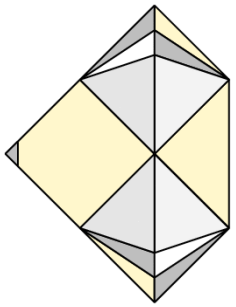
Diamonds for Present/Future LHC Applications

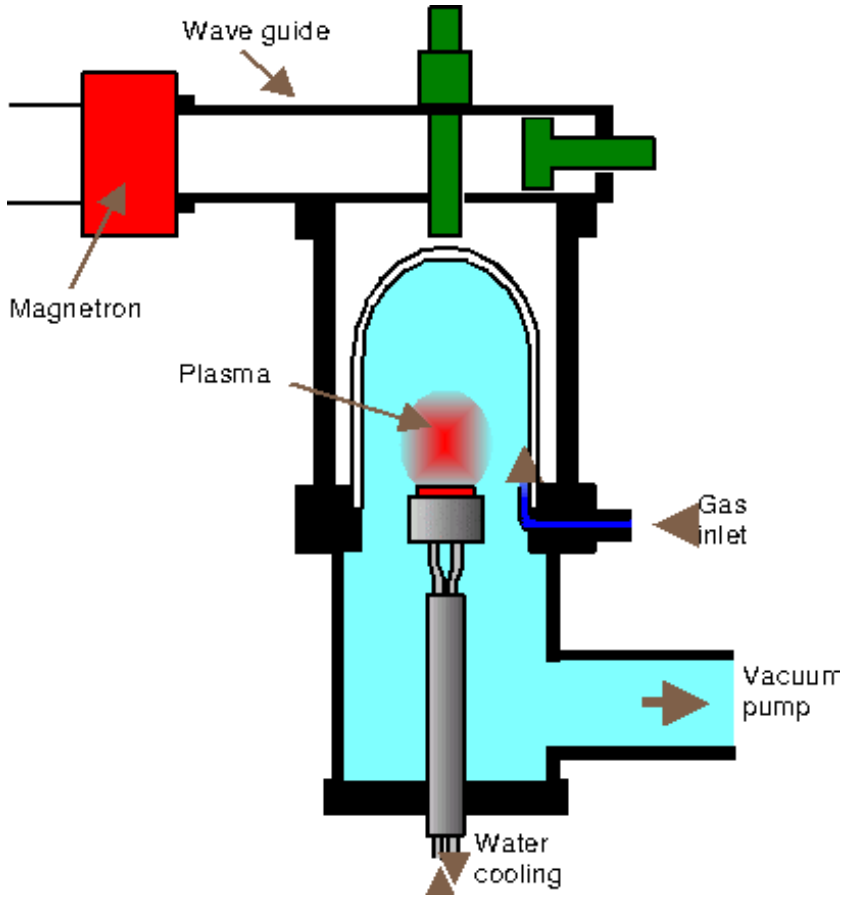
- How diamond works as a sensor material
  - Growth, Properties, Signal, Morphology, Manufacture
- Radiation tolerance of recent sensors
  - Tracker signals, irradiations, damage scaling
- Applications
  - CDF and ATLAS beam conditions monitors
  - The ATLAS pixel detector upgrade



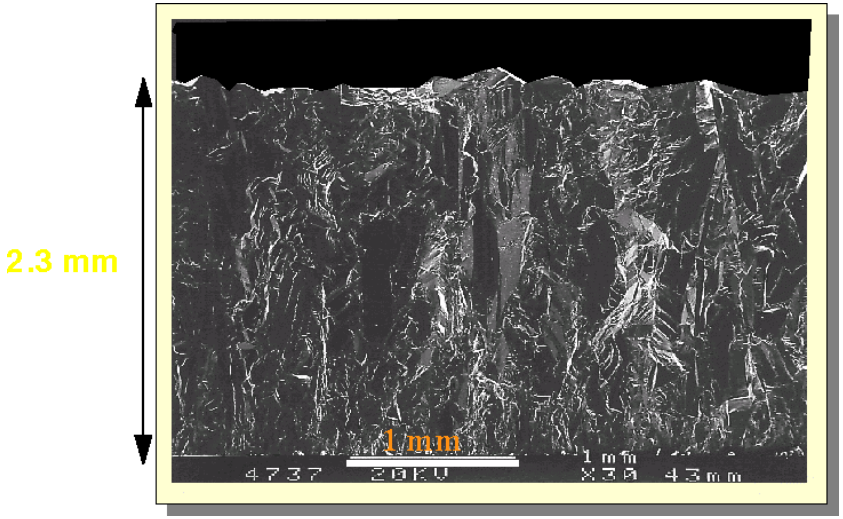
William Trischuk
University of Toronto
January 2014

CVD Diamond as a Particle Detector

- Microwave growth reactor



- Material copies substrate
- Dominant crystallites appear

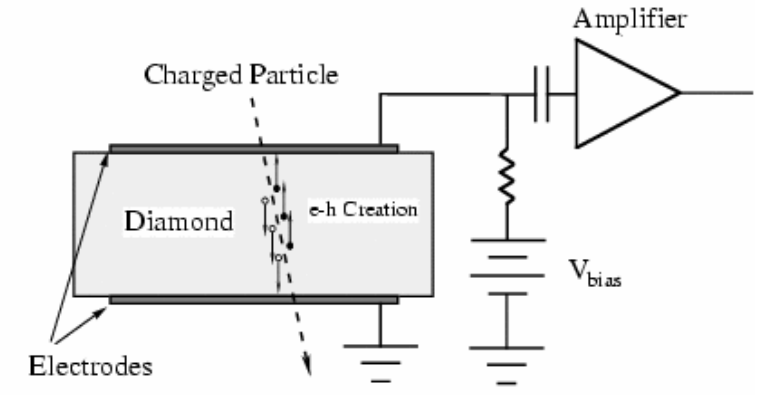


- Edge view of pCVD sample
  (Courtesy of Element6)

- Diamond synthesized from plasma

Signals from Diamond Sensors

- Image charge signal
  - induced on surface electrodes

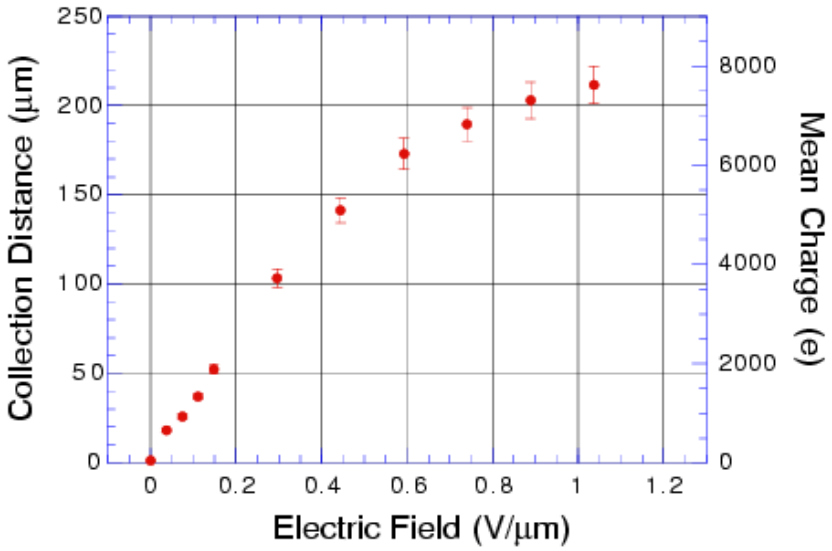


- Charge collected, Q

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

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

- d is the Charge Collection Distance

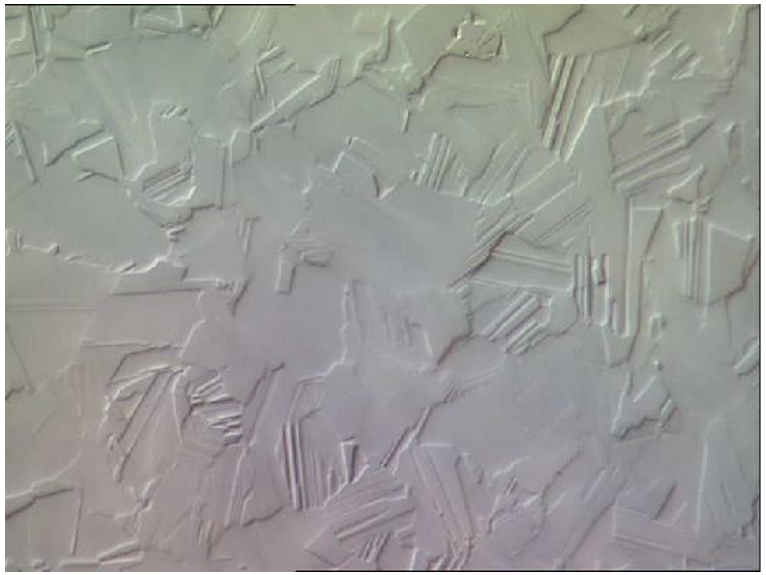


- Mobility saturates at $|\vec{E}| \approx 1V/\mu$m
- Operate typical sensor at 300-400 V

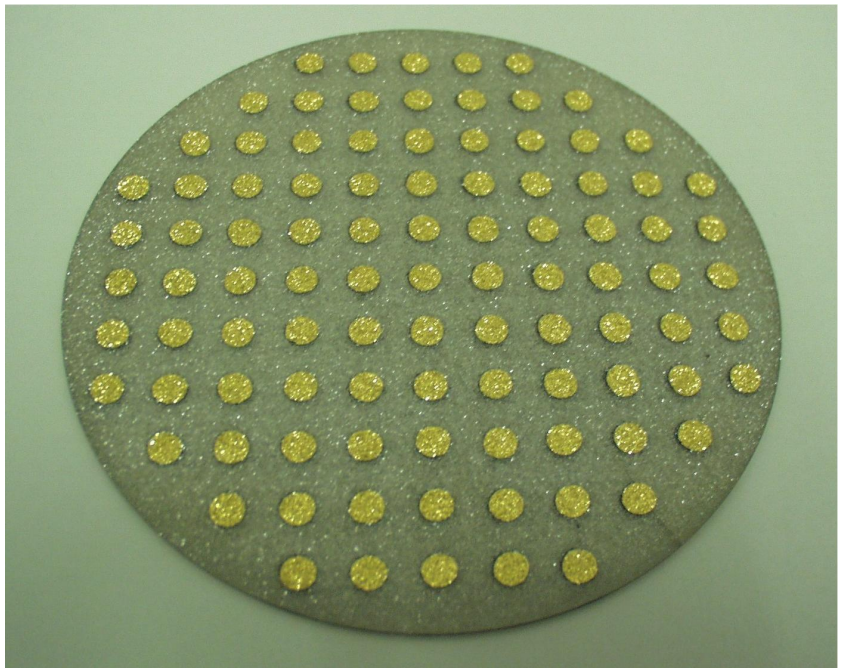
Properties of Diamond and Silicon

Property	Diamond	Silicon	
Band gap [eV]	5.5	1.12	
Breakdown field [V/cm]	10^7	$3x10^5$	
Intrinsic resistivity @ R.T. [Ω cm]	$> 10^{11}$	$2.3x10^5$	✪ Low leakage
Intrinsic carrier density [cm^{-3}]	$< 10^3$	$1.5x10^{10}$	
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



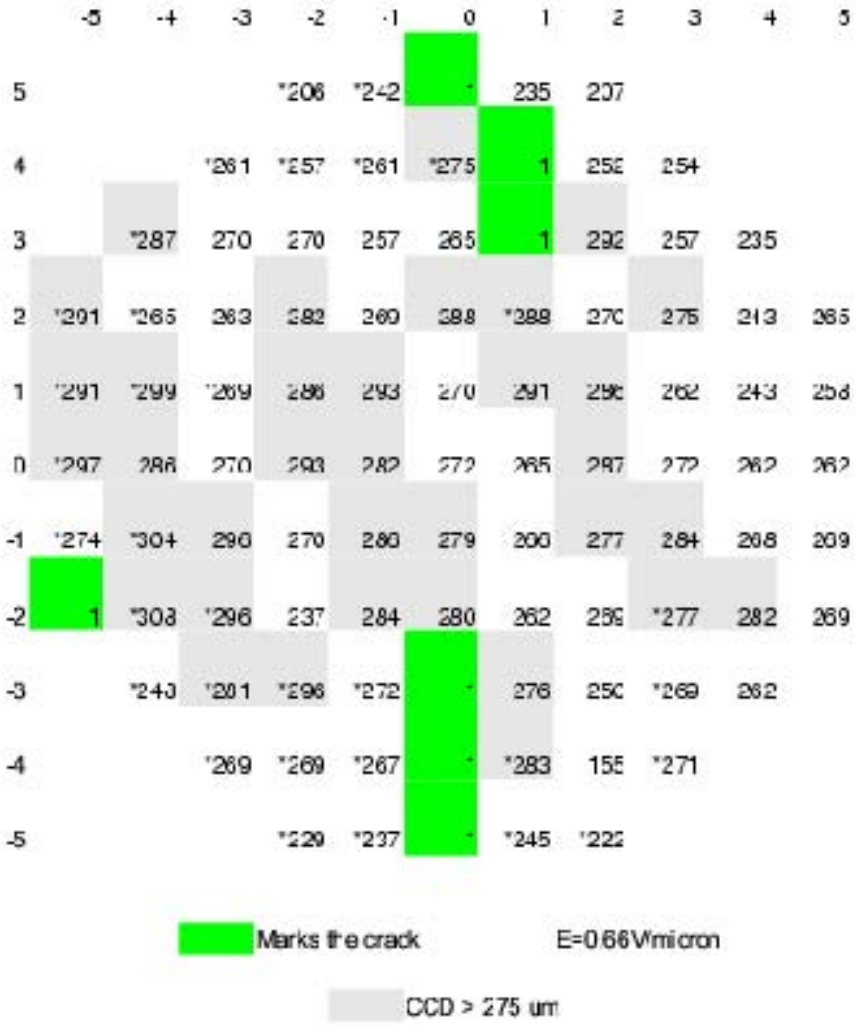
Surface image of pCVD sample
(Courtesy Element6)

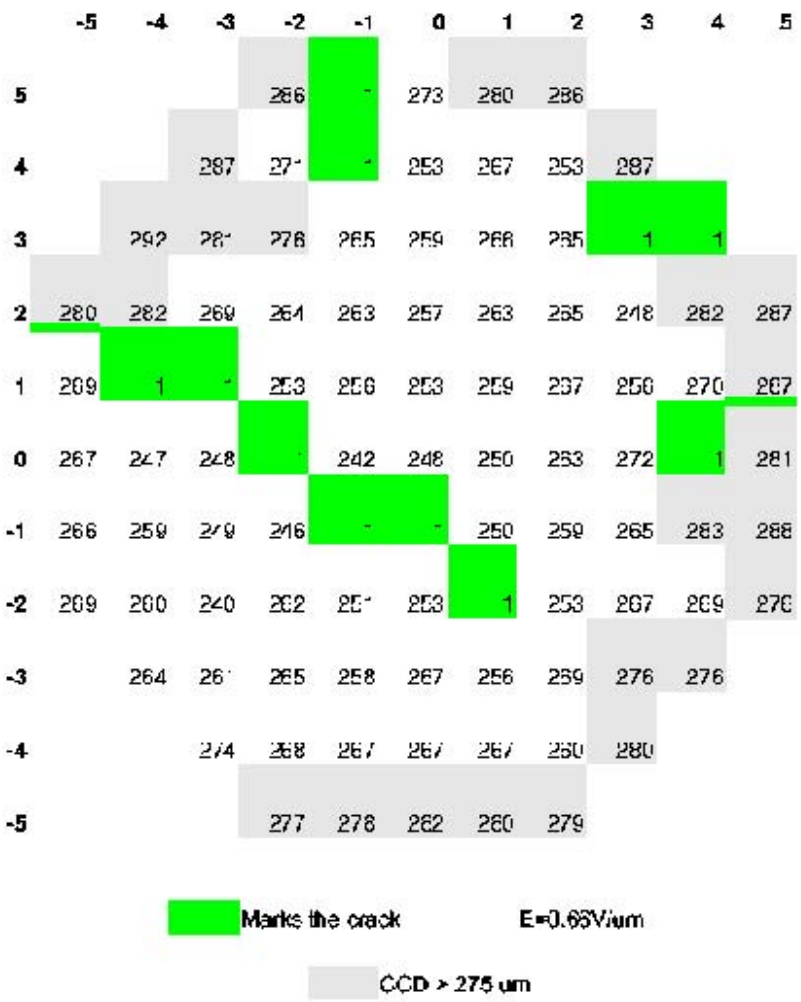


- pCVD diamond wafer
- Dots are on 1 cm grid

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

Surface Characterisation of Wafers

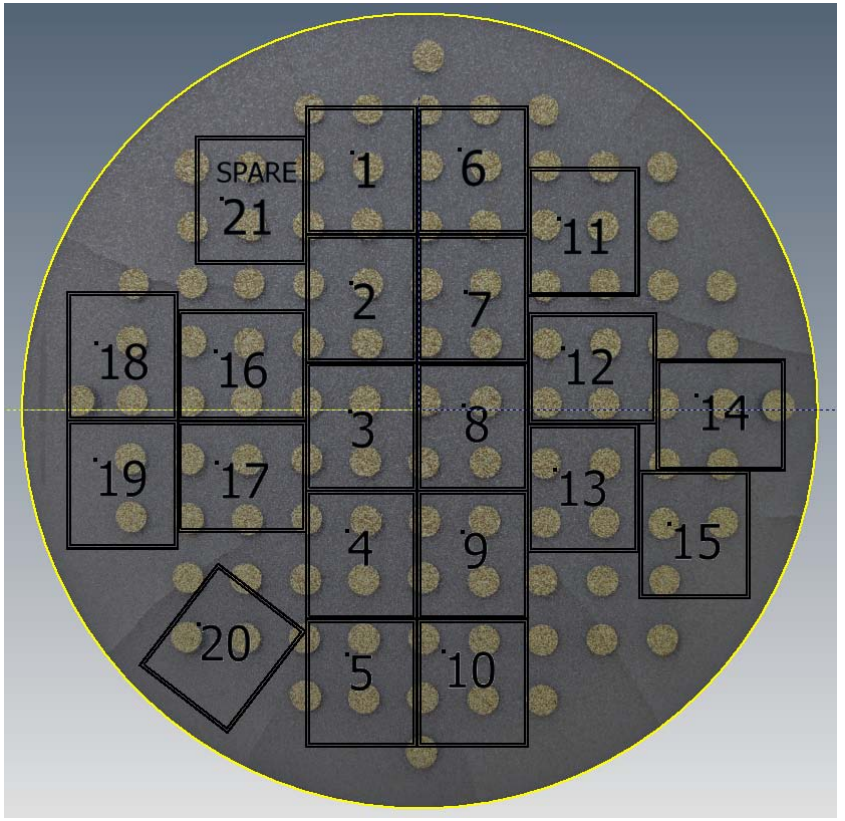




Wafers now have typically 250-300 μm collection distance

Additional Manufacturers

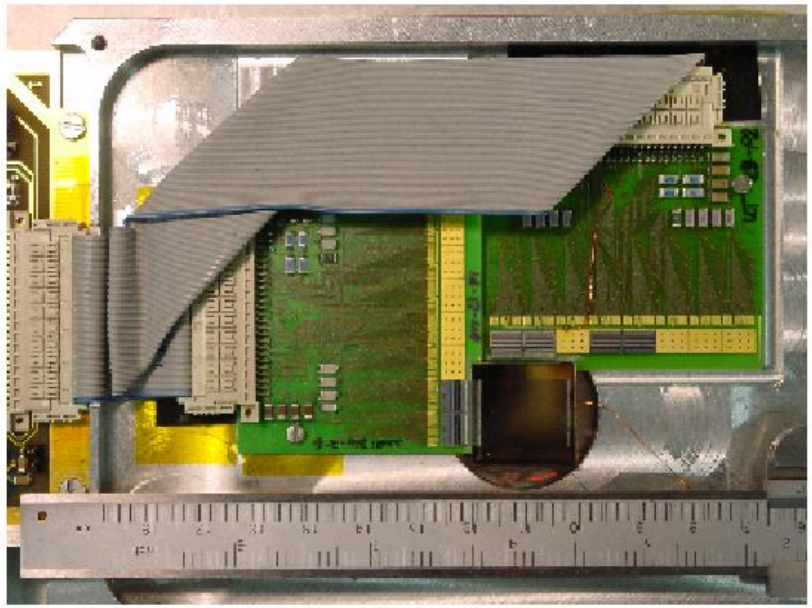




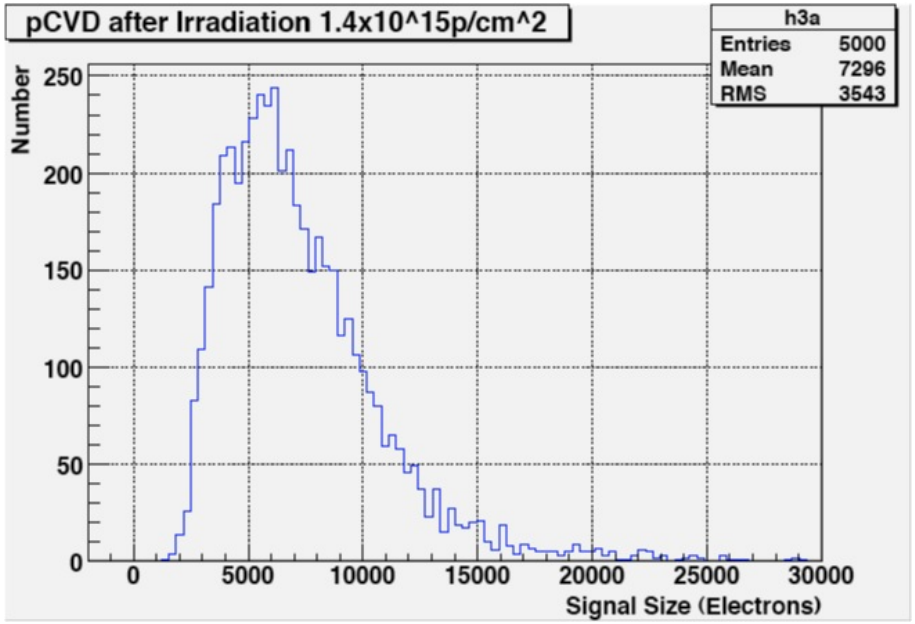
- American supplier (II-VI Inc) providing sensors for ATLAS upgrade
- RD42 working to qualify additional new vendors

Radiation Tolerance of Diamond Sensors

Typically tested as strip tracker



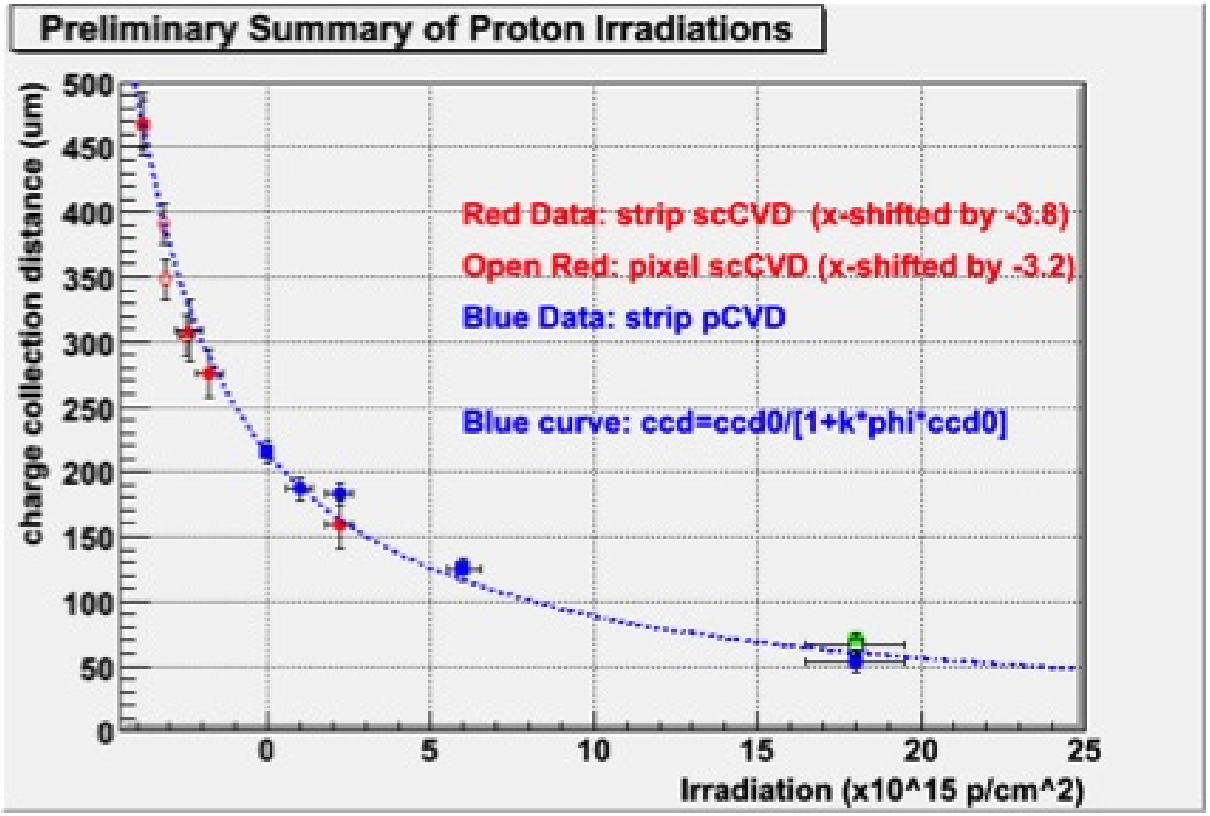
Pulse height from irradiated tracker



- 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

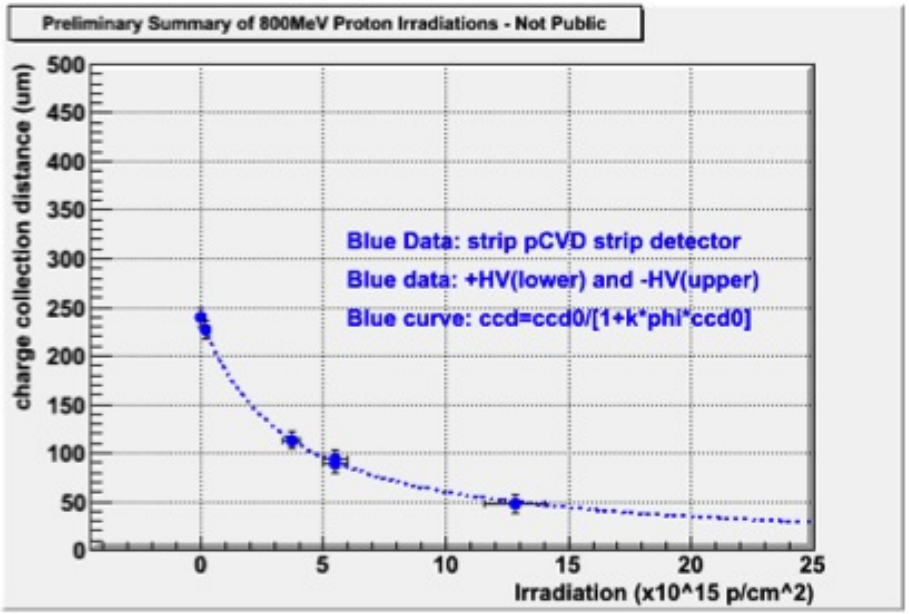
This pCVD material $\equiv$ scCVD material **after** $\approx 3.8 \times 10^{15}$ p/cm^2

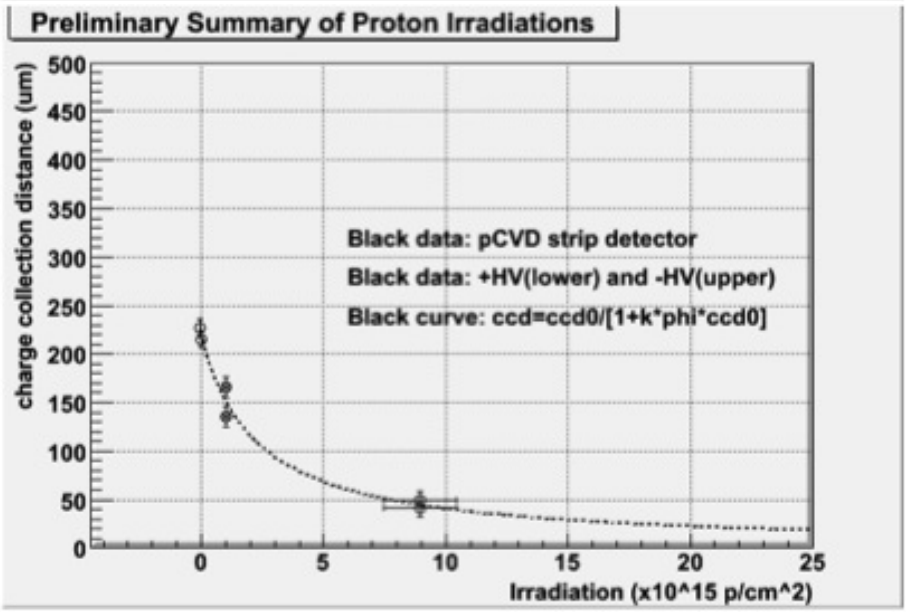
- pCVD and scCVD follow same damage curve:

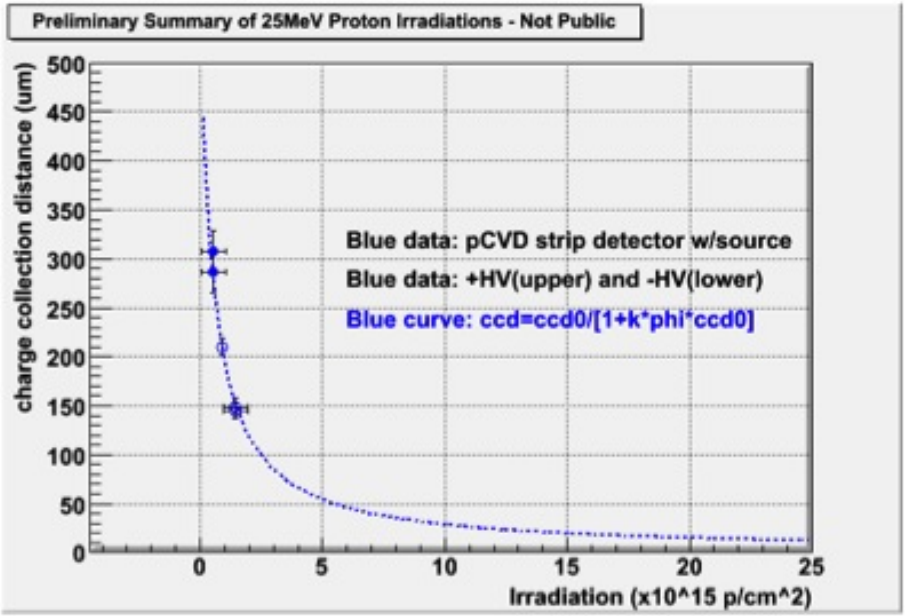
$$1/\mathrm{d} = 1/\mathrm{d}_0 + k\phi$$

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

Irradiations with Lower Energy Protons





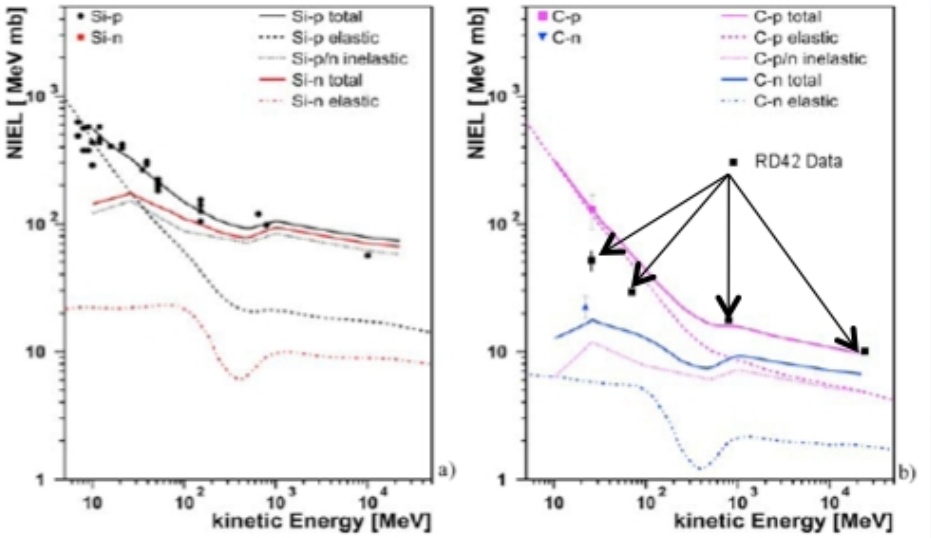


- 800 MeV protons (Los Alamos):
  1.9 times 24 GeV protons
- 70 MeV protons (Sendai):
  2.9 times 24 GeV protons
- 25 MeV protons (Karlsruhe):
  4.7 times 24 GeV protons

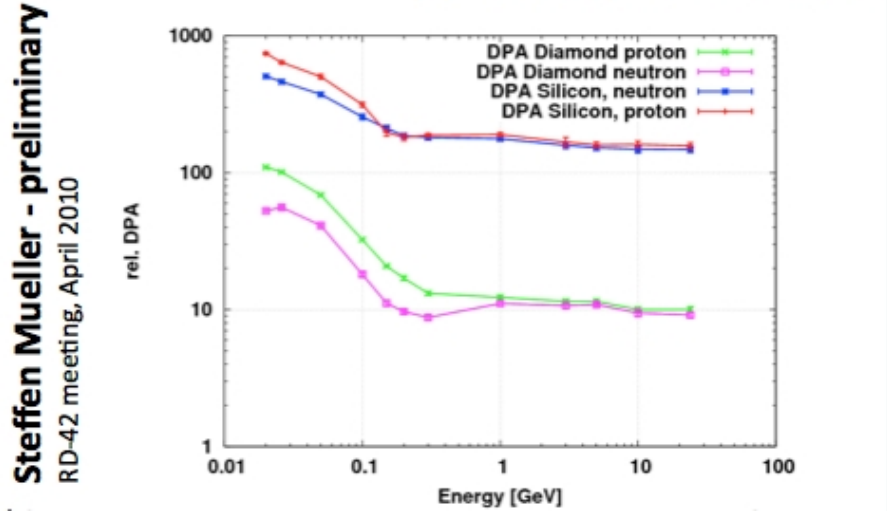
Interpreting Radiation Damage

- 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

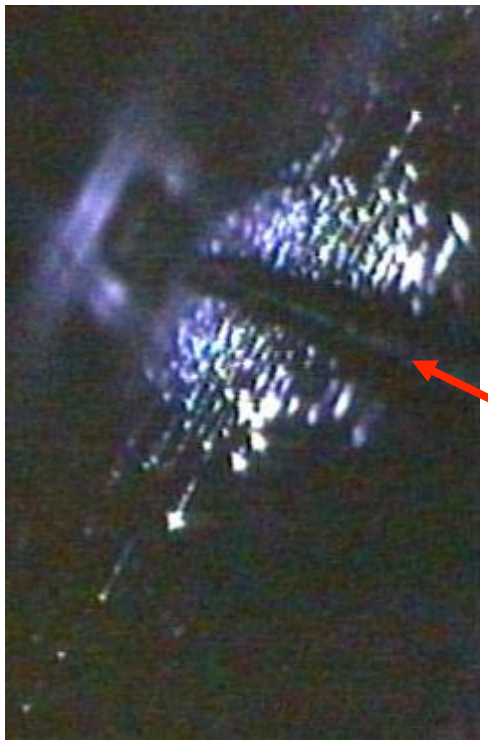


Applications of Diamond Sensors

- 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 telescope (DBM) installed in ATLAS
- All LHC experiments using CVD-diamond beam monitor systems
- Several considering diamond sensors for tracker upgrades

The Beam Conditions Monitor Mission

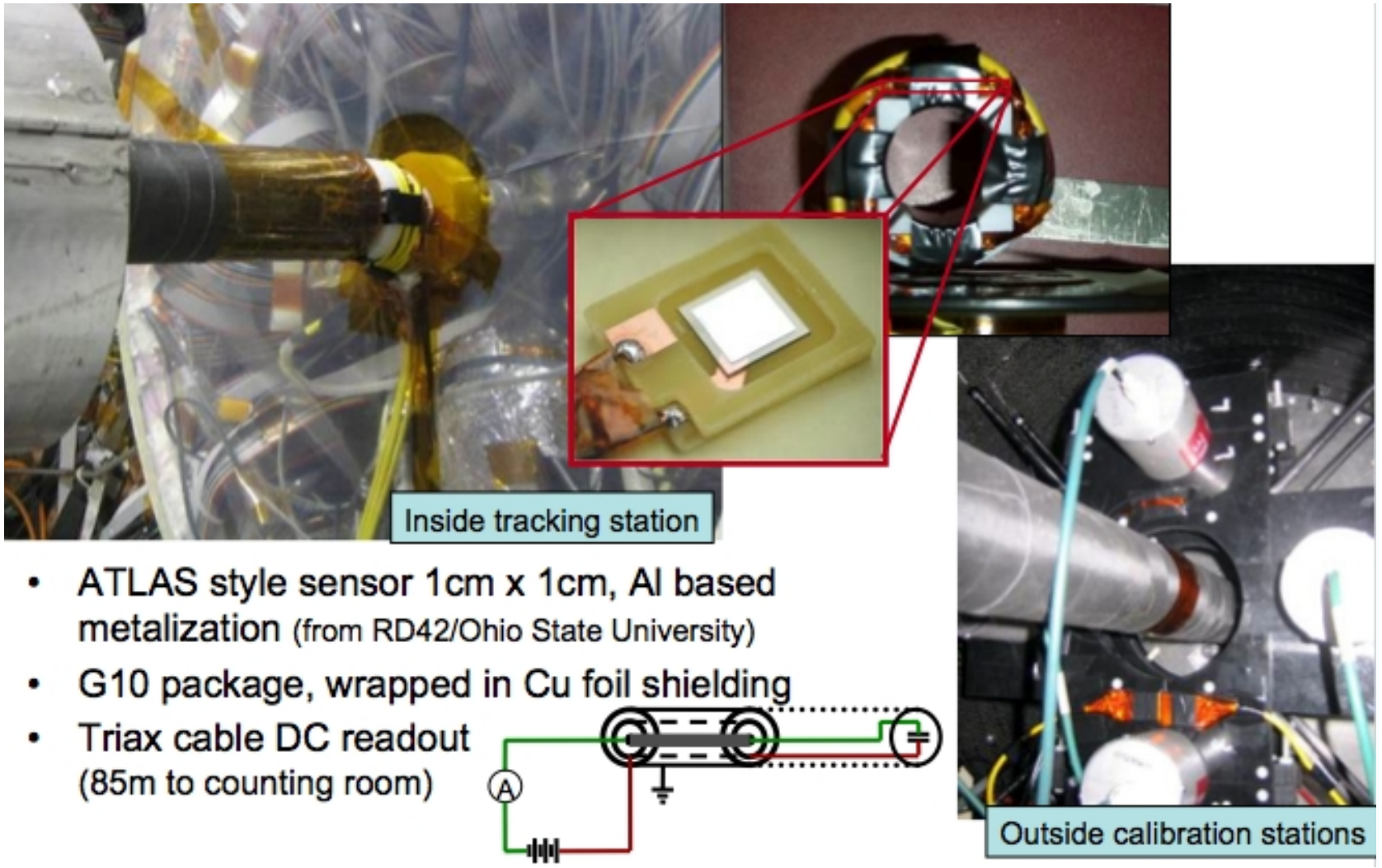
- Primary goal: Protect ATLAS and the LHC machine
  - Tevatron beam ~10 MJ (bus at 120 km/h)
  - LHC beam ~1.4 GJ (an A380 at takeoff)



A 1m long melted stretch of Tevatron collimator

- 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

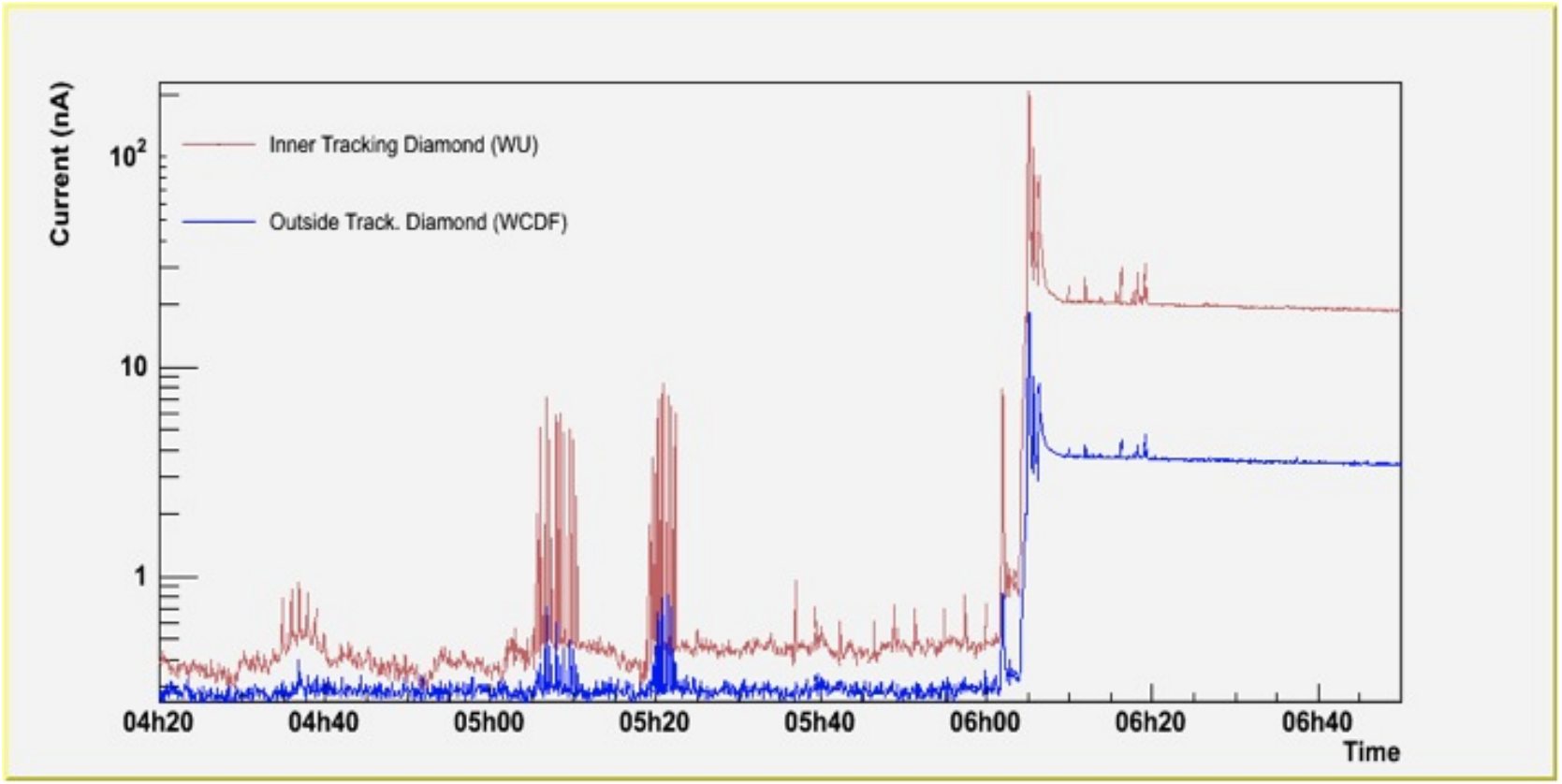
pCVD Diamond Sensors in CDF



- 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)

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

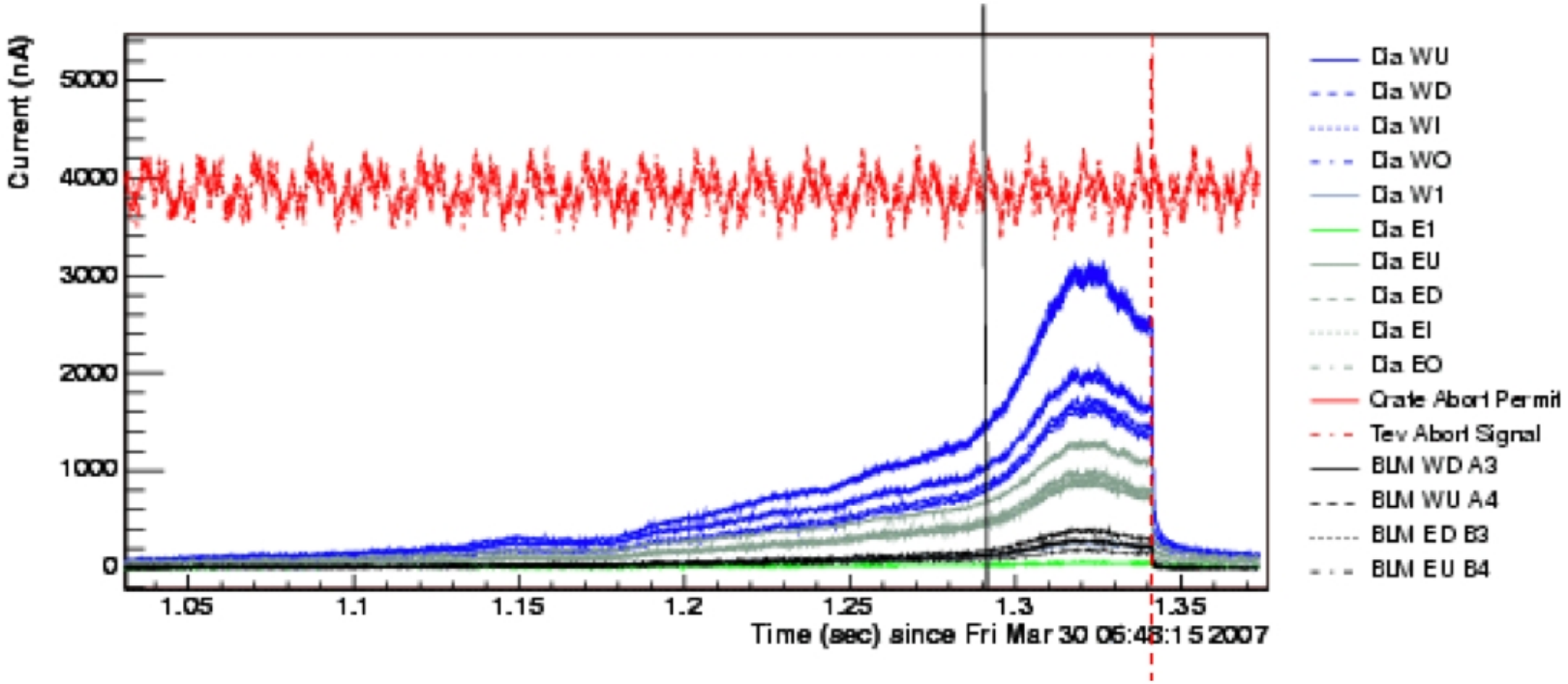
Sensitivity to Tevatron 'events'



- 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

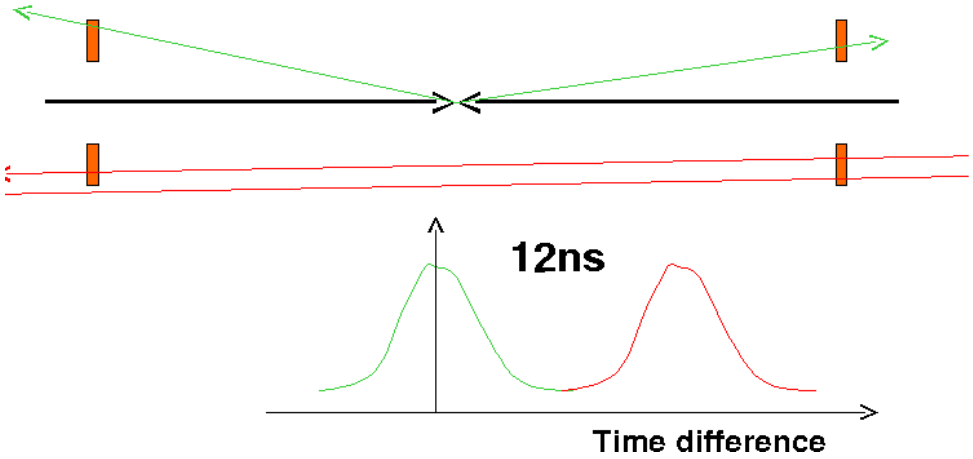
- During 11-month monitoring phase (2006)
  - Tuned diamond abort algorithm
  - Observed four aborts that diamond could have triggered sooner



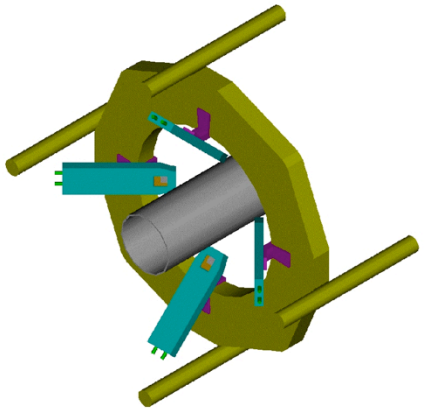
- Was the primary CDF abort system for the last 4 years of Run II
- Post-operation assessment shows no degradation of sensors

The ATLAS Beam Conditions Monitor

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

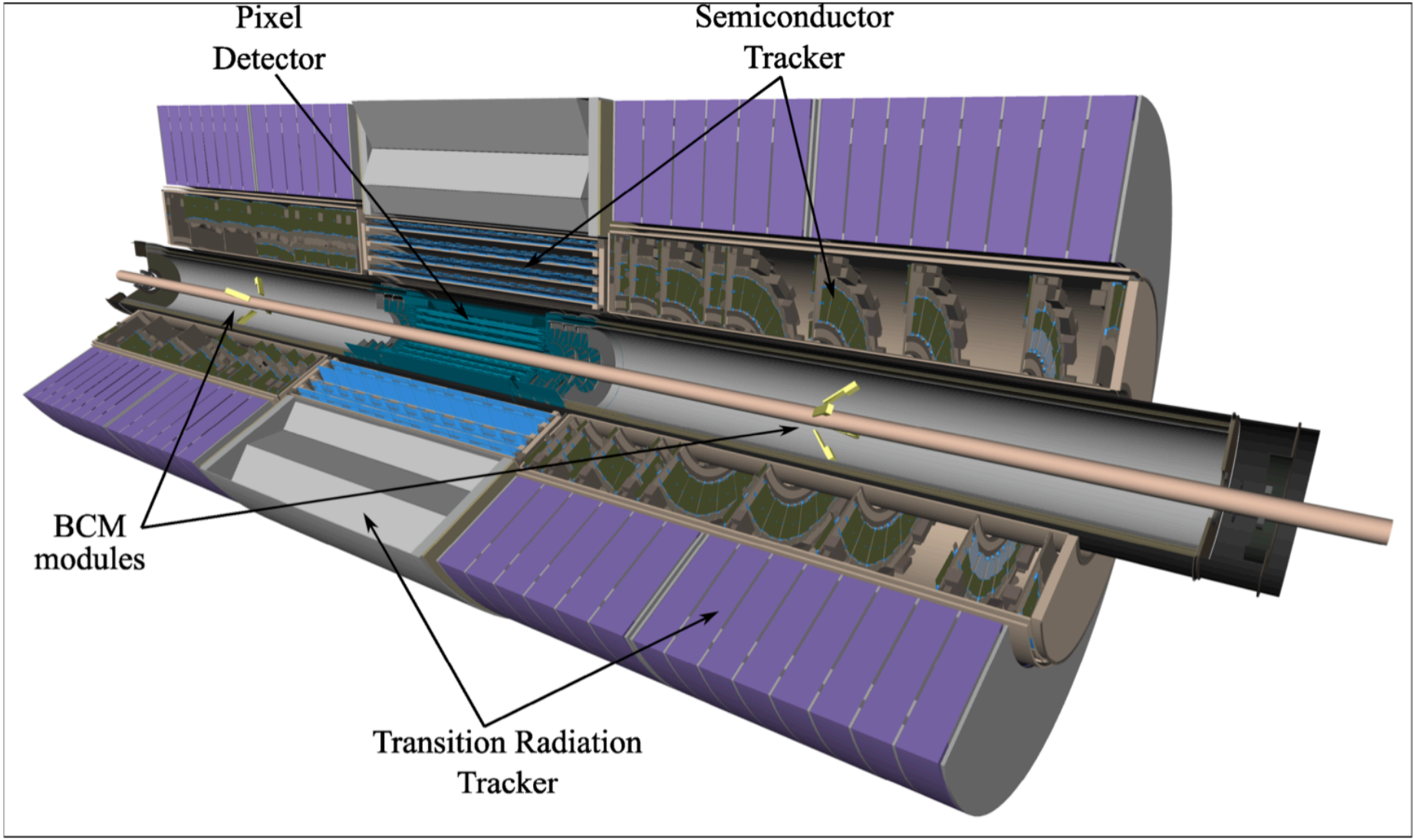


- 4m separation gives 12ns time-of-flight: optimal
- Pixel space-frame support at ± 1.9m

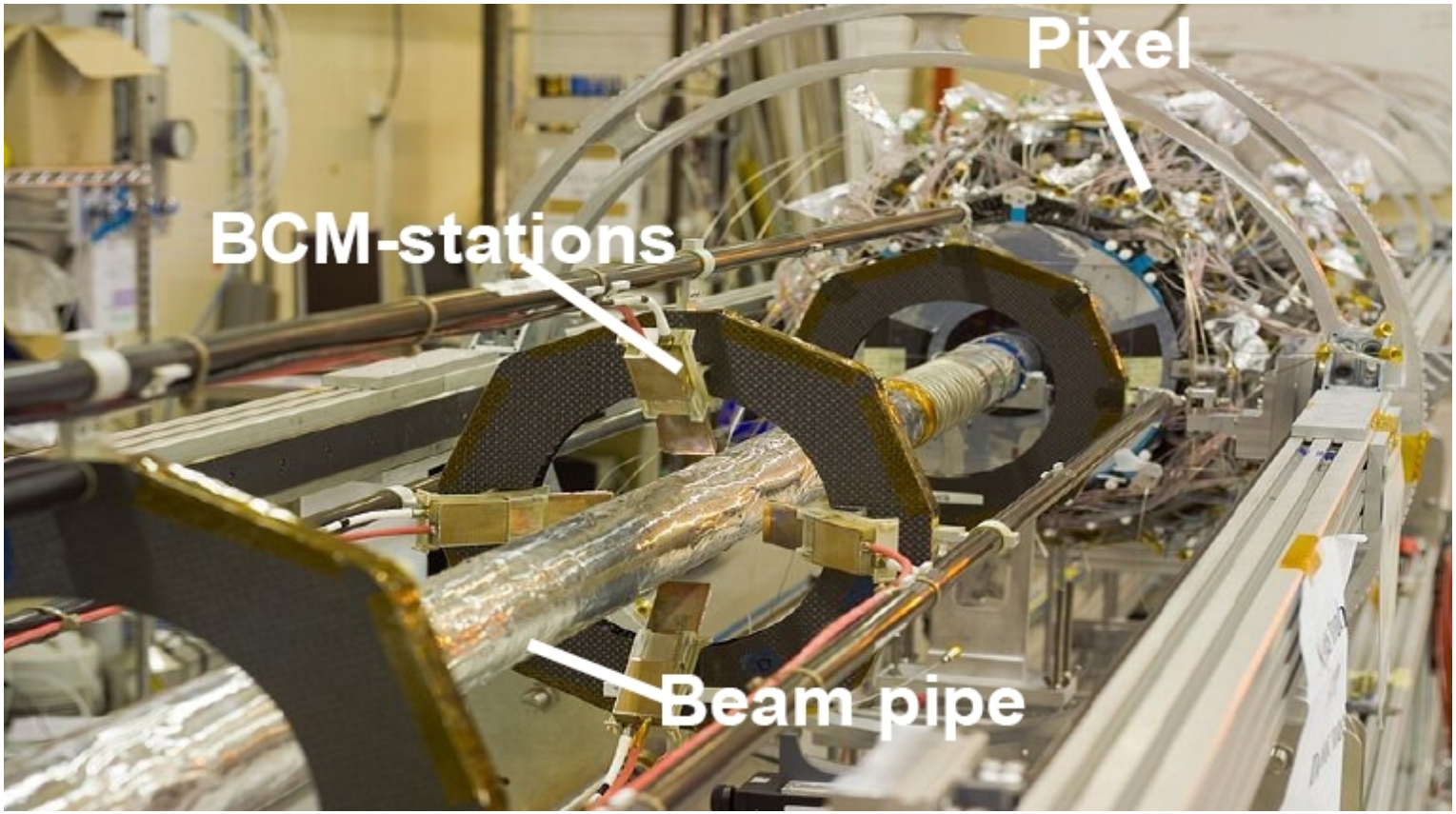


- Use CVD diamond sensors
  - 10x faster signals and 10x more radiation tolerant than silicon
- Use GaAs amplifiers with 1ns rise-time, 5ns baseline restoration

The BCM in ATLAS



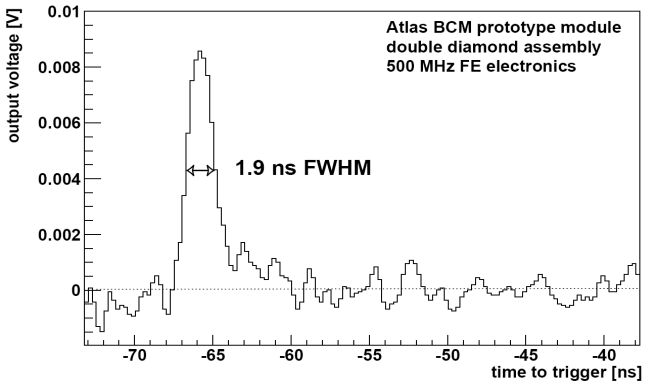
The BCM Installation

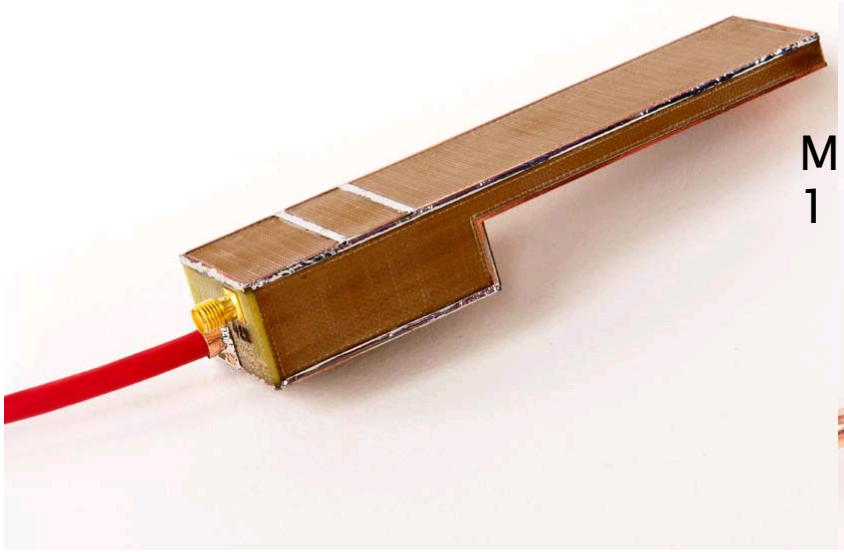


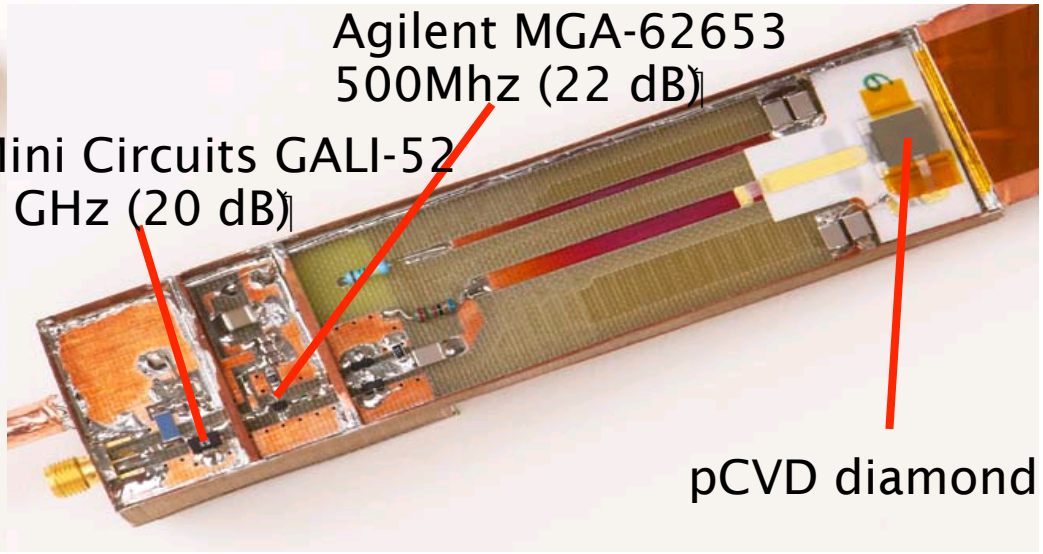
- Half of BCM modules on ATLAS Pixel support frame
- BCM module support mechanics designed in Toronto

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)

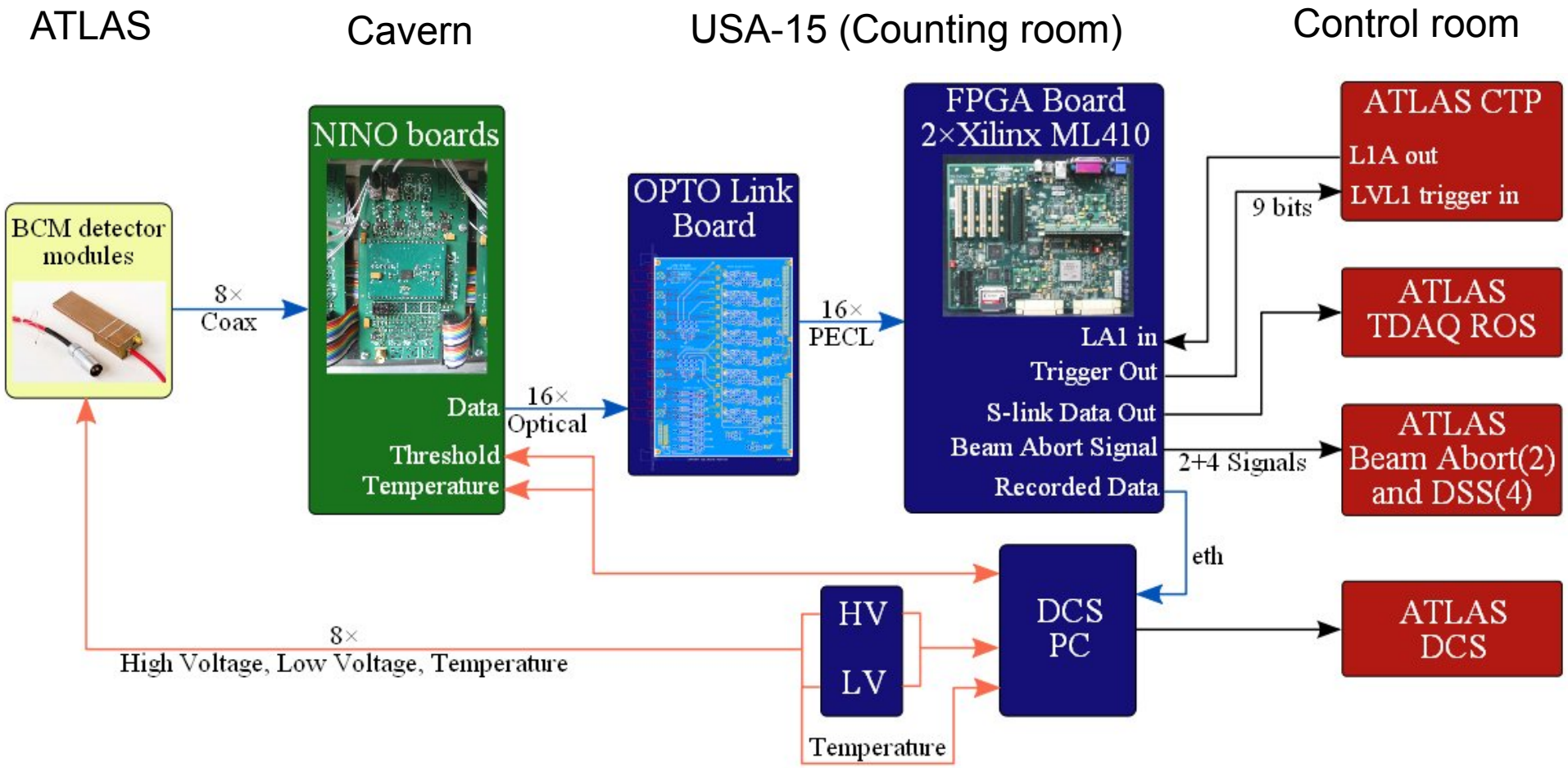






The BCM Readout

- 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

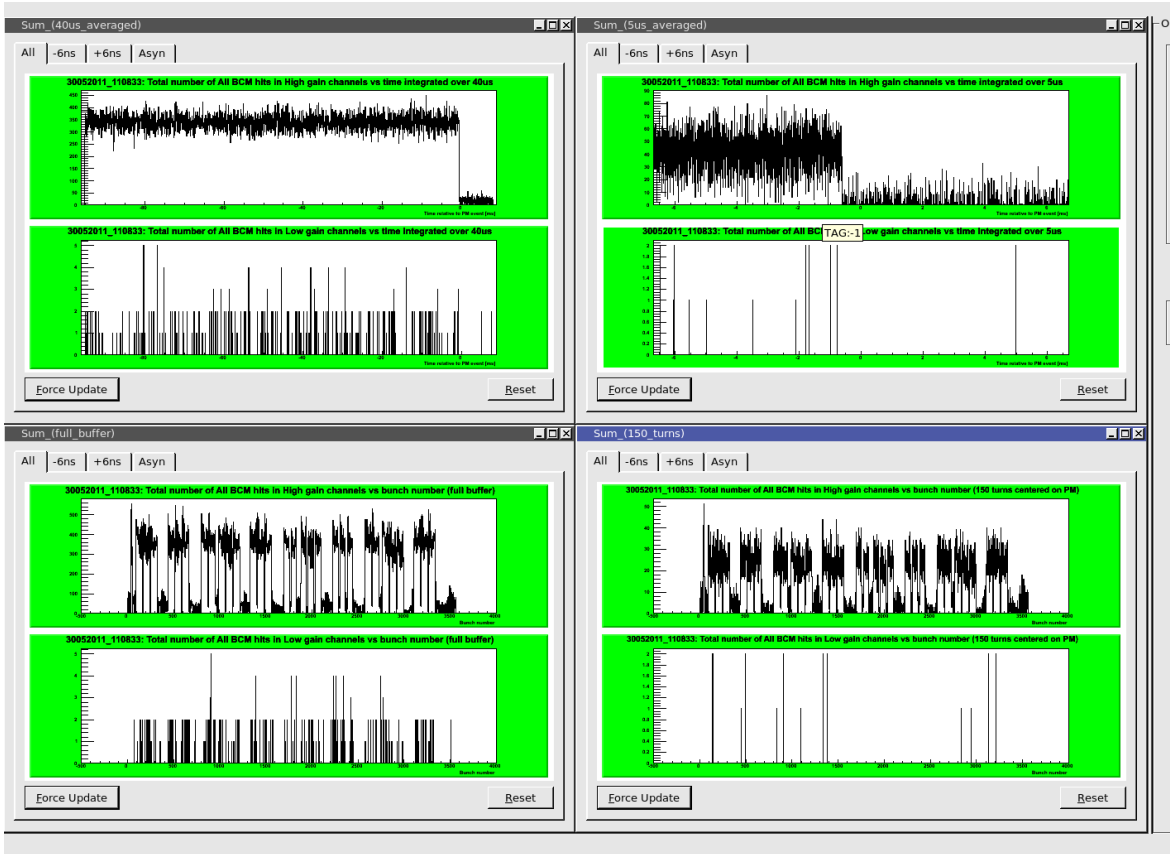
100 turns

Single MIP

Hundred MIP

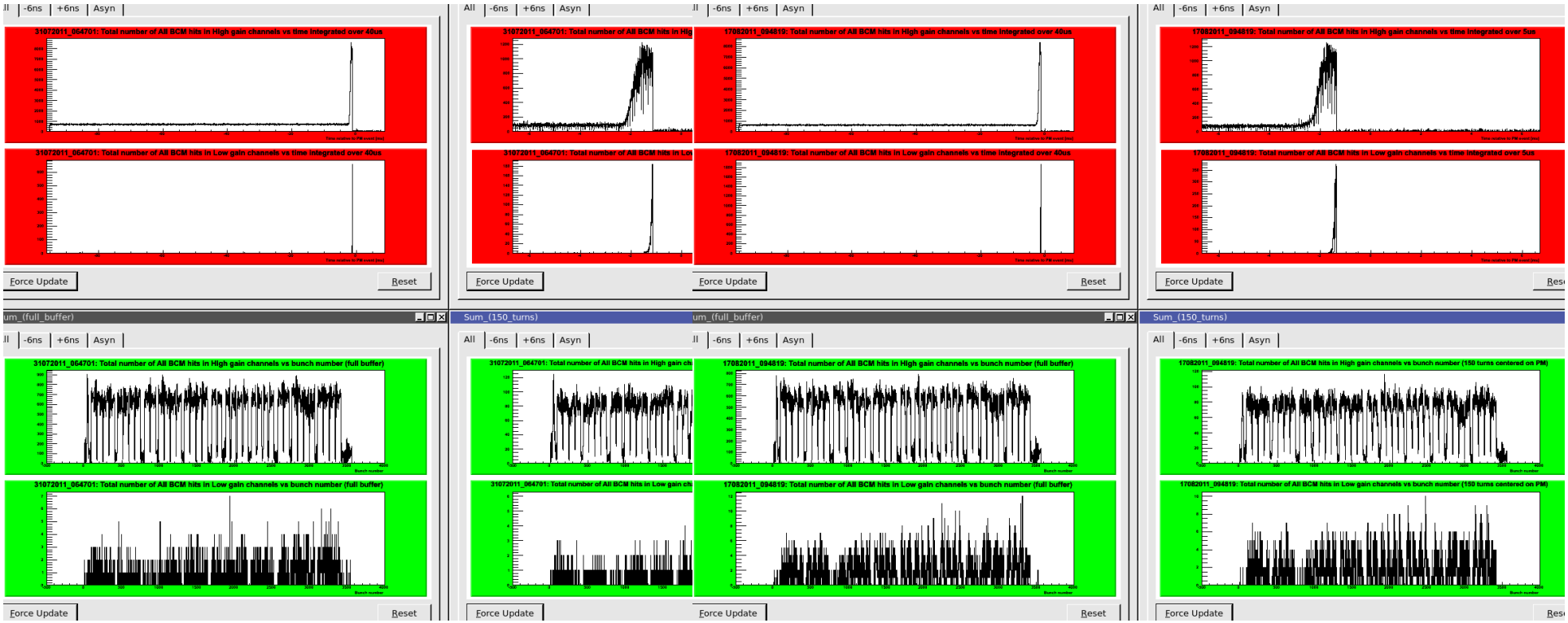
vs. Time

vs. BCID



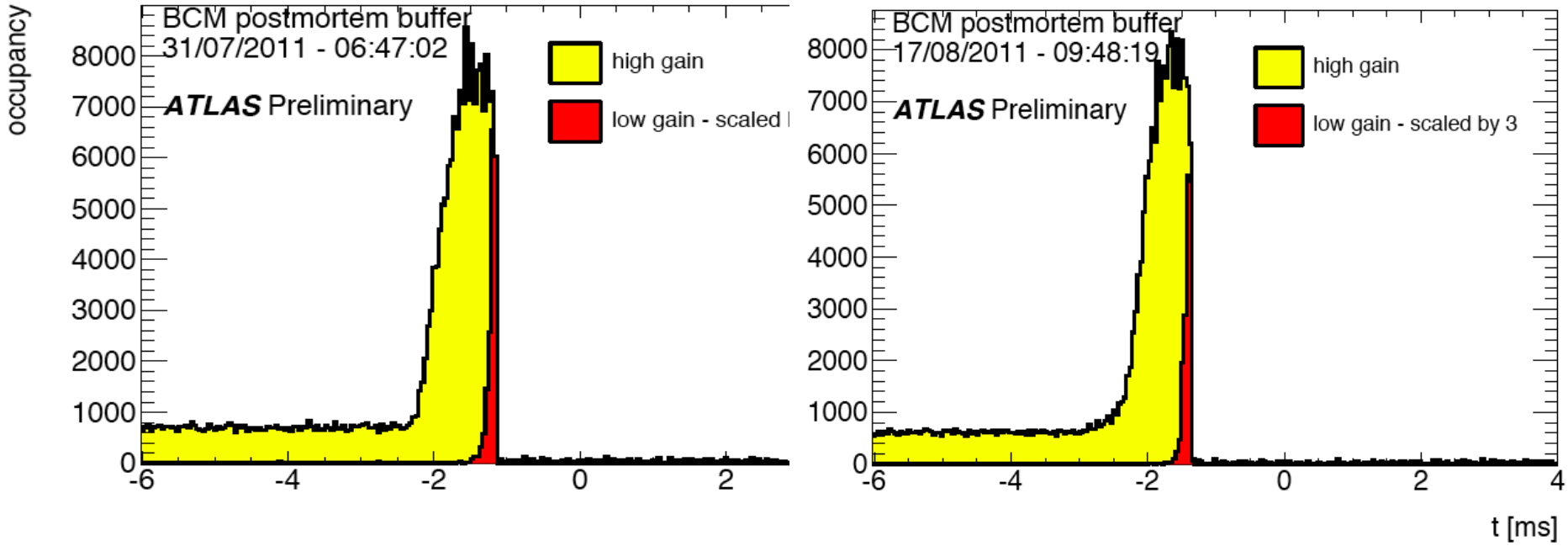
Two Aborts Seen – 2+ Years of Operation

- 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



Two Aborts Seen – 2+ Years of Operation

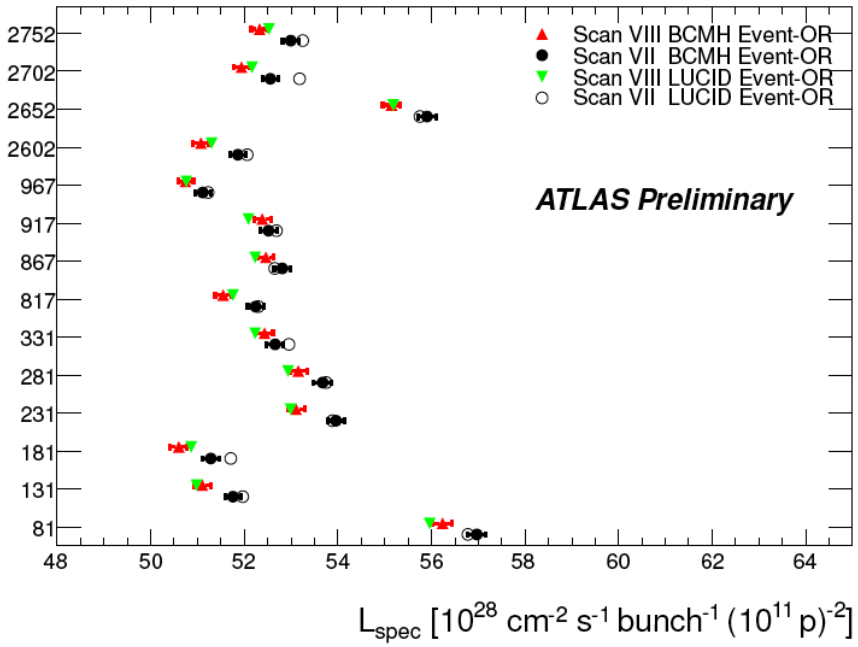
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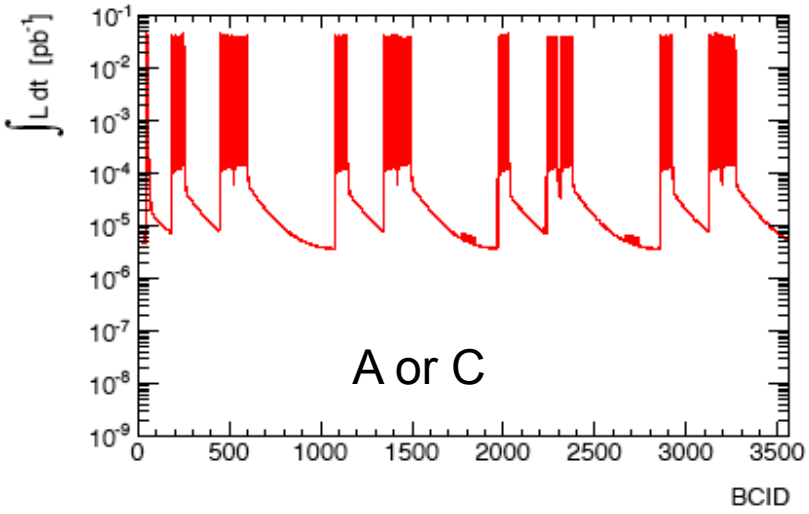
BCM: ATLAS Default Luminosity Monitor

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

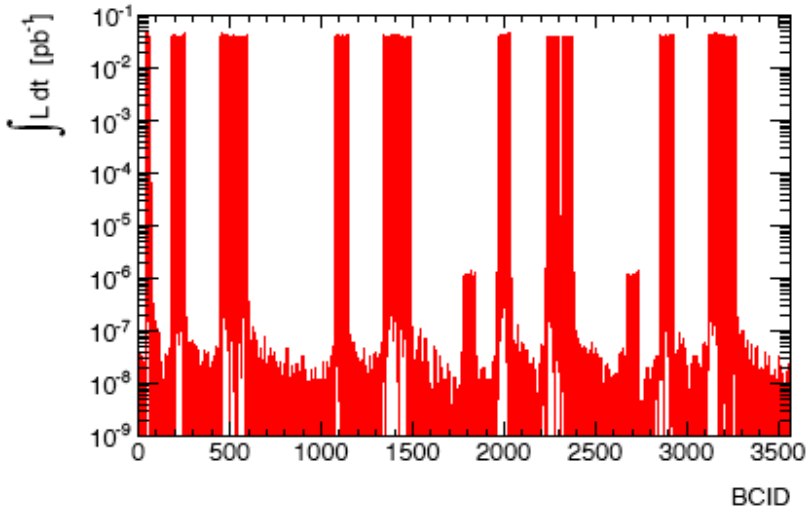
- Used during all Van de Meer scans
  - Measure few % variations in bunch currents
  - Reproducibily and reliably

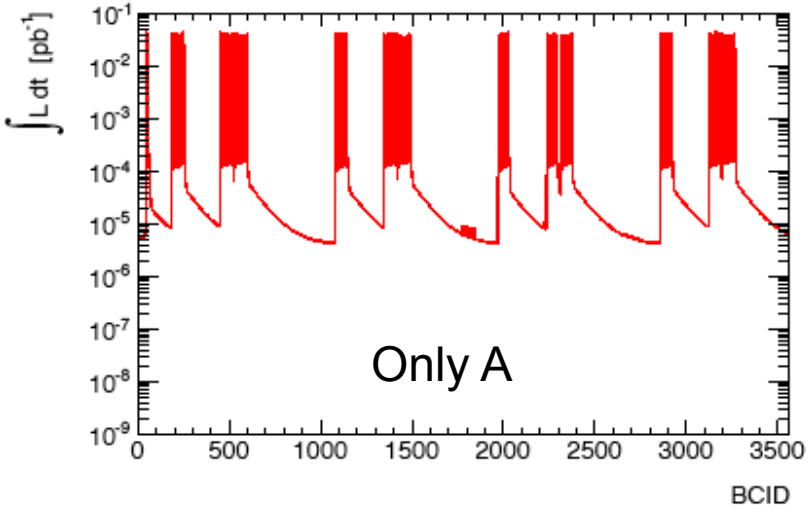


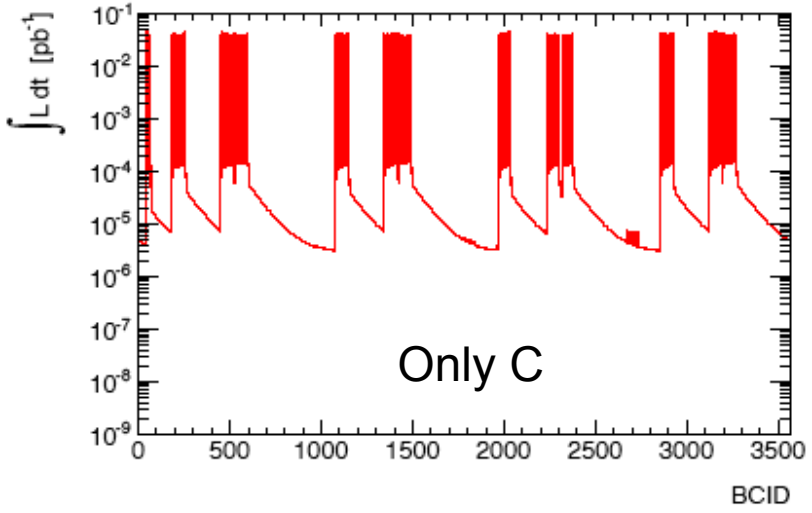
BCM Luminosity Maps



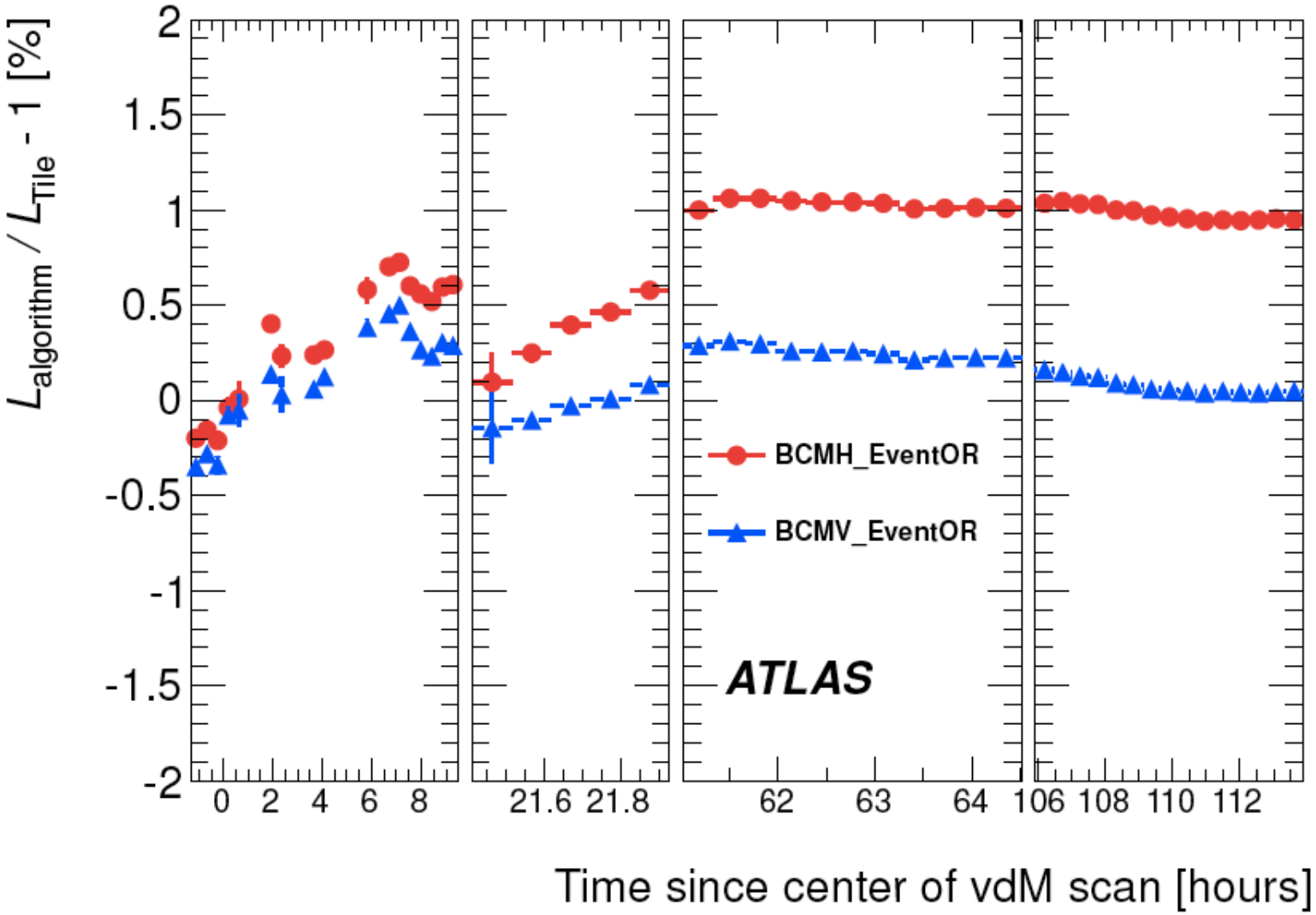
A and C





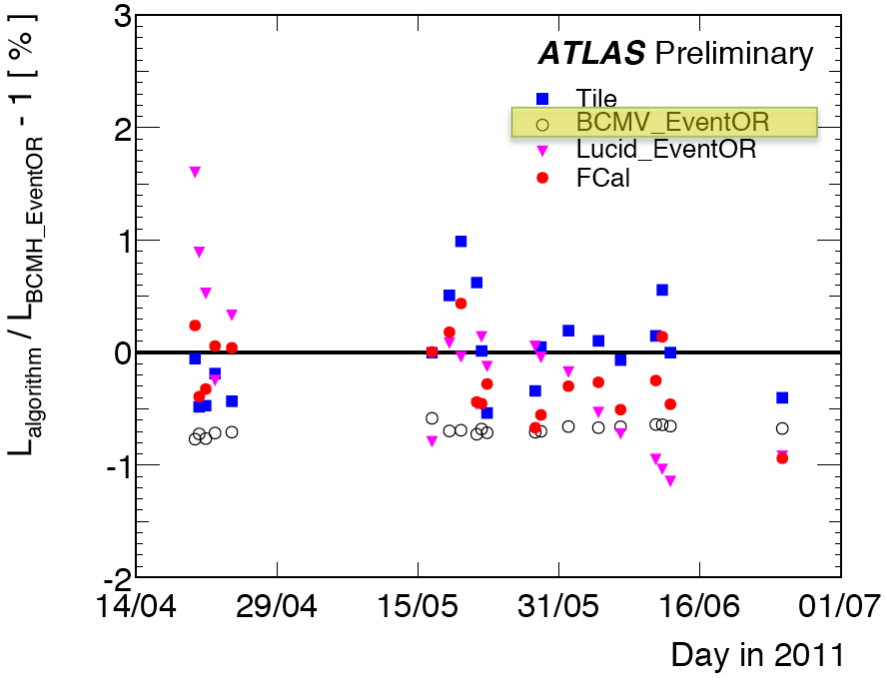


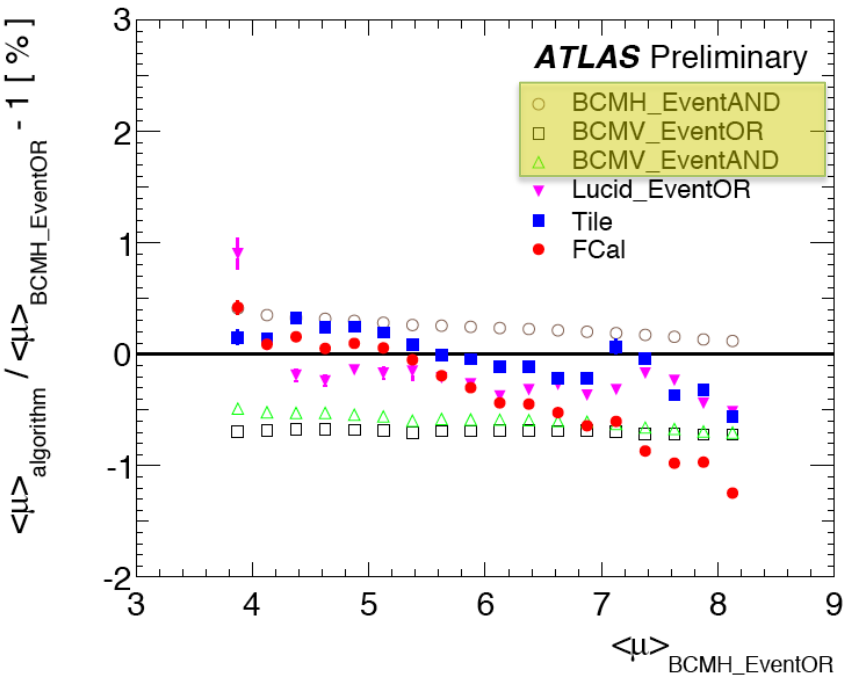
BCM: Gain (In)stability



BCM: Luminosity Stability

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



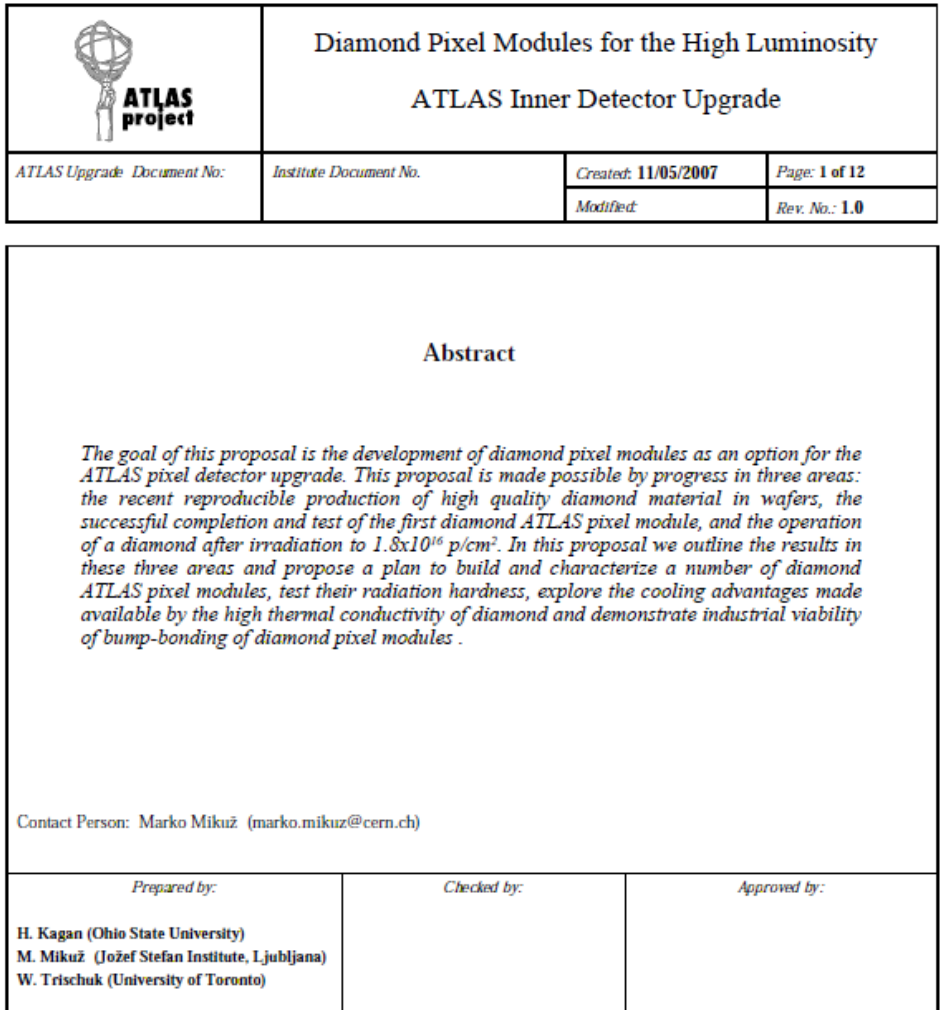


One of the keys to ATLAS' 1.8 % absolute luminosity uncertainty

CERN-PH-EP-2013-026, arXiv:1302.4393, Submitted to EPJC

ATLAS Diamond Pixel Sensor EOI

- Institutions:
  - Bonn, Carleton, CERN, Ljubljana, Ohio State, Toronto
- Underway since 2008
- Goals:
  - Make 10 modules
  - Industrialise fabrication
  - Test radiation hardness
- IBL sensor decision 2011
- B-layer replacement? 2013
- Tracker upgrade 2022?



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

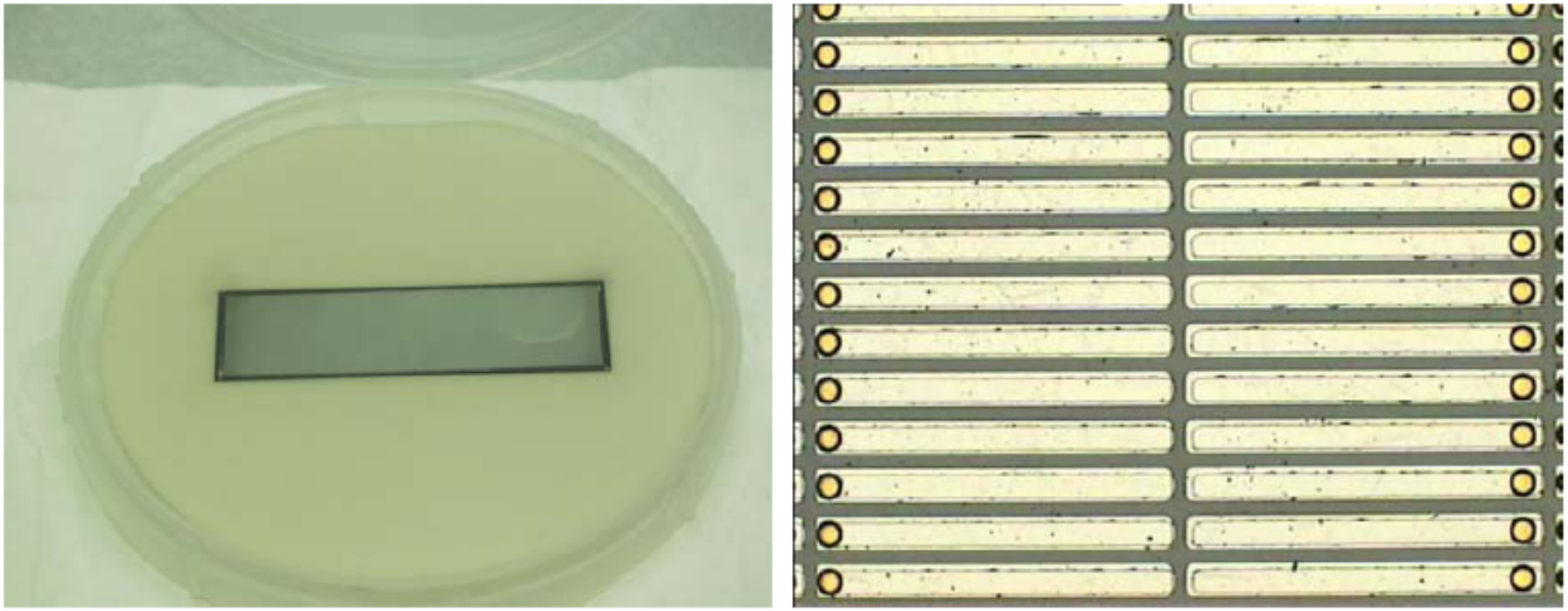


Figure 5: (a) Photograph of the ATLAS pixel diamond mounted in the carrier ready for bump bonding. (b) Zoom view of the pixel pattern after the under-bump metal is deposited.

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

Diamond Pixel Prototypes

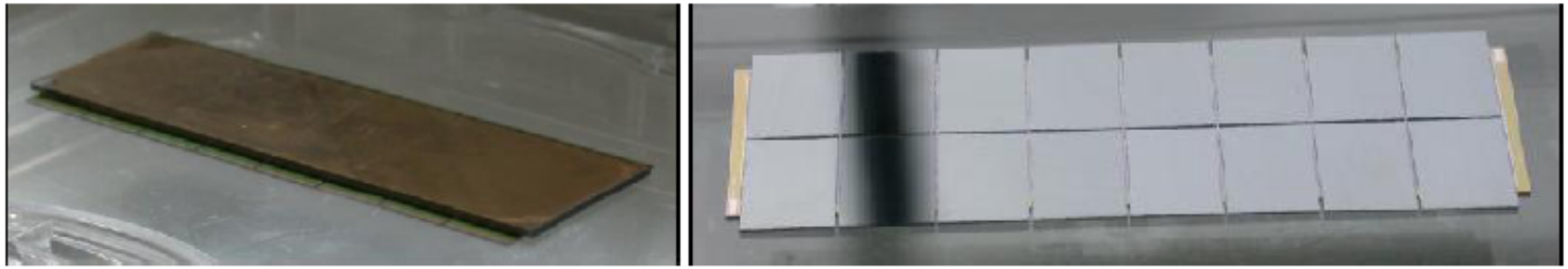


Figure 6: Photograph of the detector side (a) and electronics side (b) of the final ATLAS pixel module.

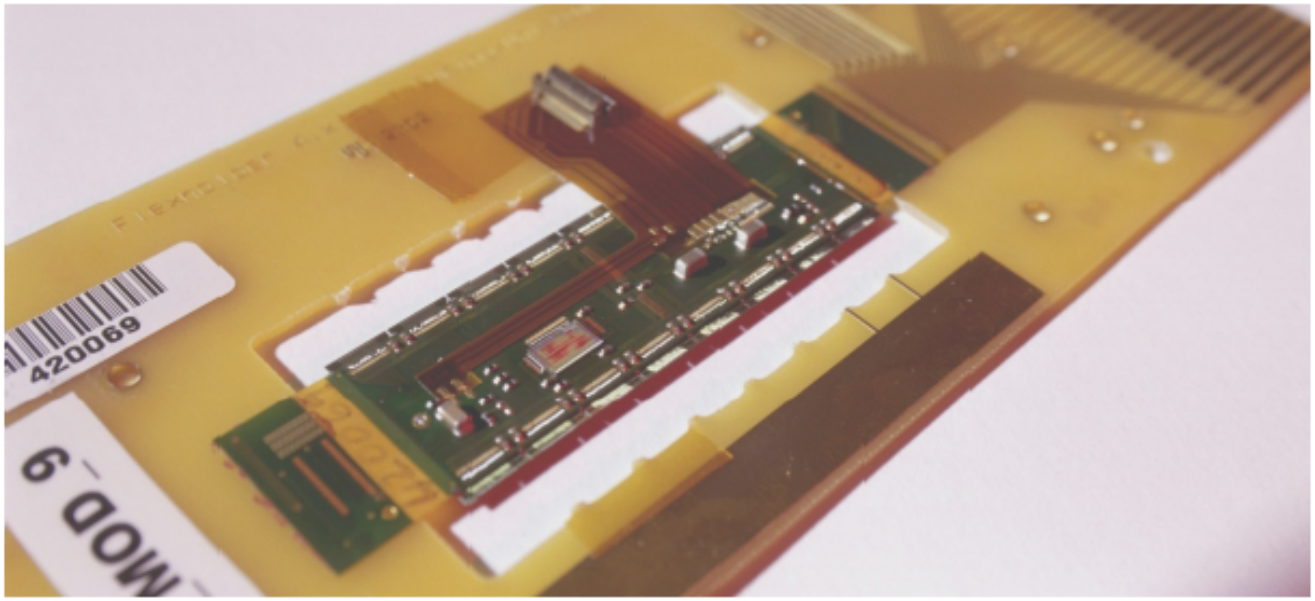
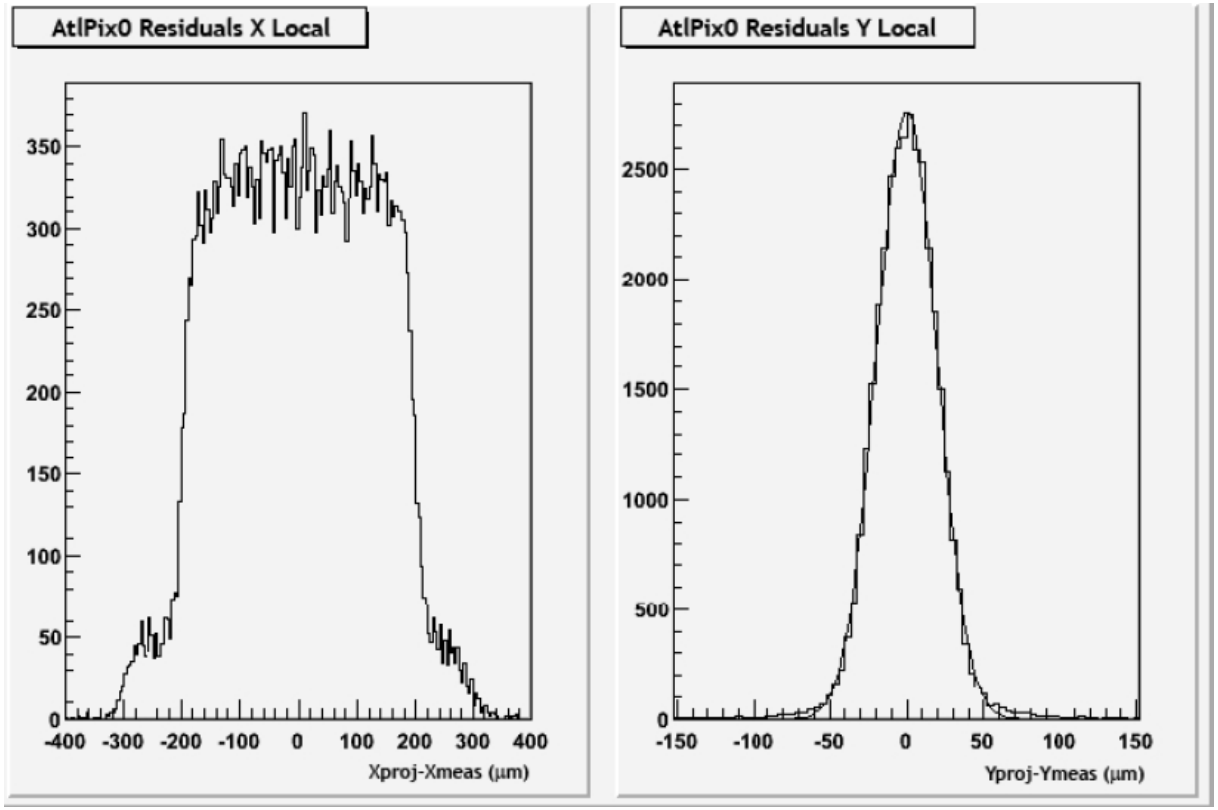


Figure 7: Photograph of the fully dressed diamond ATLAS Pixel Module ready for test.

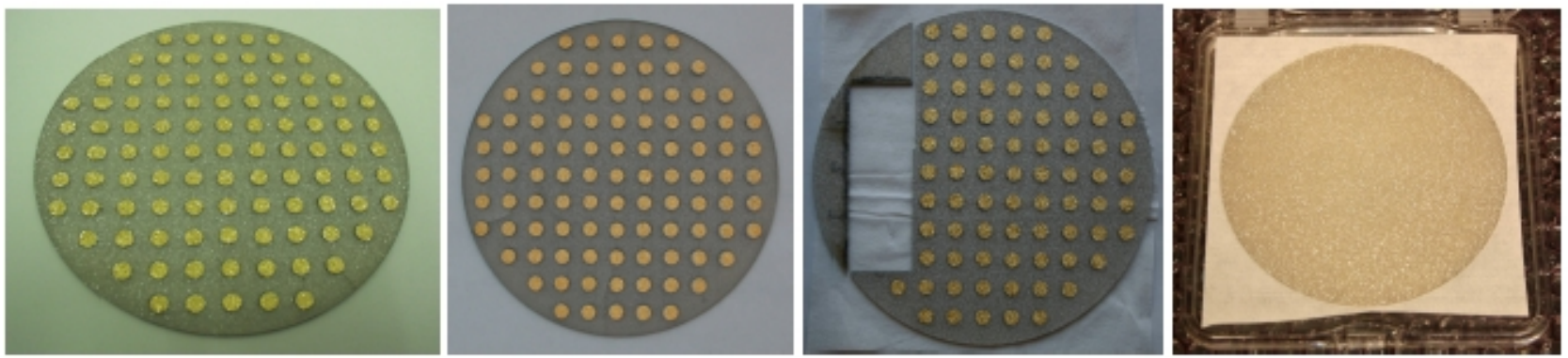
- Modules bump-bonded at IZM, tested at Bonn
- Noise: 140e^-, Efficient threshold: 1500e^-, In-time threshold: 2300e^-

Results from Pixel Prototypes



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

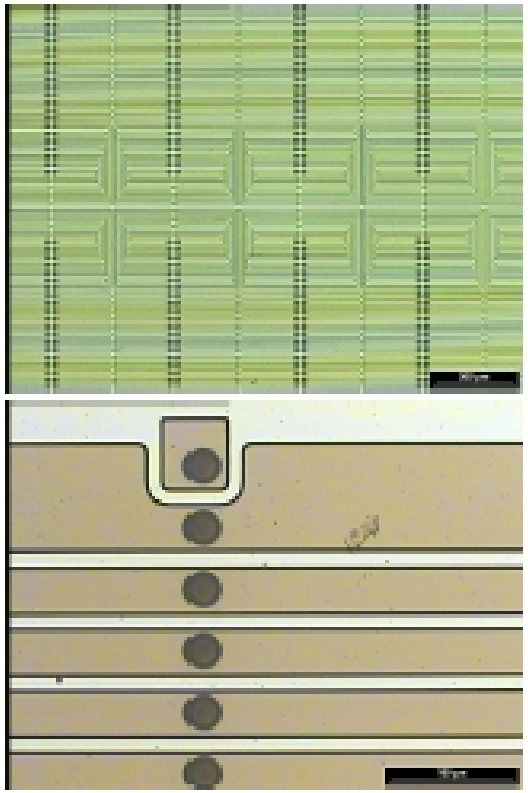
Mass Production of Diamond Wafers



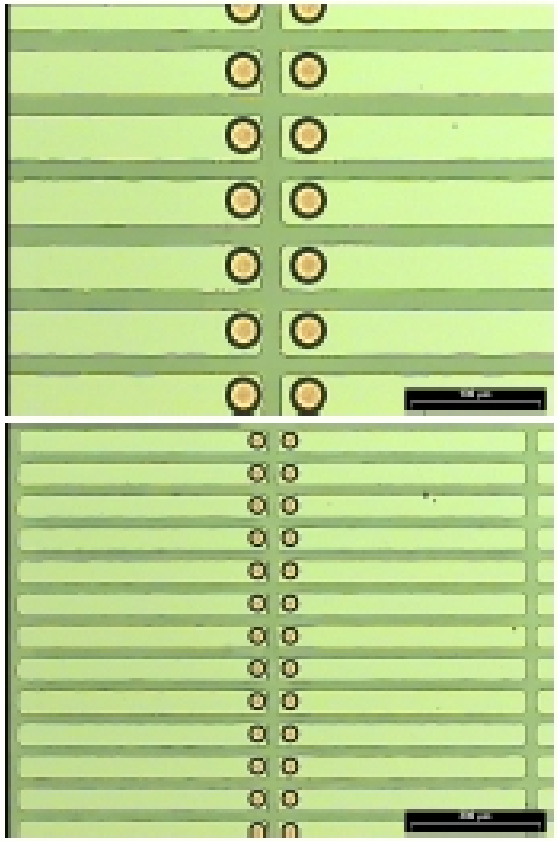
- Diamond manufacturer(s) deliver wafers
- We do a coarse scan for quality (signal size)
- Are allowed to specify sensor dicing locations
- Takes 2-3 months to turn around each wafer

Pixel Patterning in Industry (IZM-Berlin)

Diamond sensor pixel metallisation



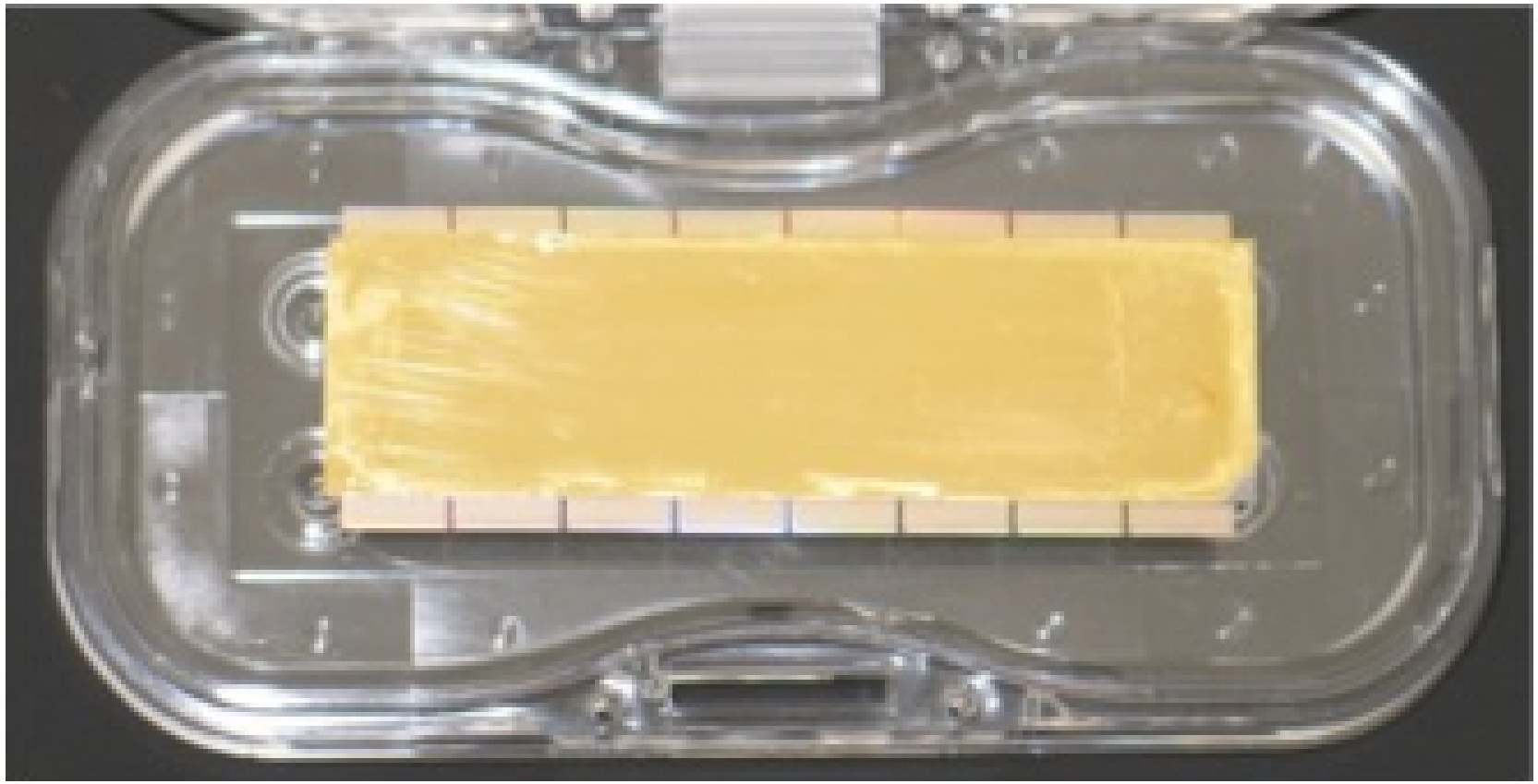
Status after elelctroplating of pad metallisation and lithography for pixel metallisation patterning



result after pixel metallisation patterning

Fraunhofer Institut Zuverlässigkeit und Mikrointegration

First IZM Module



- Bump-bonded in early 2012
- In testbeam at CERN during last summer

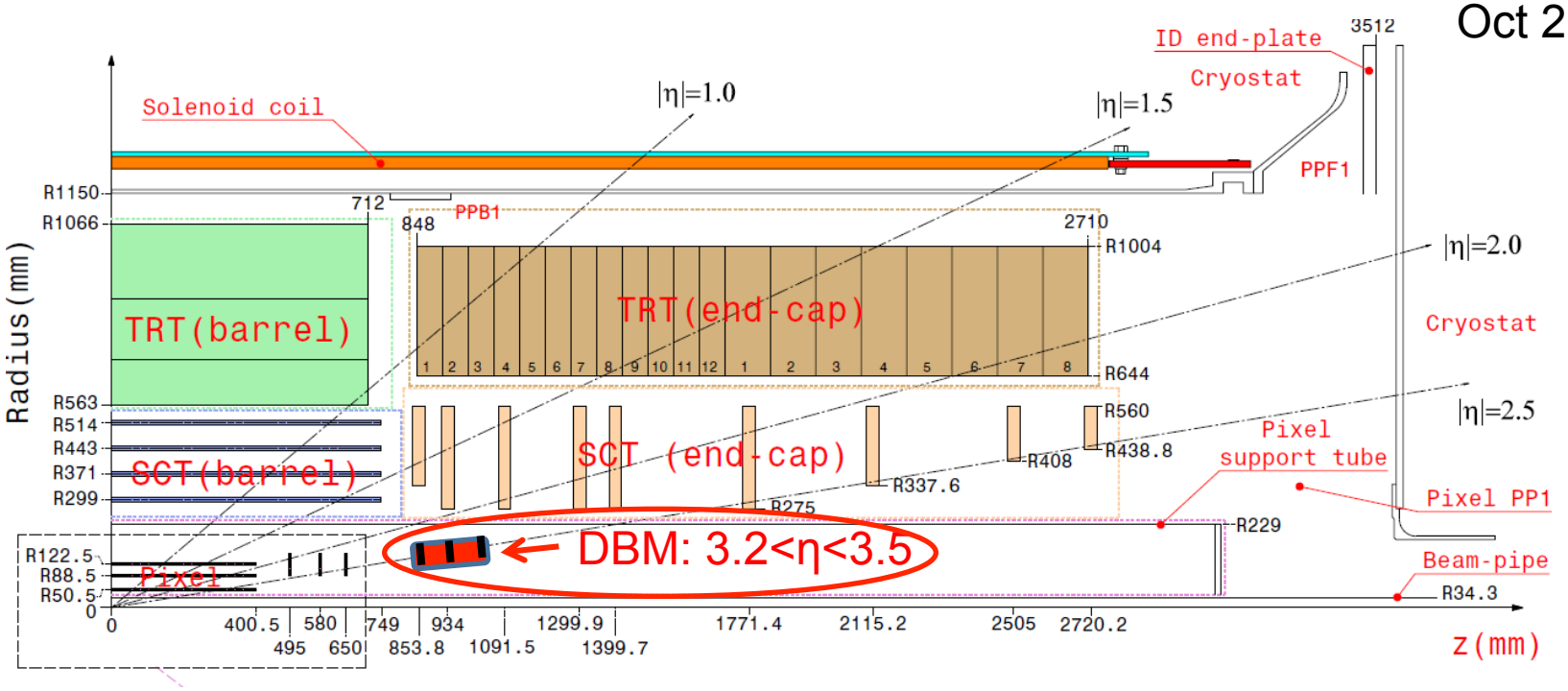
The Diamond Beam Monitor (DBM)

- 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

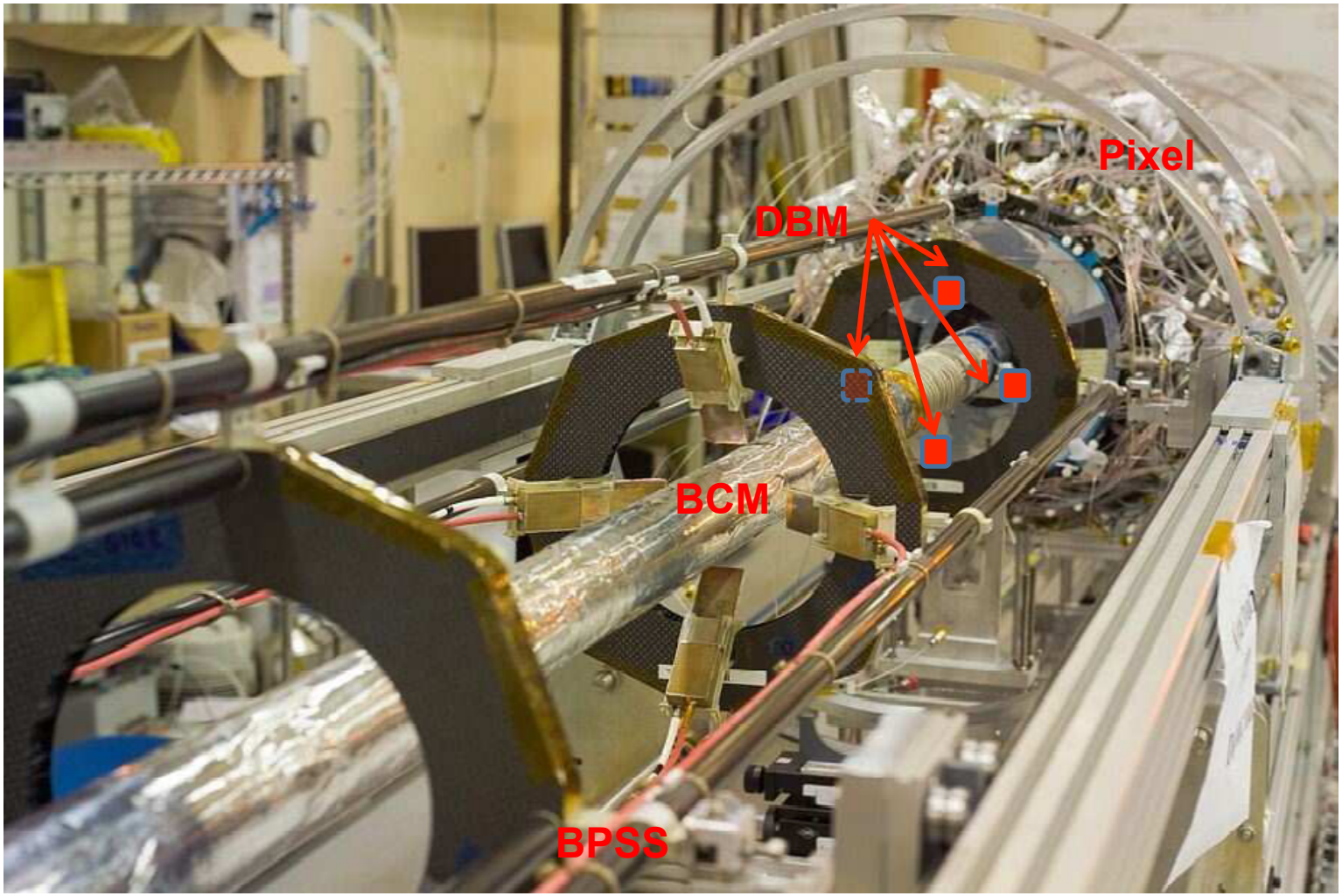
~~July 2013~~

- nSQP replacement sets installation date – ~~Februrary 2013~~

Oct 2013

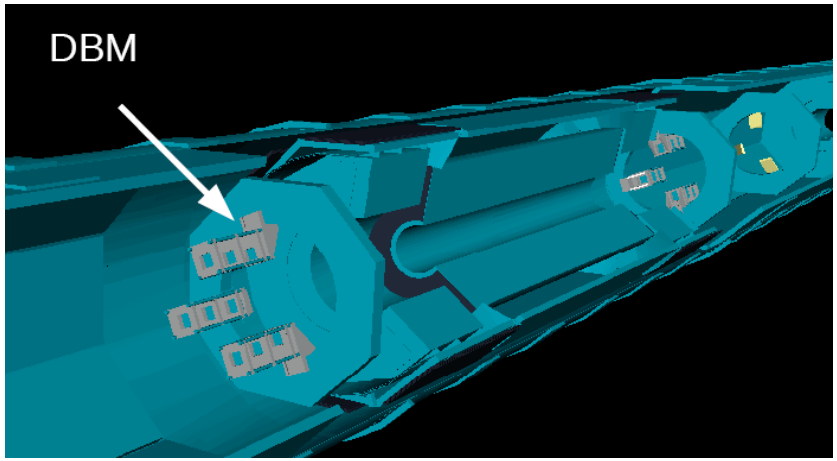


DBM Location

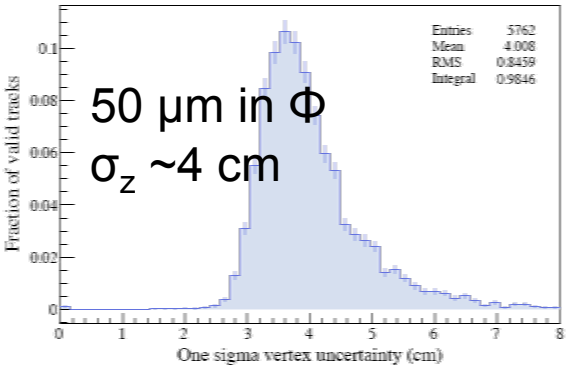


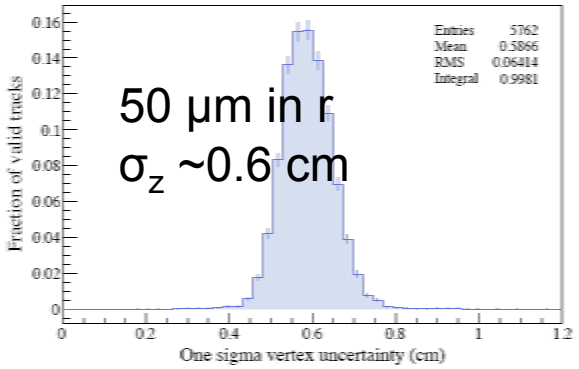
DBM: Simulation/Reconstruction

- Full GEANT model available



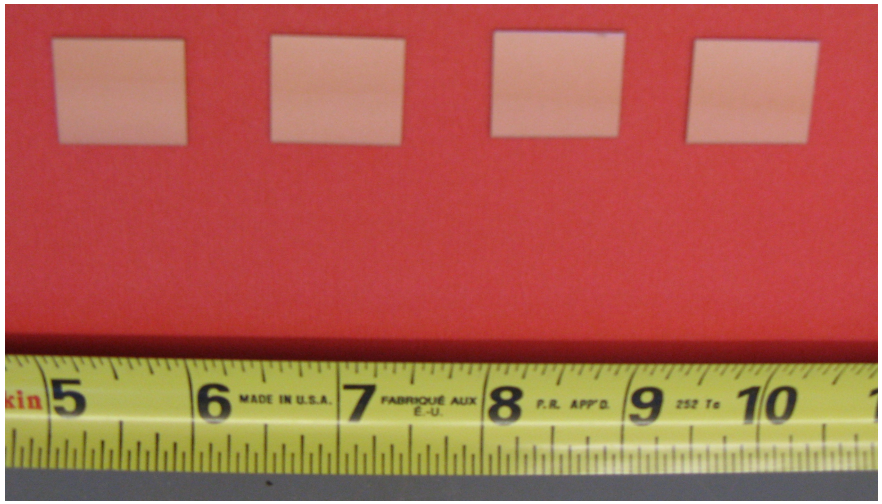
- Geometry forces us to focus on z, θ reconstruction
- Momentum resolution weak anyway => precise pixel in *r*

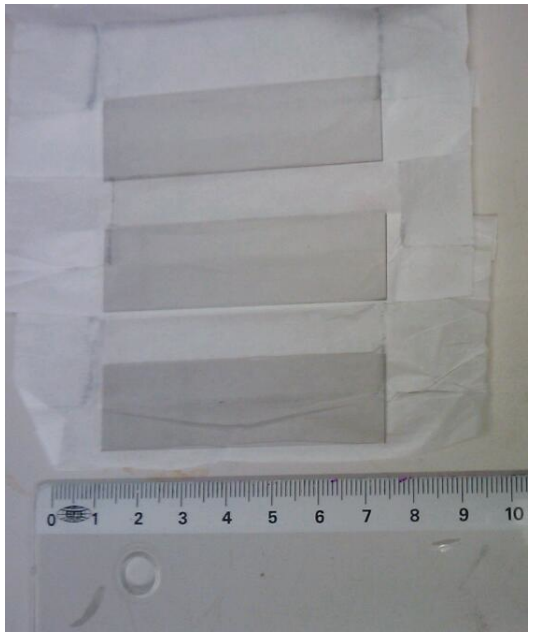




DBM Sensor Inventory

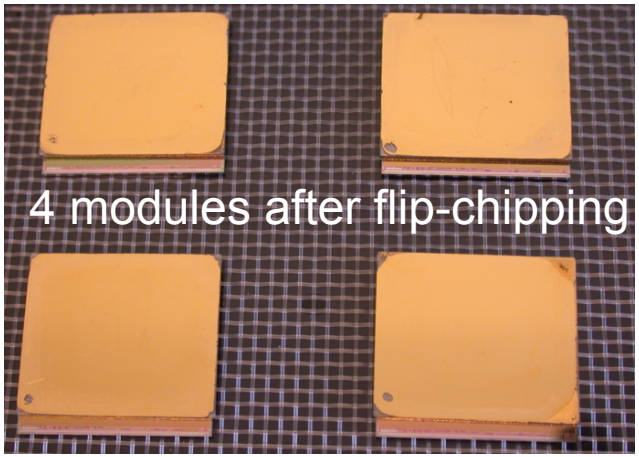
- 27 sensors ``in hand'' from IBL demonstrator work
  - Most need thinning
  - 5 FE-I3 sensors were cut to give 15 DBM sensors
  - 4 DBM sensors bump-bonded as prototypes in 2012
- All met initial DBM specifications
- 17 sensors from II-VI Inc.

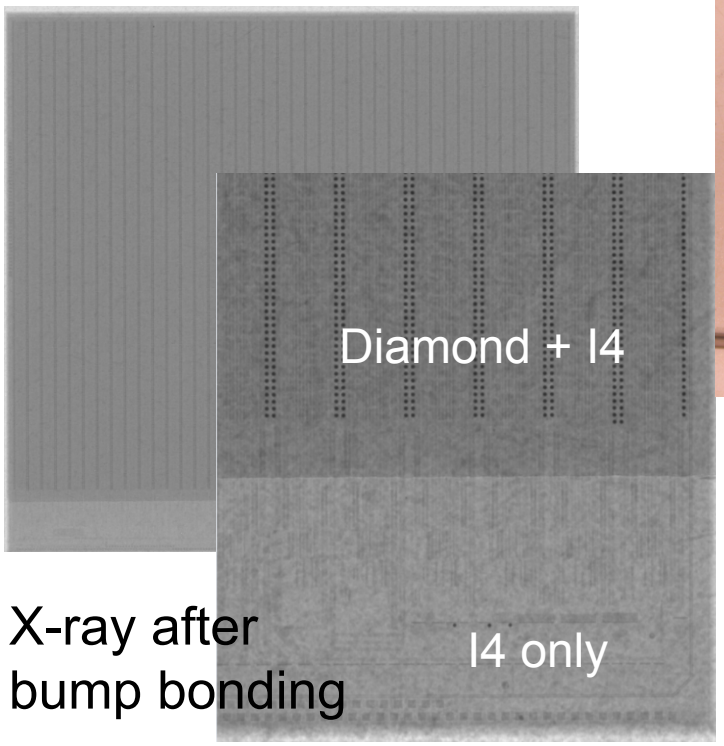




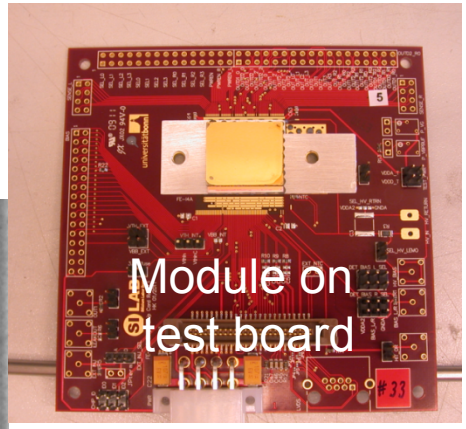
DBM Prototype Modules

- 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

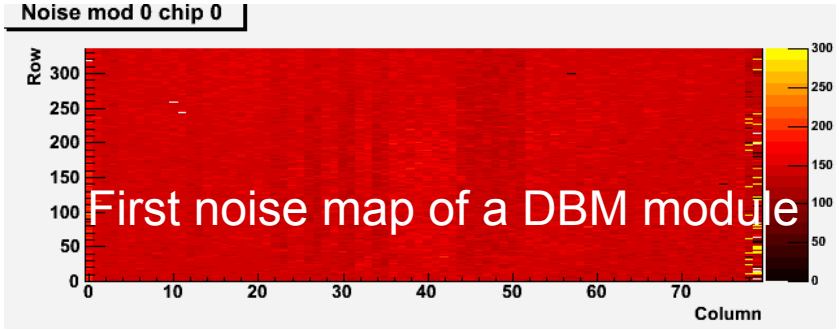




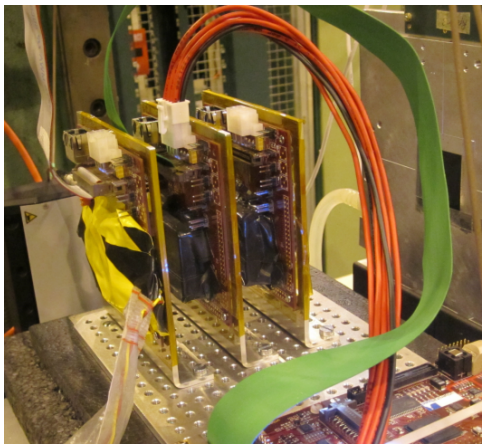
X-ray after bump bonding

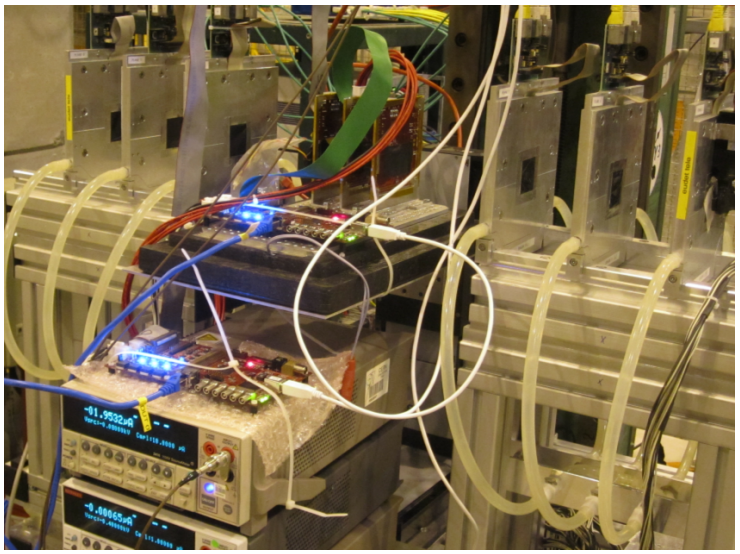


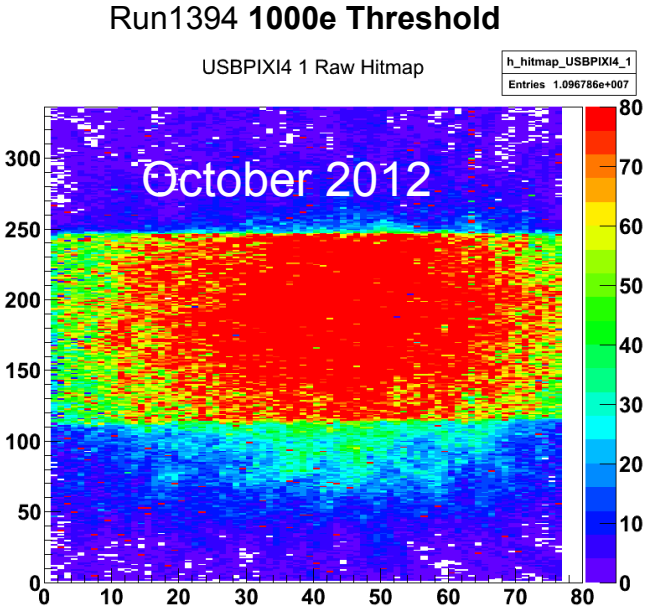
- ✓ X-ray perfect
- ✓ Noise map uniform
  - Indication of success
- ❖ HV issues due to IZM metallization up to edge



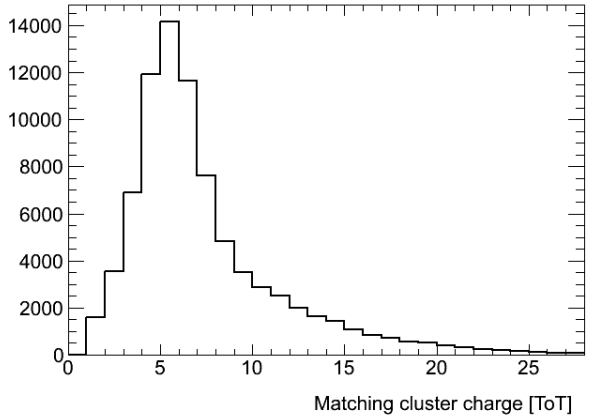
DBM: Module Testbeam Studies







- Three Testbeam campaigns
  - July, late August, October 2012
- Learning about FE-I4 performance
  - Calibration/tuning for low thresholds unique to diamond
  - Achieved 1000 e threshold (also needed for irradiated silicon)
- Use testbeam data to tune charge model



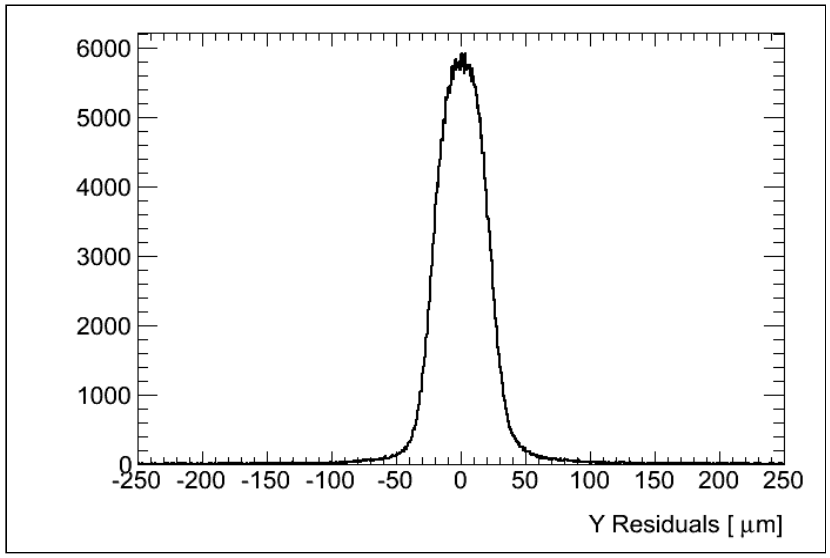
Lessons Learned: Testbeam

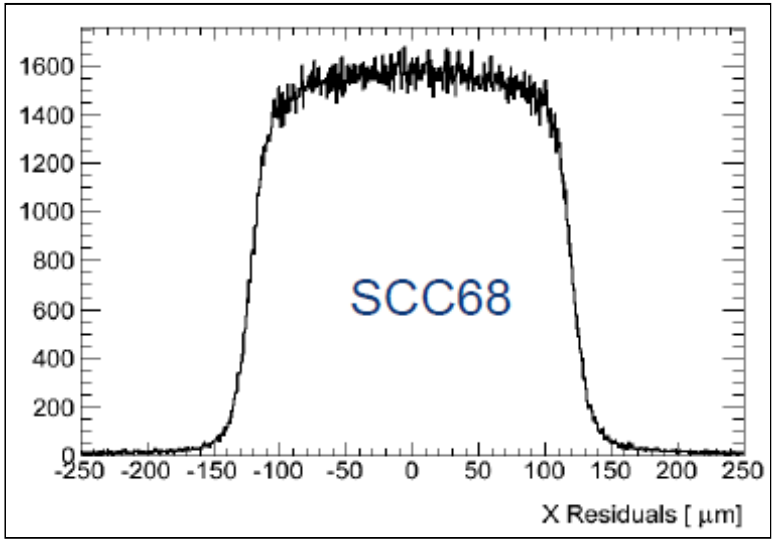
Prototype Modules Tested:

- 21mmx 18mm pCVD diamond w/FE-I4A
- 336 x 80 = 26880 channels
- 50 x 250 μm^2 pixel cell

Results

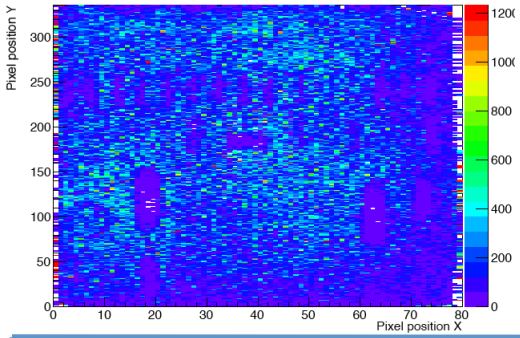
- Spatial resolution looks digital



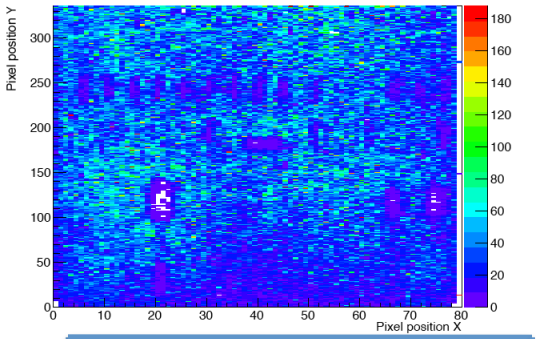


Bump-Bonding Diamond Sensors: Module QA

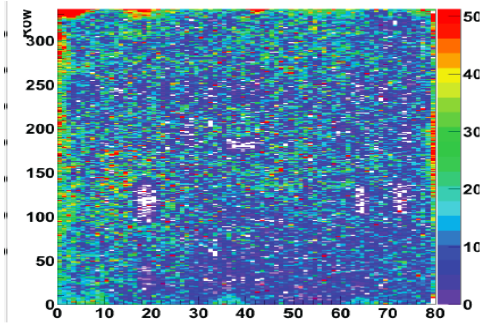
MDBM03 (TDBM01)



MDBM09 (TDBM01)

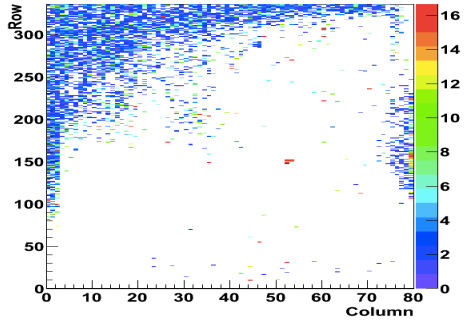


MDBM10 (chip died)

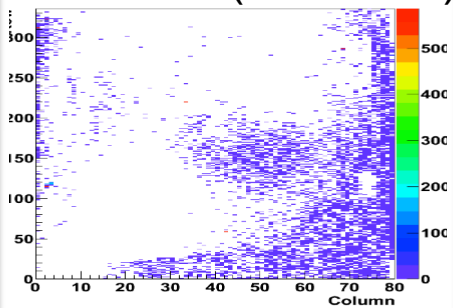


Bonded prior to May 2013

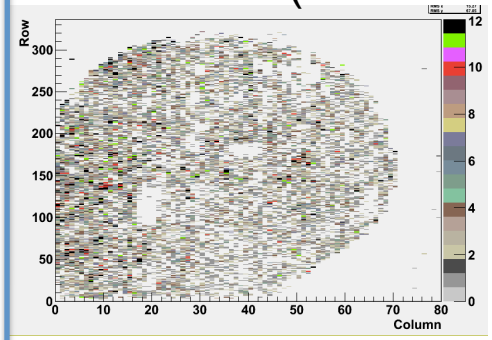
MDBM17 (reworked)



MDBM18 (reworked)

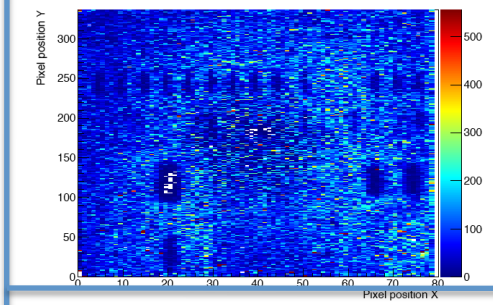


MDBM15 (15um bow)

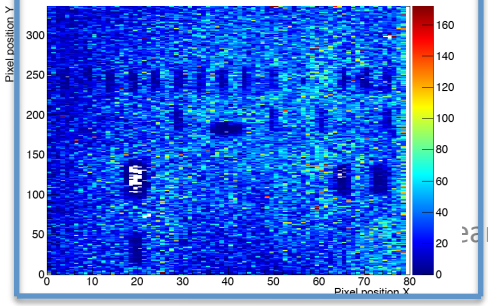


Bonded in June/July 2013

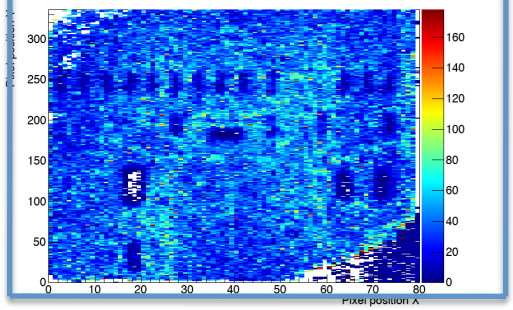
MDBM17 (TDBM04)



MDBM31 (TDBM05)



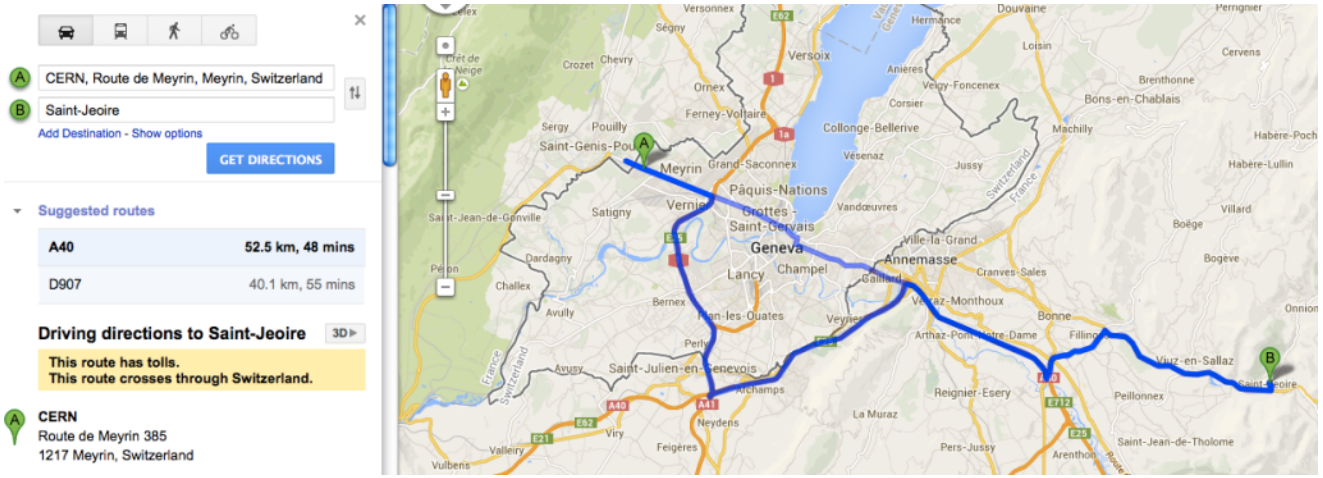
MDBM30 (not used)



Bonded in Sept 2013

Bump-bonding at SET

- After success pushed to re-work all remaining assemblies at SET
- Dismounted and re-furbished 6 sensors prior to this campaign



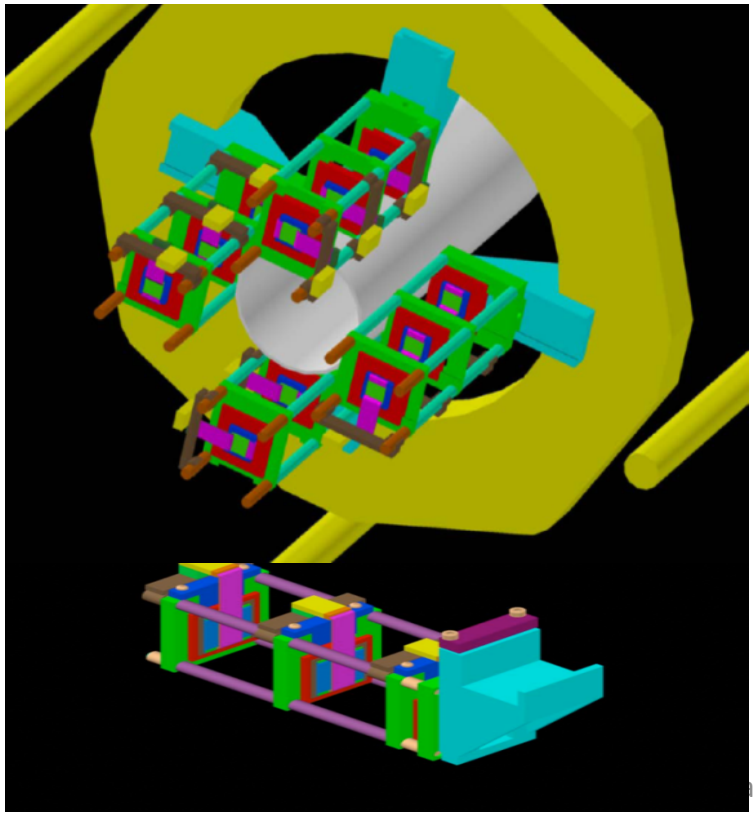
14 parts bonded during evening of September 18th

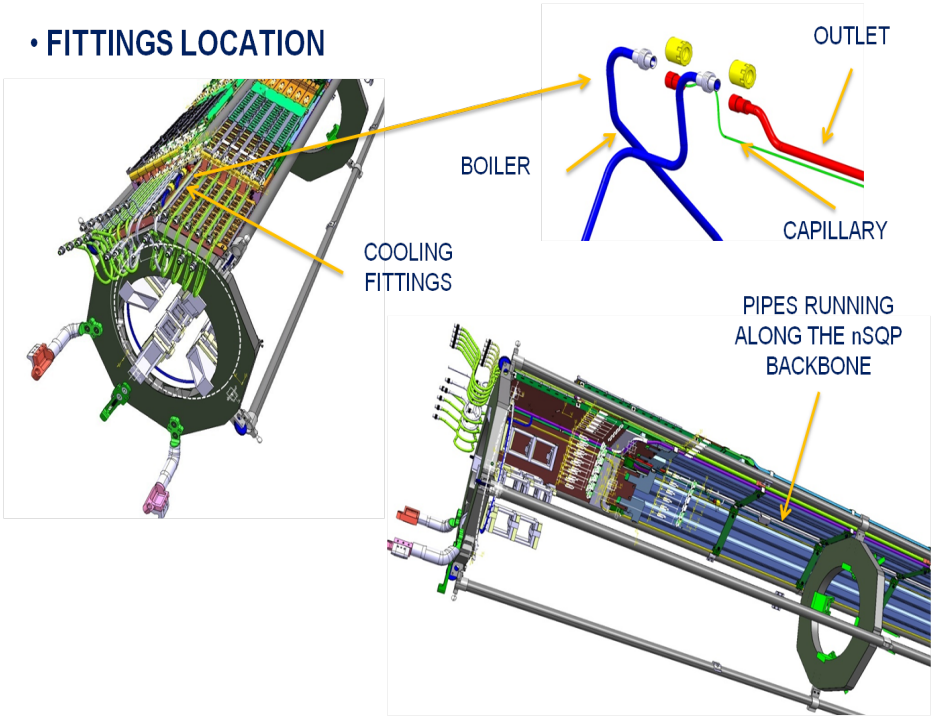
6 hand carried to CERN for module assembly before weekend.

- All of these assemblies were well connected
  - 11 ended up in the DBM telescopes over the following two weeks
- 7 additional sensors were re-furbished
  - Bonded on original machines in early October
  - Only 2 of these ended up in DBM
- In total 34 diamond sensors available, 47 modules assembled…

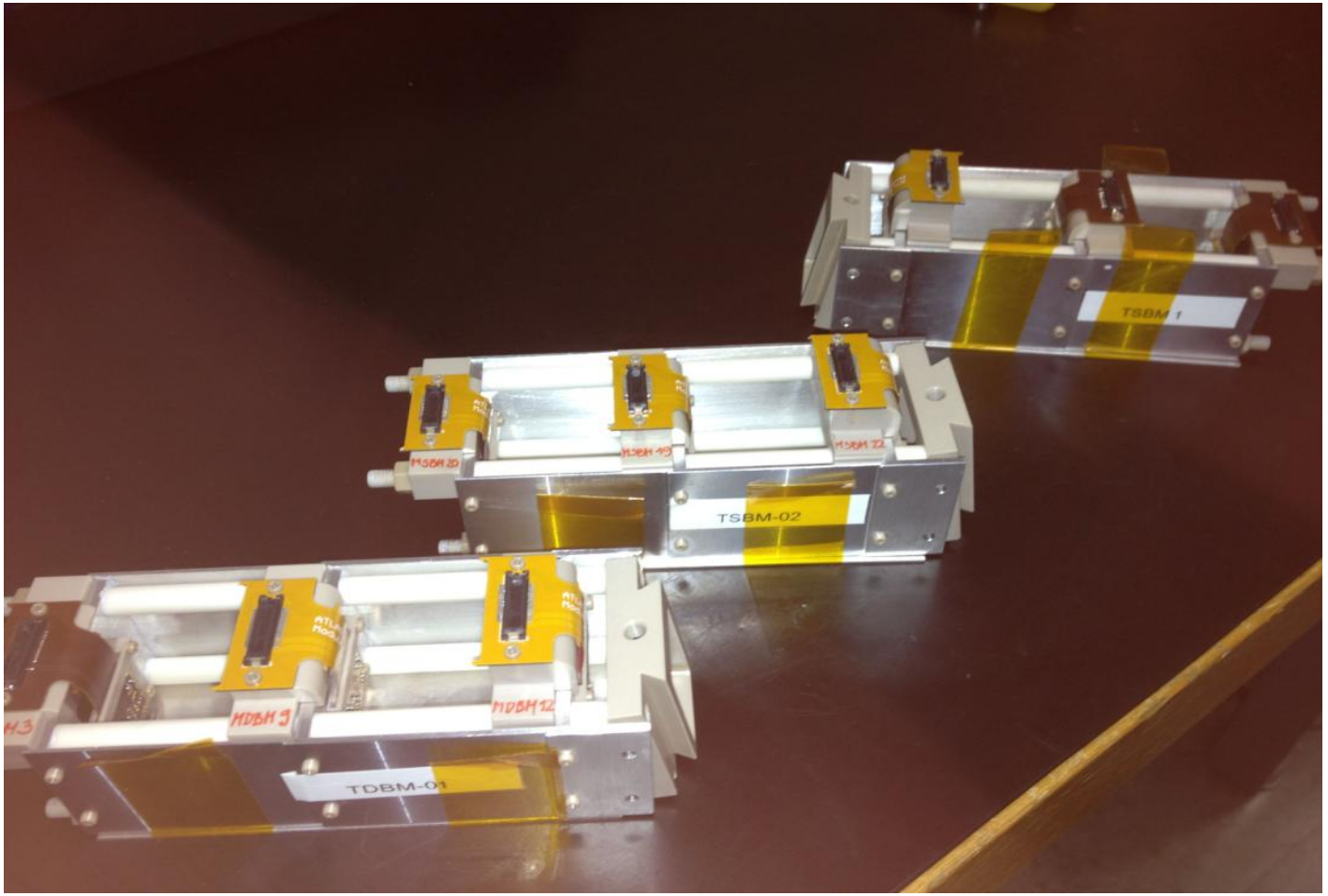
DBM: Support Mechanics

- Projective telescope design has been prototyped
  - Integrate cooling circuit in a simple way
  - Ensure DBM is thermally neutral, but diamond can run at room T

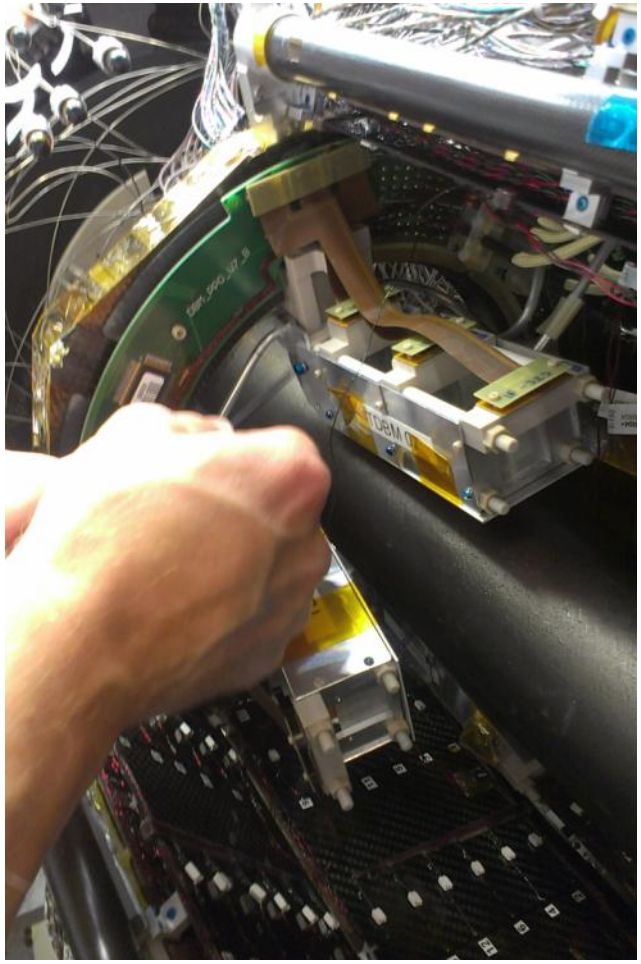


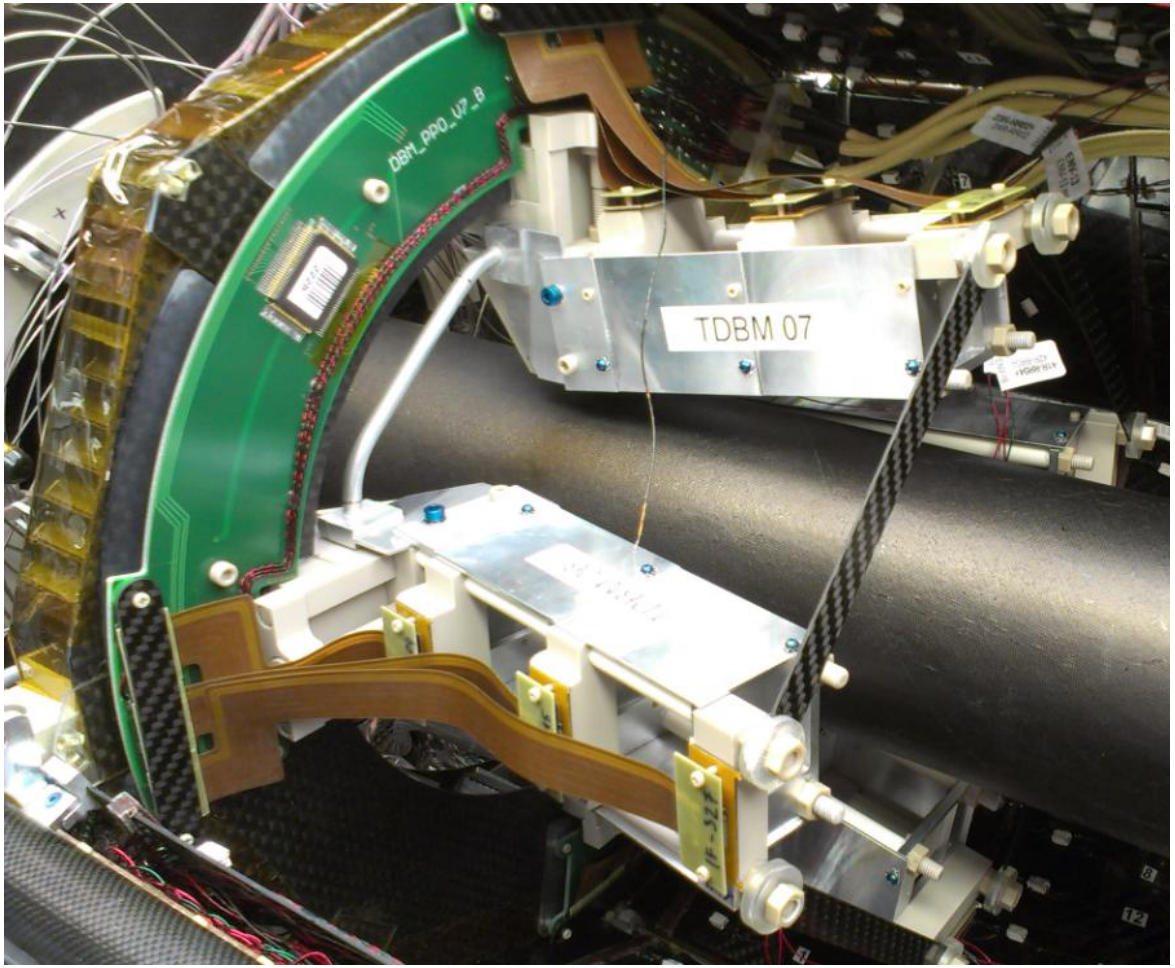


Telescope Assemblies



DBM Installation in Pixel package





Final Acceptance Tests

DBM telescope – SR1 acceptance checklist v1.1 Telescope: TDBM-06

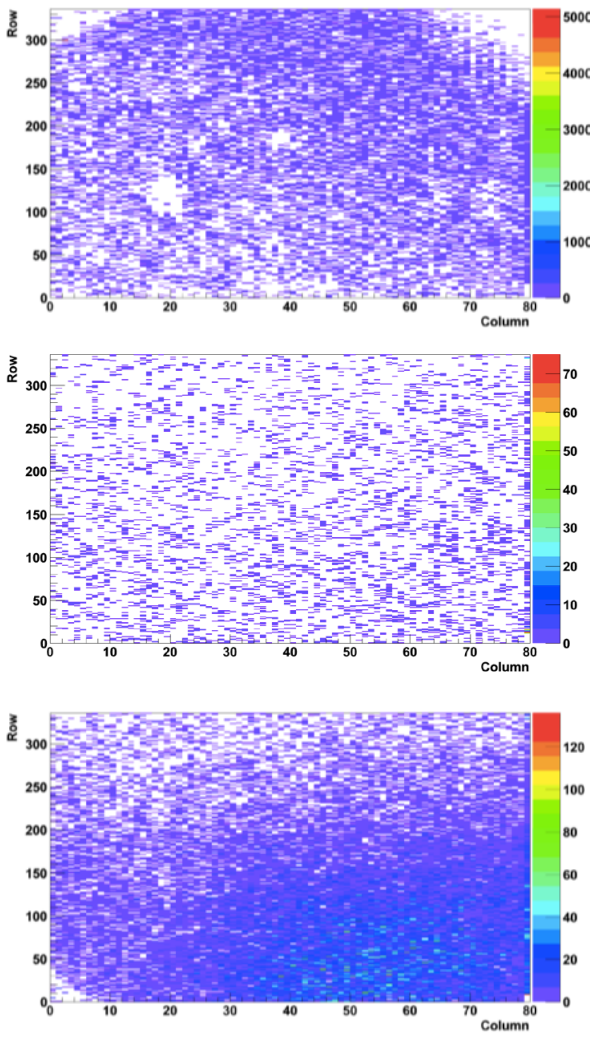
ATLAS DBM telescope
-- SR1-acceptance checklist --

Date	October 8, 2013
Place	SR1 RL
Shifter	Garvin, Andrej, Chav, Aleš

Telescope name	**TDBM-06**
Description	

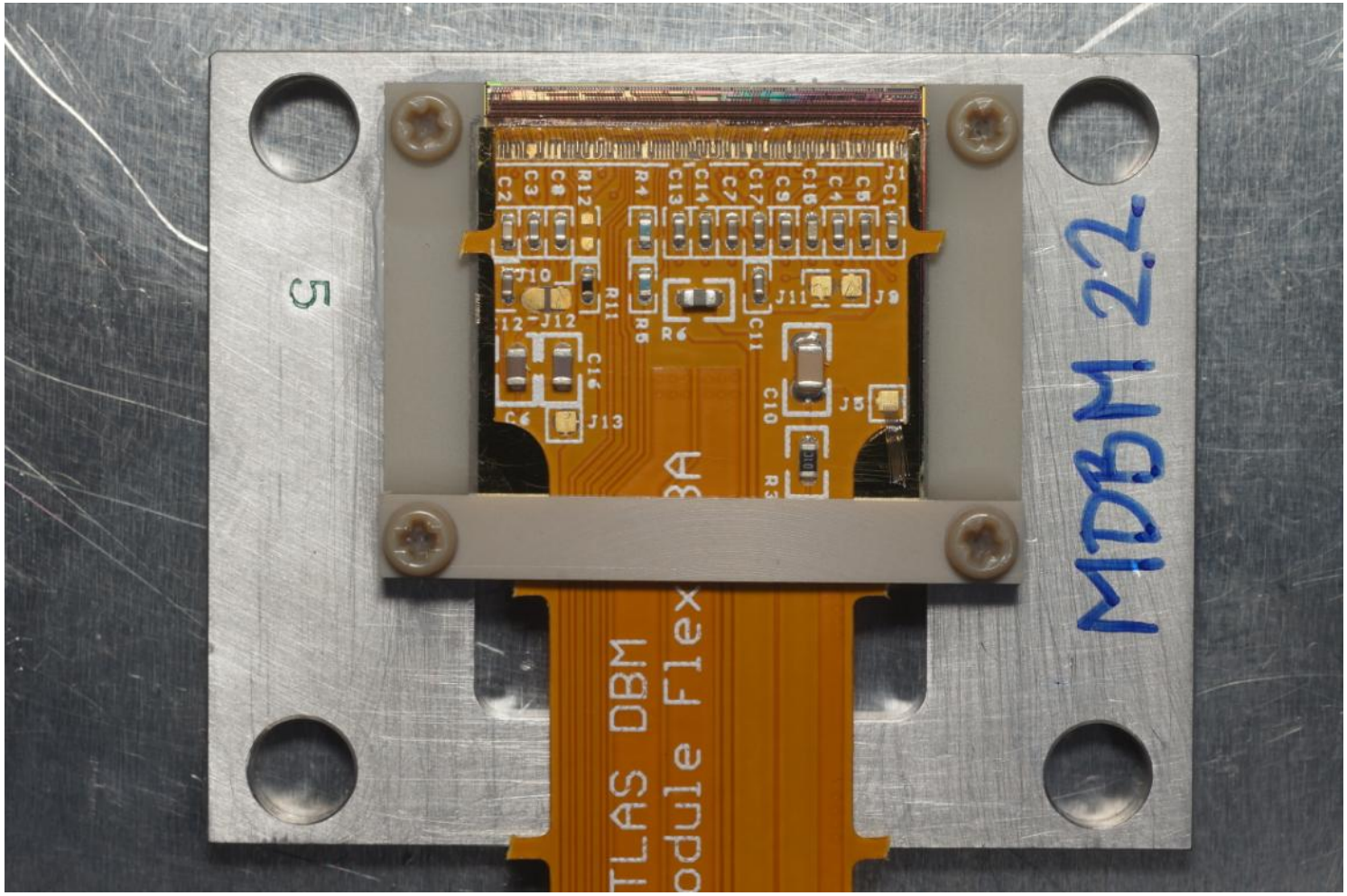
Positioning	
Side	C
Board	B
Position	8-1

Modules	
Sensor type	Diamond
Module on layer 0 (closest to the bracket)	MDBM-36, Link 2/2, FEID 0 (in config file FEID changed to **36** to differentiate between the modules)
Module on layer 1 (middle)	MDBM-33, Link 1/1, FEID 0 (in config file FEID changed to **33** to differentiate between the modules)
Module on layer 2 (outermost)	MDBM-34, Link 0/0, FEID 0 (in config file FEID changed to **34** to differentiate between the modules)



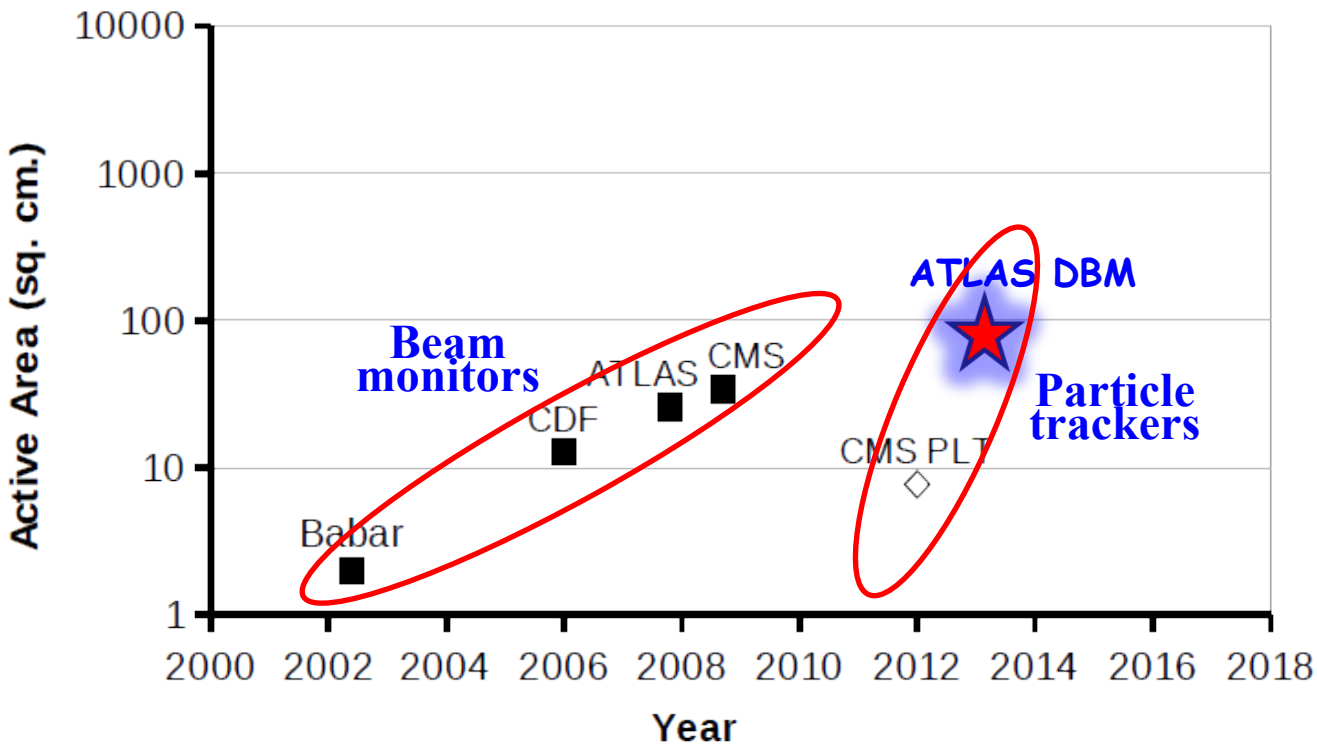
Source hits on installed telescope modjules

Module Alignment



Resolution of 12um/pixel in photo ➔ digitising these for initial as-built alignment

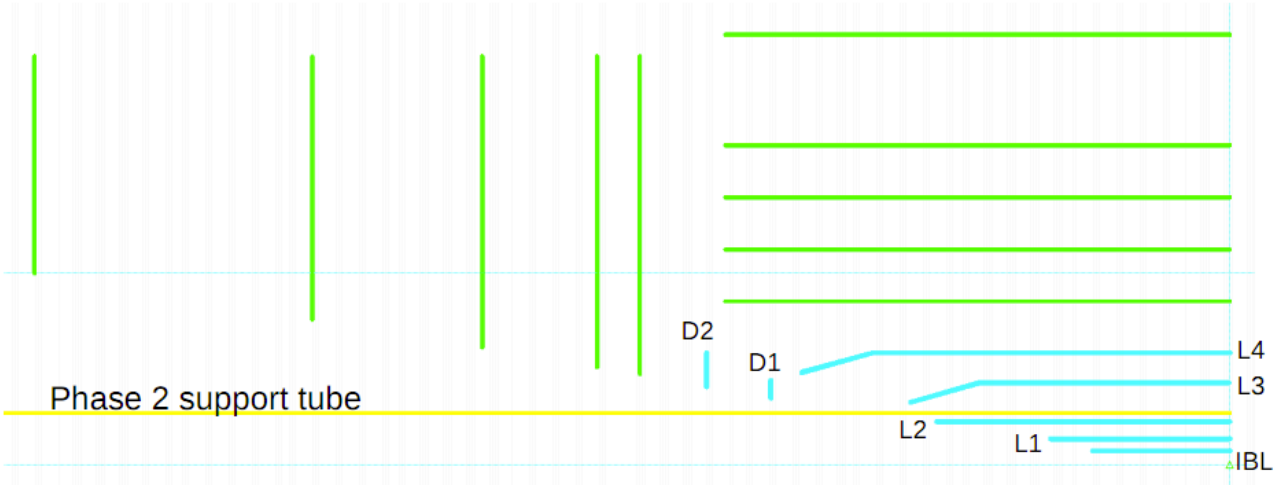
Diamond Production



Future detectors will require 10x – 100x more devices

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



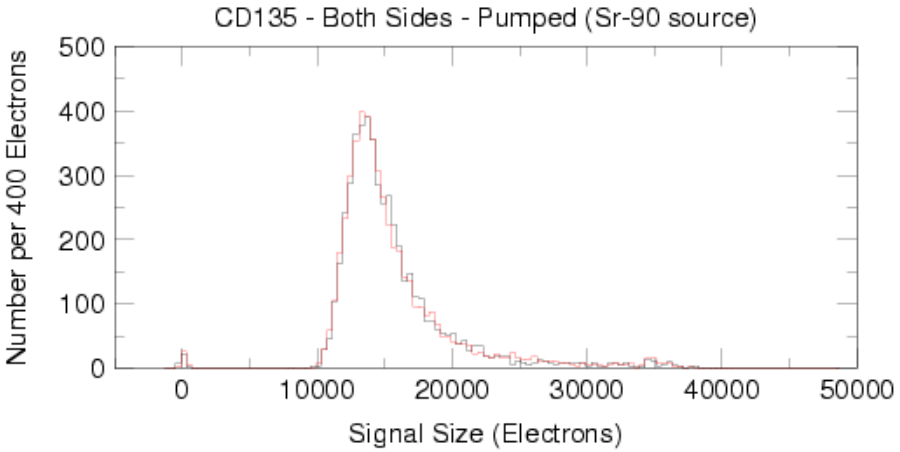
Summary

- 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 the ATLAS upgrade
  - Commission ATLAS Diamond Beam Monitor recently installed

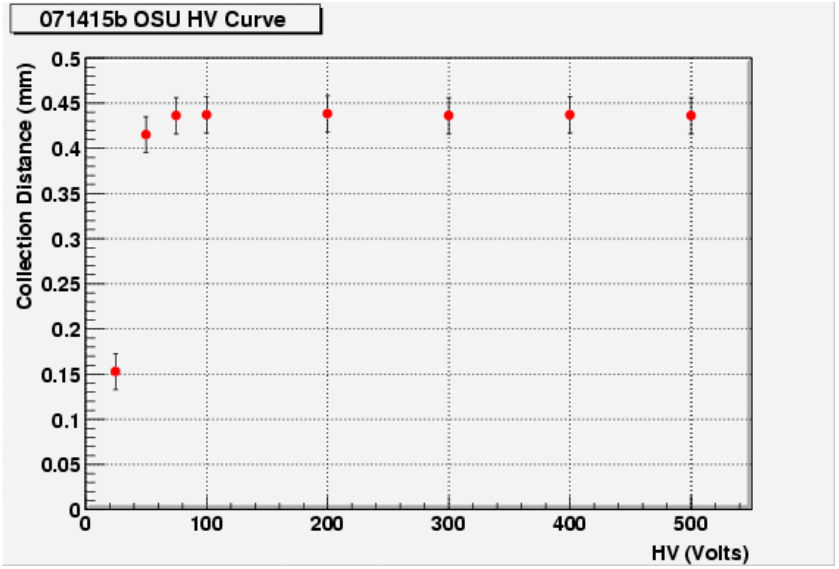
Single Crystal (scCVD) Diamond

- Improve material eliminating grain boundaries, defects/charge traps
- Almost a decade trying to scale up area from 0.5×0.5 cm^2

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

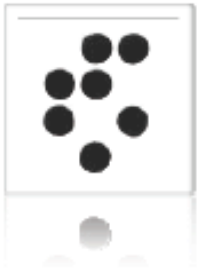
M. Artuso[25], D. Asner[22], L. Bäni[29], M. Barbero[1], V. Bellini[2], V. Belyaev[15], E. Berdermann[8], P. Bergonzo[14], S. Blusk[25], A. Borgia[25], J-M. Brom[10], M. Bruzzi[5], G. Chiodini[32], D. Chren[23], V. Cindro[12], G. Claus[10], M. Cristinziani[1], S. Costa[2], J. Cumalat[24], A. Dabrowski[3], 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

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

The ATLAS BCM Collaboration



JSI, Ljubljana

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

A. Svetek
M. Deliyergiyev



Univ. Toronto

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

E. Jiankowski
N. Venturi



Univ. of Applied Science - Wiener Neustadt

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



OSU, Columbus

- H. Kagan
- S. Smith

M. Fischer
H. Merritt
J. Moss



CERN

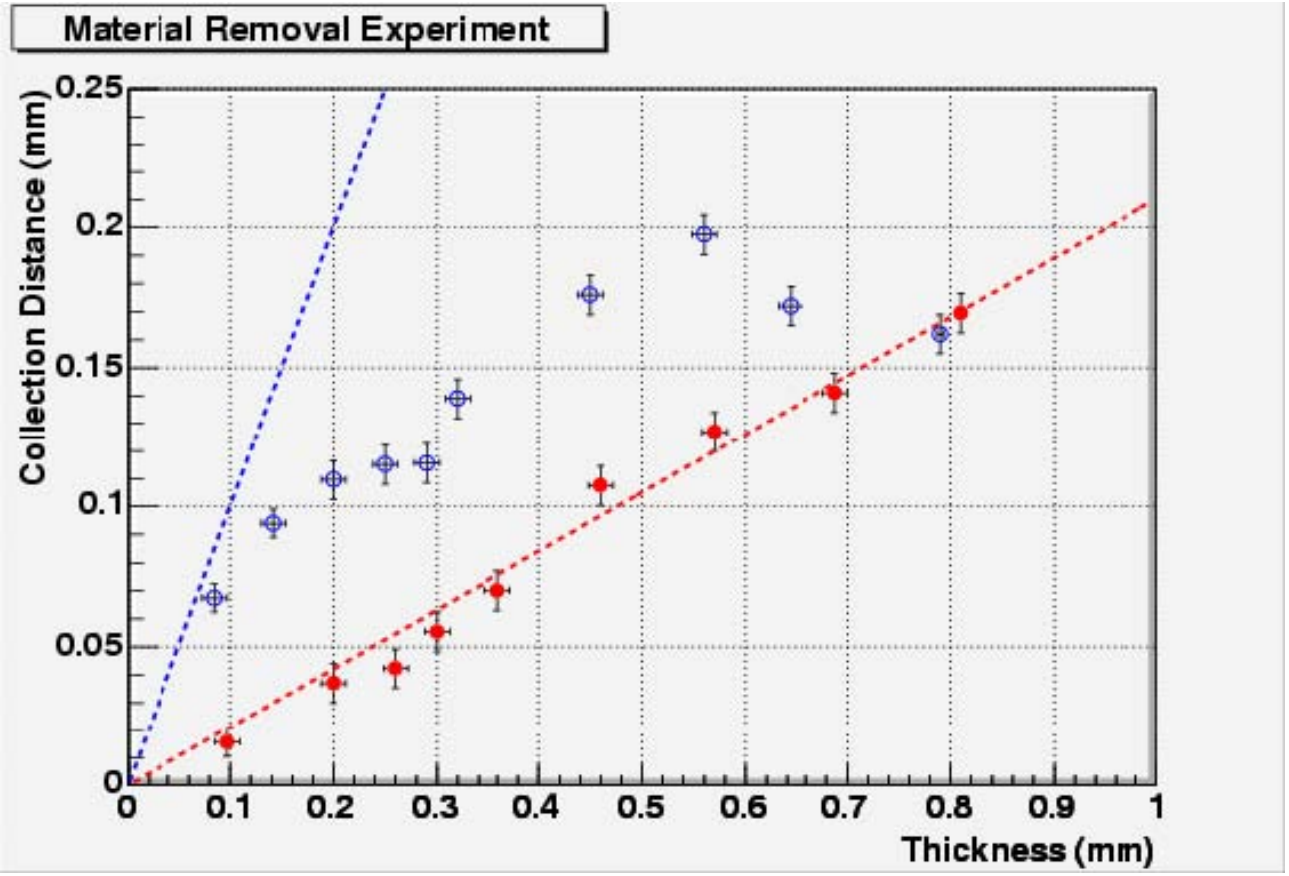
- D. Dobos
- K. Lantzsch
- H. Pernegger
- E. Stanecka

H. Jansen

DBM: Simulation/Reconstruction



Depth Characterisation of CVD Material



Material removal

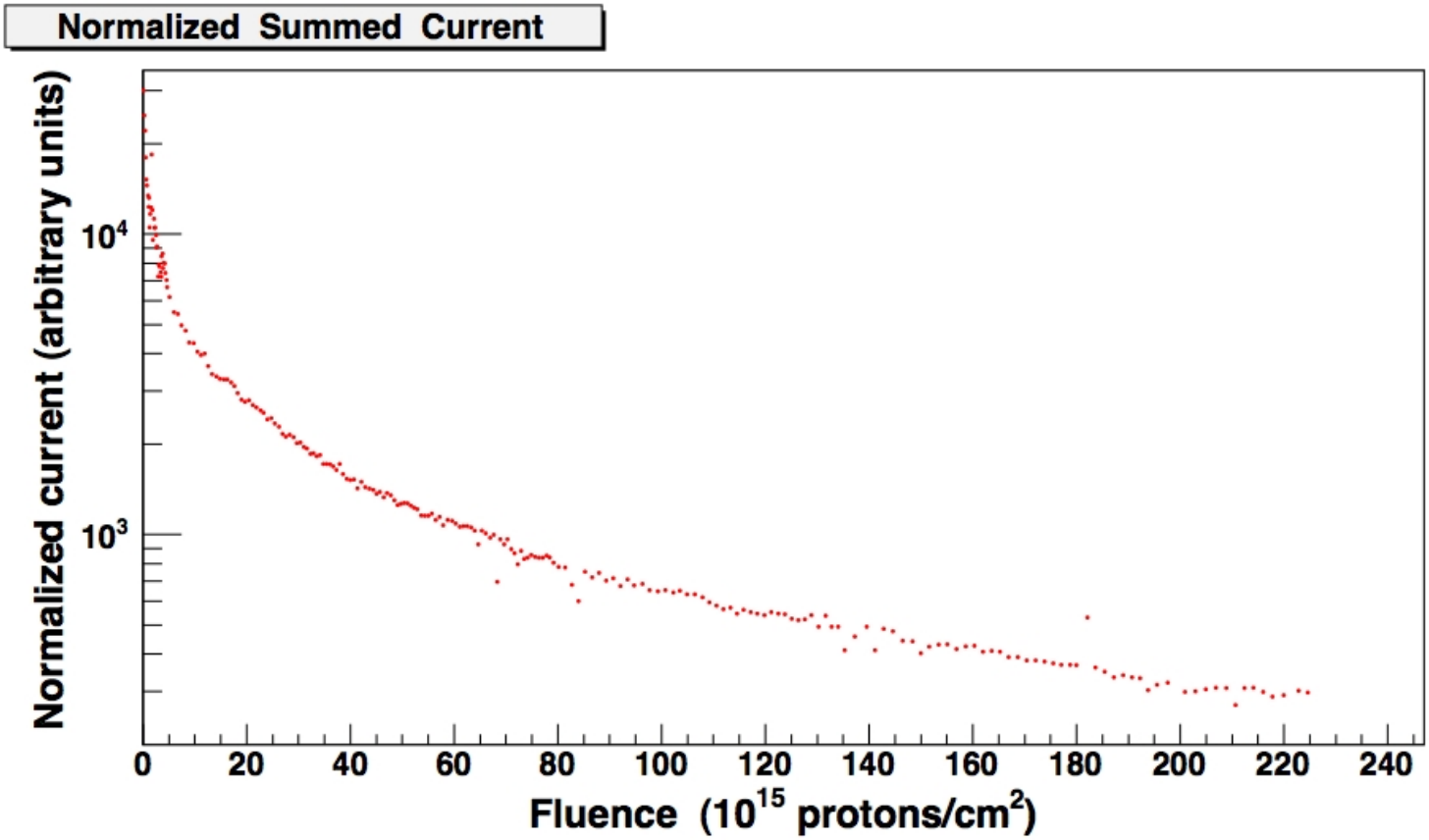
Growth side

Substrate side

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

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