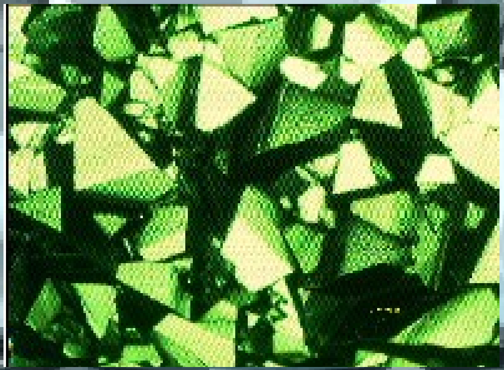
Diamond Sensors
for High Energy Radiation and Particle Detection



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TIPP 2011
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Outline

- Diamond as sensor material
- Radiation hardness: RD-42
- Diamond sensor applications
  - Radiation detection – beam monitors
    - ATLAS BCM/BLM
    - CMS BCM
  - Particle tracking
    - CMS PLT
    - ATLAS DBM

Diamond as sensor material

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	

Sensor types - pCVD

- Polycrystalline Chemical Vapour Deposition (pCVD)
  - Grown in µ-wave reactors on non-diamond substrate
  - Exist in Φ = 12 cm wafers, >2 mm thick
  - Small grains merging with growth
  - Grind off substrate side to improve quality

    → ~500-700 µm thick detectors

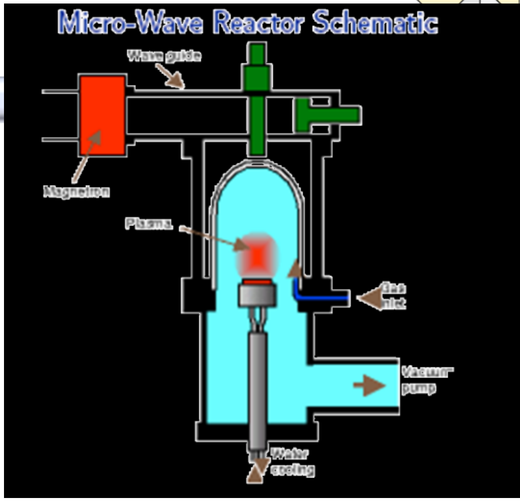
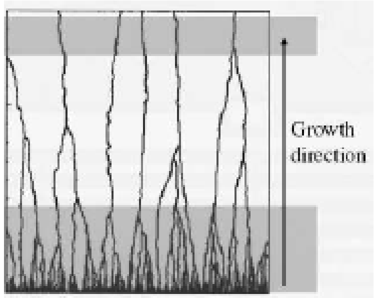
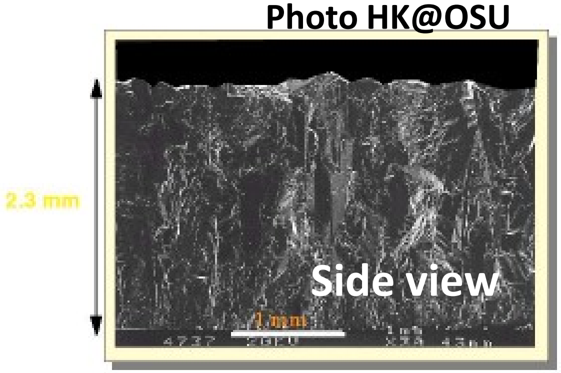


Photo HK@OSU

Test dots on 1 cm grid

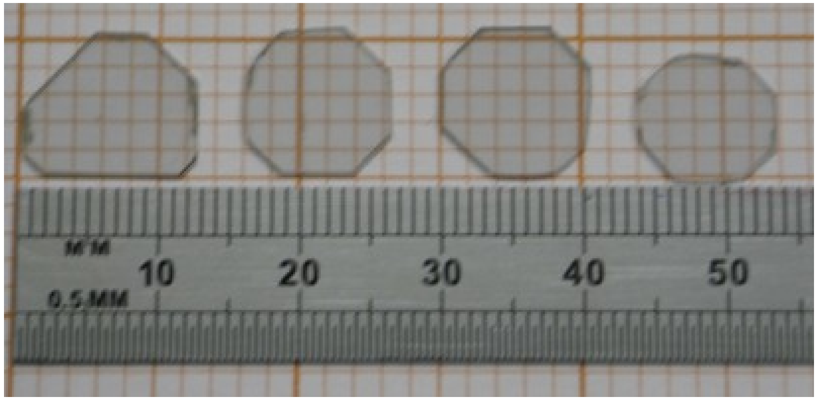


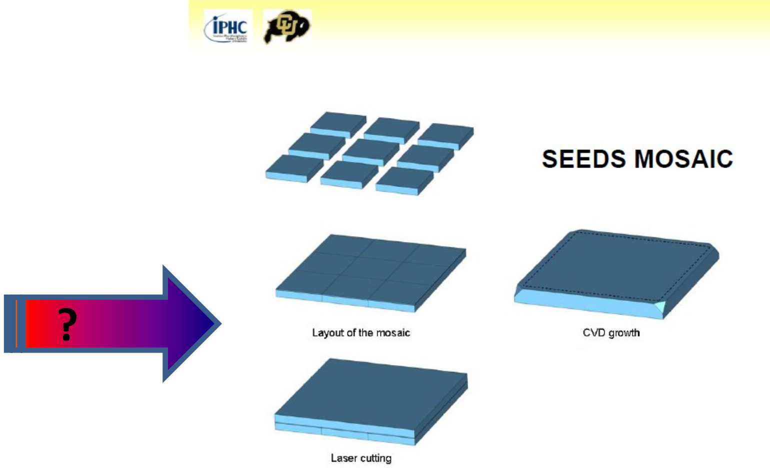


Photograph courtesy of E6

Sensor types - scCVD

- Single Crystal Chemical Vapour Deposition (scCVD)
  - Grown on HTHP diamond substrate
  - Exist in ~ 1 cm^2 pieces, max 1.4 cm x 1.4 cm, thickness > 1 mm
  - A true single crystal





☺ Fall-forward for sLHC pixel upgrade (single chips, wafers ?)

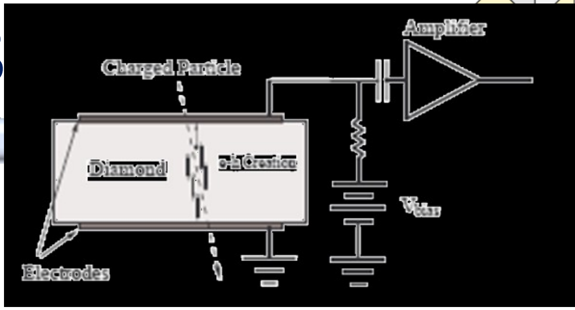
- ➢ Needs significant improvement in size & price, ideas are around
- ➢ After heavy irradiations properties similar to pCVD, headroom ~$3x10^{15}$ p/cm^2

☹ Recent commercial developments in adverse direction

- ➢ Concentrate on max. ~5x5 mm^2 pieces & packaging, main target market: dosimetry

➢ Used on large scale in CMS PLT project

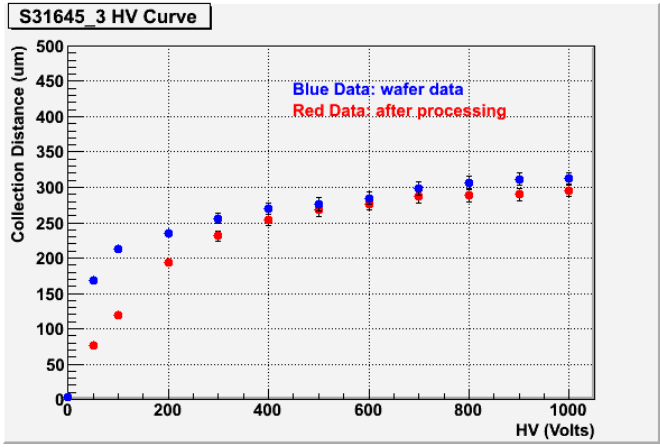
Signal from CVD diamonds



- No processing: put electrodes on, apply electric field
  - Surface preparation and metallization **non-trivial !**
- Trapping on grain boundaries (pCVD) and in bulk
  - Much like in heavily irradiated silicon
- Parameterized with Charge Collection Distance, defined by

$$CCD = \frac{<Q_{col}>}{36\frac{e_0}{\mu m}}$$

☝ **mean** not **most probable**



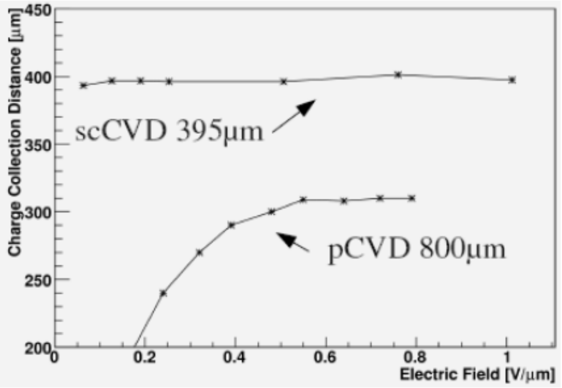
***CCD* measured on recent 1.4 mm thick pCVD wafer from E6, and after thinning to 0.8 mm**

- *CCD* = average distance e-h pairs move apart
- Coincides with mean free path in infinite ($t \gg CCD$) detector, *CCD* ~ *t* for scCVD

$$Q_{col} = Q_{created}\frac{d}{t}$$

$$d = d_e + d_h - \text{distance e-h move apart}$$

$$t \text{ - detector thickness}$$



***CCD* vs. field for pCVD and scCVD diamond**

Radiation damage in diamond

Radiation induced effect	Diamond	Operational consequence	Silicon	Operational consequence
Leakage current	small & decreases	none	$I/V = \alpha\Phi$ $\alpha \sim 4\text{x}10^{-17}$ A/cm	Heating Thermal runaway
Space charge	~ none	none	$\Delta N_{eff} \approx -\beta\Phi$ $\beta \sim 0.15\ \text{cm}^{-1}$	Increase of full depletion voltage
Charge trapping	Yes	Charge loss Polarization	$1/\tau_{eff} = \beta\Phi$ $\beta \sim 4\text{-}7\text{x}10^{-16}\ \text{cm}^2/\text{ns}$	Charge loss Polarization

Charge multiplication

- At extreme fluences charge trapping the paramount radiation damage effect
- Difference O(10) in x-section between charged/neutral traps
  - Filled (neutral) traps trap less (of the opposite carrier)
  - Basics of "pumping"
- E_{gap} in diamond 5 times larger than in Si
  - Many processes freeze out
  - Typical emission times order of months
- Works also in Si at 300/5 = 60 K – "Lazarus effect"

$$\frac{1}{\tau_{eff}} = \sum_t N_t (1-P_t)\sigma_t v_{th}$$

Radiation damage studies: RD-42

RD42 Collaboration 2011

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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30 Texas A&M, Collage Park Station, TX USA
31 University of Tennessee, Knoxville TN USA
32 INFN-Lecce, Lecce, Italy

100 participants from 32 institutes

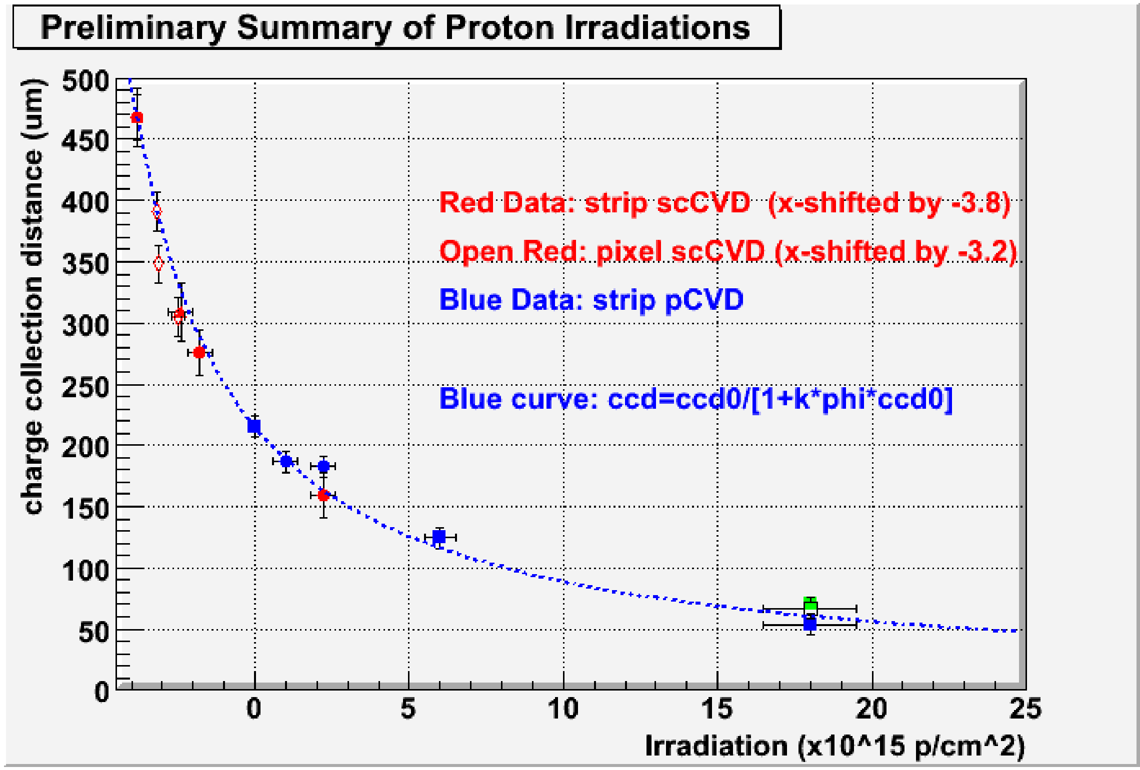
Irradiation: 24 GeV protons (PS)

- For mean free path in infinite detector expect

$$\frac{1}{CCD} = \frac{1}{CCD_0} + k \times \Phi$$

- With CCD_0 initial trapping, k a damage constant
  - Larger CCD_0 **performs better (larger collected charge) at any fluence**
  - Can turn 1/ CCD_0 into effective “initial” fluence
  - expect $CCD_0 \sim \infty$ for scCVD
  - **pCVD and scCVD diamond follow the same damage curve**

- k ~ **0.7x10^{-18} μm^{-1}cm^{-2}** for PS (24 GeV) protons

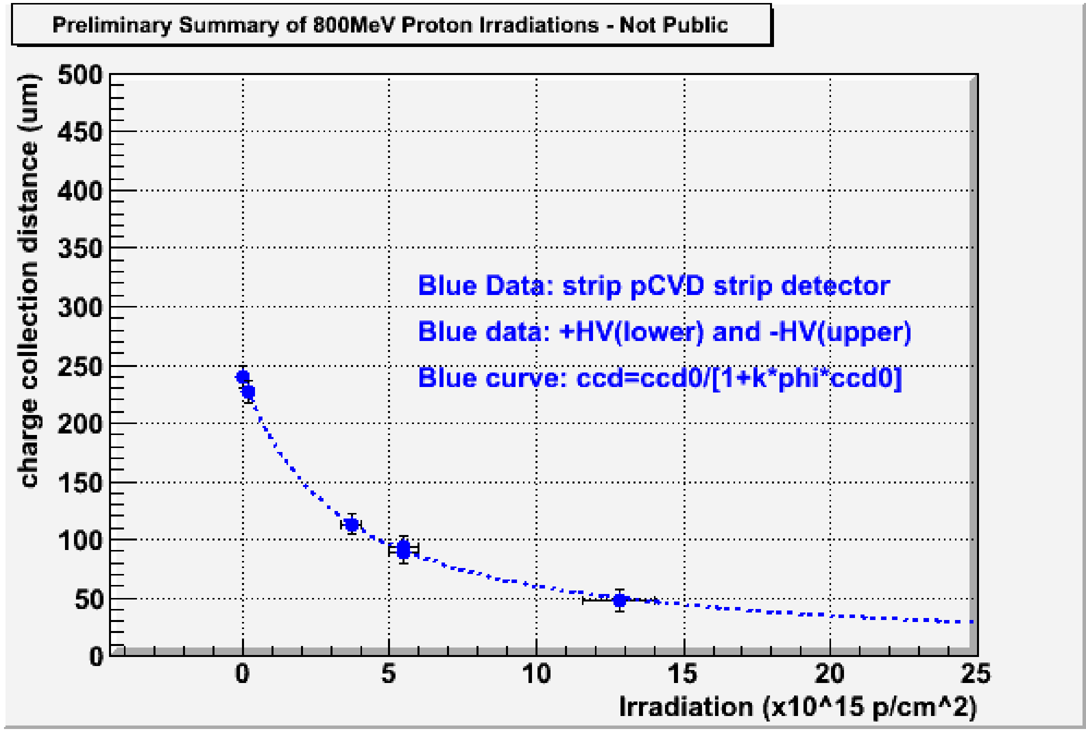


Test beam results

Irradiation: 800 MeV protons (LANL)

- Recent irradiations with 800 MeV protons at LANSCE Facility in Los Alamos, US
- ~2x more damaging than PS protons

  k ~ **1.3x10^{-18} µm^{-1}cm^{-2}**
- Consistent with NIEL prediction
- Work in progress, one more data point being analyzed



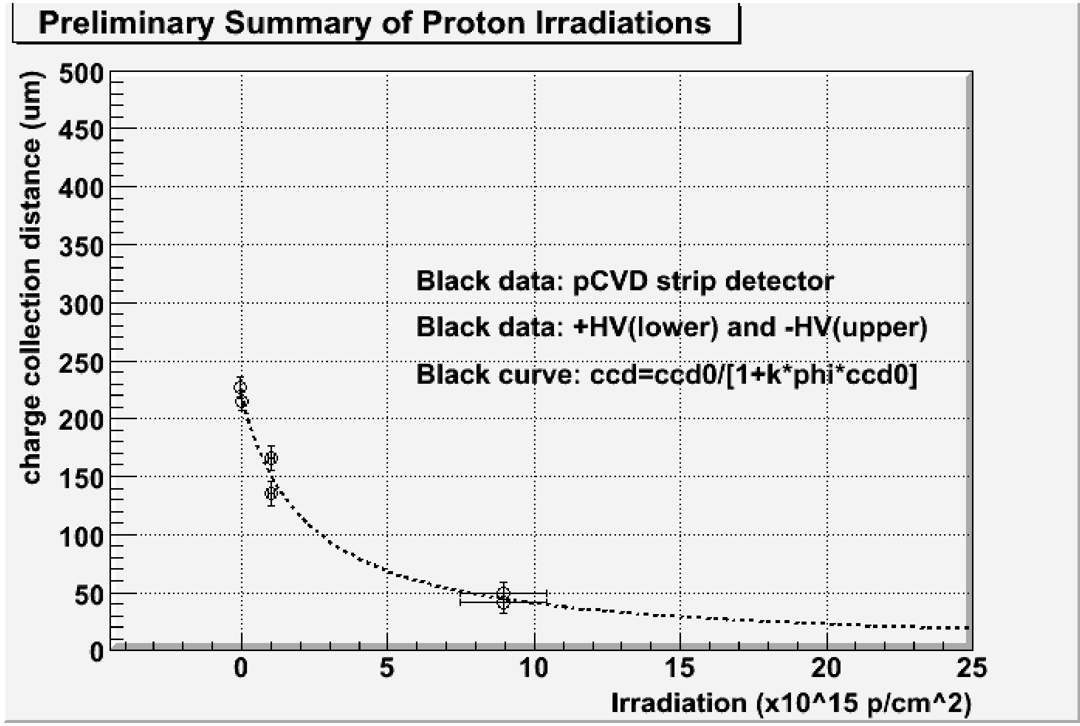
Test beam results

Irradiation: 70 MeV protons (Sendai)

- Recent irradiations with 70 MeV protons at Cyric Facility in Sendai, Japan
- 3x more damaging than PS protons

  ***k* ~ 2×10^{-18} $\mu m^{-1} cm^{-2}$**

- NIEL prediction
  - factor of 6
  - NIEL violation ?!
- One more sample being analyzed

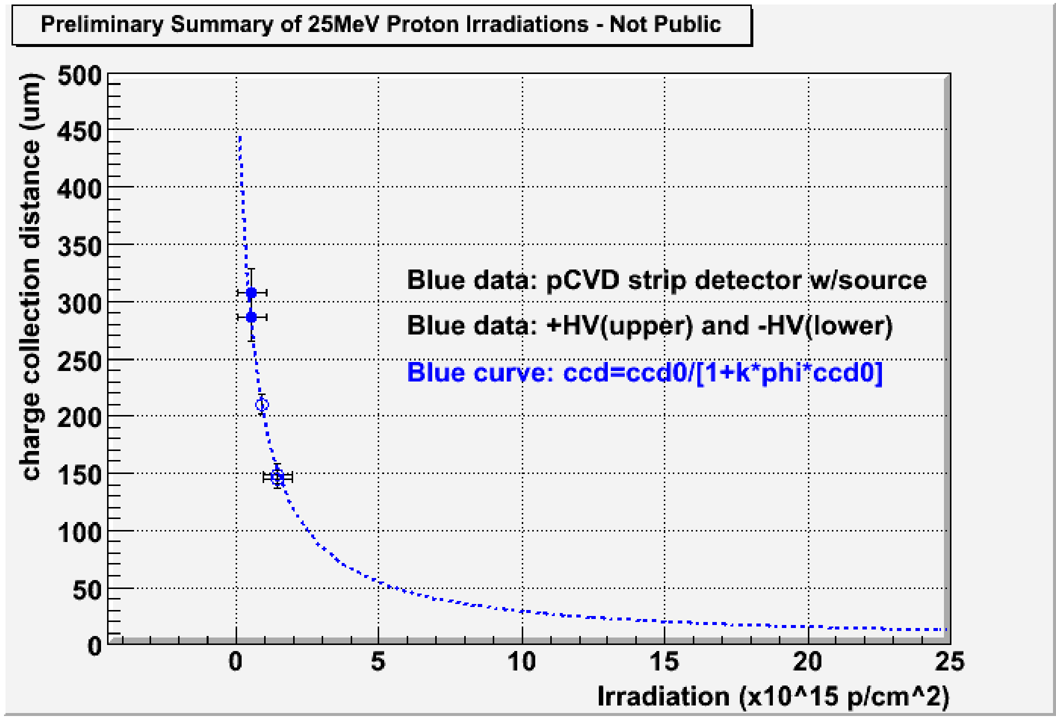


Test beam results

Irradiation: 25 MeV protons (KIT)

- Recent irradiations with 25 MeV protons at Karlsruhe, Germany
- 5x more damaging than PS protons

  $k \sim 3.3\text{x}10^{-18}\ \mu m^{-1} cm^{-2}$
- NIEL prediction
  - factor of 15
  - NIEL violation !
- Work in progress

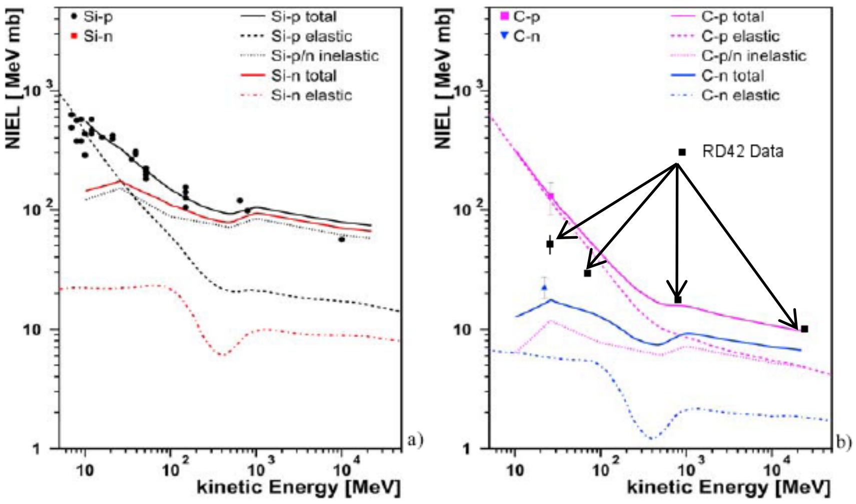


Source/test beam results

NIEL/DPA calculations

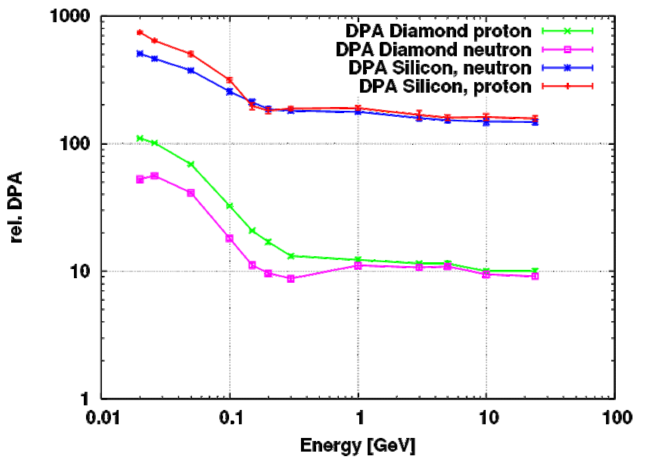
- NIEL calculations published by KIT group in Phys. Stat. Sol.
  - Protons
    - Ratio 800 MeV / 24 GeV: ~ 2 ✓
    - Ratio 70 MeV / 24 GeV: ~ 6 !
    - Ratio 25 MeV / 24 GeV: ~ 15 !!
  - Neutrons
    - 10 MeV n ~ 24 GeV p !!
- Recent calculation by S. Mueller based on displacement per atom (DPA) value given by FLUKA (development version, preliminary)
  - Proton ratios: 1.2, 5, 10 (800, 70, 25MeV)
  - n(10 MeV)/p(24 GeV) ratio: 6 ✓

☹ NIEL not fully applicable to diamond



W. de Boer et al.

Steffen Mueller - preliminary



Damage constant from scCVD data

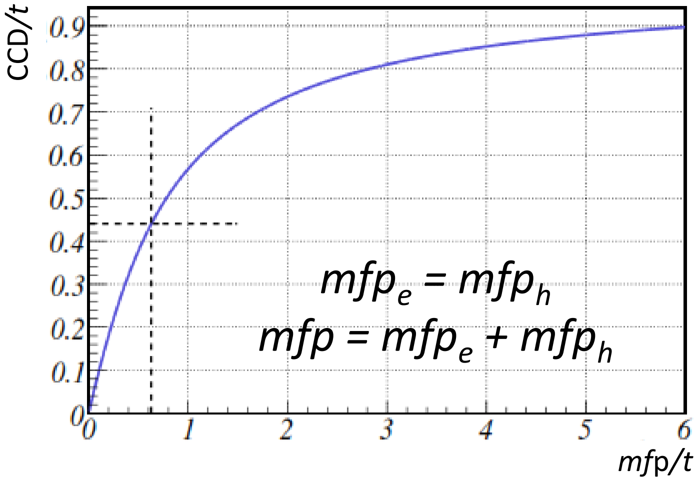
- The radiation induced introduction of traps decrease the mean free path *mfp*
- We measure *CCD*
- *CCD~ mfp_e+mfp_h* in thick detectors *t >> mfp, CCD*
- CCD degradation formula not applicable to scCVD since $CCD_0 = t$; $mfp_0 \rightarrow \infty$
- Relation *CCD* ↔ *mfp* for homogeneous material

$$\frac{1}{mfp} = \frac{1}{mfp_0} + k \times \Phi$$

$$CCD = \frac{< Q_{col} >}{36 \dfrac{e_0}{\mu m}}$$

$$CCD = \sum_{e,h} mfp_{e,h} \left[1 - \frac{mfp_{e,h}}{t} (1 - \exp(-\frac{t}{mfp_{e,h}})) \right]$$

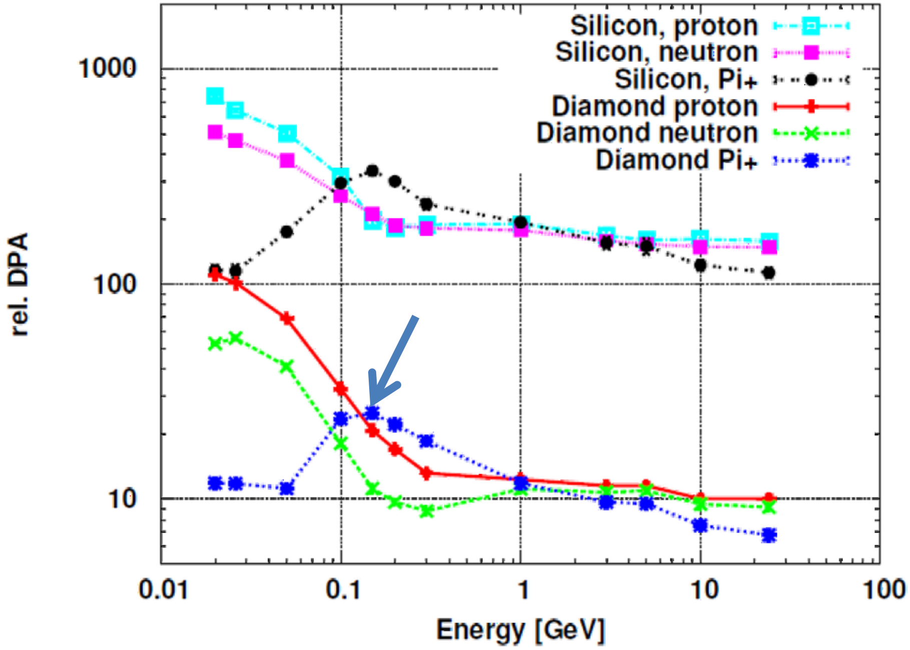
- For lack of data assume $mfp_e = mfp_h$
- Comparison:
  - 24GeV p $k_{sc} = 0.9\text{x}10^{-18}\mu m^{-1}cm^{-2}$ ~ $k_{pCVD} = 0.7\text{x}10^{-18}\mu m^{-1}c$
  - 25MeV p $k_{sc} = 3.0\text{x}10^{-18}\mu m^{-1}cm^{-2}$ ~ $k_{pCVD} = 3.3\text{x}10^{-18}\mu m^{-1}c$
- Work in progress, but looks quite good!



scCVD irradiation at PSI

- Single scCVD, *d* = 500 µm, irradiated with 200 MeV pions at PSI, Villigen, CH
- Measured (source) *CCD* = 260 µm after 6.52x10^{14} π/cm^2
- Turns into *mfp* of 420 µm
- ***k* = 3.6x10^{-18} µm^{-1}cm^{-2}**
- Appears high, but DPA peaks at 200 MeV (Δ)
- Again, work in progress
  - Test-beam under way

$$\frac{1}{mfp} = k \times \Phi$$



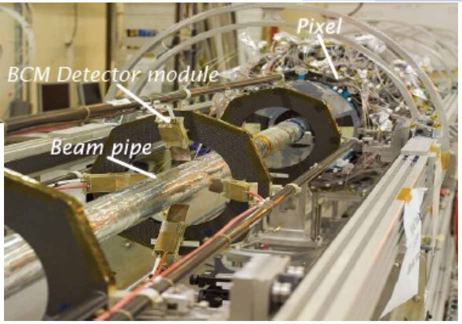
Steffen Mueller – priv. comm.

Diamond sensor applications in HEP

- All LHC exp's use diamonds for beam monitoring & accident protection
  - Current and counting mode operation, TOF capability
  - *O*(100) diamond sensors employed
- CMS is building Pixel Luminosity Telescope
  - 48 scCVD pixel modules (5 mm x 5 mm)
- ATLAS is proposing Diamond Beam Monitor
  - 24 pCVD pixel modules (21 mm x 18 mm)
- Upgrade plans include diamond as candidate for innermost pixel tracker layer(s)
- Elaborate on four projects
  - Radiation monitoring: ATLAS BCM/BLM, CMS BCM/BCM-F
  - Particle detection: CMS PLT, ATLAS DBM

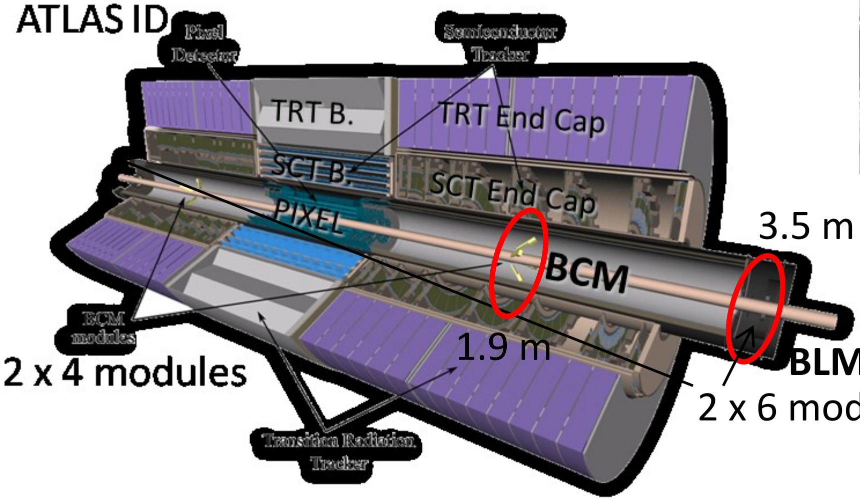
ATLAS BCM/BLM

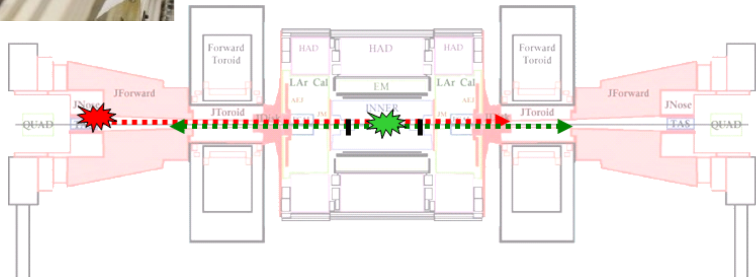
TIPP talk by M. Fisher



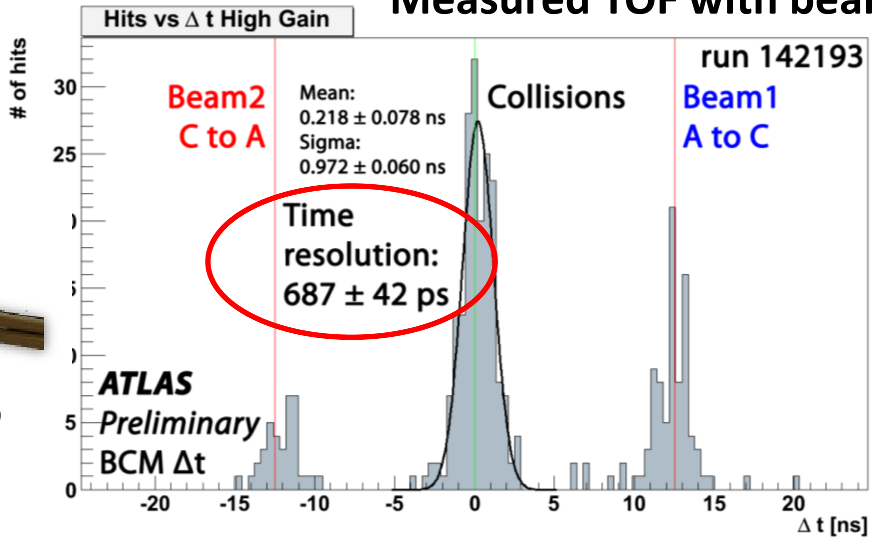
BCM TOF concept

- Collisions: in time
- Background: out of time

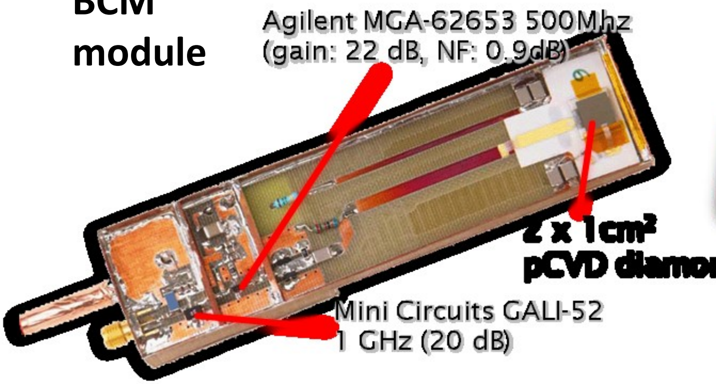




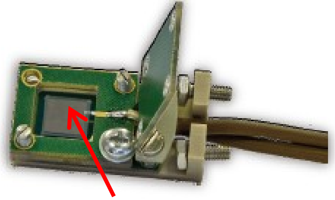
Measured TOF with beam



BCM module

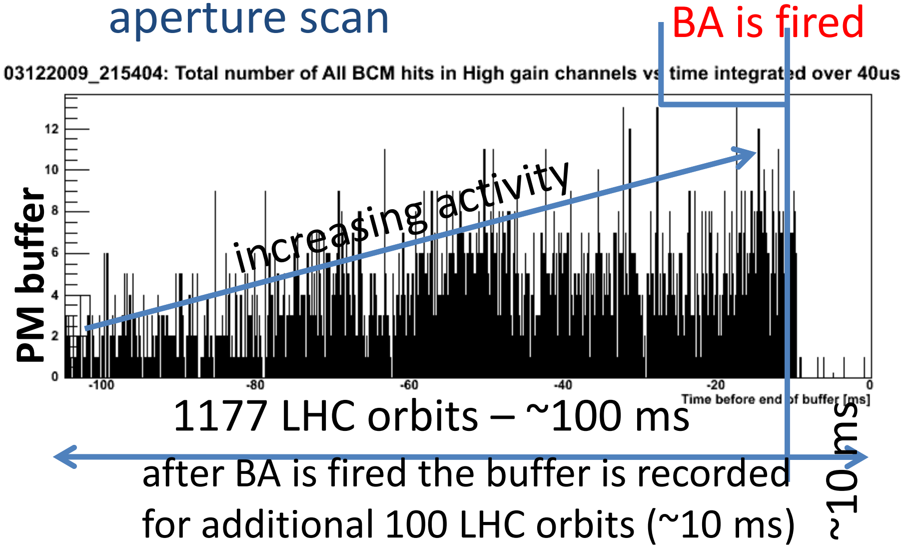


BLM module



BCM performance

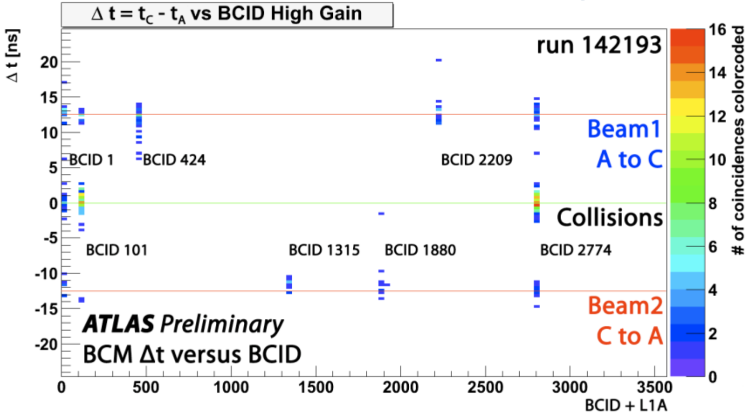
- Dual threshold readout NINO
- BA condition: $3/4_L+3/4_H$ on both sides
- Beam dump fired by BCM during LHC aperture scan


03122009_215404: Total number of All BCM hits in High gain channels vs time integrated over 40us

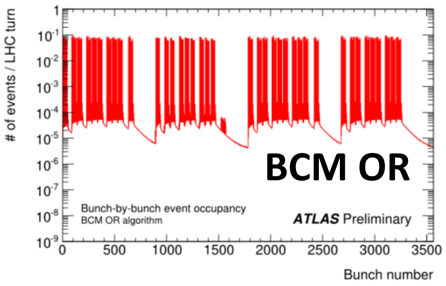
after BA is fired the buffer is recorded for additional 100 LHC orbits (~10 ms)

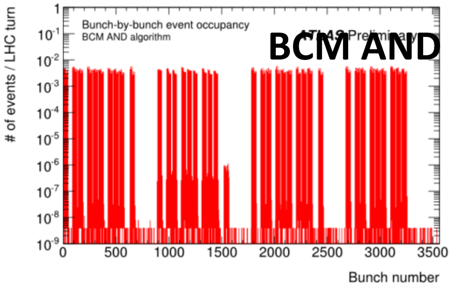
- Too sensitive at current conditions
  - Measures taken in 2011 to restore abort functionality, still passive
- BLM - 12 diamonds read by machine BLM system (40 µs) provide beam protection
  - Active in beam abort system
  - Threshold set at conservative ID damage level

- Beam conditions monitoring



- Luminosity monitoring
  - 3564 hit maps for OR, AND_{AC}, XOR_A





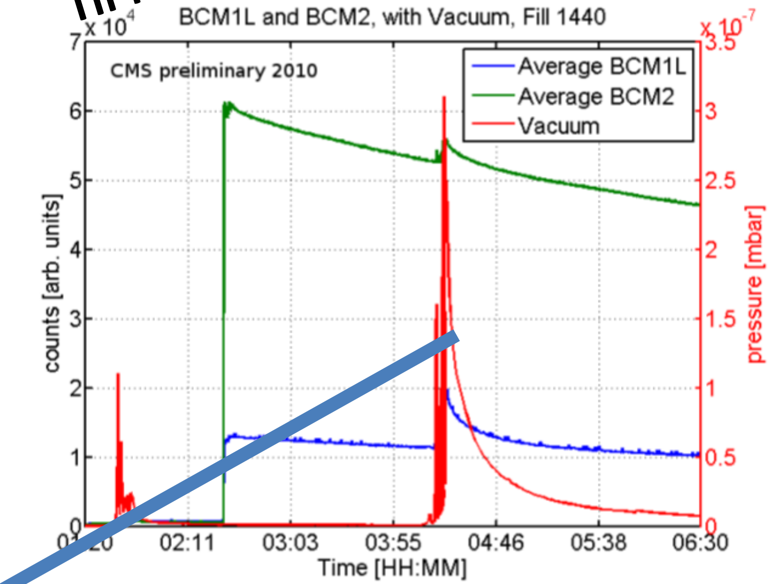
- Main ATLAS lumi monitor in 2011
  - Insensitive to pile-up at high bunch lumi

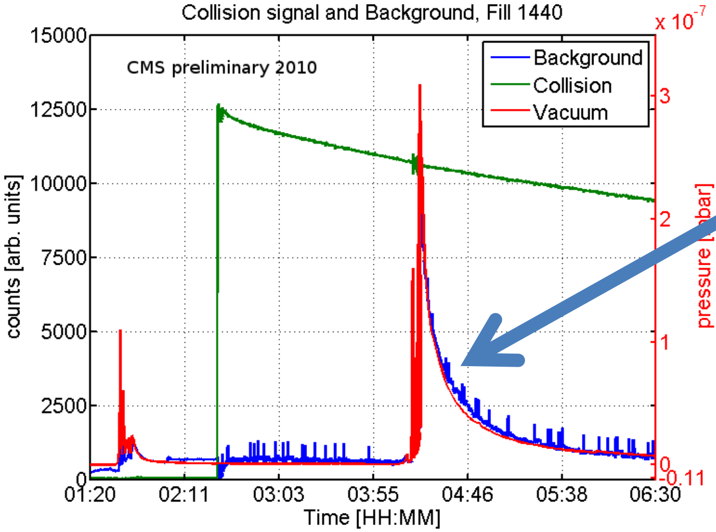
BCM1L
BCM2

CMS Beam Condition Monitoring

TIPP talk by M.E.CASTRO CARBALLO

- 32 diamond detectors with standard LHC BLM readout.
- Main purpose: Protection of Pixel and Tracker. Can assert beam dump if conditions are too bad.
- Four positions for measurement:
  - BCM1L (Z=±1.8m), BCM2 (Z=±14.4m)
- Different sensitivities of BCM2 and BCM1L to collision signal and background allow extraction of background from raw signal.





- This fill with high background due to bad vacuum shows the calculation of background.
- Detectors follow well the vacuum time structure

So far ... no conditions that would have triggered a beam dump

- No failures of the system
- No false beam aborts.

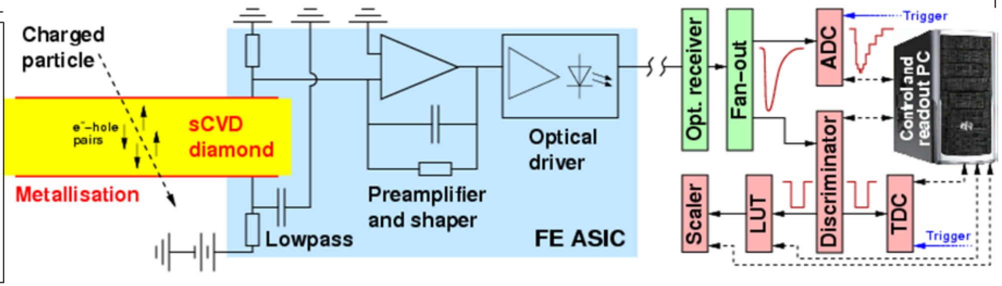
BCM1F CMS Fast Beam Conditions Monitor

***<u>Description:</u>* BCM1F is a diamond based detector that is installed inside the CMS tracker, around the beam pipe, and that monitors the flux of particles from beam halo and collision products with nanosecond time resolution.**

Readout chain of BCM1F

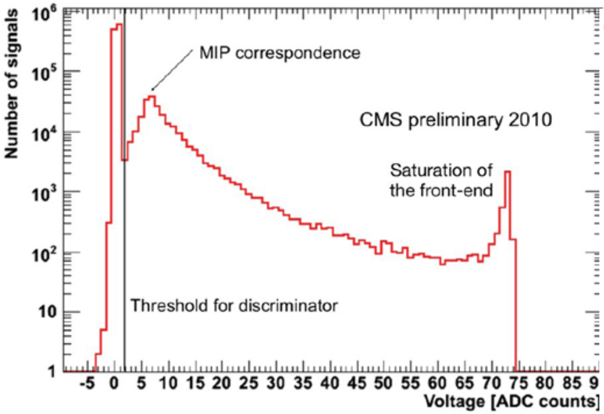
The front-end consists of sensor, radiation hard pre-amplifier, and optical driver.

The back-end contains the DAQ devices: scalers, ADC, and TDC.

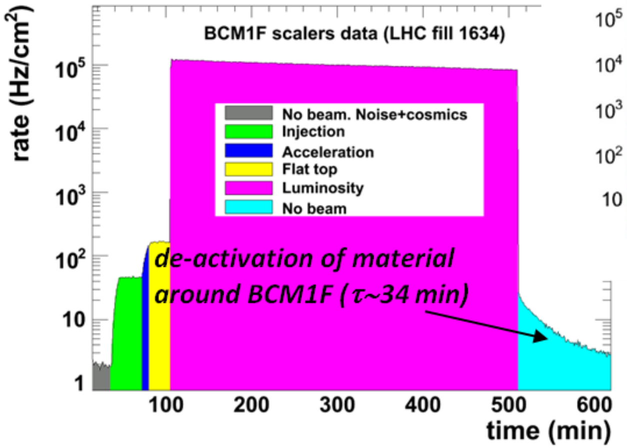


BCM1F performance It has been successfully recording data since November 2009. The different DAQ systems offer beam conditions information, among them the beam flux, that is forwarded to LHC operators.

Signal amplitude spectrum from ADC

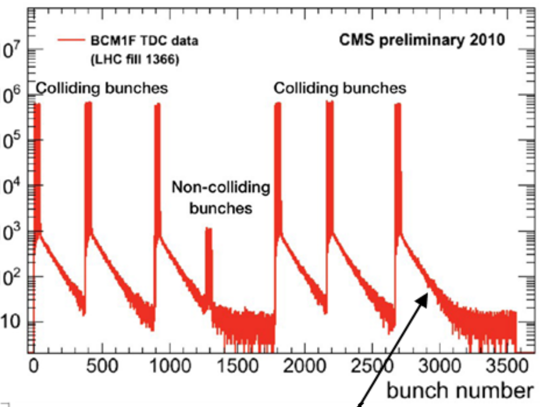


Count rates during a proton fill



de-activation of material around BCM1F (τ~34 min)

Bunch identification with TDCs

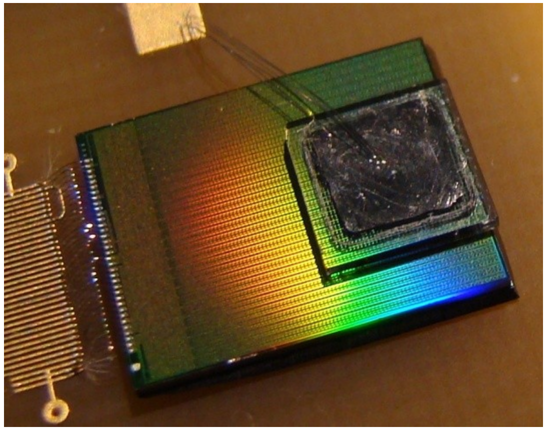


Albedo effect
***tails τ~2.12 μs** (from simulations due to n, e-, p+ and γ)*

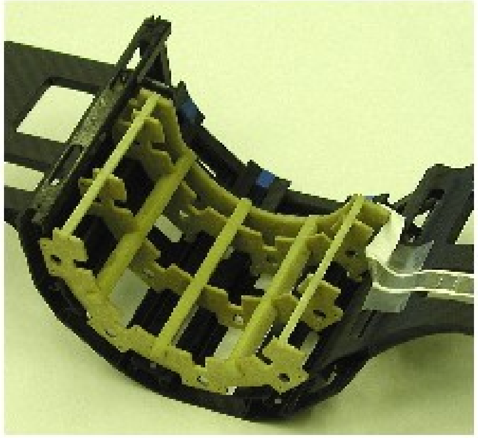
CMS Pixel Luminosity Telescope

- Dedicated, stand–alone luminosity monitor
  - Eight 3-plane telescopes each end of CMS
  - 1.60^o pointing angle r = 4.8 cm, z = 175 cm
- Diamond pixel sensors active area:
  - 3.9 mm x 3.9 mm, scCVD diamond
- Count 3-fold coincidences fast-or signals (40 MHz)
- Full pixel readout pixel address, pulse height (1 kHz)

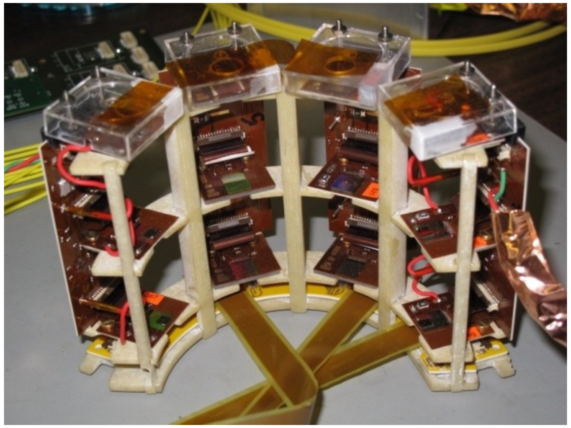
➢ Stable 1% precision on bunch-by-bunch relative luminosity



PLT plane



Cassette for 12 planes



Full cassette in test-beam

PLT Production Status

- 48 planes needed for PLT
- will produce 60 planes

Characterization

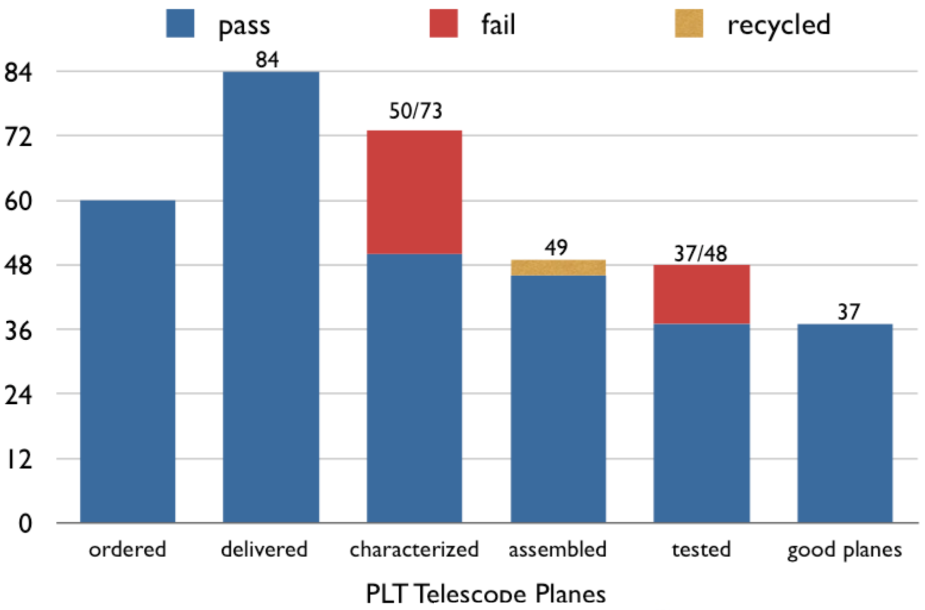
  - 32% rejected 23/73
  - replaced by vendor
  - 11 remain to be characterized

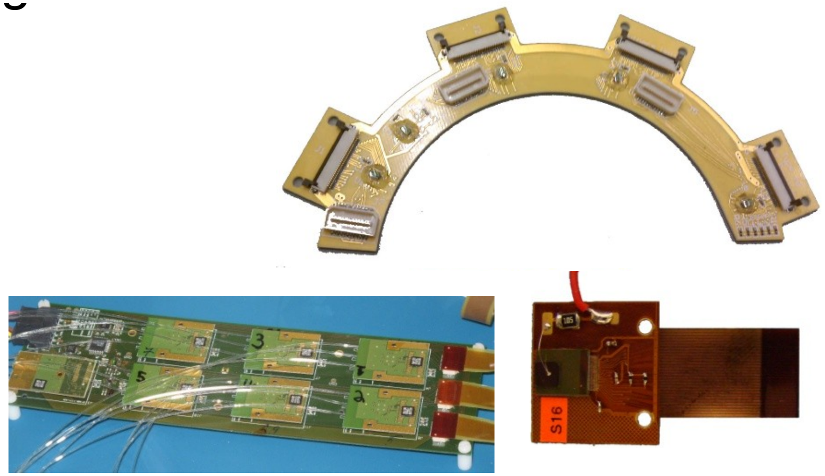
Plane assemblies

  - 77% pass 37/48
  - double column loss after bump
  - currently 37 good planes

System and schedule

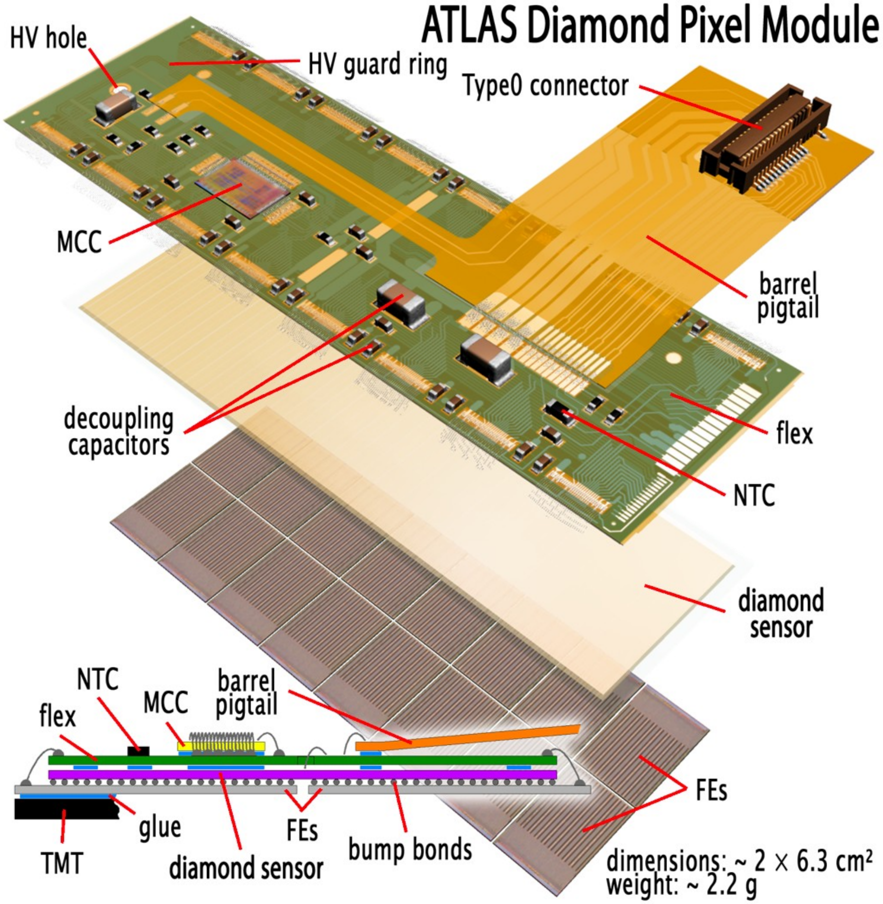
  - all components being delivered
  - final system test in July
  - plan to install during technical stop at beginning of 2012



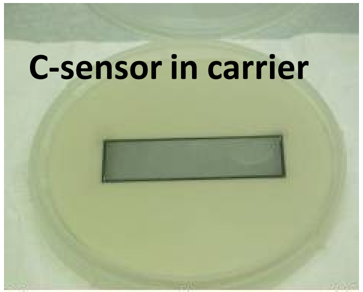


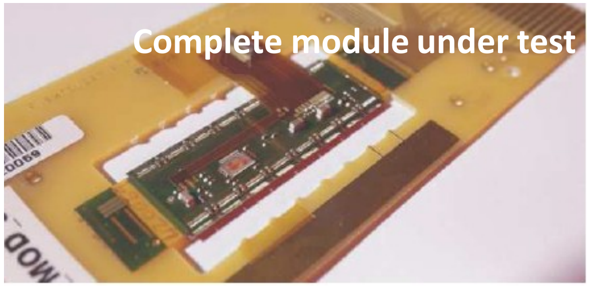
Diamond pixel modules

- Full modules built with I3 pixel chips @ OSU, IZM and Bonn

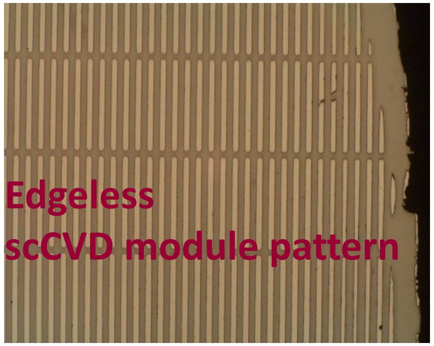


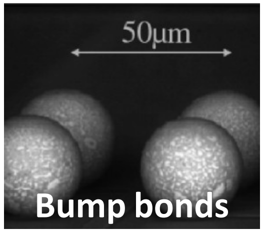

Module after bump bonding


C-sensor in carrier


Complete module under test

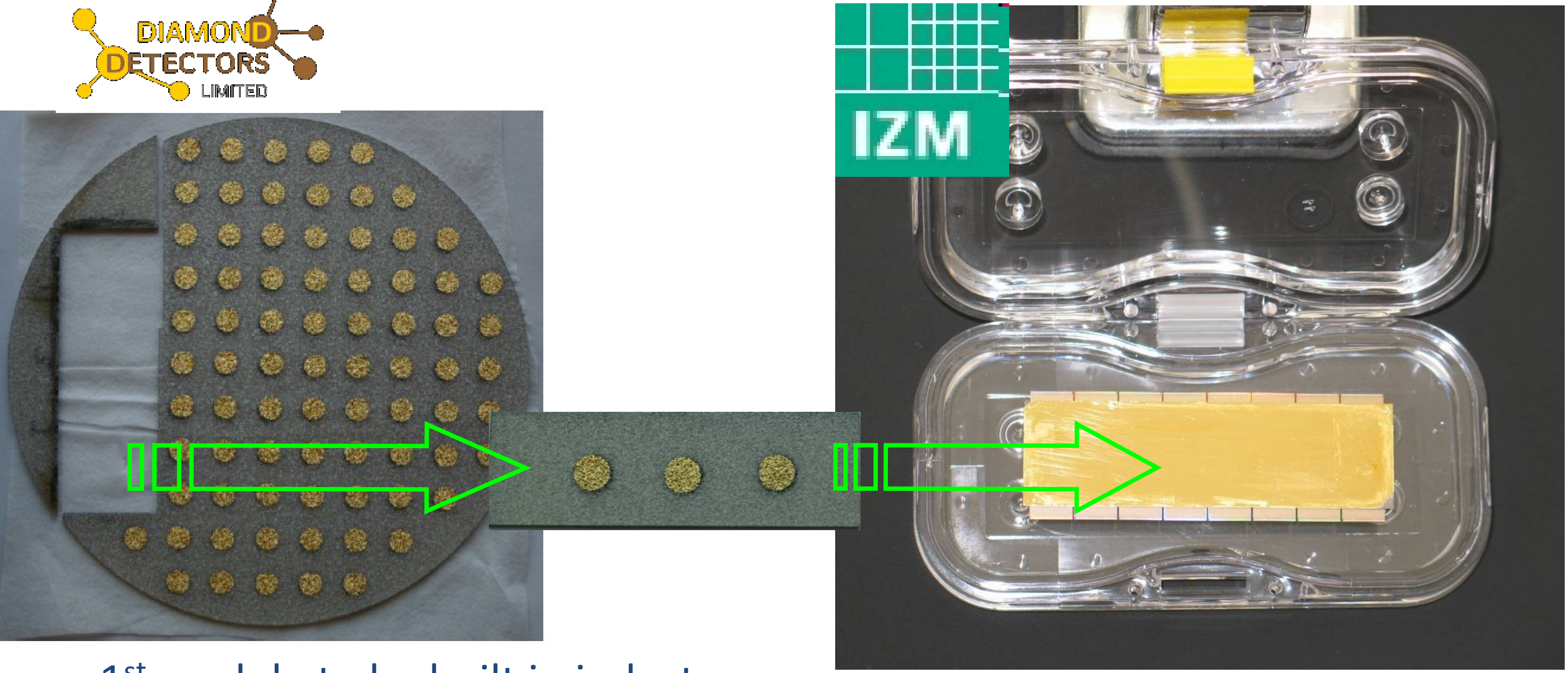

Pattern with In bumps


Edgeless
scCVD module pattern



Bump bonds

Industrialization: 2nd full pixel pCVD module



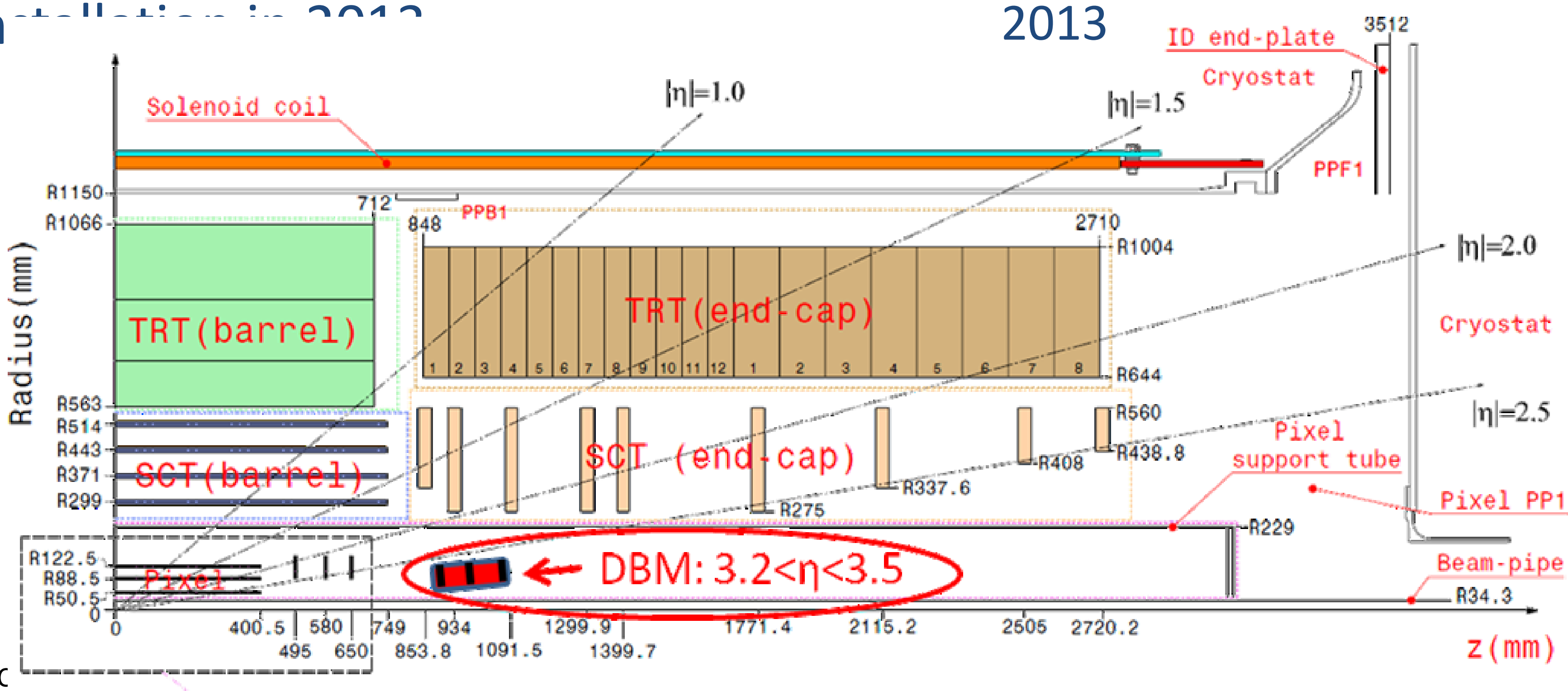
- 1st module to be built in industry
- All steps from polished sensor to bump-bonding performed at IZM Berlin

- Embedding in a ceramic wafer
- Wafer scale metallization & UBM process
- Removal from the ceramics
- Backside metallization & cleaning
- Flip chip

ATLAS Diamond Beam Monitor

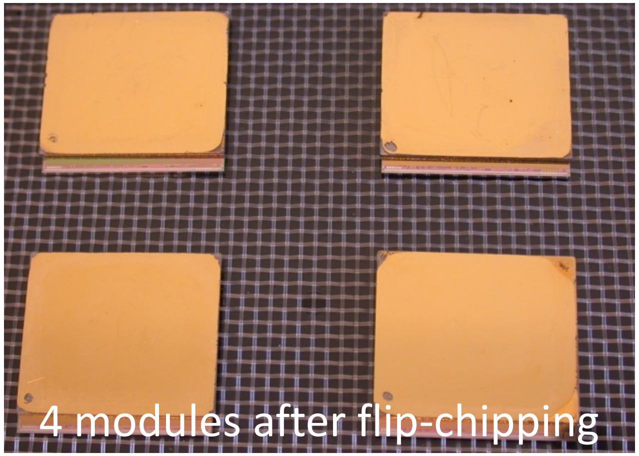
- Spin-off from diamond bid for IBL
- 24 diamond pixel modules arranged in 8 telescopes around interaction point
  - Bunch by bunch luminosity monitoring
  - Bunch by bunch beam spot monitoring
- Installation in 2013

- Proposed during last months as add-on to IBL
- ATLAS decision expected soon
- Contingent on pixel services replacement in 2013



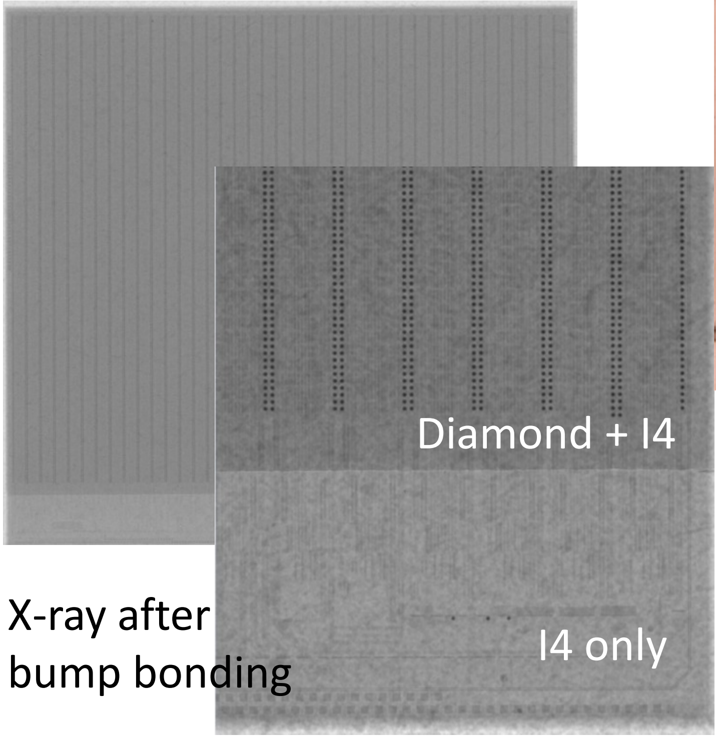
DBM first modules

- 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

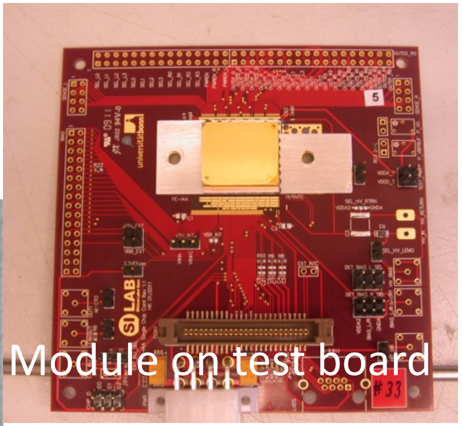


4 modules after flip-chipping

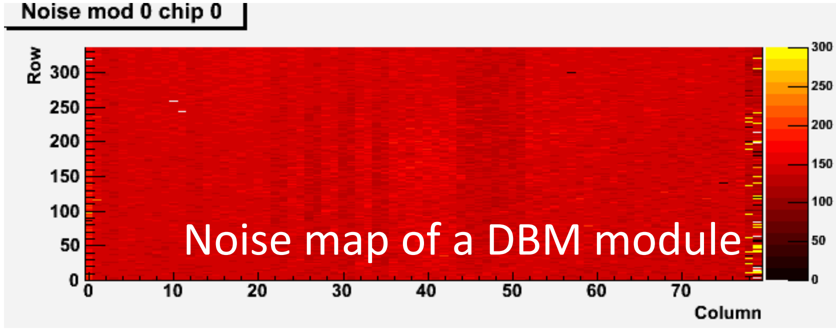
- X-ray perfect
- Noise map uniform
  - Indication of success
  - Need source/test-beam to confirm



X-ray after bump bonding

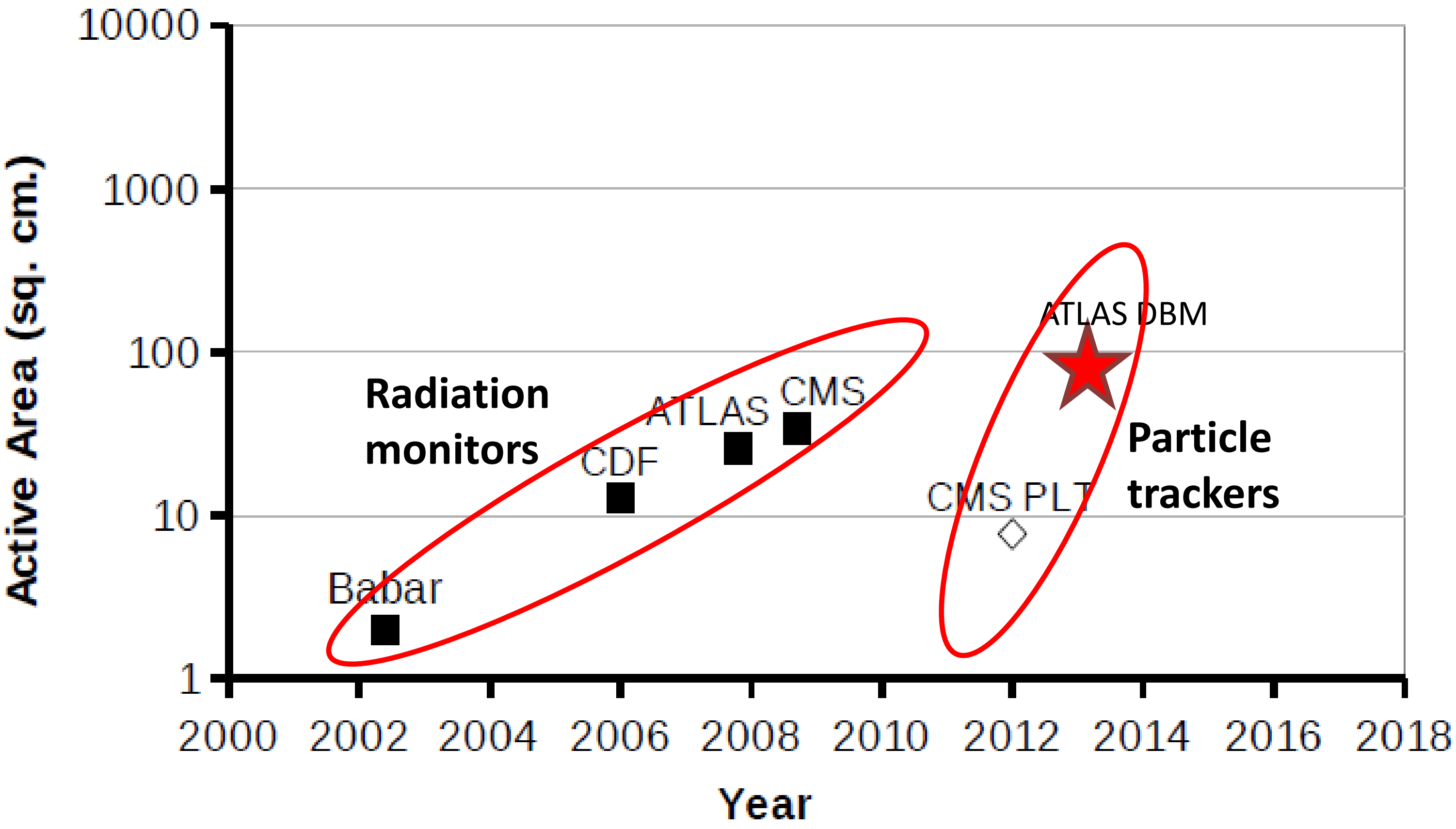


Module on test board



Noise map of a DBM module

Applications in HEP: wrap-up



Summary

- Recent progress in the diamond world
  - Improved understanding of radiation damage
  - Application in all LHC experiments
  - Building of pixel modules in industry
  - Diamond trackers under way !

Very interesting times for diamond in HEP ahead of us !