Diamond for High Energy Radiation and Particle Detection

- How diamond works as a sensor material
  - Growth, signal, characterisation, manufacture
- Radiation tolerance
  - Tracker signals, irradiations, damage scaling
- Applications
  - Beam monitors: ATLAS BCM, BaBar, CDF, CMS
  - Pixel detectors: CMS PLT, ATLAS DBM

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July 22, 2011

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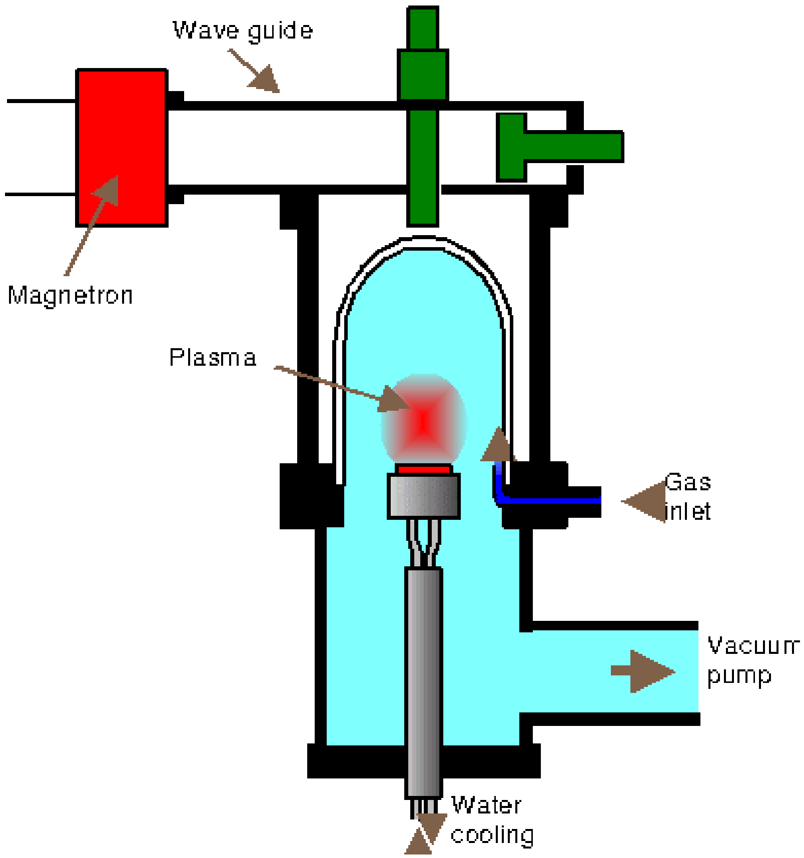
Over 100 Collaborators from 32 institutions

CVD Diamond as a Particle Detector

- Microwave growth reactor

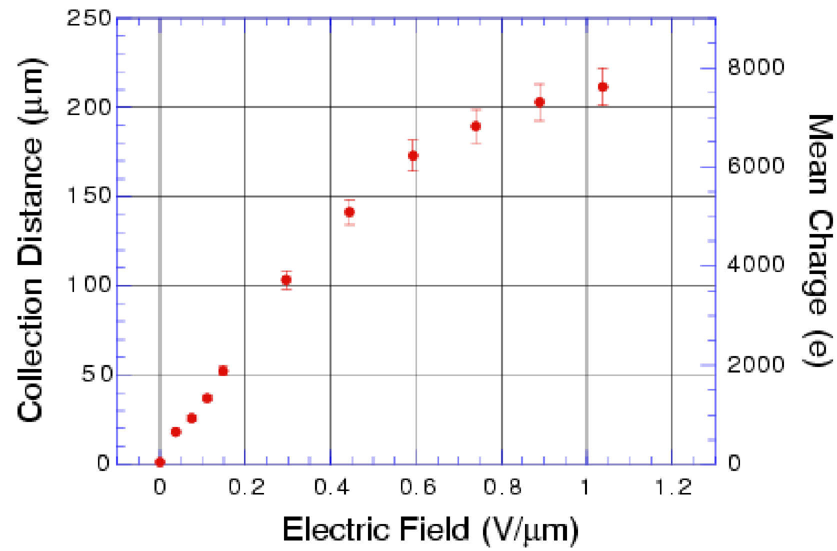


- Diamond synthesis from plasma

- Charge deposited Q_0; collected Q

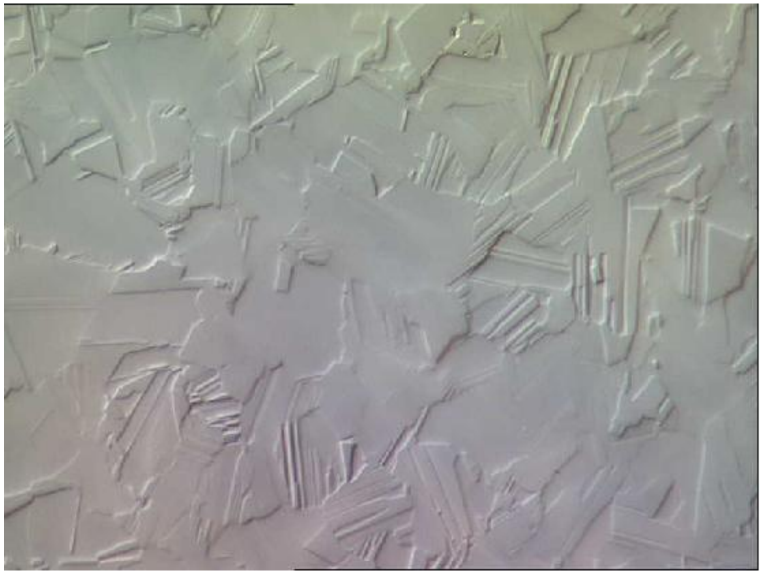
$$Q = \frac{\mathrm{d}}{t} \, Q_0$$

- d is the Charge Collection Distance
- t is the sensor thickness

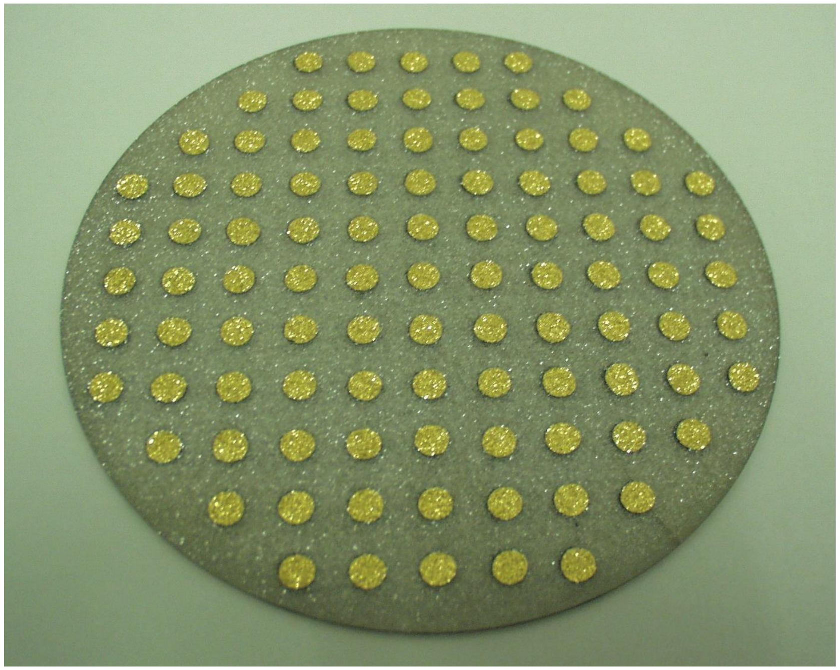


- Carrier velocity saturates at $|\vec{E}| \to 1V/\mu$m
- Typical operating point for sensors

Examples of CVD Material



Surface image of pCVD sample
(Courtesy Element6)

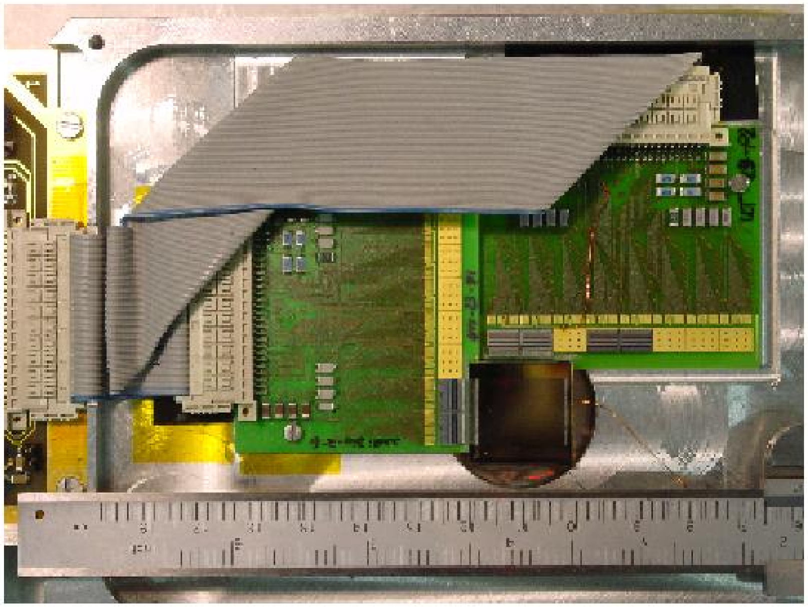


- pCVD diamond wafer
- Dots are on 1 cm grid

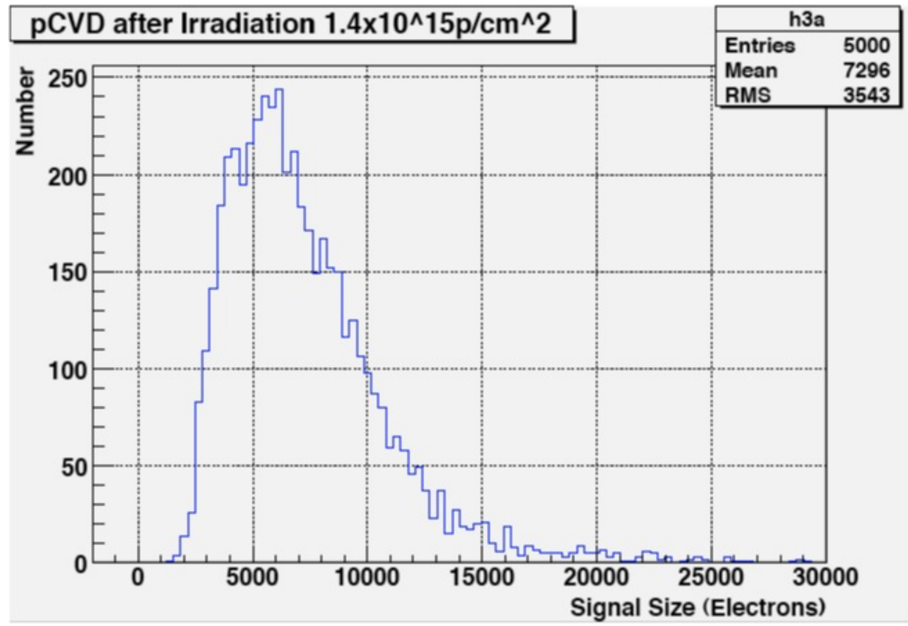
- High quality wafers grown 12 cm in diameter
- Best material from wafers grown up to 2 mm thick

Radiation Tolerance of Diamond Sensors

Typically tested as strip tracker



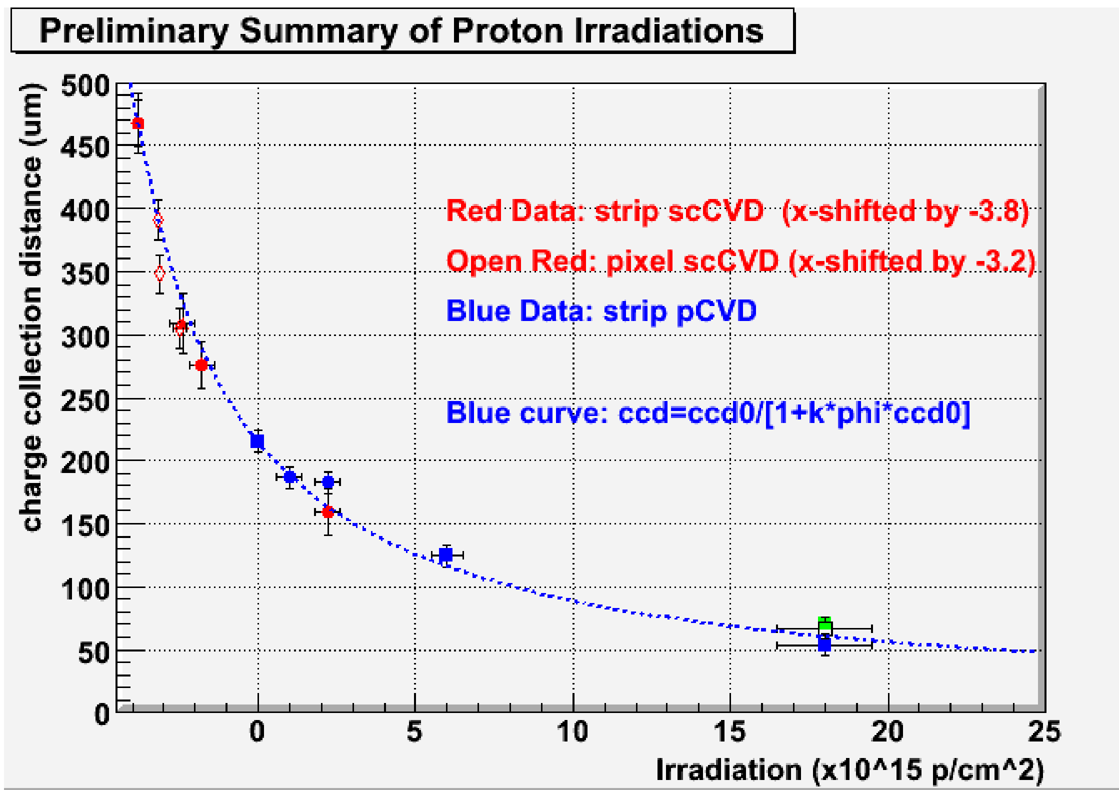
Pulse height from irradiated tracker



- 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

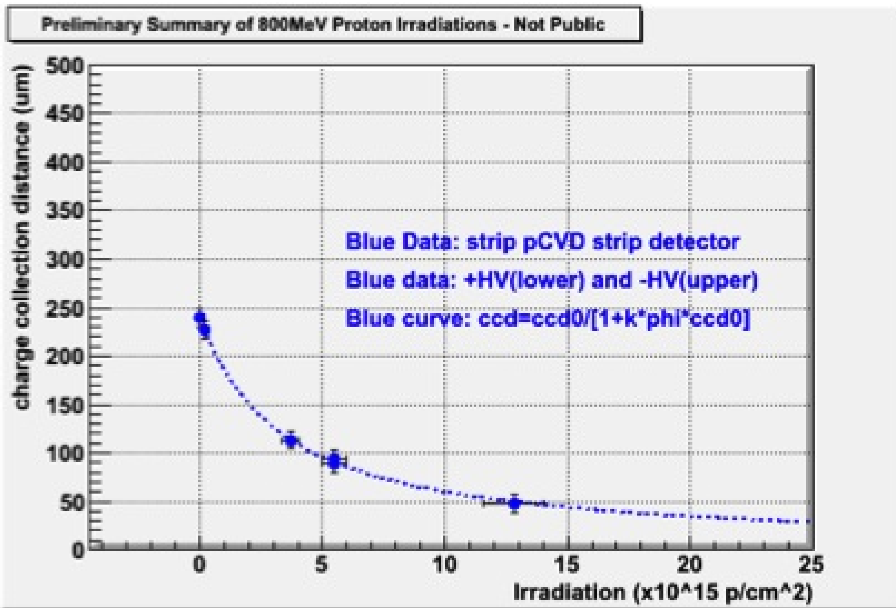
This pCVD material $\equiv$ scCVD material **after** $\approx 3.8 \times 10^{15}$ p/cm^2

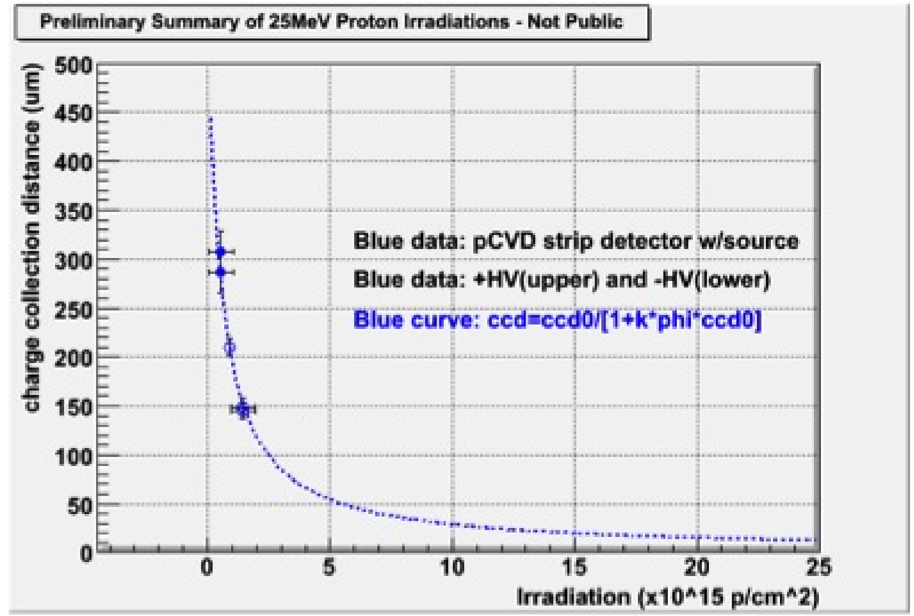
- pCVD and scCVD follow same damage curve:

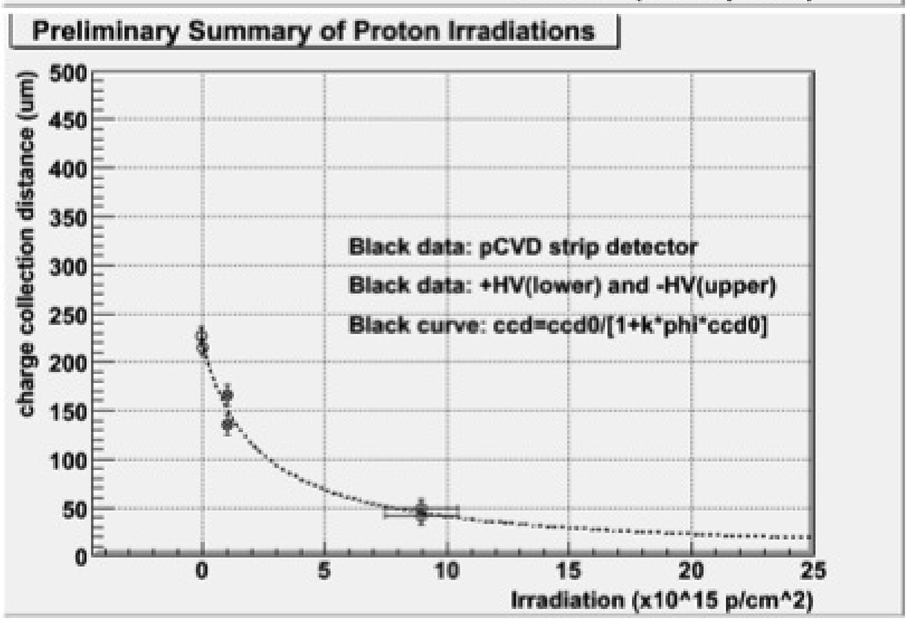
$$1/\mathrm{d} = 1/\mathrm{d}_0 + k\phi$$

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

Irradiations with Lower Energy Protons



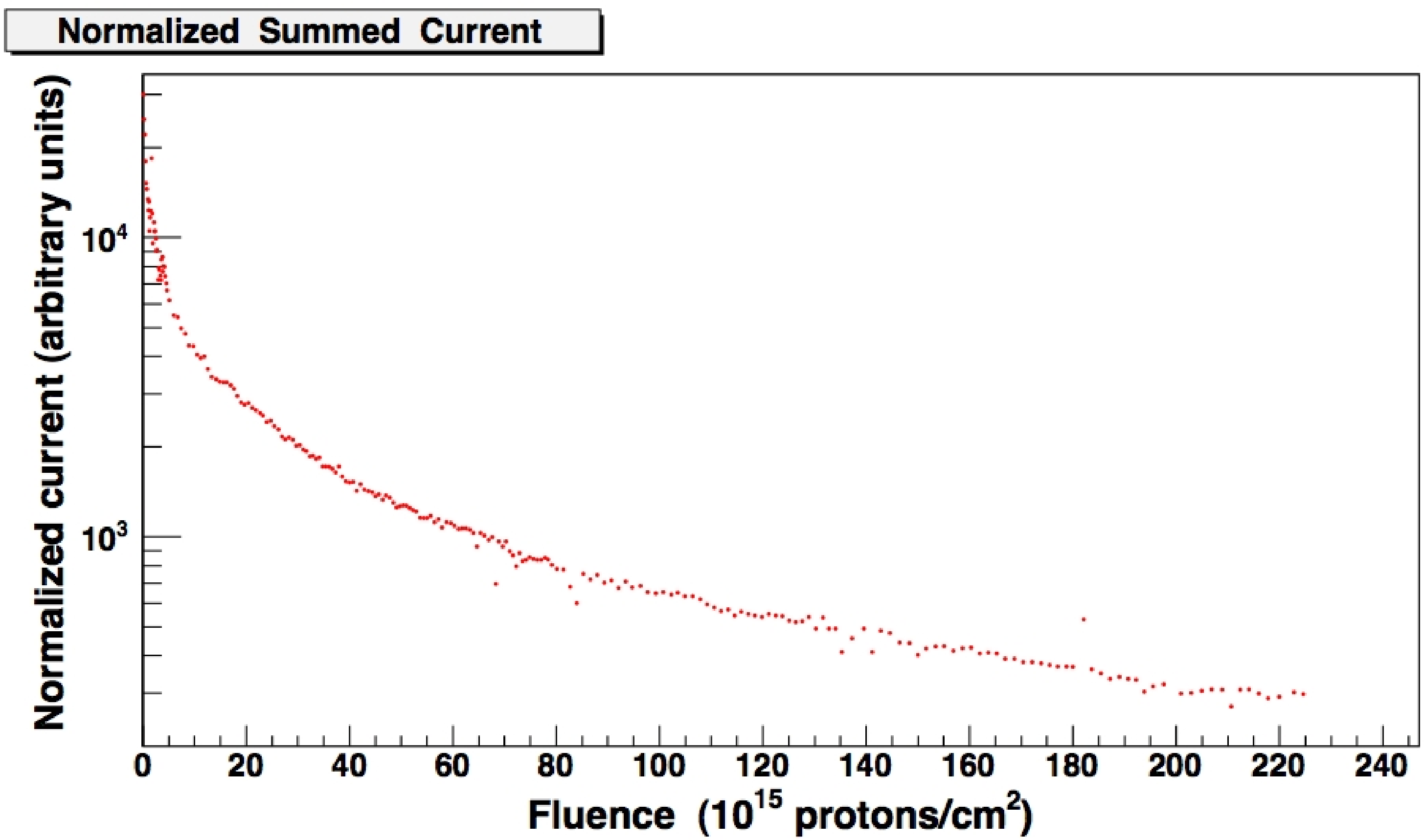




- 800 MeV protons (Los Alamos):
  1.9 times 24 GeV protons
- 70 MeV protons (Sendai):
  2.9 times 24 GeV protons
- 25 MeV protons (Karlsruhe):
  4.7 times 24 GeV protons

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 $\geq 10^{17}$



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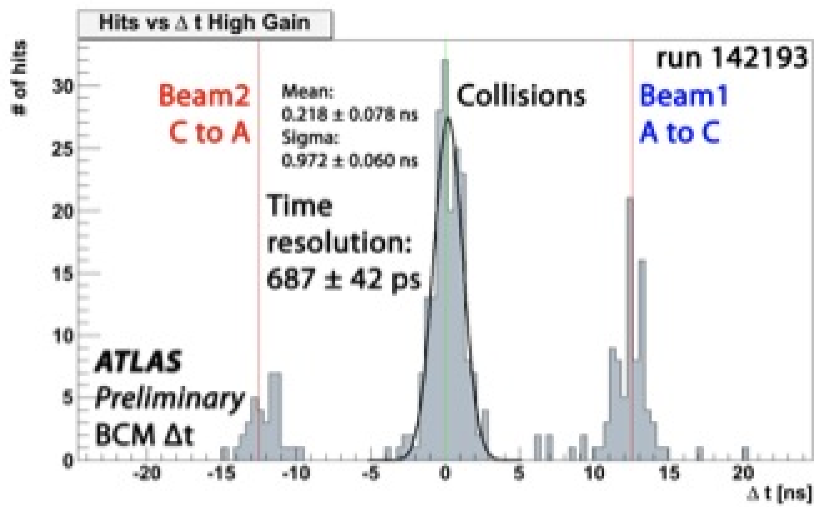
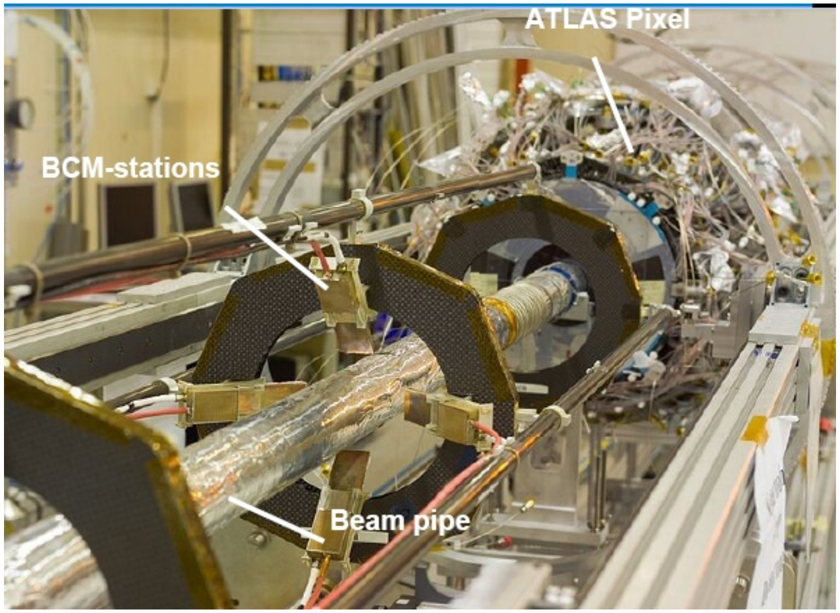
Applications of Diamond Sensors

- Several exciting applications for 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
    * LHC: ATLAS Beam Conditions Monitor
  - Pixel detector prototypes for LHC tracker upgrades
    * CMS Pixel Luminosity Telescope
    * ATLAS Diamond Beam Monitor

ATLAS Beam Conditions Monitor

- ATLAS BCM uses time-of-flight to distinguish collisions ($\Delta t = 0$) from background ($\Delta t = \pm 12$ns)
- Supported in pixel space-frame 1.9m from interaction point





- Use diamond sensors
  - 10x faster response and 10x more radiation hard than silicon
- Very fast, rad hard InGaP front end amplifier gives sub-ns resolution

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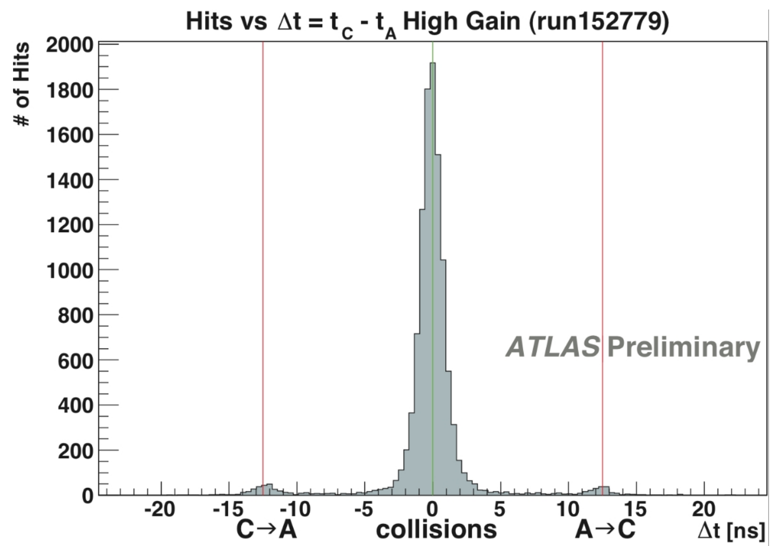

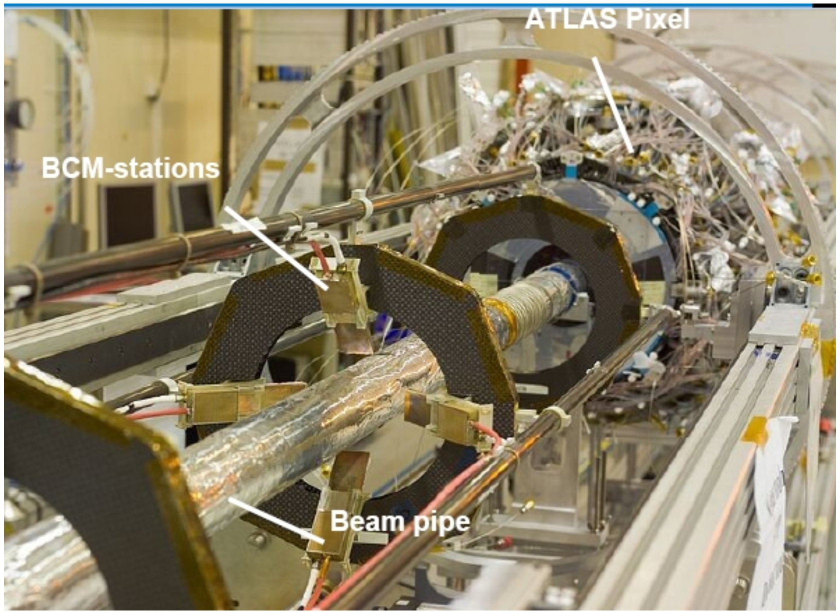

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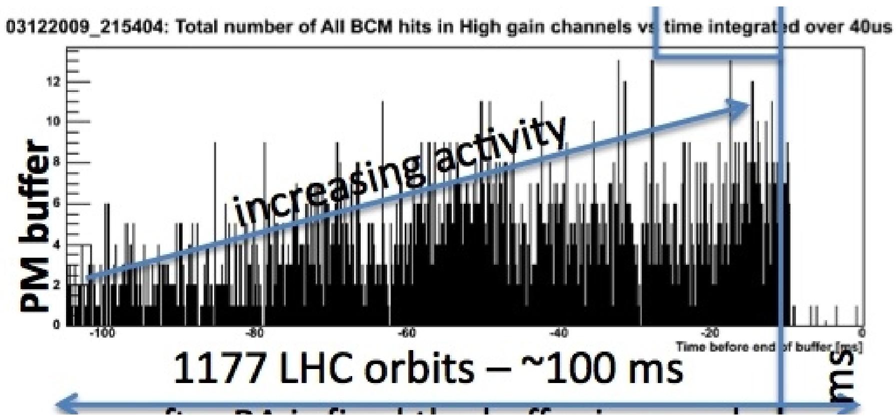
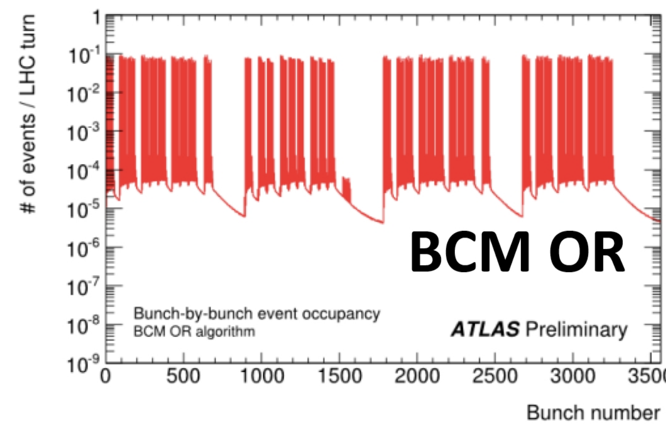
ATLAS BCM Performance

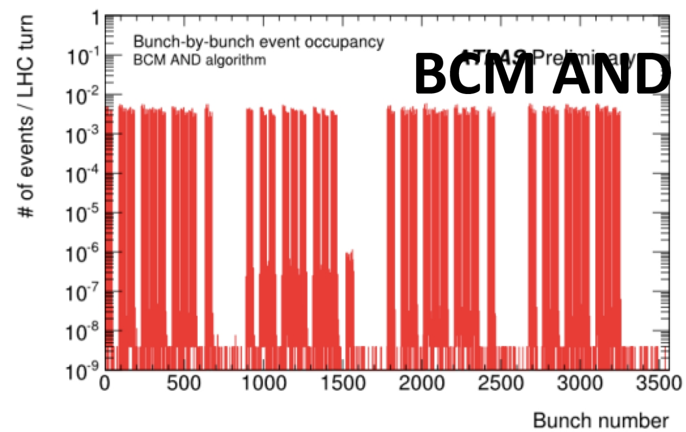
- Triggered abort in March 2010
- 3/4 stations on both sides of IP



- Sensitivity attenuated by 1/100
- Handful of abort conditions in 2011
- Analysing passively, prior to re-integration in LHC abort logic

- BCM provides online luminosity

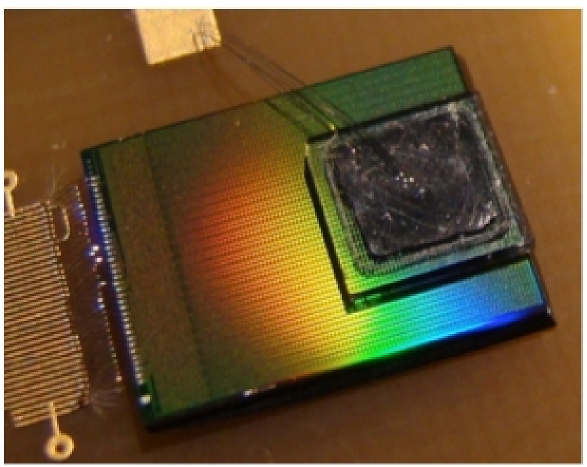




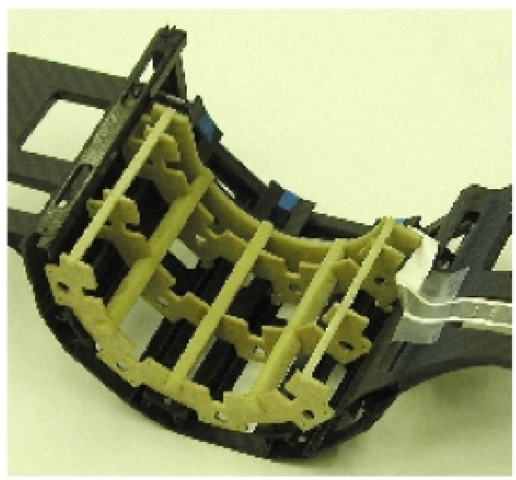
- Pile-up insensitive to $\mathcal{L} \approx 10^{34}$
- Provides automatic feedback after every beam-dump ($\approx$ 1000/year)

CMS Pixel Luminosity Telescope

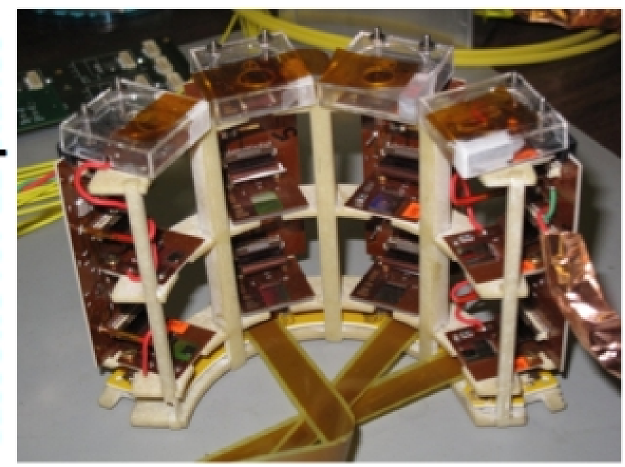
- Stand-alone luminosity monitor
  - Eight 3-plane pixel telescopes at each side of CMS
  - 0.4×0.4 cm^2 single crystal sensors at $r = 4.8$cm, $z = 175$cm
- Count 3-fold coincidences “fast-or” (40 MHz)
- Full pixel readout (tracking) (1 kHz)
- 1% bunch-by-bunch relative luminosity precision possible in minutes



PLT plane



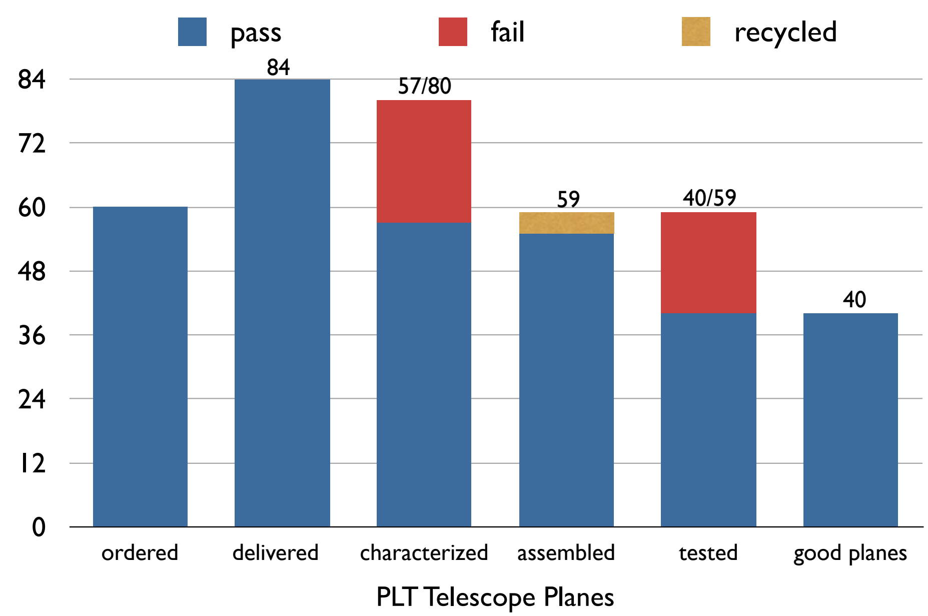
Cassette for 12 planes



Full cassette in test-beam

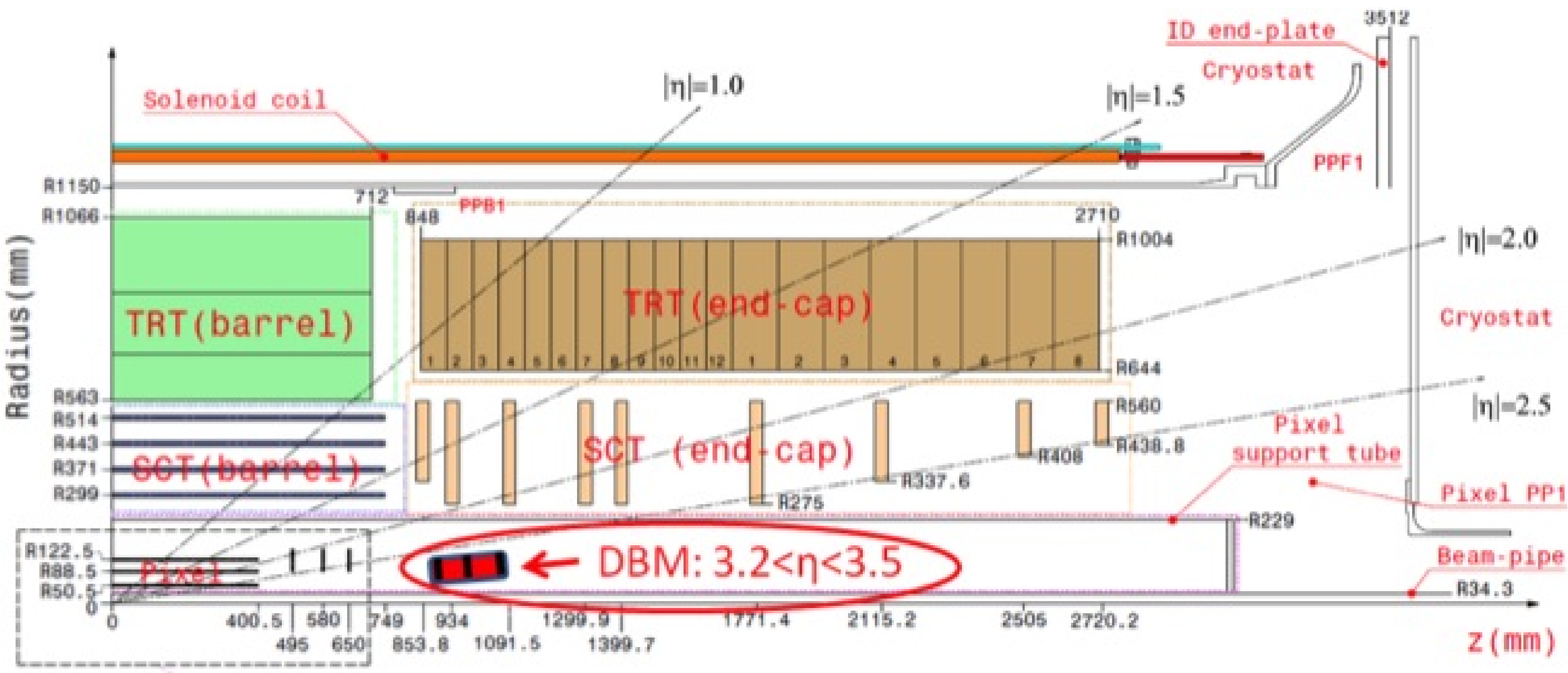
CMS PLT Construction Status

- Producing 60 planes (48 installed)
  - 57/80 sensors good (71%)
  - Failures replaced by vendor
- 40/59 modules assembled and working (70%)
- Full system test in beam **now**
- Plan to install in 2012



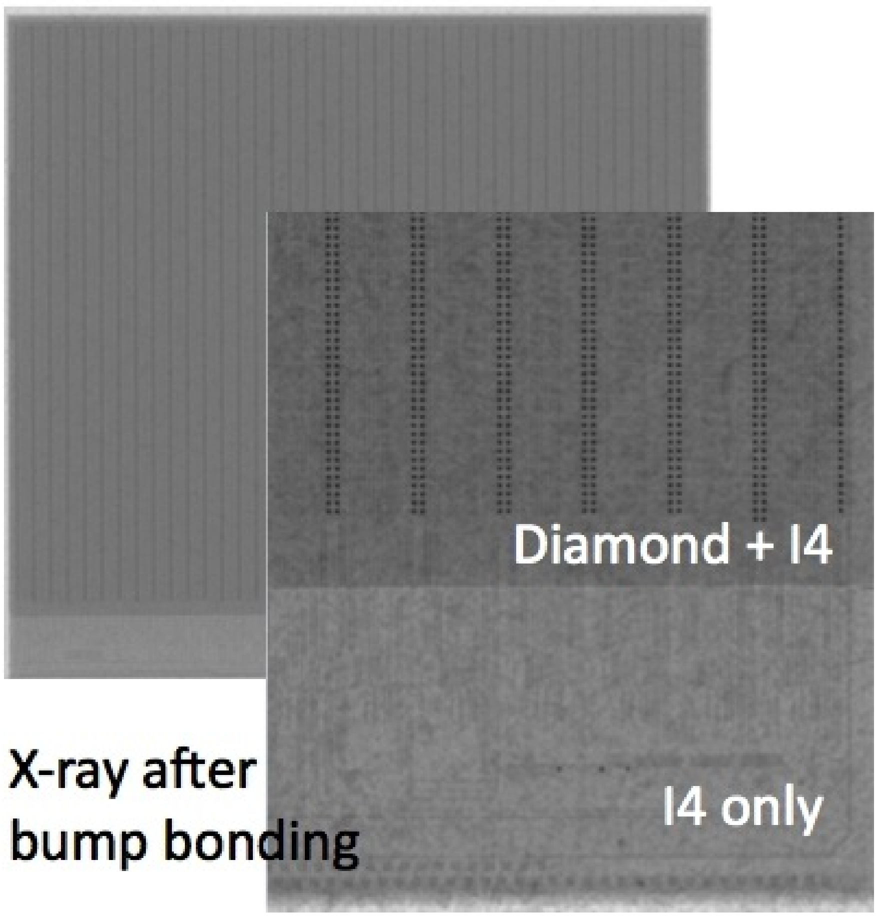
Diamond Beam Monitor

- Diamonds were a candidate sensor for ATLAS IBL upgrade
- Eight 3-plane telescopes around ATLAS interaction point
- Use enhanced spatial resolution to
  - Complement timing precision from BCM
  - Provide luminosity and beam-spot monitoring
- Install with ATLAS IBL in 2013

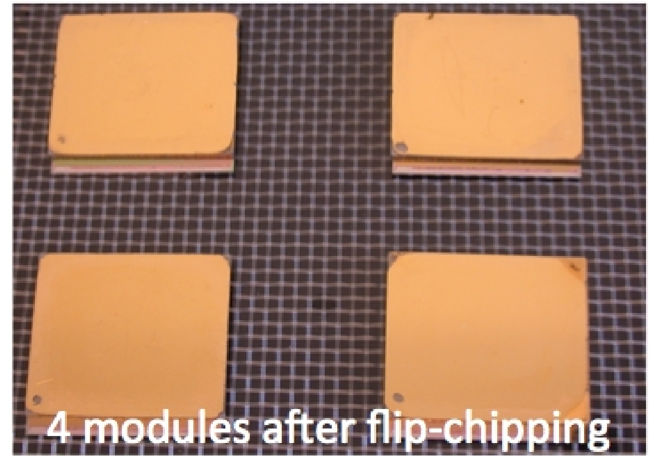


Current State of the ATLAS DBM

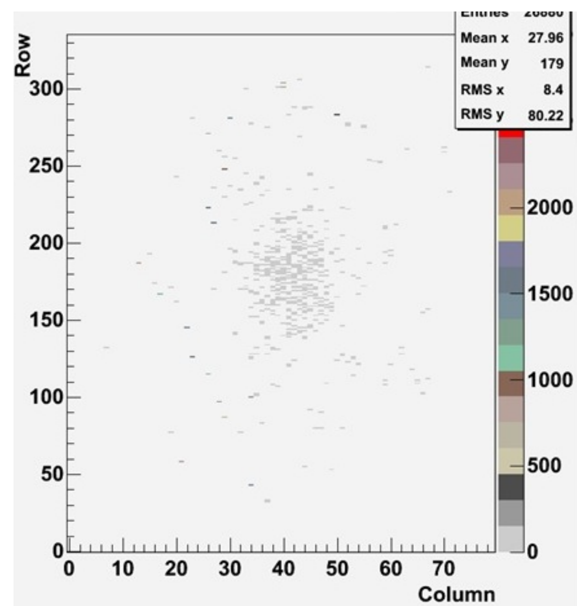
- Four modules assembled at IZM
  - 21x18 mm^2 sensors from DDL
  - 27k pixels $50 \times 250\mu m^2$
- Bumps look good in x-ray



- Modules under test in lab now

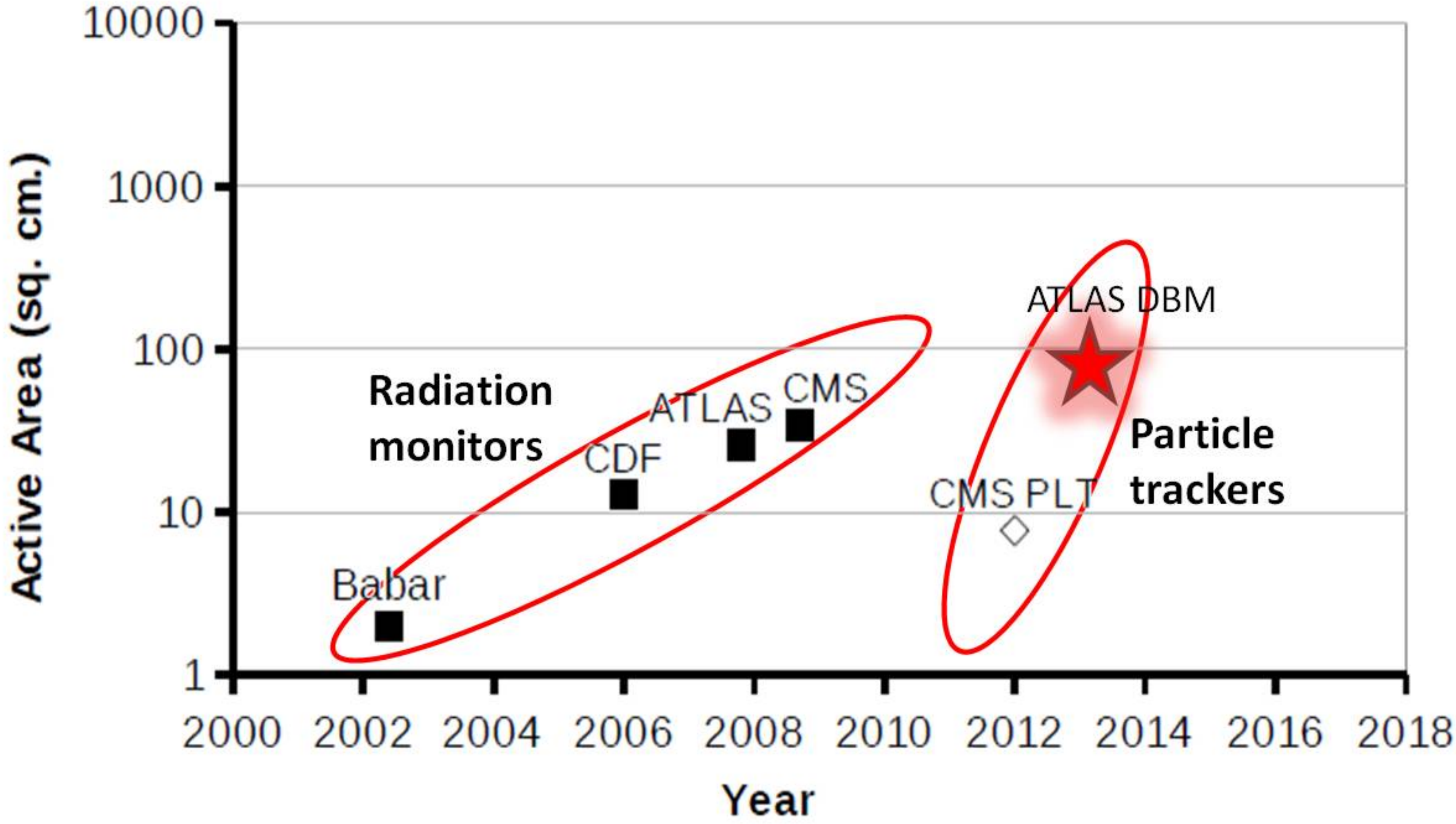


- First source signals seen



- Test in beam in early August

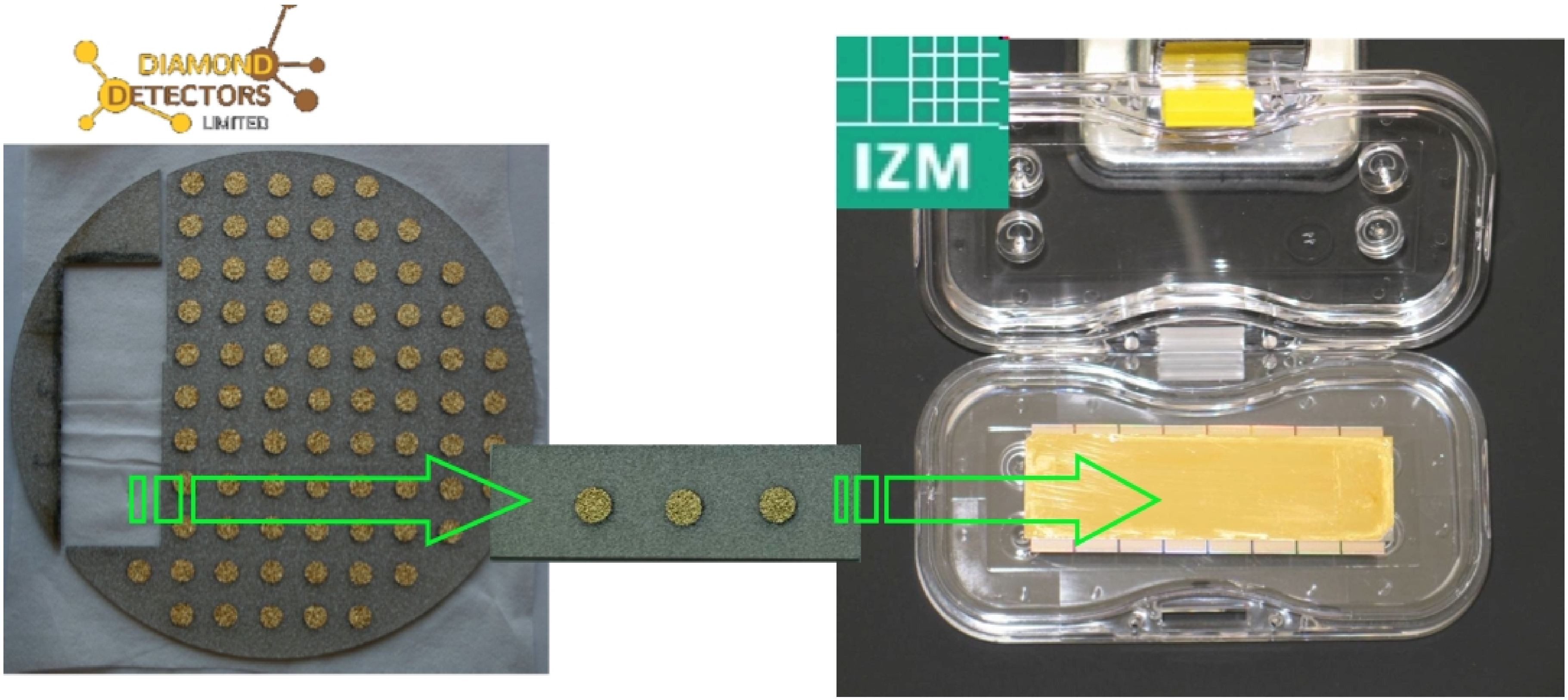
Diamond Detector Systems in HEP



Summary

- Ever improving understanding of radiation damage in diamond
  - Quantifying damage from different species of particles
  - Beginning to understand the source of damage mechanisms
- Application in all LHC experiments, the machine itself and beyond
- Pixel modules are being assembled in industry
- Diamond trackers should start to appear in the next few years
- Promising for future LHC upgrades at the inner-most radii

Industrial Diamond Pixel Module Production



- Work done as part of ATLAS IBL sensor qualification process
- Plan to use 24 Diamond IBL modules as enhanced beam monitor

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	