CERNCOURIER

60 years 1959–2019

IN FOCUS DETECTORS

A retrospective of 60 years' coverage of detector technology

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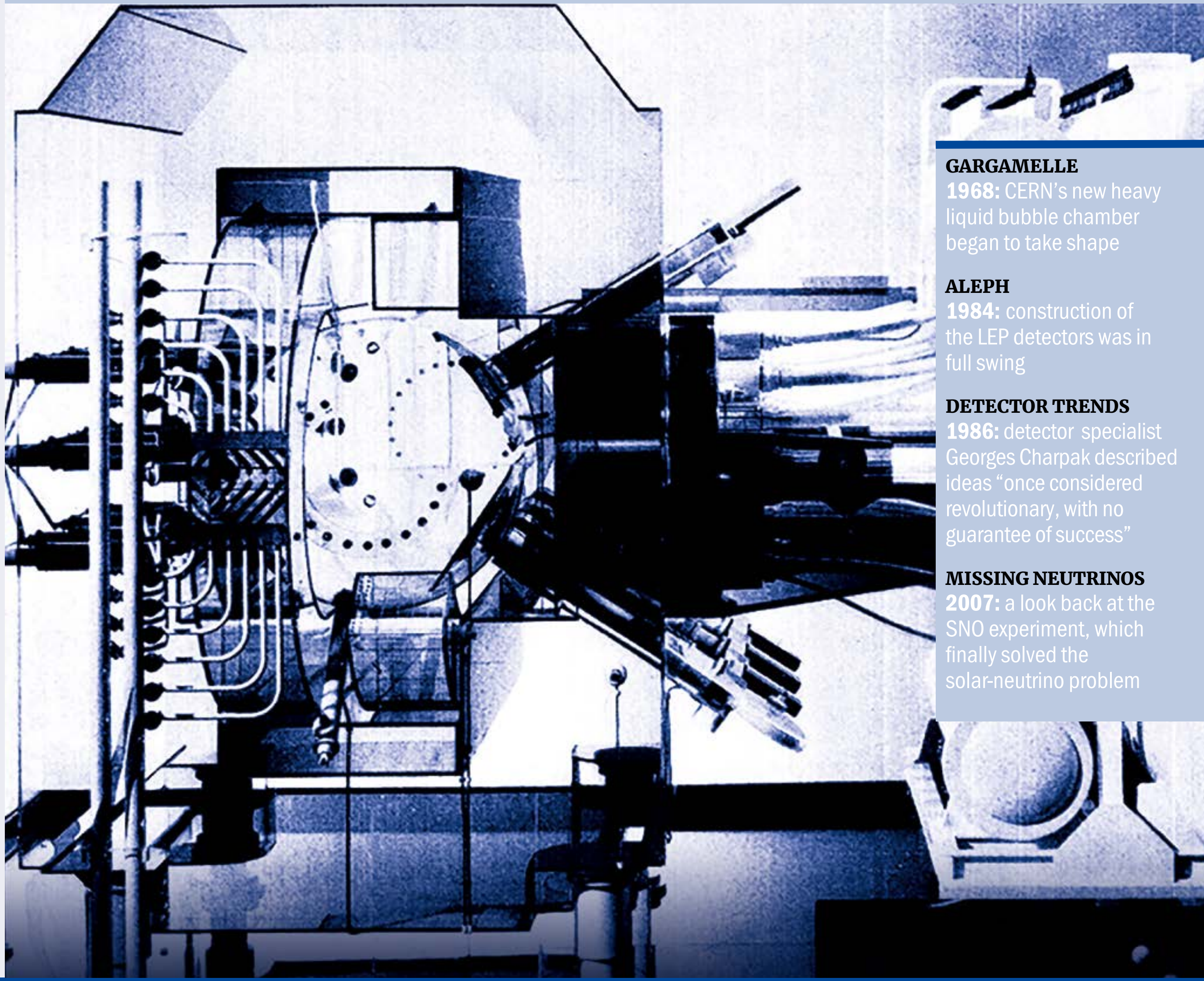
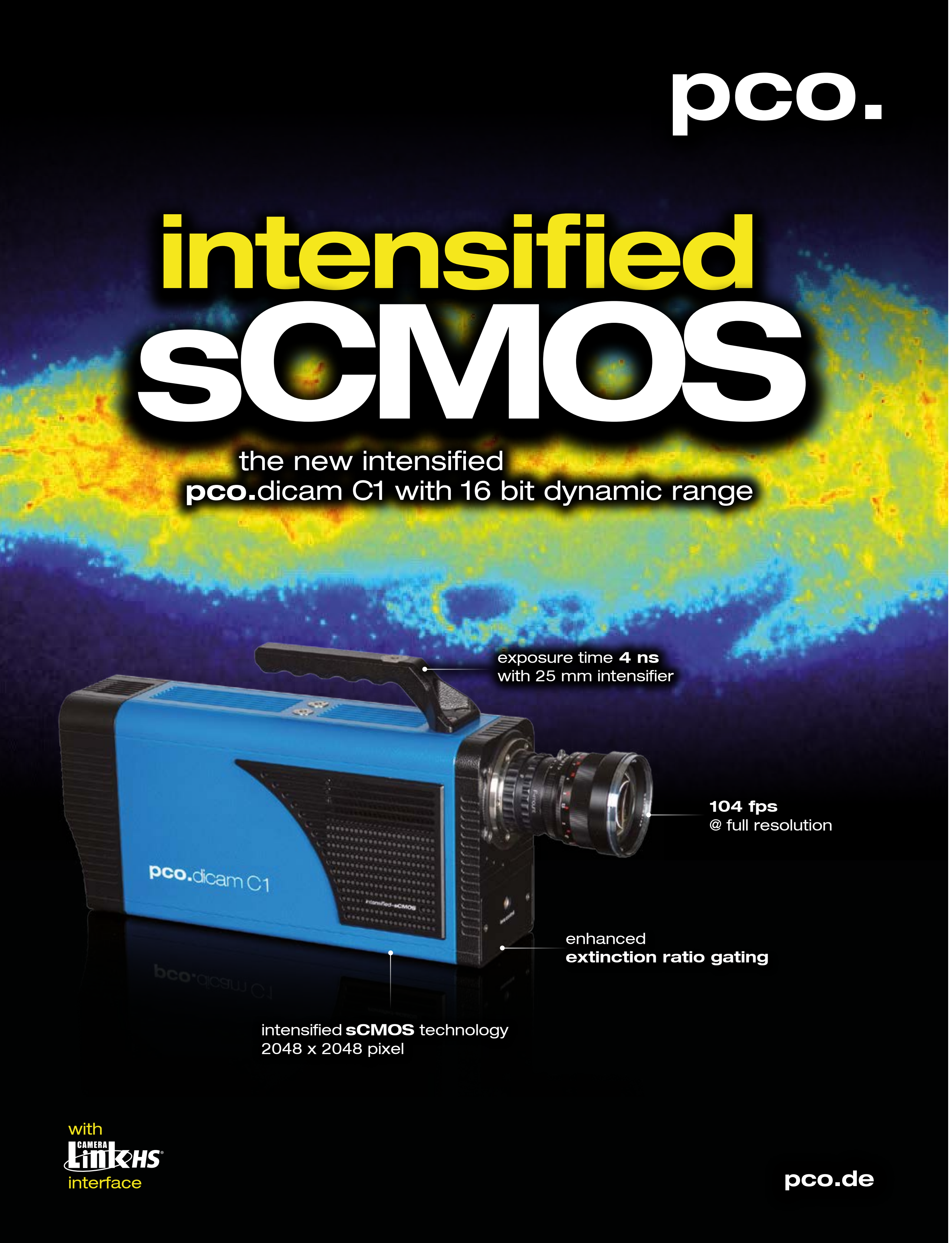


GARGAMELLE
1968: CERN's new heavy liquid bubble chamber began to take shape

ALEPH
1984: construction of the LEP detectors was in full swing

DETECTOR TRENDS
1986: detector specialist Georges Charpak described ideas "once considered revolutionary, with no guarantee of success"

MISSING NEUTRINOS
2007: a look back at the SNO experiment, which finally solved the solar-neutrino problem



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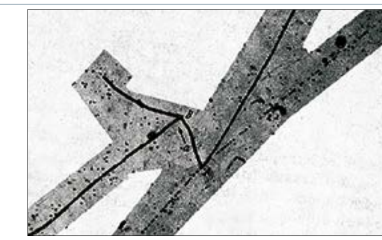
CERN COURIER IN FOCUS DETECTORS

From the Editor

Welcome to this special *CERN Courier* retrospective, which takes stock of the staggering advances in particle detectors that have taken place during the past six decades. It is part of a series of limited-production issues planned throughout the year to mark the magazine's 60th anniversary, showcasing the treasure-trove of information that is the *Courier*'s fully available archive. From early tools of the trade, such as photographic plates, nuclear emulsions and bubble chambers, to the state-of-the-art technologies underpinning experiments at the Large Hadron Collider, innovations in particle-detection techniques have driven numerous breakthroughs in our understanding of the fundamental laws of nature. The articles in this issue, framed by an exclusive foreword, offer a mere glimpse of some of the most striking examples. There were many more to choose from, not least concerning technologies that have impacted the world beyond particle physics, and, if the history of particle detectors is a judge, we can look forward to many decades of discoveries and applications ahead.

Matthew Chalmers



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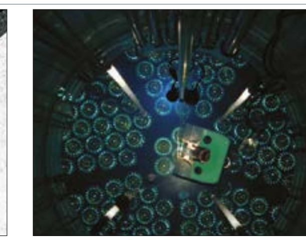

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SPECIAL FOREWORD

Deciphering elementary particles

Former CERN physicist Christian Fabjan takes a whirlwind tour of 60 years of innovation in particle-detection technology at CERN and beyond.

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Christian Fabjan *of Vienna University of Technology and the Austrian Academy of Sciences began his career with experiments at CERN's ISR. Following his involvement in the SPS heavy-ion programme, he moved to detector R&D for ATLAS and then to ALICE as technical coordinator.*

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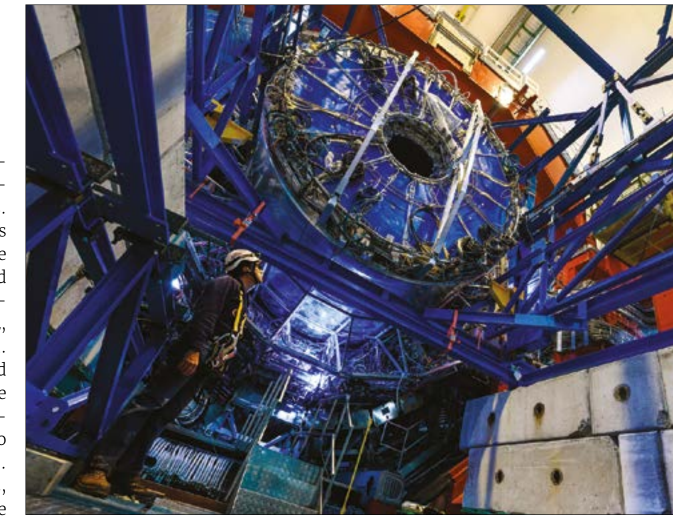


Looking ahead *Extraction of the ALICE time projection chamber in February 2019, as part of a major upgrade to the LHC experiments.*

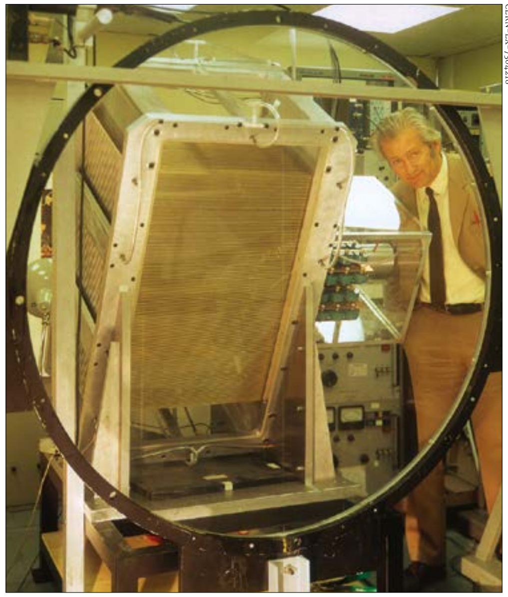
Particle physics began more than a century ago with the discoveries of radioactivity, the electron and cosmic rays. Photographic plates, gas-filled counters and scintillating substances were the early tools of the trade. Studying cloud formation in moist air led to the invention of the cloud chamber, which, in 1932, enabled the discovery of the positron. The photographic plate soon morphed into nuclear-emulsion stacks, and the Geiger tube of the Geiger–Marsden–Rutherford experiments developed into the workhorse for cosmic-ray studies. The bubble chamber, invented in 1952, represented the culmination of these "imaging detectors", using film as the recording medium. Meanwhile, in the 1940s, the advent of photomultipliers had opened the way to crystal-based photon and electron energy measurements and Cherenkov detectors. This was the toolbox of the first half of the 20th century, credited with a number of groundbreaking discoveries that earned the toolmakers and their artisans more than 10 Nobel Prizes.

Game changer

The invention of the Multi Wire Proportional Chamber (MWPC) by Georges Charpak in 1968 was a game changer, earning him the 1992 Nobel Prize in Physics. Suddenly, experimenters had access to large-area charged particle detectors with millimetre spatial resolution and staggering MHz-rate capability. Crucially, the emerging integrated-circuit technology could deliver amplifiers so small in size and cost to equip many thousands of proportional wires. This ingenious and deceptively simple detector is relatively easy to construct. The workshops of many university physics departments could master the technology, attracting students and "democratising" particle physics. So compelling was experimentation with MWPCs that within a few years, large detector facilities with tens of thousands of wires were constructed – witness the Split Field Magnet at CERN's Intersecting Storage Rings (ISR). Its rise to prominence was unstoppable: it became the detector of choice for the Proton Synchrotron, Super Proton Synchrotron (SPS) and ISR programmes. An extension of this technique is the drift chamber, a MWPC-type geometry, with which the time difference between the passage of the particle and the onset of the wire signal is recorded, providing a measure of position with 100 μm-level resolution. The MWPC concept lends itself to a multitude of geometries and has found its "purest" application as the readout of time projection chambers (TPCs). Modern derivatives replace the wire planes with metallised foils with holes in a sub-millimetre pattern, amplifying the ionisation signals.

The ISR was a hotbed for accelerator and detector inventions. The world's first proton–proton collider, an audacious project, was clearly ahead of its time and the initial experiments could not fully exploit its discovery potential. It prompted, however, the concept of multi-purpose facilities capable of obtaining "complete" collision information. For the first time, a group developed and used transition-radiation detectors for electron detection and liquid-argon calorimetry. The ISR's Axial Field Spectrometer (AFS) provided high-quality hadron calorimetry with close to 4π coverage. These technologies are now widely used at accelerators and for non-accelerator experiments. The stringent performance requirements for experiments at the ISR encouraged the detector developers to explore and reach a measurement quality only limited by the laws of detector physics: science-based procedures had replaced the "black magic" of detector construction. With collision rates in the 10 MHz range, these experiments (and the ISR) were forerunners of today's Large Hadron Collider (LHC) experiments. Of course, the ISR is most famous for its seminal accelerator developments, in particular the invention of stochastic cooling, which was the enabling technology for converting the SPS into a proton–antiproton collider.

The SPS marked another moment of glory for CERN. In 1976 first beams were accelerated to 400 GeV, initiating a diverse physics programme and motivating a host of detector developments. Advances in semiconductor technology led to the silicon-strip detector. With the experiments barely started, Carlo Rubbia and collaborators launched the idea, as ingenious as it was audacious, to convert the SPS into a proton–antiproton collider. The goal was clear: orchestrate quickly and rather cheaply a machine with enough collision energy to produce the putative W and Z bosons. Simon van der Meer's stochastic-cooling scheme had to deliver the required beam intensity and lifetime, and two experimental teams were charged with the conception and construction of the equally novel detectors. The centrepiece of the UA1 detector was a 6 m-long and 2 m-diameter "electronic bubble chamber", which adapted the drift-chamber concept to the event topology and collision rate, combined with state-of-the-art electronic readout. The electronic images were of such illuminating quality that "event scanning", the venerable bubble-chamber technique, was again a key tool in data analysis. The UA2 team pushed calorimetry and silicon detectors to new levels of performance, provided healthy competition and independent discoveries. The discovery of the W and Z bosons was achieved in 1983 and, the following year, Rubbia and van der Meer became Nobel Laureates.



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Revolutionary *Charpak's invention of the multi-wire proportional chamber in 1968 revolutionised particle detection and underpins many of the technologies used today.*

Laying foundations

In 1981, with the approval of the Large Electron Positron (LEP) collider, the community laid the foundation for decades of research at CERN. Mastering the new scale of the accelerator dimension also brought a new approach to managing the larger experimental collaborations and to meeting their more stringent experimental requirements. For the first time, mostly outside collaborators developed and built the experimental apparatus, a non-trivial, but needed success in technology transfer. The detection techniques reached a new state of matureness. Silicon-strip detectors became ubiquitous. Gaseous tracking in a variety of forms, such as TPCs and jet chambers, reached new levels of size and performance. There were also some notable firsts. The DELPHI collaboration developed the Ring Imaging Cherenkov Counter, a delicate technology in which the distribution of Cherenkov photons, imaged with mirrors onto photon-sensitive MWPC-type detectors, provides a measure of the particle's velocity. The L3 collaboration aimed at ultimate-precision energy measurements of muons, photons and electrons, and put its money on a recently discovered scintillating crystal, bismuth germanate. Particle physicists, material scientists and crystallographers from academia and industry transformed this laboratory curiosity into mass-producible technology: ultimately, 12,000 crystals were grown, cut to size as truncated pyramids and assembled into the calorimeter, a pioneering trendsetter.

The ambition, style and success of these large, global collaborations was contagious. It gave the cosmic-ray community a new lease of life. The Pierre Auger Observatory, one of whose initiators was particle physicist and Nobel Laureate James Cronin, explores cosmic rays at extreme energies with close to 2000 detector stations spread over an area of 3000 km^2. The IceCube collaboration has instrumented around a cubic kilometre of Antarctic ice to detect neutrinos. One of the most ambitious experiments is the Alpha Magnetic Spectrometer, hosted by the International Space Station – again with a particle physicist and Nobel Prize winner, Samuel Ting, as a prime mover and shaker.

The ambition, style and success of these large, global collaborations was contagious

These decade-long efforts in experimentation find their present culmination at the LHC. Experimenters had to innovate on several fronts: all detector systems were designed for and had to achieve ultimate performance, limited only by the laws of physics; the detectors must operate at a GHz or more collision rate, generating some 100 billion particles per second. "Impossible" was many an expert's verdict in the early 1990s. The successful collaboration with industry giants in the IT and electronics sectors was a life-saver; and achieving all this – fraught with difficulties, technical and sociological – in international collaborations of several thousand scientists and engineers was an immense achievement. All existing detection technologies – ranging from silicon-tracking, to transition-radiation and RICH detectors, liquid-argon, scintillator and crystal calorimeters to 10,000 m^3-scale muon spectrometers – needed novel ideas, major improvements and daring extrapolations. The success of the LHC experiments is beyond the wildest dreams: hundreds of measurements achieve a precision, previously considered only possible at electron–positron colliders. The Higgs boson, discovered in 2012, will be part of the research agenda for most of the 21st century, and CERN is in the starting block with ambitious plans.

Sharing with society

Worldwide, more than 30,000 accelerators are in operation. Particle and nuclear physics research uses barely more than 100 of them. Society is the principal client, and many of the accelerator innovations and particle detectors have found their way into industry, biology and health applications. A class of accelerators, to which CERN has contributed significantly, is specifically dedicated to tumour therapy. Particle detectors have made a particular impact on medical imaging, such as positron emission tomography (PET), whose origin dates back to CERN with a MWPC-based detector in the 1970s. Today's clinical PETs use crystals, very similar to those used in the discovery of the Higgs boson.

Possibly the most important benefit of particle physics to society is the collaborative approach developed by the community, which underpins the incredible success that has led us to the LHC experiments today. There are no signs that the rate of innovation in detectors and instrumentation is slowing. Currently the LHC experiments are undergoing major upgrades and plans for the next generation of experiments and colliders are already well under way. These collaborations succeed in being united and driven by a common goal, bridging cultural and political divides. ●

NUCLEAR EMULSIONS

In the May 1966 issue of CERN Courier, A J Herz (Nuclear Physics Division) and W O Lock (Personnel Division) described the development of nuclear-emulsion detectors, highlighting a CERN experiment that determined the magnetic moment of the Λ^0 baryon. By then, as the authors described, the heyday of emulsions was over, and the field had moved on to fewer, more specialised and complex experiments.

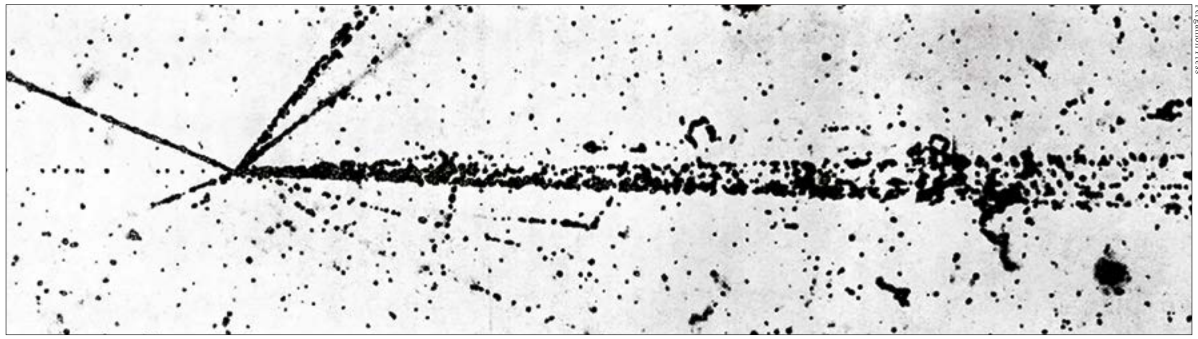

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Figure 1. *An example of a 'jet' of secondary particles seen in nuclear emulsion following a collision involving a cosmic-ray particle of very high energy. In this case, observed by Daniel, Davies, Mulvey and Perkins in 1952, the particle had an estimated energy of 600 GeV.*

The possibility of detecting *individual* charged particles by means of a photographic emulsion was first investigated as long ago as 1910 by Kinoshita, working at Manchester University. He was continuing some earlier work by Lord Rutherford in the same field. Kinoshita showed that a single α particle was capable of rendering a silver-halide grain developable. A year later, Reinganum showed that the passage of an α particle at glancing incidence to a photographic emulsion produced, when the emulsion was developed, a row of silver grains outlining the trajectory of the particle.

This early work was carried out with the type of emulsion used for conventional photography, which had a thickness of only a few microns. It was not until around 1930 that thick-layered emulsions (about 50 microns) were produced, first in research laboratories and later (1935–1937) on a commercial scale by Ilford Ltd in England. These emulsions were exposed for some months at mountain altitudes, for example by Blau and Wambacher, and on subsequent examination 'stars' were found which were ascribed to the disintegration of nuclei in the emulsion caused by cosmic rays.

By 1939, the technique was recognized as a useful tool for the investigation of nuclear and cosmic-ray phenomena, but it was considered to be only a qualitative method and of limited application. The systematic investigations of Powell from 1940 onwards showed, however, that the method was capable of giving accurate quantitative results. For example, Chadwick, May, Pickavance and

This article was adapted from text in *CERN Courier* vol. 6, May 1966, pp83–87

Powell studied in great detail the scattering in various gases of particles accelerated in a cyclotron. At the end of the war, Ilford produced a concentrated 'nuclear-research' emulsion containing eight times the normal amount of silver bromide per unit volume. It was in emulsions of this type exposed to cosmic rays at mountain altitudes that the pion was discovered by Powell and his colleagues in 1947.

Finally, in 1947–48, first Kodak Ltd and then Ilford produced an emulsion capable of recording the tracks of particles moving with velocities such that they suffer the minimum possible energy loss (causing minimum ionization) in passing through the emulsion. Such emulsions are commonly known as 'electron-sensitive emulsions'; they can be purchased, if required, with thicknesses as great as 2 mm on glass or 1.2 mm as stripped emulsion, and in sizes up to 40 cm × 40 cm, or greater.

Advantages and disadvantages

Nuclear emulsion possesses one most significant advantage over all other techniques. It is capable of extraordinarily high spatial resolution. Other techniques can resolve events separated by a few millimetres; using emulsion we can resolve events separated by a few microns. This has made possible the measurement of the lifetime of the π^0 meson (about 10^{-16} s) and is the basis of our confidence that there are no other commonly occurring unstable particles with lifetimes in the range 10^{-11} to 10^{-16} s.

There are some further advantages which are particularly significant in the case of complex experiments

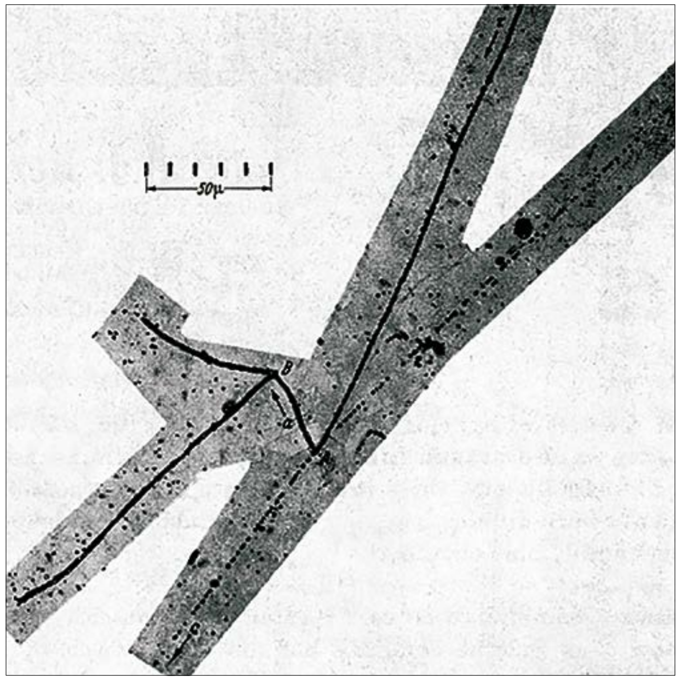


Figure 2. *The famous observation of the τ meson in nuclear emulsion exposed to cosmic rays. This was the first clear indication of the existence of the many heavy mesons which have now been identified. The experiment used electron sensitive emulsion, which had just been produced, and was carried out by Brown, Camerini, Fowler, Muirhead, Powell and Ritson in 1948. The τ enters the emulsion from the top of the photograph; b and c are π^+ mesons; a is a π^- meson which gives rise to a star at B.*

in which nuclear emulsion is used as a detector. First of all, it is an integrating device which can be exposed or irradiated until sufficient data have been stored in it; secondly, it can be used in very confined volumes, as will be illustrated later in this article in the discussion of the experiment to determine the magnetic moment of the Λ^0 hyperon.

Its chief disadvantage is that it consists of a mixture of complex nuclei – silver and bromine (as silver bromide) suspended in gelatine, which is largely carbon, nitrogen and oxygen. Further, the scanning of large volumes of emulsion, of necessity in three dimensions, is frequently very tedious. Thus, with the development of other powerful detectors such as the spark chamber and the bubble chamber (with its simple target material of hydrogen or deuterium for example) which are readily adaptable to automatic methods of analysis and data handling, nuclear-emulsion work has inevitably developed into a supplementary technique, except in certain special fields.

Use of the technique in research

There are two distinct ways in which nuclear emulsions can be used. Firstly, they may be placed in the path of particles (from an accelerator or in the cosmic radiation) and the interactions which these particles produce in the emulsion can be studied in detail. The charged pions and many of the 'strange particles' were first discovered, and their decay modes studied, in large stacks of emulsion exposed for considerable periods of time to the cosmic radiation (see Figure 2). The relatively small size and weight of emulsions enable them to be carried to great heights by means of free balloons. In this way, many studies have been carried out of a) the interactions of very energetic particles – energies greater than 50 GeV (see Figure 1), b) the composition of the primary cosmic radiation and c) the development of the electron–photon cascade in the high atmosphere.

One well-known example is the work carried out by groups all over the world on emulsions which were exposed on a high-altitude balloon flight as a very large stack (60 × 45 × 30 cm) known as the 'Schein stack' after the American physicist who initiated the project.

The second way in which emulsion may be used is simply for particle detection, placed near to a target which is bombarded by a suitable particle beam. The target employed is often liquid hydrogen, although at cyclotron energies targets of many solids and gases have been used. In many cases the geometry of the experimental arrangement is so designed that the particles we wish to investigate stop in the emulsion, thus allowing their energy to be determined by measuring the distance they travel in the emulsion.

The Λ^0 magnetic moment experiment

It is thought by many that nuclear-emulsion work is somehow different from experimental research with other techniques, that it requires the application of special skills laboriously acquired during a long period of training, and that 'emulsion workers' spend their days looking down microscopes rather like classical botanists, making up descriptions of what they see. To judge how much truth there is in this view, we will describe one of the major experiments in which the CERN Emulsion Group has participated.

The idea that it would be possible to determine the magnetic moment of the Λ^0 hyperon using nuclear emulsions and a very-high-field pulsed magnet came first to V. Z. Peterson at the California Institute of Technology (CalTec), following a theoretical paper by M. Goldhaber. In 1957, Peterson proposed such an experiment, describing many of the essential features of the project finally carried out six years later. In the background of the proposal, there was the clear need to measure the magnetic moments of the hyperons. Peterson had started to develop pulsed magnets at CalTec and nuclear emulsion was suggested as the most suitable detector because of space limitations inside the magnet, coupled with a need for very high precision in the measurements on the decay products of the Λ^0. The idea was carried to CERN by Ph. Rosselet, then of the University of Lausanne, who worked with Peterson on the CalTec pulsed-magnet project during 1958. After his return to Lausanne in 1959, the group there (under Professor Haenny) took up the development of pulsed-magnet coils suitable for magnetic-moment experiments, and a proposal was submitted to CERN.

It was found that an existing slow-K-meson beam could be modified to provide a flux of almost 10^5 π^- mesons per pulse, and test exposures took place in early February 1962. Most of the information needed was obtained, and it was possible to conclude that the experiment would be feasible with a magnetic field of 150 kG instead of the 75 kG used in the test runs.

The Λ^0 hyperons are in the field from production to decay. They are 'polarized' at production such that their magnetic moments are predominantly lined up perpendicular to the plane containing the incident π^- meson and the Λ^0 itself. The interaction between the magnetic moment and the applied field results in the rotation of this direction through an angle which is proportional to the magnetic moment and other, known, quantities such as the intensity of the field. The problem is to determine this angle Θ. It can be done because the most probable direction of emission of the pion in decay is the direction of the magnetic-moment vector. Thus if we measure the direction of emission of the pions from many Λ^0 decays, and transform them in each case from the laboratory system to the centre-of-mass system of the Λ^0 in question, we can find the average value of Θ. The precision depends on the number of Λ^0 decays collected, on the accuracy of measurement of direction and momentum in the emulsion, and on the errors in the determination of the value of the magnetic field and of other constants associated with the apparatus.

The main run took place, without major mishaps, in October 1963. Analysis began at the four collaborating Laboratories as soon as the processed plates had been distributed, and by Spring 1964 results were beginning to emerge. The character of the work had now changed, for the many technical tasks associated with the preparation of the experiment had been replaced by scanning, measurement and data analysis. Much comparison and discussion of data took place in meetings and by correspondence, and by June 1964 it was clear that the experiment would yield an improved estimate of the Λ^0 magnetic moment. A preliminary paper was read at the International Conference on High-Energy Physics held in Dubna in September. More complete results were published in Physics Letters in March 1965.

This determination of the Λ^0 magnetic moment is an example of an experiment using nuclear emulsions in a complex arrangement in which the application of many of the techniques of experimental physics, and some of engineering, was involved. The handling and processing of the emulsions, the subsequent scanning and the measurements, whilst crucial to the success of the project, did not constitute the major part of the work, nor, we might add, were they the most difficult.

The future

It is always risky to predict the future in print, and especially so in the present case where there is already a long record of unfulfilled pessimistic prophecy. We do not think that the emulsion technique is dead, to be soon forgotten. It is simple, easy to adapt to new requirements, and a physicist does not need a long apprenticeship in order to use it.

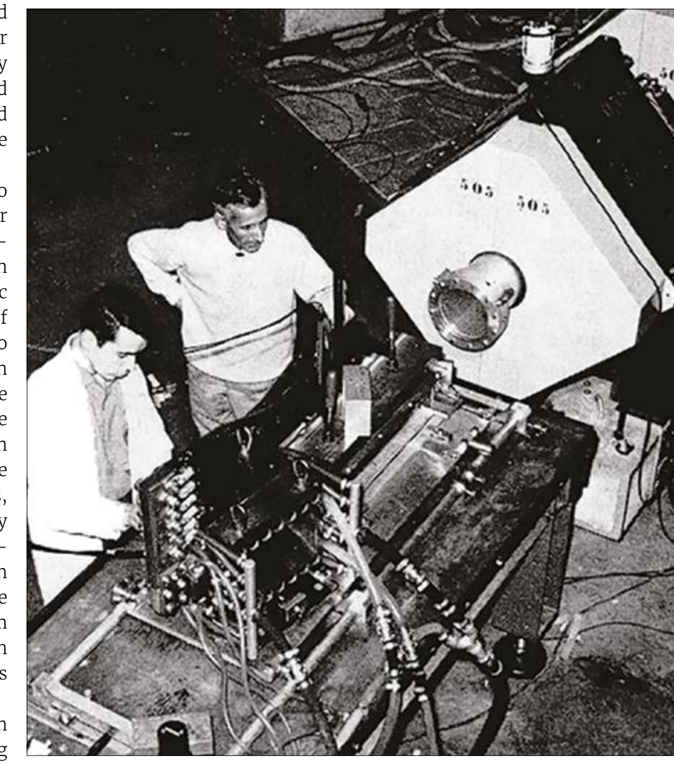


Figure 3. *The Λ^0 magnetic moment experiment. The block in the centre is the pulsed magnet containing the emulsions. The beam comes out of the quadrupole magnet seen at the top right of the photograph.*

As with the bubble-chamber technique, the analysis of the experimental material can be done at small university laboratories, far away from the accelerator. The investment in equipment for analysis can, moreover, be relatively modest, much less than for bubble-chamber work for which access to a large computer is always needed.

Except in special applications, such as hyperfragment studies, nuclear emulsion is basically unsuitable for the investigation of very rare events and for the detection of complex processes where neutral links travel more than a few hundred microns before giving rise to a visible secondary event. Accumulated background will swamp the rare events, unless they have very striking characteristics, whilst complex processes will usually escape detection because the background obscures the relationship between vertices connected by neutral links, and because only a very small region of the emulsion can be in view at any one time.

It is clear, therefore, that future applications will be of the kind in which one or other of the strong points of the technique is of paramount importance. Such applications have always existed since the time of Kinoshita, fifty-five years ago, and we can expect that they will continue to be found in the future. For that reason, it is important not to let the emulsion technique disappear from the arsenal available to experimental physics. It may be put into storage, perhaps, but if it remains at the disposal of those who want it, it will almost certainly continue to be used from time to time. ●

GARGAMELLE

CERN's new heavy liquid bubble chamber

The famous Gargamelle bubble chamber, featured in the May 1968 issue, operated from 1970 to 1976 with a muon-neutrino beam produced by the Proton Synchrotron, before moving to the Super Proton Synchrotron until 1979. In July 1973, the Gargamelle collaboration presented the first direct evidence of the weak neutral current, and the chamber body is now an exhibit in CERN's Microcosm garden.


An aerial view of part of the CERN site. The wheel shape of the proton synchrotron itself is fairly obvious and, pointing from it towards the bottom of the picture, is the tunnel housing the neutrino beam-line.
CERN/PI 166.5.68

In the April issue of CERN COURIER we reproduced a photograph of the arrival of the first piece of the new heavy liquid bubble chamber 'Gargamelle'. The 140 ton base-plate for the magnet was towed onto the site by two tractors in a 48-wheel convoy on 31 March. It seems an appropriate time to say something about this significant addition to CERN's research equipment.

Its use

Gargamelle has been conceived principally as an instrument for research on neutrinos. The fascination of these elusive particles has been brought out in several previous articles in CERN COURIER (see particularly the article by C.A. Ramm, vol. 6, p. 211). They are the most abundant particles in the universe and their study will tell us much about the weak interaction, the only one in which they take part. Their interactions are so rare that ten years ago, our present ability to observe neutrinos was unimaginable. By 1963, it had become possible at high-energy accelerators, where large, refined detection equipment was already in use, to 'see' about one neutrino an hour from the millions that the accelerator produced. This will have increased by the early 1970s to something like 10 000 per day and the study of neutrinos will be on the same footing as that of most other particles. At CERN, Gargamelle will be one of the important contributors to this advance.

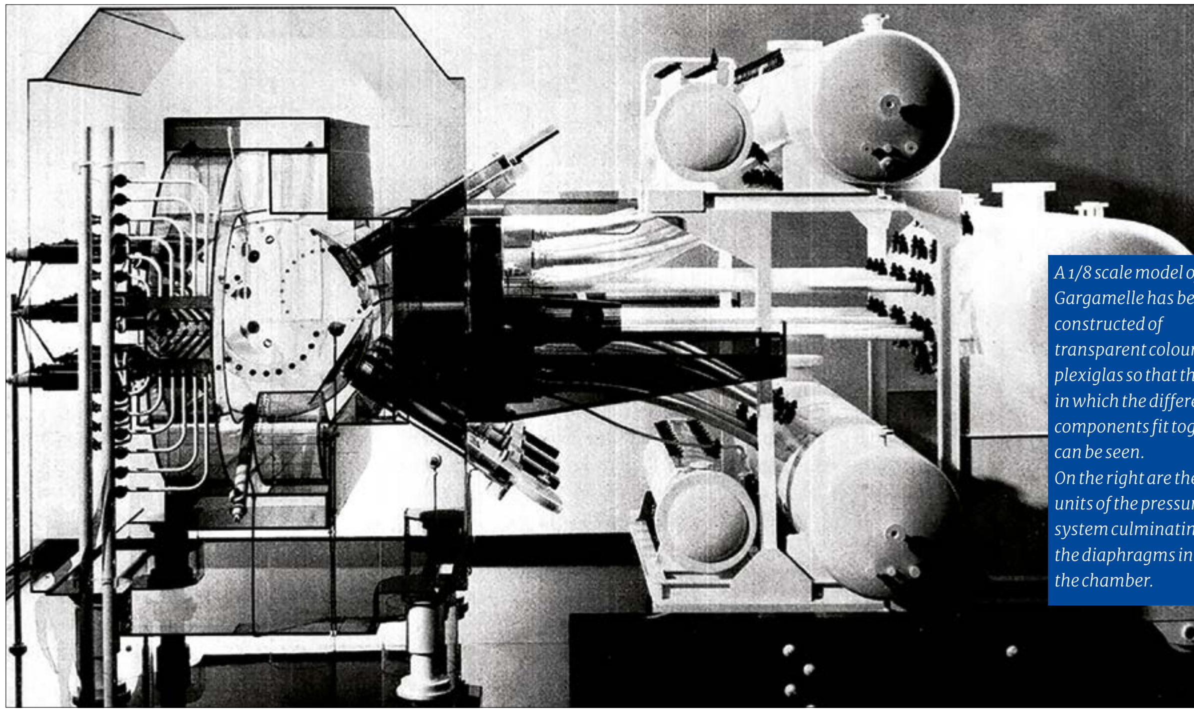
For neutrino experiments, a heavy liquid bubble chamber has two advantages over a hydrogen bubble chamber: i) It presents a more dense target so that there are more particles with which the neutrino can interact;

This article was adapted from text in *CERN Courier* vol. 8, May 1968, pp95–96

ii) The distance a neutral particle travels in the liquid before producing charged particles (which leave tracks giving information about the parent neutral particle) is shorter. Many important neutrino interactions – such as the elastic scattering of an antineutrino and a proton producing a neutron – yield neutral particles, and the ability of the heavy liquid chamber to give information on them is therefore invaluable.

A heavy liquid chamber is less favourable than the hydrogen chamber in the complexity of the target it presents to the incoming beam and in the accuracy with which the particle tracks can be measured. Also, it is worth adding here that modified hydrogen chambers are now coming into vogue containing hydrogen/neon mixtures or a hydrogen target surrounded by a hydrogen/neon mixture, which compromise between the advantages and disadvantages of pure hydrogen and heavy liquid.

The main detector in the neutrino experiments previously carried out at CERN has been the CERN heavy liquid bubble chamber, which has a volume of 1180 litres.



A 1/8 scale model of Gargamelle has been constructed of transparent coloured plexiglas so that the way in which the different components fit together can be seen. On the right are the units of the pressure system culminating in the diaphragms in the chamber.

Gargamelle is much bigger with 10 000 litres of useful volume. In a uniform neutrino beam the event rate would be proportional to the volume for the same liquid. In fact, Gargamelle will contribute about a factor of seven to the rate at which neutrino interactions can be observed.

The new chamber is being designed and built at the Saclay Laboratory in France, with help from Ecole Polytechnique, Orsay and industry and is being given to CERN who are providing its buildings and supplies. As mentioned above, the first piece arrived recently and the other components will arrive during the course of the next year. The magnet is coming directly to be assembled at CERN. The other components will be first assembled and tested at Saclay. It is hoped to have the chamber in operation at the end of 1969.

Description of the chamber

The main features of the chamber are as follows: the body (which is almost ready for delivery) is a welded cylinder with dished ends, 1.85 m in diameter and 4.5 m long, with the axis of the cylinder in the direction of the beam. It is constructed of low carbon steel, 60 mm thick increasing to 150 mm in the region of the ports. Its total volume is 12 m^3 of which 10 m^3 is 'useful volume', i.e. can be seen by two cameras. Two diaphragms, made of polyurethane elastromer 4 m by 1 m, running in the direction of the axis on one side of the chamber are used to vary the pressure on the liquid. The liquid can be pure propane (when the chamber would contain 5 tons of liquid) to freon (15 tons) or any intermediate mixture. Four fish-eye lenses, with an angle of view of 110° are set in apertures in each diaphragm; each set of four have their images recorded on a single film. There are 21 xenon flash tubes distributed over the chamber behind diaphragms to give 'dark field' illumination (see CERN COURIER vol. 7, p. 144).

The chamber is surrounded by a magnet designed to produce a field of 19 kG. The magnet yoke, weighing 800 tons, serves as support for the chamber, the expansion system and the coils. The two sets of coils weigh 80 tons each and are mounted vertically; the field direction is horizontal.

The name Gargamelle is taken from the satirical novel 'Gargantua' by Rabelais (1534) in which Gargamelle was the mother of the giant Gargantua. She gave birth to Gargantua through her ear. The association of headaches with Gargamelle is appropriate even in modern times. The construction of the new chamber has created many problems for its makers. Bringing forth the data from Gargamelle will also cause some headaches. The direct interpretation of the events recorded on the two films will be much more complicated than with smaller bubble chambers. New scanning and measuring techniques will be essential and already, under the auspices of the Gargamelle Users' Committee, much development is in progress.

Gargamelle, in combination with the increases in repetition rate and intensity per pulse of the proton synchrotron and the refinements incorporated in the new neutrino beam-line, should make the coming years of neutrino research at CERN very fruitful ones. ●

SOLVING THE MYSTERY OF THE MISSING NEUTRINOS

In the 2007 issue, Nick Jelley (University of Oxford) and Alan Poon (Lawrence Berkeley National Laboratory) looked back at the achievements of the SNO experiment, which helped reveal a new world of massive neutrinos.

This article was adapted from text in *CERN Courier* vol. 47, May 2007, pp26–28

The end of an era came on 28 November 2006 when the Sudbury Neutrino Observatory (SNO) stopped data-taking after eight years of exciting discoveries. During this time the observatory saw evidence that neutrinos, produced in the fusion of hydrogen in the solar core, change type – or flavour – while passing through the Sun on their way to Earth. This observation explained the long-standing puzzle as to why previous experiments had seen fewer solar neutrinos than predicted and also confirmed that these elusive particles have mass.

Ray Davis's radiochemical experiment first detected solar neutrinos in 1967, a discovery for which he shared the 2002 Nobel Prize in Physics (*CERN Courier* December 2002 p15). Surprisingly, he found only about a third of the number predicted from models of the Sun's output. The Kamiokande II experiment in Japan confirmed this deficit, which became known as the solar-neutrino problem, while other detectors saw related shortfalls in the number of solar neutrinos. A possible explanation, suggested by Vladimir Gribov and Bruno Pontecorvo in 1969, was that some of the electron-neutrinos, which are produced in the Sun, "oscillated" into neutrinos that could not be detected in Davis's detector. This oscillation mechanism requires that neutrinos have non-zero mass.

In 1985, the late Herb Chen pointed out that heavy water (D_2O) has a unique advantage when it comes to detecting the neutrinos from ^8B decays in the solar-fusion process, as it enables both the number of electron neutrinos and the number of all types of neutrinos to be measured. In heavy water neutrinos of all types can break a deuteron into its constituent proton and neutron (the neutral-current reaction), while only electron neutrinos can change the deuteron into two protons and release an electron (the charged-current reaction). A comparison of the flux of electron neutrinos with that of all flavours can then reveal whether flavour transformation is the cause of the solar-neutrino deficit. This is the principle behind the SNO experiment.

International collaboration

Scientists from Canada, the US and the UK designed SNO to attain a detection rate of about 10 solar neutrinos a day using 1000 tonnes of heavy water. Neutrino interactions were detected by 9456 photomultiplier tubes surrounding the heavy water, which was contained in a 12 m diameter acrylic sphere. This sphere was surrounded by 7000 tonnes of ultra-pure water to shield against radioactivity. Figure 1 shows the layout of the SNO detector, which is located about 2 km underground in Inco's Creighton nickel mine near Sudbury, Canada, so as to all but eliminate cosmic rays from reaching the detector. Figure 2 shows what the detector "sees": the photomultiplier tubes that were hit following the creation of an electron by an electron neutrino.

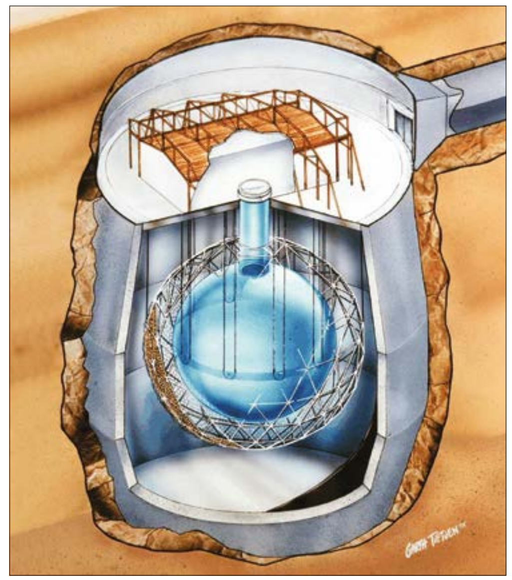


Fig. 1. *Artist's impression of the Sudbury Neutrino Observatory. The heart of the detector, which is located 2 km underground in a cleanroom, comprises 1000 tonnes of heavy water.*

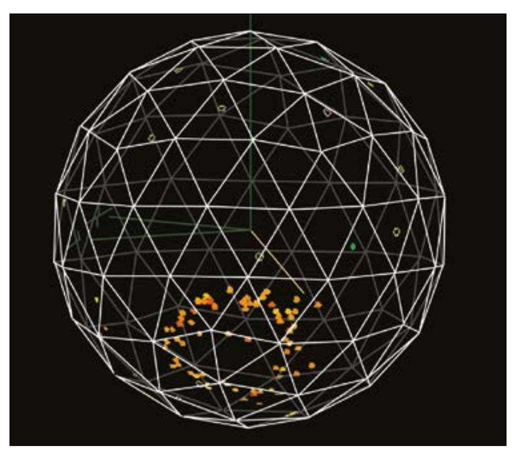


Fig. 2. *Event display of a neutrino candidate. Photomultiplier tubes mounted on a geodesic structure detect Cherenkov light from relativistic electrons following a neutrino interaction.*

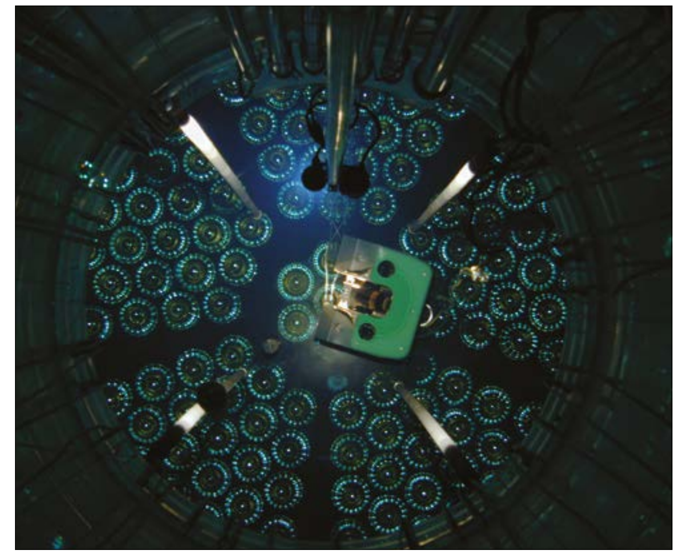


Fig. 3. *Deployment of the proportional counter array, comprising 36 filled with ^3He and four filled with ^4He, with a remotely operated submarine in 2004. Bright reflections from four of these proportional counters can be seen in this picture.*

Fig. 4. *On behalf of the SNO Collaboration, SNO director Art McDonald (left) accepts the inaugural John C Polanyi Award from the president of NSERC, Suzanne Fortier (middle), and Nobel Laureate John C Polanyi (right).*

It was crucial to the success of this experiment to make the components of SNO very clean and, in particular, to reduce the radioactivity within the heavy water to exceedingly low levels. To achieve this aim the team constructed the detector in a Class-2000 cleanroom and entry to SNO was via a shower and changing rooms to reduce the chance of any dust contamination from the mine. The fraction of natural thorium in the D_2O had to be less than a few parts in 10^{15}, roughly equivalent to a small teaspoonful of rock dust added to the 1000 tonnes of heavy water. Such purity was necessary to reduce the break-up of deuterons by gamma rays from natural uranium and thorium radioactivity to a small fraction of the rate from the solar neutrinos. This required complex water purification and assay systems to reduce and measure the radioactivity. Great care in handling the heavy water was also needed as it is on loan from Atomic Energy of Canada Ltd (AECL) and is worth about C$300 million.

SNO's results from the first phase of data-taking with unadulterated D_2O were published in 2001 and 2002, and provided strong evidence that electron neutrinos do transform into other types of neutrino (*CERN Courier* June 2002 p5). The second phase of SNO involved adding 2 tonnes of table salt (NaCl) to the D_2O to enhance the detection efficiency for neutrons. This large "pinch of salt" enabled SNO to make the most direct and precise measurement of the total number of solar neutrinos, which is in excellent agreement with solar-model calculations (*CERN Courier* November 2003 p5). The results to date reject the null hypothesis of no neutrino flavour change by more than 7 σ.

Together with other solar-neutrino measurements, the SNO results are best described by neutrino oscillation enhanced by neutrinos interacting with matter as they pass through the Sun – a resonant effect that Stanislav Mikheyev, Alexei Smirnov and Lincoln Wolfenstein predicted in 1985. To a good approximation, the electron-neutrino flavour eigenstate is a linear combination of two mass eigenstates with masses m_1 and m_2. The mixing angle between these two mass eigenstates, which the ratio (measured by SNO) of the electron-neutrino flux to the total neutrino flux constrains, is found to be large (around 34°) but is excluded from maximal mixing (45°) by more than 5σ. The matter enhancement enables the ordering (hierarchy) of the two mass eigenstates to be defined, with $m_2 > m_1$ and a difference of around 0.01 eV/c². The KamLAND experiment, which uses 1000 tonnes of liquid scintillator to detect anti-neutrinos from Japan's nuclear reactors, confirmed in 2003 that neutrino mixing occurs and is large, as seen for solar neutrinos.

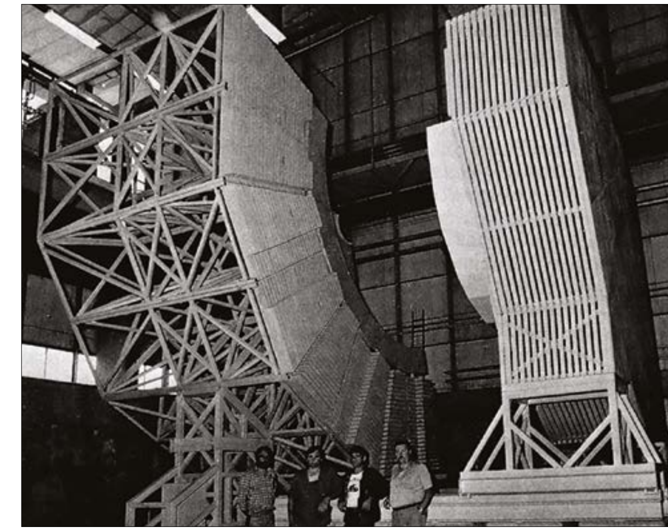
After the removal of salt from the heavy water, the third and final phase of SNO used an array of proportional counters in the heavy water to improve further the neutrino detection. Researchers filled 36 counters with ^{3}He and four with ^{4}He gas. Figure 3 shows part of this array during its deployment with a remotely operated submarine. The additional information from this phase will enable the SNO collaboration to determine better the oscillation parameters that describe the neutrino mixing. Data analysis is still in progress.

SNO's scientific achievements were marked at the end of data-taking when the collaboration received the inaugural John C Polanyi Award (figure 4) of the Canadian funding agency, the Natural Sciences and Engineering Research Council (NSERC). The completion of SNO does not mark the end of experiments in Sudbury, however, as SNOLAB, a new international underground laboratory, is nearly complete, with expanded space to accommodate four or more experiments. SNOLAB has received a number of letters of interest from experiments on dark matter, double beta decay, supernovae and solar neutrinos. In addition, a new collaboration is planning to put 1000 tonnes of scintillator in the SNO acrylic vessel once the heavy water is returned to the AECL by the end of 2007. This experiment, called SNO+, aims to study lower-energy solar neutrinos from the "pep" reaction in the proton–proton chain, and to study the double beta decay of ^{150}Nd by the addition of a metallo-organic compound.

As a historical anecdote, SNO was not the first heavy-water solar-neutrino experiment. In 1965, Tom Jenkins, along with other members of Fred Reines' neutrino group, at what was then the Case Institute of Technology, began the construction of a 2 tonne heavy-water Cherenkov detector, complete with 55 photomultiplier tubes, in the Morton salt mine in Ohio. Unlike Chen's proposal, Jenkins had only considered the detection of electron neutrinos through the charged-current reaction as other flavours were not expected, and the neutral-current reaction had not yet been discovered. This experiment finished in 1968 after Davis had obtained a much lower ^{8}B solar-neutrino flux than had been predicted. ●

ALEPH

As part of a series of articles about the new detectors for the Large Electron Positron (LEP) collider, the September 1984 issue of CERN Courier *featured ALEPH. Located at point 4 of the LEP ring, in a cavern now filled with radio-frequency cavities for the LHC, ALEPH was a general-purpose detector that began data-taking in July 1989 and operated for 11 years until the end of LEP programme.*


CERN 103.6.84

Full-scale mock-up of part of the ALEPH detector, showing (right), a portion of one end-cap, and a segment of the hadron calorimeter with (inside) the fine-grain electromagnetic calorimeter.

This article was adapted from text in *CERN Courier* vol. 24, September 1984, pp269–272

Our previous issue carried the first of a series of articles (DELPHI, page 27) on the four major experiments for CERN's 9 kilometre diameter LEP electron–positron ring, now under construction and scheduled to produce its first colliding beams in 1988.

This month we continue with the ALEPH (Apparatus for LEP pHysics) detector. The typical electron–positron annihilations produced in LEP will be very complex, producing many particles, distributed in turn into showers ('jets') which may turn up anywhere in the spherical volume surrounding the beam crossing point. The ALEPH detector is designed to collect as much information about each event over as wide a spherical volume as possible.

It features a large superconducting coil enclosing a Time Projection Chamber as central track detector, designed to permit precise momentum determination of charged particles over a wide energy range, and a fine-grain calorimeter measuring electromagnetic energy deposition with very good spatial resolution.

ALEPH's cost will work out at about 75 million Swiss francs at current prices, but will be 'staged', with a slightly cut-down version being ready to intercept the first beams, and final features being added later.

Like all the LEP experiments, ALEPH involves a lot of people – some 300 scientists from 25 research centres in nine countries and three continents. The line-up: Bari, Beijing, CERN, Clermont-Ferrand, Copenhagen, Demokritos Athens, Dortmund, Ecole Polytechnique, Edinburgh, Frascati, Glasgow, Heidelberg, Imperial College London, Lancaster, Marseille, Munich (Max Planck), Orsay, Pisa, Rutherford Appleton, Saclay, Sheffield, Siegen, Trieste, Westfield College London, and Wisconsin.

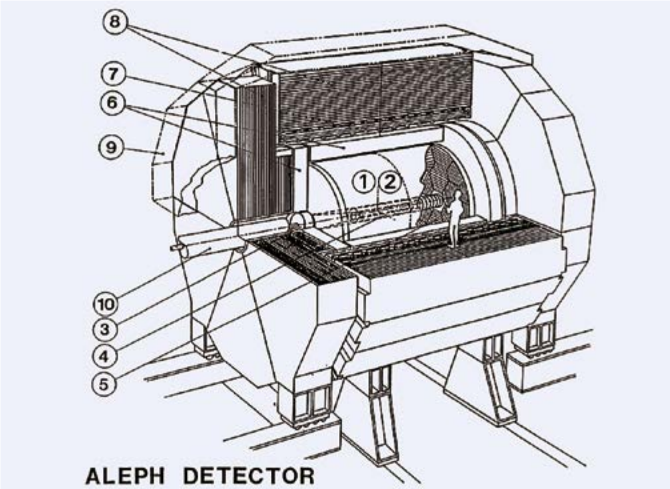
The design is for concentric layers of detector, both inside and outside the main superconducting magnet coil, each fulfilling a separate function. The region is closed by multilayered endcaps, reflecting the configuration of the central detector.

The main solenoid, being built at Saclay, will provide a highly uniform magnetic field of 1.5 T in the central detector. The design owes much to the highly successful CELLO detector at the PETRA electron–positron ring at the German DESY Laboratory. It consists of a 6.4 m long, 5.3 m diameter main coil, with additional 40 cm compensators at either end. The superconducting cable is made of a copper-niobium-titanium composite, embedded in an aluminium band by an extrusion process.

With some 25 tons of equipment involved, cooldown from ambient temperature to the 4.2 K working point will take some two weeks. The rated current in the main coil will be 5000 A, giving some 130 MJ of stored energy. The coil and its cryostat will be built in two halves and transported to CERN by road. The iron supports have to be solidly built, as they have to withstand a magnetic force of 4000 tons pulling the two opposite end caps towards each other. The iron structure, refrigeration and necessary power supplies are being constructed at CERN.

The cylindrical central tracking detector inside the solenoid has to provide good momentum and angular resolution of particle tracks, while assuring good pattern recognition and distinguishing different types of particles by rate of energy loss. Thinking soon centred on a Time Projection Chamber (TPC), using an argon-methane mixture at atmospheric pressure and an applied drift field of about 20 kV/m in a volume of 42 m³.

Tracks of ionizing particles in the TPC will be measured by recurrent sampling of signals during the electrons' drift time of some 35 microseconds before they arrive at the endplates, where they are recorded by a system of 3000



Schematic of the ALEPH detector for the LEP electron–positron collider at CERN: 1 – beam pipe, 2 – minivertex detector, 3 – luminosity monitor, 4 – inner chamber, 5 – Time Projection Chamber, 6 – electromagnetic calorimeter, 7 – superconducting coil, 8 – hadron calorimeter, 9 – muon detector, 10 – superconducting quadrupole.

proportional wires and 22 000 cathode readout pads. The electrode configuration reflects experience gained with the TPC used at the PEP electron–positron ring at Stanford.

An ingenious laser calibration system will take care of field irregularities inside the TPC. Time Projection Digitizer (TPD) and Time Projection Processor (TPP) electronics will naturally take care of the huge amount of raw generated data, only a small proportion of which will actually correspond to useful track information.

A prototype (TPC 90, with endplates approximately the size of one of the 18 sectors for the final version) has been constructed and is now being put through its paces, using tracks produced by laser beams.

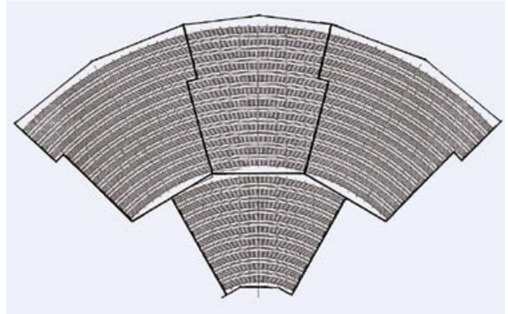
Development and construction work for the TPC is shared by CERN, Dortmund, Pisa, Munich, Trieste and Wisconsin, with Dortmund and Glasgow supplying the calibration system.

Inside the TPC will be the ALEPH Inner Chamber (Imperial College, London), a conventional cylindrical small cell drift chamber (outer radius 280 mm, inner radius 128 mm). This will provide additional tracking close to the beam pipe and its signals will provide an essential part of the primary electronics trigger.

Inside the Inner Chamber, a 105 mm outer radius minivertex detector (Pisa) will eventually be installed. Based on multi-electrode silicon detectors, it will provide the close tracking increasingly used these days to detect the short-lived particles which decay very close to the interaction point. Either side of the inner detectors and at the centre of the end-caps will be luminosity monitors (Copenhagen and Siegen).

Inside the solenoid but outside the TPC will be the electromagnetic calorimeter, based on a 2 mm lead plus wire chamber sandwich design providing good transverse granularity, matched to the size of the produced electromagnetic showers, and organized into 'microtowers', each with three longitudinal sections. The central barrel, made up of 12 11-ton modules, will contain 48 000 microtowers, while a further 24 000 will be in the end-caps, giving a total of 216 000 electronics channels.

The electromagnetic calorimeter end-caps are supplied



Not a reservation chart for concert tickets but a diagram of four of the 18 sectors for each end-plate of the ALEPH Time Projection Chamber, showing the arrangement of some of the 22 000 readout pads.

by the Rutherford Appleton Laboratory and Glasgow, while the barrel involves a French (Clermond-Ferrand/Ecole Polytechnique/Marseille/Orsay/Saclay) collaboration.

Outside the solenoid, the 120 cm of iron which supports the rest of the detector and provides the magnet return yoke will be packed with instrumentation (1 cm^2 plastic streamer tubes) to measure the deposition of hadronic energy and to pick up the muons which penetrate the rest of the apparatus. The instrumentation comprises a total of 56 000 streamer tubes and a further 82 000 tubes in the 9 m diameter end-caps. The readout is organized into projective towers. The hadron calorimeter is an Italian effort, with Frascati providing the barrel, and with Pisa and Bari supplying the end-caps.

The muon detector uses double layers of streamer tubes to pick up the muons traversing the iron of the hadron calorimeter. The outer layer will probably only come into operation after the initial electron–positron collisions have been studied.

As with all experiments using high luminosity colliding beams, great emphasis is placed on ALEPH's data acquisition and handling system. A fast first level trigger, using information from the inner chamber, the hadron calorimeter, the electromagnetic calorimeter, the muon chambers and the luminosity monitor, will act within a few microseconds, priming the TPC electronics and initializing the second level trigger. Since beam crossing occurs only every 23 microseconds, this will not lose precious information.

The second level trigger will mainly use information from the TPC to ensure that tracks point back towards the beam crossing point. This will reduce the trigger rate to something less than 10 Hz.

The final trigger will reduce the data collection rate down to a level (a few events per second) suitable for writing to magnetic tape for subsequent off-line processing. The development of the triggering system is supervised by Heidelberg and Rutherford. Fastbus electronics will be prominent throughout.

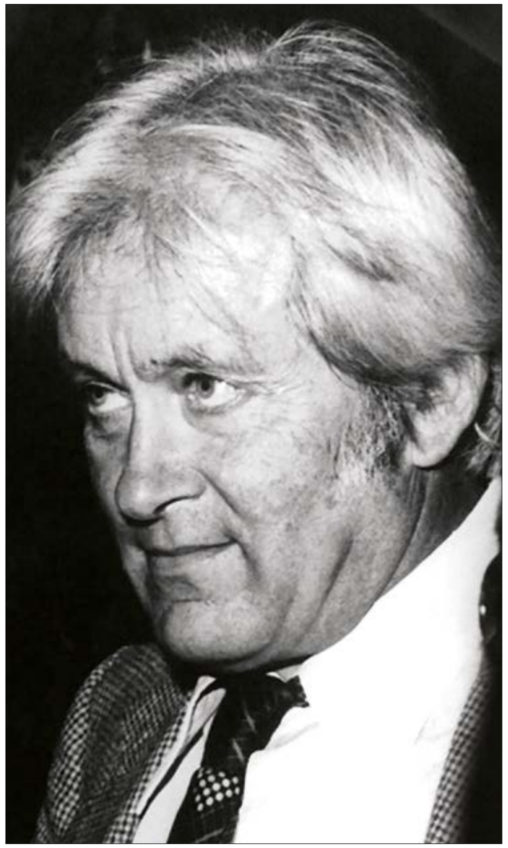
There is no recipe for building a detector for discovering the unknown, especially when the unknown is likely to involve rare and complex particle interactions. However the ALEPH team believes that its detector will be able to disintangle much of this complexity, providing an optimal instrument both for studying the known and discovering the unknown. ●

DETECTOR TRENDS

by Georges Charpak

In the January/February 1986 issue, CERN's Georges Charpak described how the huge detectors under construction at the time incorporated ideas "once considered revolutionary, with no guarantee of success". Two decades earlier, Charpak had himself invented such a technology, the multi-wire proportional chamber, and six years later he would be awarded the 1992 Nobel Prize in Physics – to date the last Nobel Prize in Physics to be awarded to a single person.

This article was adapted from text in *CERN Courier* vol. 26, January–February 1986, pp2–6



Detector specialist Georges Charpak of CERN gave the review talk on detectors at the Lepton–Photon Symposium in Kyoto last summer, providing a useful snapshot of the work in this continually evolving field.

Every year sees the emergence of new breeds of detectors and the improvement of existing ones, but the innovations which go on to make a significant impact on physics research are limited. The large investment in man-years and money required for today's large experiments can cool the enthusiasm generated by new detector ideas. However many of the huge detectors now under construction or planned incorporate ideas which were once considered revolutionary, with no guarantee of success. The groups building these detectors are often the most active centres of detector research.

Tracking

Fixing the trajectories of the particles emerging from a collision can be accomplished by solid state or gaseous detectors. With rare particles having only a short lifetime, accuracy, with its possible concomitant space and cost reductions, is of increasing importance.

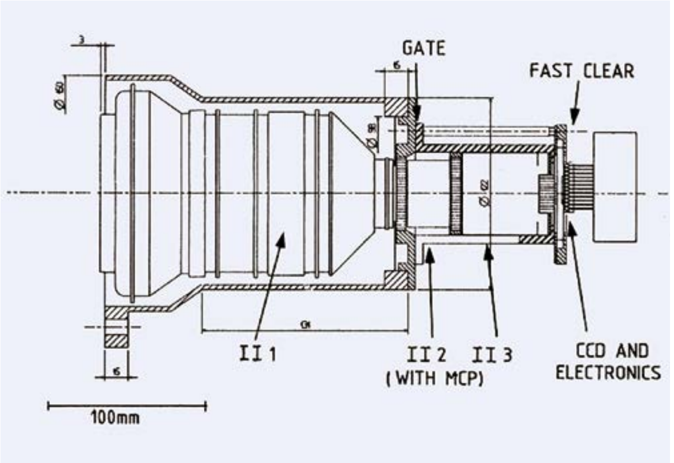
Semiconductor microstrips (see March 1982 issue, page 47) and charge coupled devices (CCD, see June 1982 issue, page 179) are now established techniques, allowing trajectories in a plane to be measured down to about 5 microns.

The initial disadvantage of microstrips was the overhead of large surface electronics, but this has diminished with the emergence of low cost, high density integrated circuits. The considerable advantages of CCDs have led to the development of improved readout to handle high data rates. Solid state drift chambers with their simpler readout also look promising.

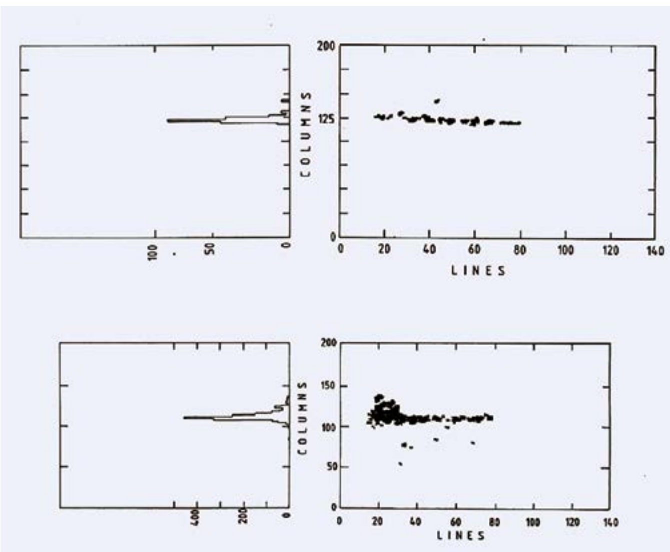
Despite the emergence of solid state detectors, there is continual interest in the more traditional gaseous detectors, with their unrivalled flexibility and ease of construction for large surfaces. One development aimed at increasing accuracy is higher pressure, where 4 atm appears optimal.

In principle the position of an ionization cluster can be measured down to 20 microns, but difficulties arise from the geometry of the chamber wires and in measuring distances for particles not travelling exactly parallel to a wire plane. Tracks parallel to anode wires have been fixed down to about 60 microns.

New techniques strive to improve this accuracy by measuring separate ionization electron clusters (H. Walenta), by grouping small individual drift tubes (Stanford), or by fitting many sense wires inside a



New detector techniques in action: the UA2 experiment's idea to exploit scintillating plastic fibres for its upgraded vertex detector. Light from the fibres is amplified by image intensifiers (II) and read out through a charge coupled device (CCD).



CCD images from a UA2 prototype array of fibres exposed to 40 GeV beams, showing (top) a hadron track, and (bottom), using lead radiator, an electron.

readily interchangeable carbon tube (CERN). Other developments aim at improving position measurements along the wires.

Visual detectors

Improving the optics of bubble chambers by holographic means (see October 1983 issue, page 317) has increased accuracies down to 10 microns. However the limitations of bubble chambers for handling many close tracks have led people to look instead towards streamer chambers. Illumination of ionization avalanches by laser light (Munich/CERN) permits smaller avalanches to be picked up.

Accuracy is lost when ionization electrons start to diffuse before the triggering signal, but this can be overcome by a clever method (Yale) of temporarily attaching the electrons to a heavy (oxygen) ion, subsequently removed by laser irradiation.

At CERN, another development involves catching the avalanche electrons on mylar foil and developing the electrostatic image with an appropriate toner to give a track 'xerox'.

One new material now increasingly being used is scintillating optical fibre, offering possibilities for both tracking and, when embedded in heavy materials, for electromagnetic calorimetry (energy deposition measurement).

The UA2 experiment at the CERN Collider is using plastic scintillating fibres in its current upgrade (see November 1985 issue, page 384). Other developments use glass fibres (Fermilab) and lead/fibre matrices for calorimetry (Saclay, see April 1984 issue, page 107).

Calorimetry

In the measurement of energy deposition, many developments aim to improve geometry, cost and energy resolution. Liquid argon calorimeters, a rarity not that long ago, are now firmly established, but work goes on to find liquids with more convenient ionization properties.

The electron yield of liquid argon can be improved by doping it with photosensitive liquids. However there is increasing effort to find suitable materials which operate at room temperature, in particular for the new calorimeter for the UA1 experiment at CERN (see November 1985 issue, page 384).

'New' methods for particle identification now being used include the Transition Radiation Detector, where optimal designs are now appearing, and the Ring Imaging Cherenkov (RICH). 100 m^2 of RICH will be installed in the DELPHI detector for CERN's new LEP electron–positron collider.

Heavy scintillators such as bismuth germanate (BGO) offer improved energy resolution for calorimetry. As a result of development work for the L3 experiment at LEP, the cost of BGO has been considerably reduced. However the more traditional and cheaper iodide materials continue to be attractive.

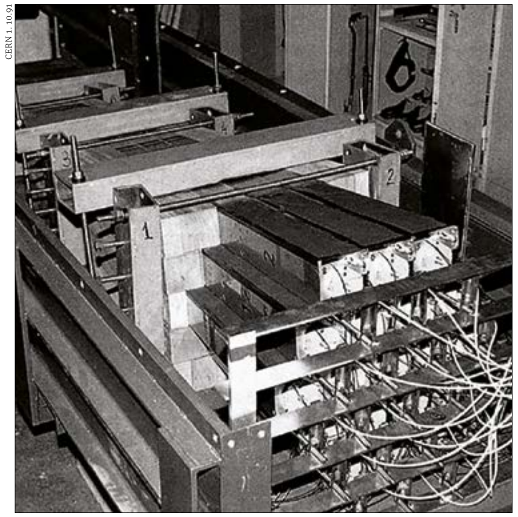
A newcomer material is barium fluoride, which permits scintillation photons to be measured in a wire chamber. This potentially considerable step forward, combining the photon stopping power of a heavy solid with the tested versatility of a wire chamber, enables energy deposition to be localized (see May 1984 issue, page 141).

One new and simple detector now being investigated at CERN relies on emitted light, rather than electronic signals, to localize ionization avalanches. A lot of work went into finding the best geometry and gas mixture (noble gases and triethylamine), and the payoff looks near.

If the hopes raised by these and other tests are fulfilled, experimental particle physics will have powerful new tools to exploit the conditions offered by the big machines now being built. ●

NEEDLES IN HIGH-SPEED HAYSTACKS

In 1991, the year that the CERN Council voted unanimously that the Large Hadron Collider (LHC) is "the right machine for the advance of the subject and for the future of CERN", the Courier *took a look at the challenges facing detectors in dealing with the LHC's unprecedented collision rate. The same challenges faced the Superconducting Super Collider (SSC) in the US. Alas, while the LHC was approved three years later, the SSC never had the chance to put these ideas into practice.*



For the LHC at CERN, research and development work on detector components and techniques is pushing ahead on a wide front. Seen here is the rear of a lead-scintillating fibre calorimeter recently tested at the SPS synchrotron.

This article was adapted from text in *CERN Courier* vol. 31, November 1991, pp2–7

The new generation of big proton–proton colliders now being planned in Europe and the US aims to open up the collision physics of the constituent quarks and gluons hidden deep inside the proton. Locked inside nuclear particles, quarks and gluons cannot be liberated as free particles, at least under current laboratory conditions. To study them needs microscopes the size of the LHC collider foreseen for CERN's 27-kilometre LEP tunnel and the 87-kilometre Superconducting Supercollider (SSC) planned in the US. But the researchers using these gigantic new microscopes have to have good eyesight – they need the right detectors.

Seeing things this small needs collision energies of some 1 TeV (1000 GeV) per constituent quark/gluon, or at least 15 TeV viewed at the proton–proton level. Most of the time, the collisions would be 'soft', involving big pieces of proton, rather than quarks and gluons. To see enough 'hard' collisions, when the innermost proton constituents clash against each other, physicists need very high proton–proton collision rates.

These rates are measured by luminosity. (The luminosity of a two-beam collider is the number of particles per second in one beam multiplied by the number of collisions per unit area of the other beam.) For LHC, luminosities of up to a few times 10^{34} are needed.

Quite apart from the challenge of delivering this number of high energy protons, having such intense beams continually smashing through physics apparatus makes problems for detector designers.

As well as quickly wearing out detector components, these conditions imply new dimensions of data handling. Proton bunches would sweep past each other some 60 million times per second, each time producing about 20 interactions of one kind or another. Only one in a billion of these interactions would be of the hard kind which interests the physicists, and the instrumentation and data systems would have to filter out interesting physics fast enough to avoid being swamped by the subsequent tide of raw data.

It is as though a passenger in a train, watching haystacks flash past the window at high speed during a thunderstorm, had to locate a single needle hidden in one haystack, without stopping the train.

To look for these needles, physicists use detectors built like a series of boxes packed one inside the other, each box doing a special job before the particles pass through to the next. The innermost box is the tracker which takes a snapshot of the collision, tracing the path of the emerging particles.

Quark/gluon collisions, each expected to give a few hundred tracks, would be superimposed on many soft proton collisions, each producing about 25 tracks.

Traditional tracking, with a full 'picture' of emerging charged particle tracks bent by a magnetic field (to measure momentum) looks feasible at luminosities up to about 10^{33}. Physics would certainly need higher rates, but this would blind the innermost tracker, and for these runs it would be best removed. However a certain amount of tracking has to be retained, even at higher rates, to pick up the isolated electrons accompanying special processes. Promising tracking technologies include semiconductor microstrips and scintillating fibres.

After the tracker traditionally follows the calorimeter to measure the energy deposited by the emerging particles. As well as measuring the energies of special particles, like photons and electrons, the calorimeter has to be 'watertight'. Any mismatch in energy flow between two sides of the detector ('missing energy') can then be attributed to invisible particles, like neutrinos, escaping the detector, and not to otherwise visible particles disappearing through cracks.

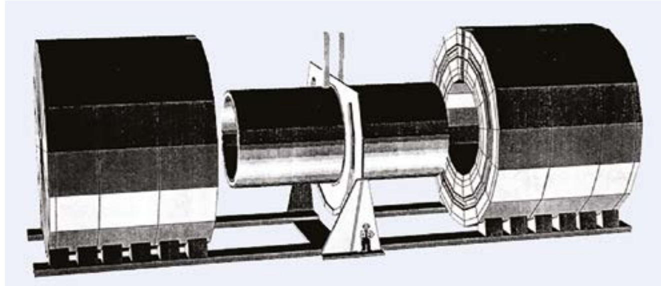
The signals from hard quark/gluon interactions would necessarily be obscured by 'pile-up' from soft interactions.

Overlap from different interactions can be minimized by having a fine-grained calorimeter, and some soft background can be allowed for. Promising general-purpose calorimeter technologies include liquid argon and scintillating fibre/lead matrices, while dedicated calorimeters for electromagnetic energy measurement could be based on special crystals or noble liquids.

Electrons and muons are very important for this kind of physics, and could be a vital part of special signatures indicative of new processes. Muons, with their ability to pass through thick sheets of absorber, remain an 'easy' option, however requirements for precise momentum resolution could have a major impact on the design of these anyway very large detectors.

Electrons are much less easy to isolate than muons, and would also tend to be masked by other signals. Accurate location with a fine-grain detector would help, but additional electron identification still would be needed. Such information could be given by correlating calorimeter measurements with upstream signals from the tracker or a dedicated track/preshower detector, or by independent electron identification (using a transition radiation detector).

Seeing anything at all depends on the initial level of event filtering by electronic triggers. These will have to select out one event in ten or even a hundred thousand within a microsecond. In addition, the information coming from different parts of the very large detectors will have to be synchronized, all this some 60 million times a second!



A possible superconducting solenoid design for an experiment at CERN's proposed LHC proton collider. For giving an idea of the scale, some people have suggested that the 'standard man' could be usefully replaced by a 'standard dinosaur'.

For the SSC, 'generic' research and development work began in 1986, eventually overlapping with the R&D for specific detector subsystems. This overlaps in turn with development work for the two major proposed experiments (October, page 12). For the LHC at CERN, research and development work on detector components and techniques is pushing ahead on a wide front pending the appearance of initial proposals for complete detectors (October, page 25), while a magnet study group coordinates the designs for the big magnets at the heart of new detector schemes. ●

PET AND CT

A perfect fit

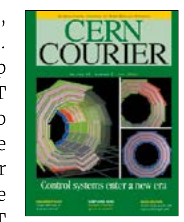
In the June 2005 issue of CERN Courier *(the last to be published jointly in French and English), David Townsend – who began his pioneering work in PET imaging 30 years earlier while a staff member at CERN – talked to Beatrice Bressan about the development and clinical impact of this field.*

David Townsend is a professor in the Department of Medicine, University of Tennessee Medical Center in Knoxville, Tennessee (TN). The winner of the 2004 Clinical Scientist of the Year Award from the Academy of Molecular Imaging, he is an internationally renowned researcher with 30 years' experience as a physicist working in the field of positron emission tomography (PET). Townsend began his eight years at CERN in 1970. While working at the Cantonal Hospital in Geneva from 1979 to 1993, he recognised the importance of combining the functionality of PET with that of computed tomography (CT). During that same period, Townsend also worked with Georges Charpak, CERN physicist and 1992 Nobel laureate in physics, on medical applications of Charpak's multi-wire chambers.

Video-capture of David Townsend giving his "Advances in PET Imaging" seminar at CERN on 9 February 2005.

After Townsend moved to Pittsburgh in 1993, his group in the US helped to develop the first combined PET/CT scanner; more than 1000 are now used worldwide to image human cancer. In 1999, Townsend received the Image of the Year Award from the Society of Nuclear Medicine in the US, for an image he produced using the first prototype scanner combining state-of-the art PET with true diagnostic-quality CT.

Current research objectives in instrumentation for PET include advances in PET/CT methodology and the assessment of the role of combined PET/CT imaging for a range of different cancers. The PET/CT combination, pioneered by Townsend and Ron Nutt, CEO and president of CTI Molecular Imaging in Knoxville, TN, is a milestone in these developments, revealing in particular the role of the physicist and engineer in bringing such developments into clinical practice and exploring how they affect patient care.



This article was adapted from text in *CERN Courier* vol. 45, June 2005, pp23–25

The past 20 years have seen significant advances in the development of imaging instrumentation for PET. Current high-performance clinical PET scanners comprise more than 20 000 individual detector elements, with an axial coverage of 16 cm and around 15% energy resolution. Can you identify the most important factors that have contributed to this remarkable development in PET?

This impressive progress is due essentially to developments in detector construction, new scintillators, better scanner designs, improved reconstruction algorithms, high-performance electronics and, of course, the vast increase in computer power, all of which have been achieved without an appreciable increase in the selling price of the scanners.

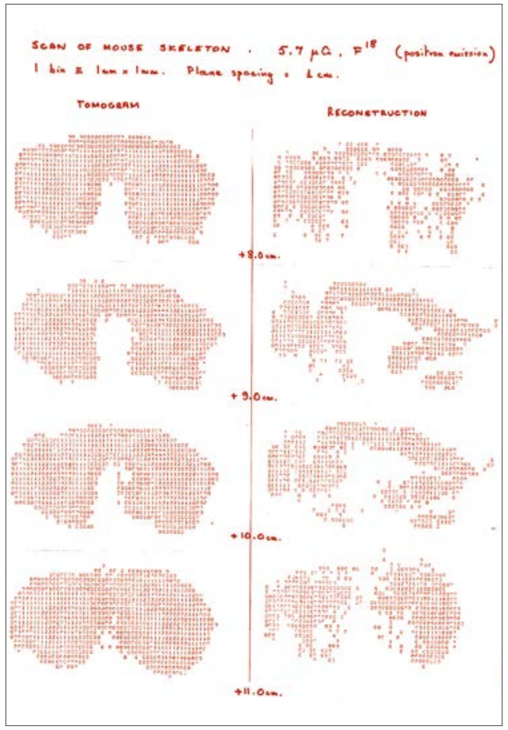
The PET/CT image is one of the most exciting developments in nuclear medicine and radiology, its significance being the merging not simply of images but of the imaging technology. Why is the recent appearance of combined PET and CT scanners that can simultaneously image both anatomy and function of particular importance?

Initial diagnosis and staging of tumours are commonly based on morphological changes seen on CT scans. However, PET can differentiate malignant tissue from benign tissue and is a more effective tool than CT in the search for metastases. Clearly, valuable information can be found in both, and by merging the two it is possible now to view morphological and physiological information in one fused image. To acquire the PET/CT image, a patient passes through the CT portion of the scanner first and then through the PET scanner where the metabolic information is acquired. When the patient has passed through both portions, a merged or fused image can be created.

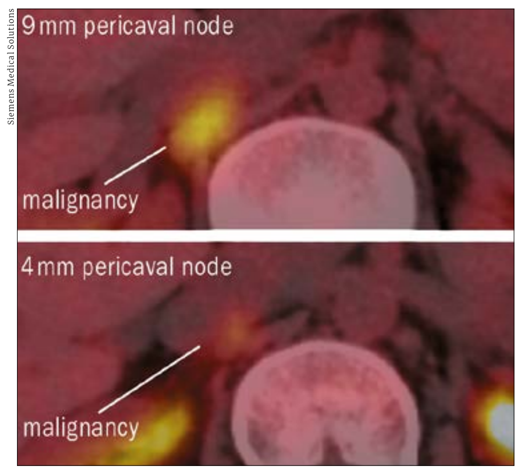
Let's take a step back. The history of PET is rich, dynamic and marked by many significant technological achievements. Volumes of books would be required to record the history of PET developments and its birth still remains quite controversial. Could you identify the most important events that have shaped modern PET?

You are indeed correct that the birth of PET is somewhat controversial. One of the first suggestions to use positron-emitting tracers for medical applications was made in 1951 by W H Sweet and G Brownell at Massachusetts General Hospital, and some attempts were made to explore the use of positron-emitting tracers for medical applications in the 1950s. During the late 1950s and 1960s, attempts were made to build a positron scanner, although these attempts were not very successful. After the invention of the CT scanner in 1972, tomography in nuclear medicine received more attention, and during the 1970s a number of different groups attempted to design and construct a positron scanner.

S Rankowitz and J S Robertson of Brookhaven National Laboratory built the first ring tomograph in 1962. In 1975, M Ter-Pogossian, M E Phelps and E Hoffman at Washington University in St Louis presented their first PET tomograph, known as Positron Emission Transaxial Tomograph I (PETT I). Later the name was changed to PET, because the transaxial plane was not the only plane in which images could be reconstructed. In 1979, G N Hounsfield and A M Cormack were awarded the Nobel Prize for Physiology and Medicine in recognition of their development of X-ray CT.



The first mouse image taken in 1977, when PET began at CERN.



A 48-year-old patient with a history of stage IIIA ovarian cancer. The PET/CT scan reveals malignancy in two pericaval nodes. The ability to identify radiotracer uptake in such small lymph nodes is a strength of the new HI-REZ, 16-slice biograph PET/CT scanner.

Since the very early development of nuclear-medicine instrumentation, scintillators such as sodium iodide (NaI) have formed the basis for the detector systems. The detector material used in PET is the determining factor in the sensitivity, the image resolution and the count-rate capability. The only detector of choice in the mid-1970s was thallium-activated NaI – NaI(Tl) – which requires care when manufactured because of its hygroscopic nature. More importantly, it also has a low density and a low effective atomic number that limits the stopping power and efficiency to detect the 511 keV gamma rays from positron annihilation. Which other scintillators have contributed to modern PET tomography?

Thanks to its characteristics, bismuth germanate, or BGO, is the crystal that has served the PET community well since the late 1970s, and it has been used in the fabrication of most PET tomographs for the past two decades. The first actual tomograph constructed that employed BGO was designed and built by Chris Thompson and co-workers at the Neurological Institute in Montreal in 1978.

Although the characteristics of BGO are good, a new scintillator, lutetium oxyorthosilicate (LSO) (discovered by C Melcher, now at CTI Molecular Imaging in Knoxville, TN), is a significant advance for PET imaging. BGO is very dense but has only 15% of the light output of NaI(Tl). LSO has a slightly greater density and a slightly lower effective atomic number, but has five times more light output and is seven times faster than BGO. The first LSO PET tomograph, the MicroPET for small animal imaging, was designed at the University of California in Los Angeles (UCLA) by Simon Cherry and co-workers. The first human LSO tomograph, designed for high-resolution brain imaging, was built by CPS Innovations in Knoxville, TN, and delivered to the Max Planck Institute in February 1999.

What were your key achievements in PET during your career at CERN? Did CERN play a role in its birth?

In 1975, I was working at CERN when Alan Jeavons, a CERN physicist, asked me to look at the problem of reconstructing images from PET data acquired on the small high-density avalanche chambers (HIDACs) he had built for another application with the University of Geneva. We got the idea for using the HIDACs for PET because a group in Berkeley and University of California, San Francisco (UCSF) was using wire chambers for PET. I developed some software to reconstruct the data from Jeavons' detectors, and we took the first mouse image with the participation of radiobiologist Marilena Streit-Bianchi in 1977 at CERN.

The reconstruction methods I developed at CERN were further extended mathematically by Benno Schorr (a CERN mathematician), Rolf Clackdoyle and myself from 1980 to 1982. We used those, and other algorithms developed by Michel Defrise in Brussels and Paul Kinahan in Vancouver, in 1987 and 1988 to reconstruct PET data from the first CTI [Computer Technology and Imaging Inc, renamed CTI Molecular Imaging in June 2002] multi-ring PET scanner installed in London at Hammersmith Hospital. PET was not invented at CERN, but some essential and early work at CERN contributed significantly to the development of 3D PET, and then to a new scanner design, the Advanced Rotating Tomograph (ART).

The prototype of the ART scanner, the Partial Ring Tomograph (PRT), was developed at CERN from 1989 to 1990 by Martin Wensveen, Henri Tochon-Danguy and myself, and evaluated clinically at the Cantonal Hospital within the Department of Nuclear Medicine under Alfred Donath. The ART was a forerunner of the PET part of the combined PET/CT scanner, which has now had a major impact on medical imaging.

What has to happen for us to reach a more highly performing PET/CT combination?

The sensitivity of the PET components must be improved in order to acquire more photons in a given time. That is still a challenge, because the axial coverage of current scanners is only 16 cm, whereas after injection of the radiopharmaceutical, radiation is emitted from everywhere in the patient's body where the radiopharmaceutical localizes. So, if the detector covered the whole body, the patient could be imaged in one step. However, building such a system would be very expensive.

Do you think that it is still possible to have alternative combinations with other imaging techniques?

Yes, absolutely, but only if there is a medical reason to do it – such a development won't be driven by advances in technology alone. When we looked at building a PET/CT scanner, we found that most whole-body anatomical imaging for oncology is still performed with CT, whereas in brain and spinal malignancies, anatomical imaging is performed with magnetic resonance.

PET/CT is less technologically challenging than combining PET with magnetic resonance. PET and CT modalities basically do not interfere with each other, except maybe when they are operated simultaneously within the same gantry. The combined PET/CT scanner provides physicians with a highly powerful tool to diagnose and stage disease, to monitor the effects of treatment, and to potentially design much better, patient-specific therapies.

What is the actual cost of a PET/CT scanner?

The cost of the highest-performing system is about $2.5 million [€1.98 million], but it may be significantly less if a lower-performance design is adequate for the envisaged application. ●

CERN-HI-1007146-13

The AMS detector under preparation at CERN in July 2010.

AMS TAKES OFF FOR KENNEDY SPACE CENTER

The October 2010 issue reported on the final steps of the unique AMS detector en route to the International Space Station. Powered up the following year, AMS continues to make precision measurements of charged cosmic rays.

The Alpha Magnetic Spectrometer (AMS), an experiment that will search for antimatter and dark matter in space, left Geneva on 26 August on the penultimate leg of its journey to the International Space Station (ISS). Following work to reconfigure the AMS detector at CERN, it was flown to the Kennedy Space Center in Florida on board a US Air Force Galaxy transport aircraft.

The AMS experiment will examine fundamental issues about matter and the origin and structure of the universe directly from space. Its main scientific target is the search for dark matter and antimatter, in a programme that is complementary to that of CERN's LHC.

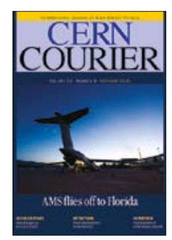
Last February the AMS detector travelled from CERN to the European Space Research and Technology Centre (ESTEC) in Noordwijk for testing to certify its readiness for travel into space (*CERN Courier* April 2010 p5). Following the completion of the testing, the AMS collaboration decided to return the detector to CERN for final modifications. In particular, the detector's superconducting magnet was replaced by the permanent magnet from the AMS-01 prototype, which had already flown in space in 1998. The reason for the decision was that the operational lifetime of the superconducting magnet would have been limited to three years because there is no way of refilling the magnet with liquid helium – which is necessary to maintain the magnet's superconductivity – on board the space station. The permanent magnet, on the other hand, will now allow the experiment to remain operational for the entire lifetime of the ISS.

Following its return to CERN, the AMS detector was reconfigured with the permanent magnet before being tested with particle beams. The tests were used to validate and calibrate the new configuration before the detector leaves Europe for the last time.

On arrival at the Kennedy Space Center, AMS will be installed in a clean room for further tests. A few weeks later, the detector will be moved to the space shuttle. NASA is planning the last flight of the space-shuttle programme, which will carry AMS into space, for the end of February 2011.

Once docked to the ISS, AMS will search for antimatter and dark matter by measuring cosmic rays. Data collected in space by AMS will be transmitted to Houston and on to CERN's Prévessin site, where the detector control centre will be located, as well as to a number of regional physics-analysis centres set up by the collaborating institutes.

The AMS experiment stems from a large international collaboration, which links the efforts of major European funding agencies with those in the US and China. The detector components were produced by an international team, with substantial contributions from CERN member states (Germany, France, Italy, Spain, Portugal and Switzerland), and from China (Taipei) and the US. The detector was assembled at CERN, with the assistance of the laboratory's technical services. ●



This article was adapted from text in *CERN Courier* vol. 50, October 2010, p5