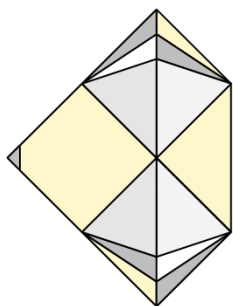


Diamonds for Present/Future LHC Applications

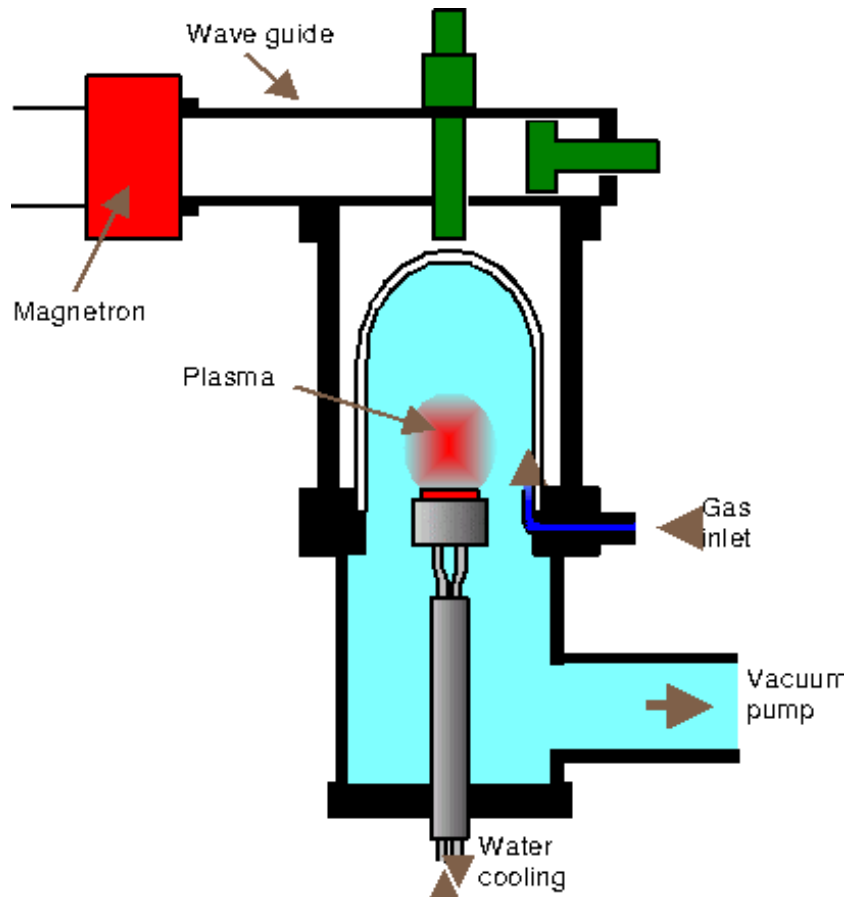
- How diamond works as a sensor material
 - Growth, Properties, Signal, Morphology, Manufacture
- Radiation tolerance of recent sensors
 - Tracker signals, irradiations, damage scaling
- Applications
 - CDF and ATLAS beam conditions monitors
 - The ATLAS pixel detector upgrade



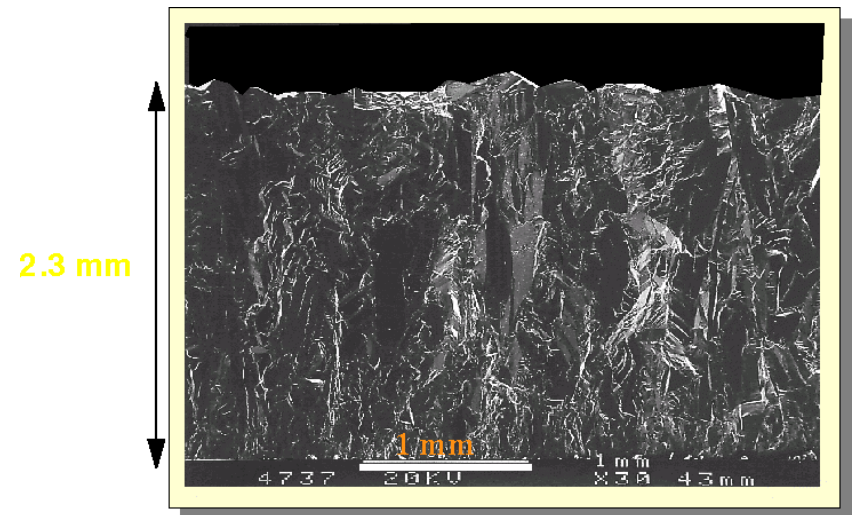
William Trischuk
University of Toronto
November 2011

CVD Diamond as a Particle Detector

- Microwave growth reactor



- Material copies substrate
- Dominant crystallites appear

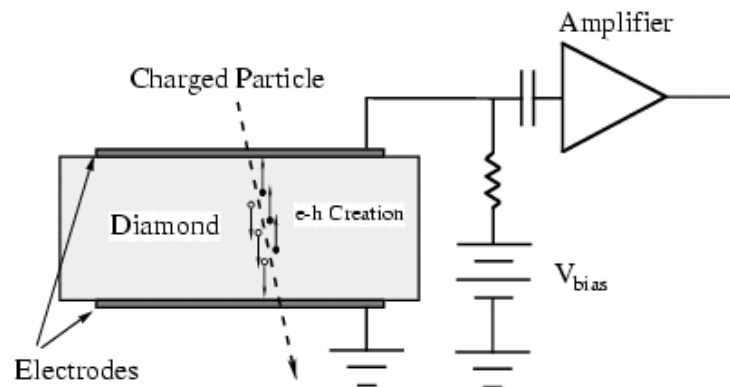


- Edge view of pCVD sample
(Courtesy of Element6)

- Diamond synthesized from plasma

Signals from Diamond Sensors

- Image charge signal
 - induced on surface electrodes

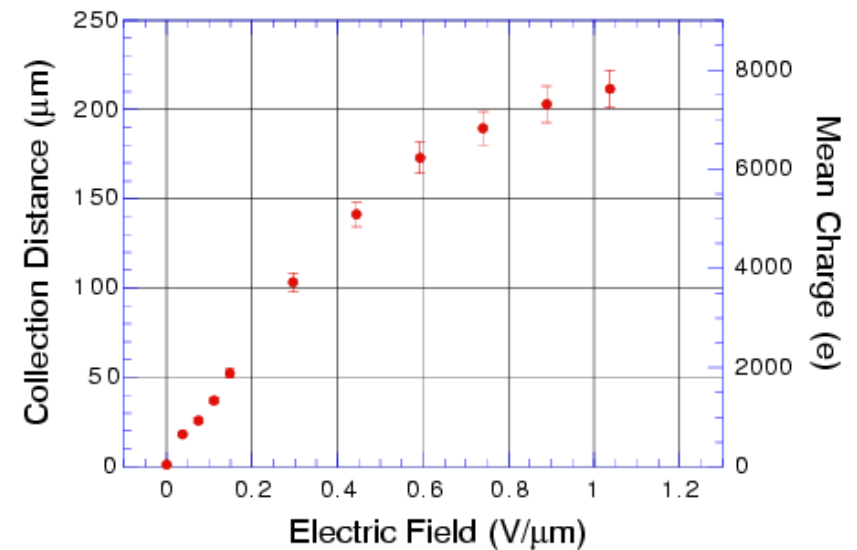


- Charge collected, Q

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

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

- d is the Charge Collection Distance



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

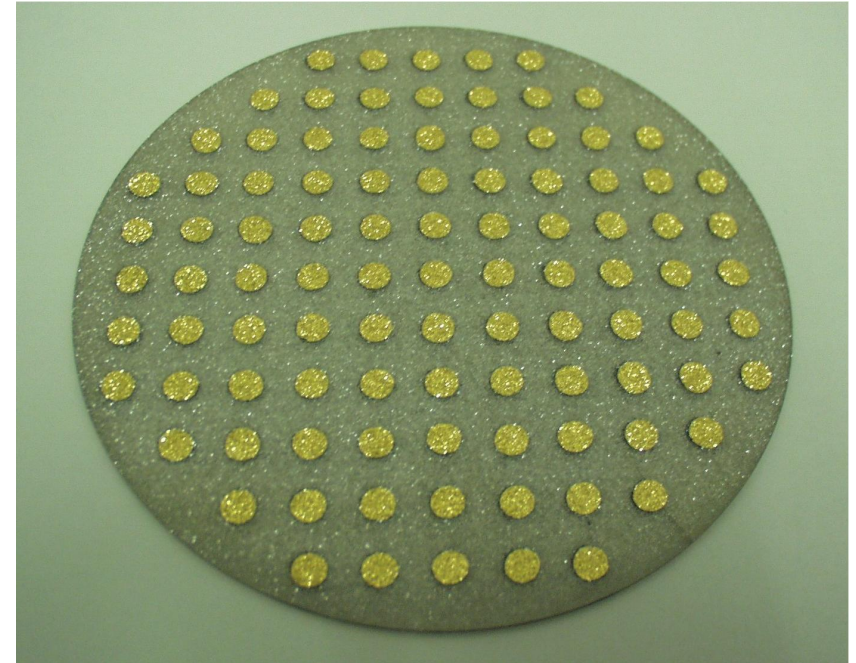
Properties of Diamond and Silicon

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]	$1.3(\text{e})\text{-}1.7(\text{h}) \times 10^7$	$1.1(\text{e})\text{-}0.8(\text{h}) \times 10^7$	
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



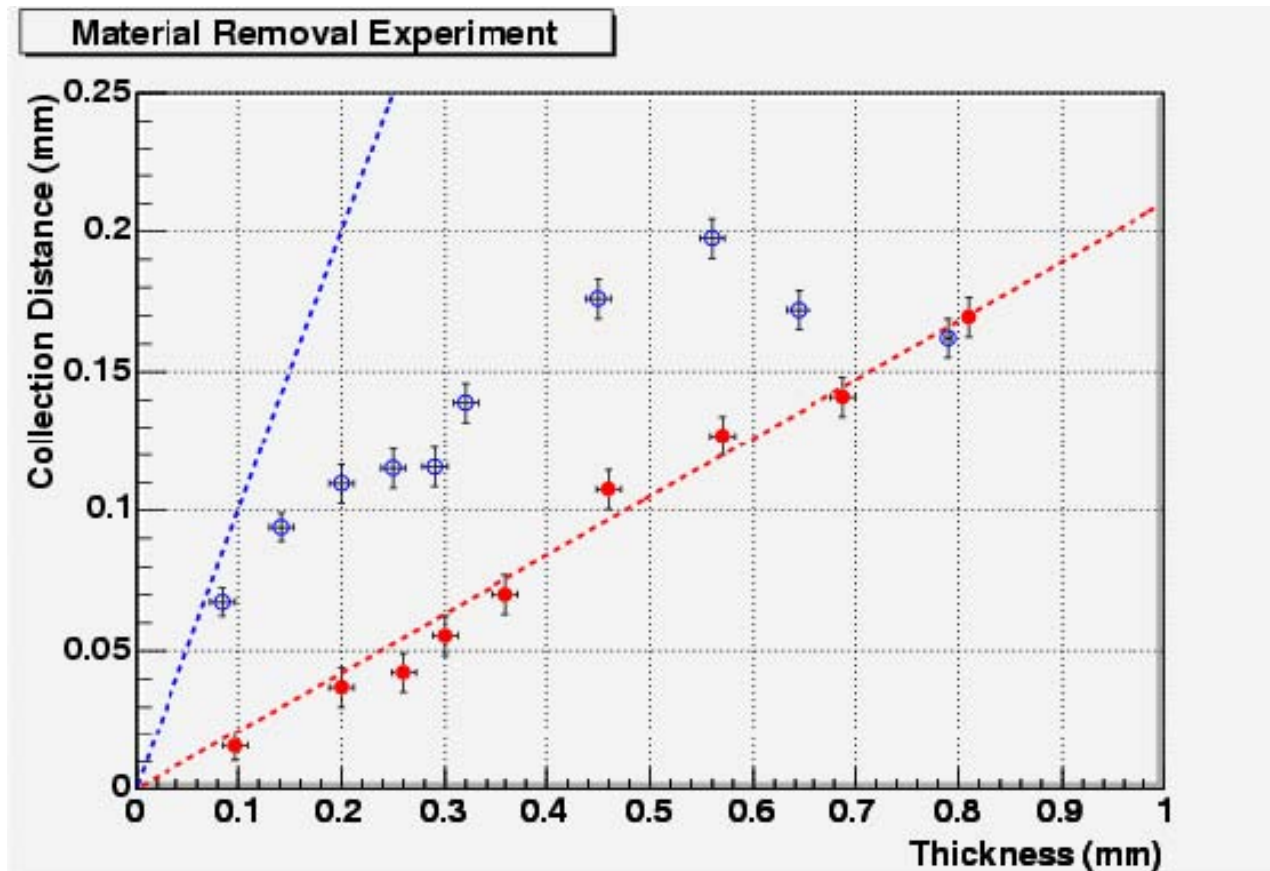
Surface image of pCVD sample
(Courtesy Element6)



- 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



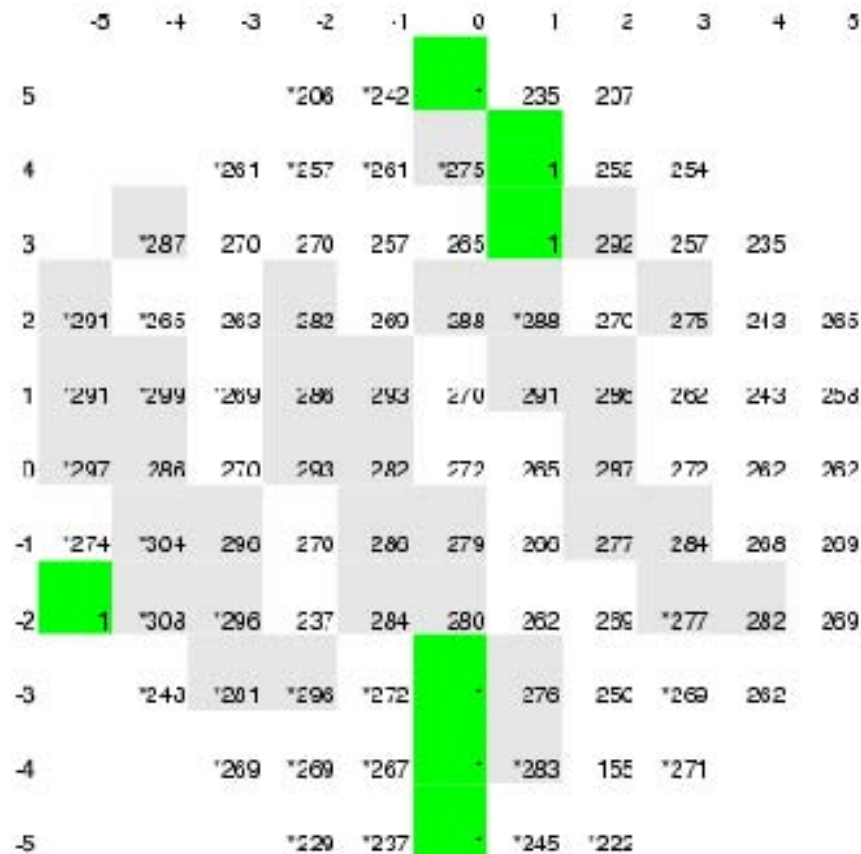
Material removal

Growth side

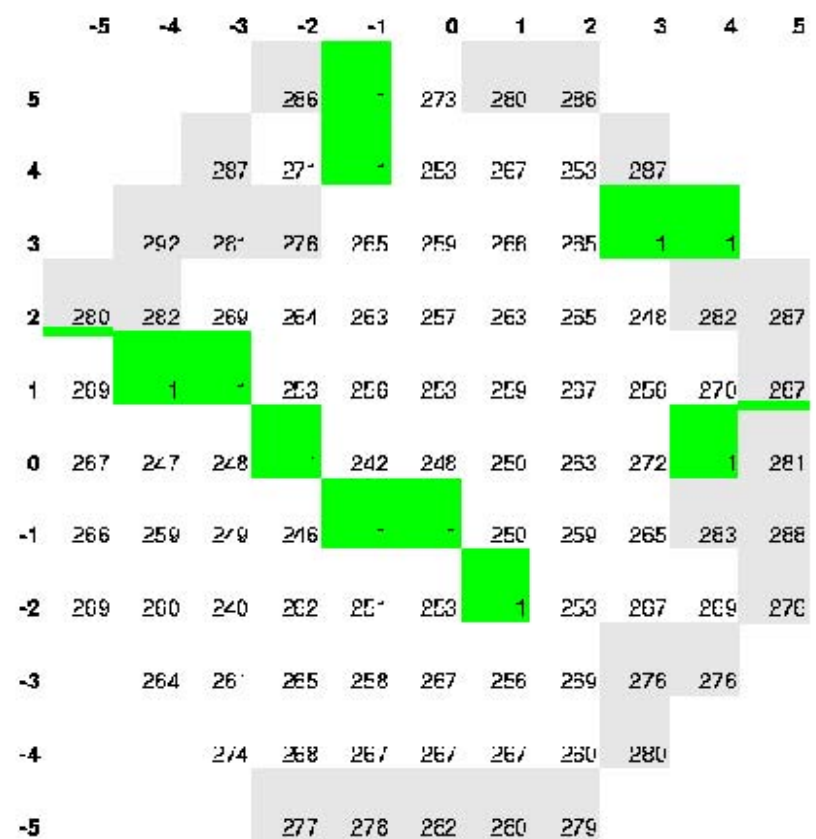
Substrate side

- 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



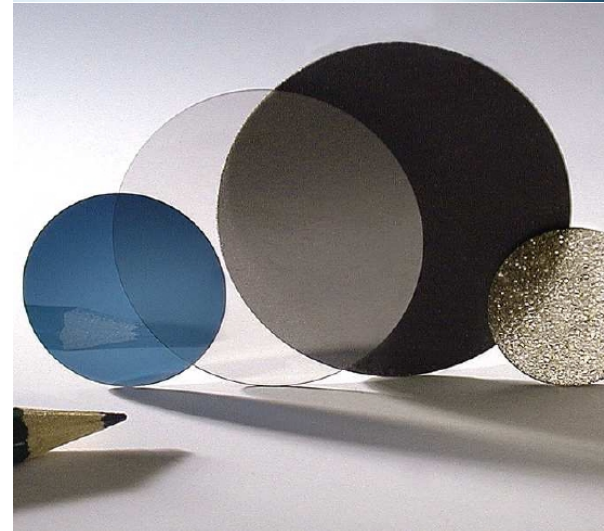
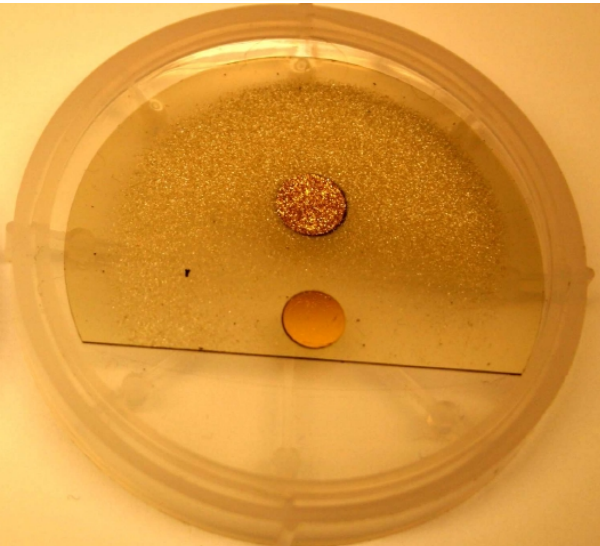
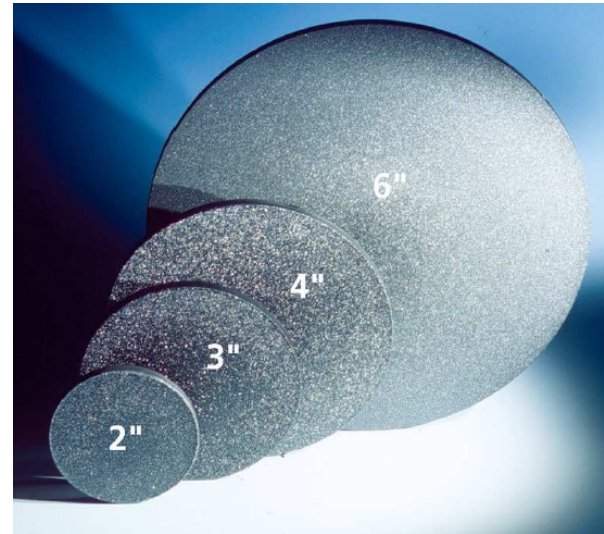
Marks the crack E=0.66V/micron
CCD > 275 μ m



Marks the crack E=0.66V/ μ m
CCD > 275 μ m

Wafers now have typically 250-200 μ m collection distance

Additional Manufacturers

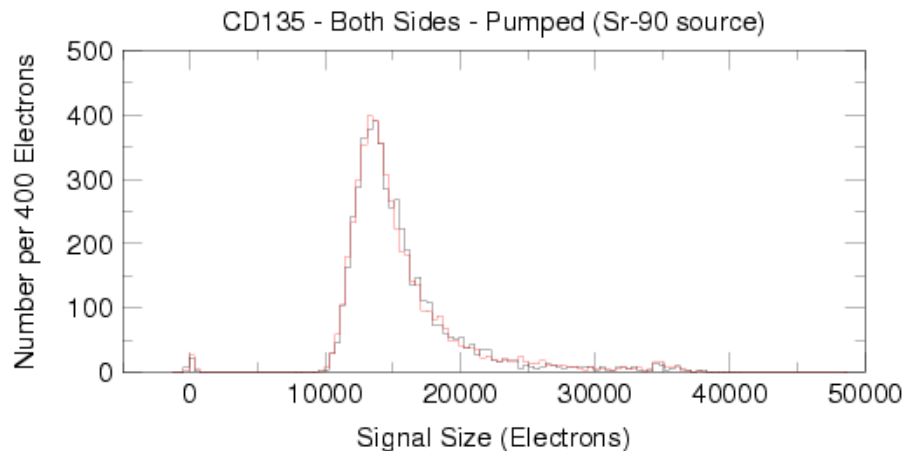


- Other manufacturers interested in radiation tolerant sensor market
- RD42 working to qualify two new vendors

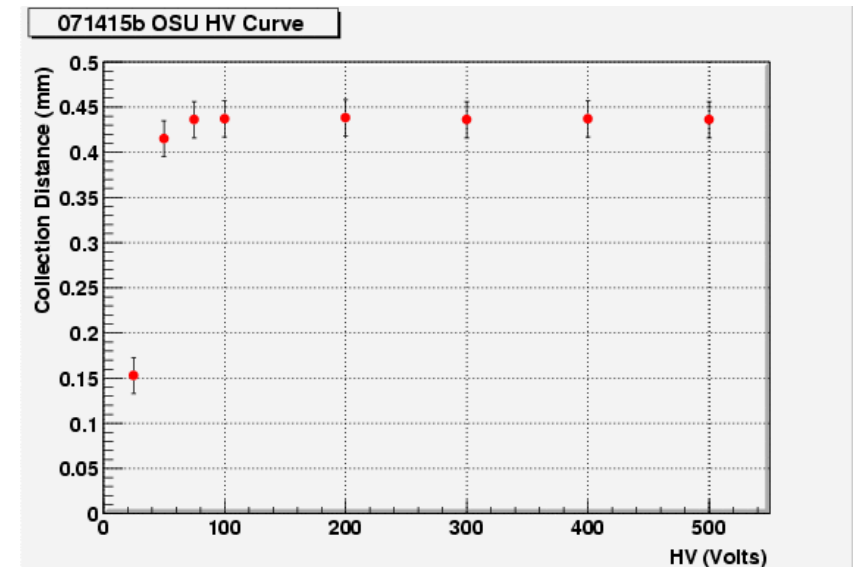
Single Crystal (scCVD) Diamond

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

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



- Features of this material include
 - Full collection at $0.2 \text{ V}/\mu\text{m}$



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

The RD42 Collaboration

M. Artuso²⁵, D. Asner²², L. Bäni²⁹, M. Barbero¹, V. Bellini², V. Belyaev¹⁵, E. Berdermann⁸, P. Bergonzo¹⁴, S. Blusk²⁵, A. Borgia²⁵, J-M. Brom¹⁰, M. Bruzzi⁵, G. Chiodini³², D. Chren²³, V. Cindro¹², G. Claus¹⁰, M. Cristinziani¹, S. Costa², J. Cumalat²⁴, A. Dabrowski³, R. D'Alessandro⁶, W. de Boer¹³, M. Dinardo²⁴, D. Dobos³, W. Dulinski¹⁰, J. Duris²⁰, V. Eremin⁹, R. Eusebi³⁰, H. Fraix-Kolbl⁴, A. Furgeri¹³, C. Gallrapp³, K.K. Gan¹⁶, J. Garofoli²⁵, M. Goffe¹⁰, J. Goldstein²¹, A. Golubev¹¹, A. Gorisek¹², E. Grigoriev¹¹, J. Grosse-Knetter²⁸, M. Guthoff¹³, D. Hits¹⁷, M. Hoferkamp²⁶, F. Huegging¹, H. Kagan^{16,♦}, R. Kass¹⁶, G. Kramberger¹², S. Kuleshov¹¹, S. Kwan⁷, S. Lagomarsino⁶, A. La Rosa³, A. Lo Giudice¹⁸, I. Mandic¹², C. Manfredotti¹⁸, C. Manfredotti¹⁸, A. Martemyanov¹¹, H. Merritt¹⁶, M. Mikuz¹², M. Mishina⁷, M. Moench²⁹, J. Moss¹⁶, R. Mountain²⁵, S. Mueller¹³, G. Oakham²², A. Oh²⁷, P. Olivero¹⁸, G. Parrini⁶, H. Pernegger³, R. Perrino³², M. Pomorski¹⁴, R. Potenza², A. Quadt²⁸, K. Randrianarivony²², A. Robichaud²², S. Roe³, S. Schnetzer¹⁷, T. Schreiner⁴, S. Sciortino⁶, S. Seidel²⁶, S. Smith¹⁶, B. Sopko²³, S. Spagnolo³², S. Spanier³¹, K. Stenson²⁴, R. Stone¹⁷, C. Suter², M. Traeger⁸, D. Tromson¹⁴, W. Trischuk¹⁹, J-W. Tsung¹, C. Tuve², P. Urquijo²⁵, J. Velthuis²¹, E. Vittone¹⁸, S. Wagner²⁴, R. Wallny²⁹, J.C. Wang²⁵, R. Wang²⁶, P. Weilhammer^{3,♦}, J. Weingarten²⁸, N. Wormes¹

♦ Spokespersons

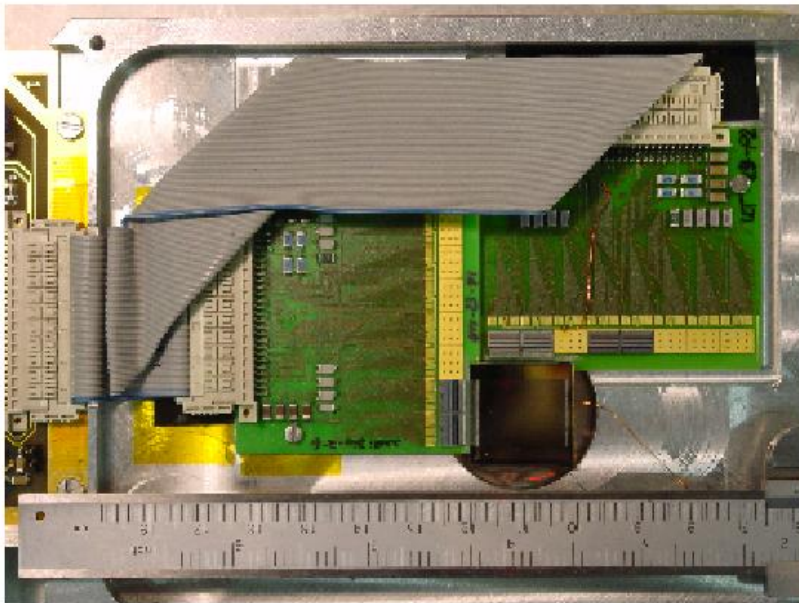
1 Universitaet Bonn, Bonn, Germany
 2 INFN/University of Catania, Catania, Italy
 3 CERN, Geneva, Switzerland
 4 FWT Wiener Neustadt, Austria
 5 INFN/University of Florence, Florence, Italy
 6 Department of Energetics/INFN, Florence, Italy
 7 FNAL, Batavia, USA
 8 GSI, Darmstadt, Germany
 9 Ioffe Institute, St. Petersburg, Russia
 10 IPHC, Strasbourg, France
 11 ITEP, Moscow, Russia
 12 Jozef Stefan Institute, Ljubljana, Slovenia
 13 Universitaet Karlsruhe, Karlsruhe, Germany
 14 CEA-LIST, Saclay, France
 15 MEPhI Institute, Moscow, Russia
 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
 20 UCLA, Los Angeles, CA, USA
 21 University of Bristol, Bristol, UK
 22 Carleton University, Ottawa, Canada
 23 Czech Technical Univ., Prague, Czech Republic
 24 University of Colorado, Boulder, CO, USA
 25 Syracuse University, Syracuse, NY, USA
 26 University of New Mexico, Albuquerque, NM, USA
 27 University of Manchester, Manchester, UK
 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

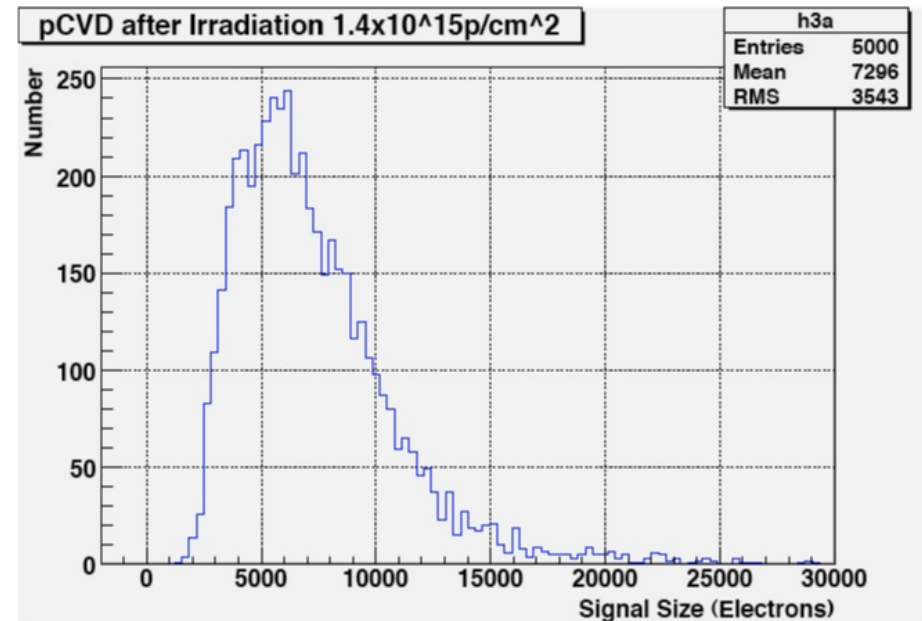
from 32 institutions

Radiation Tolerance of Diamond Sensors

Typically tested as strip tracker



Pulse height from irradiated tracker

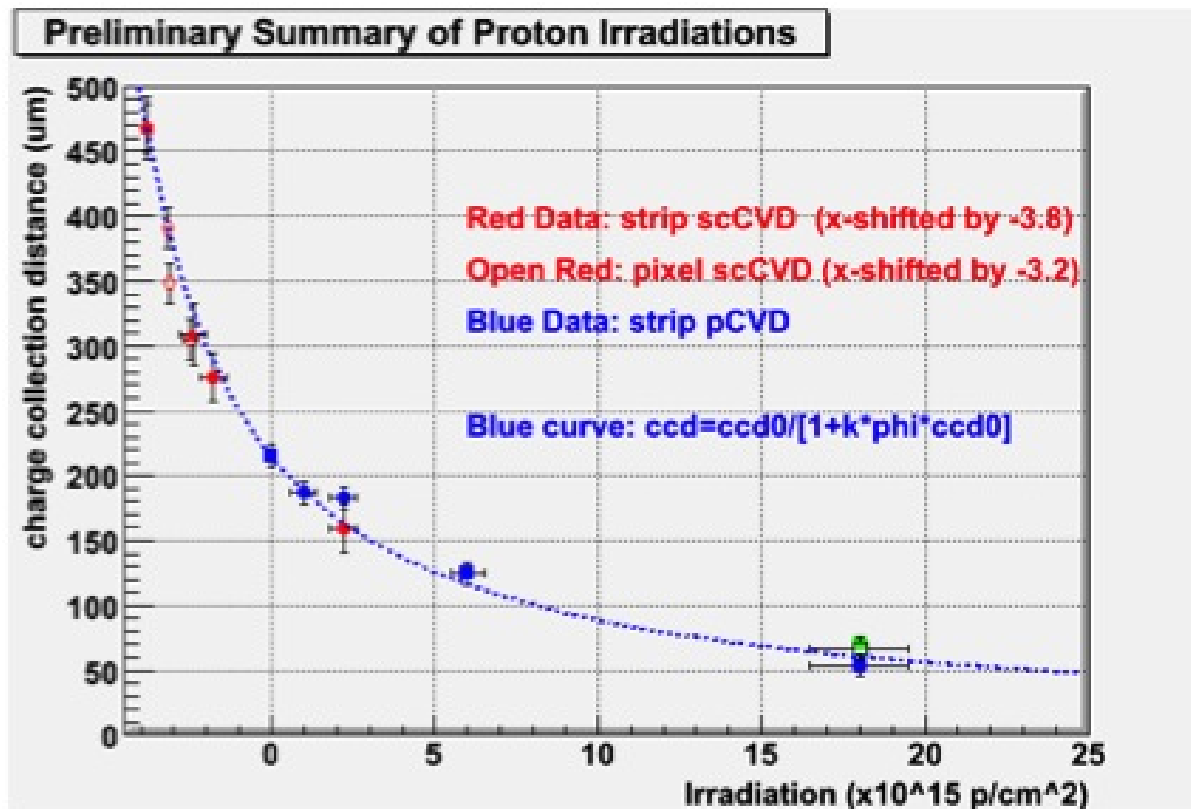


- Use long ($2 \mu\text{s}$) shaping time for precision materials studies
- After $1.4 \times 10^{15} \text{ p/cm}^2$ signal uniform/well separated from pedestal
 - 99 % of hits have more than 2500 electrons signal
 - Most probable signal 6000 electrons at $1 \text{ V}/\mu\text{m}$

24 GeV Proton Irradiations

- Have irradiated:
 - pCVD samples to 1.8×10^{16} p/cm²
 - scCVD samples to 5×10^{15} p/cm²
- Characterise signal at intermediate fluences

- Default $E = 1$ V/μm
- Green at $E = 2$ V/μm
- Align by shifting
 - 3.8×10^{15} p/cm²



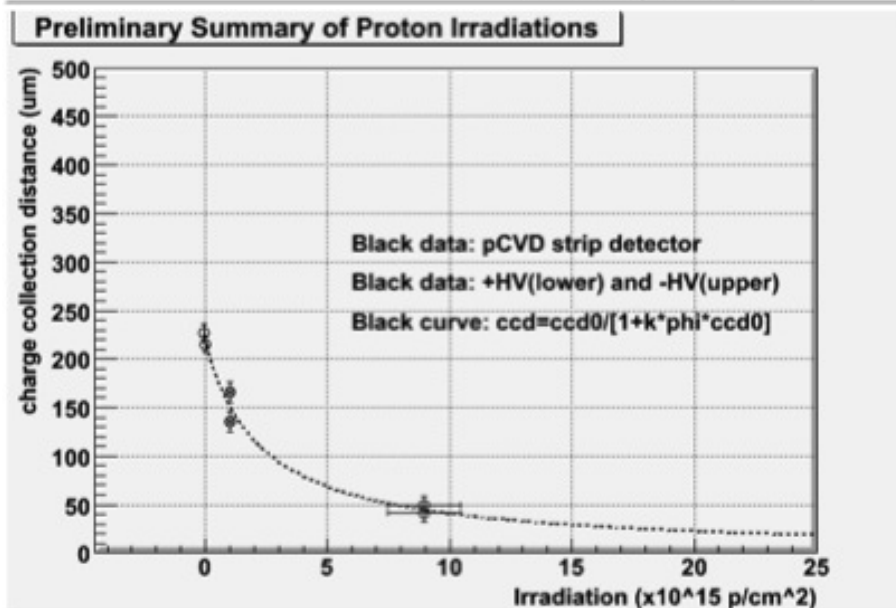
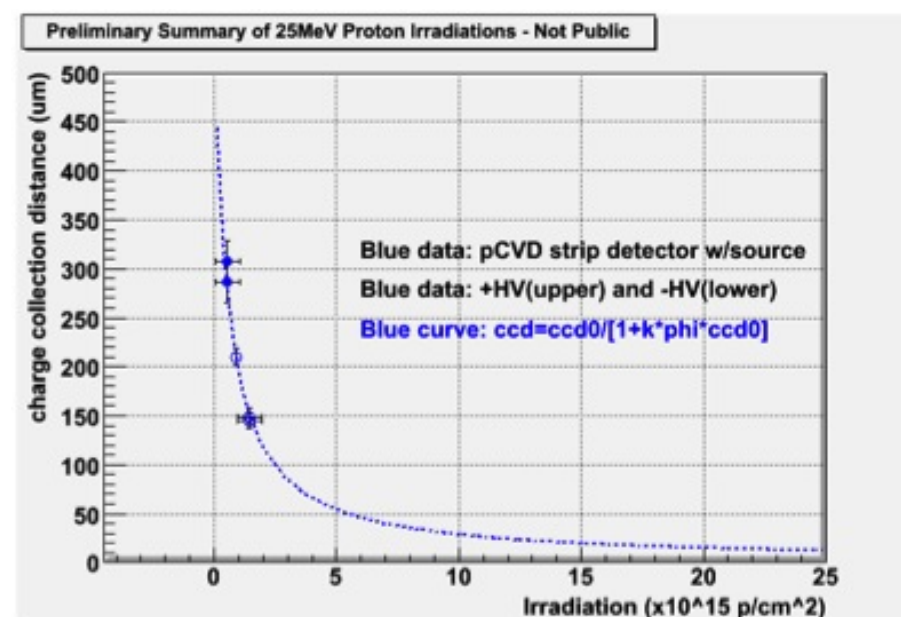
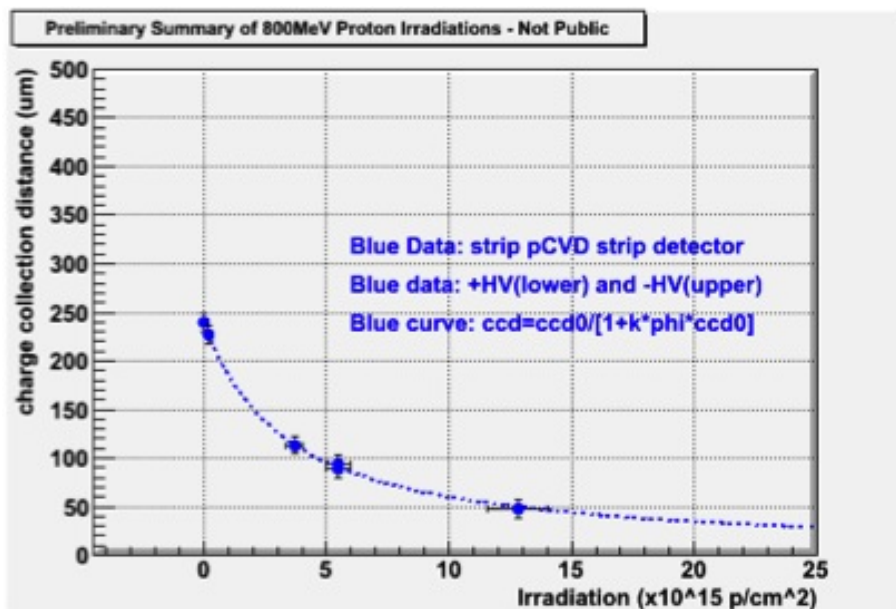
This pCVD material $\equiv$
 scCVD material after
 $\approx 3.8 \times 10^{15}$ p/cm²

- pCVD and scCVD follow same damage curve:

$$1/d = 1/d_0 + k\phi$$

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

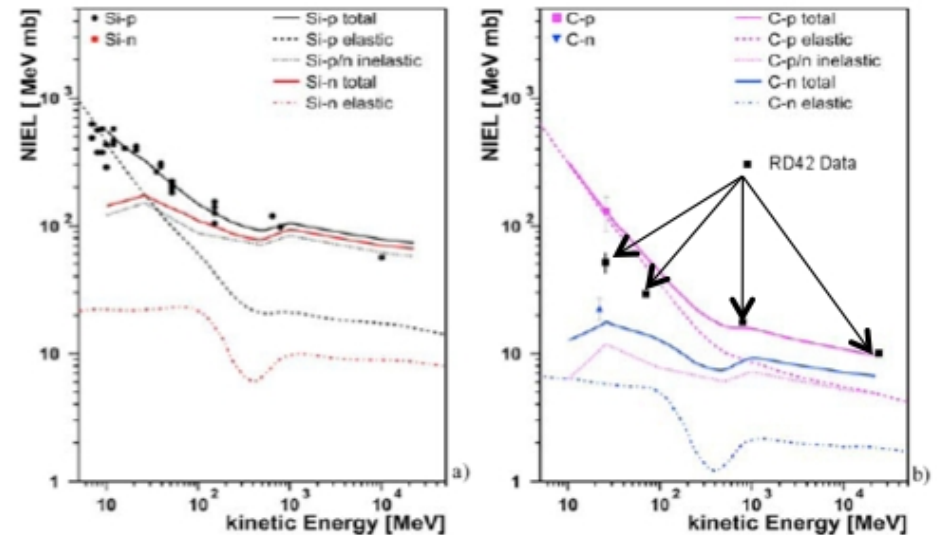
Irradiations with Lower Energy Protons



- 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

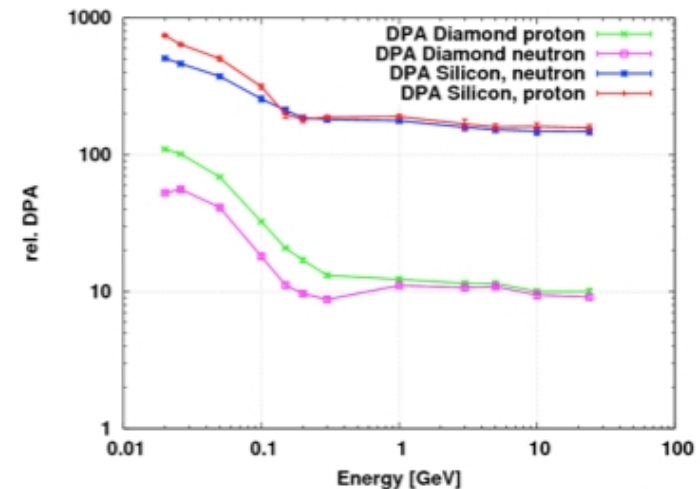
- Non-ionising energy calculations predict:
 - 0.8/24 GeV p : 2
– confirmed
 - 0.07/24 GeV p : 6
– see factor of 3
 - 0.025/24 GeV p : 15
– see factor of 5
 - 10 MeV $n \equiv$ 24 GeV p
– in progress
- FLUKA calculations give
 - Protons: 1.2, 5, 10
for 800, 70, 25 MeV
 - Neutrons: 6



W. de Boer et al.

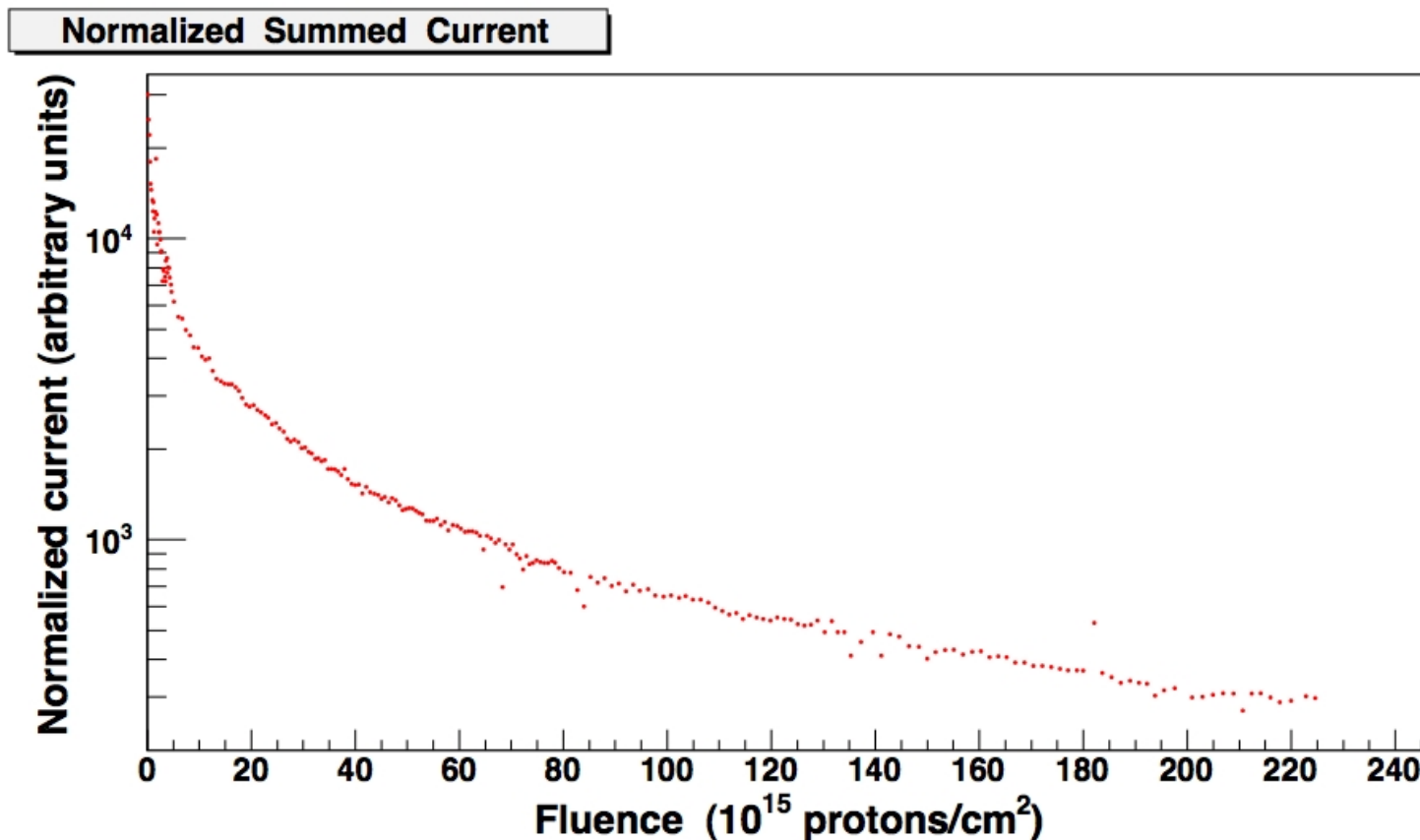
phys. stat. sol. (a) 204, No. 9 (2007)3009

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 $\geq 10^{17}$

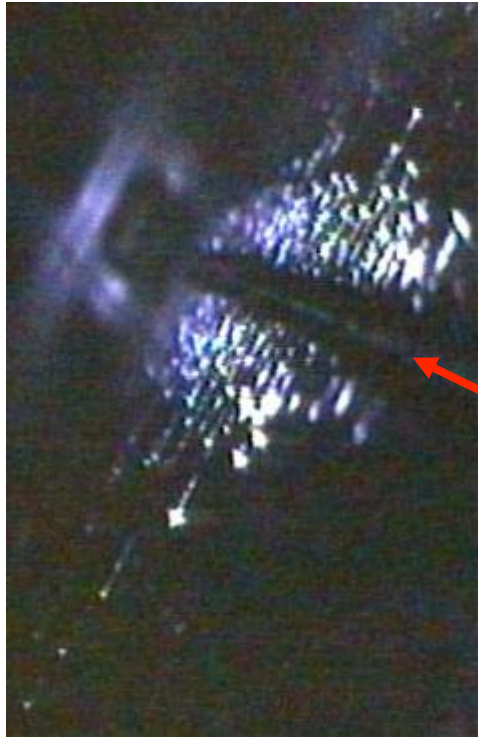


Applications of Diamond Sensors

- 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)

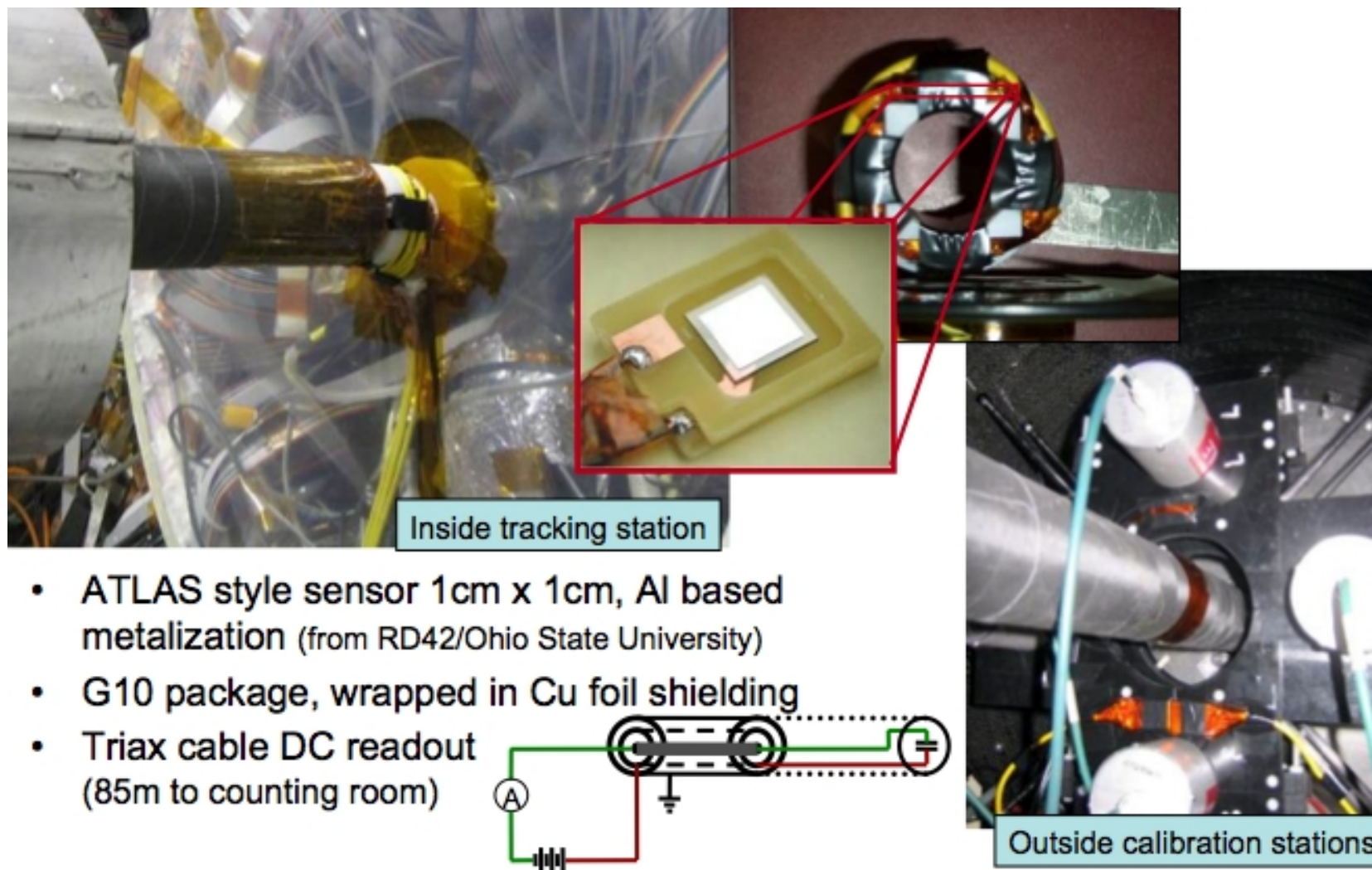


Protons

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

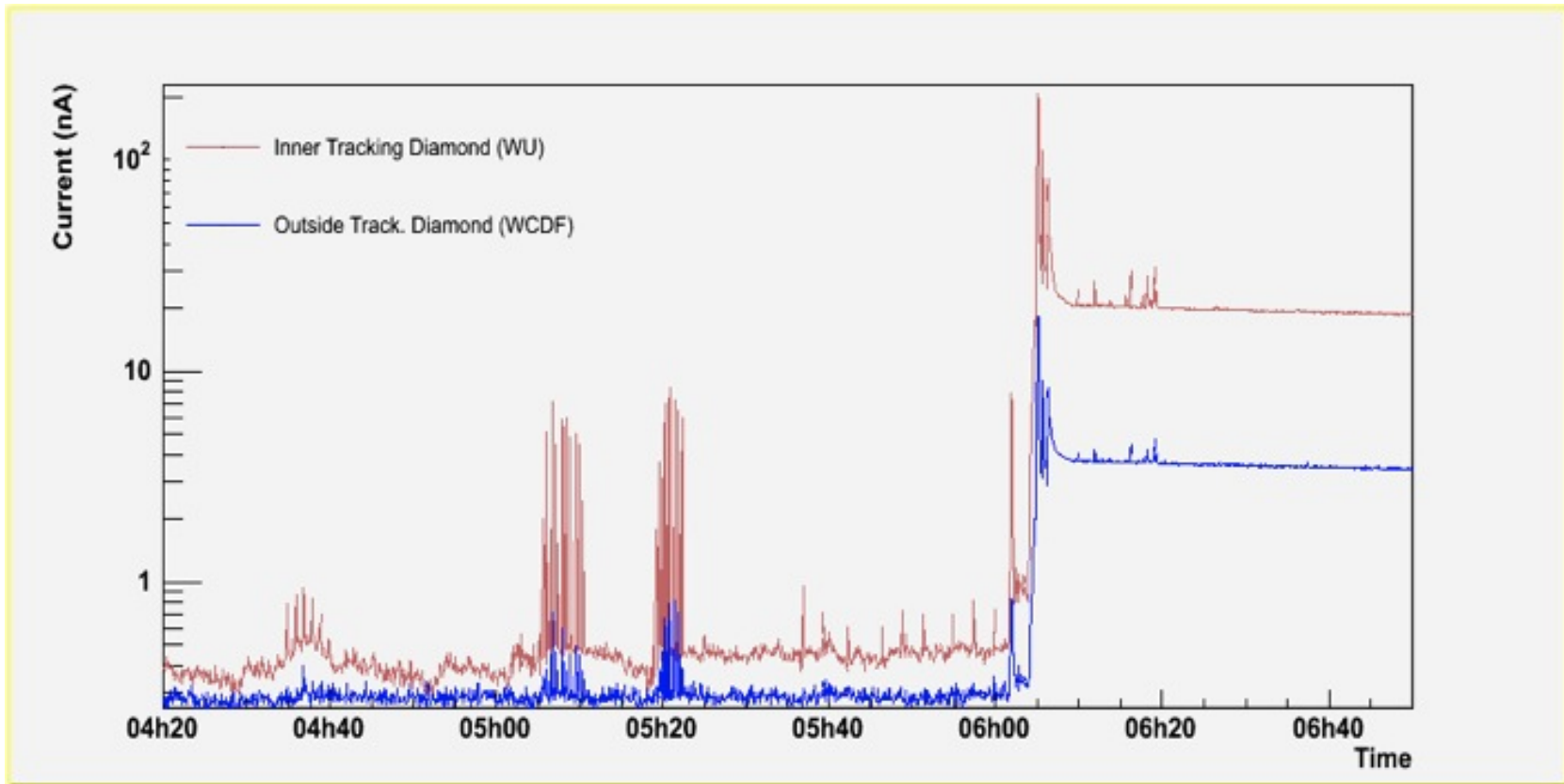
A 1m long melted stretch of Tevatron collimator

pCVD Diamond Sensors in CDF



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

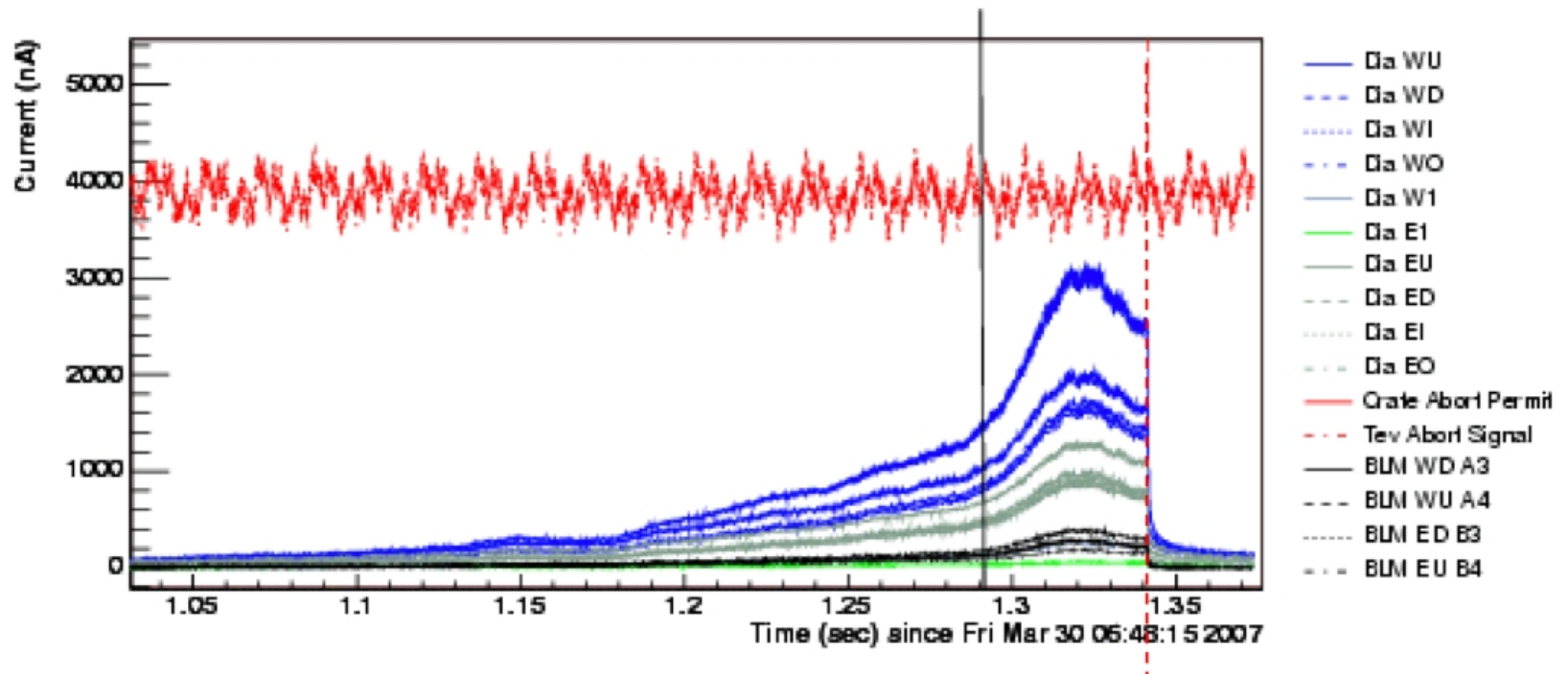
Sensitivity to Tevatron 'events'



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

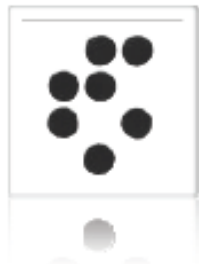
A Typical Tevatron Abort

- 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



Univ. Toronto

• M. Cadabeschi
• W. Trischuk
• D. Tardif



Univ. of Applied Science -
Wiener Neustadt

• H. Frais-Kölbl
• E. Griesmayer
• M. Niegler



OSU, Columbus

• H. Kagan
• S. Smith

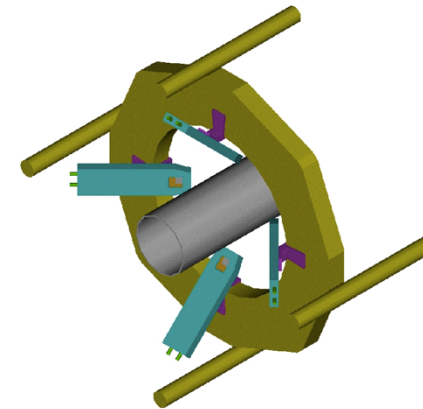
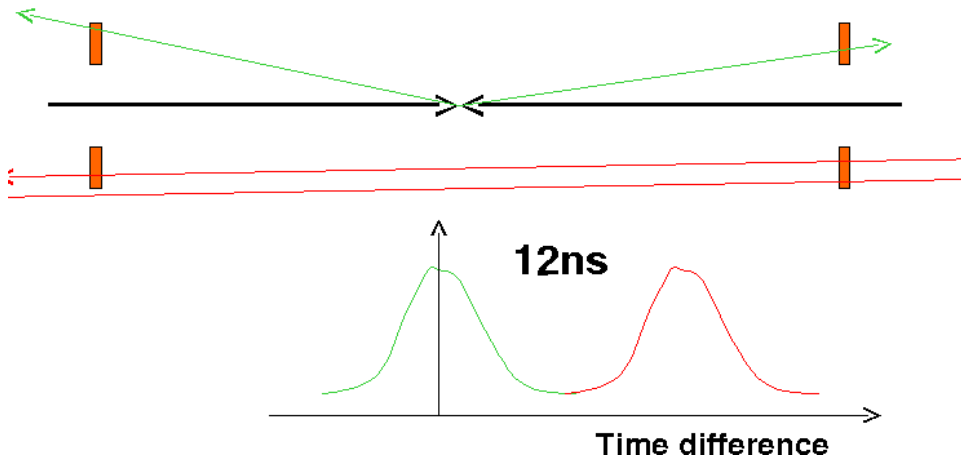


CERN

• D. Dobos
• K. Lantzschi
• H. Pernegger
• E. Stanecka

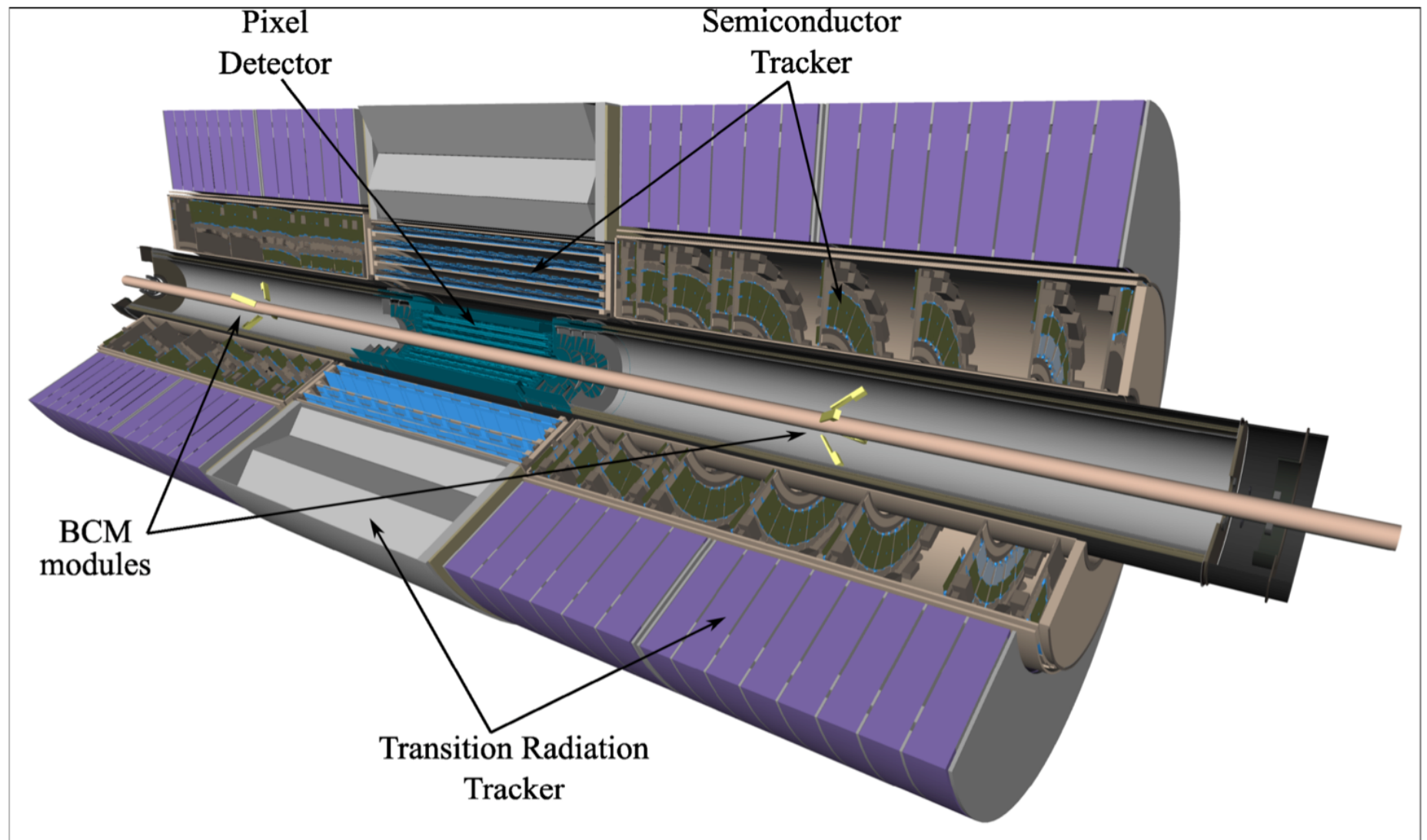
The ATLAS Beam Conditions Monitor

- 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 $\pm 1.9\text{m}$

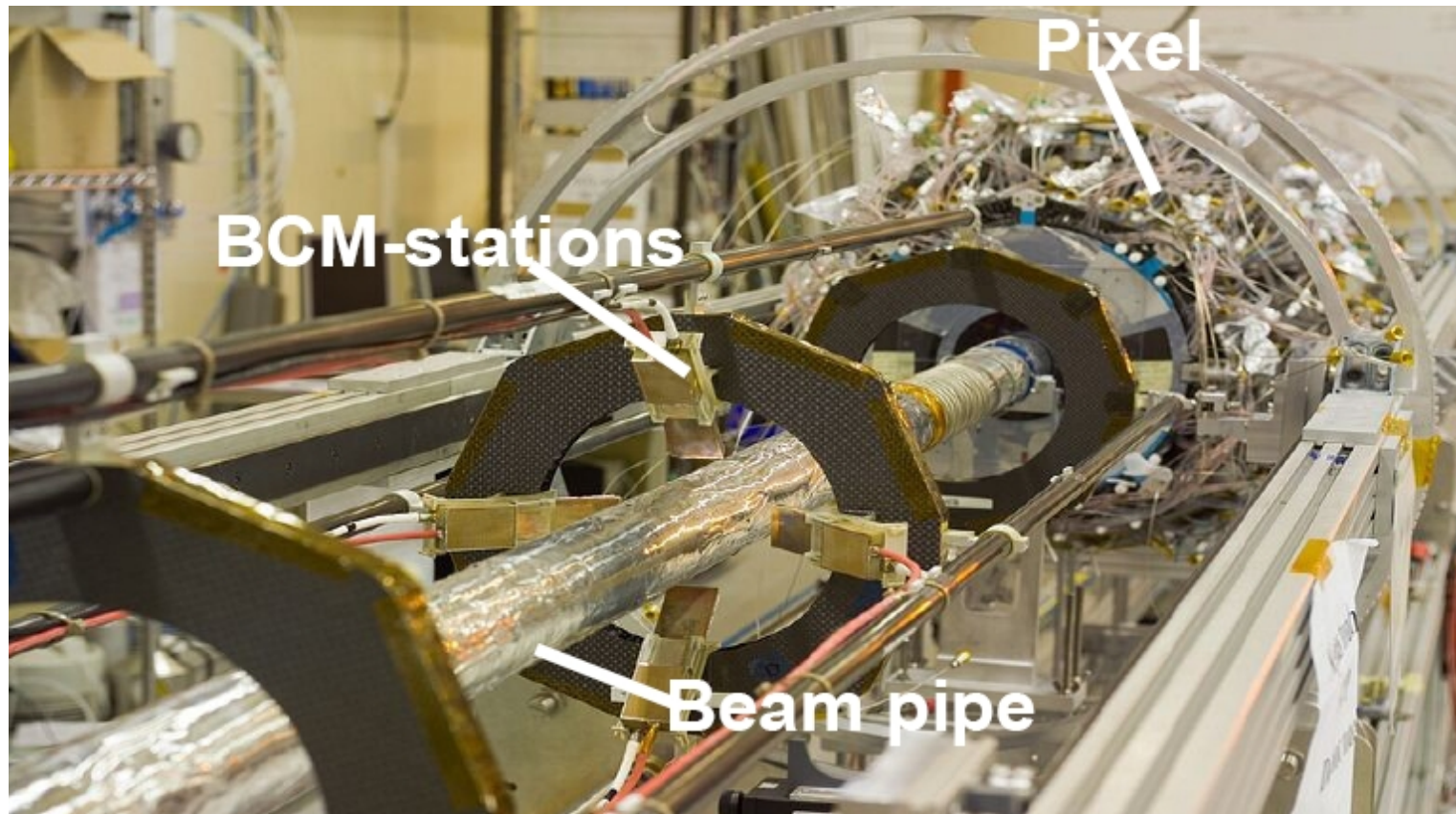


- Use CVD diamond sensors
 - 10x faster signals and 10x more radiation tolerant than silicon
- Use GaAs amplifiers with 1ns rise-time, 5ns baseline restoration

The BCM in ATLAS



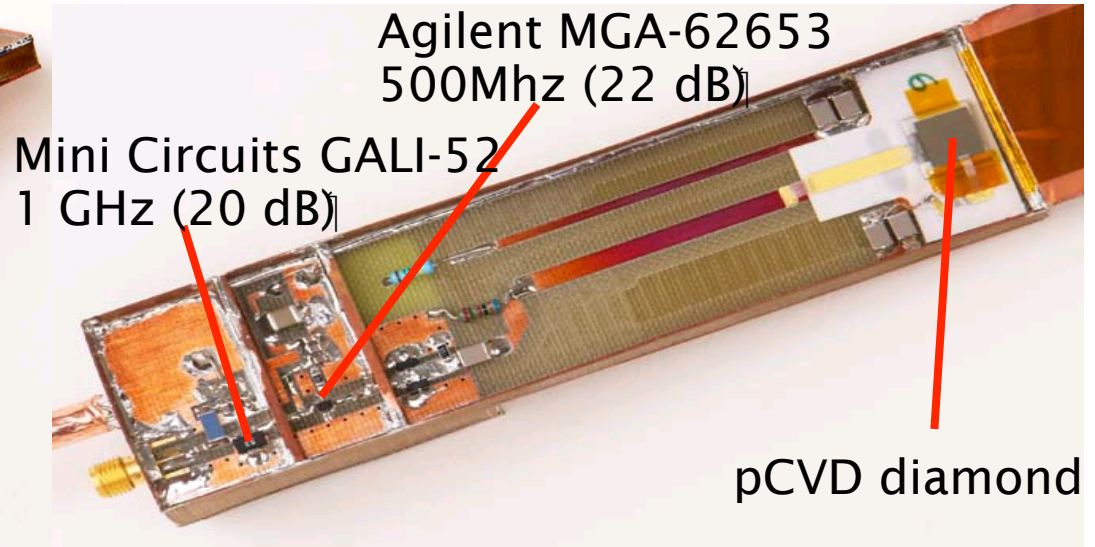
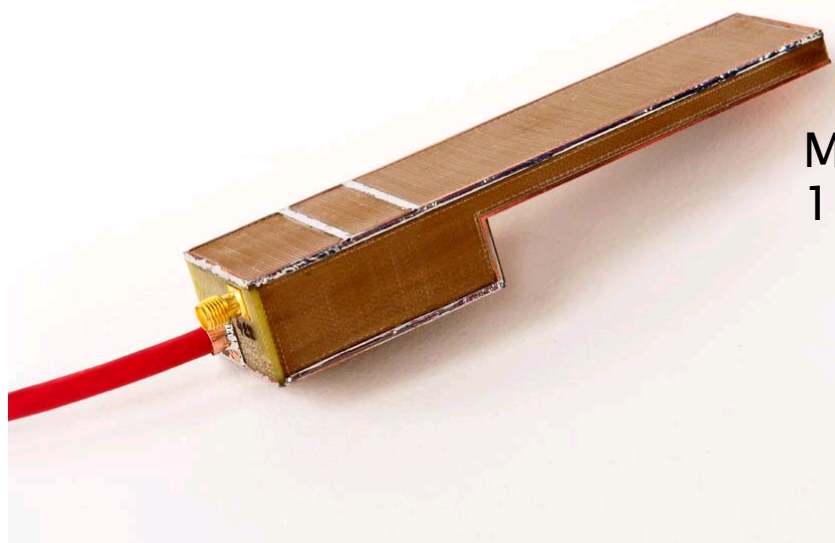
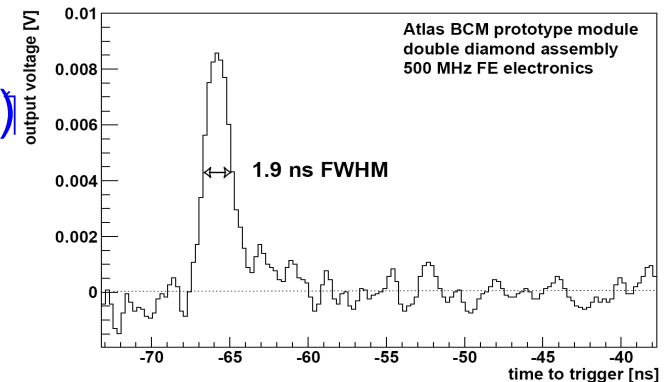
The BCM Installation



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

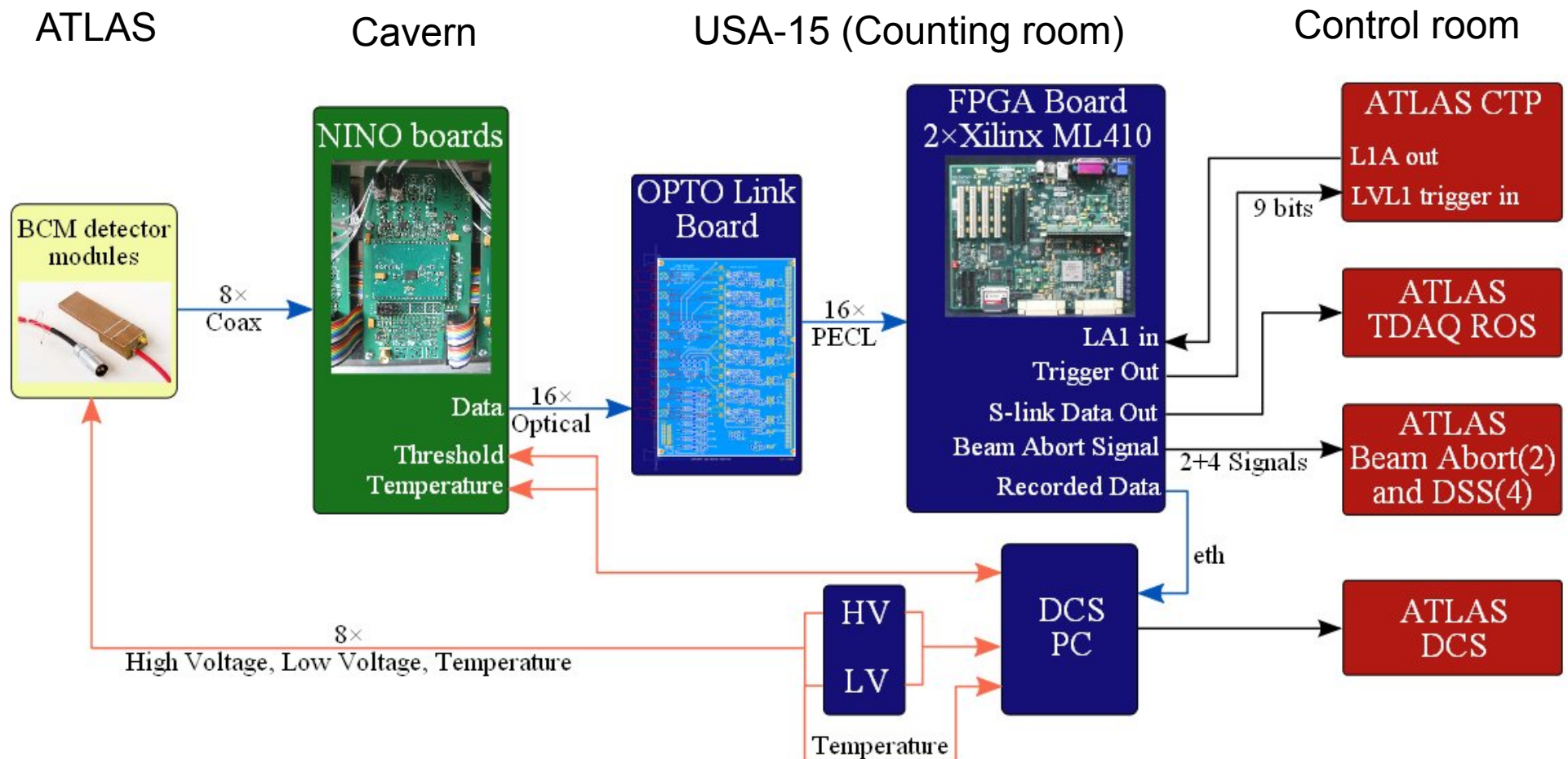
The BCM Detector Modules

- pCVD diamond sensors ($10 \times 10 \text{ mm}^2$, $2 \times 500 \mu\text{m}$ thick)
 - Withstand doses $> 10^{15} \text{ p/cm}^2$
- Fast & short signal (FWHM $\sim 2 \text{ ns}$, rise time $< 1 \text{ ns}$)
- Count hits above two thresholds:
 - $\frac{1}{2}$ 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)

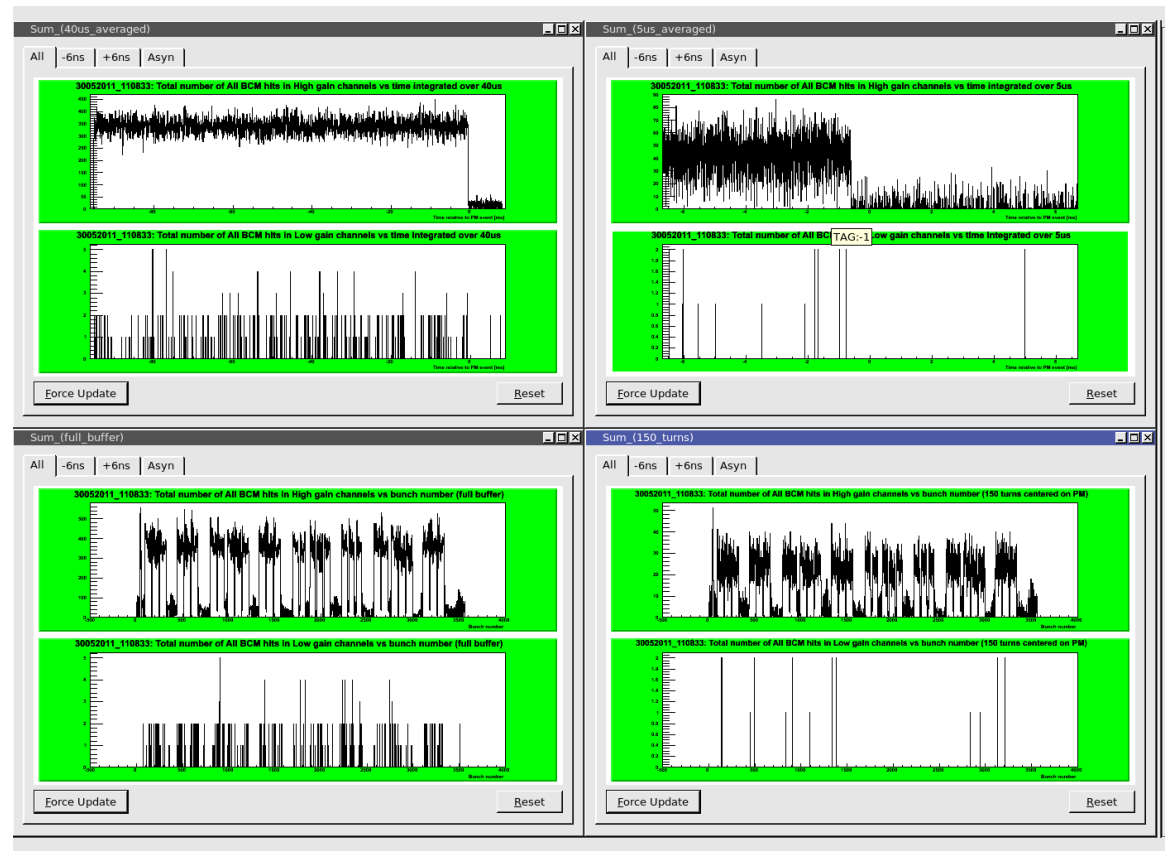
- Provide fast feedback (within 5 minutes of abort) to LHC Control
 - After every abort (about 3000 per year)
- Normally look like:

1000 turns

100 turns

Single MIP

Hundred MIP

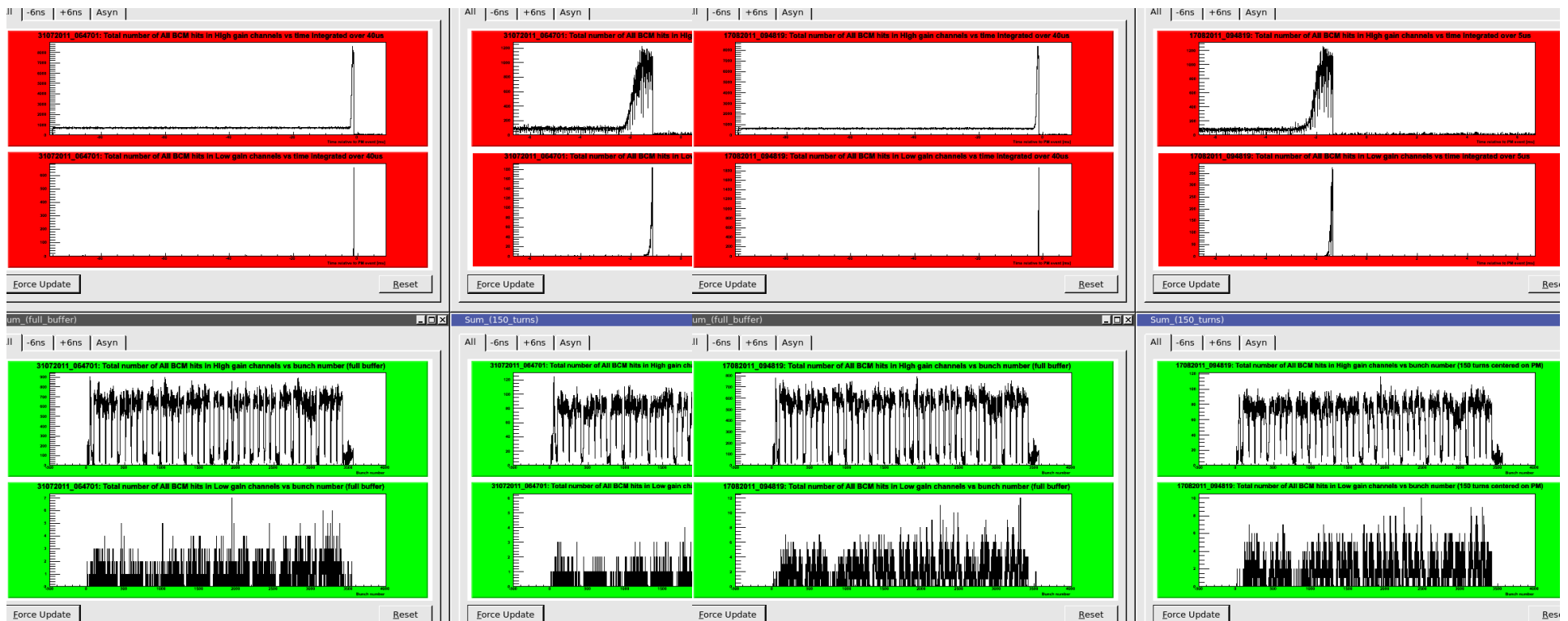


vs. Time

vs. BCID

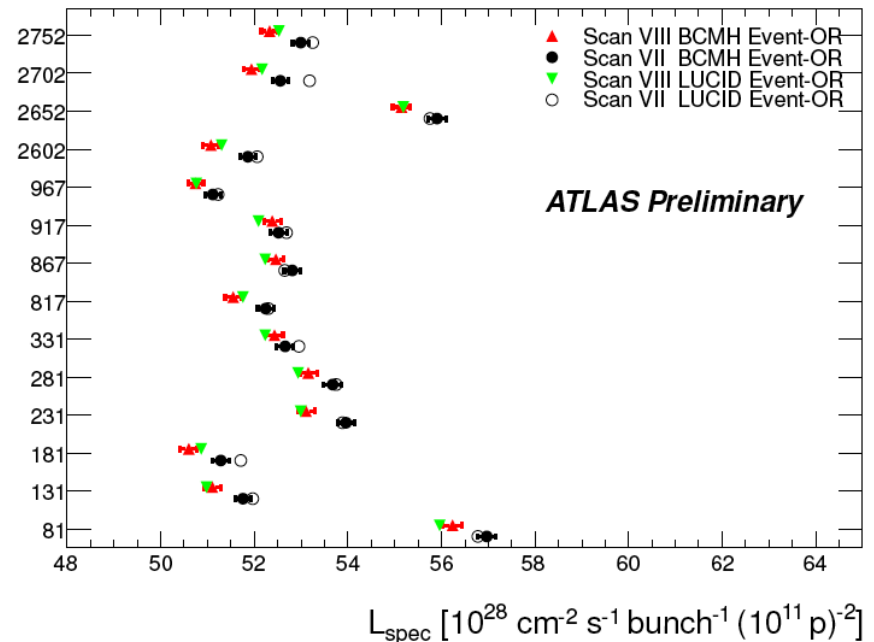
Two Aborts Seen – 2+ Years of Operation

- 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



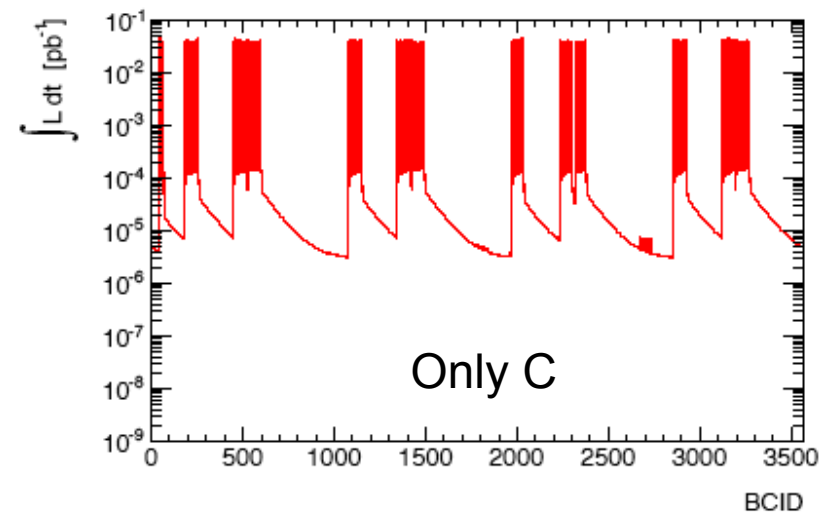
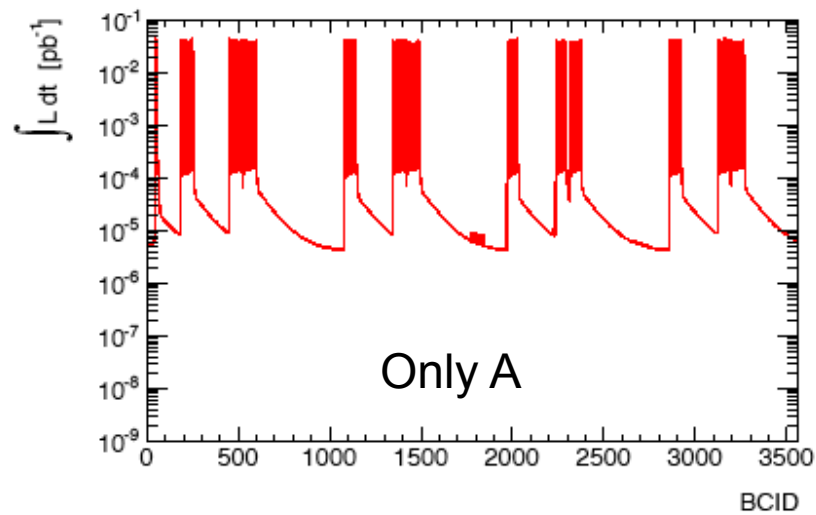
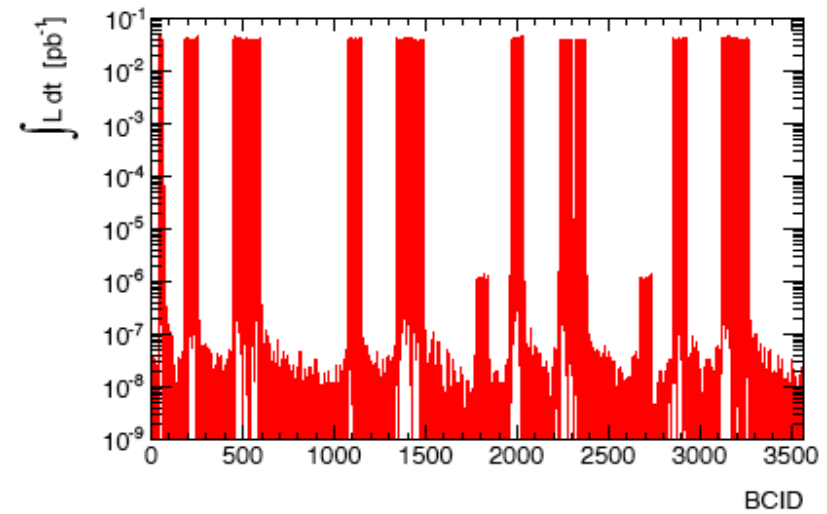
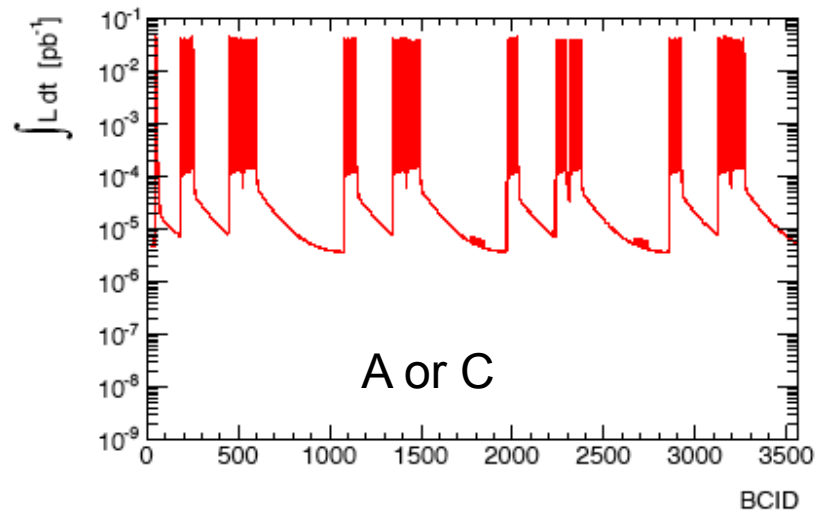
BCM: ATLAS Default Luminosity Monitor

- 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
 - Reproducibly and reliably



BCM Luminosity Maps

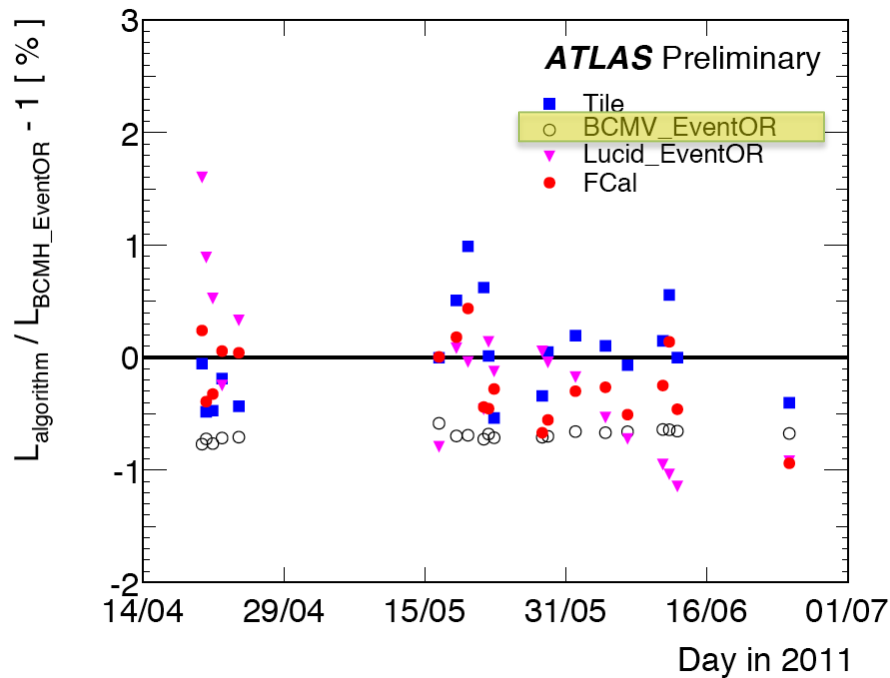
A and C



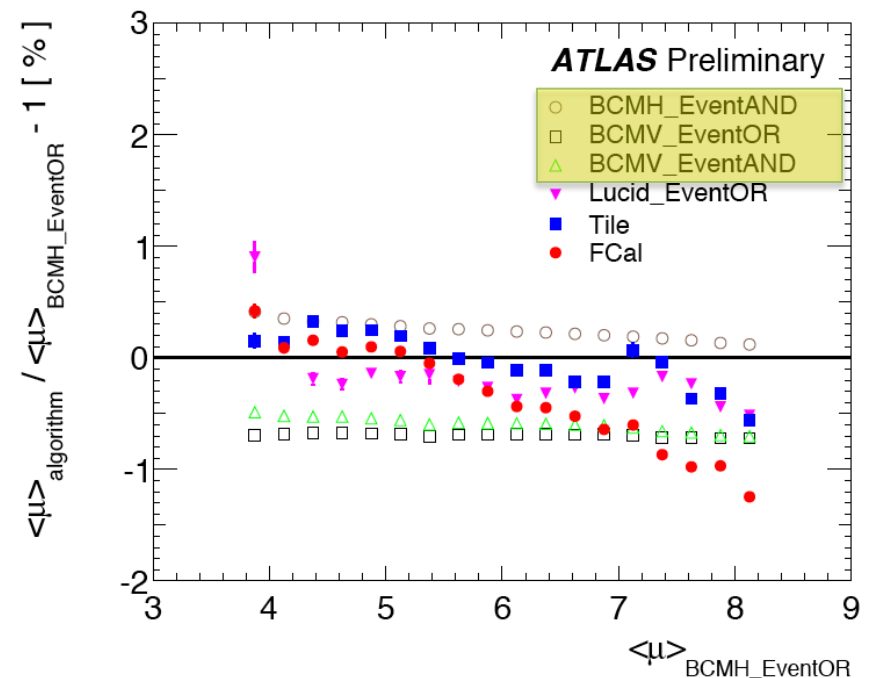
BCM: Luminosity Stability

- Two independent lumi measurements (BCM_H (ref), BCM_V (o))

- Stable over months (left)



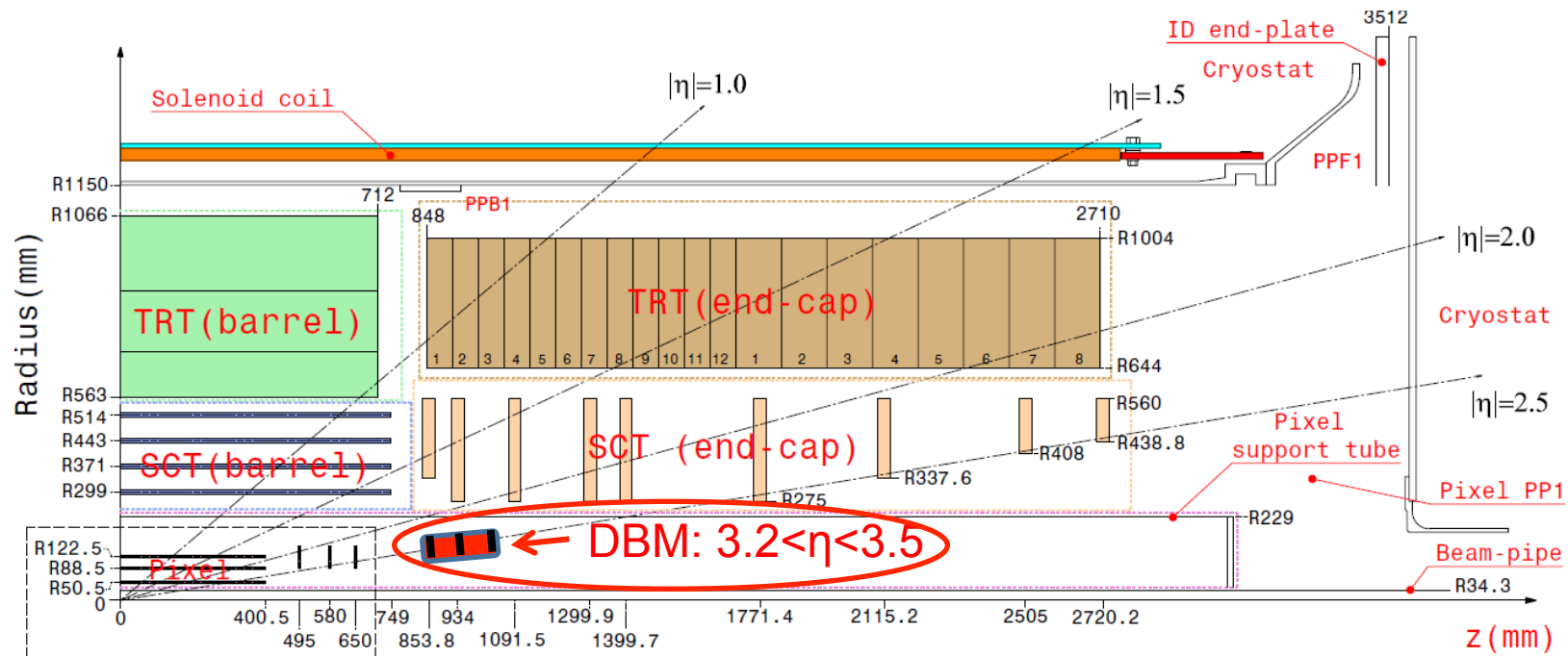
- Stable against pile up (right)



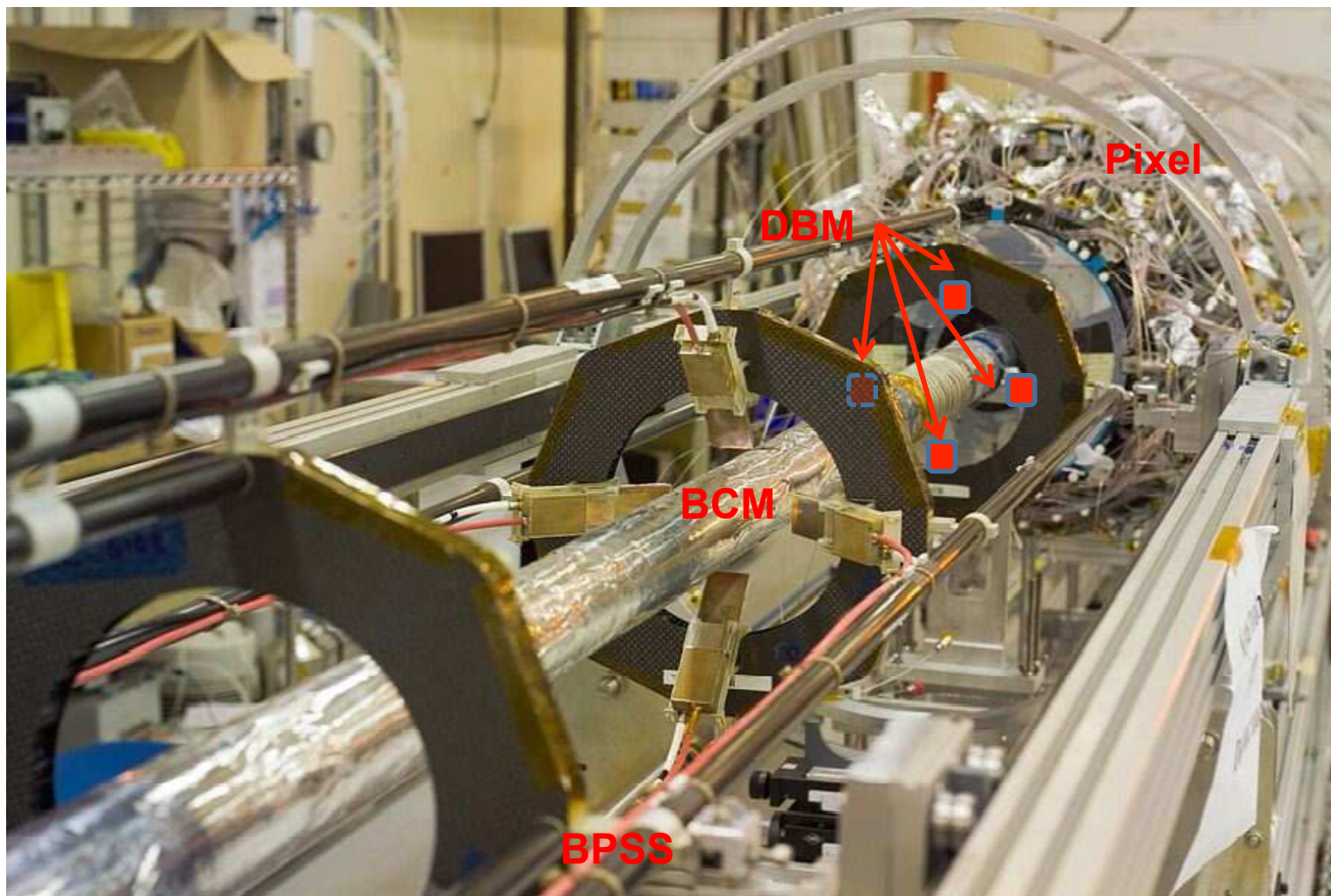
One of the keys to ATLAS stated 3.4% absolute luminosity uncertainty

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 – February 2013

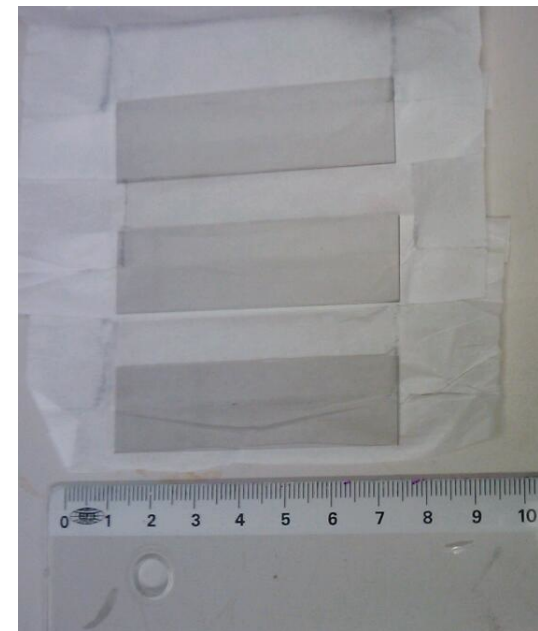
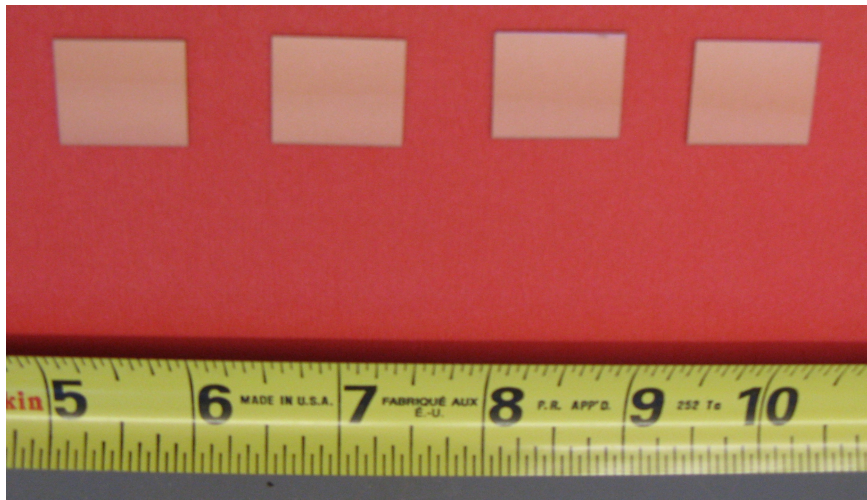


DBM Location



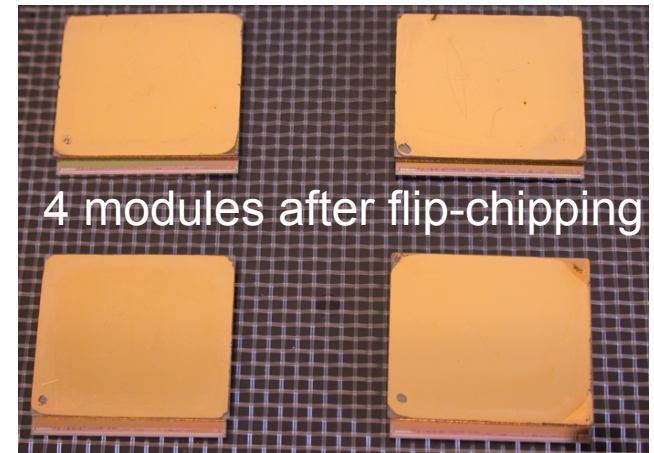
DBM Sensor Inventory

- 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

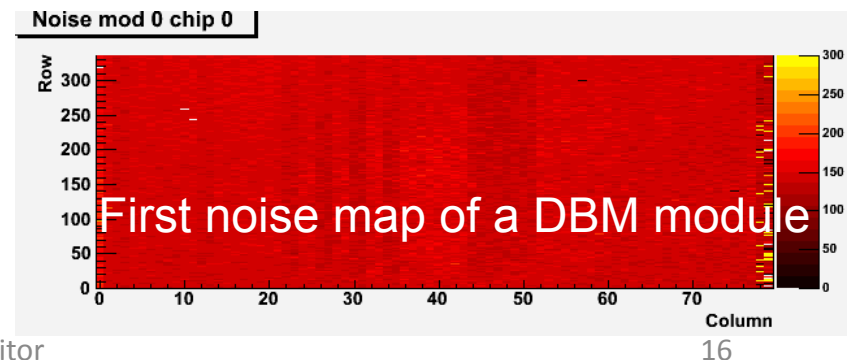
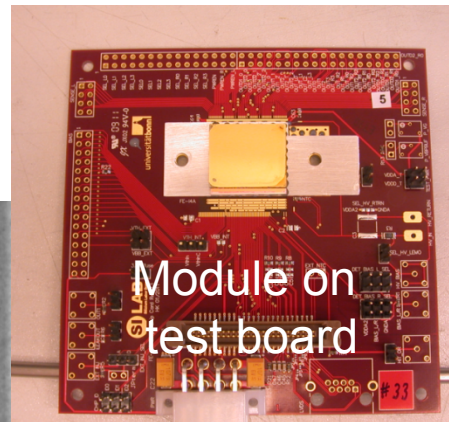
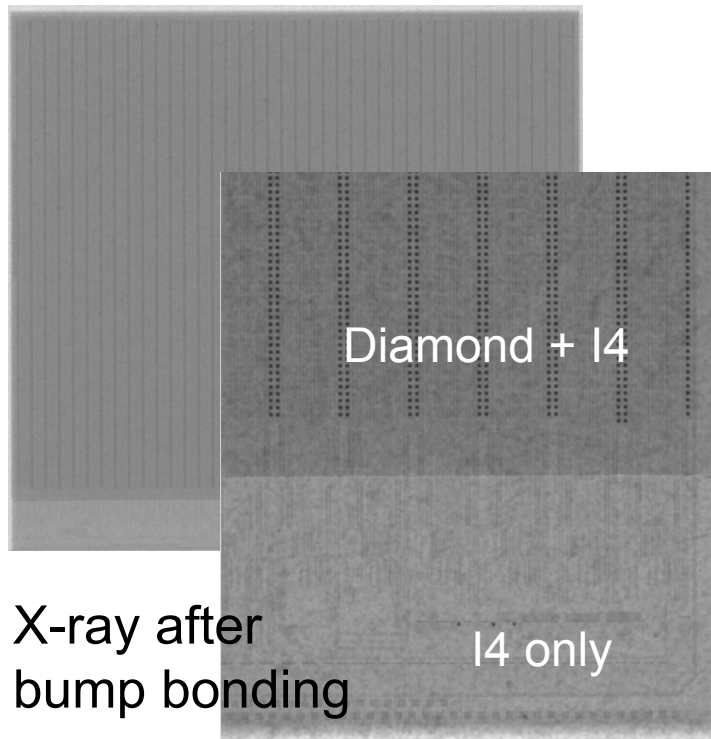


First four DBM modules

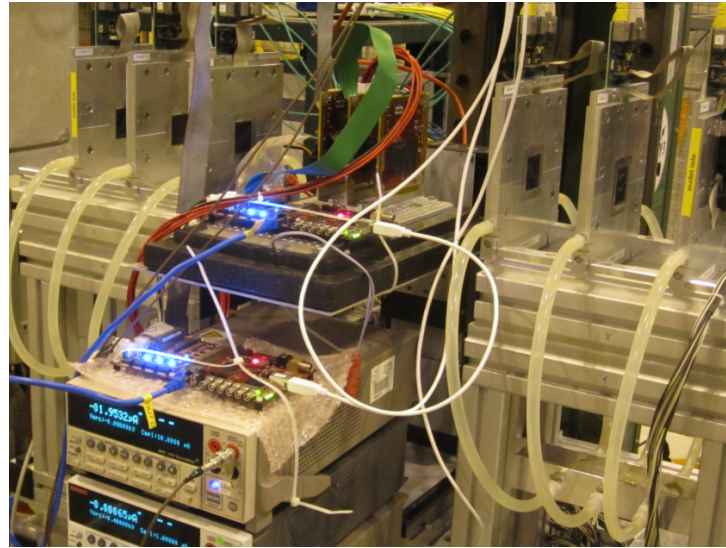
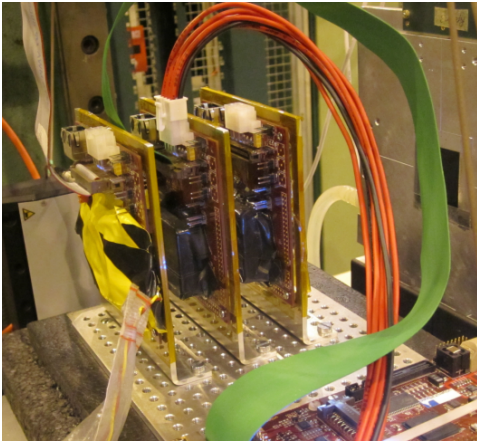
- Four DBM modules built at IZM
 - 21x18 mm² pCVD from DDL
 - FE-I4 ATLAS IBL pixel chip
 - 336x80 = 26880 channels, 50x250 μm²
- Largest ASIC/diamond flip chip assembly



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



DBM: Module Testbeam Studies



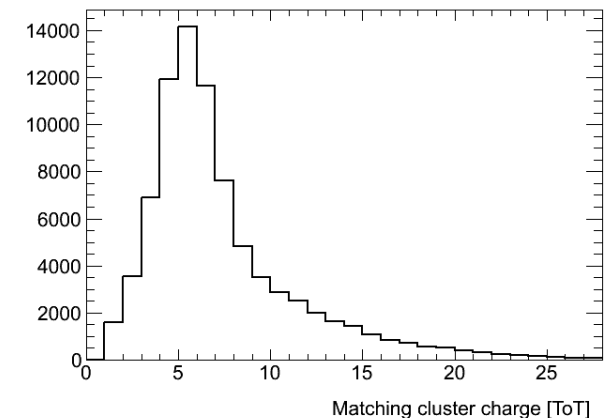
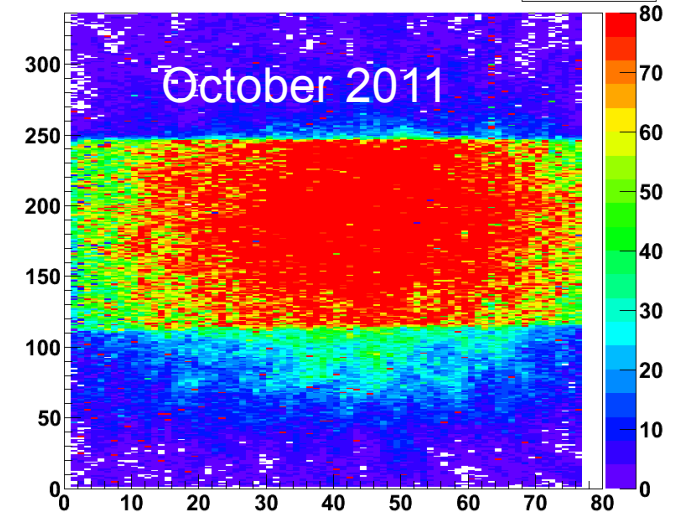
- Three Testbeam campaigns
 - July, late August, October
- Learning about FE-I4 performance
 - Calibration/tuning for low thresholds unique to diamond
 - Achieved 1000 e threshold (needed for irradiated silicon)
- Use testbeam data to tune charge model

Diamond Beam Monitor

Run1394 1000e Threshold

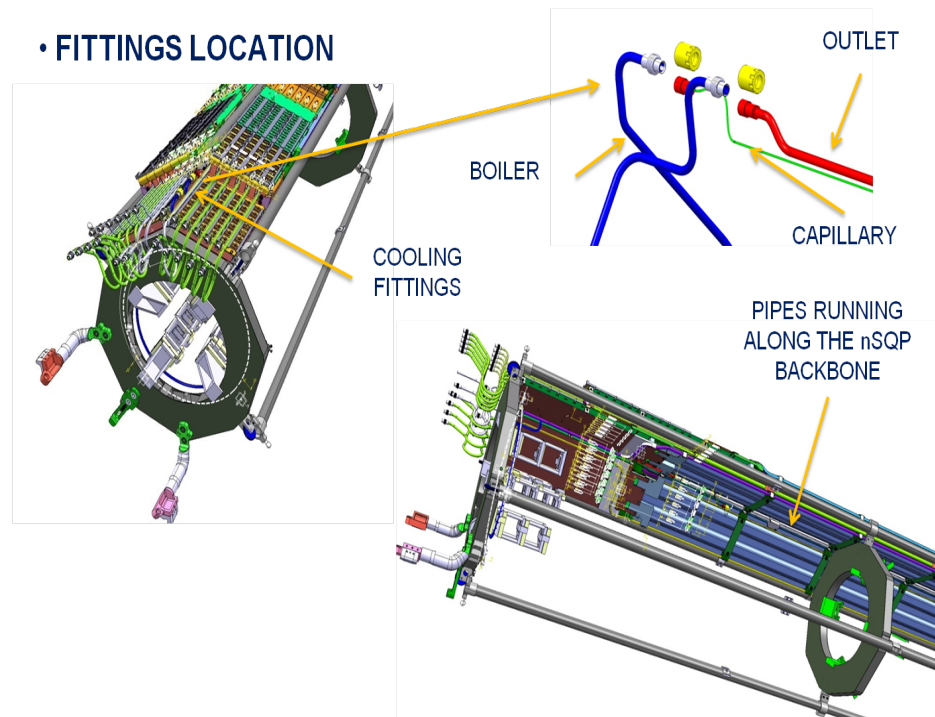
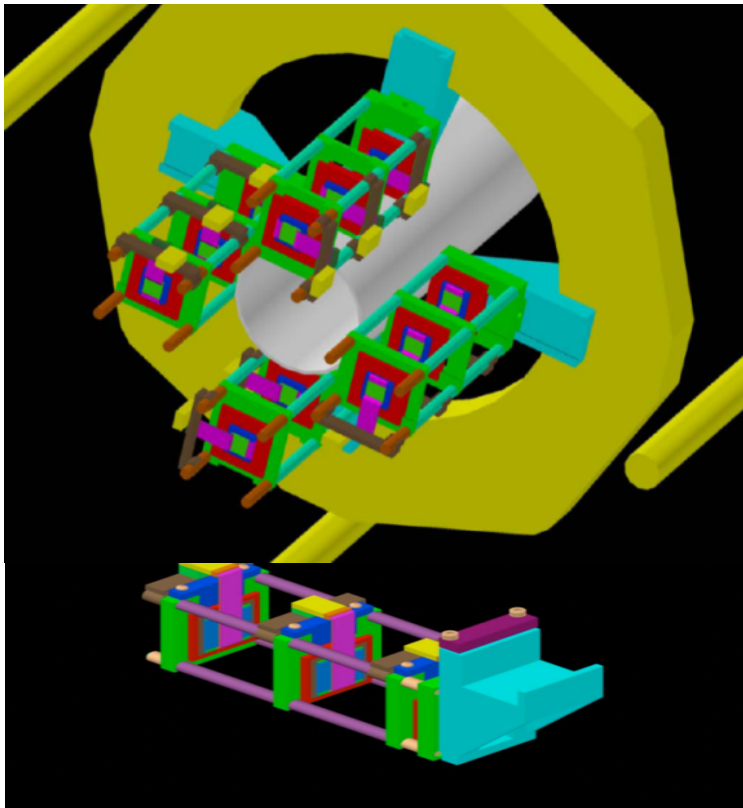
USBPIXI4 1 Raw Hitmap

h_hitmap_USBPIXI4_1
Entries 1.096786e+007



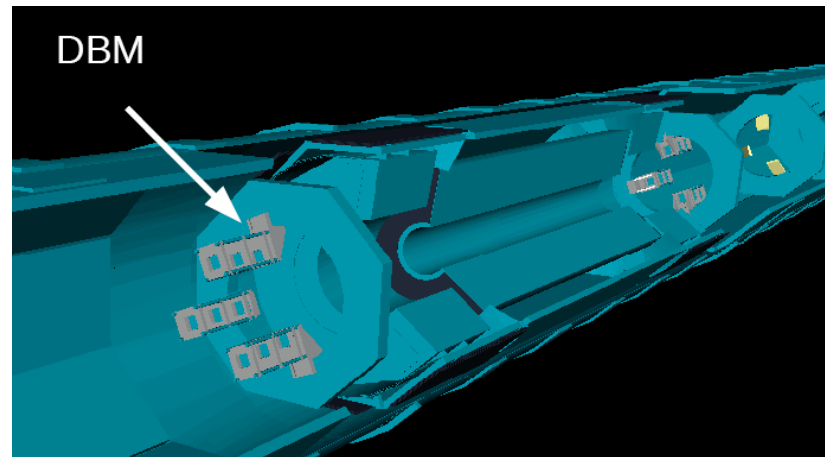
DBM: Support Mechanics

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

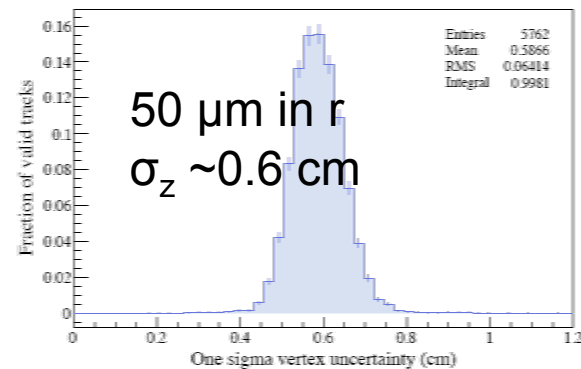
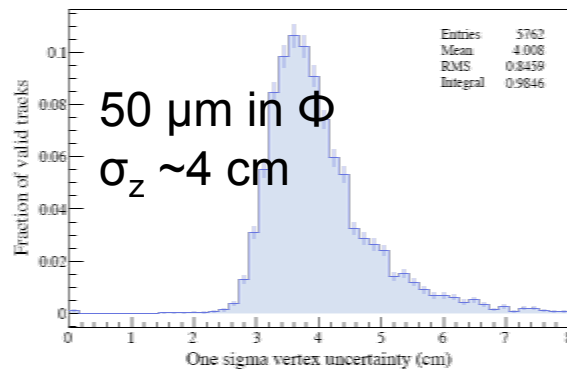


DBM: Simulation/Reconstruction

- Full GEANT model available



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



DBM: Simulation/Reconstruction



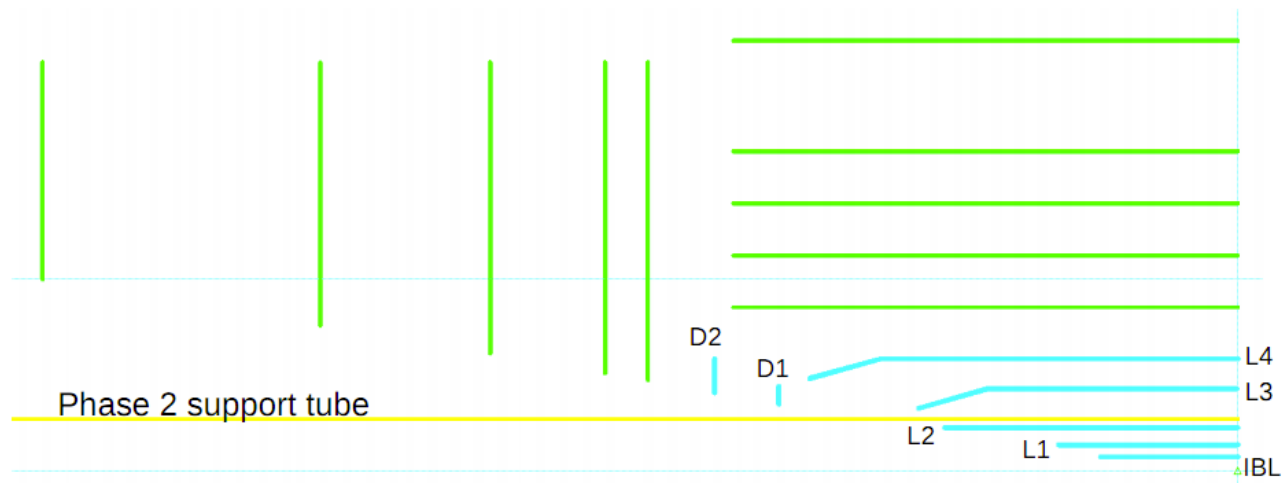
Diamond Beam Monitor

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?

	Diamond Pixel Modules for the High Luminosity ATLAS Inner Detector Upgrade		
ATLAS Upgrade Document No:	Institute Document No.	Created: 11/05/2007 Modified:	Page: 1 of 12 Rev. No.: 1.0
Abstract <i>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 1.8×10^{16} p/cm². 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 .</i> Contact Person: Marko Mikuz (marko.mikuz@cern.ch)			
Prepared by: H. Kagan (Ohio State University) M. Mikuz (Jožef Stefan Institute, Ljubljana) W. Trischuk (University of Toronto)	Checked by:	Approved by:	

Pixel Diamond Prototypes

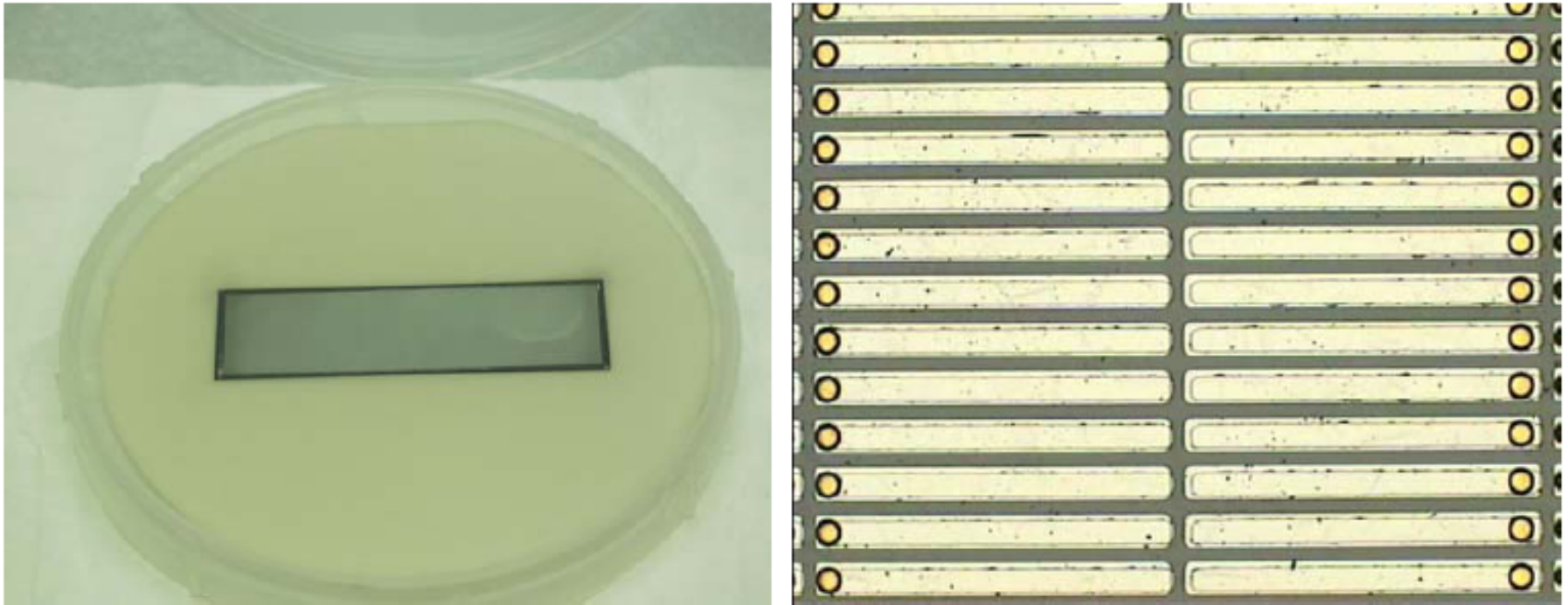


Figure 5: (a) Photograph of the ATLAS pixel diamond mounted in the carrier ready for bump bonding. (b) Zoom view of the pixel pattern after the under-bump metal is deposited.

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

Diamond Pixel Prototypes

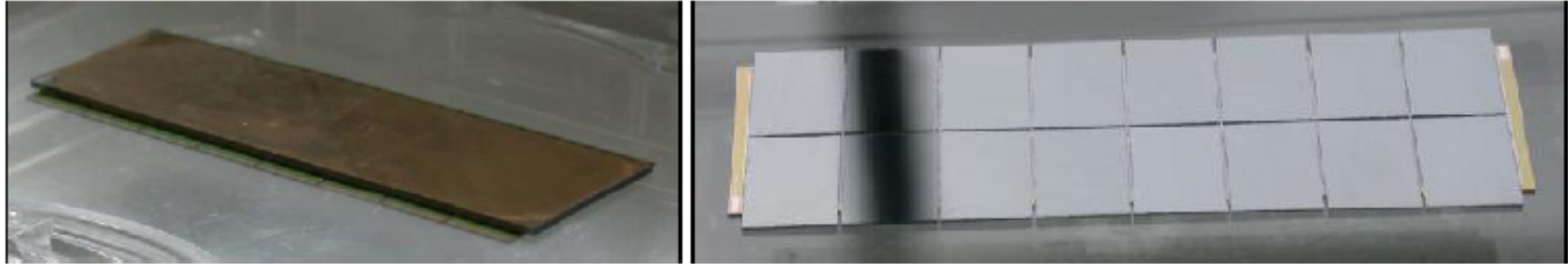


Figure 6: Photograph of the detector side (a) and electronics side (b) of the final ATLAS pixel module.

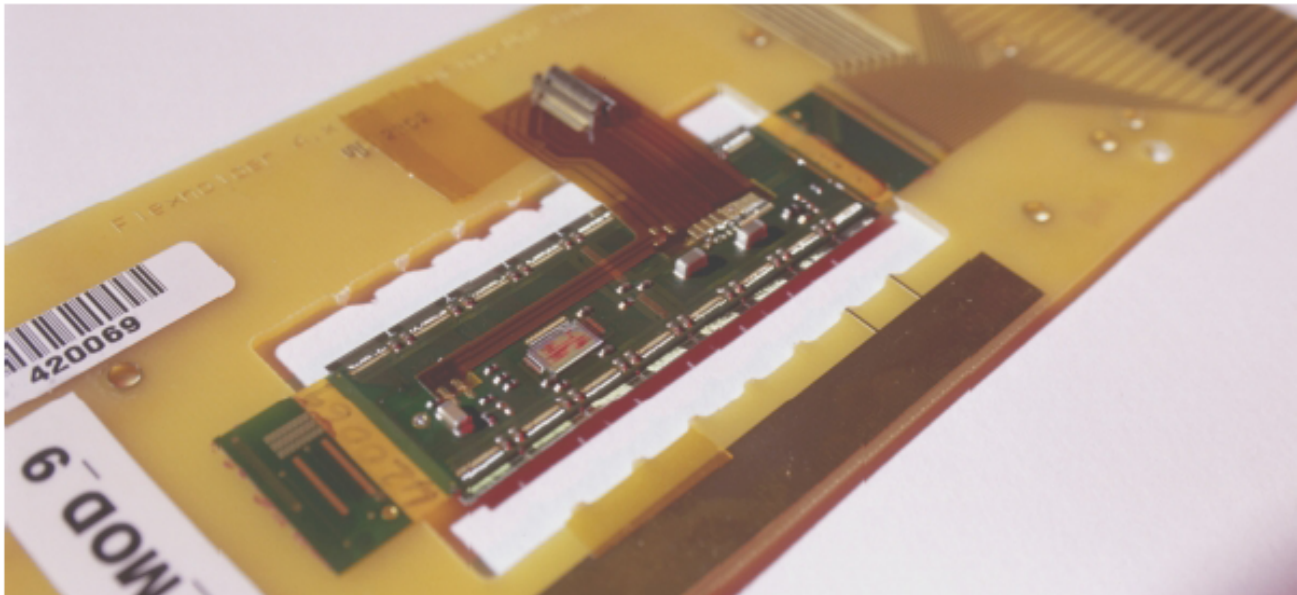
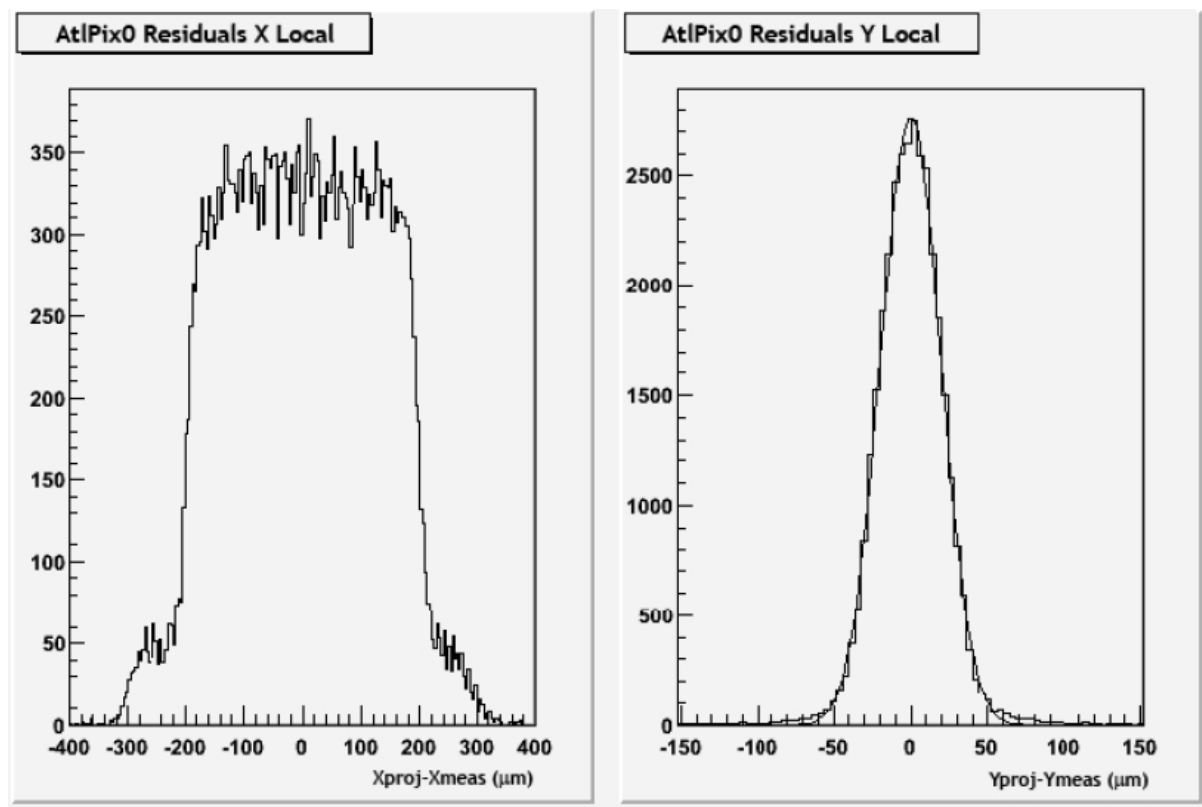


Figure 7: Photograph of the fully dressed diamond ATLAS Pixel Module ready for test.

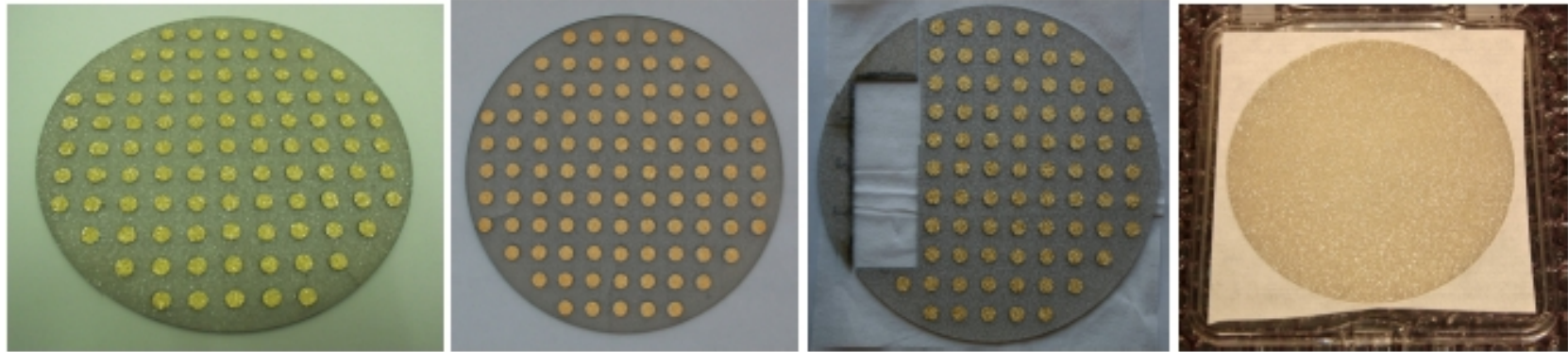
- Modules bump-bonded at IZM, tested at Bonn
- Noise: $140e^-$, Efficient threshold: $1500e^-$, In-time threshold: $2300e^-$

Results from Pixel Prototypes



- Position resolution of $14\mu\text{m}$ ($17\mu\text{m}$ residual includes telescope)
- Few % missing bonds – dominant inefficiency

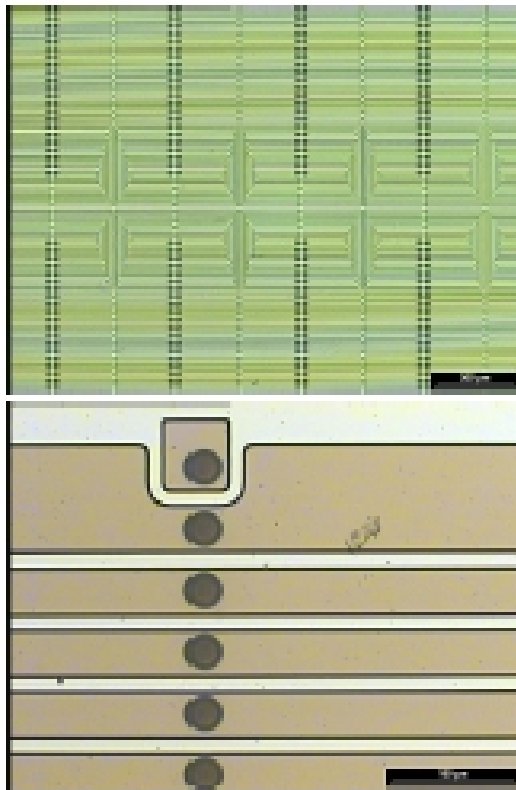
Mass Production of Diamond Wafers



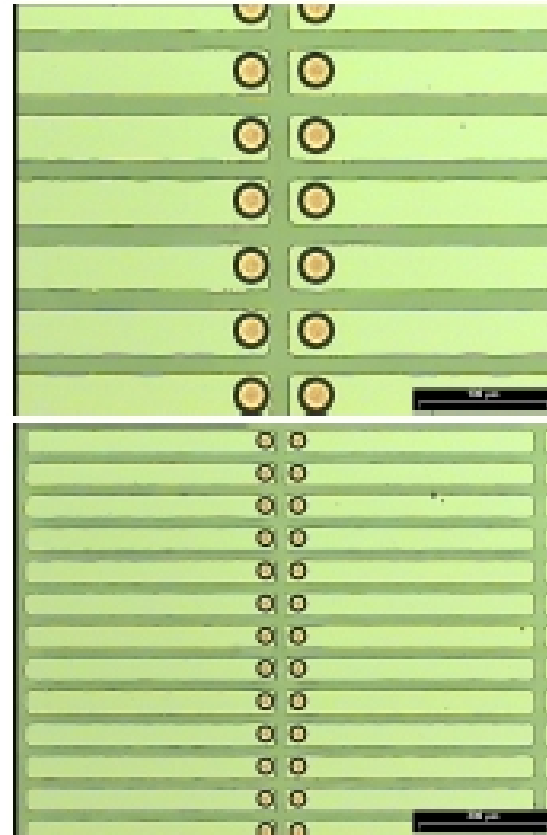
- Diamond manufacturer(s) deliver wafers
- We do a coarse scan for quality (signal size)
- Are allowed to specify sensor dicing locations
- Takes 2-3 months to turn around each wafer

Pixel Patterning in Industry (IZM-Berlin)

Diamond sensor pixel metallisation



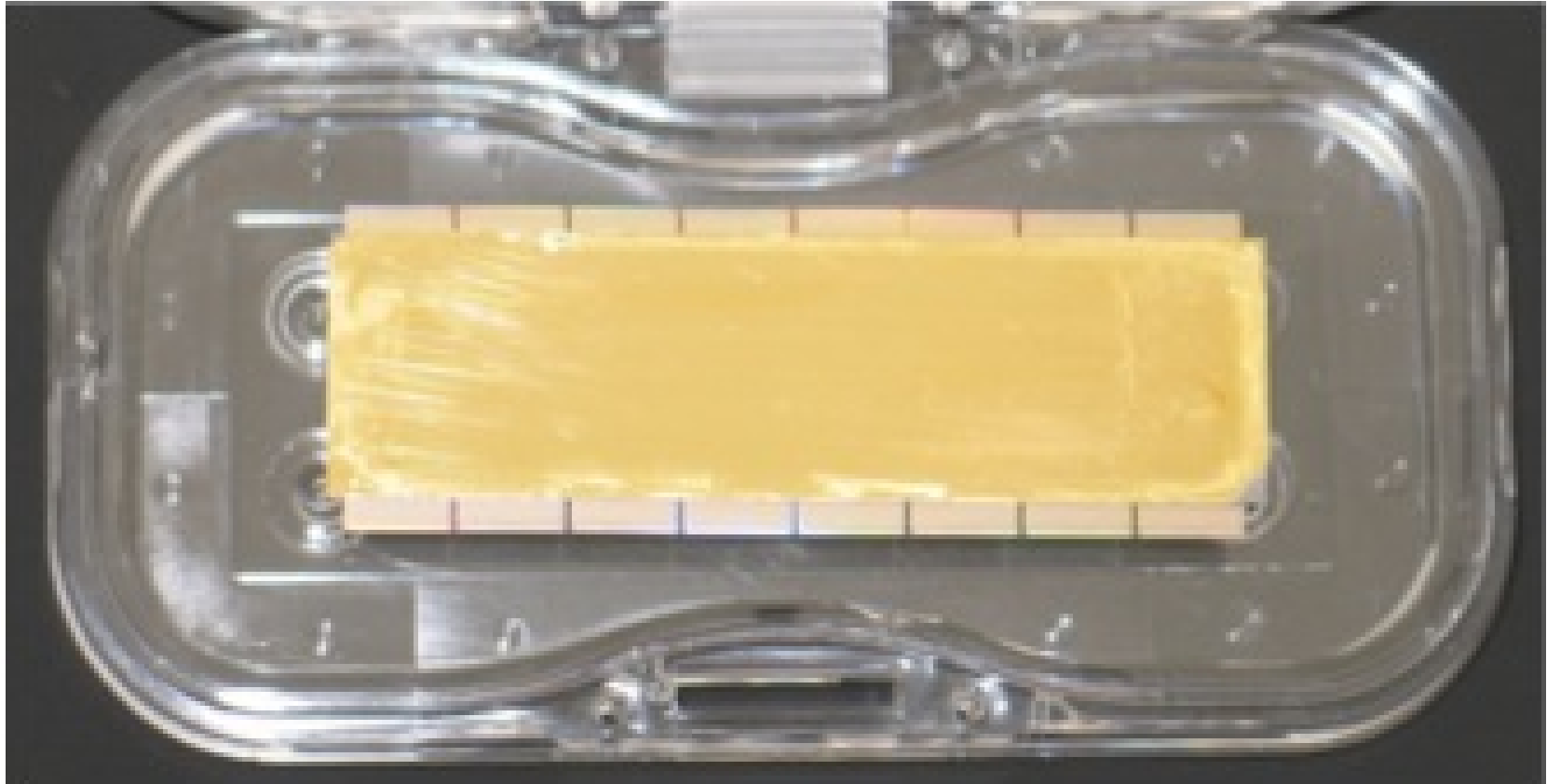
Status after electroplating of pad metallisation and lithography for pixel metallisation patterning



result after pixel metallisation patterning

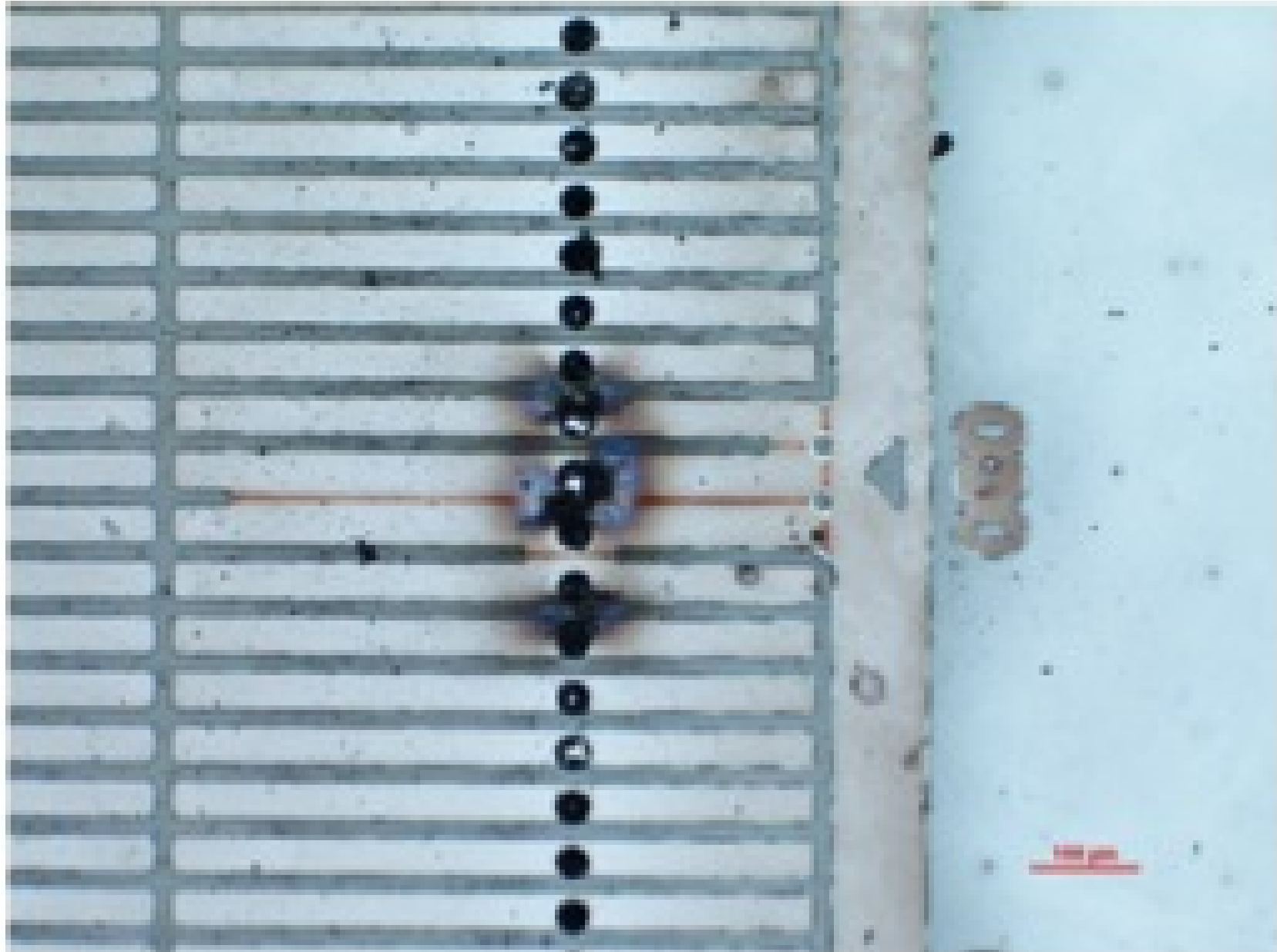


First IZM Module

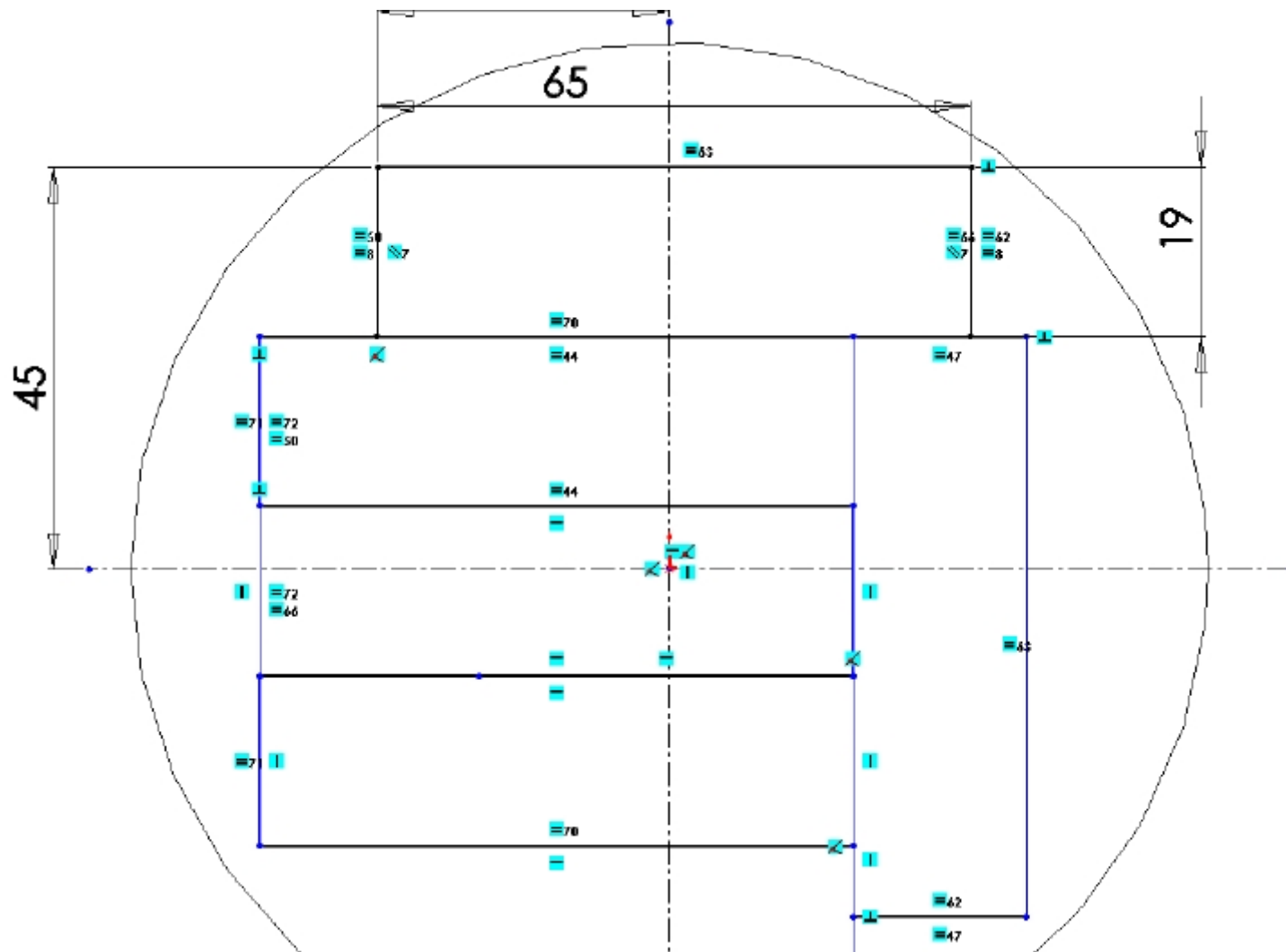


- Bump-bonded in January
- First tested at Bonn in February
- Hope to test in June testbeam at CERN

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 $5 \times 10^{15}/\text{cm}^2$
- 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