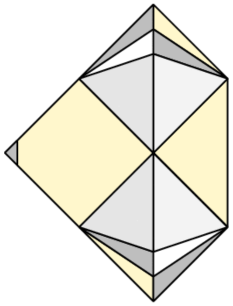
Diamonds for Present/Future LHC Applications

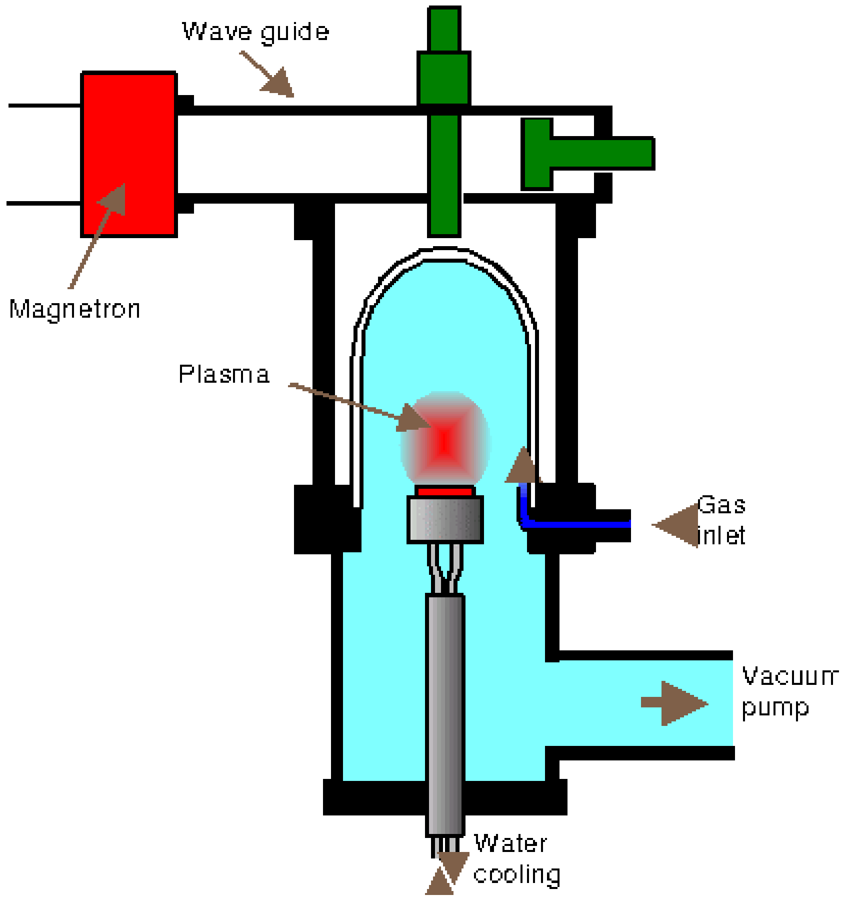
- How diamond works as a sensor material
  - Growth, Properties, Signal, Morphology, Manufacture
- Radiation tolerance of recent sensors
  - Tracker signals, irradiations, damage scaling
- Applications
  - CDF and ATLAS beam conditions monitors
  - The ATLAS pixel detector upgrade



William Trischuk
University of Toronto
November 2011

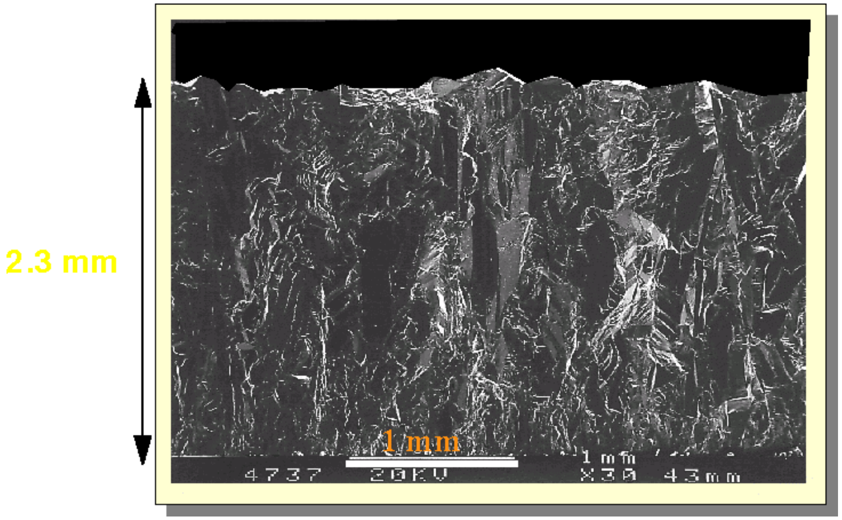
CVD Diamond as a Particle Detector

- Microwave growth reactor



- Diamond synthesized from plasma

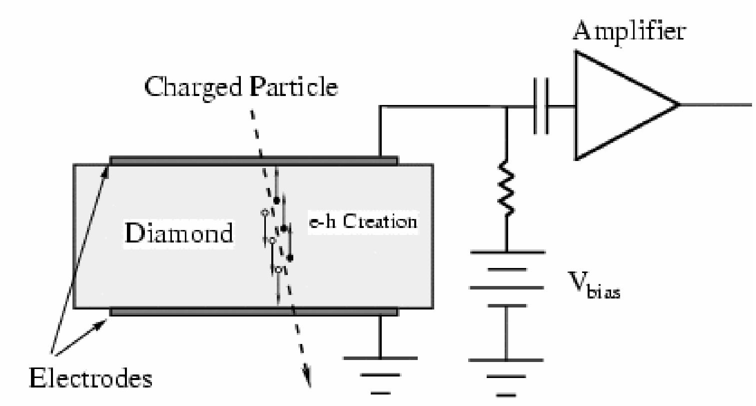
- Material copies substrate
- Dominant crystallites appear



- Edge view of pCVD sample
  (Courtesy of Element6)

Signals from Diamond Sensors

- Image charge signal
  - induced on surface electrodes

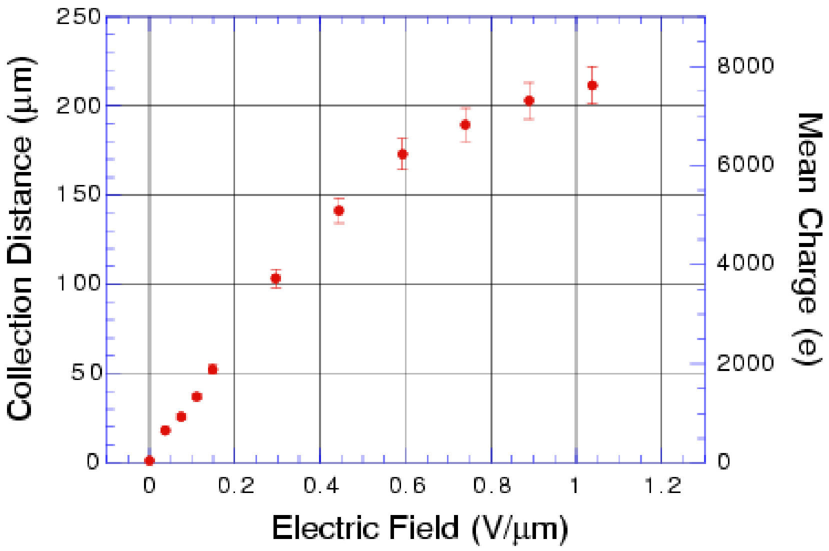


- Charge collected, Q

$$Q = \frac{d}{t}\ Q_0$$

$$d \equiv (\mu_e\tau_e + \mu_h\tau_h)|\vec{E}|$$

- d is the Charge Collection Distance

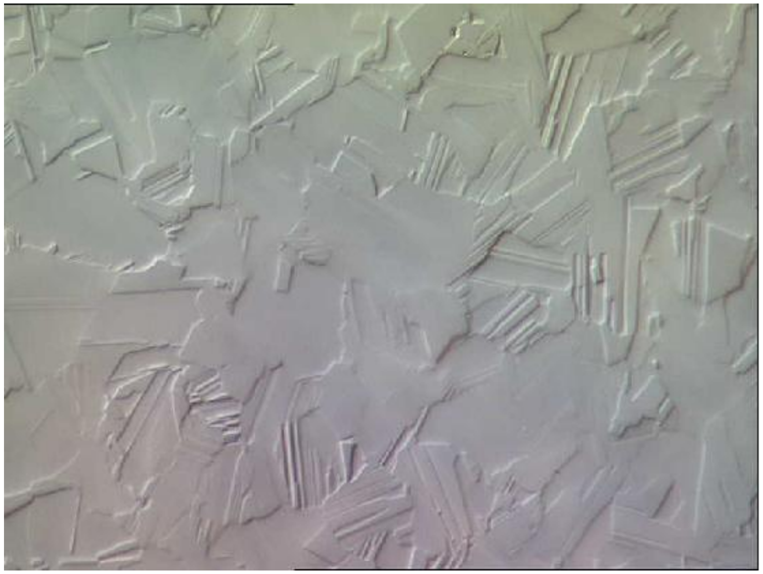


- Mobility saturates at $|\vec{E}| \approx 1V/\mu$m
- Operate typical sensor at 300-400 V

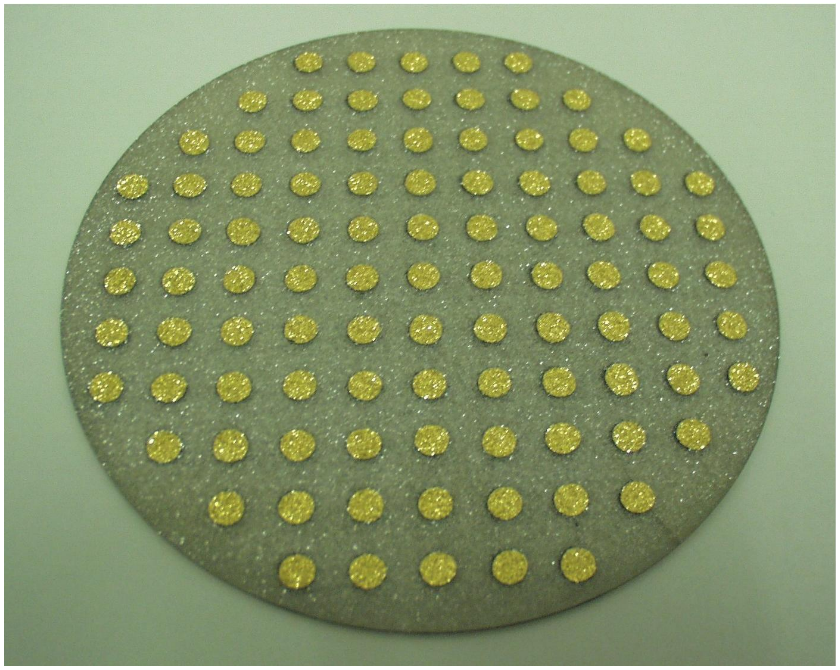
Properties of Diamond and Silicon

Property	Diamond	Silicon	
Band gap [eV]	5.5	1.12	
Breakdown field [V/cm]	10^7	3×10^5	
Intrinsic resistivity @ R.T. [Ω cm]	$> 10^{11}$	2.3×10^5	✪ Low leakage
Intrinsic carrier density [cm^{-3}]	$< 10^3$	1.5×10^{10}	
Electron mobility [cm^2/Vs]	1900	1350	✪ Fast signal
Hole mobility [cm^2/Vs]	2300	480	
Saturation velocity [cm/s]	1.3(e)-1.7(h)x 107	1.1(e)-0.8(h)x 10^7	
Density [g/cm^3]	3.52	2.33	
Atomic number - Z	6	14	
Dielectric constant - ε	5.7	11.9	✪ Low capacitance
Displacement energy [eV/atom]	43	13-20	✪ Radiation hard
Thermal conductivity [W/m.K]	~2000	150	✪ Heat spreader
Energy to create e-h pair [eV]	13	3.61	
Radiation length [cm]	12.2	9.36	
Spec. Ionization Loss [MeV/cm]	6.07	3.21	
Aver. Signal Created / 100 μm [e_0]	3602	8892	★ Low signal
Aver. Signal Created / 0.1 X_0 [e_0]	4401	8323	

Examples of CVD Material



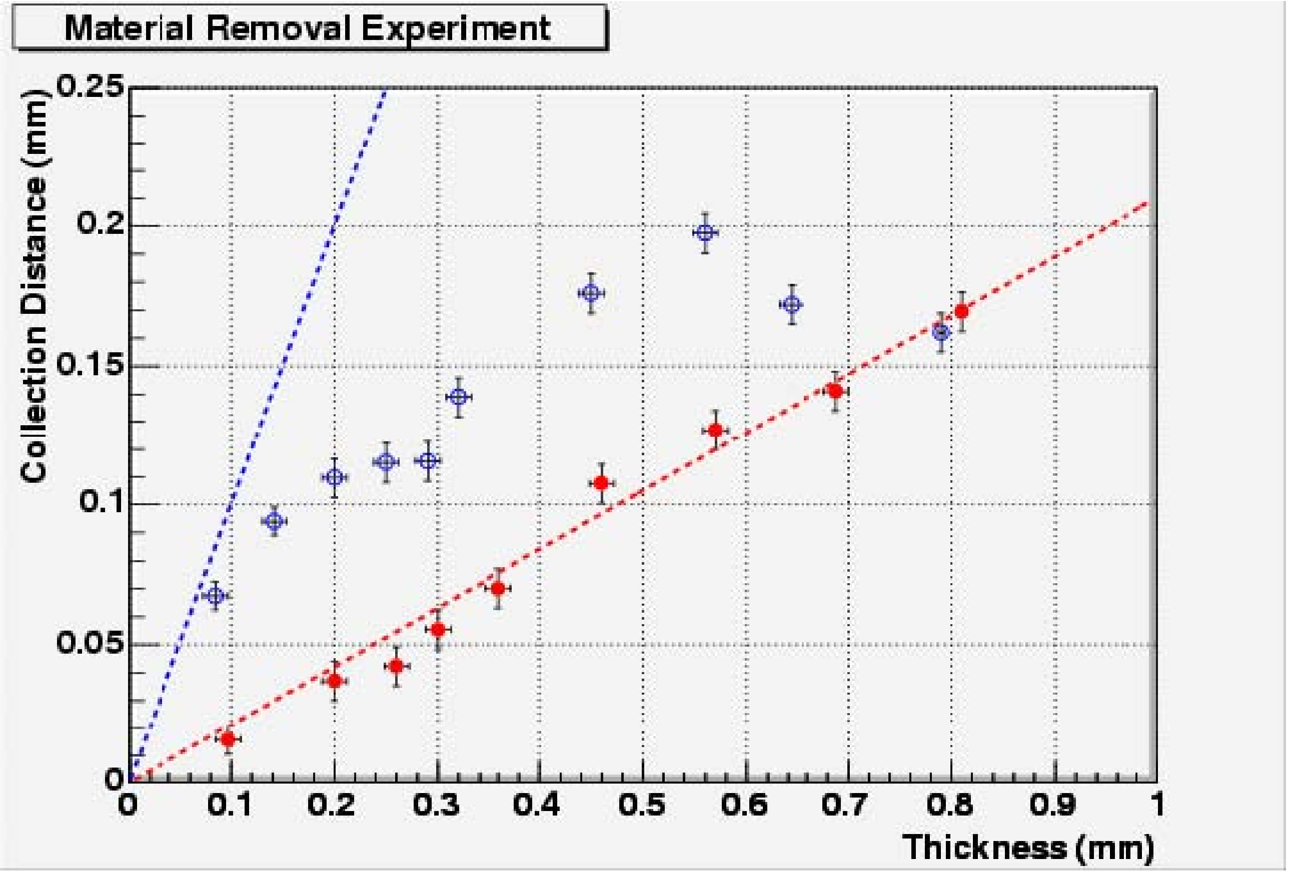
Surface image of pCVD sample
(Courtesy Element6)



- pCVD diamond wafer
- Dots are on 1 cm grid

- High quality wafers grown 12 cm in diameter
- Best material from wafers grown up to 2 mm thick

Depth Characterisation of CVD Material



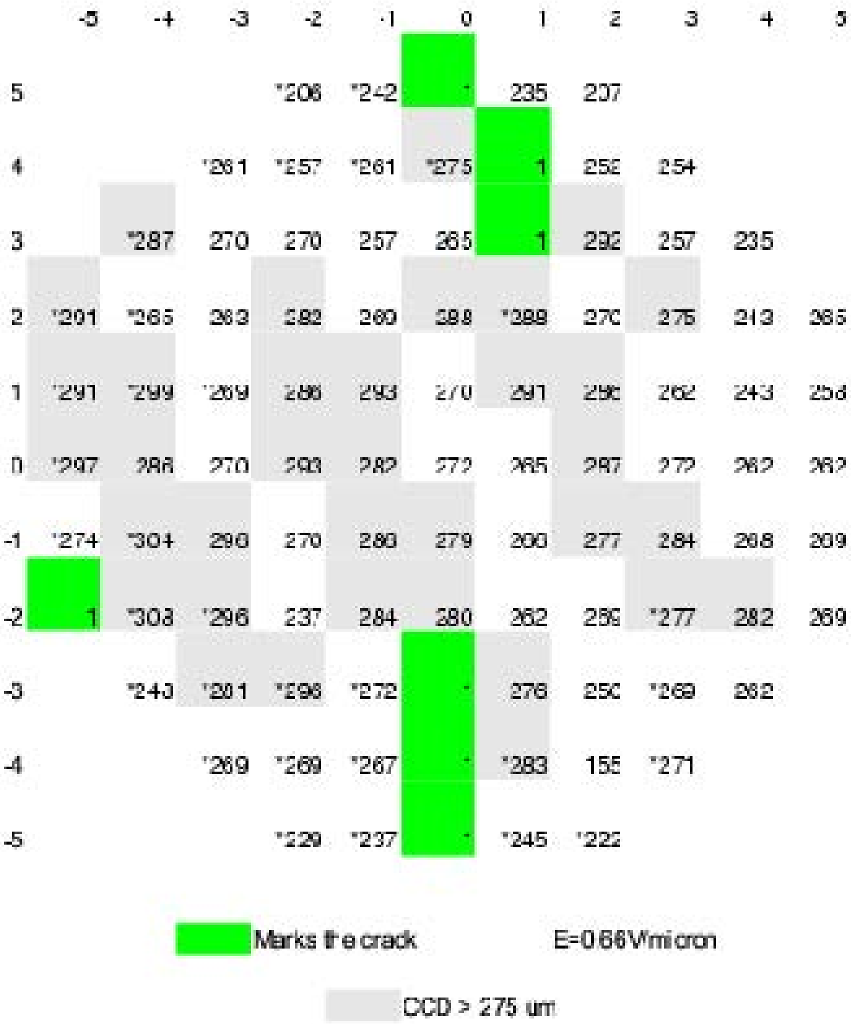
Material removal

Growth side

Substrate side

- Crystal quality increases with distance from substrate side
- Last deposited material has highest quality
- Can improve average signal by removing *some* material

Surface Characterisation of Wafers

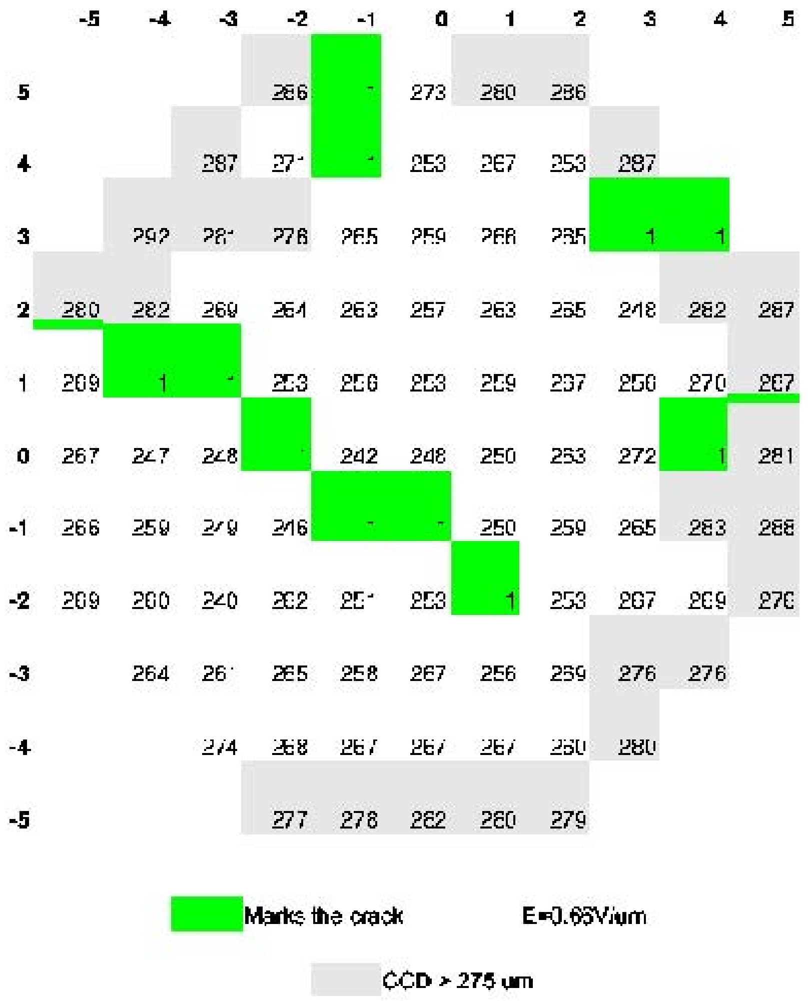


	-5	-4	-3	-2	-1	0	1	2	3	4	5
5				*206	*242	1	235	207			
4			*261	*257	*261	*275	1	252	254		
3		*287	270	270	257	265	1	292	257	235	
2	*291	*265	263	282	260	288	*289	270	275	213	265
1	*291	*299	*269	286	293	270	291	296	262	243	258
0	*297	286	270	293	282	272	265	297	272	262	262
-1	*274	*304	296	270	280	279	200	277	284	268	209
-2	1	*303	*296	237	284	280	262	259	*277	282	269
-3		*240	*281	*298	*272	1	276	250	*269	282	
-4			*269	*269	*267	1	*283	155	*271		
-5				*229	*237	1	*245	*222			

🟩 Marks the crack

E=0.66V/micron

▨ CCD > 275 um



	-5	-4	-3	-2	-1	0	1	2	3	4	5
5				286	1	273	280	286			
4			287	271	1	253	267	253	287		
3		292	281	276	265	259	266	285	1	1	
2	280	282	269	264	263	257	263	265	248	282	287
1	209	1	1	253	256	253	259	237	250	270	267
0	267	247	248	1	242	248	250	253	272	1	281
-1	266	259	279	246	1	1	250	259	265	283	288
-2	209	200	240	202	251	253	1	253	267	269	270
-3		264	261	265	258	267	256	259	276	276	
-4			274	268	267	267	267	250	280		
-5				277	278	282	280	279			

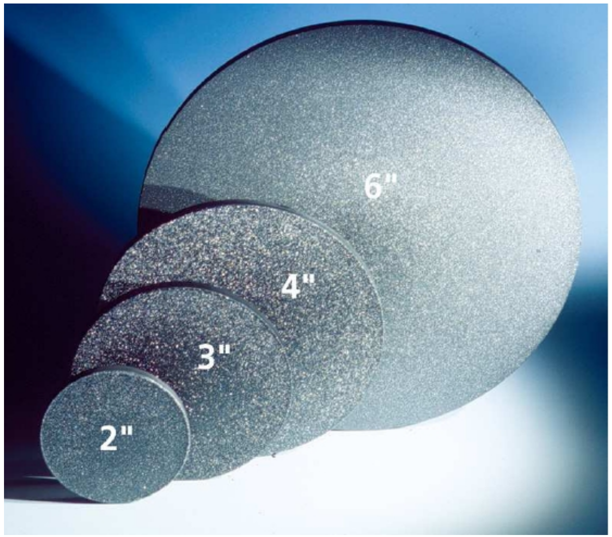
🟩 Marks the crack

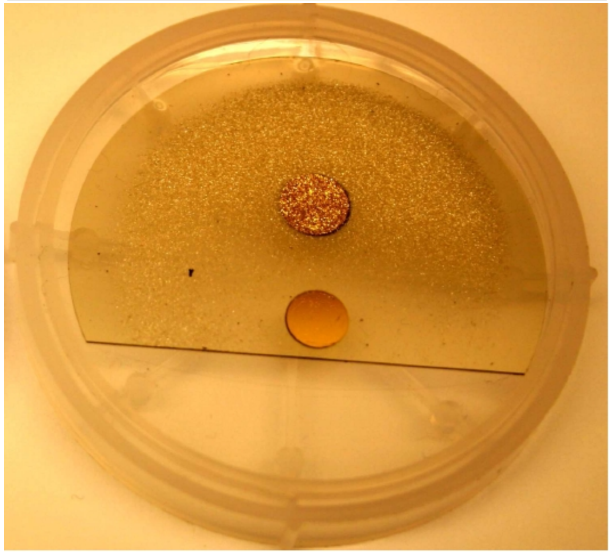
E=0.65V/μm

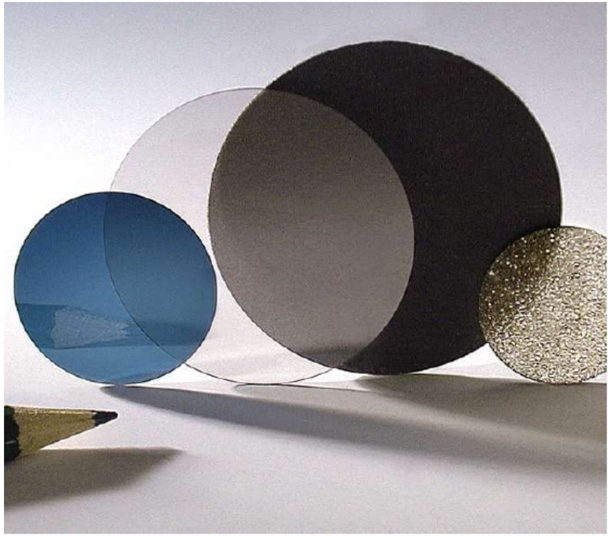
▨ CCD > 275 μm

Wafers now have typically 250-200 μm collection distance

Additional Manufacturers





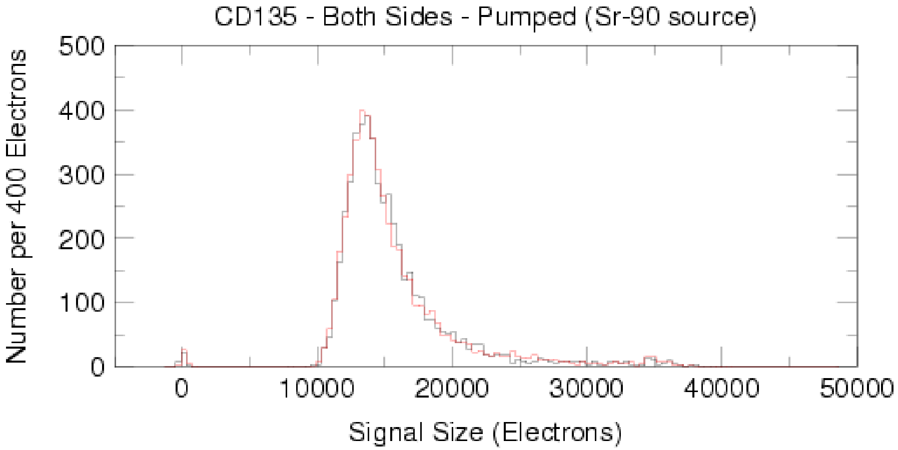


- Other manufacturers interested in radiation tolerant sensor market
- `RD42` working to qualify two new vendors

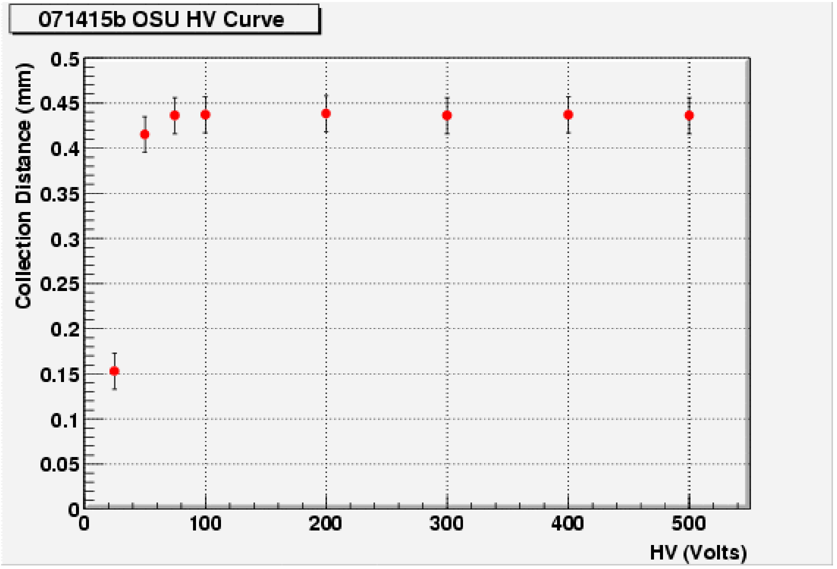
Single Crystal (scCVD) Diamond

- Improve material eliminating grain boundaries, defects/charge traps
- Only make small $(0.5 \times 0.5\ \mathrm{cm}^2)$ scCVD samples at this point

Isberg *et al*, Science 297 (2002), p1670



- Features of this material include
  - Full collection at 0.2 V/μm



  - Collection distance $\equiv$ thickness
  - Charge collection very uniform
- Grain boundaries limit pCVD

The RD42 Collaboration

M. Artuso[25], D. Asner[22], L. Bäni[29], M. Barbero[1], V. Bellini[2], V. Belyaev[15], E. Berdermann[8], P. Bergonzo[14], S. Blusk[25], A. Borgia[25], J-M. Brom[10], M. Bruzzi[5], G. Chiodini[32], D. Chren[23], V. Cindro[12], G. Claus[10], M. Cristinziani[1], S. Costa[2], J. Cumalat[24], A. Dabrowski[3], R. D'Alessandro[6], W. de Boer[13], M. Dinardo[24], D. Dobos[3], W. Dulinski[10], J. Duris[20], V. Eremin[9], R. Eusebi[30], H. Frais-Kolbl[4], A. Furgeri[13], C. Gallrapp[3], K.K. Gan[16], J. Garofoli[25], M. Goffe[10], J. Goldstein[21], A. Golubev[11], A. Gorisek[12], E. Grigoriev[11], J. Grosse-Knetter[28], M. Guthoff[13], D. Hits[17], M. Hoeferkamp[26], F. Huegging[1], H. Kagan[16,♦], R. Kass[16], G. Kramberger[12], S. Kuleshov[11], S. Kwan[7], S. Lagomarsino[6], A. La Rosa[3], A. Lo Giudice[18], I. Mandic[12], C. Manfredotti[18], C. Manfredotti[18], A. Martemyanov[11], H. Merritt[16], M. Mikuz[12], M. Mishina[7], M. Moench[29], J. Moss[16], R. Mountain[25], S. Mueller[13], G. Oakham[22], A. Oh[27], P. Olivero[18], G. Parrini[6], H. Pernegger[3], R. Perrino[32], M. Pomorski[14], R. Potenza[2], A. Quadt[28], K. Randrianarivony[22], A. Robichaud[22], S. Roe[3], S. Schnetzer[17], T. Schreiner[4], S. Sciortino[6], S. Seidel[26], S. Smith[16], B. Sopko[23], S. Spagnolo[32], S. Spanier[31], K. Stenson[24], R. Stone[17], C. Sutera[2], M. Traeger[8], D. Tromson[14], W. Trischuk[19], J-W. Tsung[1], C. Tuve[2], P. Urquijo[25], J. Velthuis[21], E. Vittone[18], S. Wagner[24], R. Wallny[29], J.C. Wang[25], R. Wang[26], P. Weilhammer[3,♦], J. Weingarten[28], N. Wermes[1]

♦ Spokespersons

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2 INFN/University of Catania, Catania, Italy
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16 Ohio State University, Columbus, OH, USA
17 Rutgers University, Piscataway, NJ, USA
18 University of Torino, Torino, Italy
19 University of Toronto, Toronto, ON, Canada
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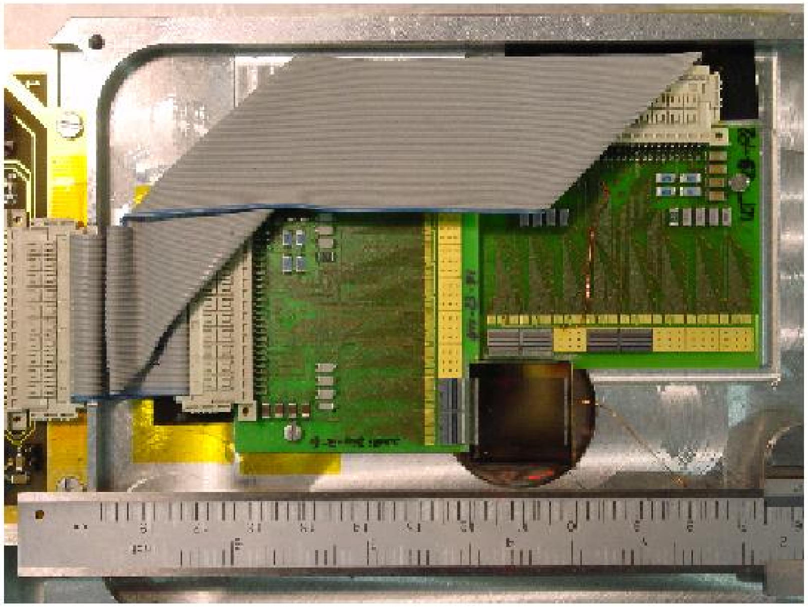
28 Universitaet Goettingen, Goettingen, Germany
29 ETH Zurich, Zurich, Switzerland
30 Texas A&M, Collage Park Station, TX USA
31 University of Tennessee, Knoxville TN USA
32 INFN-Lecce, Lecce, Italy

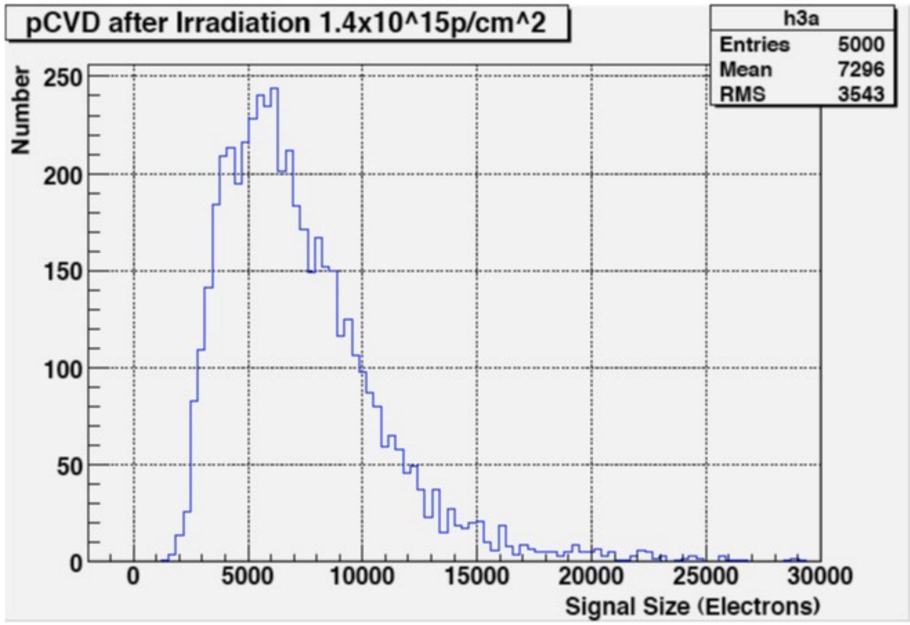
Over 100 Collaborators from 32 institutions

Radiation Tolerance of Diamond Sensors

Typically tested as strip tracker



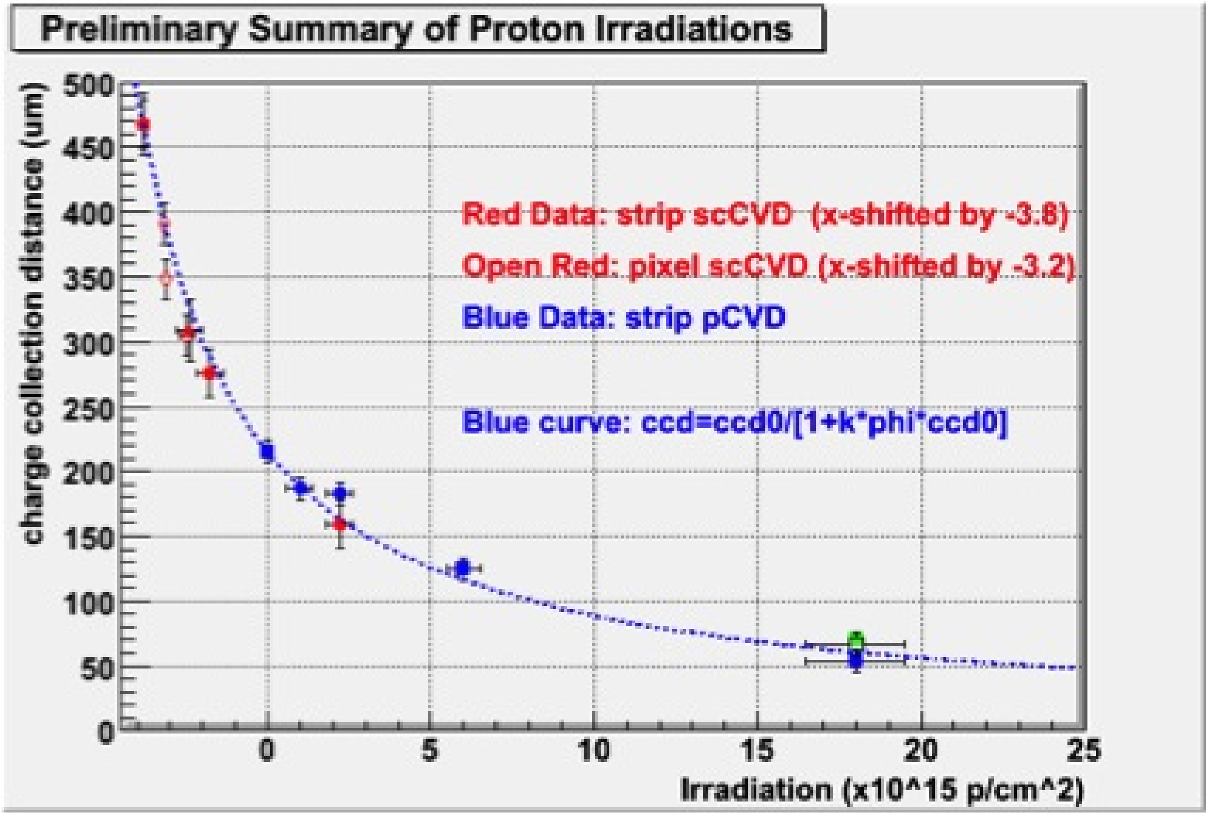
Pulse height from irradiated tracker



- Use long (2 μs) shaping time for precision materials studies
- After 1.4×10^{15} p/cm^2 signal uniform/well separated from pedestal
  - 99 % of hits have more than 2500 electrons signal
  - Most probable signal 6000 electrons at 1 V/μm

24 GeV Proton Irradiations

- Have irradiated:
  - pCVD samples to 1.8×10^{16} p/cm^2
  - scCVD samples to 5×10^{15} p/cm^2
- Characterise signal at intermediate fluences



- Default $E = 1$ V/μm
- Green at $E = 2$ V/μm
- Align by shifting -3.8×10^{15} p/cm^2

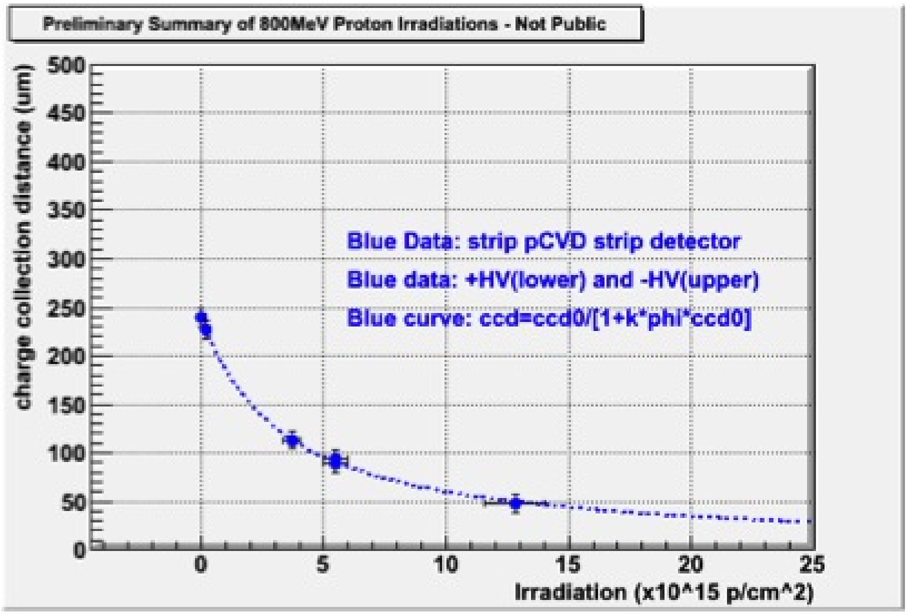
This pCVD material $\equiv$ scCVD material **after** $\approx 3.8 \times 10^{15}$ p/cm^2

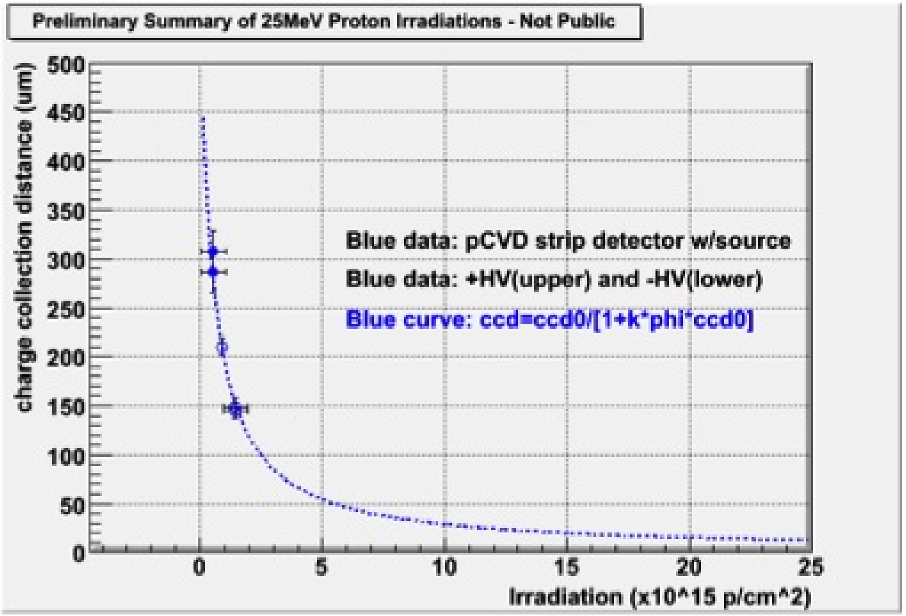
- pCVD and scCVD follow same damage curve:

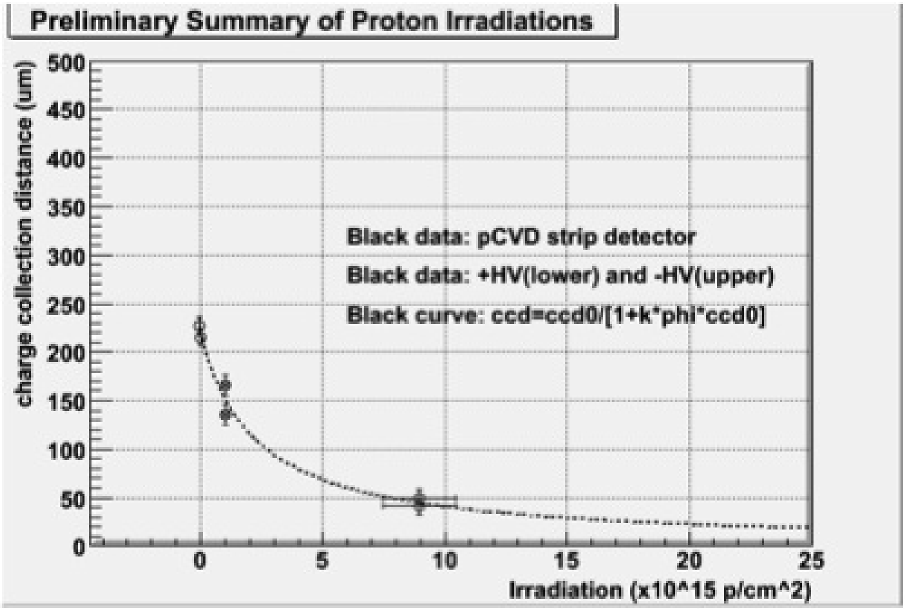
$$1/\mathrm{d} = 1/\mathrm{d}_0 + k\phi$$

$$k \approx 0.7 \times 10^{-18}\ \mu\mathrm{m}^{-1}\ \mathrm{cm}^2$$

Irradiations with Lower Energy Protons



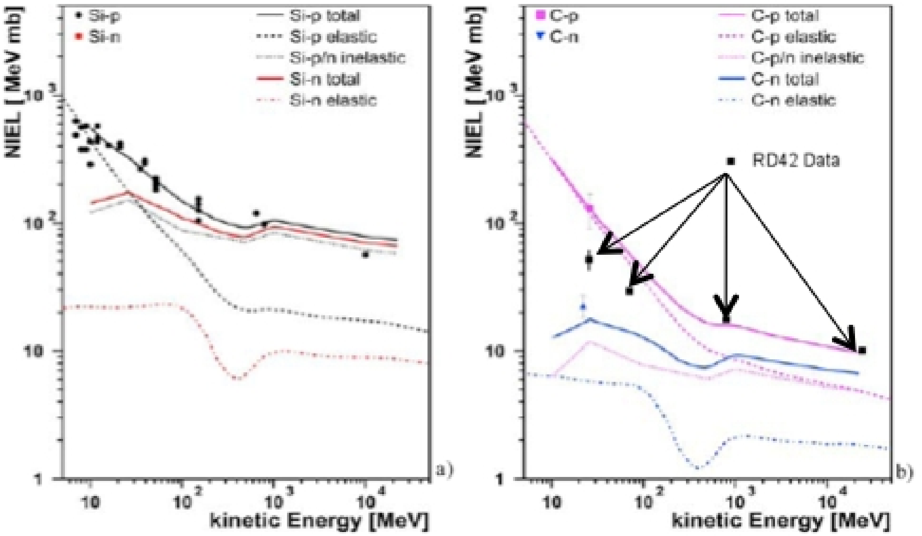




- 800 MeV protons (Los Alamos):
  1.9 times 24 GeV protons
- 70 MeV protons (Sendai):
  2.9 times 24 GeV protons
- 25 MeV protons (Karlsruhe):
  4.7 times 24 GeV protons

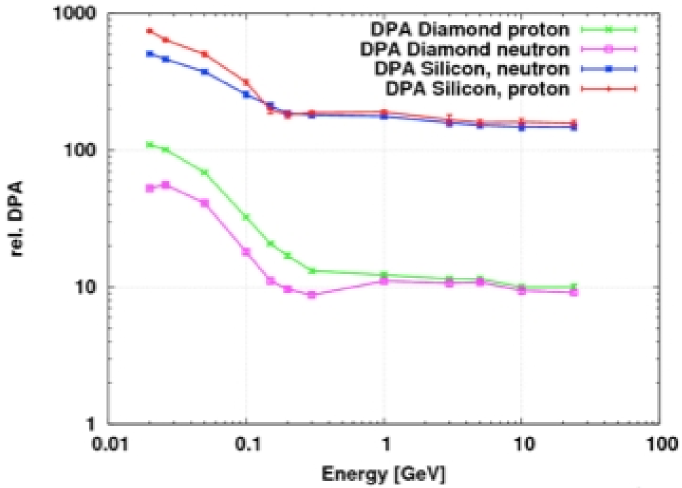
Interpreting Radiation Damage

- Non-ionising energy calculations predict:
  - 0.8/24 GeV p: 2
    – confirmed
  - 0.07/24 GeV p: 6
    – see factor of 3
  - 0.025/24 GeV p: 15
    – see factor of 5
  - 10 MeV $n \equiv$ 24 GeV p
    – in progress
- FLUKA calculations give
  - Protons: 1.2, 5, 10
    for 800, 70, 25 MeV
  - Neutrons: 6



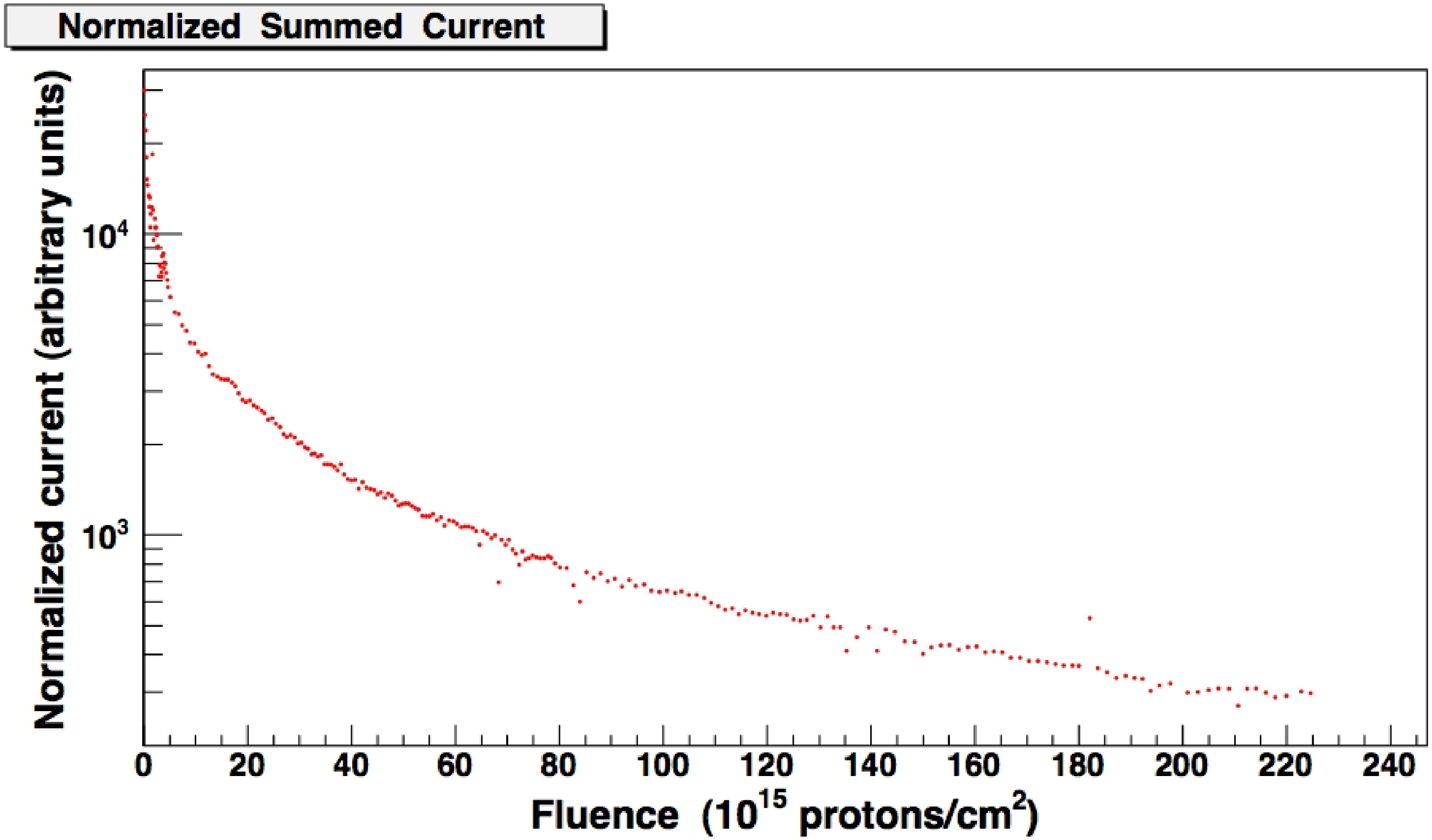
W. de Boer et al.
phys. stat. sol. (a) 204, No. 9 (2007)3009

Steffen Mueller - preliminary
RD-42 meeting, April 2010



Ultimate Fluence Tests: Very Forward Calorimetry

- Ultimate radiation test environment found in forward calorimetry
- MIP efficiency not as important as uniformity (resolution)
- Irradiated with up to 500 MeV protons (TRIUMF) to fluences $\geq 10^{17}$



JInst 6:P05011,2011

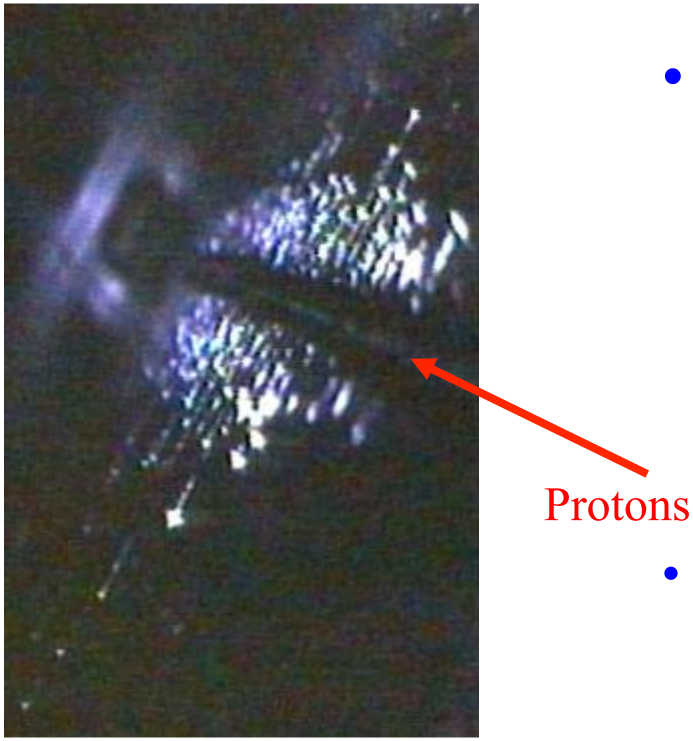
Applications of Diamond Sensors

- Several exciting applications for pCVD diamond sensors
  - High Energy Physics
  - Heavy Ion beam diagnostics
  - Synchrotron light source beam monitoring
  - Neutron and α detection

- Here I will discuss
  - Beam monitoring at
    - FNAL/Tevatron (`CDF`)
    - LHC (`ATLAS`)
  - Pixel detector prototypes for the `ATLAS` tracker upgrade
- All LHC experiments using CVD-diamond beam monitor systems
- Several considering diamond sensors for tracker upgrades

The Beam Conditions Monitor Mission

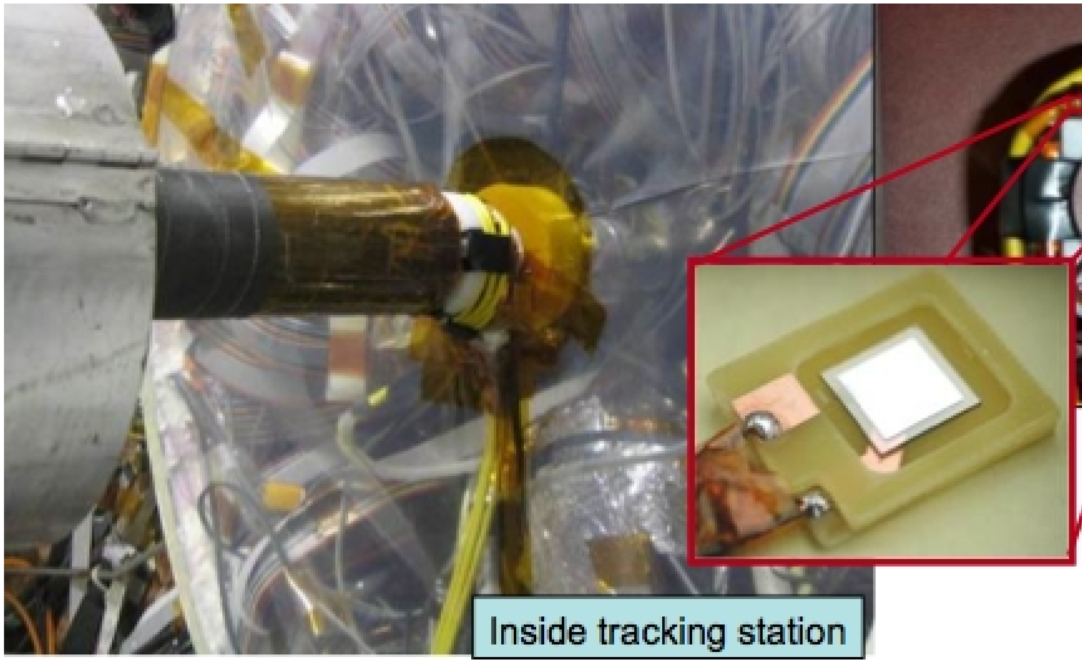
- Primary goal: Protect ATLAS and the LHC machine
  - Tevatron beam ~10 MJ (bus at 120 km/h)
  - LHC beam ~1.4 GJ (an A380 at takeoff)



- Protect against beam accidents
  - Monitor backgrounds during injection
  - Montior losses during abort
  - Detect instabilities early
  - Warn of deteriorating conditions
  - Abort the beam if necessary
- Secondary goals
  - Monitor collision rate
  - IP location and shape

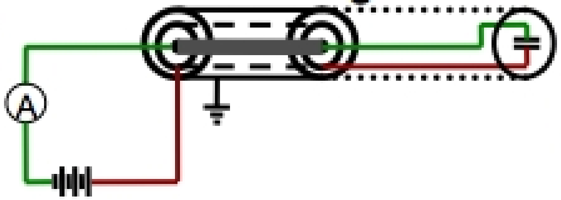
A 1m long melted stretch of Tevatron collimator

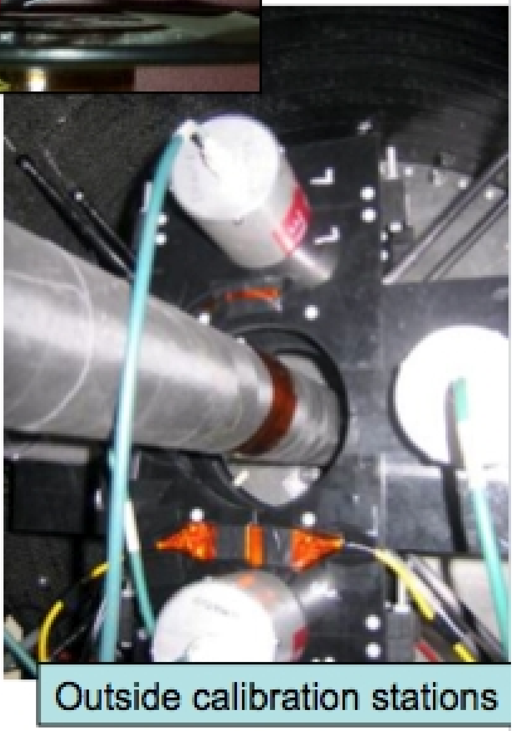
pCVD Diamond Sensors in CDF



Inside tracking station

- ATLAS style sensor 1cm x 1cm, Al based metalization (from RD42/Ohio State University)
- G10 package, wrapped in Cu foil shielding
- Triax cable DC readout (85m to counting room)

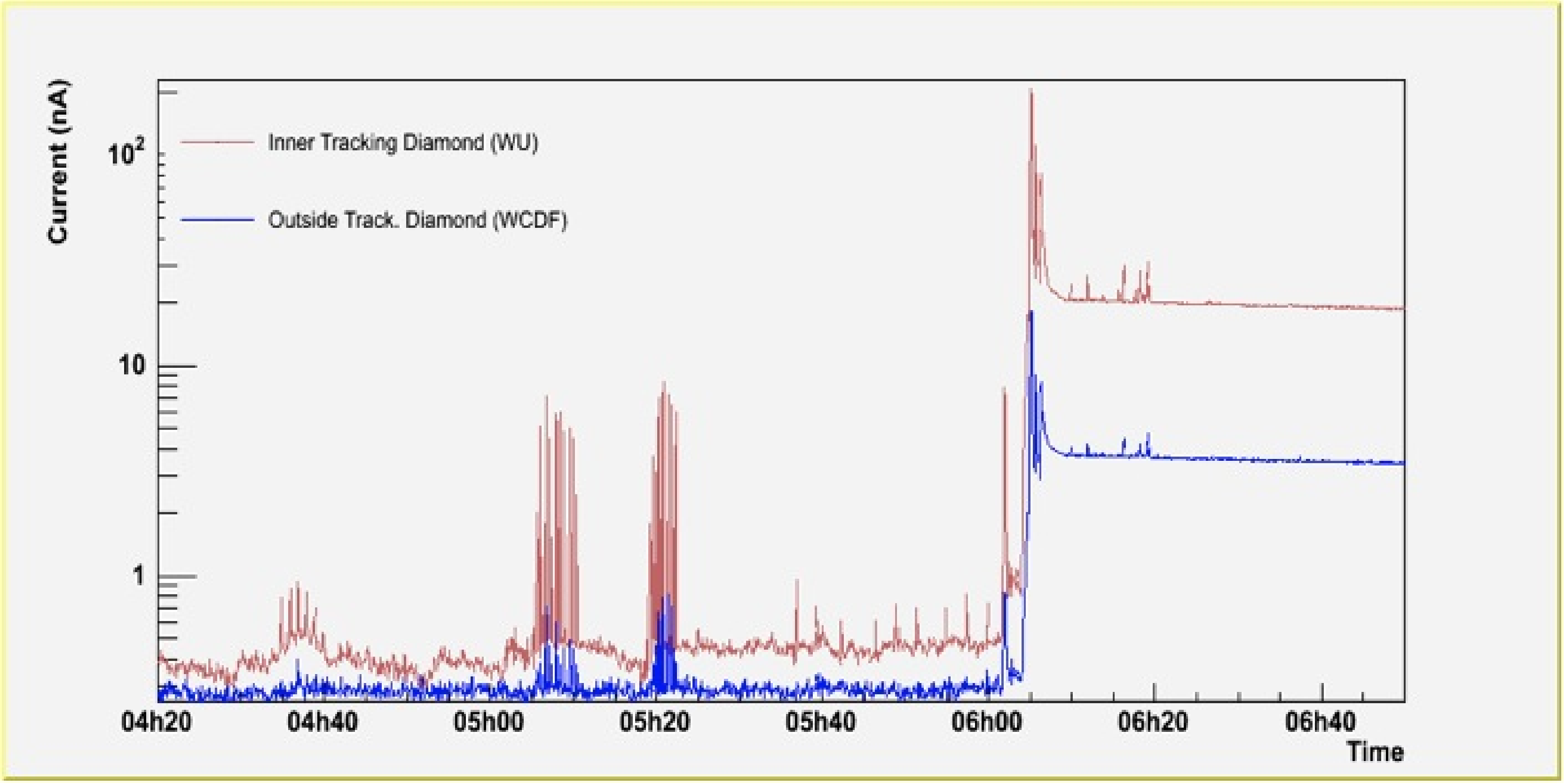




Outside calibration stations

- Monitors beam(loss) induced currents in diamond sensors
- Installed 2005, Monitoring 2006, Operational 2007-2011

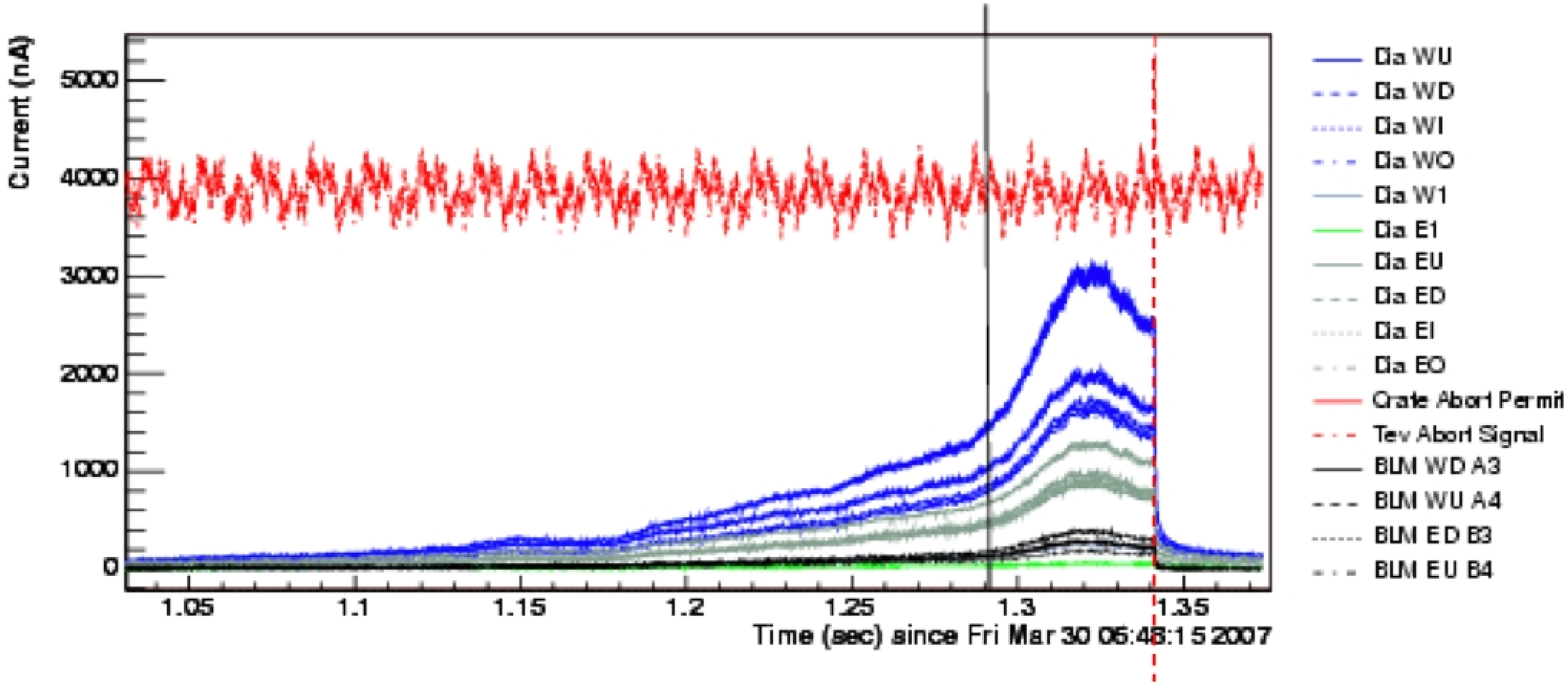
Sensitivity to Tevatron 'events'



- Sensors near IP (red) much more sensitive to losses
- Tevatron has *learned* a lot about what goes on at IP during injection

A Typical Tevatron Abort

- During 11-month monitoring phase (2006)
  - Tuned diamond abort algorithm
  - Observed four aborts that diamond could have triggered sooner



- Was the primary CDF abort system for the last 4 years of Run II
- Now doing a post operation assessment of diamond sensors

The ATLAS BCM Collaboration

JSI, Ljubljana

- V. Cindro
- I. Dolenc,
- A. Gorišek
- G. Kramberger
- B. Maček
- I. Mandić
- E. Margan
- M. Mikuž
- M. Zavrtanik

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- M. Cadabeschi
- W. Trischuk
- D. Tardif

Univ. of Applied Science - Wiener Neustadt

- H. Frais-Kölbl
- E. Griesmayer
- M. Niegl

OSU, Columbus

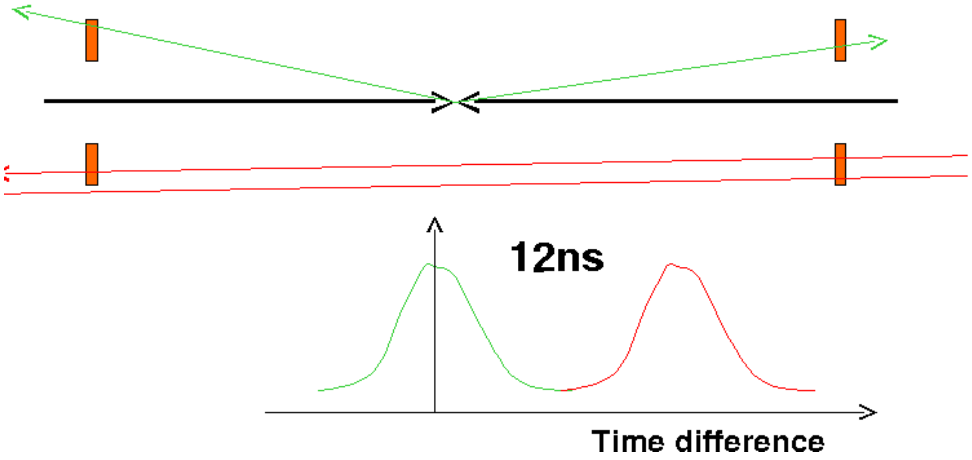
- H. Kagan
- S. Smith

CERN

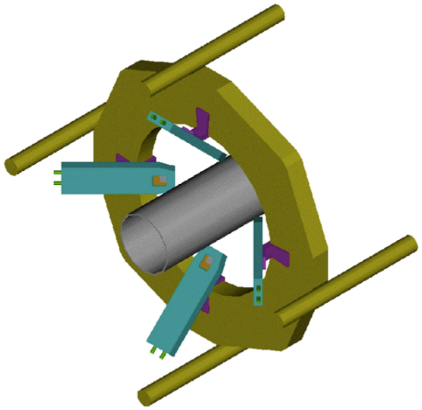
- D. Dobos
- K. Lantzsch
- H. Pernegger
- E. Stanecka

The ATLAS Beam Conditions Monitor

- ATLAS will use time-of-flight to distinguish collisions from lost beam particles

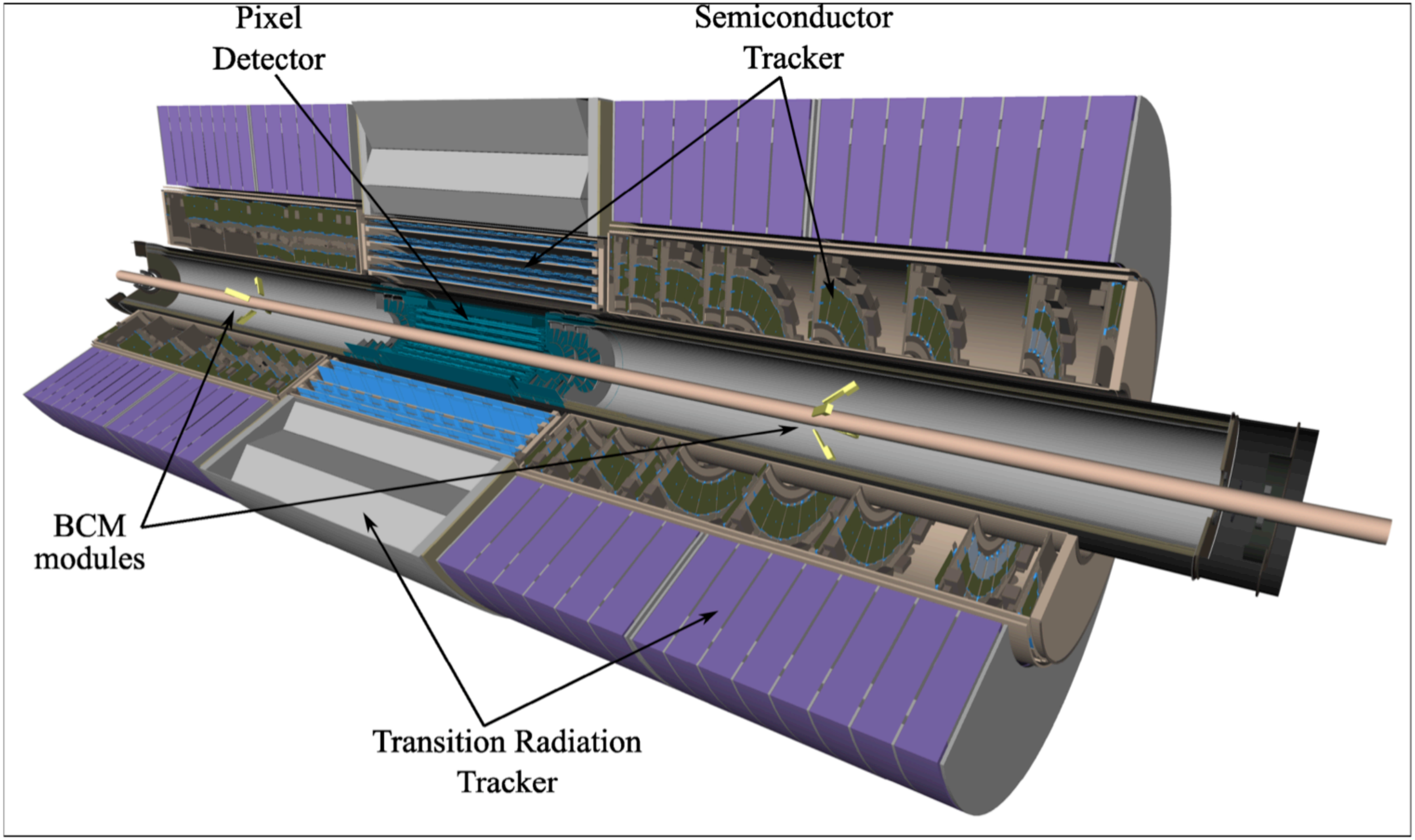


- 4m separation gives 12ns time-of-flight: optimal
- Pixel space-frame support at ± 1.9m

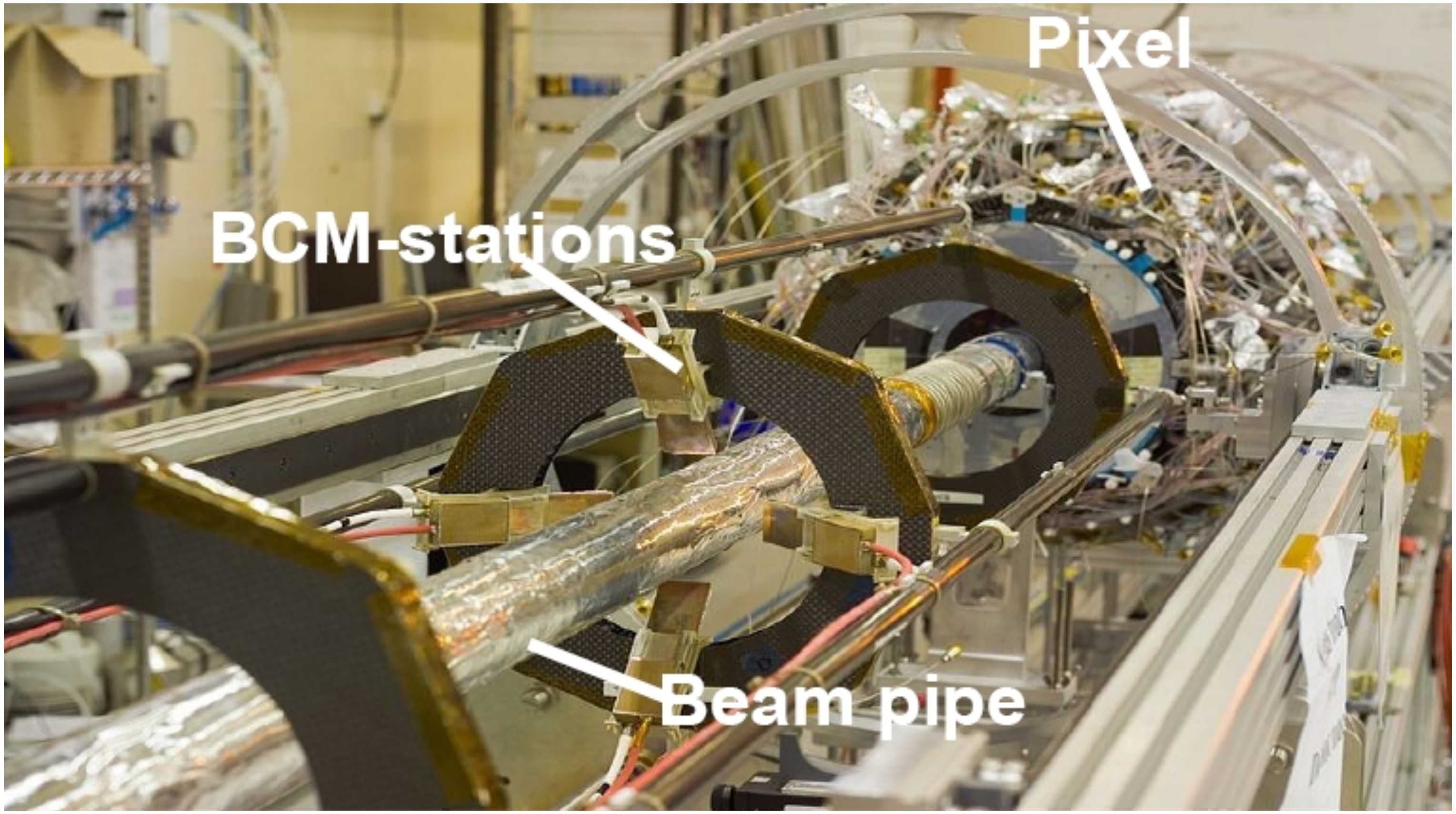


- Use CVD diamond sensors
  - 10x faster signals and 10x more radiation tolerant than silicon
- Use GaAs amplifiers with 1ns rise-time, 5ns baseline restoration

The BCM in ATLAS



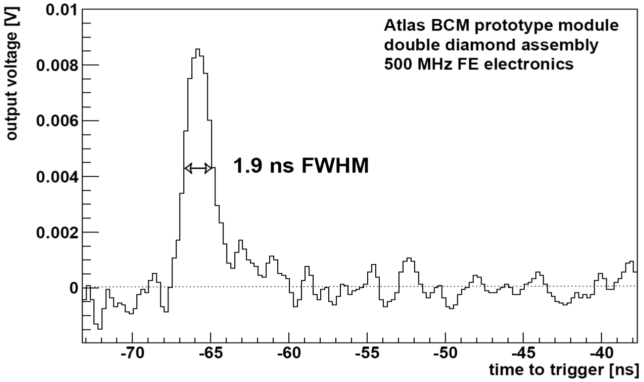
The BCM Installation

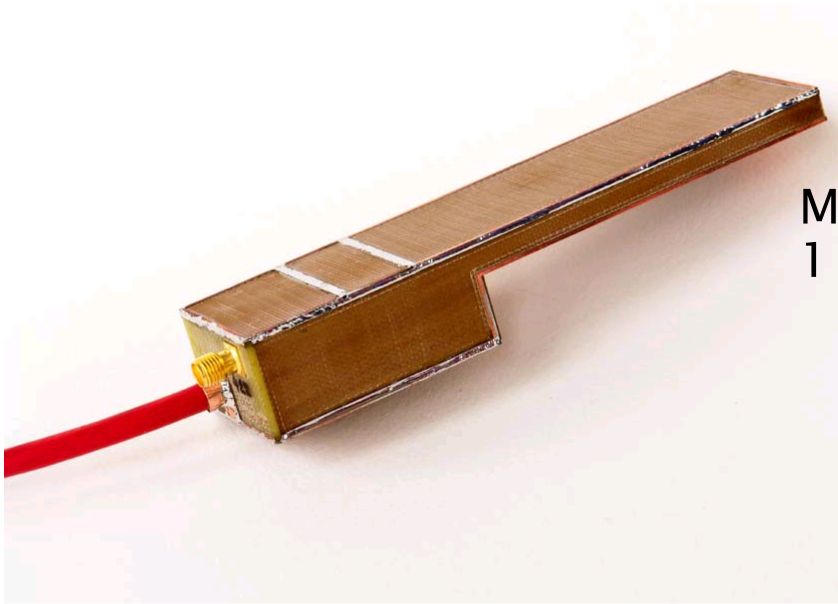


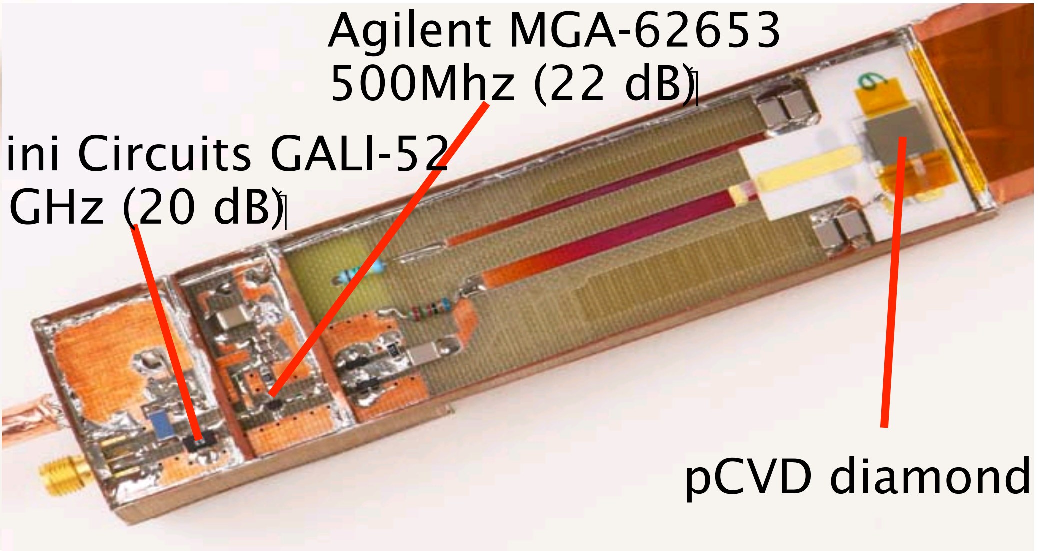
- Half of BCM modules on ATLAS Pixel support frame
- BCM module support mechanics designed in Toronto

The BCM Detector Modules

- pCVD diamond sensors (*10x10 mm*^{2}, 2x500μm thick)
    - Withstand doses > 10^{15} p/cm^2
- Fast & short signal (FWHM~2ns, rise time<1ns)
- Count hits above two thresholds:
    - ½ MIP (for luminosity measurements
    - 100 MIPs (for beam protection)

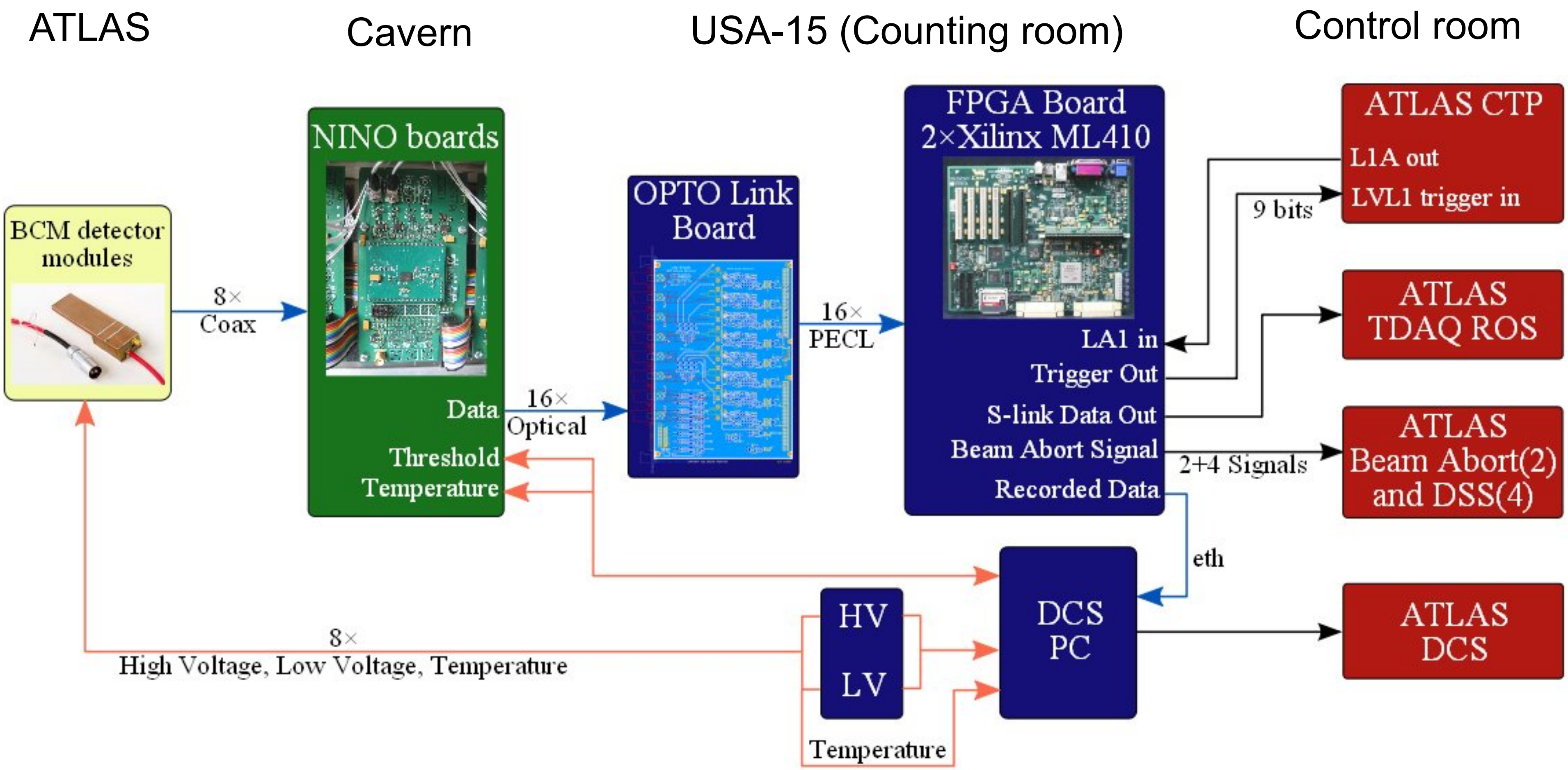






The BCM Readout

- Must provide independent beam background assessment
- Also provides luminosity and trigger information for ATLAS



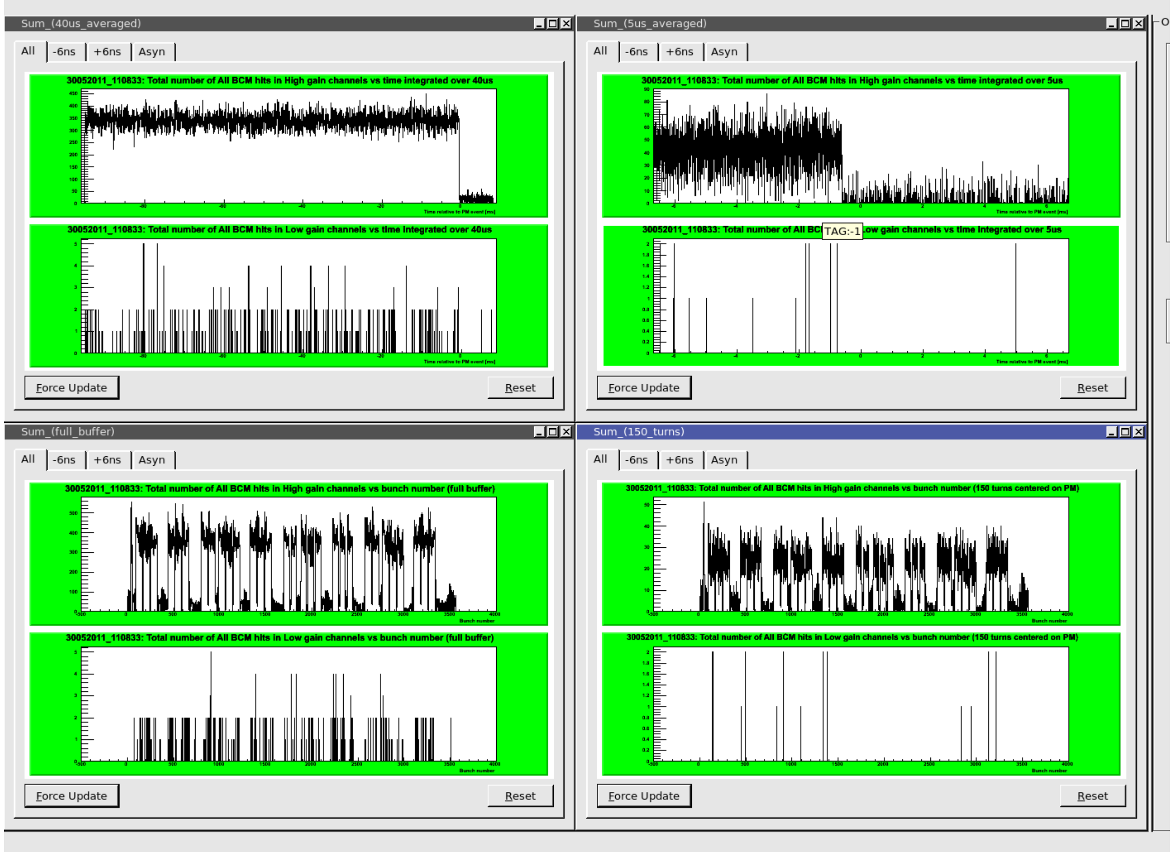
BCM Abort Post-mortem (Toronto)

- Provide fast feedback (within 5 minutes of abort) to LHC Control
  - After every abort (about 3000 per year)

- Normally look like:

1000 turns

100 turns



Single MIP

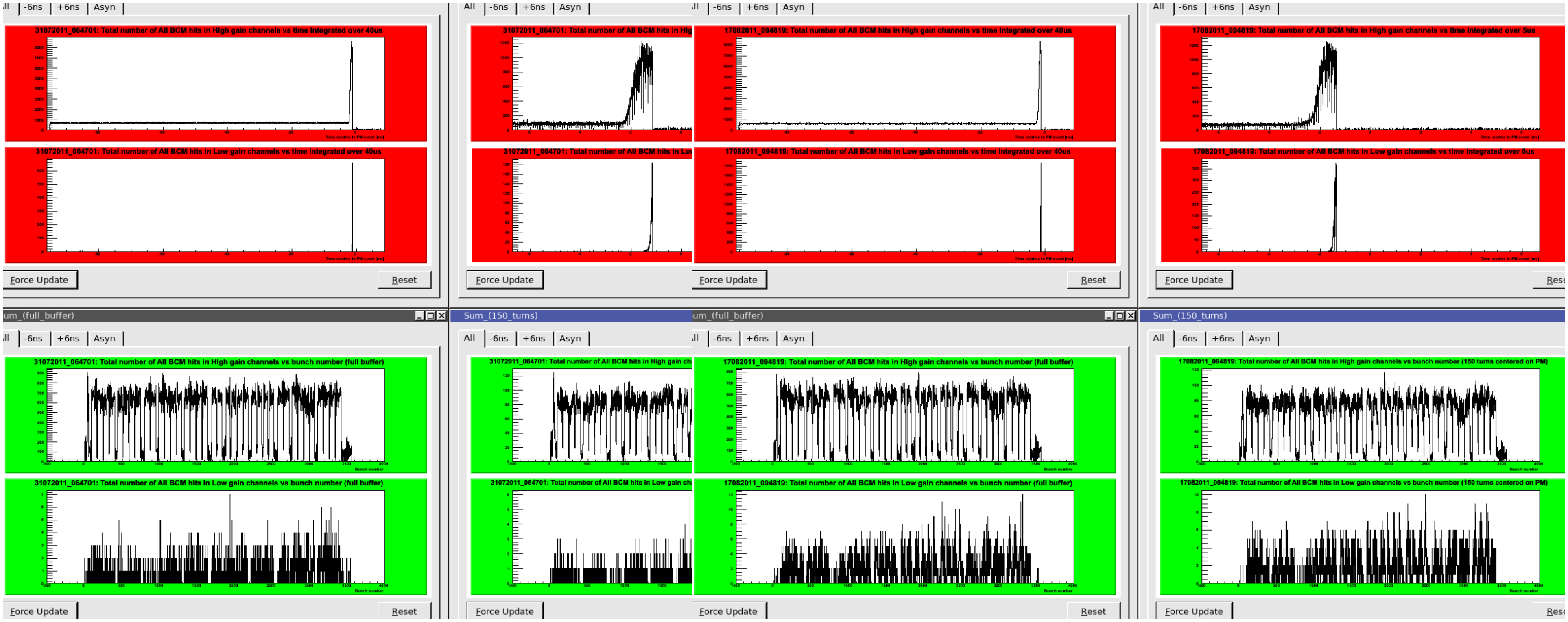
Hundred MIP

vs. Time

vs. BCID

Two Aborts Seen – 2+ Years of Operation

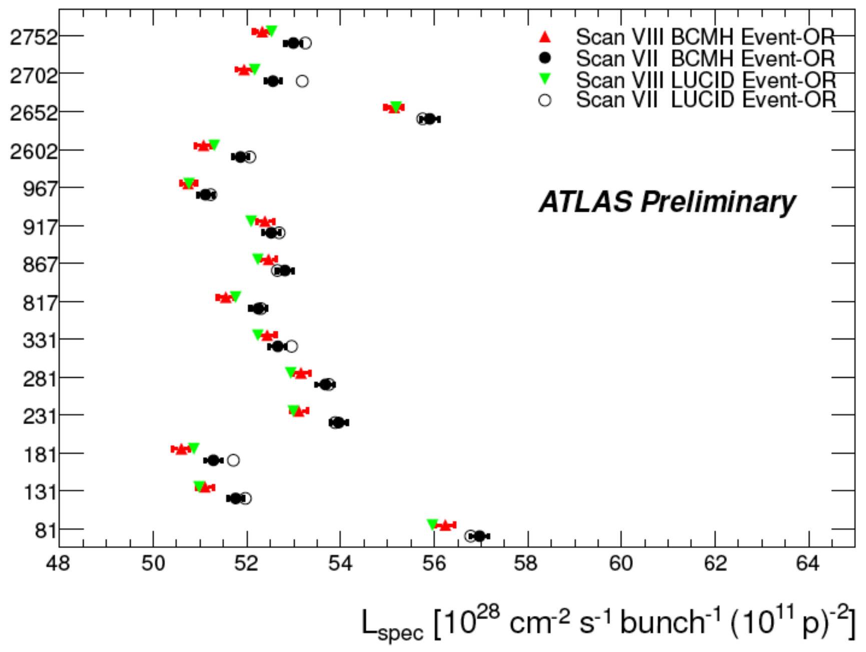
- Two aborts seen (July 31, 2011, August 18, 2011)
- Both corroborated by LHC machine beam loss monitors
    - Typical of unidentified falling objects seen elsewhere in machine
    - Approaching danger levels for SCT and Pixel detectors



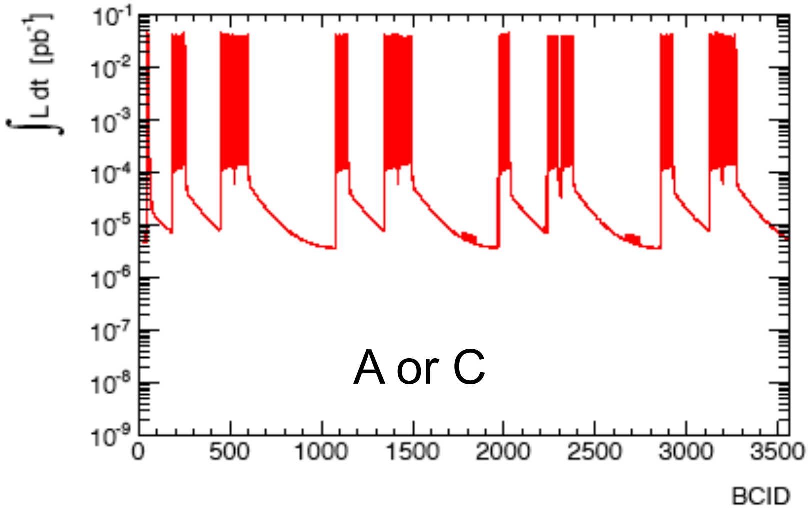
BCM: ATLAS Default Luminosity Monitor

- Since early 2011 the BCM is ATLAS' default luminosity monitor
  - Provides robust rate measurements
  - Negligible backgrounds
  - Operates when other systems are not active

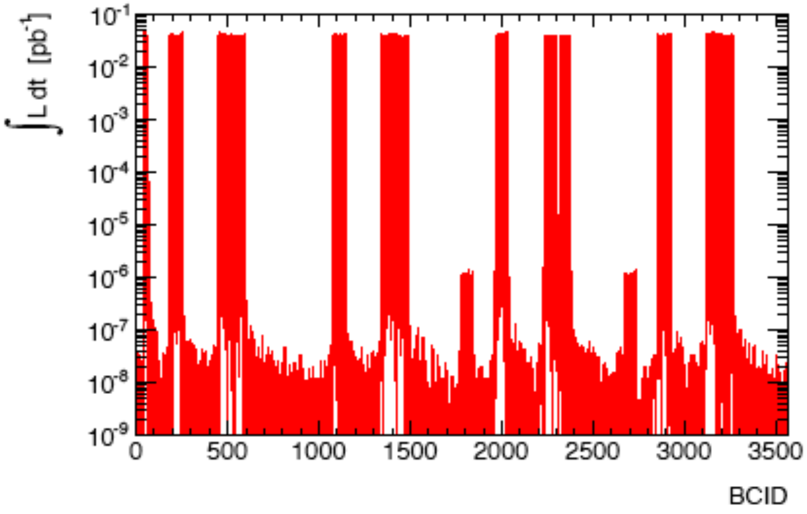
- Used during all Van de Meer scans
  - Measure few % variations in bunch currents
  - Reproducibily and reliably

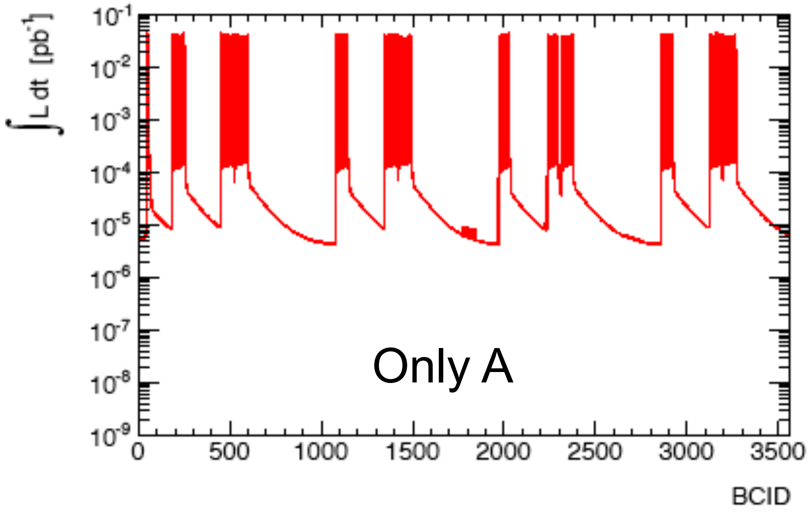


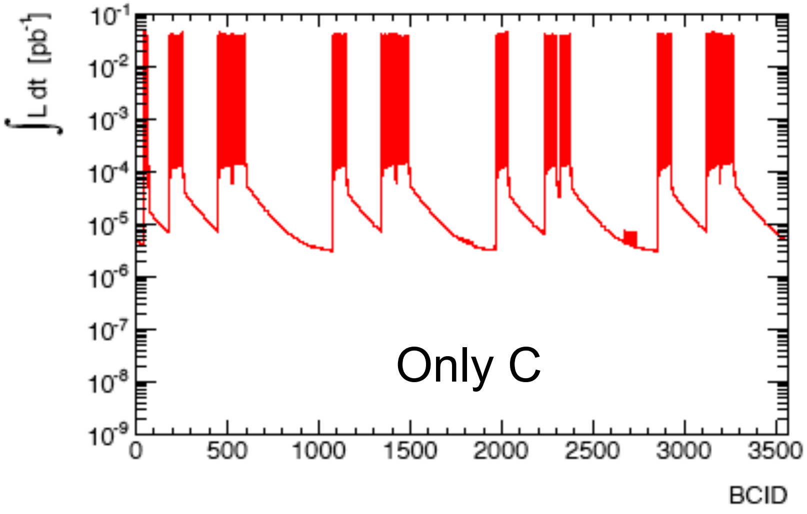
BCM Luminosity Maps


A or C

A and C



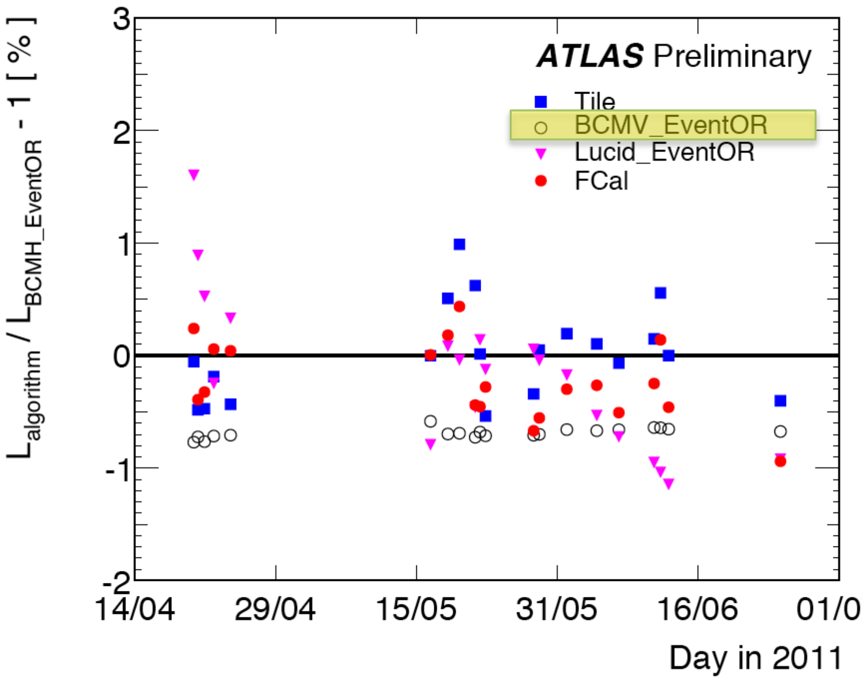

Only A

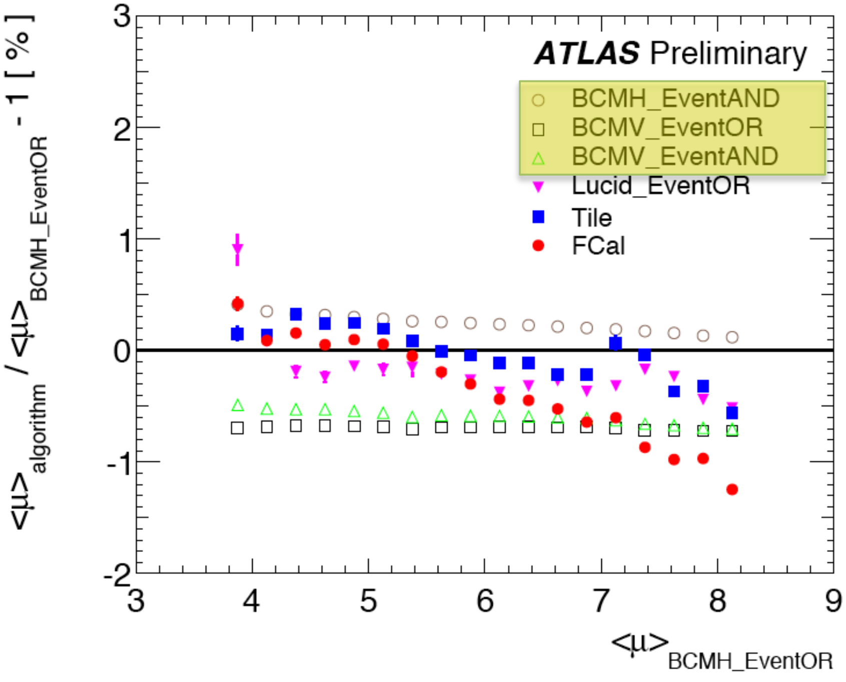

Only C

BCM: Luminosity Stability

- Two independent lumi measurements (BCMH (ref), BCMV (o))
  - Stable over months (left)

Stable against pile up (right)

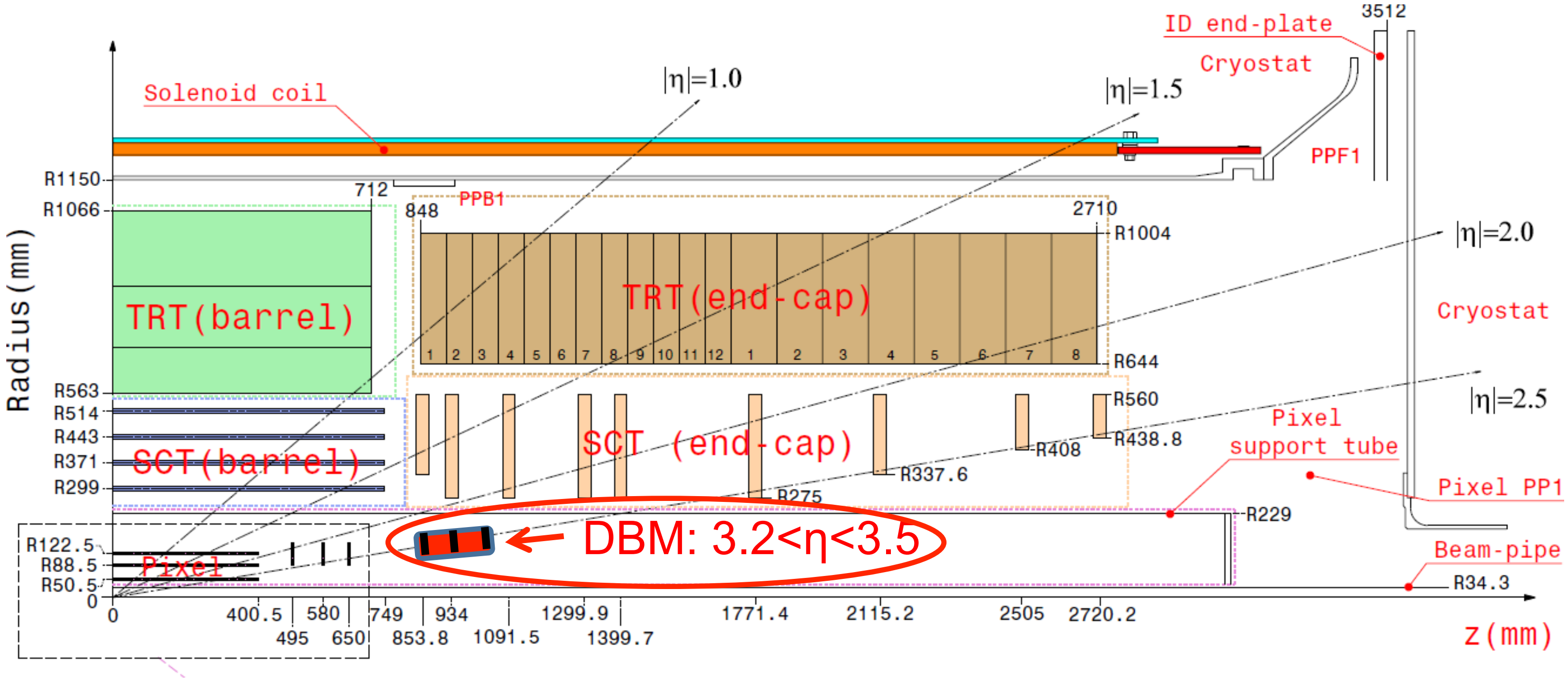




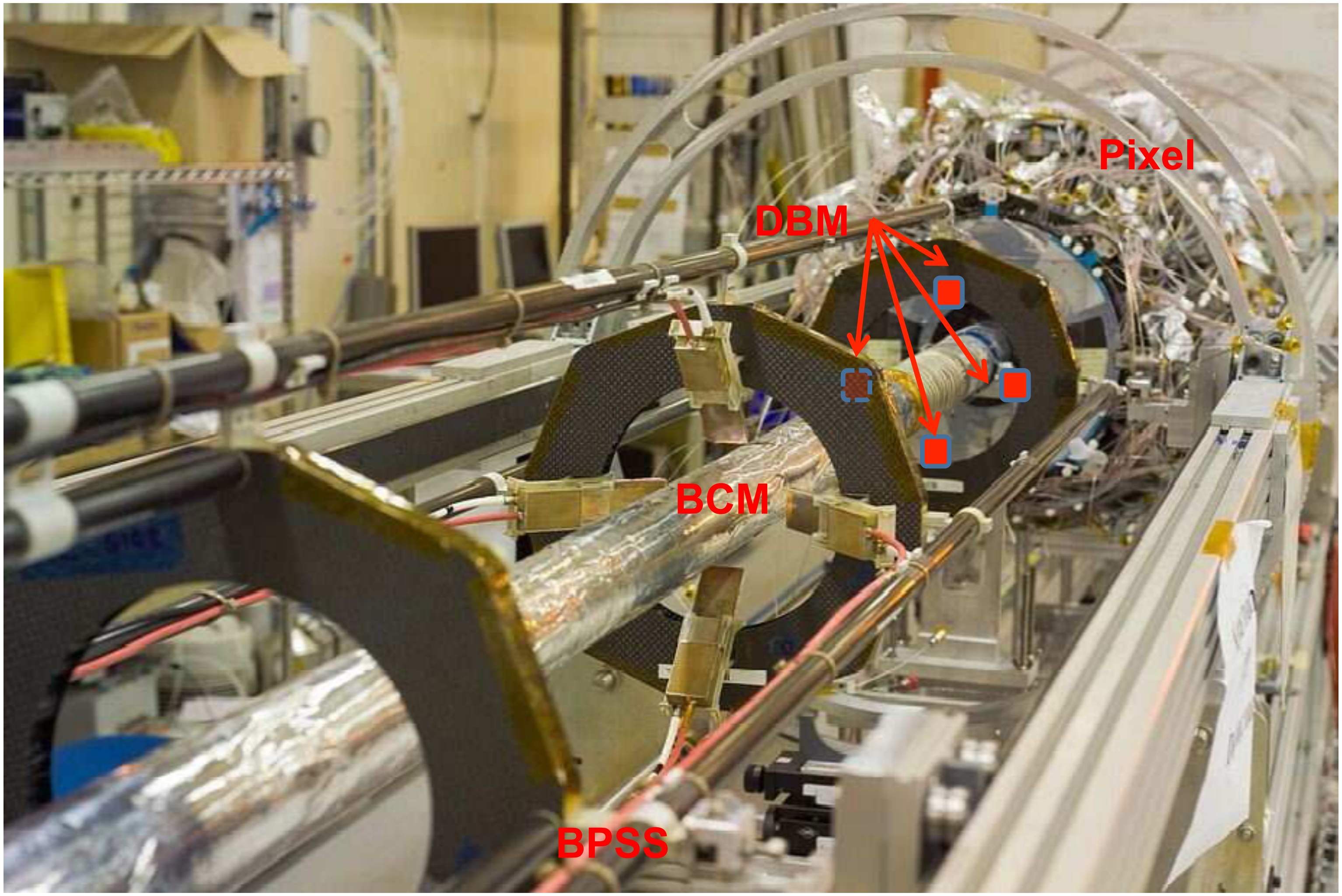
One of the keys to ATLAS stated 3.4% absolute luminosity uncertainty

The Diamond Beam Monitor (DBM)

- Build on success of BCM – include pixel readout pattern
  - Install with service quarter panel (nSQP) replacement
  - Four 3-plane stations on each side of ATLAS-IP
- nSQP replacement sets installation date – Februrary 2013

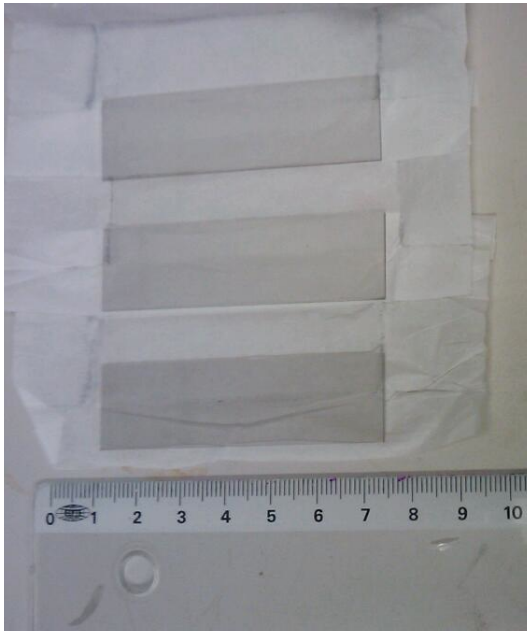


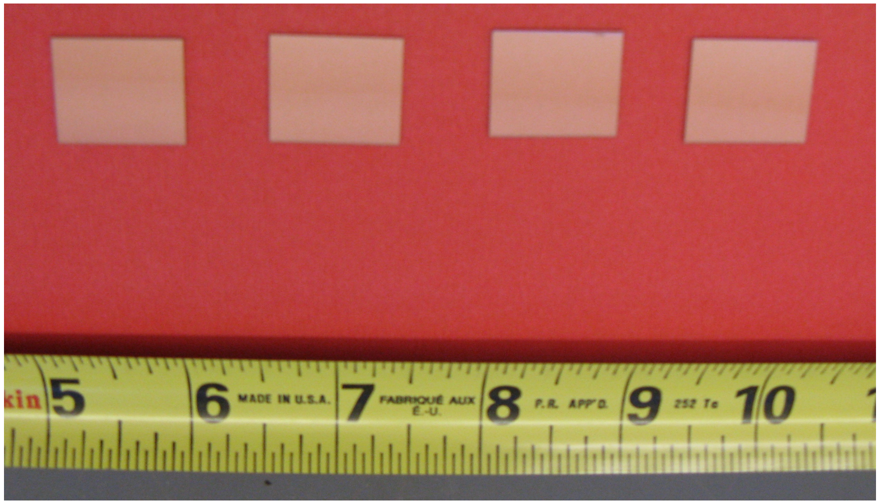
DBM Location



DBM Sensor Inventory

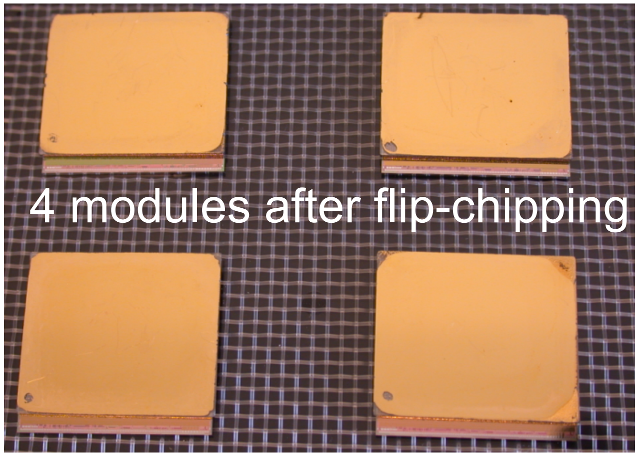
- 27 sensors ``in hand’’ from IBL demonstrator work
  - Most need thinning
  - 5 FE-I3 sensors will be cut to give 15 DBM sensors
  - 4 DBM sensors ready for bump-bonding
  - 4 (thick) built into I4 modules
- All currently meet DBM specifications

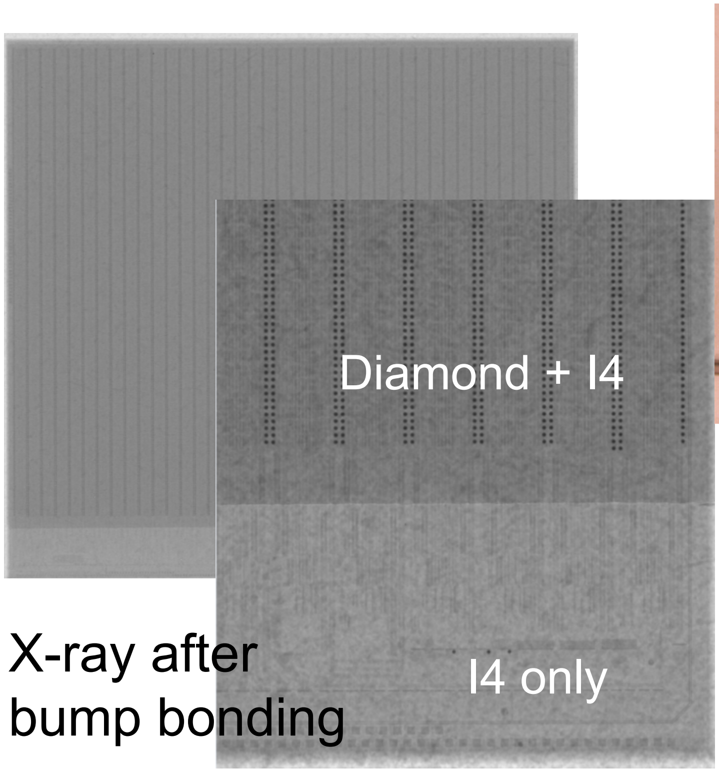




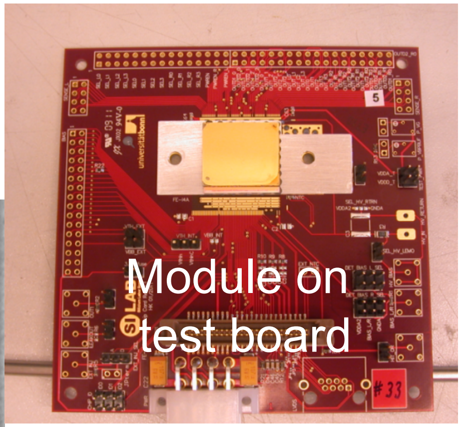
First four DBM modules

- Four DBM modules built at IZM
  - 21x18 mm^2 pCVD from DDL
  - FE-I4 ATLAS IBL pixel chip
  - 336x80 = 26880 channels, 50x250 µm^2
- Largest ASIC/diamond flip chip assembly

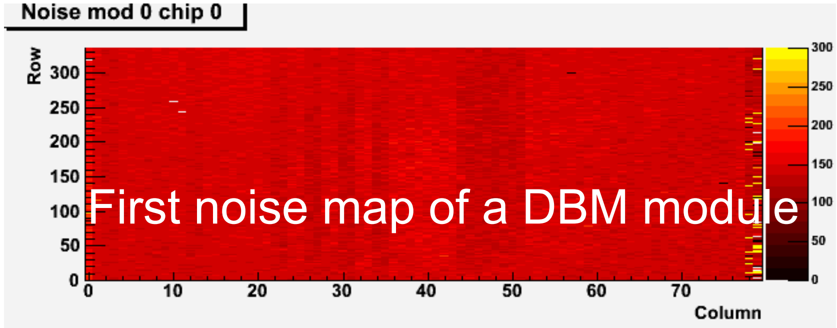

4 modules after flip-chipping



X-ray after bump bonding

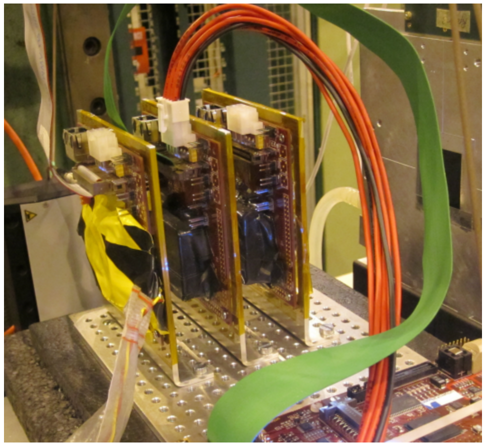

Module on test board

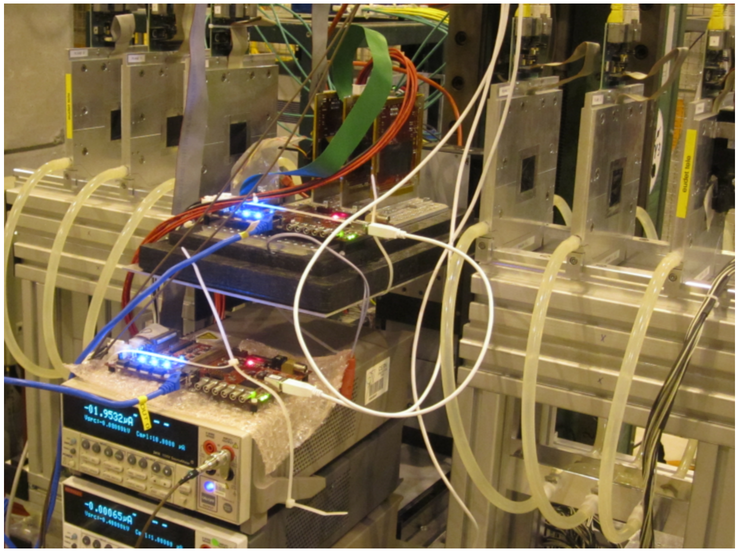
- ✓ X-ray perfect
- ✓ Noise map uniform
  - Indication of success
- ❖ HV issues due to IZM metallization up to edge



First noise map of a DBM module

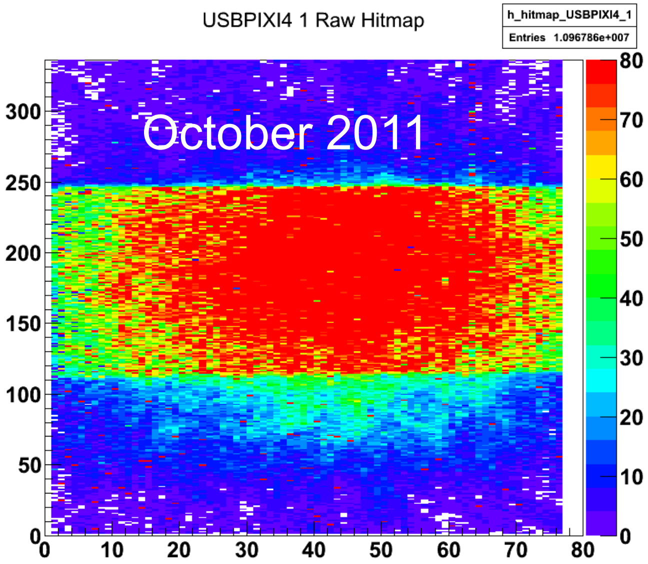
DBM: Module Testbeam Studies

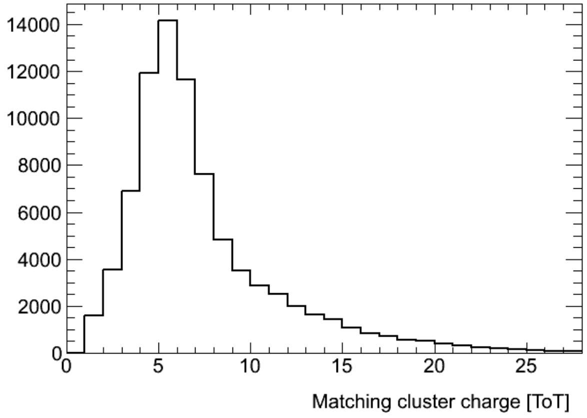




- Three Testbeam campaigns
  - July, late August, October
- Learning about FE-I4 performance
  - Calibration/tuning for low thresholds unique to diamond
  - Achieved 1000 e threshold (needed for irradiated silicon)
- Use testbeam data to tune charge model

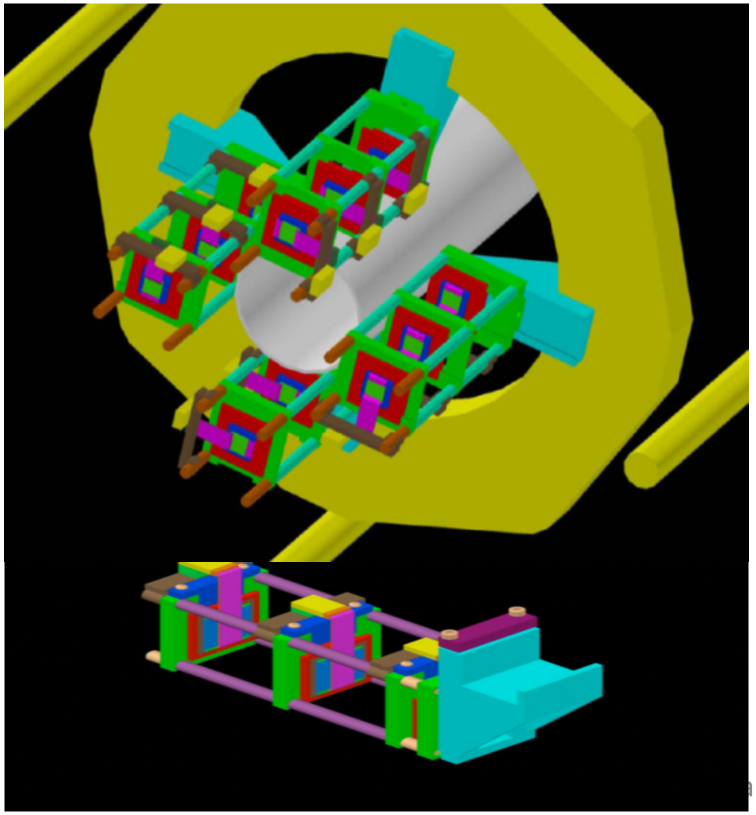
Run1394 **1000e Threshold**

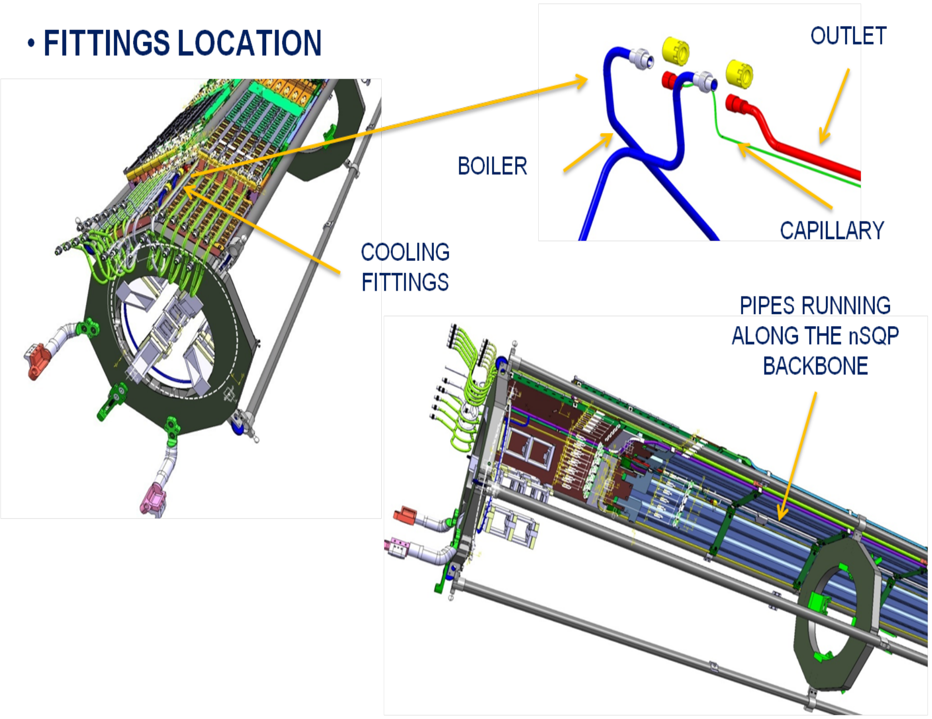




DBM: Support Mechanics

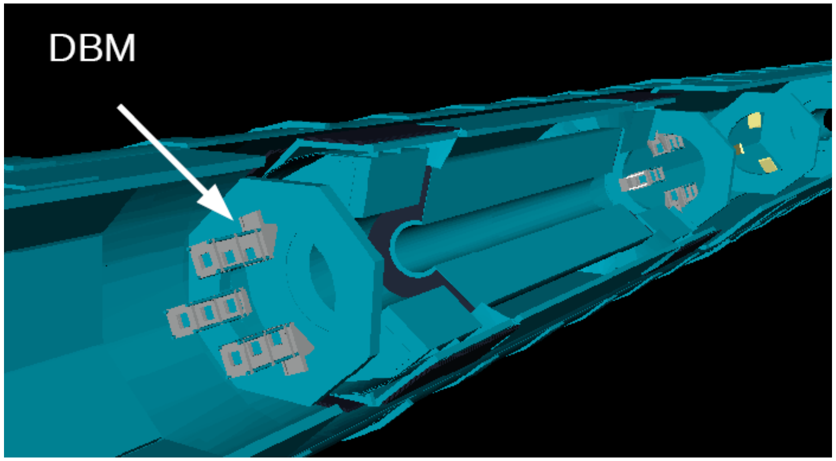
- Projective telescope design now being prototyped
  - Integrate cooling circuit in a simple way
  - Ensure DBM is thermally neutral, but modules can run at 40C



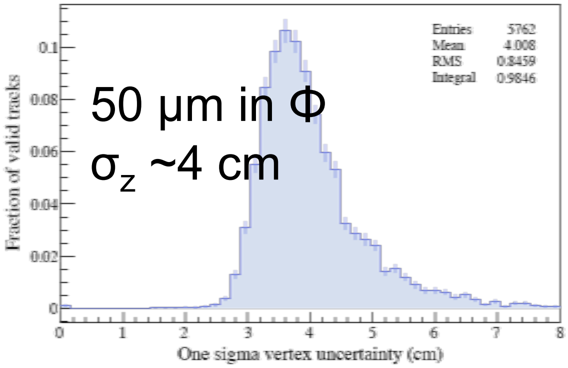


DBM: Simulation/Reconstruction

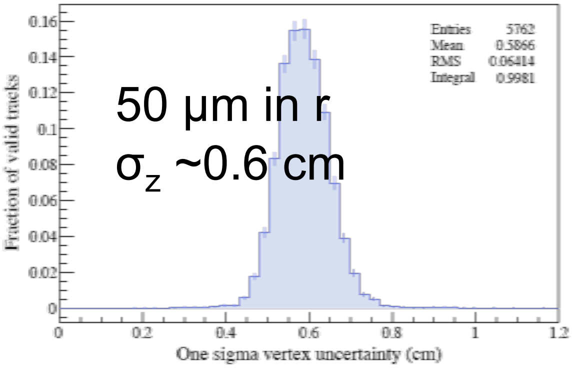
- Full GEANT model available



- Geometry forces us to focus on z, θ reconstruction
- Momentum resolution weak anyway => precise pixel in r



50 µm in Φ
σ_z ~4 cm



50 µm in r
σ_z ~0.6 cm

DBM: Simulation/Reconstruction

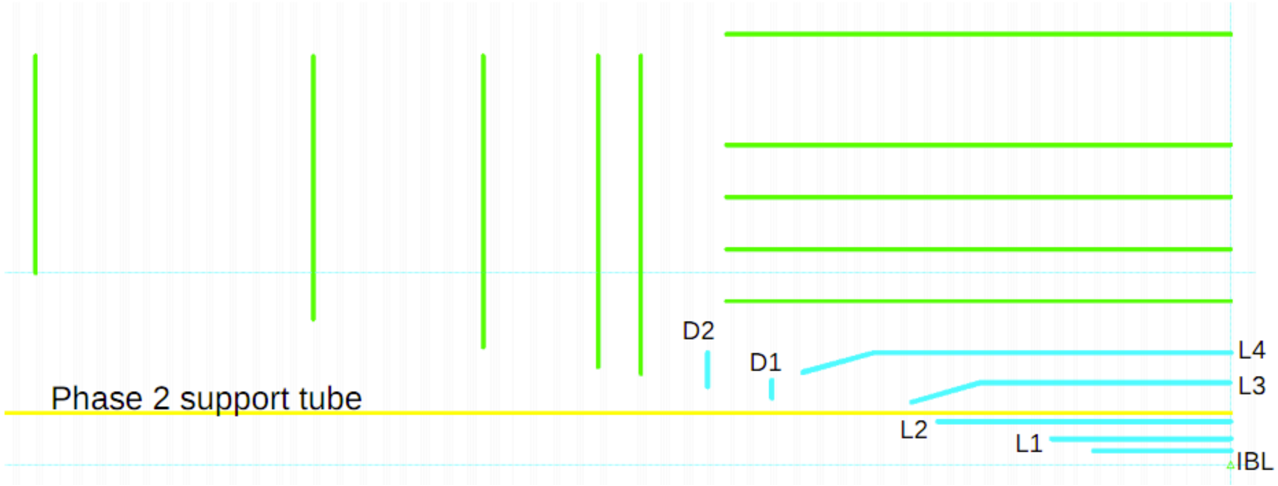
DBM: Next Steps

- Apart from sensors, mechanics and DBM just adds 24 single chip modules to the 448 foreseen in IBL
  - Services: two half-staves in addition to 2x14 for IBL
  - Requires a ~5 % increase of most components
- Schedule tight – 9 of the 24 months already elapsed
  - Designing, building and testing system simultaneously
    - Built first modules, becoming familiar with them
  - Following/adopting/helping to establish IBL developments
- Showstopper:

💣 nSQP project abandonned ➔ pixel package stays in ATLAS 💣

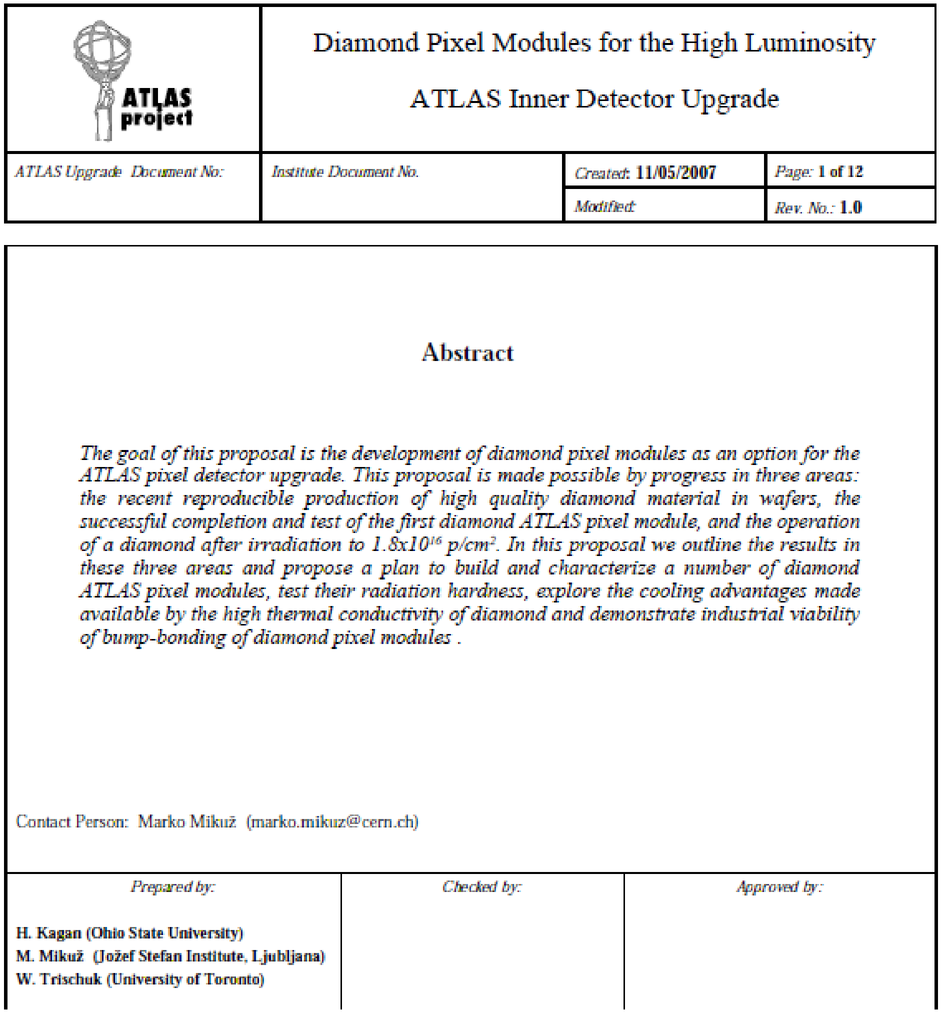
ATLAS Full Tracker Upgrade (2020++)

- ATLAS is preparing for full tracker replacement
  - Will have silicon strips through most of volume
  - Silicon pixels move out in radius
  - Will need ultra-radiation hard sensors inside support tube
- IBL sensor technologies will be initial candidates
  - Evaluate them after they've operated for a few years



ATLAS Diamond Pixel Sensor EOI

- Submitted 2007
- Institutions:
  - Bonn, Carleton, CERN, Ljubljana, Ohio State, Toronto
- Approved 2008
- Goals:
  - Make 10 modules
  - Industrialise fabrication
  - Test radiation hardness
- IBL sensor decision 2011
- B-layer replacement? 2013
- Tracker upgrade 2018?



ATLAS project

Diamond Pixel Modules for the High Luminosity

ATLAS Inner Detector Upgrade

ATLAS Upgrade Document No:	*Institute Document No.*	*Created:* **11/05/2007**	*Page:* **1 of 12**
		Modified:	*Rev. No.:* **1.0**

Abstract

The goal of this proposal is the development of diamond pixel modules as an option for the ATLAS pixel detector upgrade. This proposal is made possible by progress in three areas: the recent reproducible production of high quality diamond material in wafers, the successful completion and test of the first diamond ATLAS pixel module, and the operation of a diamond after irradiation to $1.8x10^{16}$ p/cm^2. In this proposal we outline the results in these three areas and propose a plan to build and characterize a number of diamond ATLAS pixel modules, test their radiation hardness, explore the cooling advantages made available by the high thermal conductivity of diamond and demonstrate industrial viability of bump-bonding of diamond pixel modules .

Contact Person: Marko Mikuž (marko.mikuz@cern.ch)

Prepared by:	*Checked by:*	*Approved by:*
H. Kagan (Ohio State University) **M. Mikuž (Jožef Stefan Institute, Ljubljana)** **W. Trischuk (University of Toronto)**		

Pixel Diamond Prototypes

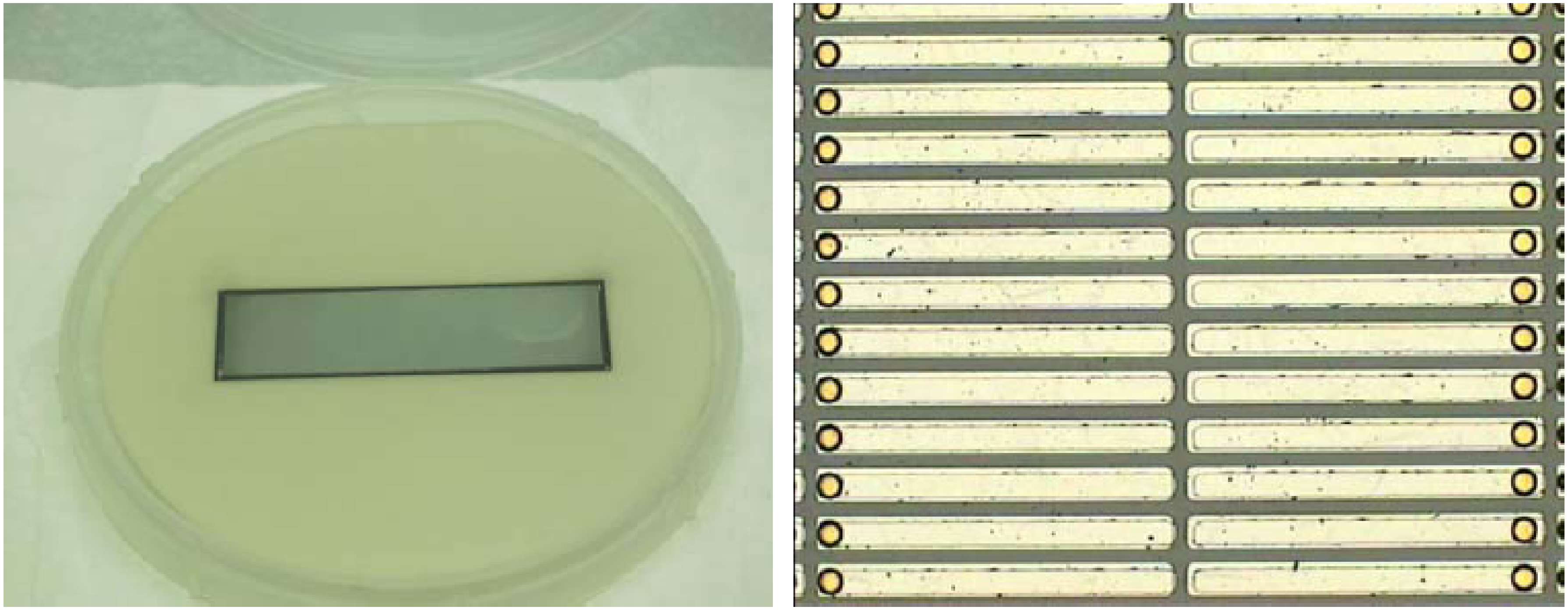


Figure 5: (a) Photograph of the ATLAS pixel diamond mounted in the carrier ready for bump bonding. (b) Zoom view of the pixel pattern after the under-bump metal is deposited.

- Sensor metalised at Ohio State, bumps deposited at IZM-Berlin
- Transferring complete process to IZM

Diamond Pixel Prototypes

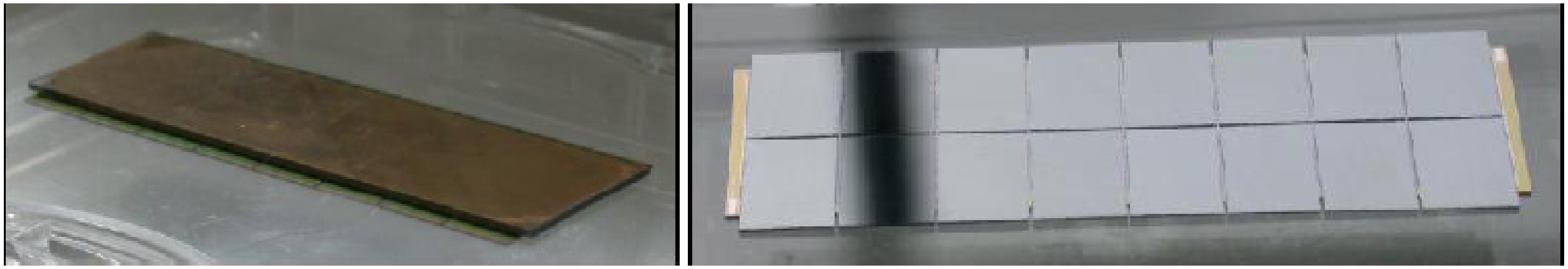


Figure 6: Photograph of the detector side (a) and electronics side (b) of the final ATLAS pixel module.

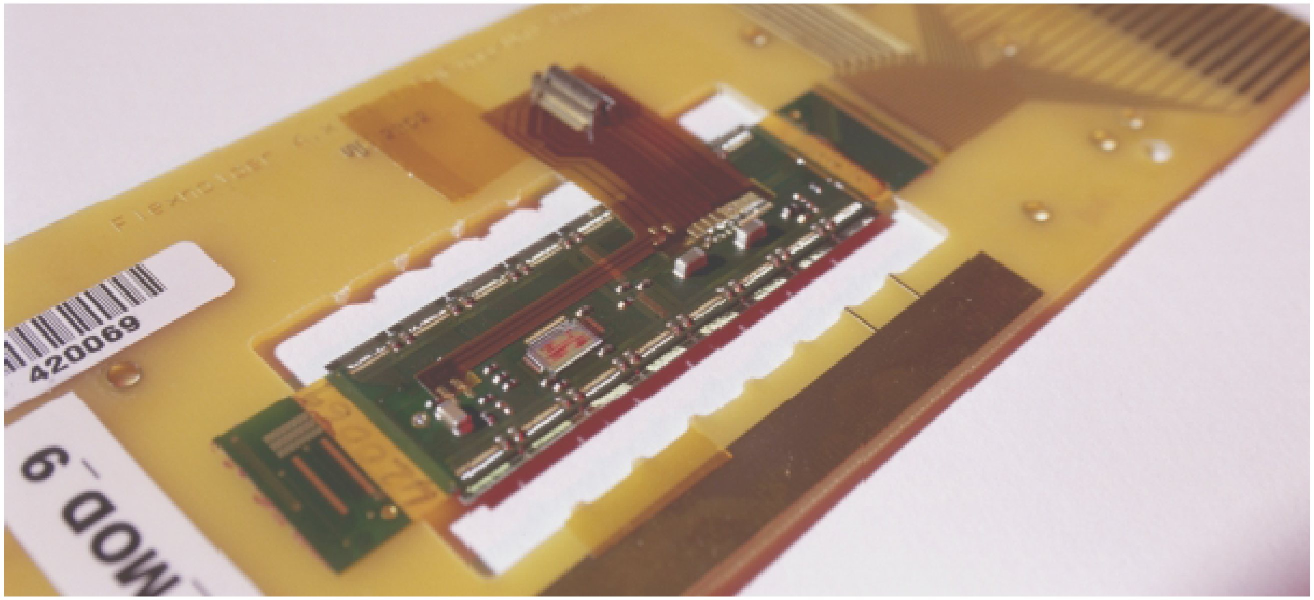
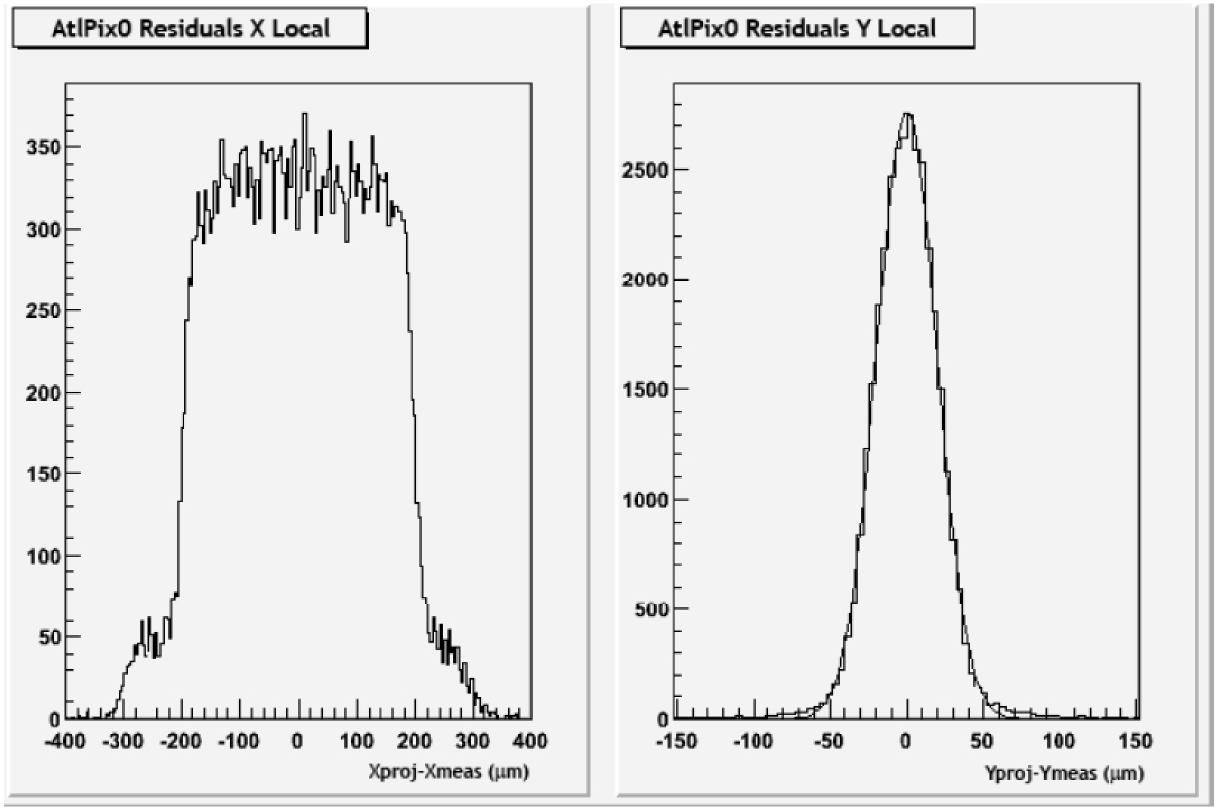


Figure 7: Photograph of the fully dressed diamond ATLAS Pixel Module ready for test.

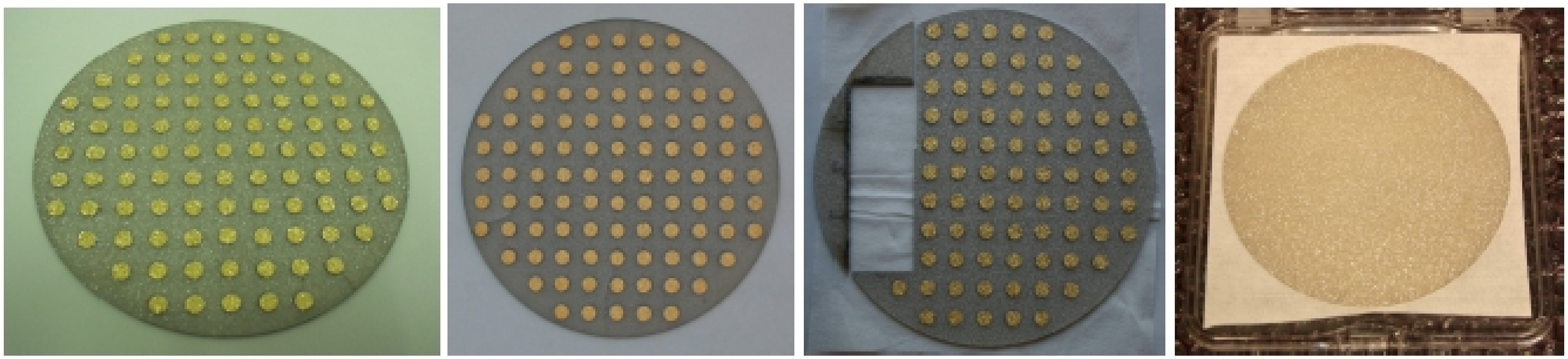
- Modules bump-bonded at IZM, tested at Bonn
- Noise: 140e^-, Efficient threshold: 1500e^-, In-time threshold: 2300e^-

Results from Pixel Prototypes



- Position resolution of 14μm (17μm residual includes telescope)
- Few % missing bonds – dominant inefficiency

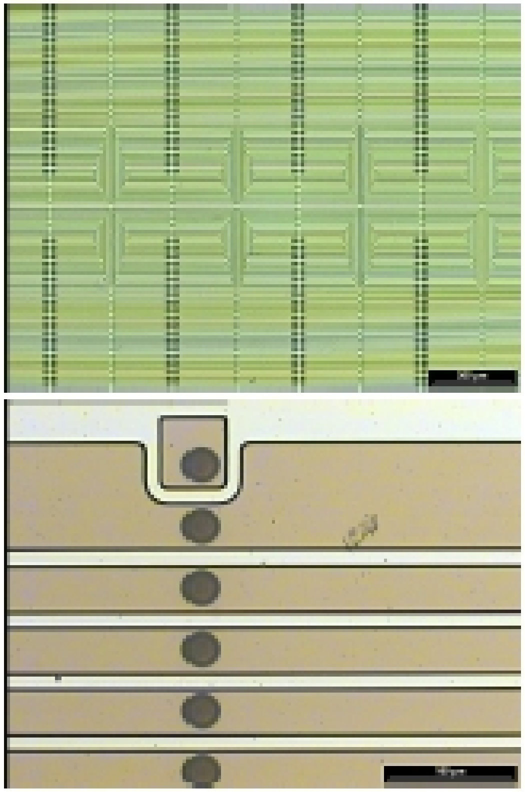
Mass Production of Diamond Wafers



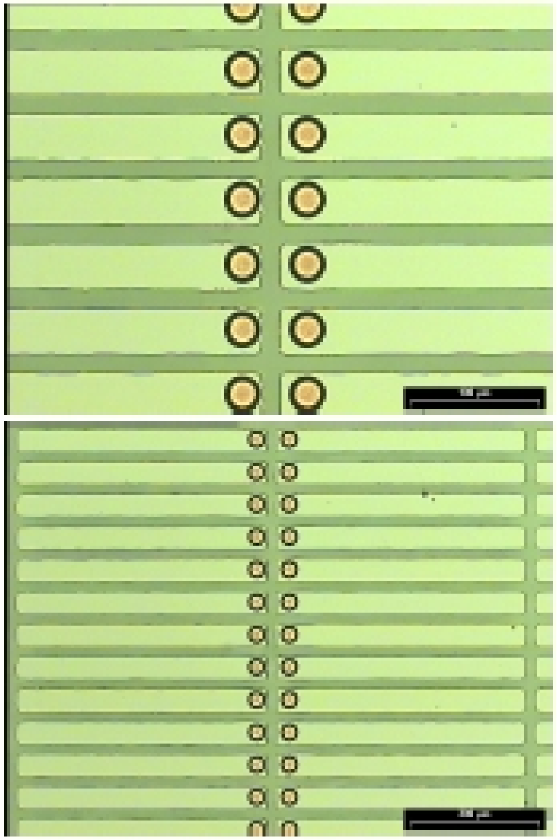
- Diamond manufacturer(s) deliver wafers
- We do a coarse scan for quality (signal size)
- Are allowed to specify sensor dicing locations
- Takes 2-3 months to turn around each wafer

Pixel Patterning in Industry (IZM-Berlin)

Diamond sensor pixel metallisation



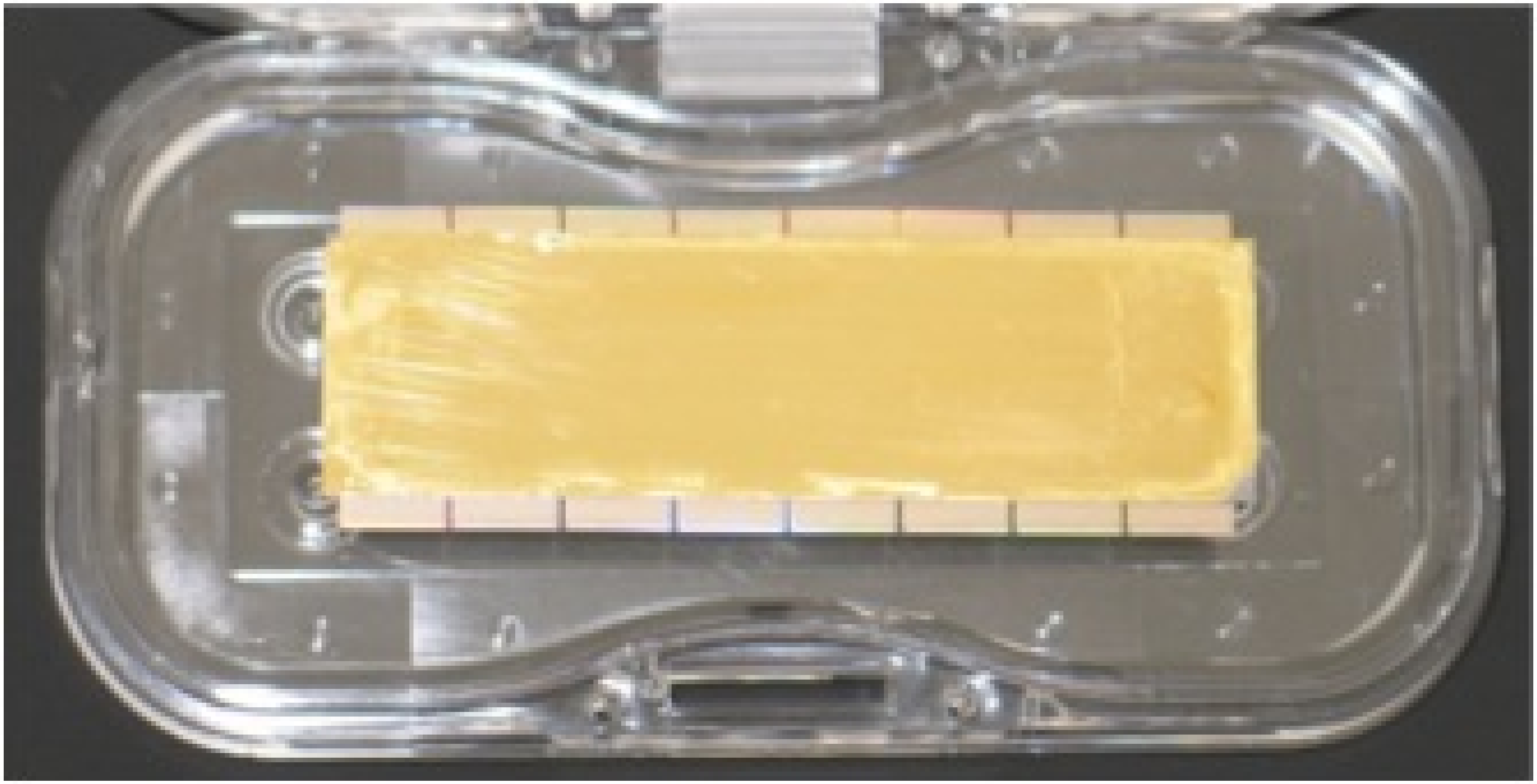
Status after elelctroplating of pad metallisation and lithography for pixel metallisation patterning



result after pixel metallisation patterning

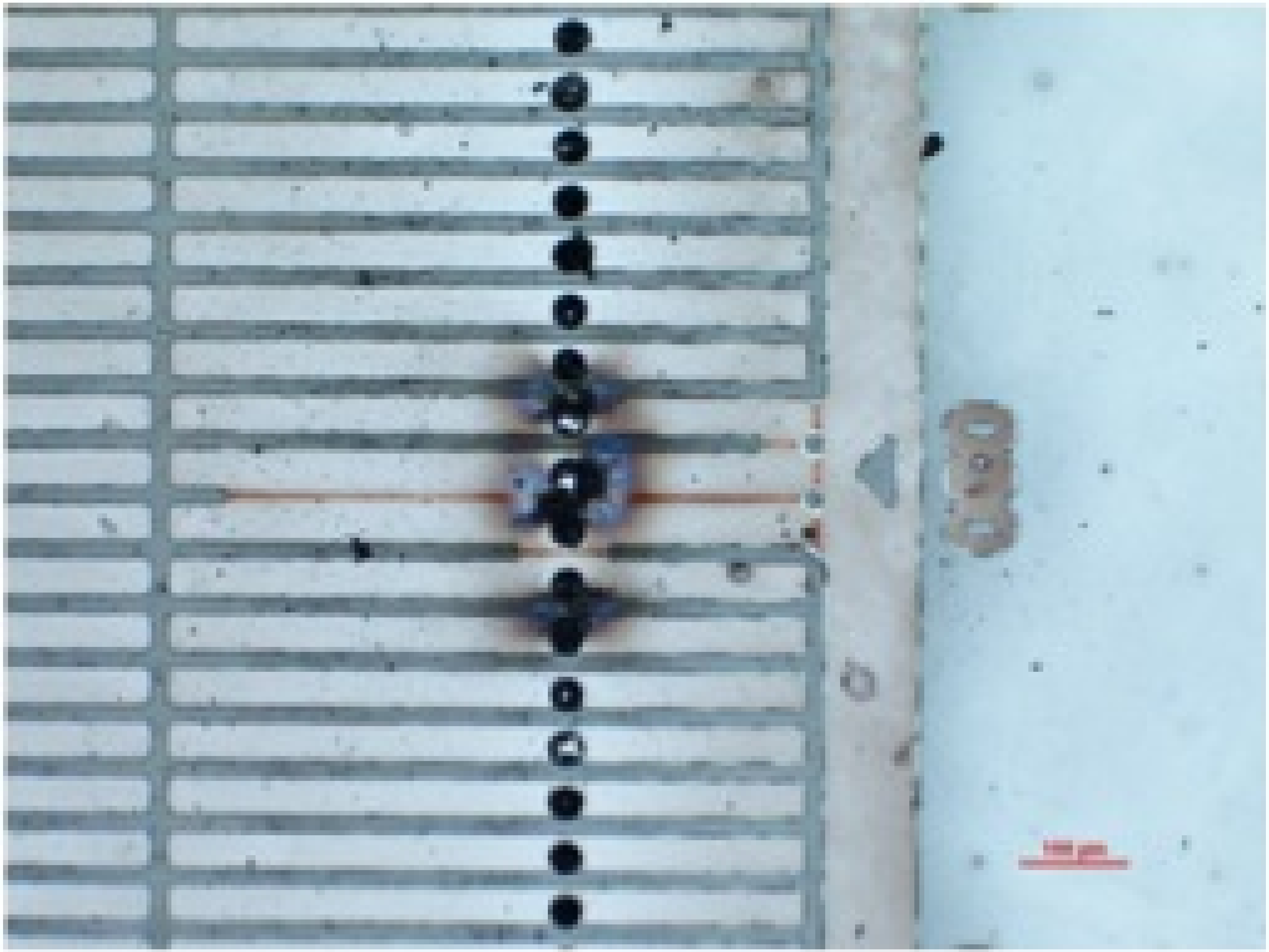
Fraunhofer Institut Zuverlässigkeit und Mikrointegration

First IZM Module

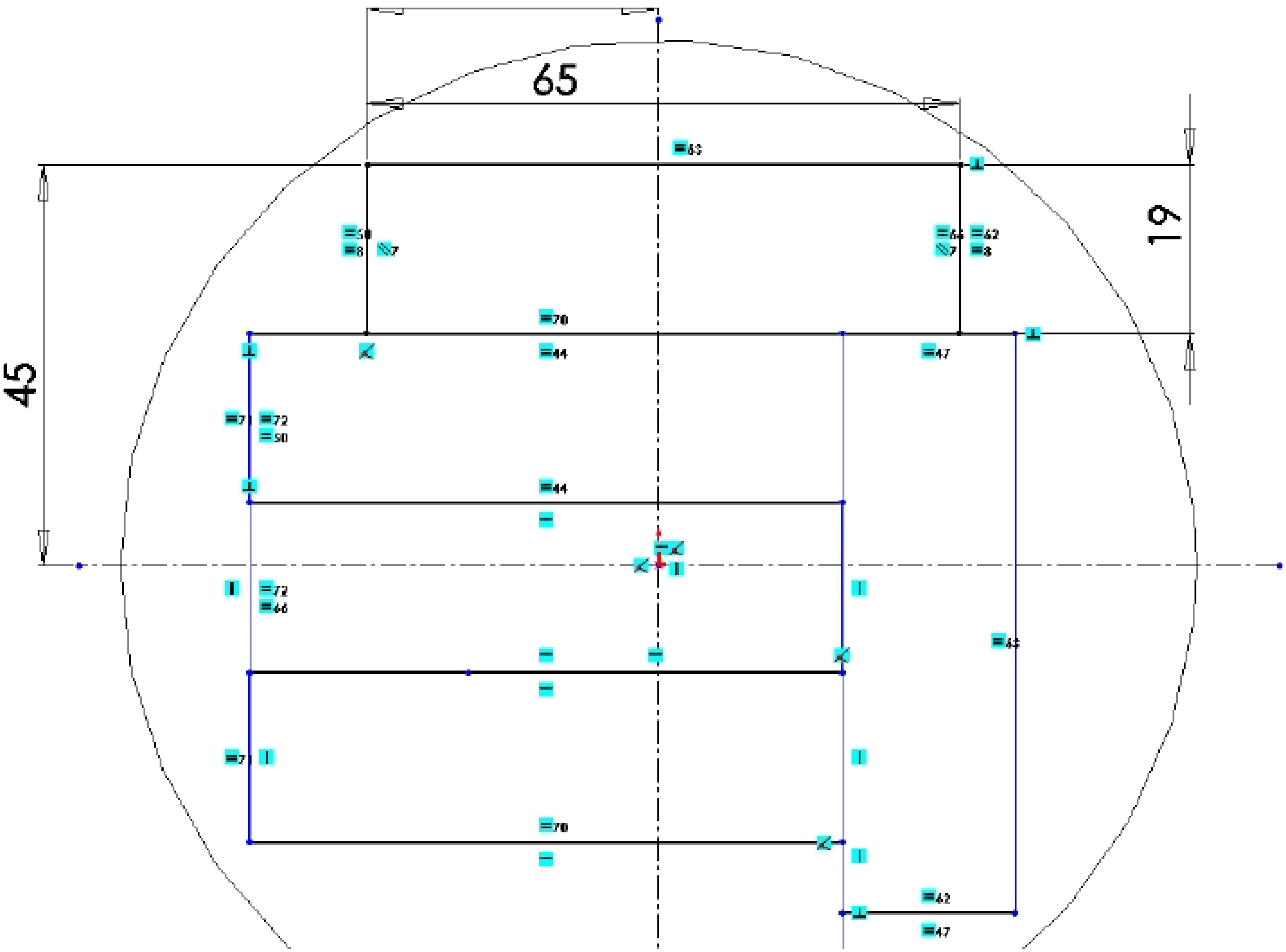


- Bump-bonded in January
- First tested at Bonn in February
- Hope to test in June testbeam at CERN

A few kinks still to work out



Diamond Sensor Wafer Pattern



- Giving input to diamond supplier(s) on part count and delivery rate
- Have budgetary quotations that inform sensor cost estimates

Summary

- pCVD sensors with signals of $8,000$ electrons over large areas
- Proven radiation tolerant up to 2×10^{15} particles per cm^2
- Established universal charge-trap density for protons up to 5×10^{15}/cm^2
- Diamond sensors are finding applications in a number areas
  - Beam abort systems at Tevatron and LHC
  - Pixel module prototypes for LHC trackers
- Currently working to:
  - Test radiation hardness beyond 10^{16} particles per cm^2
  - Commercialise production of sensors for `ATLAS` upgrade
  - Build the ATLAS Diamond Beam Monitor for installation in 2013