, with the help of Mr. Antonini (Sales representative), Pierre Solignac (L2C engineer) and Abdel El-Fatimy (CNRS engineer). This structure under formation has so far received the support of the Languedoc-Roussillon region, of French the government and of Europe (FEDER, OSEO, LR-incubation). The future small company is currently under creation procedure. It will be formally registered once first commercial THz detectors will be finalized (mid~2014).

Through participation in the dissemination of scientific culture, our team has moreover managed numerous scientific events for primary school, college and high school students during the last 5 years: the week of Science (Science en fête), the centenary of our University of Sciences in Montpellier, the Laser year event, the Physics Teachers congress, conference JMC 2012. We have organized scientific workshops around electricity (hydraulic/electrical analogy), mechanics (historical experience of Galileo's tilted plane), states of matter. Since this year we participate actively, in connection with the master of physics, Faculty of Science, the Languedoc Roussillon region, and the "Rectorat" of Montpellier, in the project "science bus".

Implication de l'équipe dans la formation par la recherche

Our team is part of the I2S doctoral school of UM2, and is deeply involved in the formation of the Master degree. As a responsible for the first year until 2010, C. Chaubet was in charge of the orientation of students in the different L2C teams. For the second year, our team is in charge of the course of nanotransport and disseminates the research results to the students: THz emitters and detectors theory, electronics of nanotransistors, and the basis of quantum metrology. Our team proposed for next year to invite P. Degiovanni from ENS Lyon for a PhD course on quantum electronics. Since 2013, our team is involved in the master degree of the University of Hanoi, Vietnam, which is linked to our university. During the last five years, our team had 7 PhD students, two of them are still with us (defense in the next few months), 4 Master students, 3 undergraduate students.

Présentation synthétique de l'entité

Unité de recherche

Vague E : campagne d'évaluation 2013-2014

Team "Terahertz Spectroscopy and Quantum Metrology "

Intitulé de l'unité : Laboratoire Charles Coulomb, Département SMC, Equipe "Spectroscopie Terahertz et Métrologie Quantique

Nom du directeur de l'unité : Jean-Louis SAUVAJOL

Nom du responsable de l'équipe : Wojciech KNAP

Effectifs de l'entité (au début du contrat en cours ; préciser si l'entité a été créée au cours de la période d'évaluation).
2 teacher-researchers; 3 researchers; 1 technician; 3 post-docs and PhD students.
Personnels ayant quitté l'entité pendant le contrat en cours (et nombre de mois cumulés passés dans l'entité au cours de cette période).
2 PhD (54 months); 1 post-doc (12 months).
Nombre de recrutements réalisés au cours de la période considérée et origine des personnels
2 engineers coming from other lab teams. One of them is at 50% of his time in our team and the rest working in the lab's public service.

Production scientifique au cours de la période écoulée (1er janvier 2008 – 30 juin 2013) :

1) One of the most important realizations of the team during this period is the MOS-transistor-based pixel allowing for world record sensitivity at 300 GHz and room temperature. This result obtained in collaboration with "CEA-LETI, Grenoble" was published in Laser Focus World in 2011.
2) In 2012 we have demonstrated in collaboration with the "Scuola Normale Superiore (SNS) di Pisa", Terahertz detectors based on antenna-coupled graphene field effect transistors. This work was published in Nature Materials.
3) We have proposed together with Tohoku University (Sendai, Japan) an original 2D-plasmon-resonant micro-chip emitter as a new terahertz light source. This idea of asymmetric multigrating gate structures for THz emission, mixing and detection, was patented together with our Japanese colleagues in 2010.
4) With the University of Regensburg, we have also written an European patent on Terahertz helicity sensitive photodetectors based on GaAs/AlGaAs high electron mobility transistors. This provides the basis for a new all-electric, room-temperature, and fast characterization of all polarization parameters of terahertz radiation.
5) We have evidenced new quantum effects associated with bound acceptors states in a two dimensional electron gaz, using transport experiments in the quantum Hall effect regime. This result, obtained in collaboration with LPN of Marcoussis and Academy of Science of Warsaw, was published in Physical Review (2012).

Bilan quantitatif des publications de l'entité.
79 publications in journals, 64 conference proceedings, 42 invited talks in conferences and 4 patents.

Indiquer les **5 publications majeures** de l'équipe (avec leur titre et en soulignant, dans le cas de publications communes, le nom du ou des membre(s) de l'entité).

[1] F. Schuster, W. Knap, and V. Nguyen, Terahertz imaging achieved with low-cost CMOS detectors, *Laser Focus World* **47**(7), 37 (2011). **[2]** L. Vicarelli, M. S. Vitiello, D. Coquillat, A. Lombardo, A. C. Ferrari, W. Knap, M. Polini, V. Pellegrini and A. Tredicucci, Graphene Field Effect Transistors as room-temperature Terahertz detectors, *Nature Materials*, 11, 865-871 (2012). **[3]** Miriam S. Vitiello, Dominique Coquillat, Leonardo Viti, Daniele Ercolani, Frederic Teppe, Alessandro Pitanti, Fabio Beltram, Lucia Sorba, Wojciech Knap, and Alessandro Tredicucci, Room-Temperature Terahertz Detectors Based on Semiconductor Nanowire Field-Effect Transistors, *Nano Lett.* 12, 96-101, (2012). **[4]** M. Zholudev, F. Teppe, M. Orlita, C. Consejo, Torres J., N. Diakonova, M. Czapkiewicz, J. Wróbel, G. Grabecki, N. Mikhailov, S. Dvoretskii, A. Ikonnikov, K. Spirin, V. Aleshkin., V. Gavrilenko, K. Knap, Magnetospectroscopy of two-dimensional HgTe-based topological insulators around the critical thickness *Phys. Rev. B* 86, 205420 (2012). **[5]** I. Bisotto, C. Chaubet, A. Raymond, J.C. Harmand, M. Kubisa and W. Zawadzki, Magnetic thaw down and boil-off of electrons in the quantum Hall effect regime due to magnetoacceptors in GaAs/GaAlAs heterostructures, Physical Review B 86, 085321, (2012) .

Indiquer **au maximum 5 documents majeurs** (autres que publications) produits par l'entité

[1] W. Knap, O. Klimenko, Y. Mityagin, P. Solignac, Laser device for emitting waves in the THz range. (2011-04-19) Patent number: WO2012143410 (A1). **[2]** T. Otsuji, V. Popov, W. Knap, Y. Meziani, N. Dyakonova, D. Coquillat, F. Teppe, D. Fateev, and J. E. Velazquez Perez, Terahertz Electromagnetic Wave Conversion Device Japanese Patent PCT/JP2010/007074 (3 December 2010). **[3]** Knap W.,Teppe F.,Diakonova N.,Dyakonov M.,Klimenko Oleg,Ganichev S.,Drexler C. Terahertz polarization analyzer based on field effect transistors, French priority patent filed on 14/12/2011 under No. 1161615. PCT extension took place on 04/12/2012 under n° EP2012074375. **[4]** H. Roskos, A. Lisauskas, T. Loeffler, W. Knap, F. Teppe, D. Coquillat, M. Dyakonov, Method and system for three-dimensional detection of objects using Thz radiation. (2010-03-18) Patent number: WO2010028972.

Indiquer **au maximum 5 faits illustrant le rayonnement ou l'attractivité académiques** de l'entité

[1] 42 invited talks in international conferences**.** **[2]** Highlight in Laser Focus World "Terahertz imaging achieved with low-cost CMOS detectors", in 2011 [F. Schuster, et al., Laser Focus World 47(7), 37 (2011)]. **[3]** Nomination of Dr W.Knap to the title of Professor by President of Poland (Warsaw fenruary 2013). **[4]** International CNRS-GDRI 373 THz Project has been created in 2006 and renewed for 4 years in 2010 coordinators: W. Knap, C. Sirtori and V. Gavrilenko. 6 meetings since 2008 [5] ANR-JST « WIreless communication using TeraHertz plasmonic-nano ICT devices" in 2010.

Indiquer **au maximum 5 faits illustrant les interactions de l'entité avec son environnement socio-économique ou culturel**

[1] Industrial cooperation agreement with STMicroelectronics (Nano2008 and Nano2012)
[2] Industrial cooperation agreement with Italian company "New Terahertz Technologies" 2008-2012
[3] Industrial cooperation agreement with the company Canon-France 2012-2015
[4] Startup creation currently incubating with the help of "Languedoc-Roussillon Incubation" and "Transfert-LR". (Also OSEO competition winner)
[5] Creating scientific workshops for educational purposes, distributed in schools and at scientific events. Implementation of the project "Science Bus" on a partnership with the region and the university.

Indiquer **les principales contributions de l'entité à des actions de formation**
a) Design and coordination of the module "Atom Molecules and Radiation" Master 1 Physics Research since 2008, **b)** design and coordination of the module "Nanotransport Nanoelectronics" Master 2 Physics Research since 2008, **c)** Annual seminar for students of the Master on the team activities, **d)** Supervision of 7 PhD students, five students of Master 2 and 3 from Master 1, **e)** Design and organization of a training module for teachers of Physical Chemistry

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Le **directeur d'unité/le responsable de l'équipe** peut indiquer ici brièvement **3 points précis** sur lesquels il souhaite obtenir l'expertise du comité.

The activity of the team in the domain of THz properties of Solids developed since 25 years allowed brought our group in the highest national and international level. We need expertise of the committee on 2 points: 1) Shall this group be reinforced by a recruitment? As the 3 of the 4 members of the group are approaching retirement age (53, 55, 58) and without rapid recruitment there will be no time to form young researchers. 2) Shall the team apply for LIA based on THz properties of Graphene-like materials? GDR-I projects allowed to define two partners (Russian Academy of Sciences and Polish Academy of Sciences). Working with these groups can provide access of our team to unique technologies of Graphene-like compounds based on HgCdTe and GaInN.

Team: “Physics of the Exciton, Photon and Spin”

Team: "Physics of the Exciton, Photon and Spin"

The scientific activity of the team mainly revolves around radiation-matter interaction, considered either as an object or as a tool for our studies, but other specific tools such as magneto-transport and magnetization measurements are also used for the studies devoted to magnetism. As an object, the radiation-matter interaction is tailored in order to get original optical properties or functionalities. This is illustrated by our activity in nanophotonics and metamaterials, and in the physics of exciton-photon coupling (Light-matter coupling and quantum phenomena). Some other fundamental aspects of the radiation-matter interaction are also investigated (Coupled light-matter systems). As a tool, the radiation-matter interaction serves for studying widely different objects such as excitons (Optical properties of nanostructures), and spin (Spin dynamics) in various semiconductors nanostructures, or such as cells at the interface with biology (Bionanophotonics). Our studies are not limited to radiation-matter coupling but also deal with the investigation of magnetic interactions in semiconductors nanostructures and in single particles (Magnetism).

These widespread activities of PEPS involve numerous academic or industrial collaborations at national and international level. These collaborations are generally organized by participating into, or coordinating European networks, and ANR projects.

The most outstanding results and activities of the team, and the perspectives for the next five years, are presented below.

Topic: *Light-matter coupling and quantum phenomena*

Participants: C. Brimont (MCF), T. Guillet (MCF), P. Lefebvre (DR2), B. Gil (DR1), S. Cronenberger (MCF), M. Vladimirova (CR1), D. Scalbert (DR2), G. Cassabois (PR2), E. Rousseau (CR2), M.Mexis (Post-Doc), O. Kamoun (PhD), R. Hahe (PhD), J. Sellés (PhD), D. K. Van (Post-Doc)

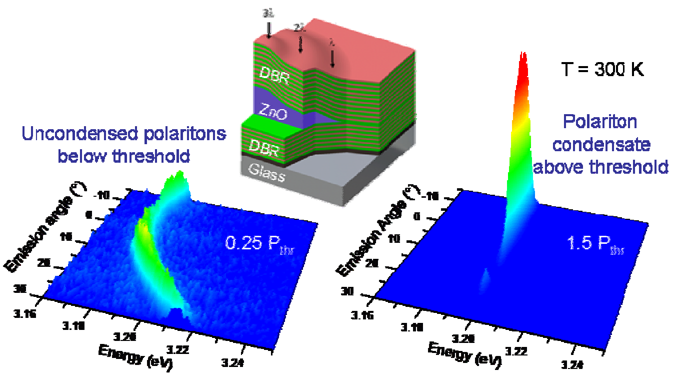
During the last five years, the PEPS team has been strongly developing the interface between semiconducting nanostructures and photonics. Well controlled quantum emitters coupled to photonic resonators have been designed and investigated in order to study various regimes of light-matter coupling. A broad range of configurations have been explored, based on quantum dots, quantum wells and bulk semiconductors on the excitonic side, and 0D, 1D, 2D dielectric and plasmonic resonators on the photonic side. This impulse results from both long standing activities on microcavities in the team, and a new synergy between the theoretical and experimental activities dedicated to photonics and nanostructures.

Exciton-photon coupling in planar microcavities and photonic crystal membranes

Important results have been obtained in the field of polariton physics, i.e. when excitons and photons are brought in the strong coupling regime, leading to new collective properties and the generation of Bose condensates.

D. Scalbert, V. Vladimirova and S. Cronenberger measured by pump and probe spectroscopy the polariton interaction constants in a GaAs microcavity, which are determining the condensation regimes for polaritons [PRB2009, PRB2010].

C. Brimont and T. Guillet investigated the potential of ZnO-based microcavities for room-temperature polariton condensation, thanks to the specificities of ZnO excitons (Coordination of the ANR program ZOOM, 2007-2009; participation to the FP7 ITN Clermont4, 2009-2013). They first characterized the efficiency of polariton relaxation in such planar microcavities [PRB2008, APL2009], during the PhD thesis of Stéphane Faure. The samples are grown in two steps at CHREA and LPN. As the quality factor of the cavities increased, excitonic lasing and polariton lasing were demonstrated [2 APL in 2011], and finally polariton condensation was



Polariton condensation at 300K in a ZnO microcavity obtained up to 300K [PRL2013], with an unprecedented tunability of the temperature and of the exciton/photon composition of the polariton condensate. This phase transition is modeled within collaborations with G. Malpuech at Institut Pascal, and a new partnership with S. Jaziri (El Manar University, Tunis) started in 2012 with the co-direction of the PhD student O. Kamoun.

The problematic is different when excitons are considered as quantum emitters weakly coupled to the cavity modes. The use of GaN quantum dots in UV photonic resonators based on AlN allowed C. Brimont, T. Guillet and M. Mexis (Postdoctoral fellow) to investigate the spectroscopy of photonic modes in photonic crystal cavities and microdisks (ANR PNano Sinphoni, 2009-2011). The originality of those cavities lies in the newly accessed UV spectral range, the broad transparency window of nitride materials, and the large quality factors that were demonstrated in microdisks [OptLett2011] and in photonic cavities [APL2011, APL2012]. Those resonators are grown at CRHEA and processed at IEF. They are now mature for the development of new nano-lasers, hopefully up to 300K, based on a few quantum dots coupled to a strongly confined photon mode and triggered by the Purcell effect (the so-called threshold-less lasers).

Plasmonics and quantum metamaterials

In september 2010, G. Cassabois, hired as professor in 2009, joined the PEPS team and transferred from Paris to Montpellier a complete pump-probe setup devoted to nonlinear optical spectroscopy in the telecommunication wavelength range. E. Rousseau, hired as Chargé de Recherche-CNRS in 2010, has built a new complementary setup for single nanostructure spectroscopy around 1.55 µm. These experimental developments are to address novel issues in strong collaboration with D. Felbacq, B. Guizal and M. Antezza on the theoretical side. The first one deals with the demonstration, around 1.55 µm, of efficient single photon sources coupled to plasmonic annoantennas. Indeed, the relevance of plasmonic antennas made of metallic structures raises in the infrared spectral range because of the low ohmic losses and small mode volume of plasmonic devices. The second project intends to develop the new emerging field of quantum metamaterials. Based on the internationally recognized expertise of D. Felbacq in metamaterials, our goal is to introduce an active part in the metamaterial and to use a quantum degree of freedom to tailor the optical properties of this artificial photonic structure. We are currently investigating macroscopic arrays of InP nanowires with embedded InAsP (fabricated by J.C. Harmand-LPN) as a first realization.

Topic: *Optical properties of nanostructures*

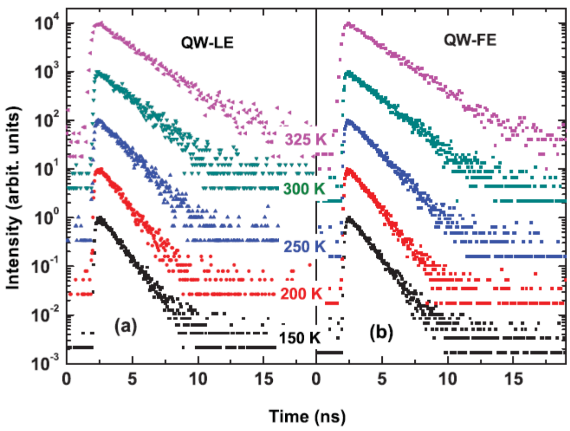
Participants: B. Gil (DR1), T. Bretagnon (MCF), P. Lefebvre (DR2), T. Guillet (MCF), C. Brimont (MCF), G.Cassabois (PR2), E. Rousseau (CR2), L. Béaur (PhD), D. Rosales (PhD), L. Colombier (PhD), J. Sellés (PhD), D. K. Van (Post-Doc)

UV-Visible Spectroscopy

One important field of research of the spectroscopists in the PEPS team is the optical study of electronic excitations in wide band gap semiconductors, such as ZnO, GaN, AlN... The PEPS team (including our theoreticians D. Felbacq and B. Guizal) has published a number of results [PRB81,2010-APL99] on the anisotropic features and the binding energies of excitons in such semiconductors, in line with B. Gil's longstanding experience on symmetry-related issues. Time-of flight studies of light-pulses in bulk GaN and ZnO involved fruitful collaborations with the Ioffe Institute in St. Petersburg, Russia, the Linköping University in Sweden and the LASMEA-UMR 6602, in Clermont-Ferrand.

This said, low-dimensional nanostructures remain the recognized field of expertise of this team who, along the last five years, has studied quantum wells (QWs), quantum dots (QDs) and nanowires (NWs), based on (Ga,In,Al)N and on (Zn,Mg)O. We have, more specifically, focussed our interest onto relaxation/recombination processes in nonpolar heterostructures, free of internal electric fields, on one hand, and in nanowires, on the other hand.

Most salient on this five-year period, are the results obtained under T. Bretagnon's supervision on nonpolar m-plane $ZnO/Zn_{0.8}Mg_{0.2}O$ quantum wells fabricated in CRHEA-UPR10 in Valbonne. The steady increase of excitonic lifetime with temperature along with the constancy of the photoluminescence (PL) intensity, testified to the domination of radiative recombination processes, up to 325K and therefore to the exceptional quality of those nonpolar quantum wells [PRB84,2011] (*see* figure: increase of both free and localized excitons PL decay times with T, in a 1.7 nm-



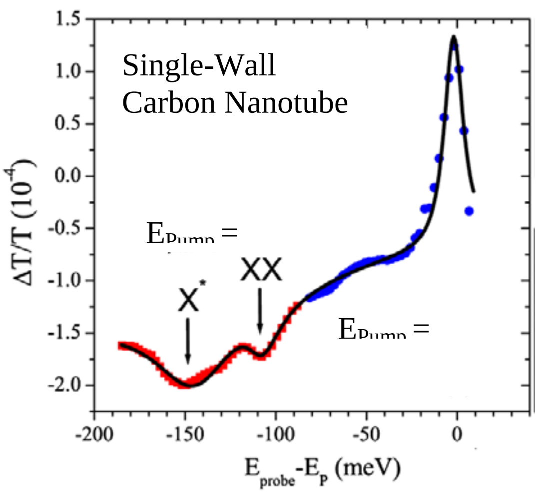
wide QW). Polarized reflectance spectroscopy revealed strong in-plane optical anisotropies, as predicted by group theory and allowed for identification of excitonic features analogous to the A, B and C excitons of the bulk [APL98, 2011].

Concerning GaN-based nanostructures, many results were obtained within the still-ongoing collaborations initiated by P. Lefebvre during his 12-month stay at EPF-Lausanne (2008), in B. Deveaud's team, and 18-month stay at Polytechnic University in Madrid (2009-10), at the Institute of Opto- and Micro-electronic Systems (ISOM), in E. Calleja's team. In nonpolar GaN/(Al,Ga)N QWs grown, at EPFL in N. Grandjean's group, along the *a*-plane we emphasized (i) the role of basal-plane stacking faults (BSFs) in the exciton recombination dynamics, by time-resolved (TR) cathodoluminescence, (ii) the presence of donor-BSF complexes [PRB80,2009] and (iii) the 1D character of excitons at quantum wires created at the intersection of QWs and BSFs. TR-PL revealed the role played by biexcitons in the relaxation processes in GaN/(Al,Ga)N QWs and in a microcavity containing such QWs [PRB85,2012]. The studies of GaN-based nanowires grown at ISOM emphasized the importance of lateral surfaces for the constitution of specific excitonic complexes [APL98-2011] and for the quenching of PL related to oxygen adsorption [S&M52,2012].

To perform optical spectroscopy, the PEPS team uses the TR- and micro-PL setups that had been developed, in the preceding years, for the ultraviolet range of the spectrum. Our micro-PL setup, in particular, has now reached an important position, worldwide, thanks to the efforts of Thierry Guillet, collaborating for these tasks with the two engineers of the team: P. Valvin and S. Rousset. T. Guillet supervised the PhD thesis whose final achievement was the observation of the polarized emission of isolated GaN/AlN QDs, grown at CRHEA-UPR10 in Valbonne, and their modelling [PRB77, 2008]. The implementation, in 2009-2011, of real- and k-space spectroscopic imaging is now routinely used in our studies of photonic microstructures and of condensates (*see* next section and prospective below).

The most recent (2012) developments of our setup have extended our range of measurements to wavelengths as short as 200 nm and improved our time-resolution down to 1ps. These features, along with the high flexibility of the available time-ranges (from picoseconds to milliseconds), make our platform a unique facility, worldwide. It is therefore particularly attractive to a growing number of collaborators, short-wavelength optoelectronics being nowadays an important field of research. For example, we have conducted radiative efficiency studies by TR-PL on high-aluminum-content (Al,Ga)N QWs and epilayers, as active regions of LEDs emitting in the 215-255 nm range, in collaboration with the Mie University, Japan. Still informal studies of Al-rich nanowires have also begun, in collaboration with B. Daudin's group at CEA-Grenoble and with J.C. Harmand's team at LPN-Marcoussis.

Infrared Spectroscopy



The installation of a brand new platform for infrared spectroscopy around the fibre-optic telecom wavelengths has been impulsed by G. Cassabois, following his recruitment on a professor position in 2009. This novel facility is based on a pump-probe set-up developed in Paris in 2007 and transferred to Montpellier in 2010. It was first used for absorption saturation experiments at 1.55µm, allowing for measurements on nanostructures with very weak radiative yield. With it we have measured the homogeneous linewidth of intraband transitions in an ensemble of GaN/AlN quantum dots [APL97,2010]. We have then faced the question of exciton-exciton interactions and of excitonic complexes in carbon nanotubes (CNTs). With the same absorption saturation configuration, we have shown that the collisional broadening in CNTs is controlled by the exciton-exciton scattering, like for Wannier exciton in inorganic semiconductors, whereas the population relaxation is ruled by the exciton-exciton annihilation, like for Frenkel excitons in organic materials [PRL107, 2011]. By photo-induced absorption experiments, we have performed the first observation of biexcitons in CNTs [PRL109, 2012] (*see* figure).

Topic: *Spin dynamics and magnetism*

Partcipants: S. Cronenberger (MCF), M. Vladimirova (CR1), D. Scalbert (DR2), F. Terki (MCF), S. Charar (PREC), P. Barate (PhD), S. Andreev (PhD), Z. Ben Cheikh (PhD), R. Giri (PhD), K. Souleymane (PhD), TRAN Quang Hung (Post-Doc).

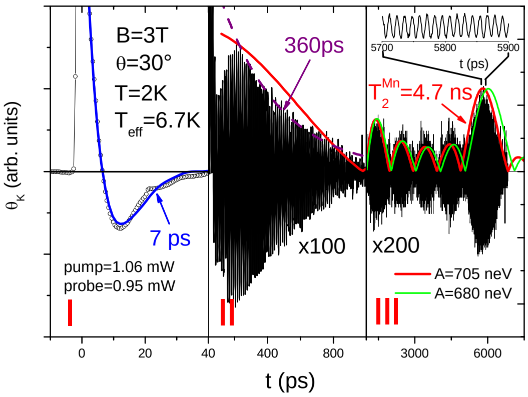
This theme encompasses to distinct activities: spin dynamics studies via ultrafast optics on one hand, and studies of magnetic interactions in diluted magnetic semiconductors such as GaMnAs thin layers and spin-crossover nanoparticles, by transport and highly sensitive magnetic measurements on the other hand.

Spin dynamics

The main objective pursued during these last five years has been to study some fundamental properties of spin excitations in semiconductor nanostructures, making intensive use of the Faraday effect and of pump-probe experiments.
Important results have been obtained by femtosecond pump-probe spectroscopy, on collective spins excitations of a spin-polarized bidimensional electron gas embedded in modulation doped CdMnTe quantum wells. These results have been obtained for most of them within the ANR Gospininfo project coordinated by F. Perez (2007-2012) in strong collaboration with Institut Néel, Institut des Nanosciences de Paris, and Institute of Physics of Polish Academy of Sciences, and also in collaboration with A. Dmitriev from Ioffe Institute at St-Pertersburg. The collective (spin-wave) nature of the spin excitations monitored in photo-induced Kerr rotation experiments was demonstrated, and the onset of the strong-coupling between the electron-spin waves and Mn spin-flip excitations revealed the many-body enhancement of the electron spin-susceptibility of the spin polarized-2DEG [Barate et al, PRB2010]. It was shown that the mixed electron-Mn spin waves do not exhaust all possible Mn spin degrees of freedom, and that room is left to build new collective Mn spin-flip excitations not coupled to the 2DEG, as we demonstrated both theoretically and experimentally [Vladimirova et al, 2008]. During the last two years, one of our main goals was to demonstrate that coherent spin-flip waves with a well-defined wavevector can be optically excited and detected in a four-wave mixing (FWM) geometry. We do observe a FWM signal at the expected frequency of the spin-flip wave but with a dispersion weaker than the dispersion observed in spin-flip Raman scattering experiments by F. Perez. This work, which was central in Gospininfo project, will be unpublished soon.

The enhancement of light-matter coupling in microcavities has been also exploited to demonstrate the concept of giant Faraday rotation based on the optical orientation of a degenerate electron gas in a n-GaAs microcavity [Giri et al, PRB2012]. The foreseen interest of cavity enhanced Faraday rotation is to provide a sensitive, non-perturbative, tool for probing electron and nuclear spins. This work was funded by ITN project Clermont 4, and involved a close collaboration with Laboratoire de Photonique et Nanostructures, where microcavities with high Q-factor, adapted to this experiment, were grown.

Developing further non-perturbative optical spin probes in semiconductors, a large-bandwidth (10 GHz) spin-noise spectroscopy setup is being built. This project is funded by the ANR through the SNS project coordinated by D. Scalbert (2011-2014), and brings together our team and teams from Institut Néel (with whom we have longstanding collaboration), from the Institut d'Electronique du Sud, with whom we started a collaboration for this particular project. The main objective is to demonstrate the equivalence between spin-noise and spin resonance spectra of magnetic impurities having complex spectra, such as Mn atoms in II-VI's. As a preliminary study, time-resolved Kerr rotation experiments (supposed to be the Fourier transform of the spin-noise spectra) have been measured on very diluted bulk CdMnTe, and revealed the Mn hyperfine beats opening a way for optical read-out of the Mn nuclear spin state [Cronenberger et al, PRL2013, see Figure].

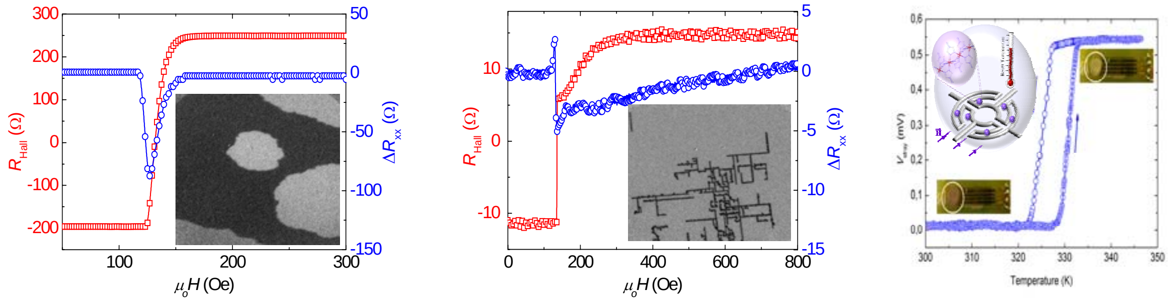


Demonstration of hyperfine beats manifested as a low-frequency modulation of the high-frequency Mn Larmor precession (zoom in the inset at large delays).

Magnetism

On spintronic aspects, we specifically study the spin dependence of electronic transport in nanostructures based on GaMnAs structures elaborated from Max Lab Sweden. During this period, we had concentrated our efforts on the possibilities offered by the Giant Planar Hall Effect as "a local magnetic probe". Based on a strong collaboration with the Néel Institute, we have developed an accurate angular magnetotransport setup to study the mechanisms of magnetization reversal governed mainly by magneto-cristalline anisotropies in these materials. This setup allows us to study the annealing effect on the magnetic anisotropy, the temperature and the angular dependence of free magnetic energy [Semicond. Sci. Technol, (2009), J. Nanosci. Nanotechnol (2012)]. We investigated structures with perpendicular magnetization in which the magnetization reversal takes place by displacement of magnetic domain walls. Combining both magneto-transport and MOKE measurements (collaboration with Institute of Nano-Science of Paris), we emphasized domain wall propagation along crystallographic axes with two distinct velocity regimes [Asiasens, invited talk 2011, KMS int. meeting, invited talk 2012]. In the case of the in-plane structures we have evidenced experimentally and approved theoretically, for the first time, the existence of sizable in-plane magnetic anisotropy at very low magnetic field. In addition, complementary SQUID measurements on these structures confirmed this very important result. Consequently, this strong collaborative work clearly demonstrated that we have achieved most of our head prospects such as the detection of the magnetization reversal through transport measurements and the manipulation of a pinning domain wall via an external magnetic field. The originality of these results gives rise to a support funding by EADS Company, 2009 - 2012. On the other hand, based on the keen interest of the understanding of the physical mechanisms, responsible to magnetic interactions at nanoscale, we have developed in March 2012 a new challenging research field dedicated to room temperature magnetic phase transition investigations in micro and nanoscale. This original implementation allows us to evidence, also for the first time, the magnetic transition of spin-crossover (SCO) nanoparticles (even from diamagnetic to paramagnetic states) by using new development of multilayers nanostructured planar Hall sensor working at room temperature [JAP 2013].

This extremely high sensitive technique is unique in the world and the very recent and first results on switchable nanoparticles have been highlighted as cover picture of high impact journal (~14: Angewandte Chemie 2013) and a related European patent will be delivered soon [EU Patent 2013]. We believe that this work will open a new area of investigations devoted to the study of both fundamental and applicative researches related to the magnetism at nanoscale and at room temperature.



Magneto-resistance anomaly Hall resistance. The ''inset'' MOKE measurements (c) First evidence of room temperature magnetic response of spincrossover nanoparticles (SCO) measured by planar Hall effect sensor. "Inset": a schematic of sensor with SCO particles. The magnetic transition is accompanied by color change: Low spin state (pink) and High high spin state (white).

Topic: *Bionanophotonics*

Participants: C. Gergely (PR1), M. Martin, T. Cloitre (MCF), E. Estephan (PhD), M. Saab (PhD), O. Benzina (PhD), S. Ramakhrishnan (PhD)

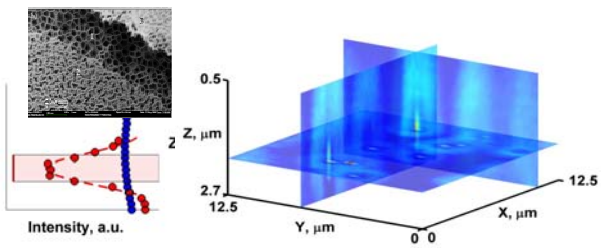
The research activities of the Bionanophotonics group are characterized by an experimental biophysical approach to study complex biological systems, typically based on monitoring interaction of light with biological material through microscopic and spectroscopic techniques. The Bionanophotonics group has got recruited Marta Martin (MCU) in September 2011, enforcing hereby the interdisciplinary activities in the team.

Our interdisciplinary laboratory comprises five techniques, namely the Optical waveguide lightmode spectroscopy, Infrared spectroscopy in attenuated total reflexion mode, Epi-fluorescence and differential interference contrast mode microscopy, Atomic Force microscopy (MFP3D-Asylum Research) combined with epi-fluorescence and phase contrast microscopy and finally a multiphotonic microscope working in two-photon excited fluorescence and second harmonic generation. The combination of advanced imaging techniques with molecular detection afforded by a novel generation of photonic biosensors is the strengths of our team addressing hereby the theme diagnosis and follow-up therapy acknowledged of high relevance by the international biomedical community. Hence our research activities can be gathered in two main axes: photonics for bioimaging and photonic biosensing. The biomedical problems we address through our collaborations with biologists and clinicians are the anti-tumor treatments and induction of neurogenesis in the treatment of peripheral sensory neuropathy. Some of our results can be summarized as following.

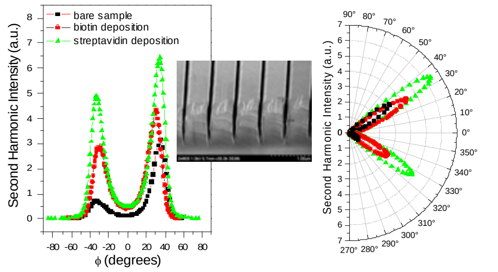
We described the differential behavior of the human epithelial of live non-malignant human mammalian epithelial cells and cancerous breast epithelial cells under curcumin treatment and we identified the microtubules as the cytoskeleton structures responding to this pharmacological product (M. Saab et al. Cell. Biochem. Biophys. 2012). We revealed the structure of dental tissues via their non-linear response in multiphoton microscopy (T. Cloitre et al. J. Biophot. 2012). Our biophysical studies on mice sensory neurons after injury revealed the mechanisms of the elongated regenerative growth mode of live cultured neurons. We demonstrated that the nanomechanical response of the cells and the sub-cellular growth cone regions correlate with the amount, organization and dynamics of the underlying cytoskeletal structure (M. Martin et al. PlosOne 2013).

We have obtained encouraging results by observing significant enhancement in the linear and/or non linear optical responses of biomolecules, when embedded in simple 1D photonic structures, compared to unstructured surfaces (PSi vertical micro-cavities and GaAs/AlGaAs structure). Amplification of linear and nonlinear optical responses in photonic crystals makes them ideal candidates for the development of miniaturized biosensors for molecular detection with extreme sensitivity (E. Estephan et al. Langmuir 2011). We successfully elaborated the adhesion peptide sequences for numerous semiconductors (GaN, InP, GaAs, ZnSe, InAs, Si, etc.) (E. Estephan et al. Biotech. Bioeng. 2012). Specific localization of peptides and reversibility of functionalization was demonstrated (E. Estephan et al. J. Phys.Chem. 2008). Importantly peptide –route functionalization was found to preserve enzyme activity while adsorption (M. Saab et al. J. Phys. Chem. 2010). Use of the peptides found for silicon for sensing and other applications was patented in EU and is now under US and Japan patenting. The specific adhesion of these peptides was successfully used for the controlled placement of biomolecules in porous silicon microcavities and enabled an enhanced optical biosensing (E. Estephan et al. Adv.Funct Mat 2011). We observed that infiltration of proteins in photonic structures acts as an internal two-photon-excited fluorescence emitter and second harmonic generator, enabling the in-depth visualization of the porous silicon microcavity by nonlinear optical microscopy (M. Martin et al. Appl.Phys.Lett. 2009).

We perform photonic studies to understand the optical behaviour of the bacteriorhodopsin (in purple membranes) that is a natural photonic crystal and a light-driven proton pump in the membrane of the Halobacterium Salinarium. Our optical waveguide lightmode spectroscopy studies provided valuable information's of the surface charges' effect on the assemblage of these membranes (M.Saab et al. Langmuir, 2009). Furthermore, non-linear optical measurements at different polarizations revealed an optical chirality of oriented purple membrane films (M. Laciprete, APL 2010). Recently we have evidenced the multipolar response and second order nonlinear optical magnetization in bacteriorhodopsin (F. Bovino et al. Opt.Exp. 2012, JOSA 2013).



Second harmonic and fluorescence enhancement in porous silicon microcavities infiltrated with the glucose oxidase enzyme



Femtomolar sensing via non-linear optics with functionalized GaAs/AlGaAs photonic crystal

All these results would have not been possible without our collaborators with whom we sign our papers: C. Larroque (CRLC Val d'Aurelle - INSERM U 896), F.J.G. Cuisinier (EA 4203, UM1), F. Scamps (Institute of Neurosciences of Montpellier, INSERM U 1051), A. M. Malvezzi (Universita di Pavia Italy), F. Bovino (Selex, Italy), C. Sibilia (Universita di Roma La Sapienza, Italy), E.Perez, G. Palestino (Universidad Autonoma San Luis Potosi, Mexico), V. Agarwal (Universidad Autonoma del Estado de Morelos, Mexico), L. Zimanyi, G. Varo (Biological Research Center, Szeged, Hungary).

The research of the Bionanophotonics group on neuropathies is inscribed in the integrated project "Aide à la personne malade ou deficient" of the LABEX NUMEV "Solutions Numériques, Matérielles et Modélisation". Also they are partners of the LABEX GANEX "Réseau national sur GaN" through their activities on nanostructured photonic biosensors. On European level they are partners of the "Photonics 4 Life" FP7 EU Network of excellence and future "Coordination support action" and two COST- EU Actions: MP0702: "Towards functional sub-wavelength photonic structures" and TD1002- AFM4NanoMed&Bio on "Applications of Atomic Force Microscopy to NanoMedecine and Life

Sciences". They are members of the Work Group 3 - Life Science and Health de Photonics 21 "European Technology Platform for photonics" and coordinators of the PHC Balaton French-Hungarian contract N° 25030RB, entitled "Structural and optical characterization of biophotonic architectures based on porous silicon and proteins".

Interdisciplinary education of the students is primordial for the Bionanophotonics group. C. Gergely and T. Cloitre are sharing the responsibility of the Medical Physics master within the ITC-Health master, created by them in 2011 and co-habilitated by Université Montpellier 1&2. This highly multidisciplinary, two years master program attracts 18-20 students yearly. The number of PhD's directed in the group at the interface of bio/physics is very high: 7 PhD students since 2008 (5 graduated already). At international scale C. Gergely has been invited to give a series of lectures for graduate students on "Introduction to Biophotonics" *at the International School on quantum electronics. Advanced Nanophotonics in Erice, Sicily, 2012*.

Topic: Theory of coupled light-matter systems

Participants : B. Guizal (PR2), M. Antezza (MCF), D. Felbacq (PR1), D. Cassagne (PR2)

Quantum metamaterials

This activity is at the crossing point of two fields of contemporary physics: the interaction of light with artificial structures, whose constitutive elements possess a quantum microstructure. These microstructures may be of two different types: artificial atoms in nanostructures (typically quantum dots in photonic crystals) or real atoms in artificial lattices (Mott crystals made of periodically arranged atoms in light fields). A strong collaboration has been started on this activity with G. Cassabois.

Plasmonics

We are studying nanostructures in which a strong coupling between plasmon and exciton can be achieved. In this regime, excitons and plasmons hybridize to form mixed quantum states: polaritons. We wish to get a precise understanding of plasmon-exciton interaction, by demonstrating the ultra-fast Rabi oscillation (10 fs) between plasmons and excitons. Besides, by optically pumping the active medium, one can enter the gain regime, and try to coherently amplify the plasmons to get the spaser phenomenon (plasmon laser). Collaboration with the experimental group of J. Bellessa at Lyon University has been settled.

Out of equilibrium quantum systems

The purpose of this activity is to study the dynamics of quantum systems in a stationary out-of-equilibrium surrounding. Our interests follow three main streams: 1) the mechanisms of quantum thermalisation, and of entanglements of elementary systems such as atoms and quantum wells, 2) the radiative heat transfer between complex objects with applications to photovoltaic cells, 3) the Casimir-Lishitz force for applications to MEMS/NEMS devices. The wealth of out-of-equilibrium systems allowed us to predict new effects of fundamental or applied interest, which are absent at thermal equilibrium.

Classical and quantum chaos

Photonic crystals have been widely studied at resonant wavelengths (i.e. of the order of the period) for the forbidden gaps, or at very large wavelengths for effective properties. We have started to study photonic crystals, in collaboration with E. Rousseau, in the case of very short wavelengths. More precisely we are studying the regime of geometrical optics for a 2D photonic crystal made of dielectric rods. The beam trajectory can be either regular or chaotic depending upon the parameters in phase space. E. Rousseau has developed an experimental setup. This opens a completely new field in photonic crystals.

Rayonnement et attractivité académiques

Invited conferences and Awards:

- Nomination à l'IUF: D. Felbacq (2009-2014), G. Cassabois (2012), M. Antezza (2013).
- Bourse d'excellence Fondation J. Schwinger: M.Antezza
- Conférences invitées : T. Guillet (7), C. Brimont (1), F. Terki (6), P. Lefebvre (8), T. Bretagnon (2), B. Gil (7), G. Cassabois (2). E. Rousseau (2), D. Scalbert (3), B. Guizal (7) D. Felbacq (36), M. Antezza (2), C. Gergely (5).

Invited researcher and recruitment:

• Chercheurs invités: M. Centini (université La Sapienza, Rome, CR1, 6 mois, sept-janvier 2010), V. Mocella (CNR-Italie, Professeur, 1 mois, avril 2011).

Organization of scientific events

• PIERS (Progress in Electromagnetic Research Symposium): Beijing (mars 2009), Marrakech (2010), Kuala Lumpur (2012), Stockholm (2013).

• META 12, Paris, "quantum PIERS 2013 Taipei.

• Workshop 2012 en l'honneur de L. Pitaevskii.

Participation à l'organisation des JMC (Montpellier, 2012) (D. Cassagne, F. Terki), et organisation de plusieurs mini-colloques (Physique et applications des semiconducteurs, P. Lefebvre ; Couplage lumière-matière, T. Guillet, Optique des Nanostructures Carbonées, G. Cassabois) ; Transfert de chaleur et forces optiques aux échelles nanométriques par E. Rousseau et M. Antezza.

Expertise and membership in councils

• Expertise: ANR, AERES, Conseil Regional d'Aquitaine, Agence Nationale de la Recherche Roumaine, NSF, conseil scientifique auprès de SAGEM-Défense.

• Coordination du Réseau ITN INDEX (novembre 2011-octobre 2015, M. Vladimirova); Organisation du congrès national de l'Union des Professeurs de physique et de Chimie (Montpellier, 2011) (F. Terki).

• Membres élus d'instance nationale: D. Felbacq (CoCNRS 2008-2012), B. Guizal (CNU, 2011-2015), G. Cassabois (CoCNRS 2012-2016), T. Bretagnon (CoCNRS 2008-2016).

Interactions avec l'environnement social, économique et culturel

- Collaboration with SAGEM-Défense.
- G. Cassabois: interview and portrait in the newspaper "Midi Libre" (edition of 04/2013).
- Organisation of "50 ans du laser à l'UM2" (2010, T. Guillet) (330 high school students, 150 students) [see podcast : http://www.univ-montp2.fr/lum2/actualites-de-l-um2/ca-s-est-passe/1693-330-lyceens-a-lum2-pour-decouvrir-les-merveilles-du-laser?server=1].
- F. Terki : Coordinator within the academic plan for formation and promoting sciences (interface high schools-university).
- Since 2008 "Days of partnership with companies" at IUT de Nîmes (headed by S. Charar).
- Two industrial contracts with EADS, which resulted in a european licence, and one maturation project at SATT (F. Terki et S. Charar).
- The recent research of the Bionanophotonics group on nerve-regeneration is inscribed in the integrated project « Aide à la personne malade ou déficiente » of the LABEX NUMEV "Solutions Numériques, Matérielles et Modélisation". Also they are partners of the LABEX GANEX "Réseau national sur GaN" through their activities on nanostructured photonic biosensors. On European level they are partners of the "Photonics 4 Life" FP7 EU Network of excellence and future "Coordination support action" and two COST- EU Actions: MP0702: "Towards functional sub-wavelength photonic structures" and TD1002- AFM4NanoMed&Bio on "Applications of Atomic Force Microscopy to NanoMedecine and Life Sciences".

Implication de l'équipe dans la formation par la recherche

The members of PEPS team are strongly involved in the management and development of physics teaching in University Montpellier 2. They have initiated three of the five pathways of the Physics Master. They are also strongly involved in the definitions of the programs of Licences and Masters. Specifically:

G. Cassabois: in charge of the new pathway Nanophysics of the Master Physics and Engineering

B. Guizal : Head of the courses of the Physics Licence

T. Bretagnon : Head of the Department Physics teaching, responsible of the specialty Physics Engineering, of the pathway Phymatech of the Physics Master, and of the Cursus Master Engineering specialty Physics

D. Cassagne : responsible of the pathway « Physique Informatique du Master de Physique », in charge of TICE (Technologies de l'information et de la communication pour l'enseignement) near the President of University

T. Guillet : responsible of the pathways of Fondamental Physics

F. Terki : responsible L2 Physics

C. Gergely : responsible of the specialty « Physique Biomédical de la mention STIC Santé (Phymed) »

S. Charar : Head of IUT de Nîmes.

- Participation of members of the team to the executive board of the Labex GaNeX; organisation of the Summer school on the physics and applications of nitrides (http://www.ganex.fr/summer-school-2013/), 23-28 june 2013 (G. Cassabois).
- involvement in the international relationships: exchange and mobility program EURASMUS MUNDUS et CREPUC (F. Terki).

Section des unités de recherche

Présentation synthétique de l'entité

Unité de recherche

Vague E : campagne d'évaluation 2013-2014

Team "Physics of Exciton, Photon and Spin"

Intitulé de l'unité : Laboratoire Charles Coulomb, L2C, UMR 5221

Nom du directeur de l'unité : Jean-Louis SAUVAJOL

Nom du responsable de l'équipe (le cas échéant) : Denis SCALBERT

Effectifs de l'entité (au début du contrat en cours ; préciser si l'entité a été créée au cours de la période d'évaluation).

15 researchers (11 university staff, 4 CNRS); 2 engineers; 7 non-permanent positions (post-doc and PhD students).

Personnels ayant quitté l'entité pendant le contrat en cours (et nombre de mois cumulés passés dans l'entité au cours de cette période).

3 PhD students (36 months) ; 3 post-doc (39 months).

Nombre de recrutements réalisés au cours de la période considérée et origine des personnels

1 come back from secondment (P. Lefebvre), 1 hiring of researcher (M. Martin), 2 attachments to PEPS (biophotonics, T. Cloitre, C. Gergely), 5 post-docs, 7 PhD students.

Production scientifique au cours de la période écoulée (1er janvier 2008 – 30 juin 2013)

1) Quantum dynamics of out of equilibrium atomic populations [EPL100, 2012].
2) Influence of coulomb correlations on the optical response of carbon nanotubes, studied by nonlinear pump-probe optical spectroscopy [PRL107,2011]; evidence of biexciton [PRL109,2012].
3) Condensation of polaritons at 300K in ZnO microcavities [PRL110,2013].
4) Detection of a magnetic phase transition at 300K in spin transition molecules by MEMS magnetometry [Angew. Chime. Int. Ed. 52, 2013].
5) Biophysical studies on mice sensory neurons after injury revealed the mechanisms of the elongated regenerative growth mode of live cultured neurons. Demonstration of the correlation between nanomechanical response of cells and the organization and dynamics of the underlying cytoskeletal structure [PlosOne 8, 2013].

Bilan quantitatif des publications de l'entité

Articles with peer review: 107 ; Invited Conf.: 99 ; Conf. with acts: 24 – without : 92 – HDR : 1 ; PhD : 4

Indiquer **5 publications majeures**

1) Detection of a biexciton in semiconducting carbon nanotubes using nonlinear optical spectroscopy, **Colombier, Selles, Rousseau**, Lauret, Vialla, Voisin, and **Cassabois**, PRL 109, 197402 (2012).
2) **Cronenberger, Vladimirova, Andreev,** Lifshits, and **Scalbert,** Optical Pump-Probe Detection of Manganese Hyperfine Beats in (Cd,Mn)Te Crystals, PRL 110, 077403 (2013).
3) *From Excitonic to Photonic Polariton Condensate in a ZnO-Based Microcavity*, Li, Orosz, **Kamoun**, Bouchoule, **Brimont,** Disseix, **Guillet**, Lafosse, Leroux, Leymarie, **Mexis**, Mihailovic, Patriarche, Réveret, Solnyshkov, Zuniga-Perez, Malpuech, arXiv:1207.7172 accepted in PRL
4) Messina, **Antezza**, and Ben-Abdallah, Three-Body Amplification of Photon Heat Tunneling, PRL 109 (2012).
5) **M. Martin, O.Benzina**, V. Szabó, A. G. Végh, O. Lucas, **T. Cloitre,** F. Scamps and **C. Gergely**. Morphology and Nanomechanics of Sensory Neurons Growth Cones following Peripheral Nerve Injury. *Plos One , (2013) 8 (2), 1. Doi:10.1371/journal.pone.0056286*

Indiquer **au maximum 5 documents majeurs** (autres que publications) produits par l'entité (par exemple : rapport d'expertise, logiciel, corpus, protocole, brevet en licence d'exploitation…).

1) *Micromagnetometry detection system and method for detecting magnetic signatures of magnetic materials*, **F. Terki, T.Q. Hung, S. Charar,** Ph. Gandit, C.G. Kim, A. Bousseksou, EU patent pending, reg. EP12305852.1. (2012) Brevet TRIPARTITE : L2C-UM2-CNRS (Montpellier), LCC-CNRS (Toulouse) et NBest (Daejeon Corée du Sud)
2) C. Gergely, E. Estephan, C. Larroque, M.-B. Saab, F. Cuisinier. European Patent DI 03435-01 n° 10290242.6. (05/05/2010); PCT extension (05/05/2011) n° IB 2011051999 Peptide derivatives for biofunctionalisation of silicon for sensing and other applications. The patent is now extended to USA and Japan.

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5 faits illustrant le rayonnement ou l'attractivité académiques de l'entité (invitations à donner des conférences, organisation de colloques nationaux ou internationaux, réseaux collaboratifs, cofinancements, prix et distinctions…).

1) Nominations at IUF: Felbacq (2009), Cassabois (2012); Antezza (2013) ; grant « Julian Schwinger » : Antezza (2011-2014).
2) Docteur honoris causa of St-Petersburg University (Gil).
3) Elected members CoCNRS: Felbacq (2008-2012), Cassabois (2012-2016), Bretagnon (2008-2016); CNU : Guizal (2011-2015), Terki (2008-2012).
4) Coordination of european network ITN INDEX (2011-2015, Vladimirova); Organisation of « congrès national de l'Union des Professeurs de physique-chimie » (Montpellier, 2011) (Cassagne, Terki); Participation to organisation of JMC 2012 (Cassagne, Terki), organisation of 4 « mini-colloques » (Lefebvre, Guillet, Cassabois, Antezza, Rousseau).
5) Invited conferences : Guillet (7), Brimont (1), Terki (6), Lefebvre (8), Bretagnon (2), Gil (16), Cassabois (2), Rousseau (4), Scalbert (3), Guizal (7), Felbacq (36), Antezza (2), Gergely (5).

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5 faits illustrant les interactions de l'entité avec son environnement socio-économique ou culturel (contrat industriel, collaboration à une exposition, émission audiovisuelle, partenariats avec des institutions culturelles…)

1) G. Cassabois, T. Bretagnon, F. Terki: interviews and portraits in daily Midi Libre.
2) Organisation of "50 ans du laser à l'UM2" (2010, T. Guillet) (330 high school students, 150 students).
3) F. Terki : coordinator academic plan for promoting science (High school-University).
4) Since 2008 Days of partnership with companies at IUT de Nîmes (Head S. Charar)
5) Two contracts with EADS (with european licence).

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principales contributions de l'entité à des actions de formation

1) **Charar**: Dir. IUT de Nîmes ; **Bretagnon**: Dir. du Département d'Enseignement de Physique; **Guizal**: Directeur des études Licence de Physique; **Gergely**: Resp. de la spécialité Physique Biomédical de la mention STIC Santé (Phymed); **Cassabois**: Resp. du nouveau parcours Nanophysique du Master Physique et Ingénierie de Montpellier; **Cassagne**: Resp. parcours Physique Informatique du Master de Physique, project manager TICE; **Guillet**: Resp. parcours Physique Fondamentale**; Terki**: Resp. L2 des parcours : Physique Fondamentale et Physique et Applications.
2) **Cassabois**: organisation of summer school on physics and applications of nitrides (23-28 juin 2013).
3) **Terki**: Responsible EURASMUS MUNDUS et CREPUC.

Team : “BioNanoNMRI”

Team : "BioNanoNMRI"

The BioNanoNMRI research group develops the instrumentation, the methodology and conducts experiments in Nuclear Magnetic Resonance with the goal to improve the sensitivity of the technique for a better understanding of the physical, chemical and biological mechanisms in materials and living systems. Historically, we are interested in NMR spectroscopy and relaxometry to study the electronic, magnetic, mechanical and structural properties of novel nanostructured materials. Since 2010, the strategy we implement is multidisciplinary and creates a synergy between well established groups of physicists, electronicians, biologists, agronomists and medical physicians to explore new topics in living sciences. Hence, great efforts have been made to develop NMR imaging on the campus of Montpellier and some innovative applications have been already demonstrated both in agronomy and in biology and health.

Topic: *Micro and Nano Systems, and NMR instrumentation*

Participants: Goze-Bac C. (DR2), Rachdi F. (DR2), Zanca M.(PU-PH), Permanent Staff: Alibert E. (Tech); Invited Professor above one month: Stein P. (2008-2009) and Wagberg T. (2009); PostDoc: Abou-Hamad E. (2009), Berouthy J. (2009) and Mahieu-Williame L. (2009-2010); PhD students: Akel M. (2012-2014), Abou-Hamad E. (2008) and Halidi E. (2010-2013); Master students: Akel M. (2010), Bahjankanj B. (2009), Kourhy-Hanna S. (2008), Halidi E. (2009)

Collaborators: Abou-Hamad E. (IR Kaust Saudi Arabia), Luzzi D. (PR Philadelphia), Mehring M. (PR Stuttgart), Nativel E. (MCU IES), Rubio A. (PR San Sebastian), Wagberg T. (PR Umea) and Zettl A. (PR Berkeley)

Companies: RS2D (Strasbourg 2008-)

In the recent past, we have explored low-dimensional properties of carbon based nanostructured systems and their derivatives. Most of the materials we investigated were produced, purified, modified and characterized in-house or through long standing collaborations with the Department of Physics from the Universities of Berkeley, Philadelphia, Umea and Stuttgart. We used NMR spectrosopy and relaxometry at low temperature and high resolution in the solid state to study a variety of modifications of carbon nano- structures like one dimensional confinement of molecules at the nanoscale, the intercalation and electronic charge transfer, the chemical functionalization and isotope effects... This work has been highlighted several times in nanotechweb.org [in Nano 2009], in ACS Nano, in the Journal de Société Française de Physique [SFP 2009] and the Journal du CNRS [2010].

To go further in the study of such nano- systems, we now explore their potential applications as radio frequency probes. This work is in collaboration with the Institut d'Electronique, Montpellier, and the Departement of Physics, Berkeley. It concerns a new strategy to detect nuclear spins signals with the help of micro- and nano-sensors. Our aim is to apply the near-field detection methods to the NMR phenomenon [selected talk : ENC NMR Florida 2011, invited conference FICIMT Tunisia 2012], first by taking the advantages of micro- sized electric field probes and second with the use of Nano Electro Mechanical Systems to detect, with a higher sensitivity, electromagnetic fields in the close vicinity of the objects. In the light of these potential developments, one expects unprecedented spatial, temporal and spectral resolutions which are essential for the study of biological systems.

Topic: *NMRI investigations in living systems*

Participants: Goze-Bac C. (DR), Kouyoumdjian P. (PUPH), Morrot G. (CR) and Zanca M.(PU-PH); Permanent Staff: Alibert E. (Tech) and Coillot C. (IR); Invited Professor three months: Perrin F. (2011); PhD students: Ayadi A. (2015), Kenouche S. (2014) and Massoud C. (2010), ; Master students: Carderas de Kerlau E. (2009), Ferrer C. (2013) and Saint-Martin G. (2013)

Collaborators: Bertin N. (DR INRA Avignon), Bonny JM. (DR INRA Theix), Godin C. (DR INRIA), Guarri Y. (DR ICG), Larionova J. (PU ICG), Lautier C. (MCU MMDN), Nativel E. (MCU IES), Perrin F. (PU INM), Privat A. (PU INM), Puel JL. (PU IMN), Verdier J.-M. (PU MMDN).

Association Verticale supporting research on spinal cord injury: Philibert R. Companies: Intrasense (Montpellier 2013-) and Neureva (Montpellier 2008-2010)

Over the last three years, five new permanents and four PhD students have joined our BioNanoNMRI group to develop NMR imaging in living systems. This technique offers non-invasive and functional capabilities and is a prerequisite for the development of research strategies and developments consistent, both in terms of technology and experimentation on in vitro, ex vivo and in vivo models. MRI particularly, widely used in hospital, supplies, by the richness and diversity of its contrasts, almost unlimited opportunities in mini- and micro- or nano- imaging, leading in vivo at the cellular and molecular scales.

Our efforts have turn these techniques available on the campus of Montpellier; they now constitute a major asset in the management challenges of the 21st century regarding public health, both in terms of disease progression in the population (mainly general aging of it) than in the field of nutrition. The strategy that our group implements is multidisciplinary in that respect, innovative applications are thus expected, both in agronomy and biology and health, even if predictable especially in neuroscience. The techniques we are developing will allow to establish a solid foundation for modern molecular cell biology, where the academic tradition in Montpellier has a privileged place in an international context where competition is becoming tougher and means implemented sometimes colossal.

Hence, our team, together with our close collaborators, contributes significantly and continuously to the implementation and improvement of an experimental MRI user facility which has been given the same name as our group: "plateforme BioNanoNMRI" (http://bionanonmri.univ-montp2.fr). We are now leading the development of sophisticated NMR imaging tools on the Montpellier site.

The platform is supported by the LabEx NUMEV and is open to different poles of local research, particularly Agronomy, Biology and Health, to companies (Neureva, Intrasense, RS2D, Sanofi...) and to the Association Verticale which supports the research on spinal cord injury. In that context, we are actively participating to the training of researchers, students (Canceropôle Grand Sud-Ouest Imaging School, PhyMed and BioSTIC Masters...) and to the dissemination of science at high school and college.

Our group is active in a wide range of topics, in biology and medicine [Cortex 2009, JRAD 2011], we are working on spinal cord pathologies in mouse and rat models with INM INSERM 1051 and in humans with the CHU Nîmes, on applications in brain aging in microcebus models with MMDN INSERM U710, in human olfaction at individual level by Functional-MRI with the CHU Montpellier and INRA Theix [JMR 2013], and in agronomy on functioning and quality of fruits with PSH INRA Avignon [POWDER 2012]. In the mean time, we are investigating MRI contrast agents with CMOS group at ICG UMR5253 in order to reveal, through NMR relaxometry, the biodistribution and the different properties of biological tissues.

State of art MRI Equipement, a New Building and CNRS working force

In september 2012, the BioNanoNMRI user facility has been inaugurated with a state of art 9.4T 400MHz MRI Agilent scanner (800 k€ from Association Verticale), a 4.7T 200MHz Tecmag Imaging console (200 k€) and a RS2D SpinIt Solid State NMR Console (50 k€), in a new building N°50 (280m2) financially supported (600 k€) by the University Montpellier 2 and CNRS working force: one engineer (Cristal du CNRS en 2011) and one technician.

Fundings and Grants

Molecular Foundry User Facility at Berkeley, USA (2005-2010); CIFRE Siemens CHU Lapeyronie (2007-2010); Mi-lourds CNRS / BQR UM2 (2008: 110 k€); CNRS PIR Physics Chemistry and Biology (2008: 40 k€); Region Languedoc-Roussillon ARPE (2008: 30 k€); Agropolis 3D Virtual Fruit RTRA (2008: 45 k€ + 3 years for a shared postdoc); CPER Department of Physics (2007-2013 50k€); Association Verticale (2010: 650 k€); DPI University Montpellier 2, construction of the building n°50 (2010: 600 k€); Scientific Committee UM2 (2011: 30k€); LabEx NUMEV (2012: 36 k€); Association Verticale (2011: 150 k€); Scientific Committee UM2 (2013: 15k€); Association Verticale (2013: 30 k€)

agence d'évaluation de la recherche et de l'enseignement supérieur

Présentation synthétique de l'entité
Unité de recherche
Vague E : campagne d'évaluation 2013-2014

Team "BioNanoNMRI group : NMR spectroscopy an imaging"

Intitulé de l'unité : Laboratoire Charles Coulomb UMR5221 UM2/CNRS

Nom du directeur de l'unité : Jean-Louis SAUVAJOL

Nom du responsable de l'équipe (le cas échéant) : Christophe GOZE-BAC

Effectifs de l'entité (au début du contrat en cours ; préciser si l'entité a été créée au cours de la période d'évaluation).
2 Tenured Researchers: Goze-Bac C. (DR), Zanca M. (PU-PH) **1 Invited Professor for one year :** Stein P. **2 PhD students:** Abou-Hamad E. and Massoud C. **1 Master student :** Kourhy-Hanna S.

Personnels ayant quitté l'entité pendant le contrat en cours (et nombre de mois cumulés passés dans l'entité au cours de cette période).
3 Invited Professors above one month : Perrin F. (3), Stein P. (12 + 1) and Wagberg T. (1) **3 PostDocs:** Abou-Hamad E. (12), Berouthy J. (12) and Mahieu-Williame L. (24) **2 PhD students:** Abou-Hamad E. (6) and Massoud C. (24) **5 Master students:** Akel M. (4), Bahjankanj B. (3) Carderas de Kerlau E. (6) Ferrer C. (2) Kourhy-Hanna S. (4) Saint-Martin G. (2)

Nombre de recrutements réalisés au cours de la période considérée et origine des personnels
3 Tenured Researchers: Kouyoumdjian P. (PUPH CHU Nîmes), Morrot G. (CR CNRS) and F. Rachdi (DR CNRS) **1 Research Engineer :** Coillot C. (CNRS) **1 Technician :** Alibert E. (20% CNRS) and **3 Invited Professors :** Perrin F. (2011 Uni Bilbao), Stein P. (2010 Uni Odense) and Wagberg T. (2009 Uni Umea) **3 PostDocs:** Abou-Hamad E., Berouthy J. and Mahieu-Williame L. **4 PhD students:** Akel M. (2014), Ayadi A. (2015), and Halidi E. (2013), Kenouche S. (2014) **5 Master students:** Akel M. (4), Bahjankanj B. (3) Carderas de Kerlau E. (6) Ferrer C. (2) Halidi E. (4) Kourhy-Hanna S. (4) Saint-Martin G. (2)

Production scientifique au cours de la période écoulée (1er janvier 2008 – 30 juin 2013) :
HL=highlight, JTV=journal and TV broadcast, RA=research article, INV=invited conference, BO=book, CO =conference, SD=scientific dissemination
1-Innovative nanostructured materials (HL:4, RA:19, INV:5, BO:1, CO:2, SD:1): Better understanding 1D nanosystems with the use of NMR spectroscopy and relaxometry. Studies of molecular dynamics and electromagnetic properties in carbon nanostrucures**. 2-Instrumentation and development of NMR spectroscopy and imaging** (HL:1, JTV:6, INV:3, CO:11, SD:2) Installation of a 9.4T MRI scanner and creation of the BioNanoNMRI user facility in 2012. Development of near field NMR sensors at micro- and nano- scale. **3-NMR and MRI applications in biology :** (RA:4, CO:9, SD:1) **in small animals :** Alzeihmer disease, spinal cord injury… **in plants :** water distribution and transport, bio contrast agents…**4-Human Health : brain activation, olfaction, orthopaedic trauma** (RA:9, INV:6, BO:1, CO:20, SD:10) with Nîmes and Montpellier CHU

Bilan quantitatif des publications de l'entité. 32 Research Articles, **14** Invited Conferences, **2** Chapters in Books, **42** Conferences, **11** events about Scientifc Dissemination, **6** journal and TV broadcasts

Indiquer les **5 publications majeures** de l'entité (underline names are from the lab)
1-Abou-Hamad E., Kim Y., Wagberg T., Boesch D., Aloni S.,Zettl A., Rubio A., Luzzi D.E.and Goze-Bac C., **Molecular dynamics and phase transition in one dimensional crystal of C60 encapsulated inside single wall carbon nanotubes**, ACS Nano 3 12 3878 (2009). **2**-Kim Y., Abou-Hamad E., Rubio A., Wagberg T., Talyzin A.V., Boesch D.,

Aloni S., Zettl A., Luzzi D.E. and Goze-Bac C., **Nanomagnetic shielding : High-Resolution NMR in carbon allotropes**, J. Chem. Phys. 132 2 (2010). **3**-Massoud C., Goze-Bac C., Taourel P. and Zanca M. **Evaluation of glomerular filtration rate with magnetic resonance imaging** Journal de Radiologie 92 5 369 (2011). **4**-Abou-Hamad E., Babaa M.R., Bouhrara M., Kim Y., Saih Y., Dennler S., Mauri F., Basset J.M., Goze-Bac C. and Wagberg, T. **Structural properties of carbon nanotubes derived from C-13 NMR**, Physical Review B 84 165417 (2011). **5**-Morrot G., Bonny J.M., Zanca M. **fMRI of human olfaction at the individual level: Interindividual variability**, J Magn Reson Imaging 37(1) 92 (2013)

Indiquer **3 autres documents majeurs**

1-Scientific Highlight coverages : IOP, CNRS, SFP… (4 reports in 2009 and 2010) : Better understanding 1D nanosystems by using NMR spectroscopy and relaxometry

2-BioNanoNMRI user facility : legal status, building drawings (300m^2) and technical parts at the university Montpellier (650k€) Association Verticale (800k€) and CNRS working force.

3-Expertise Consultancy for ANSM, AFSSAPS, EMEA, ANR (12 reports) : Zanca M. Autorisation de Mise sur le Marché de NL27312 laboratoires IBA-CIS BIO ; ERATRANIRMA : équipe Emergence, Haute Autorité de Santé du bon usage des examens d'imagerie médicale…

Indiquer **au maximum 5 faits illustrant le rayonnement ou l'attractivité académiques**

1-Increasing the working forces : 2 researchers, 1 PUPH, 3 Invited PU, 1 IR, 1 Tech

2-Strong collaborations with well established laboratories from CNRS INSERM EPHE UM1 UM2 CHU : Institut Electronique IES (E. Nativel) Institut Neurosciences of Montpellier (F. Perrin), INRA Avignon (N. Bertin), MMDN (C. Lautier), Institut Charles Gerhart (Y. Guari and J. Larionova)

3-Creation of a **MRI high field user facility** for small animals and plants : BioNanoNMRI platform

4-Certification and financial support from **LabEx NUMEV :** Aide à la personne malade ou déficiente

5-C. Goze-Bac : **elected member of the Board of Directors** University Montpellier 2 (2008-2012)

Indiquer **au maximum 5 faits illustrant les interactions de l'entité avec son environnement socio-économique ou culturel**

1-Numerous joined actions with **Association Verticale**, Grigny (association of diseable people). Financial support 800k€ since 2010

2-Journal, TV and radio broadcasts (9 events since 2012) : on the new experimental NMR/MRI scanners with high magnetic field (9.4T and 4.7T) in the Languedoc-Roussillon

3-Industrial contracts with Siemens, RS2D (Strasbourg), NEUREVA and INTRASENSE (Montpellier)

4-Contracts with Institution : RTRA Agropolis, ARPE Languedoc-Roussillon, PIR CNRS Biology/Physics, CPER Languedoc-Roussillon, University Odense DK, Molecular Foundry Berkeley CA USA

Indiquer **les principales contributions de l'entité à des actions de formation**

1-NMR & MRI expertises : 6 PhD, 3 postdocs, 6 Master students joined the group

2-M. Zanca is co-responsible for the **PhyMed Master** 1&2, FDS Montpellier

3-C. Goze-Bac et M. Zanca are teaching **MRI at the « Ecole d'Imagerie : GSO Cancéropôle »**

4-G. Morrot involved in SupAgro OIV **National Oenology** Montpellier : neurophysiology & olfaction

5-Local organization of **International Conferences** : NT'08, GDRE'09 NT & Graphene, JMC13 SFP

Indiquer **3 points précis** sur lesquels il souhaite obtenir l'expertise du comité.

1-Investigations of nanomaterials using NMR spectroscopy and relaxometry

2-Founded in 2012, the BioNanoNMRI user facility, future collaborations and research perspectives

3-NMR and MRI instrumentation : design of innovative sensors, multimodal methodologies and biological applications

Projects for the next contract

4. Stratégie et perspectives scientifiques pour le futur contrat

4.1. Evaluation of the current situation of the laboratory

Regarding the recommendations of the previous visiting committee, we can emphasize the following points:

Strong points:

- The creation of L2C in 2011 has contributed to improving the *scientific visibility* of Physics in Montpellier.

- The net result in terms of human potential for research has increased along the past two years, testifying to the scientific attractivity of L2C.

- With regards to its large field of activities, L2C has developed *studies at the interfaces* with the other disciplines in the form of research efforts towards Chemistry, Biology and Life Sciences.

- The implication of our members in programs encouraging such interdisciplinary research (Labex Numev, CheMISyst, OCEVU) have increased the number of PhD theses co-funded through the “co-tutelle” mechanism.

- Most of the scientific objectives given by the teams in the preceding project have been achieved.

- The scientific production is of high level, both in quantity and quality.

- Three transverse projects have been developed between teams from different departments.

- L2C has developed several experimental platforms and instruments with state-of-the-art and sometimes unique performances such as especially a large set of optical spectroscopy facilities and the “BionanoNMRI” platform.

Weak points:

-In spite of significant progress in this domain, the degrees of advancement of the different transverse projects are quite inhomogeneous and the synergy between different teams working on similar topics can be further improved. This impacts *the visibility* of those actions that we are generally recommended to promote.

- So far, the project of a new building for physics is yet to be launched.

- Finally, the main weakness of the lab concerns administrative and organisational aspects. Indeed, in a first stage, each of the three parent physics units was transformed into a “Department” of the L2C, each Department being independent as far as finance, organization and decision-making was concerned. Consequently the scientific policy and priorities were often filtered at the level of each Department.

Opportunities:

The new structure (described below) gives us the opportunity to move on towards a real scientific policy for the L2C, since references to the parent groups will be suppressed. In particular we firmly believe that, with the new Board (Conseil de Direction), we will improve the representativeness of the different research areas covered by L2C. We are confident that the conditions will be, in the next five years, favorable to decisions and mediations that will no longer be “screened” by the Heads of Departments. In the new organization, the Representative of each Department will no longer have the prerogatives of a Deputy Director and his/her impact on the choice of the Department’s priorities will be less decisive. Indeed, the Representatives –as the name indicates- will represent and defend the scientific interests of the new Departments and insure the proper circulation of information from and to the Board.

Moreover, the creation of Topical Departments will give us the opportunity to move on towards a structuration of the laboratory which fits better to the scientific activities of our researchers.

In the following, the new organization of the lab and the projects of each team are described in detail.

4.2. Strategy and director’s message for the next period

The Laboratoire Charles Coulomb does obtain and publish scientific results at the highest level. The main reason why we are now modifying our internal organization is our wish to further improve our ability to define and promote ambitious research priorities, to maintain reasonable task force on already recognized activities and to improve our visibility.

The Laboratoire Charles Coulomb indeed presents an extreme diversity of research topics, covering a wide variety of fields in Physics. This is one of the strengths of the lab. However, with regards to this large variety of topics, we have to be attentive to avoid increasing the partitioning between the different sub-groups, sub-topics…, which might, in the process, reach a sub-critical size. In particular, increasing the visibility of L2C will benefit from (1) the synergy that we will promote by encouraging cooperative research involving different teams and (2) the recognition of the useful role of Physics at the local level that we will enhance by a better communication on our interdisciplinary efforts.

For example, despite the strong voluntarism that we have been displaying in the past years for research at the interface between Physics and Life Sciences, we still have progress to make in the coherence and visibility of our activities in this field. This effort we want to make is all the more justified that we can proudly present excellent results. The relative lack of visibility makes it difficult to draw attention and support and can lead to the scenario where the most salient of our researchers end up “crossing the interface” towards Laboratories of other disciplines where they are promised a better support. The goal of the next five years is to organize a more collective approach of our communication on those activities and, *in fine*, of those activities themselves.

Quite generally, special effort will be made for a better communication on our activities, in particular towards the students (better attractivity) and towards the regional decision makers with whom we absolutely need to find a mutual understanding, at least comparable with those currently reached by our colleagues in Life Sciences, Electronics or Chemistry.

Both synergy and visibility for L2C and for Physics in general in Montpellier will most certainly benefit from the renovation of two buildings eventually devoted to hosting all the Physicists of the “Triolet” campus. Works are currently planned to begin during year 2016. We insist on the importance of this operation, also because the full achievement of our administrative organization (in particular of the support services) cannot be reached as long as our members are spread over four different buildings.

As far as those technical and administrative issues are concerned, we can already define two priorities that we wish the CNRS and the University to consider.

The first one is the necessity of an Administrator in charge of coordinating all administrative aspects, justified by the size of the Laboratory and by the current diversity of practices in the different Departments.

The second one is the necessity of an engineer in charge of implementing the techniques specific to research performed at L2C, in the local clean room. Generally, the know-hows available in this clean room are rather compatible with research in microelectronics by our colleagues of the Institut d’Electronique du Sud and the contribution of our researchers (including at the political level, through the coordination in Nanosciences) has been decisive for the availability of some nanotechnology. The clean room is about to be moved by our colleagues to a remote area, a few kilometres away from the main campus. Therefore it is crucial that we maintain a close contact with the techniques that we co-developed, through devoted personnel.

4.3. The new organization of the laboratory

The structure of the L2C (see the sketch below) is now built upon 5 Topical Departments. Administrative and technical support Services are now essentially transverse to the entire laboratory, with some important nuances, detailed below. The BioNanoNMRI Team is intrinsically multidisciplinary, and develops successful activities with researchers from local Institutes and Hospital. This group has launched and is leading the new MRI User Facility of the University of Montpellier.

The names of the Departments and Teams that will constitute them might be subject to slight alterations in the next few months, but the scientific message is clear: most theoreticians are now grouped in a single Department (I), whereas the other –mainly experimental- research activities are now grouped according to their specific scientific preoccupations: (II) “Soft Matter and Glasses” for ill-organized condensed matter, (III) “Physics of Exciton, Photon and Spin” for the study and manipulation of elementary excitations at the quantum-mechanical level, (IV) “Applied Physics” for the physics of materials and devices for applications and (V) “Nanomaterials and Spectroscopies” for specific properties of (mainly carbon-based) nanomaterials and individual nano-objects.

The Teams are now the elementary cells that will be evaluated and funded, as such. By gathering in a Department, they may choose to share any percentage of their resources, from zero to 100%, in order to organize their own internal policies.

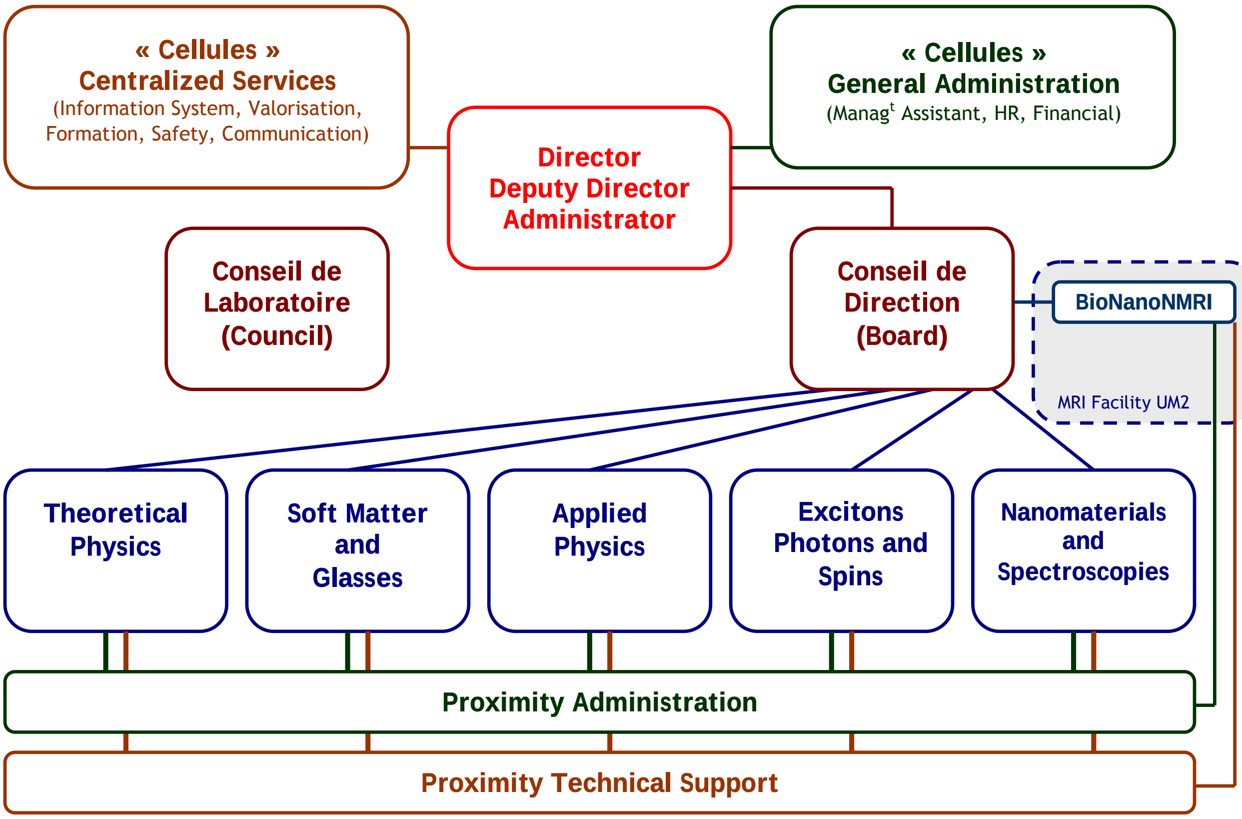
The decisional structure is twofold:

(A) *The Board* (Conseil de Direction) will include, along with the Director and Deputy, the Representatives of each Thematic Department and of the Services. In addition, we wish to *strongly emphasize the necessity of <u>a personnel specifically devoted to administrative management</u> (Administrateur/trice)*, justified by the present size of the lab. The Board will handle the day-to-day management of the lab and will define the priorities by selecting amongst the proposals arising from the Team leaders.

Indeed, the projects (grants, specific funding…) will be defended at devoted meetings in front of the peers and the members of the Board, at significant variance from the previous system where the projects were pre-selected by the "old" Departments. Importantly, the role of the Representatives will be to ensure the proper circulation of information between the Departments and the Board. The Board is to be seen as an executive structure, with meeting frequency of two weeks, typically (or more if need be), that helps the Director make decisions.

(B) *The "Conseil de Laboratoire"* (Council) is consulted in order to establish the general rules to be applied for decision-making, distribution of funds, human resource policy… The Board or sub-structures created *ad hoc* will prepare the cases and present them before the Council.

The Services will be of three types: (1) General Services, attached to the Director, such as management assistance, general accounting, human resources,… (2) Technical platforms, located and attached to specific Departments and (3) Transversal services for administrative and technical support. Given the multiple sites of the L2C (over 4 different buildings), the latter services, although tansversal, will be constituted by small entities detached to each specific site, with regards to a balanced load of work between the different agents and, above all, with regards to the proximity between researchers and technicians, which we believe warrants the quality of the relationship and therefore of the service.



4.4. The scientific project

At the level of the entire L2C, a general scientific policy can only be understood in terms of favoring the emergence of ambitious activities, favoring the constitution/maintenance of critical masses on topics that are currently strong in the lab, favoring transversal and interdisciplinary activities. In other words, the Board will promote novelty, quality and synergy on the basis of proposals arising from the teams themselves.

To that end, the levers for the Directors and the Board will be *a priori* of financial nature. In particular, the great novelty in the reorganization of the L2C, resulting from the disappearance of the old Departments, is the complete redesign of the internal fiscal system. For example, financial resources stemming from levies on institutional or industrial contracts will be centralized from year 2015 on at the level of the whole L2C.

Details of the redistribution policy will be defined in the coming months, since we will achieve this reform by the end of 2014. But it is already clear that a significant part of the resources will be used to encourage and favor the above mentioned types of research activities (novelty, quality and synergy). Nonetheless, solidarity between the different teams will be maintained and even improved from the present situation, in which 70 percent of the levies on contracts would remain in the (old) Department of origin. From year 2015 on, a significant part (to be defined) of those resources will be shared over the whole L2C for common purpose.

The scientific projects of each Team or Topic of the new Departments are detailed below:

Department “Theoretical Physics”

The merging in 2013 of three « historical » groups of the Theoretical Physics Team with the Statistical Physics group has reinforced this Team, opened new possibilities and brought new competences and expertise. A joint methodological seminar « Theoretical Physics » forms since January 2013 a common scientific platform. The critical size and the identity of this Team allow us, today, to turn it into a new Department. By combining research forces of different groups during the next contract period, this Department plans to contribute to emerging fields of Physics at the interfaces between the groups' core activities (e.g. field theory and particle physics; statistical physics and mathematical physics; statistical physics and physics of complex systems; mathematical physics and physics of complex systems) and to address qualitatively new questions. This will require closer cooperation of the groups, partial pooling of resources and, especially, joint applications to national and international calls and tenders.

Topic 1: *Mathematical Physics / Field Theory*

The Mathematical Physics/Quantum Field Theory group is a well-known international group in Quantum Integrable Field theory and Conformal Field theory with the presence of V. Fateev, A. Neveu and the late A. Zamolodchikov, who were leading international experts in this field. The CNRS has supported this team by hiring young people in the past 10 years: V. Terras, S. Alexandrov, S. Ribault, N. Crampé.

Because CNRS people are mobile, only two of them are still in Montpellier, today. One of the problems faced by the group is to stabilize these young people. Another problem is the access to students in theoretical physics. There is no local master in this domain and it is therefore much more difficult for this team to hire local students. Each of the few students working with us, so far, came from abroad.

Nevertheless people in the team are doing their best to develop new directions of research. For example Ph. Roche is involved in developing collaborations with the math department on Langlands program, N. Crampé is developing research on integrable systems on star graphs whereas S. Alexandrov is highly involved in developing the twistor approach to heterotic string theory and is looking for enhancing it to $N=1$. The team has chosen to reinforce the field of research led by S. Alexandrov and will make efforts to obtain recruitment in this direction.

Topic 2: *Statistical Physics*

The Statistical Physics group has different directions of research and is involved in different projects for the future. D. Coslovich is in the perspective of studying numerically more realistic glasses, after the works done on simplified model glasses. After having investigated dynamical heterogeneities, the problem of the glass transition at equilibrium is a major interest of W. Kob. In this perspective an ANR project has been submitted on the better identification of the Kauzmann temperature. Another ANR project has been submitted by L. Berthier on active particles, a topic that is already supported by an ERC grant obtained last year. M. Clusel aims at developing new techniques applied to the stochastic thermodynamics of open quantum systems, an ANR (Jeunes Chercheurs) project has been submitted. E. Pitard is part of an ANR submitted on large deviations techniques for out-of-equilibrium systems, and is also working in the direction of applying stochastic and statistical physics tools to dynamics in ecology. S. Ispas has a new collaboration with theoretical chemists (ICG in Montpellier), working on the modeling of organometallic complexes grafted on silica surfaces. Such collaborations are constructive but lack the presence of another permanent researcher (S. Dennler, an assistant professor, was hired on such topics but left the lab and no other recruitment since happened). N. Kern is pursuing a collaboration with the team "Complex Systems and Non linear Phenomena", especially with A. Parmeggiani, on complex transport related to biological issues. A major evolution of the team has been to join the Department of Theoretical Physics in January 2013, and the reinforcement of links between theoretical groups. A common seminar of the department has been organized. Two permanent researchers (M. Clusel and D. Coslovich) have been hired during the last period. The Statistical Physics team has made over the years a major effort in acquiring and developing a numerical cluster for intensive simulations. This tool will persist in the future and needs assistance and improvements. K. Steuckardt, who is involved from the beginning in this project, should be totally in charge of it in the future as he has made determinant contributions to its success.

Topic 3: *Complex Systems and Non-linear Phenomena (SCPN)*

The SCPN group is strongly involved in collaborative projects with: i) experimental teams of the L2C together with common collaborators on national and international levels, ii) local partners in the field of Life Sciences and Environment, including Pôle Biosanté Rabelais and OSU OREM, iii) LabEx NUMEV, iv) national networks like GDRs, and v) international networks like IPOLS (International Physics of Living Systems). The strategy of the group aims at broadening the existing collaborations and at developing new ones. Until now the group had high-level world recognized activity in the field of nanophysics, physics of spin, and TeraHz physics, but in near future this activity will involve only non-permanent members (Emeritus professor and possibly post-docs). To maintain this activity the group would need to recruit at least one new member in this field. The activity in the field of non-linear physics will surely benefit from the promoting of the group members working in this field. The group will continue to contribute to fluid mechanics and its applications to environmental science, to physics of complex fluids and charged fluids. Due to recent recruitment the group will be able to widen and strengthen its activity in the field of the physics/biology interface, namely in quantitative models in neurophysiology, in modeling of intra-cellular transport and cytoskeleton networks, in physics of genome (including DNA and RNA behavior modeling and their interaction with proteins), in modeling of DNA-lipid coupling in crucial cellular processes. The group will continue to contribute to the emerging field of physical virology. To facilitate the interaction with the partners the group exploits new possibilities. Indeed, after the recruitment of one MCF in 2013 (who replaces one team member leaving for U. Paris VII) three group members will have double affiliation with different biology labs. This will give us the opportunity to develop new research subjects in new fields of physics and to maintain access to unique experimental data.

Topic 4: *Fundamental interactions, Astroparticles and Cosmology (IFAC)*

In particle physics beyond the Standard Model, the year 2012 was crucial with the discovery of the scalar boson resonance of mass ~125 GeV at the LHC, opening a new era and evidently driving a large part of our next future projects. The group's traditional or newer activities indeed have some important complementarity to be flexible and open to various possibilities beyond Standard Model, whether it could be supersymmetry or alternatively strongly interacting/composite electroweak sector that hopefully will be resolved by next future LHC data. The group has a longstanding expertise in the phenomenology of minimal and extended SUSY models as well as Higgs physics, and moreover acquired recently further expertise in composite Higgs models and their implications. Concerning cosmology, existing data so far support the concordance model. Future surveys (weak-lensing, redshift surveys) will pinpoint more precisely the nature of dark energy. CMB anisotropy data gathered by WMap9 and Planck have constrained inflationary parameters with impressive accuracy and future polarization data will further constrain these models, offering exciting possibilities in the field of inflation and dark energy. Some of these data, ("axis of evil" and "cold spot") could challenge the standard cosmological framework.

The IFAC group is very active with undergraduate and postgraduate student formation and supervision, and also strongly implied in national and some international networks, like the GDR Terascale and the Labex OCEVU recently started, an opportunity to develop new research subjects and new collaborations. Yet it is crucial to envisage regular recruitment in the future in order to maintain a sufficiently 'critical mass' for our relatively small group.

On a more sociological/political side, it should be stressed that the group was logically (thematically) the most directly affected by the fission/fusion process, by which the 5 former physics UMR formed 2 new ones, born early 2011, the L2C and LUPM, since the thematic separation 'line' passed right through IFAC. Yet, up to now, the group managed to take this situation as an advantage, keeping a strong internal coherence and functioning, for the scientific if not administrative aspects, as a whole block (with common seminars for example etc.). Indeed over only the last two years, there has been about ~30 seminars per year jointly organized by both L2C and LUPM sides, with some prestigious speakers. This overall contributes, among other things, to keep frequent and lively discussions in the group, also largely involving PhD and graduate students. But one should remain vigilant on the situation in the future, depending on the will of both laboratories directions to maintain or not this group coherence and specificity within larger entities with various different research activities.

Department "Soft Matter and Glasses"

In the framework of the reorganization of the department structure of the laboratory, a new department with two research groups working on the physics of soft, glassy, or disordered condensed matter will be formed. The "Physics of the glassy state" group with currently 6 permanent researchers will focus its research activities on the fundamental properties of the glass state and more generally on the disorder-induced effects on material properties. The 'Soft matter group' (currently 13 permanent researchers and 1 visitor) will concentrate its experimental research activities on "Complex interfaces", "Jamming, plasticity, material failure", "Physics of biological systems", and "Soft composites". A new activity is currently added with "Soft matter physics for agronomy and environment".

One may note that the two research groups share similar experimental approaches, even if the scales are sometimes widely different. Measurement of mechanical properties as a function of frequency, e.g., or scattering methods vs. direct space observations, are common concepts in both groups. Several scientific aims are also close if not identical, like for instance the mechanical analogies between soft solid and hard glasses (plasticity, fracture, …), or the structure and mechanical properties of nanocomposites, including polymer dynamics and glassy layers.

The scientific project of these two groups is detailed in the following paragraphs.

Team: Physics of the glassy state

Strengths: A key point of our activity is the ability to successfully design original experiments and to develop in-depth analyses to achieve the scientific objectives. Several important contributions to the field of glass science have thus been obtained and disseminated through about 50 publications in peer-review journals, 25 invited conferences and 70 oral contributions. This long-standing expertise, allied to the continuous improvement of our world-class instruments, allows us to initiate numerous collaborations through granted projects, either with academic or industrial partners, as well as to play a leading role in the coordination of the international glass community. Historically focused on oxide glasses the group expertise now extends to polymer glasses.

Weaknesses/Threats: A threatening factor for our experimental activity is the lack of CNRS researchers, hindering group development. This peculiar situation needs to be solved rapidly by the recruitment of CNRS researchers.

Strategy/Opportunities: As it can be anticipated from the presentation of the recent achievements of the team, a significant part of our scientific projects are currently well on tracks and will be pursued in the coming years. Our success in various grant applications during the past years permitted the technical developments of our instruments in agreement with the scientific objectives. It should also open new opportunities for collaboration with local researchers (bio-related materials, nanomaterials…). A new topic which we want to address is the study of the out-of-equilibrium dynamics around the glass transition. This field of research has greatly developed in the last years thanks to a strong synergy between theoretical advancements and experimental work, and is at the focus of a large community of scientists in these days. The project should also benefit from local collaborations with members of the Statistical Physics Group and of the Soft Matter Group. The success of an on-going CNRS application in that field is essential.

Perspectives in our two areas of research are detailed below.

Glasses under high-stress conditions

Permanent researchers involved: M. Foret, A.-C Genix, M. George, B. Hehlen, B. Rufflé, and C. Weigel.

The study of the plasticity mechanisms responsible for the fracture in polymers will be tackled thanks to the experimental techniques and multi-scale analysis recently developed for silica-based glasses. This activity is supported by *ProMorph* ANR project (ongoing PhD thesis). We will complement this work by using spatially resolved spectroscopy to study the mechanical response in the micrometric sized process zone.

The small scale mechanical response of silicate glasses will be further explored using high performance spectroscopic measurements under advanced loadings coupled to atomistic numerical simulations in collaboration with ILM Lyon [*MecaSil* ANR project]. This information will be complemented by a quantitative description of the structural changes obtained from a Raman/hyper-Raman spectral analysis.

We also certainly plan to investigate further the unexpected poromechanical behavior of bulk glasses we discovered recently for silica. To that effect we have initiated a collaborative work, hopefully supported by the ANR (1 PhD), at the interface between physics, mechanics and physical-chemistry. Though a curiosity-driven research project, the implication of MSE[2] (MultiScale Material Science for Energy and Environment, the recently created international joint unit CNRS-MIT in Cambridge) in the consortium indicates that a better understanding of sub-nanometric poromechanical effects is of significant importance for an efficient industrial use of a wide range of multiscale porous materials.

Finally the emerging multidisciplinary research activity with LMGC (Montpellier) and IATE (INRA, Montpellier) focused on the study of the local mechanical properties of bio-polymers through AFM abrasion test will be pursued as first results are very promising (ongoing PhD thesis).

Structure, vibrations and relaxations in disordered materials

Permanent researchers involved: M. Foret, A.-C Genix, B. Hehlen, B. Rufflé, and C. Weigel.

A first project covers our long-standing research line on sound wave propagation in glasses. The main challenge which we want to tackle now is to reach the sub-terahertz frequency region using GaAs/AlAs super-lattices as efficient generators and detectors of coherent acoustic waves in collaboration with INSP Paris [*GlassPhon* ANR project]. The nature of the vibrations and their quantitative relation to the structure will also be pushed further in complex glasses using our unique hyper-Raman facility.

With soft composites we will explore different directions in the future, like studies of segmental dynamics in polymer nanocomposites, developments of new model and simplified industrial systems (ongoing PhD thesis in coll. with J. Oberdisse *Soft Matter Group*) allowing for new grafting chemistries. This ongoing work is a close collaboration with J. Oberdisse from the “Soft Matter” Group.

The fruitful hyper-Raman scattering investigations of the low-frequency dynamics of ferroelectric-type materials will be pursued (ongoing PhD thesis). In relaxors this will help to approach a coherent picture of the dynamics of the electrical polarization as well as on the local structures. The peculiarity of the polar states and phase transitions of ferro-nanoceramics will also be probed. This collaborative research program gathers the Ecole Centrale in Paris, the ASCR in Prague, and the ESRF in Grenoble. It is funded by a PICS project (2013-2016) and hopefully by the ANR (1 PhD).

Finally we would like to tackle the problem of physical aging and out-of-equilibrium dynamics around the glass transition. The recent advent of x-ray photon correlation spectroscopy (XPCS) gives now the possibility to scrutinize the dynamics on the atomic length scale in glasses and impulses a new momentum in this research field. Collaboration with researchers around G. Monaco (Univ. Trento, IT) has been initiated and a XPCS experiment is scheduled in July 2013 to investigate this phenomenon in a simple metallic glass and in oxide glasses. The large-scale facility experiments will be complemented by in-home spectroscopic measurements. We hope to develop rapidly this activity through a, hopefully, successful CNRS-application.

Team: Soft Matter

The scientific perspectives for the Soft Matter team are a pragmatic mixture of continuity in our core research activities, and introduction of new techniques and topics (like physics applied to agro-systems, holography), usually brought in by the newcomers, which is why recruitment is important.

Concerning the **strengths and weaknesses** of the soft matter team, we can put forward our strong academic record, which is – among others - due to the interconnections and complementarity of our know-how in the various fields outlined above. We have acquired visibility and recognition on an international, national, and local scale, which translates into invitations, prizes, and into an international recruitment of PhDs, post-docs and permanent researchers. We participate in teaching and science management at different levels, and try to make our scientific results accessible to non experts. Of course, not everything is perfect. We clearly encounter difficulties in attracting local students to a soft matter PhD. Due to the low student numbers in general, the presence of soft matter in teaching at the master level is far too weak. Here actions are taken by our teachers. Also on a local scale, soft matter topics are not considered a priority, and the scientific policy of University is clearly not oriented towards physics. Fortunately, the interdisciplinary character of soft matter allows us to attract some funding (e.g. Labex) via collaborations with agronomy, biology, and chemistry labs.

Finally, S. Mora and M. Abkarian, two highly active researchers, will leave the laboratory in a near future. This clearly weakens the involvement of the group in biophysics and in mechanics of soft solids. On the other hand, since both researchers are joining neighbouring labs, this also offers new opportunities to extend collaborations of the soft matter team within Montpellier's community. For instance, we intend to extend our rheology platform to a third partner, the Laboratoire de Mécanique et Génie Civil, Montpellier (LMGC, Montpellier), where S. Mora got his professorship. Actions to be taken to address this very new situation (june 2013) are still under debate within the group at the time of this report because they also relie on the final situation of D. Alexandre, a biologist currently visiting our group.

Recruitement and departures:

S. Mora has recently been offered a professorship at LMGC starting septembre 2013. The departure of M. Abkarian to the Centre de Biologie Structurale (CBS, Montpellier) is anticipated within the next two years. We (urgently) need to recruit an asssitant professor in the field of soft condensed matter to keep on the level of teaching in this field and preferentially with a background in biological soft matter or in mechanics and dynamics of soft solids to counteract the above mentionned weaknesses of the group.

For the second year now, we have a CNRS-application running in the field of mesoscopic precursors of mechanical instabilities. Last year our candidate, who also brings in some expertise in simulation and theory, was well received by the committee, and there is reasonable hope for him to reinforce the interface between rheology and light scattering of soft materials within the next years.

A senior researcher (DR CNRS) has joined us during the last reporting period. M. Gross from ENS Paris is an expert in holography, and he uses holography to study light propagation in complex media. Two young researchers, A. Banc (MdC, in charge of soft matter for agronomy and environment) and A. Stocco (CR CNRS, in charge of physico-chemistry of active colloids at interfaces), have also been recruited.

Concerning the future development of soft matter science in Montpellier, the following directions will be taken in each of our scientific activities:

1) Complex interfaces:

Permanent researchers involved: M. Abkarian (until his departure), C. Blanc, M. Gross, M. In, M. Nobili, A. Stocco.

Future studies in this field will be pursued first by elucidating the trapping dynamics of ellipsoidal particles at a fluid interface by using optical tweezers and holography methods. Both the translational and rotational diffusion of those particles will be measured to address the peculiar role played by the triple line dissipation. Moreover, the understanding of the origin of lateral forces on trapped particles will be crucial to make colloidal particles with tunable valences and directionalities. We will further extend these studies to active (self-propelled) particles by looking at the coupling motor/interface.

Concerning interfaces at structured fluids, we plan to use capillarity effects to create colloidal particles with tuneable valences and directionalities. Self-organization mechanisms and instabilities related to the interplay between interface tension and liquid crystal elasticity will continue to be explored in liquid crystals emulsions and liquid crystals Pickerings.

Our participation in the Labex Chemisyst has triggered several collaborations with chemistry laboratories in Montpellier. In the field of self-assembly at complex interfaces, a post-doc position will be opened on Pickering emulsion, with ICGM. With ICSM (Marcoule), a second post-doc will work on the effect of ultra-sound on particles trapped at interfaces.

The recently recruited CNRS scientist A. Stocco brings in his expertise for colloids and nanoparticles at complex interfaces. He is interested in the analysis of motion of active particles at interfaces. He combines ellipsometry and dynamic light scattering, and has already set up an evanescent dynamic light scattering instrument for fluid interfaces. From an instrumental point of view, M. Gross who joined us from LKB (ENS) will contribute with measurements of the field diffracted by particles at interfaces, aiming at a determination of the local geometry of the objects by fitting holographic data, possibly leading to a new particle tracking method at non planar interfaces (z-resolution and contact angle).

2) Jamming, plasticity, material failure

Permanent researchers involved: L. Berthier (Theory department), L. Cipelletti, C. Ligoure, S. Mora (coll. LMGC), L. Ramos.

a) Instrumentation development: we will pursue our effort in developing original instrumentation for investigating the slow dynamics of jammed soft matter. We will focus on the design of a light scattering instrument for the International Space Station (ongoing proposal with ESA/CNES and Lambda-X), and on exploring the industrial applicability of the light scattering methods developed in the lab (CIFRE thesis under negotiation).

b) Spontaneous slow dynamics and zero-shear viscosity of supercooled colloidal suspensions (PhD thesis ongoing support from CNES): we aim at measuring simultaneously the structural relaxation time and the viscosity of dense colloidal suspensions, in order to elucidate the relation between microscopic dynamics and flow in model glass formers.

c) Plasticity in jammed soft matter. We will explore plastic rearrangements in a variety of solid-like soft materials (colloidal polycrystals and glasses, networks...) submitted to different kinds of mechanical drives (shear, expansion/compression). Support for this research will come from the European network (ITN) SUPOLEN (1PhD Thesis), the ERC grant of L. Berthier (1 postdoc), and other contracts.

d) Failure in soft materials. We are interested in understanding the mechanisms leading to material failure (fracture, shear banding,...). The focus will be on dynamical precursors of failure. Support will come from SUPOLEN and other contracts.

e) Mechanical instabilities. Fracture and mechanical instabilities in general will remain a central activity, pursuing our understanding of surface tension effects in soft solids of various geometries, the brittle-to-ductile transition in the fracture of self-assembled networks with tunable anisotropy under confinement, and jet instabilities in sprays. Supports: SUPOLEN (1PhD thesis) and Solvay (1 CIFRE thesis).

3) Physics of biological systems:

Permanent researchers involved: M. Abkarian (until his departure), D. Alexandre (Visiting scientist). M. Gross, M. In, C. Ligoure, G. Massiera.

One of the projects is in the continuity of the cDICE project (our patented encapsulation process), and in particular the mechanisms of droplets interface crossing, both in the non-inertial and inertial case, to produce capsules. The process will be used for various middle term projects: i) the liquid flow through two concentric vesicles submitted to an osmotic pressure, ii) collaborations with Sanofi are currently set up to encapsulate active molecules using cDICE, iii) the production of an artificial tissue, and the study of its mechanical response, which will be compared to some specific living tissue mechanics. Another project concerns transient gels of biomimetic vesicles formed by addition of hydrosoluble biopolymers carrying hydrophobic modifications. We will also participate in a project on a biophysical approach of the mucociliary aspect of the bronchial epithelium (ANR 2014, PI P. Chanez). Using a new technique, we are currently setting up holographic experiments for the analysis of the dynamics of colloidal and biophysical systems in general.

4) Soft Composites:

Permanent researchers involved: E. Anglaret (Nanostructures), A. Banc, C. Blanc, L. Cipelletti, A.C. Genix (Physics of glasses), M. Nobili, J. Oberdisse.

With soft composites we will explore different directions in the future, like studies of segmental dynamics in polymer nanocomposites, and the development of new model and simplified industrial systems allowing for new grafting chemistries. In particular, the later point is also supported by the Labex Chemisyst, which finances a PhD in collaboration between IGCM (CMOS group) and L2C (soft matter). In polymer nanocomposites, we wish to pursue our fruitful collaboration with Michelin on simplified industrial nanocomposites. Here, we are interested in the interplay between the filler structure, the polymer grafting, and the mechanical properties of the composite. A related project deals with the study of the dynamics of transparent nanocomposites by light scattering.

Anisotropic soft composites and especially liquid crystals composites will continue to be explored through local collaborations, but also within the European action COST IC1208 dedicated to the modifications of liquid crystals with nanostructures and nanoparticles. Dispersions of anisotropic colloids, such as beidellite clay, with complex electro-optic behaviour to address telecom applications will also be examined in the frame of ANR Nastarod (PI L. Dupont, Telecom Bretagne). Our aim is to precise the mechanisms at the origin of high birefringence, observed above the Kerr regime with these model systems.

5) Soft matter for agronomy and environment:

Permanent researchers involved: A. Banc, C. Ligoure, G. Massiera, L. Ramos.

A. Banc has been hired as MdC two years ago. She drives the establishment of this new topic. One project is to elucidate the mechanisms at play in the structuration of proteins under shear, and a collaboration with a team of INRA has been set-up. The objective is to investigate the gelation and structural properties of model systems comprising proteins purified from gluten. Moreover, to go further into the understanding of such elastomeric proteins, we plan to study the assembly of model peptides with hydration. These peptides inspired from repetitive sequences of gluten and other elastomeric proteins will be investigated using a microfluidic tool. The microrheology of protein suspensions will also be studied.

Another project concerns the atomization of complex fluids for crop protection products. The primary objective of the research work is the understanding of the physical and physicochemical mechanisms, which control the size distribution of drops of complex fluids (including dilute oil in water emulsions and dilute polymer solutions and mixtures of these compounds). It will include the investigation of the destabilization and/or perforation of liquid sheets and liquid ligaments at high Reynolds number. This project is motivated by agrochemical applications as such drops can be used as transport agents of agrochemical active compounds, to be sprayed on agricultural land. The environmental purpose is to avoid the formation of too small drops that may be dispersed off-target by the wind, which is potentially a risk of pollution.

Also in this field, our participation in the Labex Numev with ongoing projects and a PhD in the field of protein structure and dynamics reinforces this (rather young) activity.

Department “Nanomaterials and Spectroscopies”

The new Department “**Nanomaterials and Spectroscopies**” will be composed of two teams. In order to explain the configuration of the new department, we detail the **strengths and weaknesses** of the “Nanostructures” team

Weaknesses:

The “nanostructures” team is currently composed mainly of 11 assistant professors and professors and 3 CNRS researchers. All professors and assistant professors are very much invested in teaching management tasks. One can notice that some of them have also strategic managerial duties for the institution. In addition, over the past five years, two researchers, one expert in X-ray diffraction (R. Almairac: he retired in 2009), and another one in elastic and inelastic neutron scattering (S. Rols: he has been hired as beamline scientist at the *Institut Laue-Langevin* neutron facility) left our team. Consequently, the team lost skills in these domains. Furthermore, Jean-Louis Sauvajol (DR), expert of Raman spectroscopy of carbon nanostructures, is the director of our laboratory since 2009. At the result, to maintain its research potential, the working force of the team has to be reinforced in particular in hiring scientist at the CNRS.

Two different directions of researches and strategies are presently identified in the team. A part of the team develops activities dedicated to the investigations of nanostructured materials, carbon based materials and beyond carbon materials. Another part of the team focuses its activity on the investigations of carbon-based nanostructures at the individual level. In addition this late part of the team is strongly involved in the research activities developed among the inter department graphene project, the so-called **“Axe Transverse Graphene”** which merges this part of researchers of the “**Nanostructures team** and a part of the researchers of the “**Materials, Devices and Sensors”** team.

Strengths:

The specificity of the “nanostructures” team is the ability to successfully perform the synthesis of carbon nanomaterials and design original experiments to achieve the investigation of their physical properties.

Several important contributions to the field of nano materials have thus been obtained and disseminated through about 122 publications in peer-review journals, 46 invited conferences and 108 oral contributions.

Our instrumental skills are recognized through participation in various regional platforms. The continuous improvement of our instruments and sample environments has allowed us to initiate numerous collaborations through granted projects, either with academic or industrial partners, as well as to play a leading role in the national carbon community (co-direction of the GDR-I: Graphene and Nanotubes). Historically focused on the structure and properties of carbon-based nanomaterials, the group expertise now extends to hybrid nanomaterials.

We have recruited four scientists during the reference period, two seniors’ scientists: F. Henn (PR1), R. Metz (MdC) and two young scientists: T. Michel (MdC) and M. Paillet (CR2), all pulsing new dynamics in our team.

M. Paillet drives the establishment of a new topic on the optic and optoelectronic properties of individual carbon nanotubes (this topic will be supported by ANR GAMBIT from 2014 to 2017) and graphene based materials. The researchers on graphene have been performed in the framework of an inter department axis between CVN and SMC Departments. For the next period, the specificity of these activities will result in the creation of a team dedicated to the study of the physical properties of individual nano-objects based on carbon.

T. Michel is an expert of Raman spectroscopy on both carbon nanomaterials and nano objects. He is now in charge of Raman spectroscopy platform of the lab. A “Vibrational Spectroscopies” platform, merging our Raman and infrared capabilities with those of other institutes of the university: “Institut Charles Gerhardt (ICG)” and “Institut Européen des Membranes (IEM)”, will be created. The agreement is in discussion.

R. Metz, comes from the University Lyon 1, has been hosted in our team since January 2012. He brings in his expertise for elaboration of nanocomposite materials for industrial applications. He has set up collaborations with Schneider Industry around the elaboration and study of dielectrics composites for electrotechnic applications. We plan to elaborate and study the physical properties of dielectric graphene charged nanocomposites with high thermal conductivity for electrotechnic applications.

Before joining our group in 2011, François Henn studied the confinement of biological ionic channels. He has established with Vincent Jourdain a new promising field of research concerning the confinement of biological ionic channels inside carbon nanotubes. These activities are supported by two ANR projects: TRANSION (2013-2017) and Nanophoresis (2014-2017).

Opportunities

With regards to the existence of two specific and dictinct research directions inside of the “Nanostructures” team, and also in order to make easier the management of the “Axe Transverse Graphene”, we decide to create two teams in a new “Nanomaterials and Spectroscopies” Department, namely.

- **“Nanomaterials”** team
- **“Individual low-Dimensional Carbon Structures”** team

Obviously, with regards to their common interest in the investigations of carbon based nanostructures, and the development and the use of common tools of synthesis and spectroscopy equipments, these two teams will conserve direct links.

The activities of the team: “**Nanomaterials**”, will be principally dedicated to the investigations on nanostructured materials based on carbon. These investigations include the growth mechanisms of carbon nanotubes, the ionic transport inside nanotubes, the properties of photo-active molecules confined into nanotubes and the preparation and properties of carbon based nano-composites. On the other hand, a part of the team activities will be dedicated to the investigation of nanomaterial “beyond carbon” such as hybrid organic-inorganic nanostructures or copper-based nanomaterials. To perform these investigations, the team will develop specific instrumental environments, including experiments under extreme conditions, in Raman and IR spectroscopies, and original experiments on Neutrons and Synchrotron facilities such as combining in situ doping of nanomaterials with Raman, transport and X-ray absorption. It should be emphasized that the group developed fruitful collaborations with the pole chemistry of Montpellier University and these links should be strengthened in the future.

The activities of the team: “**Individual low-Dimensional Carbon Structures**”, will be focused on the optical properties and transport and photo-transport properties of individual nano-objects based on carbon, namely individual carbon nanotubes and derivatives, and graphene and derivatives. To extract the relevant response of these individual nano-objects, the team will need to develop specific home-made optical spectroscopy tools. It must be emphasized that this team is strongly involved in the Transverse Research Axis devoted to Graphene which merges researchers of two departments: the “**Spectroscopies and Nanomaterials** ” Department and the **“Applied Physics”** Department.

Team: *Nanomaterials*

Our prospects are centered on three points:

- Pursuing our core scientific research around carbon based materials in particular in the framework of PhD thesis: A. Selvati (2013-16), A. Belhboub (2012-15), K. Yazda (2012-15), F. Torres-Canas (2012-15).

- Opening new topics around the relationship between structure and properties on original nanostructured compounds such as hybrid materials (PhD thesis Vania Freitas (2013-16)), or copper-based nanomaterials for surface-enhanced Raman scattering (SERS), (PhD thesis Deniz Cakir 2013-2016).

- Consolidation of our expertise around the vibrational spectroscopies (Raman, IR), XPS-UPS spectroscopies and large facilities skills (neutrons and synchrotron).

The key points of our strategy are to develop:

(1) Researches at the interface with the Chemistry community in order to combine their synthesis skills with our ability to study the structural and physical properties of nanomaterials;

(2) International collaborations focused on our core research activity;

(3) Development of industrial collaborations.

The directions of our scientific activities in different topics are detailed below:

Topic: **Confinement**

L. Alvarez (MCF), R. Le Parc (MCF), J-L. Bantignies (PR2), T. Michel (MCF), Lucyna Firlej (PR1), Anouar Belhboub(PhD), F Henn (PR1), V. Jourdain (MCF), Khadija Yazda (PhD), Sophie Roman (Post-doc), Ana Carolina Selvati (PhD).

a) *Endohedral filling:* The aim of the project is to study the physical interactions taking place between photo-active molecules confined in the hollow core of the host nanotubes and their consequences on the physical properties of the hybrid material. We focus our perspectives on the effect of confinement on the structural organization and dynamics of the π-conjugated molecules inside the nanotube and the dynamics of the nano container. We will combine an experimental approach using Large-Scale Facilities (Inelastic Neutron scattering, INS), Raman and infrared spectroscopies and ab-initio calculations. Raman, IR and INS spectroscopies will probe the modifications induced by confinement on the dynamics of both compounds. Whereas Raman spectroscopy is mainly probing the nanotube, neutrons and IR are mostly sensitive to the organic guest molecules. The related works will be performed in the framework of co-tutella PhD thesis of A. Selvati with *Institut Laue-Langevin* neutron facility (Grenoble Fr.). In parallel, ab-initio calculation will be done to understand the nano confinement effect on the vibrational properties (Cotutella PhD thesis with Meknes University, Marocco- A.Belhboub).

b) *Ion and molecular transport through the inner channel of a carbon nanotube*: This new research direction essentially originates from the gathering of the works led by François Henn and Vincent Jourdain. Before joining our group in 2011, François Henn studied the confinement of biological ionic channels such as gramicidin-A (gA) inside thin nanoporous polymer membrane and its influence on ionic transport (PhD thesis of Lydie Berardo). Confocal fluorescence microscopy was used to assess the confinement of gA inside the polymer membrane and ionic transport measurements (ionic diffusion coefficient, complex impedance spectroscopy) in various aqueous electrolytes were performed. The studies showed that the presence of gA in polymer nanopores of 15 nm significantly increases the membrane ionic transport [see for instance, Nanoscale. 2013 May 7;5(9):3961-8]. This work opened an extremely promising field of research that we extended to the confinement of biological ionic channels inside carbon nanotubes whose diameters are much more appropriate for accommodating gA in its biologically-active conformation and conferring to the as-built hybrid membrane a high ionic selectivity. The main perspectives is that field are thus directly related to the ANR-TRANSION project (2013-2017, coordinator F. Henn).We are also interested in using ionic transport measurements through individual carbon nanotubes as a tool for detecting and identifying small biomolecules during their translocation through the nanotube inner channel (ANR JCJC Nanophoresis, coordinator V. Jourdain). This project gathers other people: Thierry Michel for Raman analysis, Manouk Abkarian for microfluidics and J.B. Thibaud for ion current measurements through nanopores, Khadija Yazda (PhD) and Sophie Roman (post-doc).

c) **Instrumentation development:** Our effort will be pursued in developing original instrumentation for investigating Nano Confinement effect on photoactive molecules and charge transfer complexes. A photo-electron spectrometer with a UV lamp is now available in our team. We will focus on the development of this spectrometer especially to perform UV photoemission measurements. It is worth noticing that, to our knowledge, there is no such UV photoemission spectrometer in the South Ouest region. Thus, we will be able to investigate the electronic properties of the hybrid systems. In particular, measurements of the electronic density of states near the Fermi level (HOMO) of the confined molecules will allow studying the electronic interaction between the encapsulated species and the host nanotubes. Furthermore, the photo-electron spectrometer will be combined to a compact Raman spectrometer to study in situ the electronic and the vibrational properties.

Topic: **Films and composites**

V. Jourdain (MCF), E. Anglaret (PR1), C. Blanc (CR – Soft Matter team), M. Nobili (PR1- Soft Matter team), R. Metz (MCF) Fernando Torres-Canas (PhD)

a) *CCVD Growth of carbon nanotubes: Despite significant progress within the last* 10 years of investigation, numerous questions remain open concerning the fundamental processes controlling the nucleation and chiral selectivity during the CCVD growth of carbon nanotubes. These are critical issues for the application of carbon nanotubes in electronic and optical applications. To address the nucleation question, we propose to couple our in situ Raman data with in situ HRTEM observations performed in collaboration with the Renu Sharma group at NIST (Gaithesburg, USA) and compare them with ex situ HRTEM (collaboration with LEM-ONERA) and computer simulations (C. Bichara, Cinam). To address the selectivity issue, we will study bimetallic catalysts known for their high chiral selectivity (e.g. FeRu) by in situ Raman measurements. We will also study samples presenting a simple or double gradient of metal thickness by Raman mapping (collaboration with B. Maruyama from the USAF-RL, Dayton, USA, funded by the European Office of the US Air Force Research). Using the same high-throughput approach as previously, we aim at understanding the influence of the catalyst size and composition on the structural distribution of carbon nanotubes. Since chiral selectivity may also be controlled by the growth kinetics, we also develop in situ SEM monitoring of individual CNTs during CVD growth to access the growth kinetics of individual nanotubes (Collaboration with R. Podor, ICSM, and S. Hofmann, Cambridge University).

b) Carbon-based nano-composites: In order to take advantage of the exceptional properties of nanotubes in composites, one needs to contol both the dispersion and the orientation. The goal of this research topic is to prepare anisotropic nanotube-based composites (nematic liquid crystals, thin films, composites…), and to study their anisotropy and their physical properties. The PhD thesis of Fernando Torres-Canas is prepared in this framewok, in co-tutelle with Camilo Zamora-Ledezma and Pedro Silva in Caracas, and in close collaboration with Cécile Zakri and Philippe Poulin at CRPP, Bordeaux. We will especially focus on the electrical and optical properties of thin films prepared by inkjet printing and composites prepared from aqueous suspensions. One key parameter for these properties is the amount and nature of the contacts between nanotubes, which can be controlled from the density/concentration and anisotropy of the nanotube networks. Polarized Raman and photoluminescence will be used to describe the anisotropy of the materials. This topic also extends towards industrial issues : i) the mechanical reinforcement of metallic matrices by nanotubes, in collaboration with EADS Münich (and Nicole Fréty, ICG Montpellier), ii) carbon nanostructures/silica/epoxy composites and stress grading materials for enhanced thermal properties of insulators for electrotechnical applications, in collaboration with Schneider Electric Montpellier

Topic: **Beyond carbon nanomaterials**

J-L. Bantignies (PR2), R. Le Parc (MCF), C. Levelut (DR2), C. Goze Bac (DR2 – NMR Spectroscopy and Imaging team), Ph. Dieudonné (IR), Lucyna Firlej (PR1), C. Blanc (CR -Soft Matter team), V. Freitas (PhD), D. Cakir (PhD), E. Anglaret (PR1)

a) **Self-assembly of hybrid organic inorganic nanomaterials**: First projects will focus on the relation between the tuning of the material properties and the nanoscale arrangement in nano-structured hybrid silica (NSHS). Our first perspective is dedicated to the control of the photoluminescence of NSHS by encapsulation of lanthanide (III) (Ln^{3+}) salts or complexes. The new luminescent materials exhibit high quantum yields (0.2). The luminescence characteristics depend on the incorporation (Ln^{3+}) properties inside NSHS (projects PHC PESSOA 2012, LUSO 2013). The main objective is to understand how the luminescence properties can be controlled thanks to nanohybrid structuration around Ln^{3+} (Collaboration Physics Department, Aveiro, Portugal). Our second perspective in this field concerns the study of mesoporous NSHS allowing the transport and controlled release of active molecules through the tailoring of non covalent interactions in biological environment.

b) **Hybrid fibrillar materials from polymers and self-assembled systems**: This project enters the field of self-assembled functional materials with controlled nanoscale organization. It focuses on the elaboration, via physical processes, of complex hybrid architectures designated as nano-cables and nanotubes obtained through thermoreversible gelation, and self-assembling molecules (ANR Matisse 2012-2016). Our first objective is dedicated to the identification of the key parameters controlling the formation of the nanotubule gels using in situ experimental approachs (vibrational spectroscopies and microscopy). Our second objective is to study the influence of the confinement of self-assembled nanofibrils on their magnetic properties.

c) **Instrumental development:** Our efforts will focus on the development of original vibrational spectroscopy (IR, Raman) experiments for the study of nanomaterials including IR spectroscopy under pressure in the far infrared, in situ studies, polarization selective techniques for Internal and External Reflection Geometries. In the next reference period, we aim at structuring the activities of vibrational spectroscopies of the University Montpellier 2 in a single common service. This structure will develop its activity at the interface with other disciplines, in particular the Chemistry community.

d**) Copper nanomaterials**: after a first collaboration on the dispersion of copper nanostructures in conductive inks for the printing of metallic circuits, we extend the interaction with Atotech Berlin (a chemical company from the Total group, specialist in metal plating) to the preparation and study of SERS properties of copper nanomaterials, in collaboration with Nicole Fréty at ICG Montpellier. The objectives are to better understand the relation between microstructure, oxidation and SERS properties of copper, and to carry out SERS investigations of chemical and electrochemical reactions at copper interfaces.

Team: *Individual low-Dimensional Carbon Structures*

Matthieu Paillet (CR1), Ahmed-Azmi Zahab (PR1), Jean-Louis Sauvajol (DR1); H. N. Tran (PhD), A. Bakaraki (PhD)

During the next years, our activities will be centered on the physical studies of individual carbon based nanostructures: carbon nanotubes and graphene. Our aim is to maintain equilibrium between these two themes.

Concerning carbon nanotubes, our perspectives are oriented in two directions:

- The investigation of intrinsic physical properties at the individual level
- The elaboration and investigation of hybrid nanostructures (carbon nanotubes and photo-actives molecules or chemical receptors).

The related investigations on these two topics will be performed in the framework of the PhD thesis of H. N. Tran (directors: A. A. Zahab and M. Paillet).

On the first aspect, we will pursue the investigations started in 2005 focused on the phonons in nanotubes and extend them to opto-electronic excitations in collaboration with V. N. Popov (University of Sofia, Bulgaria), N. M. Phan (Institute of Materials Science, Vietnam), and the “Institut Lumière et Matière” (Lyon). The main part of our effort will presumably be devoted to the study of double-walled carbon-nanotubes (DWNT) for which there is still much to understand about their physics and in particular about the role of inner- and outer-walls interactions, coupling and screening.

On the second aspect, the main project proposes to assess the relevance of double-walled carbon nanotubes (DWNT) covalently functionalized with photoactive, conjugated, molecules and macromolecules to develop innovative hybrid nanostructures. Indeed, these DWNTs, consisting of two concentric nanotubes, offer the opportunity to use the outer tube for grafting, sacrificing its properties, while preserving intact the inner tube and its properties. The approach aims to combine in a synergetic manner the remarkable properties of carbon nanotubes (mainly electrical and thermal transport) to those of organic systems including the versatility of their optical characteristics and their ultimate selectivity as chemical or biological receptors. The central part of the project is devoted to the elaboration and study of structural, vibrational, optical and optoelectronic properties of hybrid systems based on functionalized DWNTs covalently grafted with photo-active molecules or macromolecules. In addition, we target the realization of hybrid electro-and photo-stimulable nanoelectronic devices.

This project will be held in the framework of a strong collaboration with the ICG (ENSC Montpellier), CIRIMAT Toulouse and ICS Strasbourg and will be funded by the ANR “progamme Blanc” for the period 2014-2017 (GAMBIT project, coordinator: M. Paillet).

Concerning graphene, our team is strongly involved in the research activities developed among the inter department graphene project, the so-called “**Axe Transverse Graphene”** with, for our team, a special emphasis on optical and optoelectronic properties of graphene and hybrid systems. The close collaboration with the “**Semiconductors and Nanophysics**”team of the “**Applied Physics**” Department has been fruitful and led us to define a common research project which is detailed below:

“Axe transverse Graphene”

We will sustain the research effort on the synthesis and elaboration of home-made samples, more specifically by CVD and sublimation on SiC and CVD on metallic substrates. This local source of samples combined with existing external collaborations (such as CRHEA, CNM, Linköping University) will help at the development of the following research directions.

-Beside the development of reliable optical and theoretical tools for the characterization of graphene and multi-layer graphene (MLG) samples in various environments, a dedicated effort will attempt to define accurate experimental protocols and standards.

-One part of our future work will be devoted to the investigation of phonons, electron-phonon interactions and optical properties of graphene and MLG. The ongoing projects are conducted within different emerging collaborations with F. Mauri (IMPMC, Paris; confrontation between experiments and theory), G. Baffou (nstitut Fresnel, Marseille; optical and thermal properties) and E. Dujardin (CEMES, Toulpuse; suspended graphene).

-Another part of our activities will be dedicated to the study of graphene/MLG based hybrid systems in collaboration with chemist groups (INAC, ICG, INC). The investigations of alkali doped graphene will be continued in particular on suspended graphene samples. We will also follow on non-covalent functionalized graphene with photo-active organic molecules, focusing on their optoelectronic properties. Finally, we aim at developing projects on covalent functionalization of graphene.

A PhD thesis entitled “Impacts of physical or chemical manipulations on graphene properties” starting in October 2013 will deal with most of the aspects described above. This thesis will be jointly supervised by A.-A. Zahab, M. Paillet, A. Tiberj and J.-R.Huntzinger.

Another important topic of this research axis is to manipulate and study sinlgelayer graphene (SLG). The manipulation consists, in one part, to achieve a better control of the carrier density in these samples, in order to fulfill the requirements needed for the current ANR grant "MetroGraph": large SLG sizes (~mm) and low concentration (< 1012cm-2) are mandatory.

We will also focus on the transport properties in these structures: limitations of the breakdown current in the Quantum Hall effect, in particular, should be clarified. Besides, additional manipulation will be attempted, in order to manipulate spin-orbit coupling in graphene. The study of spin-orbit coupling (SOC) in graphene is motivated by the huge experimental activity in the field of graphene spintronics. For instance, we propose an original way to study spin-orbit coupling. Instead of using ferromagnetic contacts, we will use metallic contacts with large samples, and we will look for weak anti localization (WAL) induced by SOC. This WAL has been recently predicted [PRL 108,166606 (2012)] and has nothing to do with the WAL induced by the graphene pseudo-spin. The observation of such a WAL and its understanding would make possible the realization of “graphene spintronics” devices (quantum spin Hall states, spin Hall effect, etc.).

Department "Applied Physics"

In 2011, the team "Materials, devices and sensors" was created from the merging of complementary topics: material elaboration and fundamental research on materials and devices. To evolve toward a real team spirit, some time was needed to learn to know each other through scientific animation with the desire to achieve common and cross-thematic projects. Although a lot has already been done, we will need more time to strengthen this objective.

The THz spectroscopy team was founded in 2000 having as objective to explore the new physical phenomena lying in the frontier of physics of high frequency (THz) instabilities in solids and nanotechnology. It developed strong collaborations with different industrial partners (ST Microelectronis, Canon, New Tera Technology- Italy, III-V Lab - Alcatel-Lucent/Thales) looking for validation of the results of basic physics by applications (nano-transistors based THz detectors, cameras and emitters).

Strengths: The team "Materials, devices and sensors" has a long lasting recognized experience in the fields of elaboration and physical studies of several kinds of materials: semiconductors, organic and/or inorganic materials such as bulk, ultra porous or coating. We are extremely well equipped with characterization tools for advanced materials and structures, in complementary areas such as structural, optical and electrical analysis. We combine efficiently our fundamental research activity with applied physics actions.

During the past period, as can be checked from the objectives of our last evaluation report, we have been closely sticking to our goals in promising subjects, such as the graphene activity. In contrast, we have shown our ability to make sharp decisions by terminating some activities, like the indium nitrides studies, which have shown at the worldwide scale to be limited by fundamental deadlocks, in order to start new, more promising researches on photovoltaic materials.

The graphene research activity, stemming from our expertise on SiC, was performed in the framework of an inter-department project between the CVN and SMC departments of our laboratory. This project was presented as an ambitious transversal one in the previous contract. To date, the first milestones have been fulfilled: we have obtained financial support for the purchase of a micro-Raman spectrometer, and a resistive graphite furnace which will enable us to have access to local, on-demand, samples. Additionally, we will be able to supply the scientific community with our samples, and develop new collaborations. The recruitment of an assistant-professor in charge of the growth activity is a very positive point. A good scientific production and three funded ANR projects have already confirmed the success of this activity.

Concerning our collaborations, our group has strong interactions with the industrial and economic environment, and receives significant support from it, in parallel with a number of ANR and European funding which also demonstrate the academic recognition of our research activity.

The strength of THz spectroscopy team resides mainly in very well defined research strategy focused on Terahertz excitations in nanostructures. Thanks to close collaboration with theoreticians (Prof. M. Dyakonov , Prof. M. Shur , Prof. S. Popov) and competitive experimental studies, our team became a world leader in the physics of Terahertz excitations in nano-transistors. Support from industrial partners as well as national and international projects allowed building one of the best equipped THz laboratories in Europe. The strength of the team is maintained by multiple international collaborations. The team is leading since 8 years a GDR and GDR-I networks on Semiconductor Sources and Detectors of THz radiations. The strength in applied physics domain is confirmed by many patents and by the creation of a start-up based on Terahertz imaging for industrial control.

Weaknesses: We are a new, multidisciplinary team, spread over three different buildings, hence resulting in a feeling of insufficient internal scientific communication and cooperation.

In some areas, one might point out the insufficient dissemination of scientific findings through publications and international conferences. However we have historically been involved in other types of production such as patents, due to our strong connections with the industry.

Concerning Graphene, there is a real uncertainty for future funding if the laboratory is excluded from the European Flagship Program although we have actively participated in the project elaboration for several years.

The lack of a research engineer, specialist of clean room work, in order to adequately support technological projects strongly penalized our group, as well as the whole laboratory. This will be even more critical when the clean room will be relocated outdoors from the University, next year.

The weak point of THz team is the lack of competencies and equipment necessary for time and space resolved studies of THz excitations in solids. To acquire these competences a recruitment of a researcher and/or an engineer is necessary. Such recruitment is relatively urgent because without an additional person the team has very weak chances to keep its leader position in the next years.

Opportunities: In the framework of the laboratory reorganization, we create a new “Applied Physics Department” based on three well defined teams. In order to give more visibility to our research activities, the initial team “Materials, devices and sensors” will split in two parts: “Hybrid and Nanostructured Materials” team will continue on physical studies of organic and/or inorganic materials and “Semiconductors: Graphene, Wide Bandgap and Photovoltaic” team will continue in its core research activity: physical studies of semiconductors (from zero-gap to wide bandgap and photovoltaic cells). The third team will still be named "Terahertz spectroscopy and quantum metrology", and it will continue its traditional activity on Terahertz excitations in nanostructures and nano-devices, however this new department will give us more opportunities for common projects and sharing of experimental facilities.

In the framework of the laboratory reorganization, the new Applied Physics Department is created. It gathers teams who decided to perform high level solid state physics research together. This work will aim at new applications and will be reinforced by industrial collaborations. We have decided to take advantage of our mixed knowledge and expertise in the fields of material science, epitaxy, device physics and processing, advanced transport and optical characterization. These competences create a technological synergy at the frontier of electronics, medicine, metrology, energy harvesting and optics. Three teams will compose the department:

- **“Hybrid and Nanostructured Materials” Team** will be devoted mainly to the elaboration and physical studies of organic and/or inorganic materials as bulk and ultra porous or coating materials.
- **“Semiconductors and Nanophysics” Team** will be involved in the growth of semiconductors and their studies for potential applications. Graphene activities of the team are in the main part performed in the framework of the “Axe transverse graphène”. Other activities will be oriented towards wide band gap materials (SiC, GaN,…) and photovoltaic cells based on CuGaInSe2 and related semiconductors.
- **“Terahertz Spectroscopy and Quantum Metrology” Team** will focus on physics of plasmonic excitations and topological insulator effects in semiconductor nanostructures. These investigations using optical (from THz up to mid infrared MIR) and magnetotransport methods will be performed also in view of their potential applications to THz vision, wireless communication and new metrological etalons.

Team: Hybrid and Nanostructured Materials

Pascal Etienne (PR1), Sylvie Etienne (MCF), Annelise Faivre (PR2), Nathalie Olivi-Tran (CR1), Florence Despetis (MCF), Laurent Bonnet (AI).

As mentioned above, the activity of the group is divided into 4 parts and of course projects follow this scheme.

We are near the end of the silica-cell program. This work shows feasibility in using ultraporous silica reinforced with cellulose as superinsulating materials. However, for an industrial point of view, CO_2 supercritical drying is difficult to control and expensive. The next step is then to replace such a method by a drying in subcritical conditions (evaporation type) to obtain xerogels. To avoid a densification and a potential cracking of the gel during the drying, pore surface has to be hydrophobic. We plan to use a silylation process. Then, textural, structural and thermal properties of such hybrids materials will be studied.

Concerning glass science, three main subjects will be analyzed in the next years. First, we think that a study of subcritical crack growth in mixed alkali phosphate glasses could provide a better understanding of the relation between crack propagation and cations mobility. Mixed alkali glasses indeed exhibit nonlinear changes as a function of the relative alkali content, in the properties related with cations mobility. Secondly, analysis of thermal self-healing of indentation-cracks evidenced that at 620°C the viscosity of the glass surrounding cracks can be significantly reduced by water diffusion and glass hydrolysis, or increased by glass des-hydration. We propose to better analyze the consequences of hydration and des-hydration on compositional and structural changes at the glass sub-surface during thermal treatment. Thirdly, surface tension is an important property for the understanding of phase separation in glasses and plays an important role in glass shaping. We recently develop a small moving furnace allowing to locally heat a glass fiber from the bottom to the top. Measuring the fiber elongation as a function of the furnace position allows deducing surface tension. We are interested in measuring the surface tension of different glass compositions using this set-up. We will specially concentrate on the relation between surface tension and phase separation in glasses.

We studied organic-inorganic hybrid materials used as negative resins for over twenty years. This kind of materials has been particularly relevant to make small surface structures on a substrate such as waveguides using laser writing process. However, it is completely unusable to make large surfaces required for example for microfluidic devices. Positive type resin has to be used. Such a material exists but only under organic form with a life span no long enough to perform sustainable devices. We plan to improve this behavior by using organic-inorganic material. First of all we will establish collaboration work with a chemical lab to synthesize a new precursor. We will work then on the sol synthesis suitable to be deposited on a silicon substrate and laser written in the UV range to make micron size channels.

The behavior of fluids embedded in a container of nanometric dimensions has been studied experimentally for only a few years, due to the technical difficulty to 'pour' fluids in such small containers. A solution would be to analyze fluids contained in silica gels (obtained by a sol gel route). In our group, we used the 'hint' to replace part of the solvents used in sol gel techniques by ionic liquids (organic molten salts which are liquid at room temperature). Indeed, by this way, it is possible to measure the response of the polar liquid, contained in the nanometric porosity of the gels, to an electrical pulse. We already obtained several responses in different experimental conditions. From now on, we will perform numerical simulations (Brownian dynamics, classical molecular dynamics etc.) to model our experimental results and we think that we could find new characteristics of the behavior of liquids at nanometric scales.

Team: Semiconductors: Graphene, Wide Bandgap and Photovoltaic

Sylvie Contreras (CR1), Wilfried Desrat (MCF), Jean-Roch Huntzinger (MCF), Benoit Jouault (CR1), Sandrine Juillaguet (MCF), Leszek Konczewicz (MCF), Périne Landois (MCF), Hervé Peyre (MCF), Antoine Tiberj (MCF).

Topic 1: *Wide Band Gap Semiconductors*

These research activities will continue in the framework of different contracts and collaborations.

Concerning SiC topics, the main scientific objective of Marie Curie NetFISiC project is to provide SiC material (of various polytypes) with improved and adequate functional interfaces for getting a step forward in electronic devices performance (Thesis P. Kwasnicki).

Concerning research on GaN-based structures, the collaboration with Unipress laboratory in Warsaw will focus on electrical properties of heavily doped p-type materials and semi-insulating thin layer structures and bulk material. In the framework of the national network GANEX, dedicated to the development of devices based on GaN and its alloys, we participate to the power electronic devices axis. We study the high temperature electrical properties of high electron mobility transistors (HEMTs) provided by CRHEA and CEA-LETI laboratories.

Topic 2: Graphene

Our team is strongly involved in the research activities developed among the interdepartment graphene project “Axe transverse graphene” with a special emphasis on epitaxial graphene on SiC.

The close collaboration with the “**Individual low-Dimensional Carbon Structures**” team has been fruitful and led us to define a common research project which is detailed in the **“Axe transverse graphene”** (see the section Departement: Nanomaterials and Spectroscopies, team: Individual low-Dimensional Carbon Structures)

Besides the “axe transverse graphene”, we also aim at combining transport and THz spectroscopy in graphene, in order to determine if graphene can be promising for optoelectronics applications, such as photodetector, THz imagers, or plasmonic devices. This work will be done in collaboration with the Tera Hertz Team of our department. In a first time, we will focus on photoconductivity under THz emission. Other possibilities, as graphene FET detectors, will be also attempted. In collaboration with Thz group, we also aim to control of the bandgap in 2D topological insulator structures or in 3D small gap semiconductor by the use of hydrostatic pressure.

Topic 3: Photovoltaic structures

Roger Aulombard (PREX), Olivier Briot (DR2), Matthieu Moret (IR), Sandra Ruffenach (IR).

Our project consists in building up on the know-how that we have just established. We have learned how to grow all materials involved in a CIGS solar cell. We will now fabricate and characterize full cells, in order to link the cell performances to the materials structures and properties, and identify the limiting points. We will then be able to investigate in depth the physical mechanisms involved. It may be in the device design and operation (band structure alignments in the heterojunction, carrier dynamics and recombination processes, contacts, electrical properties of the layers in relation with their microstructures (grain boundaries, …) or upstream in the fabrication process, by identifying factors limiting the material quality in the growth process and improving it.

The means to this end are already at hand : we have a large set of sophisticated characterization tools : high-resolution X-ray diffraction, AFM microscopy, reflectivity and photoluminescence experiments with closed loop temperature control from room temperature down to 4K, solar simulator, … By strengthening the links within our new department we will benefit from the expertise of our colleagues regarding transport measurement, the possible use of graphene transparent electrodes, chemical bath deposition and solution coating techniques.

At some point, we will extend our activity to new materials, in view of finding and using more abundant raw materials, since the indium resource might be questioned. In this respect, kesterites are an option, but many other paths are also suggested in the literature.

Team: Terahertz Spectroscopy and Quantum Metrology

Nina Diakonova (IR), Dominique Coquillat (DR), Petre Buzatu (IE), Pierre Solignac (IE), Boris Chenaud (MCF), Christophe Chaubet (PR), Frédéric Teppe (CR), Wojciech Knap (DR).

The main part of our team's project is concentrated on optical (THz and MIR) and magnetotransport properties of semiconductors with special accent on graphene and graphene-like semiconductor nanostructures. The two considered axes are i) plasmonics, and ii) topological insulator effects. Except graphene, two semiconductor systems are considered: HgTe/CdTe (with IPM Russia), GaN/InN (with IHPP-Unipress Warsaw).

Concerning plasmonics, the high mobility necessary for plasma waves resonances can be easily achieved in graphene and in graphene-like semiconductor structures. Such structures can be achieved using HgTe/CdTe, or GaN/InGaN based nanostructures. We will compare the nanodevices based on graphene and graphene-like semiconductor nanostructures.

For topological isolator : the specific band structure of these materials allows observing Quantum Spin Hall effect. These effects will be investigated by transport and THz optics methods.

Below we present in more details some of the planned/future research activities

Graphene like semiconducting systems: As written earlier, HgCdTe-based QWs exhibit a number of remarkable properties. For example, the very strong spin-orbit coupling in these materials makes them good candidates for experimental observation of the Spin Hall Effect in semiconductors predicted more than 40 years ago by Dyakonov and Perel. The aim of this part of the project is therefore to study by THz spectroscopy and magnetotransport, these new physical effects appearing in HgCdTe based materials. We are currently applying for different bilateral projects on the HgCdTe physics to link L2C with IPM Nizhny Novgorod and UNIPRESS Warsaw.

Plasma instabilities in Nitrides: We would like also to continue research on plasma instabilities in Nitrides based nanometer FETs. They are until now the best experimental systems because they are the only transistors that have shown both plasma wave resonant detection and emission. They have also important carrier densities that allow to rich higher plasma frequencies. In THz emission conversion efficiency is relatively low. High power levels handled by nitrides give also more efficient THz emission. There are two main scientific problems aimed to be solved by the proposed project: i) First is how to understand the physical reasons of unusual plasma wave resonance broadening and second ii) how to verify possibilities of existence of new type of plasma instabilities and in particular so called “edge or white water instability”. These two problems are linked because the edge instability, that maybe responsible for observed broad THz emission, is due to oblique plasma modes that at the same time lead to the plasma resonance broadening.

Ultrafast THz detection by plasma oscillations in FETs (THz communication): In parallel to the main line of the project, we also have different plans related to basic and applied physics. With a high detector sensitivity (optimized transistors based on new materials), high speed wireless data transfer at THz carrier frequency up to 30 Gbit/s are theoretically possible. We propose to explore the improvements by use of new devices such as graphene based FETs and InP heterojunction bipolar transistors. In one hand, owing to the zero-gap or narrow gaps in graphene monolayers and multilayers or nanoribbons, graphene–based transistors appears to be very promising for the development of new high-speed THz detectors. This research will be done in the frame of industrial contracts like for example Canon (accepted) and ANR project (accepted - ANR NADIA for 42 months), in synergy with Teralab.

Metrology: Concerning our metrology activity, we plan in the next five years to work on the a.c. measurement of the von Klitzing constant R_K. It is well known that the QHE is used by metrology laboratories around the world to conserve the Ohm's etalon, thanks to its great stability in dc : The Hall resistance at the plateau $\nu=2$ does not deviate from its theoretical value $R_K/2$ by more than one part in 10^9. However R_K is measured in a.c. conditions and until recently the quantization in a.c. has not been better than 10^{-8} in relative value due to the frequency dependence of the Hall resistance. We have proved recently that a specific sample topology suppresses the frequency dependence and allows a better measurement of R_K. We proposed a new experimental scheme to measure easily the capacitance matrix, by measuring the admittance at low frequencies. In the coming years we ought to study more precisely the geometrical and quantum capacitance of the Hall samples that are used for this metrological measurement.

Department "Physics of the Excitons, Photons and Spins" (PEPS)

The PEPS team will evolve into a new Department with theoretical and experimental research activities that will be more centered on the photon, considered both as an object of study and as a tool. Indeed, the two researchers (S. Charar and F. Terki), who were rather involved in transport and magnetism, are leaving the L2C from July 2013, towards the Institut Charles Gerhardt (Chemistry). The activity on plasmonics and quantum metamaterials will benefit from the recruitment of L. Doyennette (MCF) (experimental aspects), at the beginning of 2013 and of R. Messina (CR-CNRS), end of 2013 (theory).

The PEPS Department is strongly involved in basic physics, but we wish to emphasize the interest of our spectroscopy facilities for industrial collaborations: the originality and performance of our setups in the ultraviolet and in the telecom range of wavelengths, for example, make them particularly attractive. A growing number of one-time studies are already being performed by our devoted "plateformes", e.g. for characterization of ultra-short-wavelength LEDs, or time-resolved measurements for the French company Photonis.

Our investigations, in the next few years, will focus (1) on the extension of our studies of nanostructures in the spectral region [195-250 nm], (2) on the optical manipulation of quantum states in artificial nanostructures, (3) on the strengthening of the coupling between radiation and matter (strong coupling, Purcell effect, weak-signal detection of biological molecules, etc), (4) on the conception and study of nanostructured materials (metamaterials, quantum nanostructures...) designed to produce novel physical phenomena and novel functionalities. Obtaining significant results will therefore rely on structures fabricated by partner laboratories and technology centers with which we maintain close collaborations, e.g. within projects supported by the ANR and/or the Labex "GaNex".

The activity on polariton physics will evolve towards the study of polariton condensates, their optical control, and their propagation in polariton circuits. Among common projects, dense gases of interacting dipolar excitons will be studied, within the INDEX European project, coordinated by M. Vladimirova. A significant part of the latter project will rely on our expertise on wide-band-gap nanostructures (nitrides, ZnO…). This core of our experimental activity will evolve towards microscopic and time-resolved spectroscopy studies of aluminium-rich (Al,Ga)N nano-objects, e.g. nanowires, and of state-of-the art nonpolar and semipolar quantum wells baed on GaN or ZnO. The now well established collaboration between experimentalists and theoreticians of PEPS will continue on the topic of quantum metamaterials. Concerning spin dynamics, one important objective will be the detection of spin noise from magnetic impurities (Mn) in condensed matter, for which a specific setup is being developed (ANR project SNS). The biophotonic activity will focus on neuron regenerative growth, cancer treatment, and optimization of photonic structures for biosensing applications.

Opportunities/Risks: From the above topics, one can judge of the first duality of our research activities: we keep on helping our colleagues growers explore new paths, while –on more established material systems– we prescribe and study specific, complex structures aiming at producing novel quantum effects. Concerning our experimental facilities, we are facing a second duality: some experiments correspond to several ongoing PhD theses (long-term research), whereas the unique character of our setups induces a growing number of one-time collaborations, each of which could be a starting point for interesting new research.

Finding the proper balance between the different types of activities, with the current constraints of research funding (i.e. the necessity to constantly improve our technical offer), is really the difficult challenge that we will have to deal with in the future. The proper handling of our time investment between instrumental development and scientific results is a challenge, in the context of a growing number of our researchers involved in management tasks, of an increasing diversity of topics and of simultaneous PhD theses, often inducing a quasi-saturation of some of our setups (more specifically the UV-spectroscopy).

Our Department is faced with the constant need for competitiveness, which we handle, first, by a stronger synergy, especially between theoreticians and experimentalists. Experimentally, in order to maintain our worldwide competitive position, we will also pursue our efforts for the development of unique spectroscopic tools:

- UV-spectroscopy (time-resolved-µPL) will be enhanced to wavelengths near 200nm, on one hand, and towards quantum optics measurements of the photon statistics, e.g. on single GaN quantum dots, on the other hand.

- The multiphotonic spectroscopy setup capabilities will be extended to allow for time-resolved measurements with sub-millisecond temporal resolution with the aim to record optically the neural activity.

- For the optical manipulation of both exciton-polaritons and indirect exciton, we are performing further developments of the micro-PL setup.

- We are also developing two new setups devoted to the study of plasmonics and quantum metamaterials in the infrared range, and which require a new femtosecond laser seeding a parametric oscillator (that are not funded yet).

- The pump-probe spectroscopy setup devoted to spin dynamics needs also to be developed to allow for spatially resolved studies on indirect excitons (INDEX project), and on patterned magnetic materials to explore the transport of spin information between two magnetic layers (TRIMEMS project submitted to the ANR).

- A unique spin noise spectroscopy setup based on optical heterodyne detection will be developed.

Most of the scientific objectives of the Department proceed from our activities over the past period, but with some significant evolutions, the most important one being probably the strengthening of internal collaborations within the Department, as testified by several common projects.

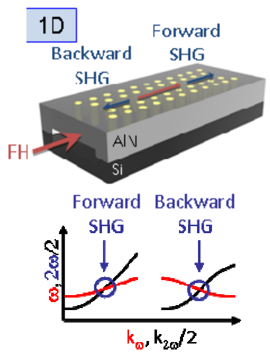
Topic 1: *Light-matter coupling and quantum phenomena*

Researchers involved: C. Brimont (MCF), T. Guillet (MCF), P. Lefebvre (DR), B. Gil (DR), S. Cronenberger (MCF), M. Vladimirova (CR), D. Scalbert (DR), G. Cassabois (PR), E. Rousseau (CR), L. Doyennette (MCF), O. Kamoun (PhD), R. Hahe (PhD), J. Sellés (PhD), D. K. Van (Post-Doc)

Those activities bridging exciton confining nanostructures and photonics, as well as theoretical and experimental activities, were initially identified as a transverse theme in the team. They now become a common orientation of many projects. They share the need for strong national collaborations, and the long time constants associated with the design, fabrication and spectroscopy of the state-of-the-art nanostructures requested for their implementation. Those activities have been pursued with persistence despite their inherent risks, with some successes, and the same policy will drive our emerging projects.

During the next years, the activities on ZnO polariton condensates (C. Brimont, T. Guillet) will bend towards their optical control and their propagation in polariton circuits (PhD thesis of R. Hahe). Existing high-Q ZnO microcavities already allow studying the propagation of polariton condensates along a potential gradient or in a flat landscape, in both regimes of small and large condensate diameters, as well as their coherence properties. Thanks to the recent progresses of nitride Distributed Bragg Reflctors and ZnO active layers (F. Semond, J. Zúñiga-Pérez, CRHEA), next generations of cavities will provide new geometries and dimensionalities, *i.e.* 0D and 1D polariton condensates. The understanding of the dynamics of the polaritons and the exciton reservoir is crucial in order to improve the generation and coherence of condensates; this dynamics will be time-resolved and modelled in close collaboration with G. Malpuech (Institut Pascal, Clermont-Ferrand) for phase diagrams, and within a new collaboration with S. Jaziri (LPMC, Bizerte, Tunisia). This is the subject of the PhD thesis of O. Kamoun (2012-2014, co-supervised by T. Guillet and S. Jaziri) and a new theoretical thesis co-supervised by B. Guizal and S. Jaziri (Partenariat Hubert Curien 2013-2015). This activity is also closely linked with the work on dipolar exciton condensation in nitride and ZnO polar quantum wells (P. Lefebvre, M. Vladimirova), both for fundamental concepts and challenging experimental developments.

Concerning nitride photonic nanostructures (C. Brimont, T. Guillet, B. Guizal, D. Felbacq), the two main goals concern the demonstration of a nano-laser based on a few GaN quantum dots, up to 300K, and the implementation of photonic waveguides for the control of second harmonic generation (SHG). This ANR project named QUANONIC (programme blanc) will start in 2014, based on our experience on nitride photonics developed in the previous ANR program SINPHONI (F. Semond, CRHEA; P. Boucaud, IEF; B. Gayral, INAC). The spectroscopy of low-threshold lasers based on GaN quantum dot excitons or GaN polaritons will be investigated. With B. Guizal and D. Felbacq, new photonic geometries will be conceived, that fullfill original phase-matching conditions for SHG as theoretically predicted some years ago by E. Centeno (GES) and illustrated on the adjacent figure.



Moreover, in the framework of the GaNeX network, Julien Selles started in october 2012 a PhD thesis, under the supervision of T. Guillet and G. Cassabois, on the optical spectroscopy of single GaN quantum dots embedded in a planar microcavity. The purpose is to increase the emission extraction and to perform quantum optics measurements of the photon statistics. Concerning the activities on plasmonics and quantum metamaterials, the development of the experimental setup will allow exploring the spectroscopy of the nanostructures elaborated at L2C and LPN.

Our projects on plasmonics and quantum metamaterials (E. Rousseau, L. Doyennette, G. Cassabois) in the infrared range aim at exploring the optical and quantum properties of novel semiconductor devices following 2 complementary guidelines: (1) investigation of a single nanostructure coupled to an optical cavity made of a plasmonic antenna; (2) collective macroscopic properties of an ensemble of nanostructures, forming a quantum metamaterial:

- Plasmonics: our strategy is twofold. First, by choosing 1.55 µm, we work in a spectral region where the metal losses are significantly reduced as compared to visible. Second, we design plasmonic antennas in order to increase their efficiency. Three types of antennas are investigated: the disk antenna, the patch antenna (a metallic disk on top a metallic plane) and the metal-dielectric patch antenna (a dielectric resonator deposited on top of a patch-type antenna). We are now testing disks antennas fabricated in the local clean room with different types of emitters (carbon nanotubes, PbS nanocrystals, InP nanowires). The increasing complexity of the designs will allow us to carefully study the specific aspects leading to the highest efficiency. Indeed, theoretical calculations indicate that an overall efficiency of 75% at 1.55 µm can be achieved with a metal-dielectric patch antenna, with a spontaneous emission rate increased by two orders of magnitude, corresponding to Purcell factors of a few hundreds.

- Quantum Metamaterials: our ambition is to initiate theoretical and experimental studies of the influence of an active medium for creating quantum properties in metamaterials. Our first implementation relies on InP nanowires with InAsP insertions. We work in collaboration with national technological centers (LPN-Marcoussis, J.C.Harmand) in order to get nanowire samples with an optimized geometry. A critical point consists in working with nanowires that are (i) a few tens to a few hundreds of nm in diameter, and (ii) long enough compared to the quantum dot absorption wavelength in order to reach a quasi-2D configuration for the metamaterial. The bottom-up approach based on the growth of nanowires, that are several µms long, is thus mandatory for this project. We are currently performing the optical characterization of pure InP nanowires samples in transmission geometry with a propagation perpendicular to the nanowires axis, thanks to planarization techniques with a low refractive index material allowing measurements in a waveguide-type configuration. We will then study the active metamaterials with embedded InAsP quantum dots by pump-probe spectroscopy with a pump laser devoted to the excitation of the quantum dot, and a probe one used for in-plane transmission measurements.

Topic 2: *Optical properties of nanostructures*

Researchers involved: B. Gil (DR), T. Bretagnon (MCF), P. Lefebvre (DR), T. Guillet (MCF), C. Brimont (MCF), G.Cassabois (PR), E. Rousseau (CR), L. Doyennette (MCF), D. Rosales (PhD), L. Colombier (PhD), J. Sellés (PhD), D. K. Van (Post-Doc)

Research on ZnO-based nanostructures will evolve towards more detailed studies of state-of-the-art QWs, including those grown along nonpolar and semi-polar planes, with special emphasis on the observation of excitonic complexes (T. Bretagnon, B Gil), in collaboration with the CRHEA-UPR10 in Valbonne.

In parallel, concerning group-III nitrides, we will pursue the study of QWs and QDs grown along high-Miller-index crystallographic planes [PhD thesis: D. Rosales, co-directed by B. Gil and T. Bretagnon], in collaboration with H. Morkoç (Virginia Commonwealth University, USA, in the context of the international ANR GASIOPHE) and J. Brault at the CRHEA in Valbonne. The objective is to conceive and realize heterostructures with high internal quantum efficiency and anisotropic optical response grown on either homo-epitaxial conditions or on textured foreign substrates like for instance silicon. The story is just beginning but we have already observed substantial anisotropy of light emission intensity and decay time for quantum wells grown M-Plane supplied by the VCU. Preliminary results obtained on (11-22)-grown samples realized by J.Brault (CRHEA) have also evidenced transitions from quantum dots to quantum wires in straightforward relation with the anisotropy of the growth plane. The study of quantum object with anisotropical optical response is a promising field that will develop in the context of GASIOPHE and besides it.

Time-resolved spectroscopy of those systems that emit at shorter wavelengths, i.e. high-Al-content AlGaN-based nano-objects (QWs, NWs…) is being supervised by C. Brimont and P. Lefebvre, in particular in a collaboration on (Al,Ga)N nanowires with the CEA-Grenoble (B. Daudin and B. Gayral), through a common thesis supported by the LabEx "GaNex". Promissing experiments have been performed in the past few months on LED structures emitting around 215 nm (Univ. of Mie, Japan) and also on diamond samples, in collaboration with J. Barjon (GEMaC, Versailles), opening the way to increasing activity and collaborations in this range of wavelength for which the configuration of our setup is unique.

Special emphasis will be put on the study of dense gases of interacting dipolar excitons, within the INDEX European project, coordinated by M. Vladimirova. Preliminary results on polar GaN- and ZnO-based QWs encourage us to pursue the production of ultra-long-lived, dipolar excitons, and experimental strategies for obtaining condensates of them, *e.g. via* optical trapping. [PhD thesis: A. Kruse, co-directed by P. Lefebvre (wide-band-gap polar QWs) and D. Scalbert (spin dynamics in GaAs double QWs).]. Specific collaboration has begun with two groups at CRHEA (Valbonne), for the growth of state-of-the art GaN-based (B. Damilano) and ZnO-based (J.M Chauveau) polar and semi-polar quantum wells, free of nonradiative recombination.

Concerning our studies in the infrared range of the spectrum (E. Rousseau, L. Doyennette, G. Cassabois), our observation of the biexciton in carbon nanotubes by nonlinear induced-absorption measurements opens the way to complementary experiments, like the search of the biexciton signal in PL spectroscopy, for which we will try resonant two-photon excitation. Non-resonant excitation has been unsuccessful so far because of efficient Auger annihilation processes. [PhD thesis: L. Colombier, directed by G. Cassabois]. Moreover, the plasmonics and quantum metamaterials activities (described above) require basic studies of the nanostructures forming the active material, namely carbon nanotubes, InP nanowires or PbS nanocrystals, with an accent put on identifying dimensionality effects.

- The coupling of a carbon nanotube to a plasmonic antenna appears as an interesting tool for enhancing the optical response of the carbon nanotube and detecting the small photoluminescence signal of the nanotube.

- In PbS nanocrystals, we will perform measurements either by single nanocrystal photoluminescence spectroscopy or nonlinear hole-burning in order to resolve the homogeneous broadening in these nanostructures. This information provides a direct access to their intrinsic properties and it will allow us to determine the optimal structure (diameter, core or core/shell) for their insertion in plasmonic antennas;

- In InP nanowires, J.C. Harmand (LPN-Marcoussis) will grow InAsP quantum dots with well-identified optical selection rules when elongated either parallel or perpendicular to the nanowire axis (with a typical diameter of 60 nm). The latter configuration leads to the best geometry for polarization matching with the plasmonic mode in the coupled nanowire/antenna systems.

Topic 3: *Spin dynamics and magnetism*

Researchers involved: S. Cronenberger (MCF), M. Vladimirova (CR), D. Scalbert (DR), S. Andreev (PhD).

Our expertise in linear and nonlinear magneto-optics will serve in the next years both to tackle some still pending fundamental issues in semiconductor spin physics (all-optical coherent generation of spin-flip waves, optical detection of magnetic impurity and of nuclear spin noise, studies of indirect exciton spin dynamics within the ITN INDEX project (2012-2016) coordinated by M. Vladimirova, etc), and also to explore the possibilities to apply these techniques in different contexts.

We hope to apply the spin noise spectroscopy technique, which we are developing in the framework of the ANR project SNS (2011-2014) coordinated by D. Scalbert, to functionalized magnetic nanoparticles, to assess their magnetization dynamics. These studies have potential bio-medical applications, and will be done in collaboration with F. Teran from IMDEA in Madrid.

Further developments of the pump-probe setup could allow us to explore the transport of spin information in different kind of magnetic spacers between two permalloy layers, in collaboration with PROMES (Perpignan) and GEMaC (Versailles), depending on eventual future fundings (a regenerative amplifier is needed to reach the required optical excitation density). We wish also to demonstrate the possibility of selective generation of magnons with well-defined k-vector in four-wave mixing experiments.

Topic 4: *Bionanophotonics*

Researchers involved: C. Gergely (Prof), M. Martin (MC), T. Cloitre (MC), O. Benzina (PhD), S. Ramakhrishnan (PhD).

Our further biophysical investigations on neurons in regenerative growth-mode, addresses the post-traumatic neuropathies, which are often chronic and mostly resistant to current treatments. We propose the use of micropatterned surfaces for controlled cell surface contact and guided neuron growth also enabling study of single cell arrays.

Atomic force microscopy and multiphoton microscopy will be used to evaluate the state of neurons in terms of their morphology, nanomechanics and activity (intracellular chloride and calcium fluctuations) under the effect of various external conditions. Via multiphoton microscopy cell activity can be simultaneously recorded at multiple locations of the dendrite-axonal tree of a neuron with sub-millisecond temporal resolution, demonstrating the ultimate power of optical recording of neural activity over conventional measuring techniques.

Such a development in our project is justified also because optical methods for monitoring membrane potential enable a greater understanding of the mechanisms underlying single neuron firing properties and cooperative electrical signaling in groups of neurons. It would be extremely innovative to be able to address a single specific cell and follow signal propagation from one or several sensory neuron.

In the framework of the studies concerning cancer treatment we already started and we'll continue monitoring drugs internalization in single malignant cells and their effect on cells biophysics. We plan to continue the development and the study of optimized photonic structures for biosensing applications. The observed unique intrinsic luminescent properties of the porous silicon structures can be further exploited as "microscopic biosensors" based on the luminescence response of individual pores when molecules are adsorbed, contrary to the previous sensing methods where detection was based on a macroscopic spectral response of the whole structure. We aim also to develop compact biosensors based on bio-selective functionalization of a GaN.

Topic 5: *Theory of Coupled light-matter systems*

Researchers involved: M. Antezza (MCF), D. Cassagne (PR), D. Felbacq (PR), B. Guizal (PR), R. Messina (CR2), B. Bellomo (Post-Doc), A. Castanié (PhD), N. Bartolo (PhD), A. Noto (PhD), R. Razafindrakoto (PhD).

Our activity comes under the theoretical and numerical study of light-matter interaction both at the classical and quantum levels. Until recently, our principal directions of research concerned electromagnetic waves in photonic crystals and metamaterials (D. Felbacq and D. Cassagne) and Plasmonics (D. Felbacq, B. Guizal). Our main results concerned the following points: (1) the generation of second harmonic in nonlinear photonic crystals and the realization of a biphotonic lens, (2) the study of the amplification of surface plasmon in layered nanostructures (PhD thesis of Aurore Castanié), (3) the theory of mesoscopic magnetism in dielectric metamaterials. We had a strong will of orienting our activities towards the quantum aspects of light-matter interaction, which led us to hire of a specialist of quantum physics (M. Antezza) and a specialist of quantum optics (R. Messina starting end of 2013).

In the future, we plan to develop the following directions:

1-Quantum metamaterials: we plan to deeply develop this topic, which consists in studying the effective electromagnetic behavior of a nanostructure in which microscopic quantum systems are embedded. A typical example is an array of dielectic nanowires inside which quantum dots are inserted. This will be one of the main new activities of our group, in close interaction with the experimental group of G. Cassabois. We hope to get a funding from the ANR (our project AQUAMETA is second on the supplementary list of the Programme Blanc SIMI 1).

2-Quantum plasmonics: this will be the follow-up of A. Castanié's PhD. It consists in studying the strong coupling of surface-plasmon polaritons with confined guided modes, with the aim of obtaining of full quantum description of the spaser effect (surface plasmon laser) in such a configuration.

3-Casimir effect and Heat transfer: we developed a general theory allowing the description of the Casimir Effect and of the Radiative Heat transfer among bodies of arbitrary geometry and dielectric function, in configuration out of thermal equilibrium. This work will allow ud to study these effects in several new configurations (nanostructured surfaces, metamaterials, gratings, many bodies…) in order to tackle important open problems of both fundamental and applicative nature like stiction in NEMS and NEMS, amplification of the heat transfer (A. Noto's PhD).

4-Quantum scattering of trapped ultracold atoms: this new direction (N. Bartolo's PhD) consists in studying the scattering of an atomic species by another species confined in a harmonic trap. It will be the elementary block to build a more general theory allowing us to tackle the problem of artificial graphene structures made by cold gases.

5-Photonic crystals and dielectric metamaterials: we will study the generation of second harmonic in such structures in the framework of the recently accepted ANR project QUANONIC led by T. Guillet. The study will be extended to nonperiodic structures such as photonic glasses (i.e. with a correlated disorder).

6-Modeling of Terahertz emitters and sensors (R. Razafindrakoto's PhD). We will model devices comprising electron gases supporting plasma instabilities embedded in photonic nanostructures, in order to design an imaging device in the THz range. This activity will be performed in collaboration with SAGEM-Défense and W. Knap's group.

Pluridisciplinary Group “BioNanoNMRI”

The Team “BioNanoNMRI” from the L2C will be composed of tenured researchers: Goze-Bac C. (DR), Kouyoumdjian P. (PU-PH), Morrot G. (CR) and Zanca M.(PU-PH); Permanent Staff: Alibert E. (Tech), Coillot C. (IR); PhD student: Akel M. (2014), Ayadi A. (2015), Kenouche S. (2014) and our main partners will be: Bertin N. (DR INRA Avignon), Bonny JM. (DR INRA Theix), Guarri Y. (DR ICG), Larionova J. (PU ICG), Lautier C. (MCU MMDN), Nativel E. (MCU IES), Perrin F. (PU INM), Puel JL. (PU IMN), Verdier JM. (PU MMDN); Association Verticale supporting research on spinal cord injury, Philibert R; Companies: Intrasense (Montpellier) and RS2D (Strasbourg).

In the framework of the BioNanoNMRI User Facility of the university Montpellier 2, these researchers and actors from civil society will continue to work together with the common objective to develop innovative MRI instrumentation/methodology and their applications in biology and health.

In terms of instrumentation, our aim is to detect NMR signals in the near field of the object of interest and to evaluate this new approach to the accurate study of physical, chemical and biological interplay existing in an ensemble or individual living cells. Our approach is based on the extreme scaling down of the radio frequency sensors and the possibility to capacitively couple the probe to the nuclear spins. With the help of an accurate control of the positioning of the RF probe, improvement of the sensitivity of the receiver at low temperature, MRI will be performed to sub-micronic scales by collecting spectral information like line shifts, line intensities, and relaxation rates in correlation with the displacements. The detection of hyper localized NMR signals from living systems will be of great interest to better understand the physical, chemical and biological mechanisms and thus potentially open new routes for diagnosis and therapeutic treatments. The living systems which are going to be investigated in the next four years will certainly be in the continuity of the actual work that just started.

Self Evaluation of the NMR activities

Strong Points: The group is clearly interdisciplinary, involving academic and industrial scientists with very different backgrounds and knowledge. The members of the team are invited twice a year to international conference on Bio Materials, Medicine and Instrumentation in order to present the recent results of our interdisciplinary research. We have been able to rapidly open our field of competence to living science and to interact locally with the BioCampus plateform UMS3426 CNRS INSERM UM1 UM2. This new synergy has successfully promoted, within 3 years, the acquisition and the installation of a new NMR imaging technique in the Languedoc-Roussillon, giving us the opportunity to develop instrumentation and methodology in order to investigate a wide range of topics. Nuclear Magnetic Resonance micro imaging is now available and accessible at the BioNanoNMRI user facility at the Montpellier Triolet campus with the joined efforts of the University of Montpellier 2 and the CNRS that provides the working force: engineer and technician.

Weak Points: The administrative work dedicated to the installation and functioning of the user facility has unfortunately slowed down the publication of our results in high impact scientific journals. Our interaction with chemistry (ICG) and Image Processing and Analysis groups (Intrasense, LIRMM, INRIA) has to be enhanced rapidly.

Opportunities: The high technology profile of our research project will certainly lead to the development of new experimental NMR/MRI approaches that will be of industrial value in our region 'Languedoc-Roussillon' where Agronomy and Life Sciences are known as “poles of excellence”. The installation of these new and innovative tools and their validation in biological sciences should allow significant advances in the understanding of the cellular machinery. In order to reinforce the group, one expects to recruit in the near future new scientists with skills in NMR spectroscopy, relaxometry and MRI expertise in image processing. An exciting opportunity is also to develop a multimodal approach and to couple micro imaging NMR to other techniques like multi-photonics, X-ray tomography and Positron Emission Tomography / Computed Tomography in the framework of the UMS BioCampus. A financial support for a PostDoc should be available in 2014-2015 to stimulate these works.

Pitfall: The broad range of topics we can now access by NMR and MRI could spread out our efforts if our working force is not extended.

Our project, for the next five years, concerns the investigations by Nuclear Magnetic Resonance Spectroscopy and Imaging of novel materials and living systems. NMR and MRI are heavily used in biochemistry, agronomy, biology and diagnosis in medicine.

In instrumentation, our aim is to detect NMR signals in the near field of the object of interest and to evaluate this new approach to the accurate study of physical, chemical and biological interplay existing in an ensemble or individual living cells. Our approach is based on the extreme scaling down of the radio frequency sensors and the possibility to capacitively couple the probe to the nuclear spins. With the help of an accurate control of the positioning of the RF probe, MRI will be performed to sub-micronic scales by collecting spectral information like line shifts, line intensities, and relaxations in correlation with the displacements. The detection of hyper localized NMR signals from living systems will be of great interest to better understand the physical, chemical and biological mechanisms and thus potentially open new routes for diagnosis and therapeutic treatments. The living systems which are going to be investigated in the next four years will certainly be in the continuity of the actual work that just started.