Diamond Pixel Detector Systems in High Energy Physics

F. Hügging for the RD42 collaboration

PIXEL 2014

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Outline

- Why diamond?
  - diamond as sensor material
- Diamond pixel devices for HEP experiments
  - ATLAS Diamond Beam Monitor (DBM)
  - CMS Pixel Luminosity Telescope (PLT)
- Summary & Conclusions

Diamond as sensor material

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 10^7	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	

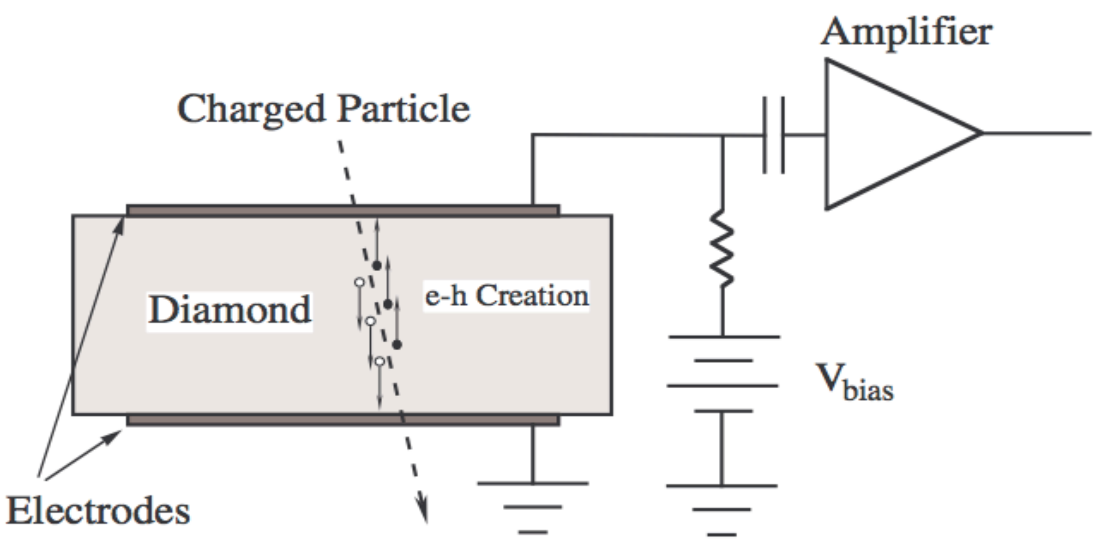
C. Bauer et al., Nucl. Instrum. Methods A 383, 64 (1996)
C. Manfredotti et al., Nucl. Instrum. Methods A 410, 96 (1998)
D. R. Kania et al., Diam. Relat. Mater. 2, 1012 (1993)

Diamond detector configurations

- External bias field across detector - connection to amplifier
- Charge trapping limits signal in pCVD -> aim for high fields
- Charge collection distance (*ccd*) used to characterize diamonds

$$Q_m = \frac{ccd}{t} Q_0$$

$$ccd = (\mu_e \tau_e + \mu_h \tau_h) E$$



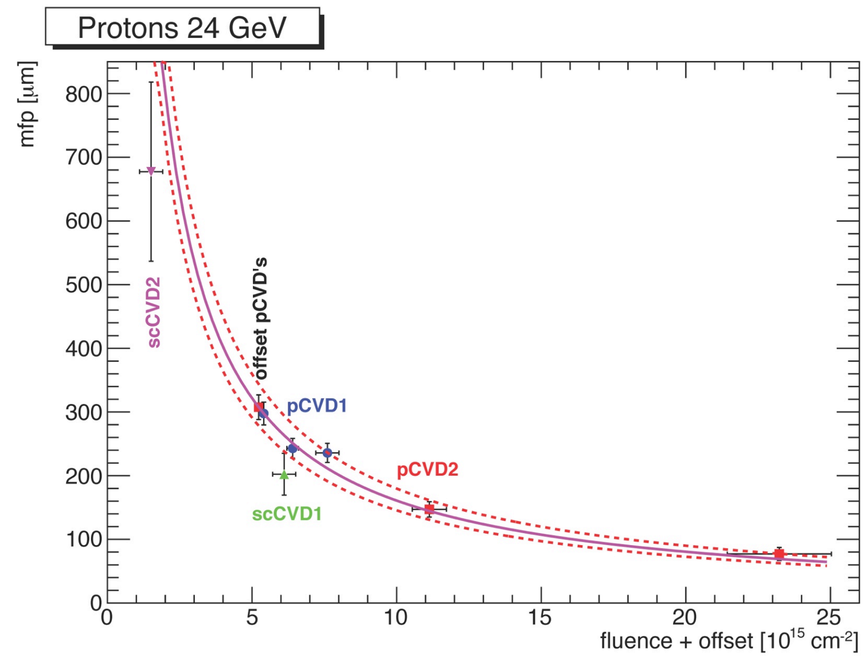
- **GHz range current amplifiers** for beam monitoring/high rate
- **CSA (30ns to ~us shaping time)** for characterization, spectroscopy,
- **Strip/pixel FE ASICs** for trackers (~typically τ~10-20ns

Radiation tolerance: 24 GeV protons

- Signal height decreases after irradiation due to trapping:
  - usually measured in degradation of the charge collection distance ccd with particle fluence ϕ
  - radiation induced traps decrease the mean free path λ according to

$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k\Phi$$

- Irradiation tests with protons and pions at different energies performed:
  - pCVD diamonds up to 1.8×10^{16} p/cm^2
  - scCVD diamonds up to 5×10^{15} p/cm^2
- Main results:
  - pCVD material behaves like scCVD after ~5×10^{15} p/cm^2 "pre-damage"
  - pCVD and scCVD detectors follow same damage curve

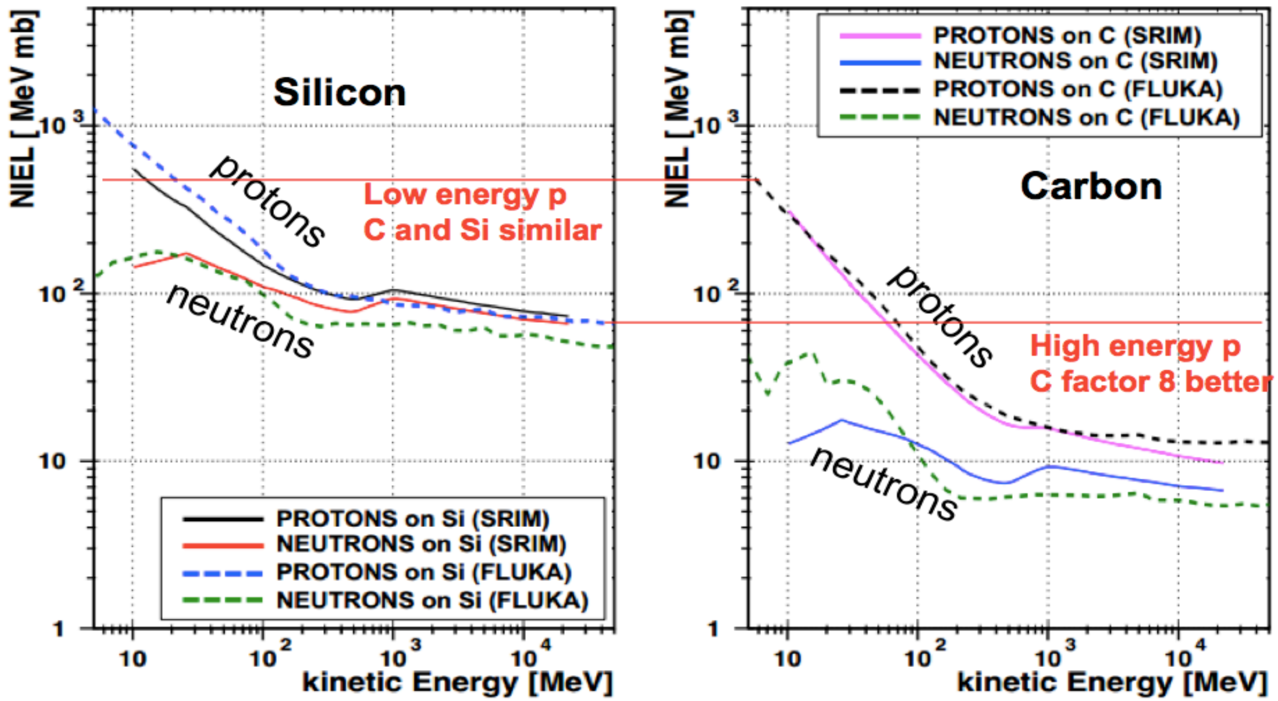


$$k[24GeVp] \approx (0.62 \pm 0.07) x10^{-18} \mu m^{-1} cm^2$$

particle	energy/ momentum	relative k to 24 GeV p
p	24 GeV	1
p	800 MeV	1.7
p	70 MeV	2.7
p	25 MeV	4.2
π	300 MeV/c	2.9

… compared to simulations

- NIEL calculations
  - Good agreement down to 800 MeV, calculations predict stronger damage at lower energies than observed so far – under investigations with new irradiations
  - Stronger damage in Si than C due to larger number of low-energy fragments

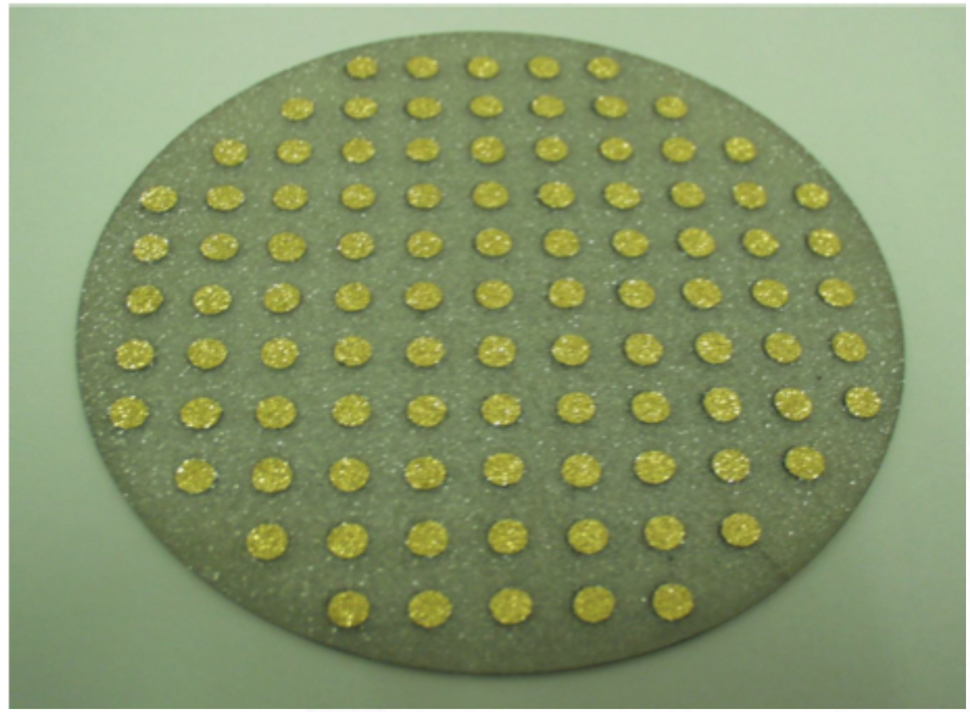


Moritz Guthoff, Wim de Boer, Steffen Müller,Simulation of beam induced lattice defects of diamond detectors using FLUKA , NIM 2014, **arXiv:1308.5419**

→ see next talk by Rainer Wallny for more details about radiation hardness

CVD diamond supplier (pCVD)

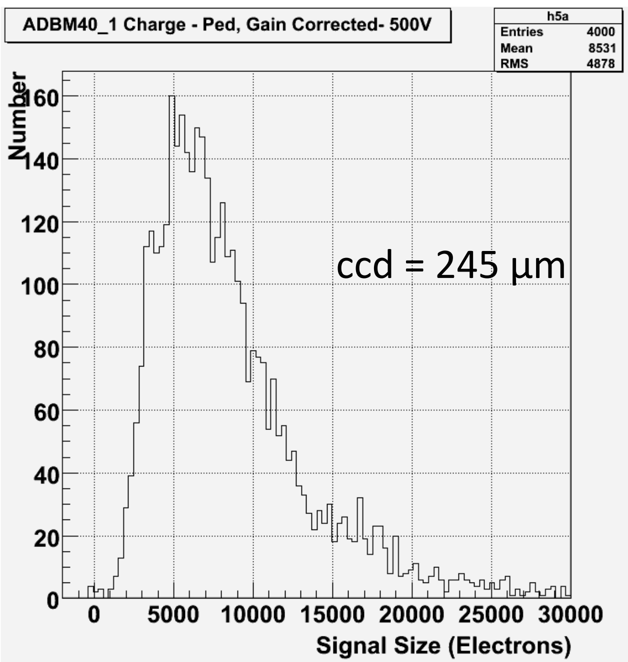
- Commercial applications require wafer scale growth
  - Heat sinks (>1200 W/mK)
  - Electronics (power transistors)
  - IR windows, UV detectors ("visible blind")…
- Well known only supplier so far was Element6/UK:
  - Detector-grade diamonds
  - Highest qualify on 120mm wafers with CCD ~250-300um
  - Up to 2mm thick for best quality

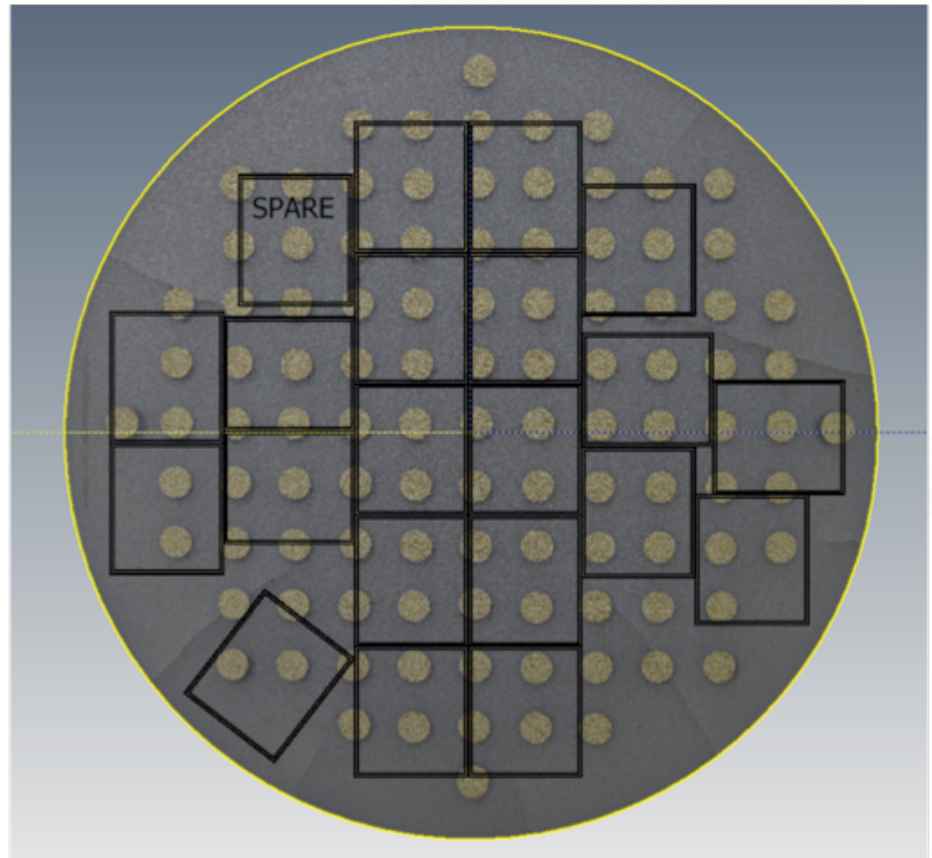


Courtesy Element6 / UK

New additional diamond supplier: II-VI

- All large samples in last year from II-VI
  - 26 ATLAS DBM sensors arrived during 2013
  - 10 CMS sensors were delivered in early 2014
- All have been (or soon will be) made into pixel detectors
- Overall quality is remarkable well





Diamond devices for HEP experiments

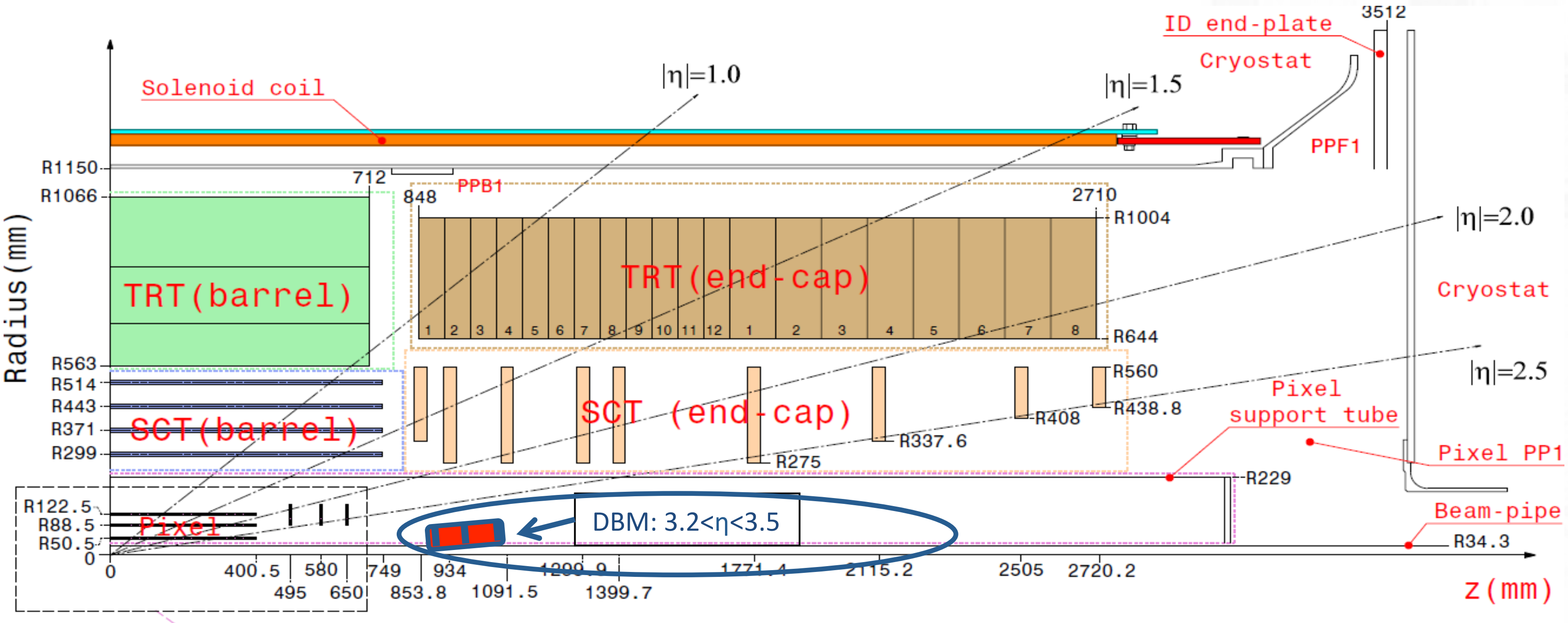
- Beam conditions monitors
  - Alice, ATLAS, CMS, LHCb
- LHC machine beam loss monitors (BLMs) → New for RD42
  - Operating in cryogenic conditions
- Current generation Pixel Detectors:
  - CMS PLT → see next talk by Rainer Wallny
  - ATLAS DBM → will focus on DBM in this talk
- Future LHC trackers
  - ATLAS, CMS, LHCb
  - 3D diamond devices

DBM – Design ideas

- Purpose
  - Bunch-by-bunch luminosity monitor (aim < 1 % per BC per LB)
    - Finer segmentation and larger acceptance than BCM
    - Never saturates
  - Bunch-by-bunch beam spot monitor
    - Need triple-module telescopes for (limited) tracking
    - Can distinguish collision tracks from beam halo
    - Unbiased sample, acceptance extends far along beam axis
- Design considerations
  - Baseline: four telescopes of 3 FE-I4 modules per side → 24 total
  - Avoid IBL insertion volume and ID acceptance (η>2.5)
    - In front of BCM (η~4.2); partial overlap (cross-calibration)
  - Place in pixel support structure close to detector and beam pipe

DBM - Geometry

- Part of pixel/nSQP volume, but uses IBL-services
  - e. g. 1000 V for detector bias
  - FE-I4 LV/power, readout/commands, temperature etc.
- nSQP re-assembly set original installation date to July 2013
  - Interleaved with nSQP panel re-installation → October 2013

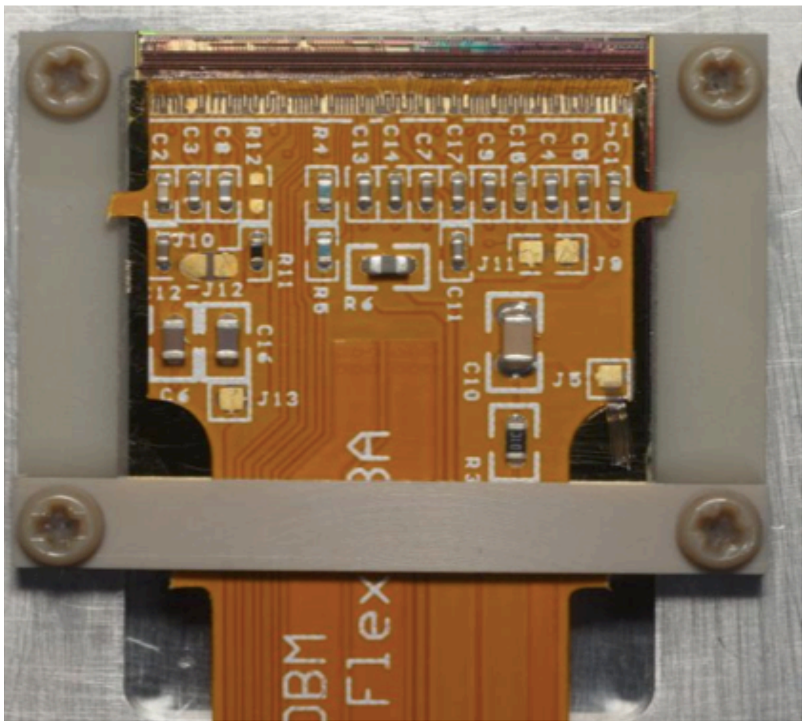


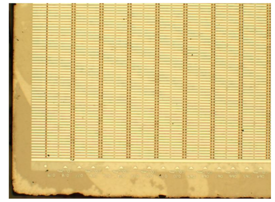
Diamond pixel modules for ATLAS

Completed Module

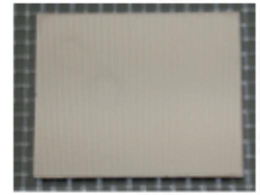
- Bump-bonding at IZM including pixel metallization
  - 21x18 mm^2 pCVD from DDL & II-VI
  - FE-I4 ATLAS IBL pixel chip
  - 336x80 = 26880 channels, 50x250 μm^2

- Module assembly at CERN

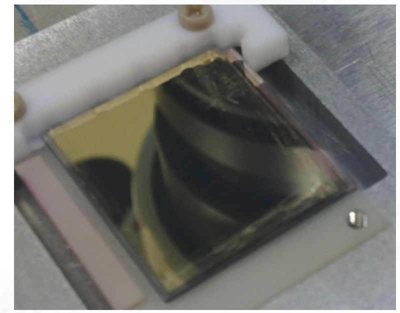




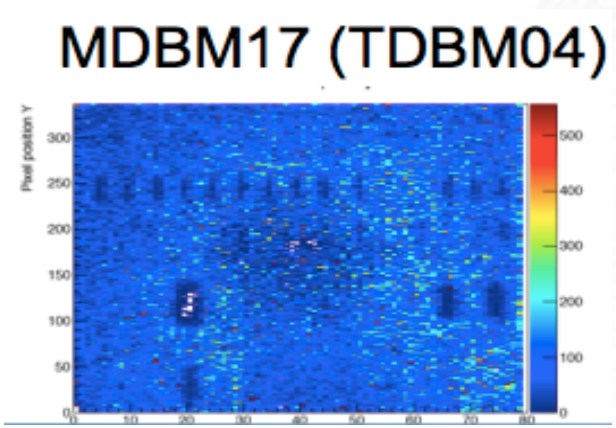
pCVD diamond with UBM

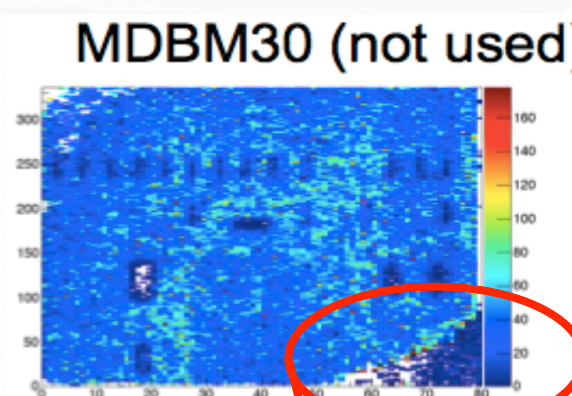


FEI4 chip



- Module QA
  - ^{90}Sr hitmaps



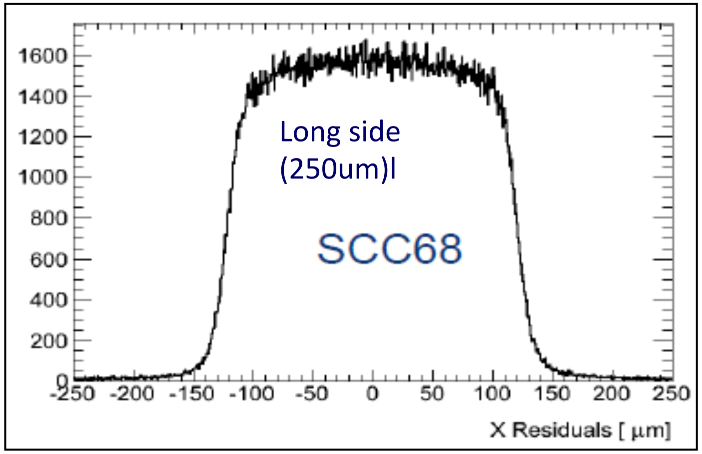


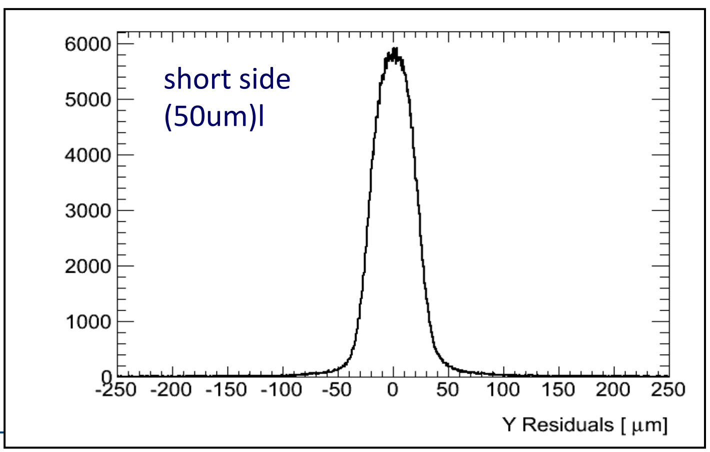
Example of disconnected corner

ATLAS DBM prototype testbeam at CERN

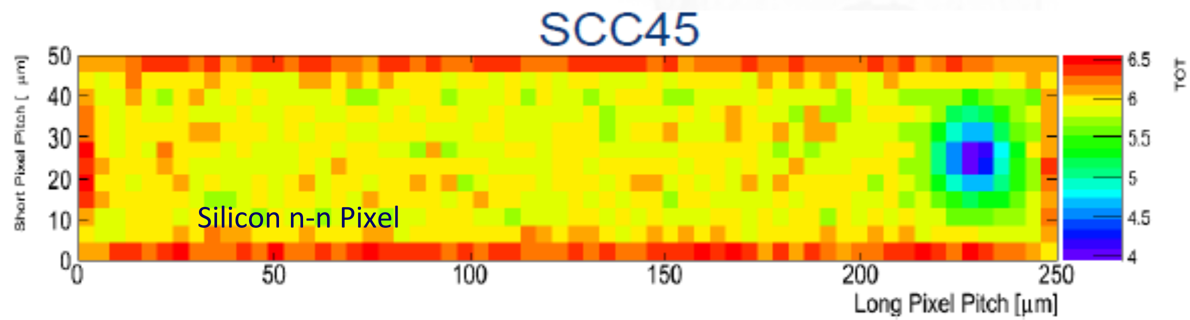
- Test beam results with FEI4+ diamond sensors in 2011 (CERN) and 2012 (DESY) showed good overall performance

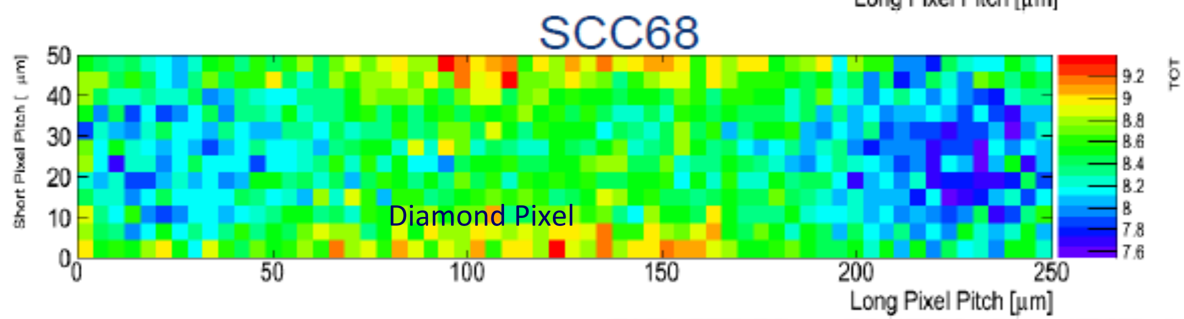
Residual

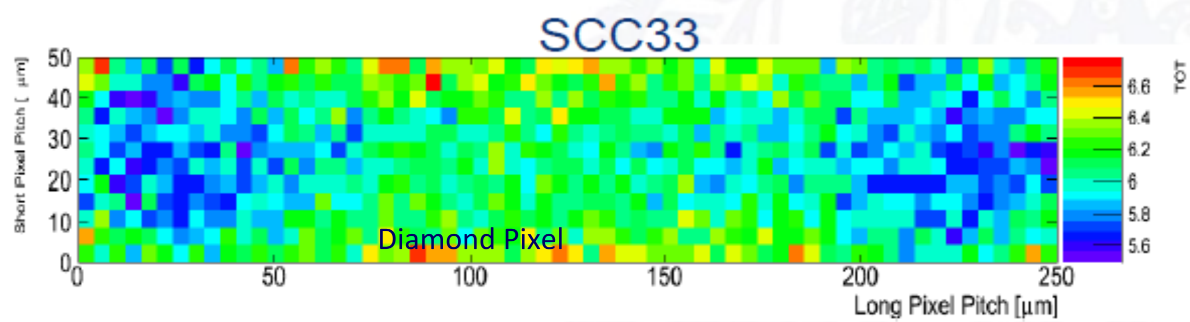




Time over threshold vs. hit position X/Y

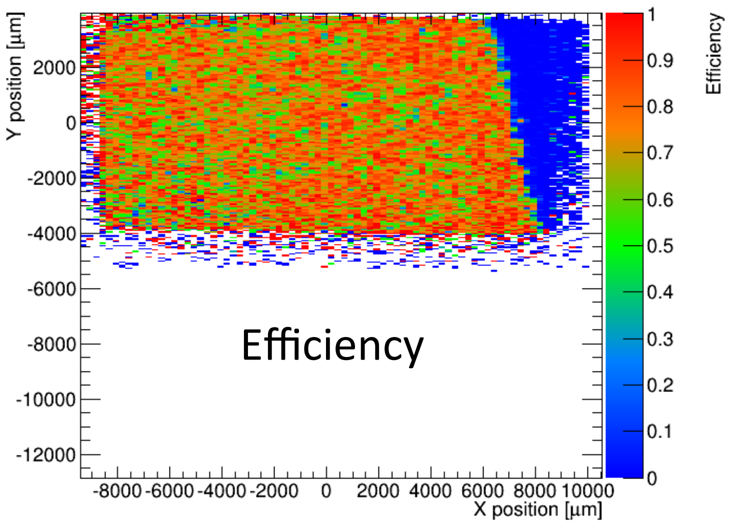


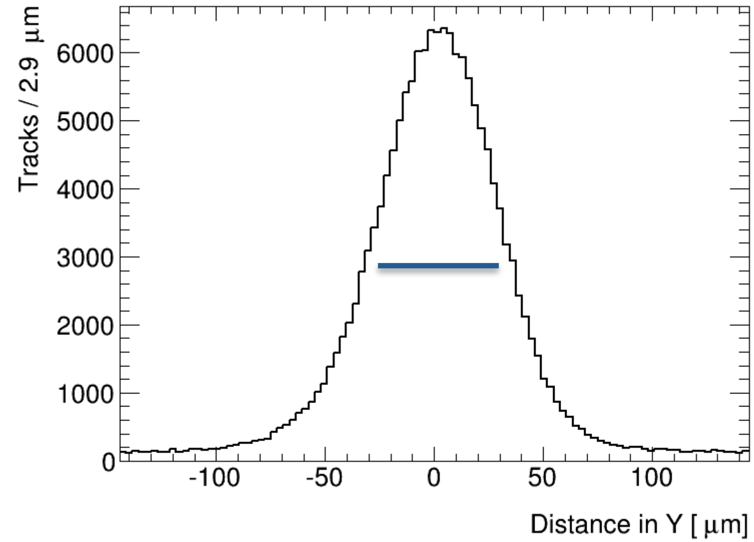


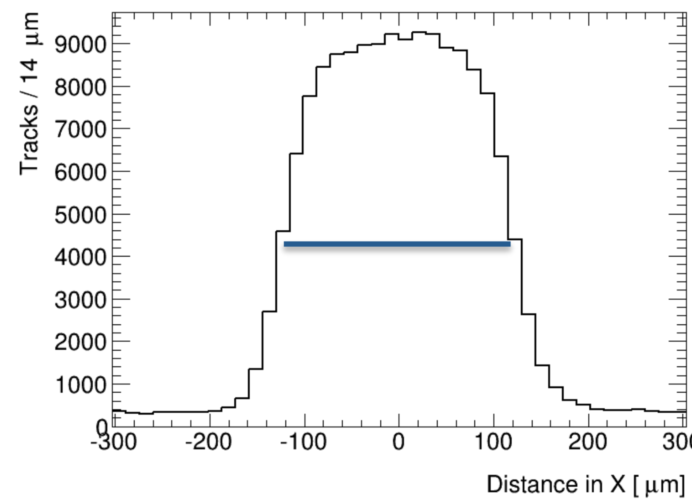


ATLAS DBM module in testbeam at Desy

- MDBM-01 in 5 GeV electron beam at DESY
  - 1100 electron threshold but only 600V bias
  - Beam only populated top half of detector



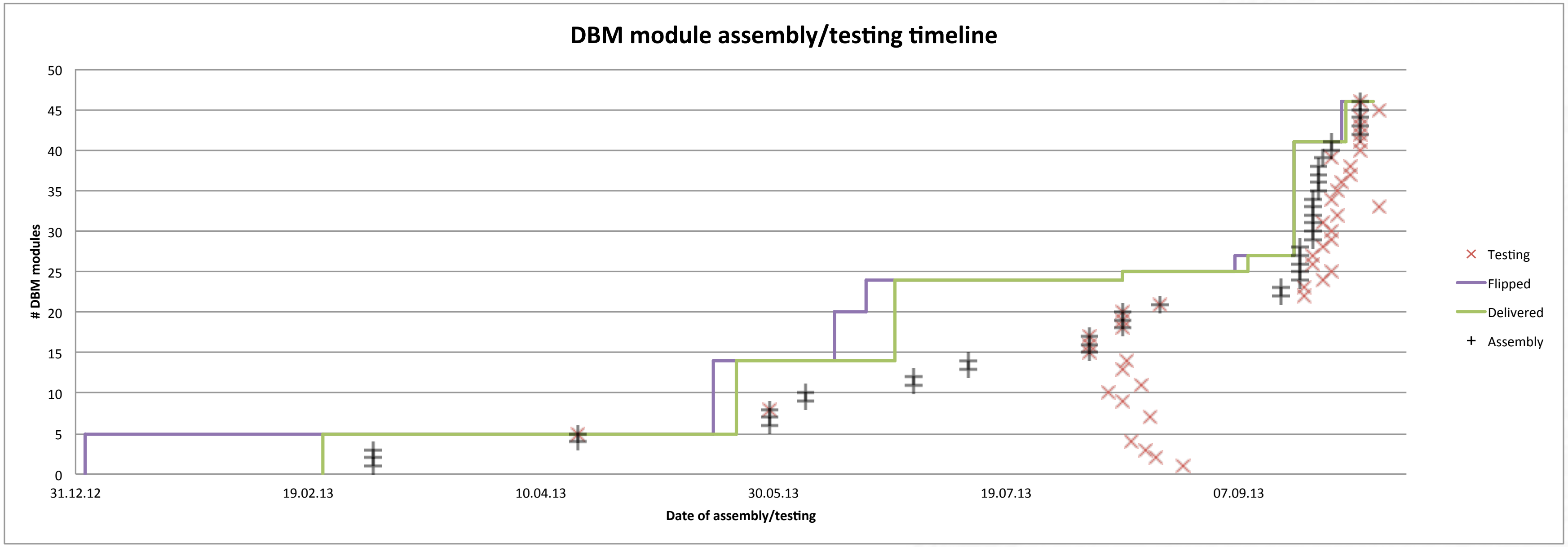




Hit residuals (pixel width)

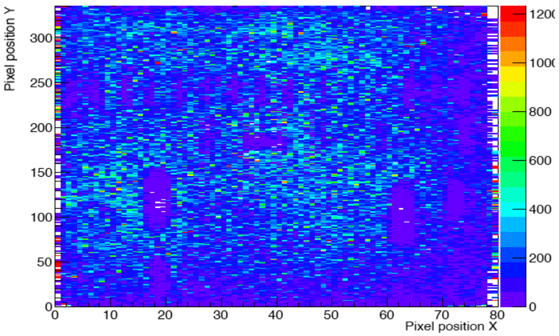
DBM module production

- Baseline: 24 modules to be installed
- Production model: Aim for 30 ATLAS-grade modules
  - Loss of 25 % during module assembly expected
    - Need parts to assemble 45 modules
      - 45 sensors, FE-I4's, flip-chippings, flexes etc.
      - 5 for irradiation studies
    - Plan on re-using diamond sensors as first modules assembled with FE-I4a, while FE-I4b final chip
      - In the end we re-worked 17 sensors
        - » This helped make up for flipping difficulties and shortage of sensors
- Reality shown to quite different → most used DBM modules were done within 4-6 weeks in late summer 2013 very close to the installation date
  - diamond supply to bump bonding was quite late →9 DDL (E6), 15 II-VI. 10 refurbished DDL(E6) after re-trimming = 34 in total
  - flip chip difficulties during the production

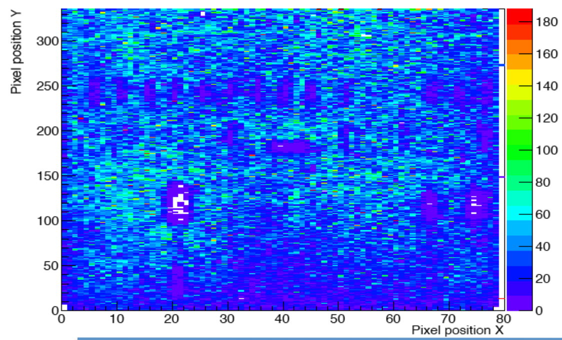


Module bump connectivity

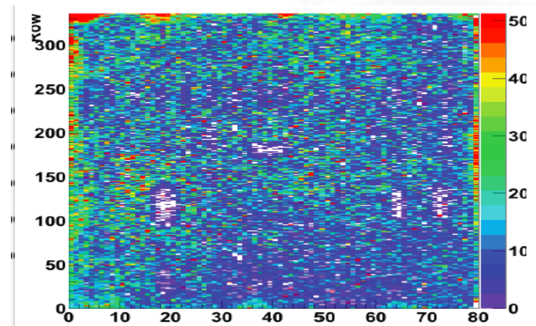
MDBM03 (TDBM01)



MDBM09 (TDBM01)

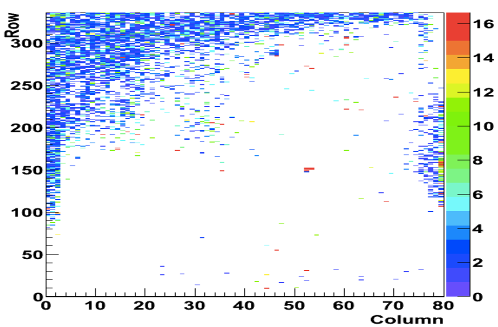


MDBM10 (re-worked)

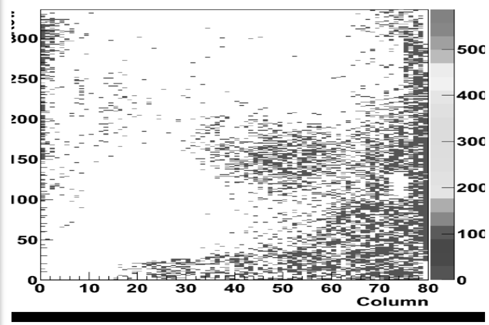


Bonded 1st batch with standard flip chip technique

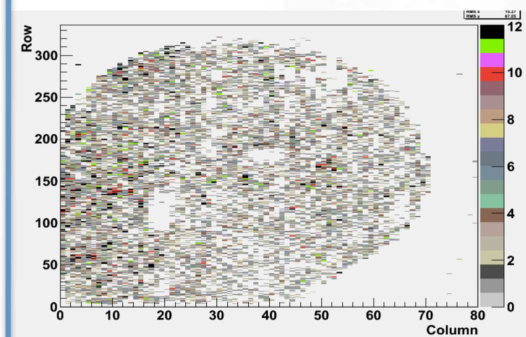
MDBM17 (reworked)



MDBM18 (reworked)

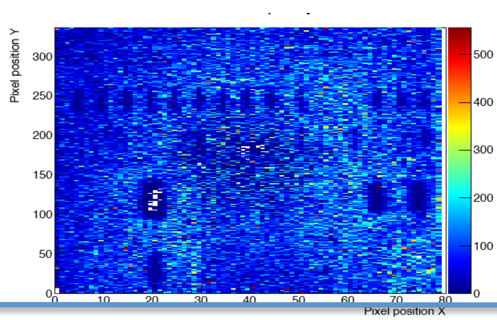


MDBM15 (15um bow)

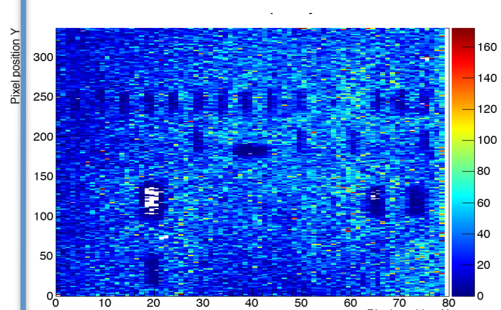


Bonded 2nd and 3rd batch with standard flip chip

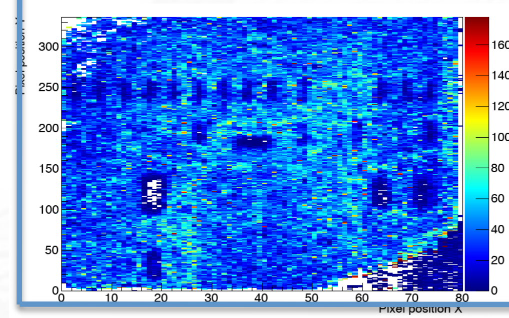
MDBM17 (not used)



MDBM31 (TDBM05)



MDBM30 (not used)

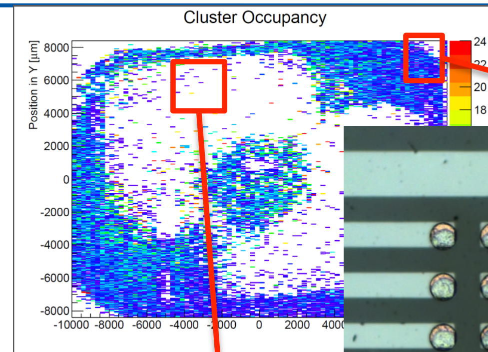


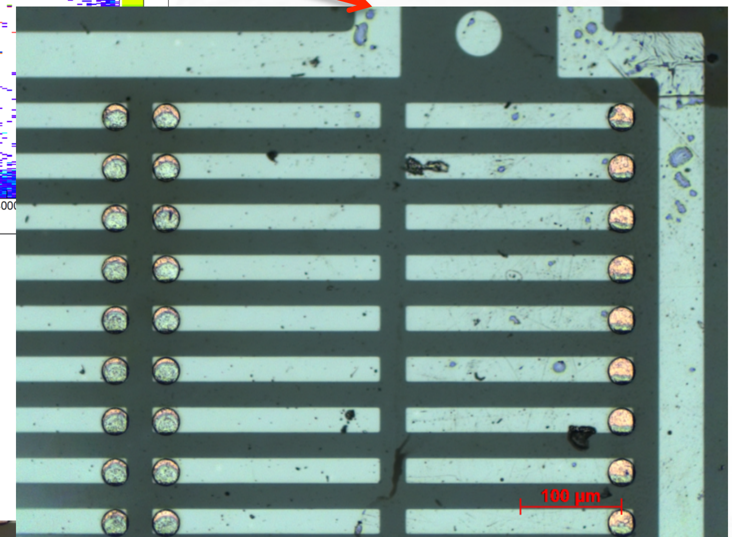
Bonded with new flip chip technique using a new bonder

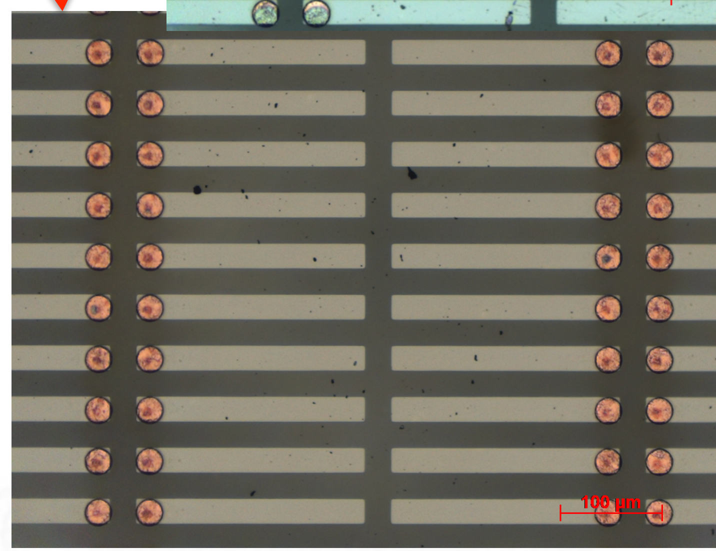
Bump connectivity investigations & yields

- Open bumps are not soldered during reflow:
  - no solder attached to the Cu pads of the diamond
  - reason not fully understood
    - excluded bow of the sensor → only 2 diamonds showed significant bow
  - new flip chip technique applies pressure during the solder reflow process shows much better yield
- Yield estimations are difficult since many changes during the production
  - reworking of modules and diamonds
  - second reflow of assemblies with new technique

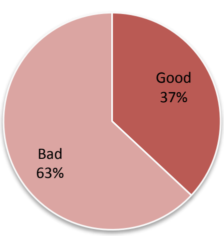
  → basically each assembly has its own history
  - 46 assemblies built and tested, 13 have been reworked or re-flipped
  - corrected yield excluded 4 assemblies with known issues: 2 with high bow and 2 have been undergo 2nd reflow with a mounted ceramic plate



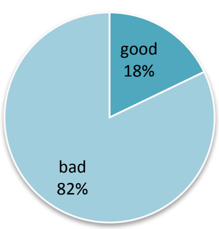




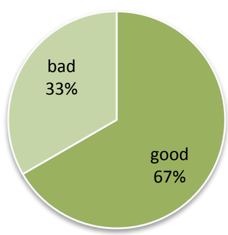
Overall yield



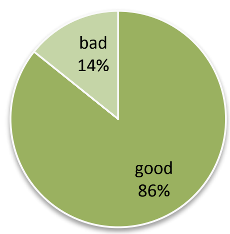
yield standard technique



yield new technique



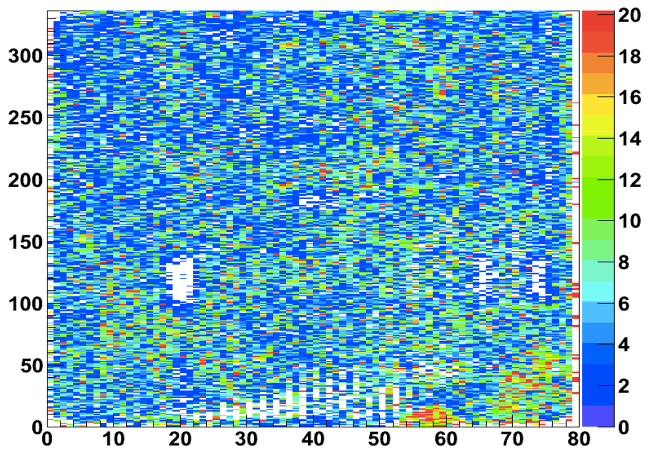
yield corrected new technique



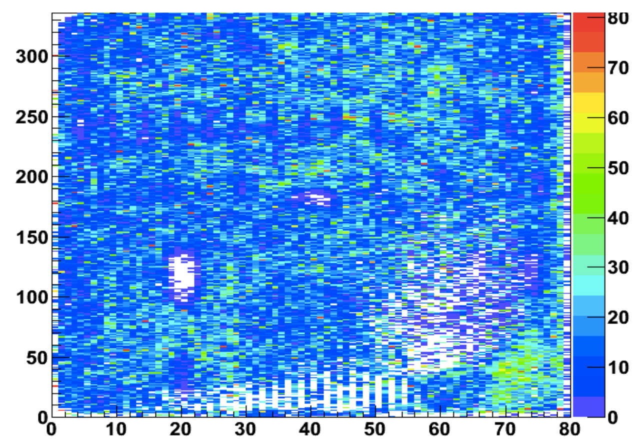
Bump connectivity after thermal cycling

- QA included thermal cycling:
  - ~10 cycles from +40C to -20C
- Almost all modules showed no change in connectivity
- Only 3 modules were rejected → reason not clear, it is maybe connected to the initial bump connectivity problem

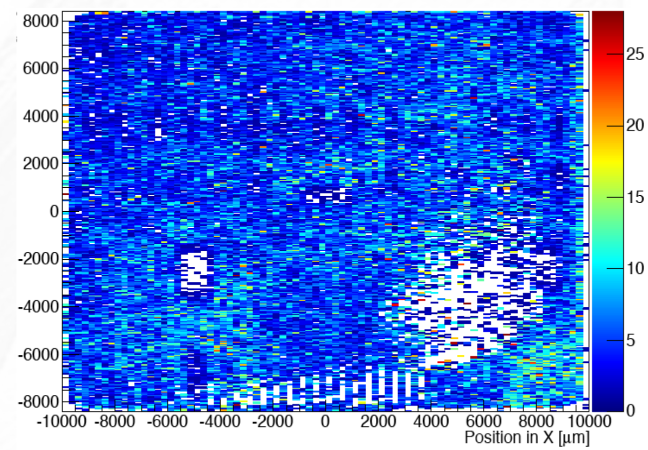
MDBM-08



Before Thermal Cycling



After Thermal Cycling (once)

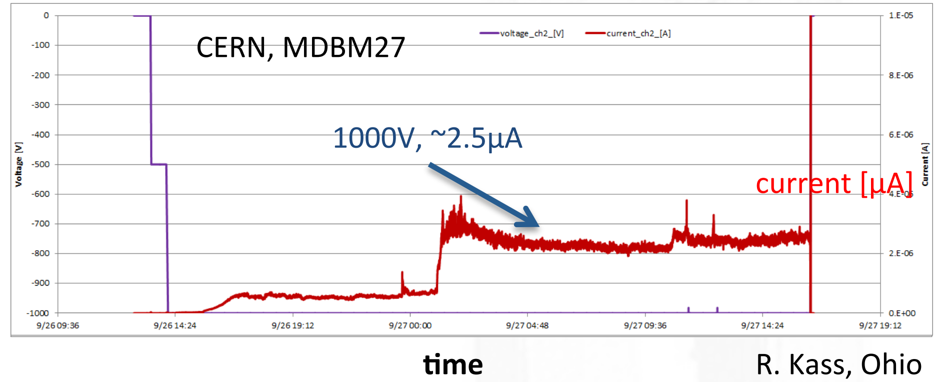


After Thermal Cycling (twice)

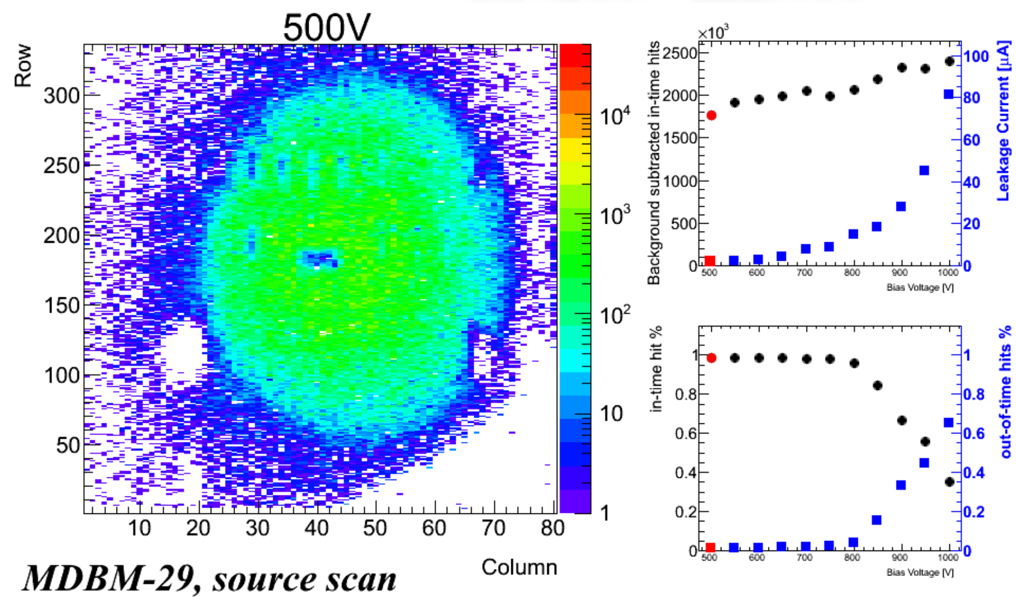
HV stability and noise

- DBM module irradiated with ^{90}Sr (1mC) at 1000V bias show unstable, rising leakage behavior with time
  - diamond prior to assembly fine and stable (>10nA@1kV for >1 hr)
- ^{90}Sr source measurements at different bias voltages shows erratic noise behavior
  - noisy spots appear at higher voltages (~850V) and high currents (~20nA)
  - these noisy spots are 'unstable' in time → some spots not visible in other runs

  → limits the maximum operation bias of some DBM modules



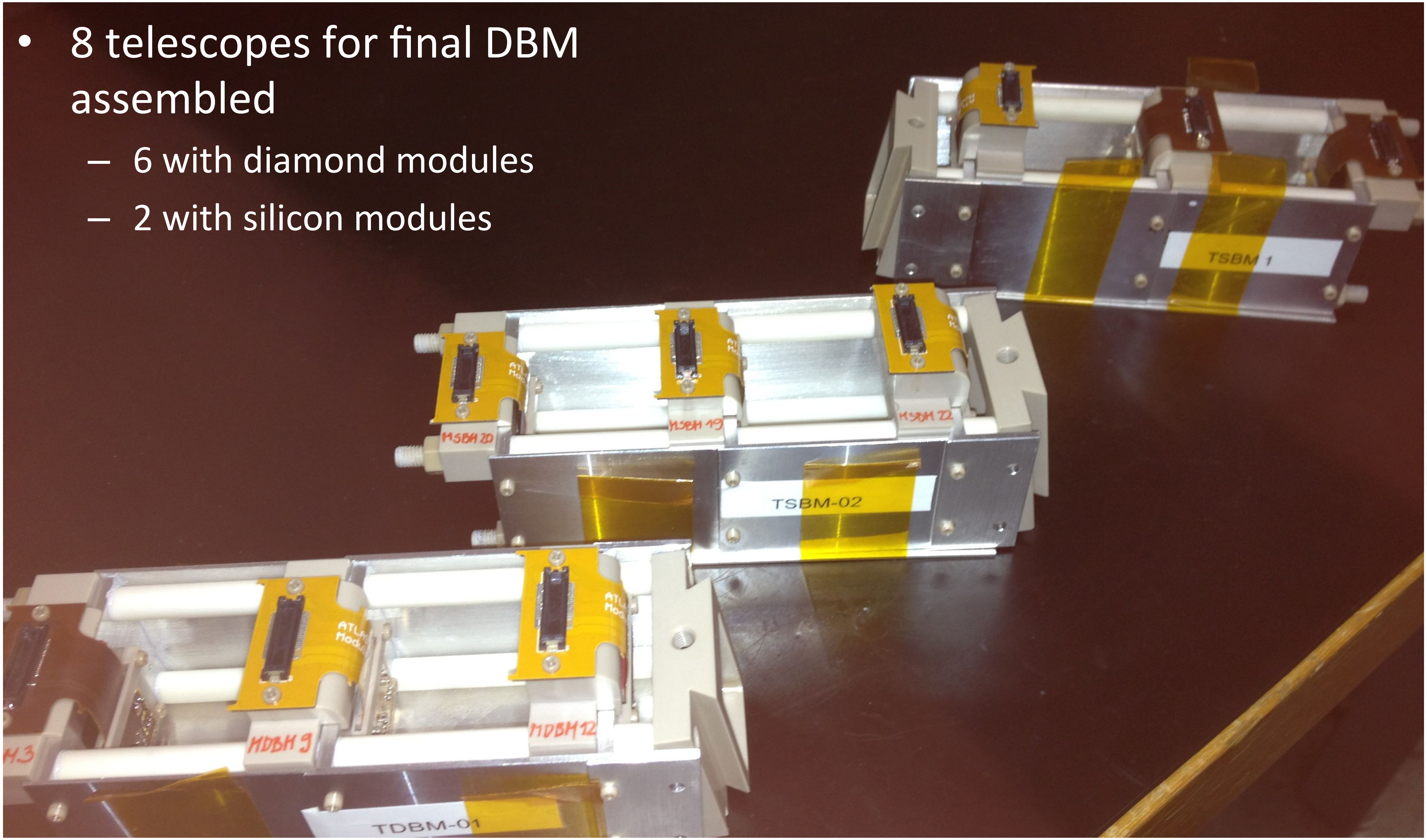
R. Kass, Ohio



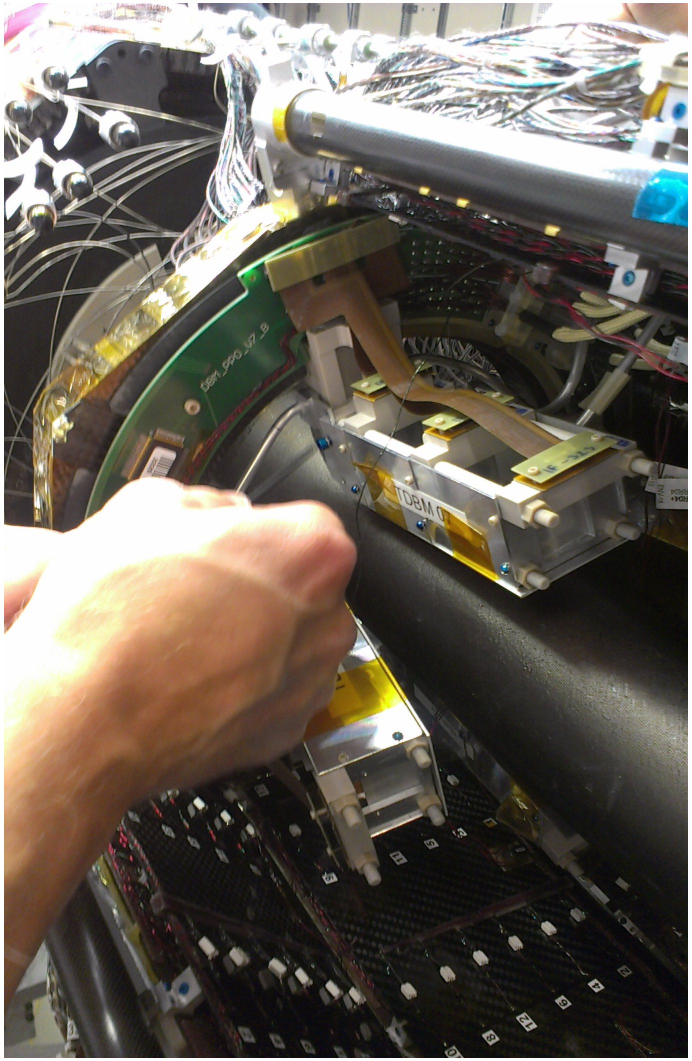
J. Moss, Ohio

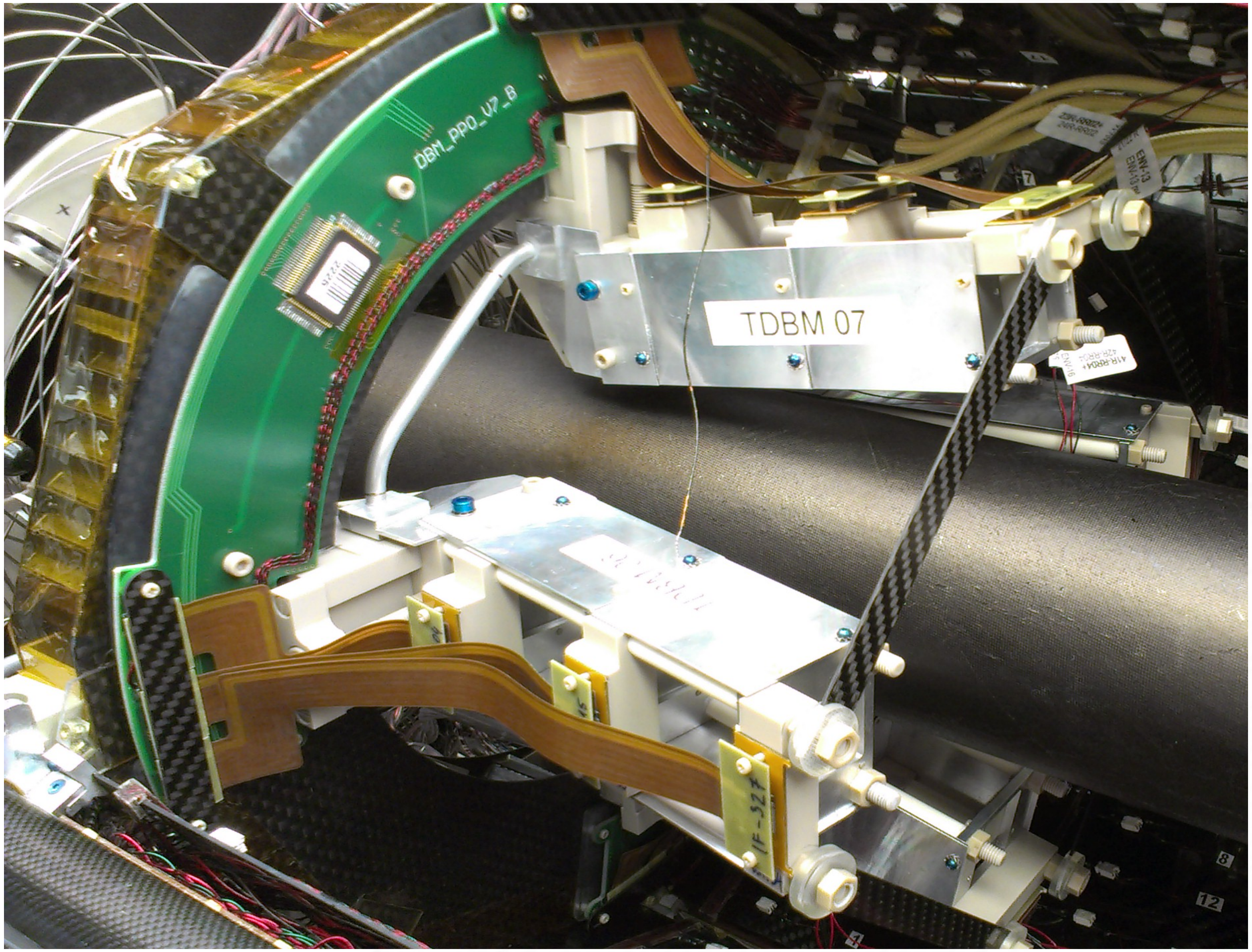
Telescopes assembly

- 8 telescopes for final DBM assembled
  - 6 with diamond modules
  - 2 with silicon modules



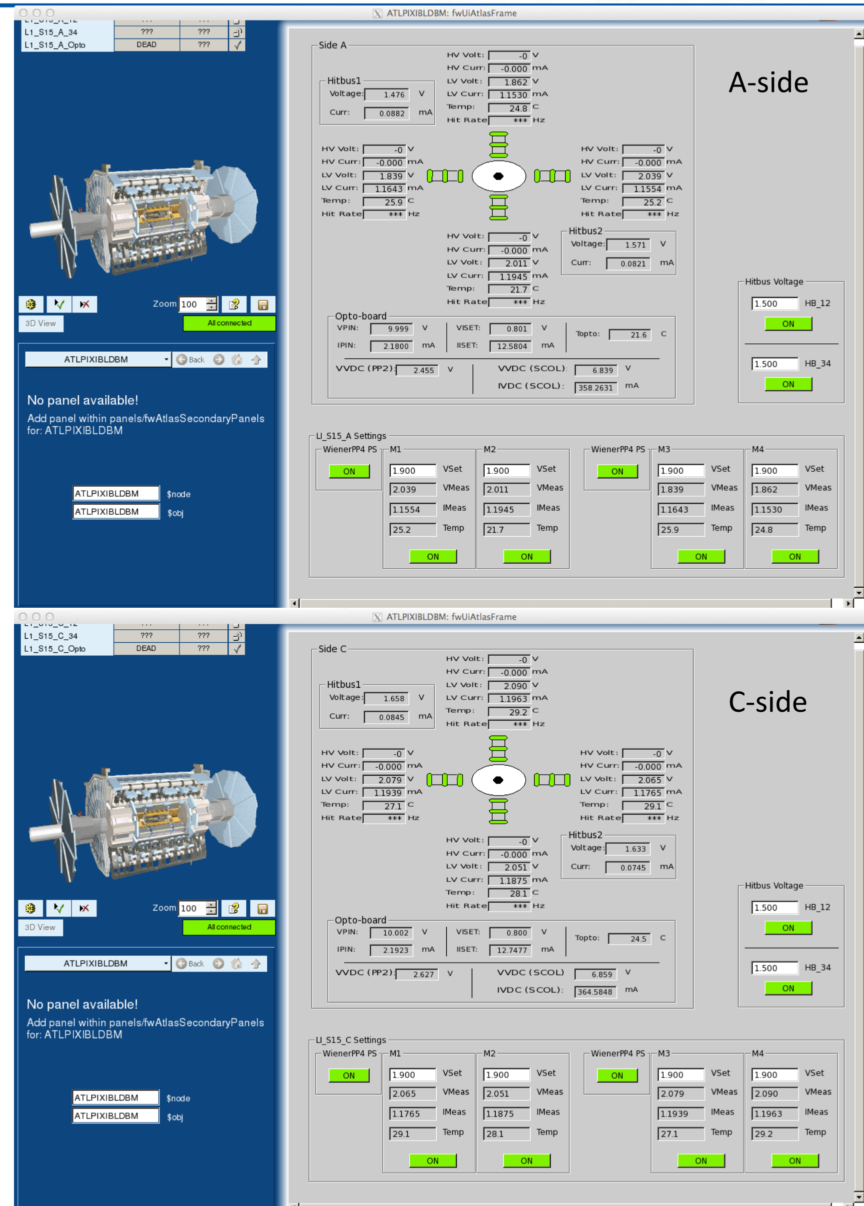
Telescope installation





DBM commissioning

- DBM telescopes are fully integrated in the Pixel/IBL operation and readout → DBM is “15th IBL stave”
- Commissioning started in July 2014:
  - Connectivity of 24 DBM modules established and tested
  - Power (LV and HV) and temperature measurement tests
  - Readout tests with non final readout successfully tested for all modules
  - Readout tests with ROD/BOC system are currently ongoing



Summary & Conclusions

- Diamond is an interesting but challenging sensor material for future HEP luminosity, beam monitor and tracking detectors in high radiation environment
- DBM production reveals several problems for large pixel devices
  - We learned a lot about bump bonding of large diamond pixel sensors
  - still try to understand all the problem and work with IZM on more robust and reliable procedure
  - noise hits and HV stability issues still under investigations
- ATLAS has installed the DBM inside the pixel package
  - Six high quality diamond telescopes and two silicon telescopes
  - Provide 100% acceptance for early DBM running
  - Commissioning close to finish
- Looking forward to operate DBM inside ATLAS during LHC Run 2

RD-42 Collaboration

RD42 Collaboration 2014

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