

Diamond Pixel Modules and the ATLAS Beam Conditions Monitor



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On behalf of RD42, the ATLAS Diamond Pixel Upgrade
collaboration and the ATLAS BCM collaboration

vCI2010, Vienna, 17.02.2010



Diamond Pixel Detectors

Diamond as Particle Detector:

- Diamond Properties and Growth
- Diamond Detector Materials

Motivation:

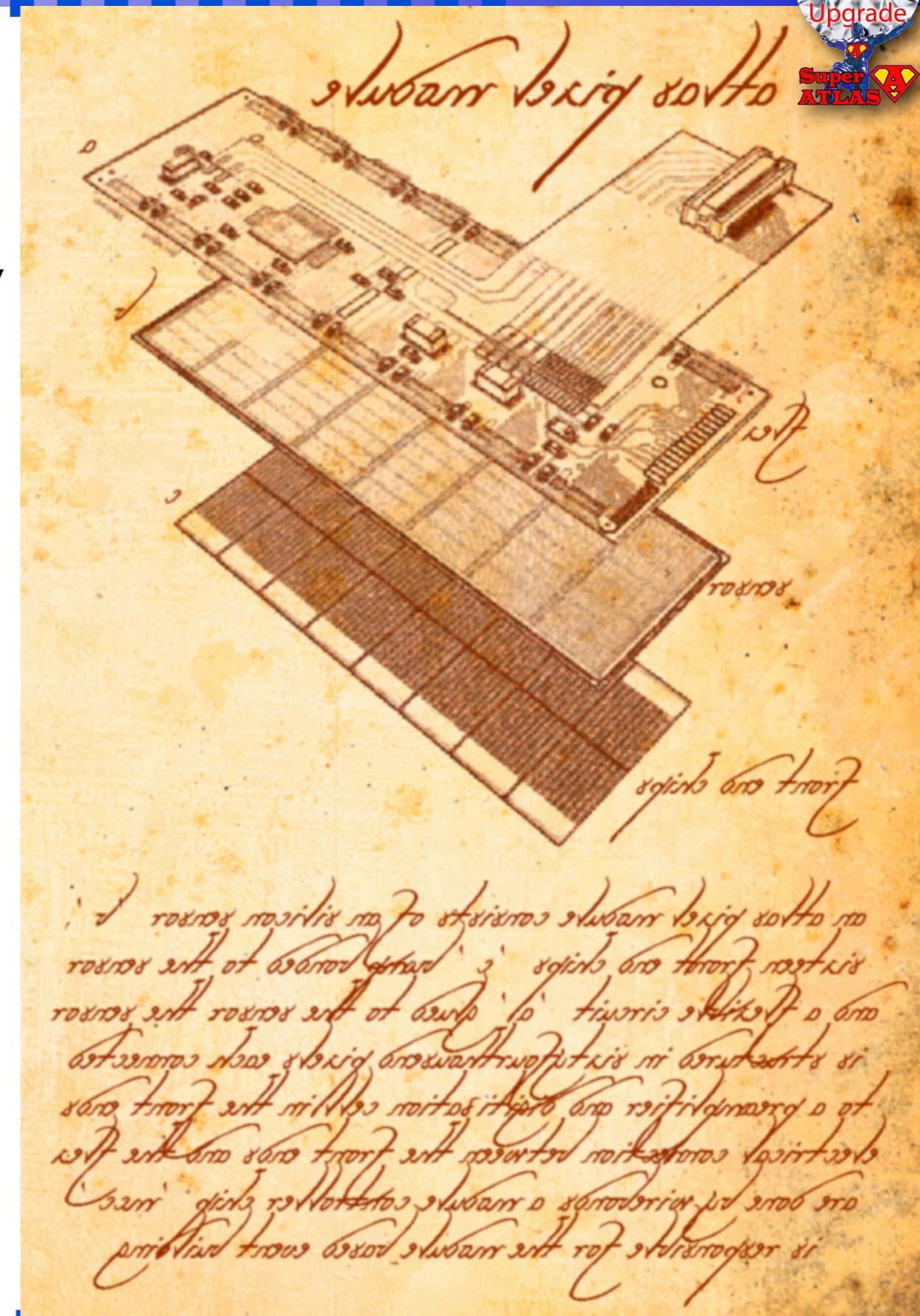
- ATLAS Insertable B-Layer
- ATLAS for sLHC: Layout & Fluences

pCVD Diamond Pixel Module:

- Threshold and Noise
- Industrialization
- Rework of Diamond Sensors

Testbeam & Diamond Irradiation:

- Resolution & Efficiency
- TOT and Charge Collection
- Radiation Hardness



Collaboration & Motivation



Collaboration

- Bonn
- Carleton
- CERN



- Ljubljana
- Ohio State
- Toronto



Motivation

- demonstrate Chemical Vapor Deposition (CVD) diamond radiation tolerance (testbeam)
- optimize Front-End electronics
- industrialize diamond bump bonding
- lightweight support (minimal cooling)



CERN

Diamond Pixel Modules and BCM

D.Dobos

	Diamond Pixel Modules for the High Luminosity ATLAS Inner Detector Upgrade
ATLAS Upgrade Document No:	Institute Document No.
Created: 15/05/2007	Page: 1 of 14
Modified: 24/12/2007	Rev. No.: 1.8

Diamond Pixel Modules for the High Luminosity ATLAS Inner Detector Upgrade

The goal of this proposal is to construct 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 polycrystalline Chemical Vapour Deposition diamond material in wafers, the successful completion and test of the first diamond ATLAS pixel module, and the preparation of diamond at irradiation rate $1.8 \cdot 10^{16}$ n/cm 2 /s. In this proposal we outline the results of these three areas and propose a plan to build 10 ATLAS diamond pixel modules, characterize their properties, 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. Based on availability of single polycrystalline Chemical Vapour Deposition diamond has been chosen as the baseline material. The technology of polycrystalline diamond is reserved as a future option if the manufacturers can attain sizes in the range 16mm x 16mm.

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EDMS: ATU-RD-MN-0012			<i>Distribution List</i>

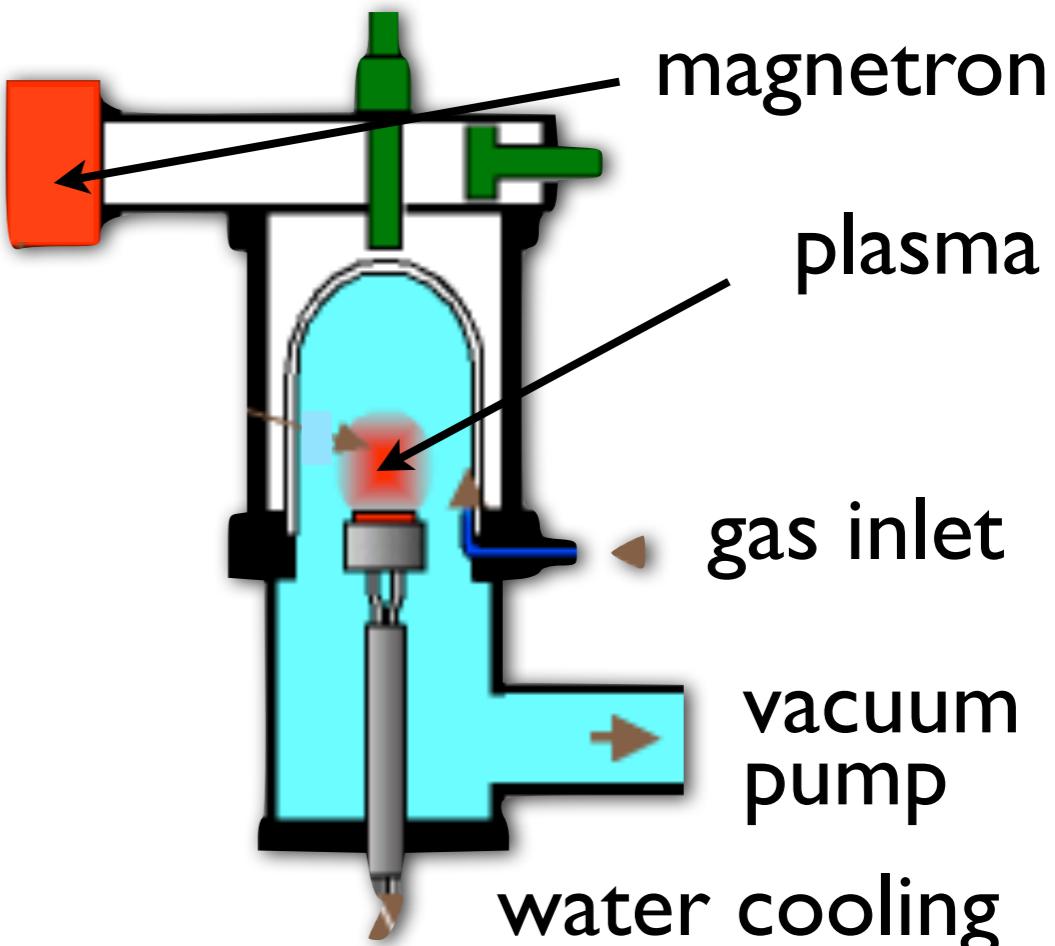
- Submitted May 07
- Updated Dec. 07
- EB Approved Mar. 08

Why diamond?



- high band gap (5.5 eV), breakdown field (10^7 V/cm) & resistivity ($>10^{11}$ Ω cm)
→ low leakage current
- low dielectric constant (5.7)
→ low capacitance
- high displacement energy (43 eV/atom)
→ radiation hard
- high thermal conductivity (~2k W/m.K)
→ no cooling
- high energy to create e/h pair (13 eV) &
low average created signal ($36 e_0 / \mu\text{m}$)
→ low signal, but also low noise

Microwave CVD Plasma Reactor



Metallization

- no doping needed
- metal contacts (pads, strips, pixels) sputtered or evaporated

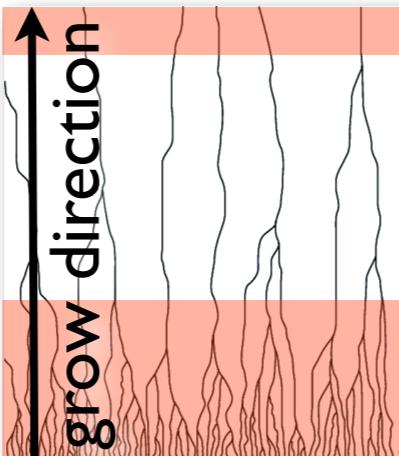
Diamond Detector Materials



polycrystalline (pCVD):

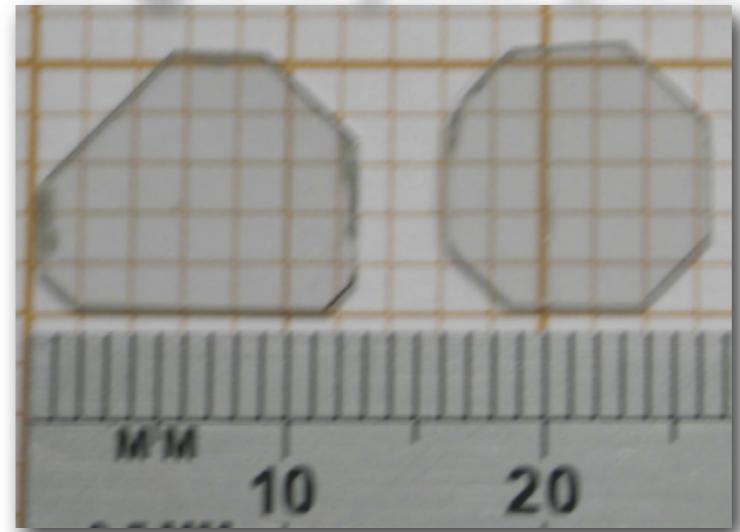


grown on
non-diamond
substrate



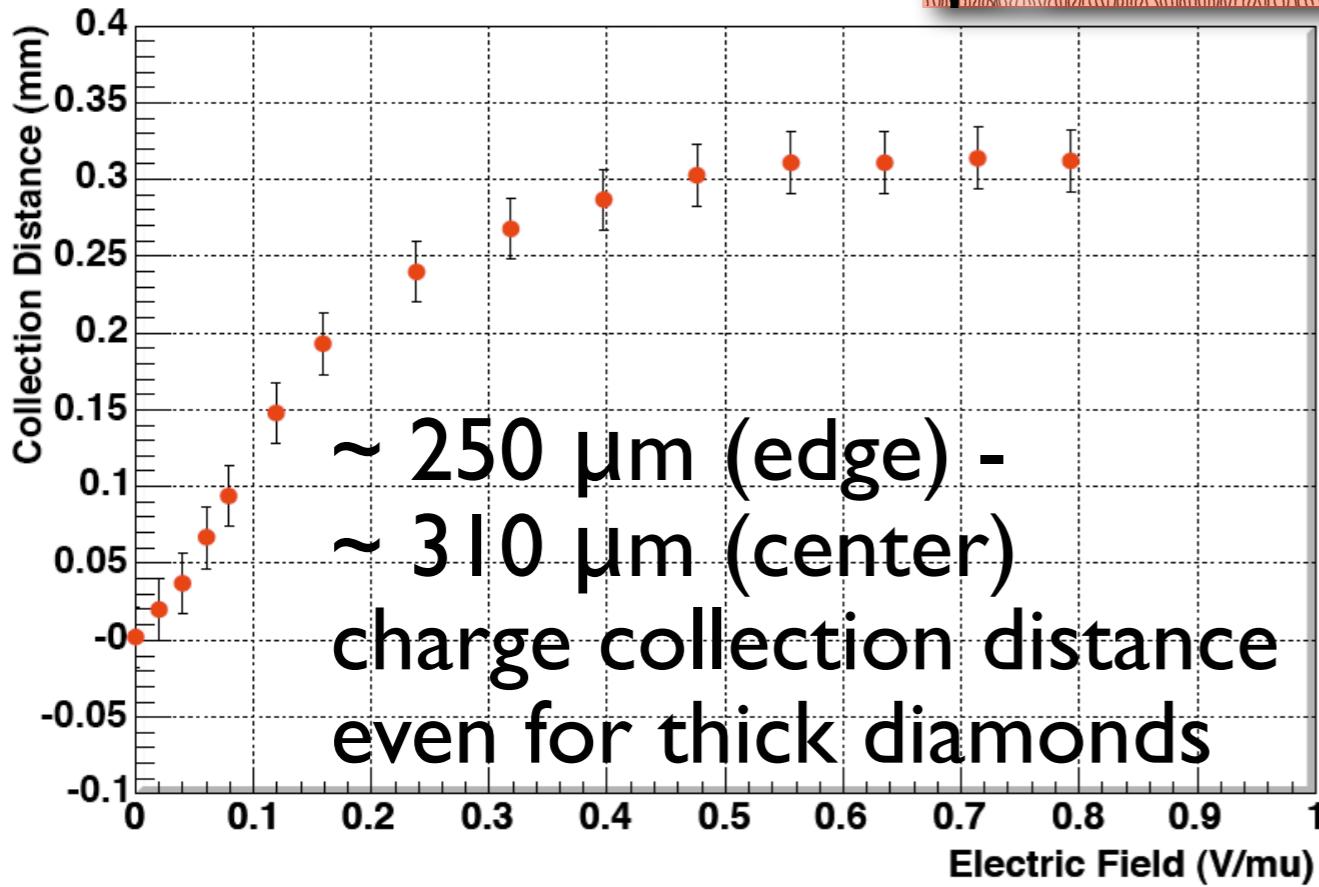
$> 12 \text{ cm } \varnothing$
 $> 2 \text{ mm thickness}$

single crystal (scCVD):

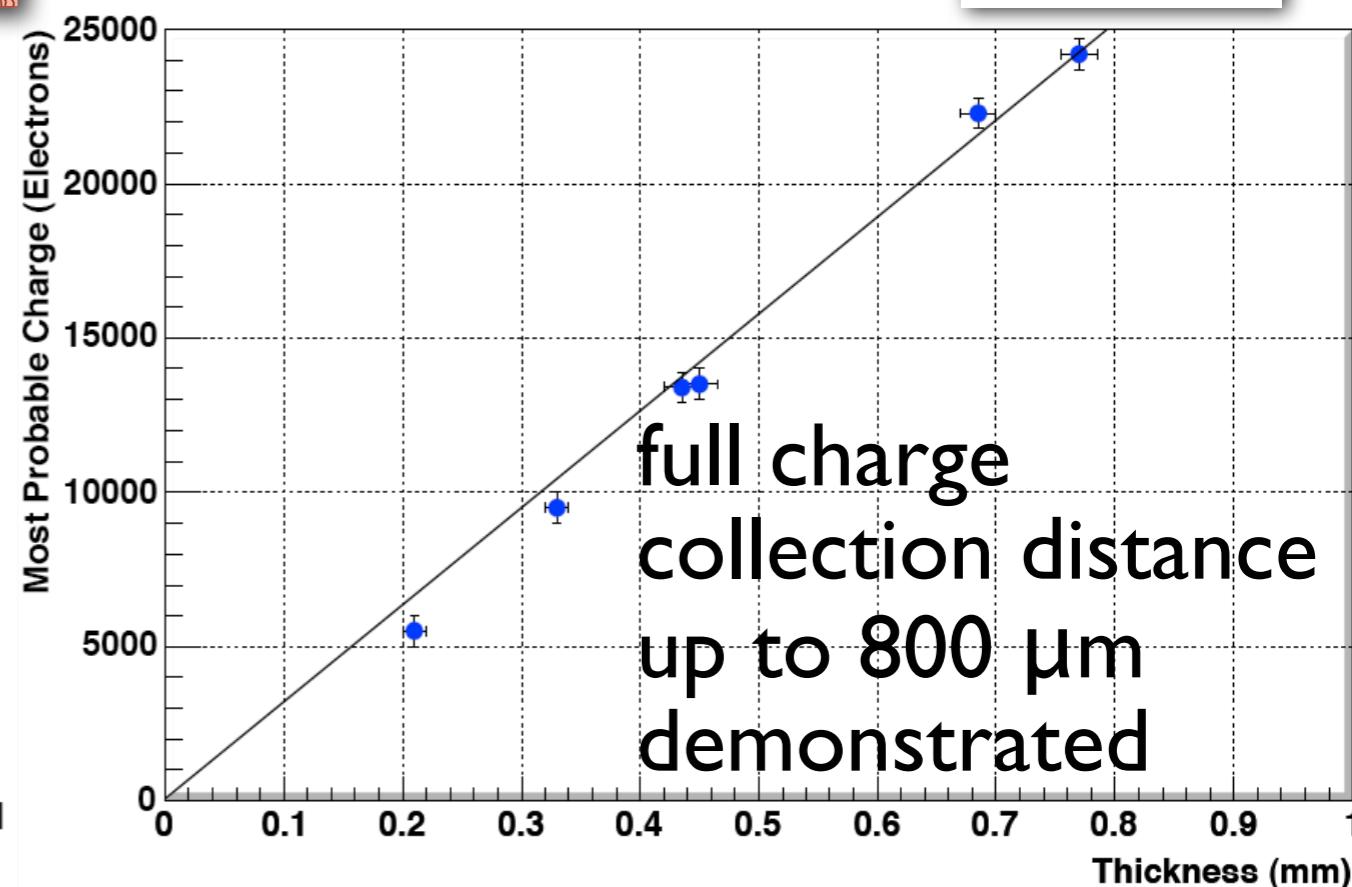


grown on
HTHP
diamond
substrate

real
single
crystal



$\sim 250 \mu\text{m}$ (edge) -
 $\sim 310 \mu\text{m}$ (center)
charge collection distance
even for thick diamonds



full charge
collection distance
up to 800 μm
demonstrated

Motivation: ATLAS Insertable B-Layer (IBL)



ATLAS Phase I upgrade:

- current innermost layer (B-Layer) usable up to $10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ → fine till

Phase I upgrade

- originally planned exchange not feasible (> 1 year)

Insertable B-Layer:

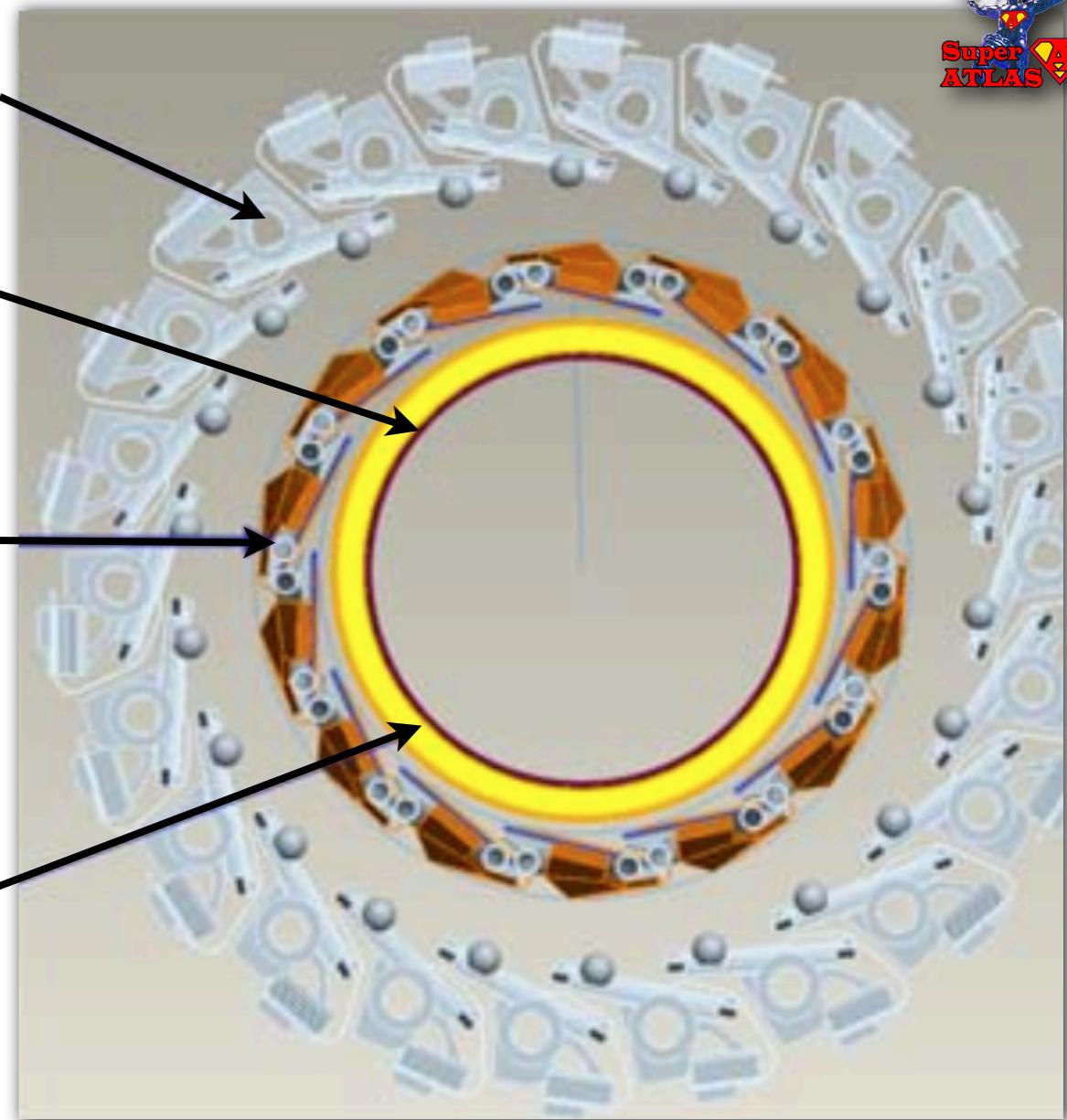
- new beam pipe with additional layer ($r = 33 \text{ mm}$)
- tight space → no shingling, slim or active edges
- 1-1.5 % X_0 material budget
- $5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ requirement

Current B-Layer

Beam Pipe

IBL

bakeout
heater &
isolation



- beam pipe radius can be reduced from 29 to 25 mm

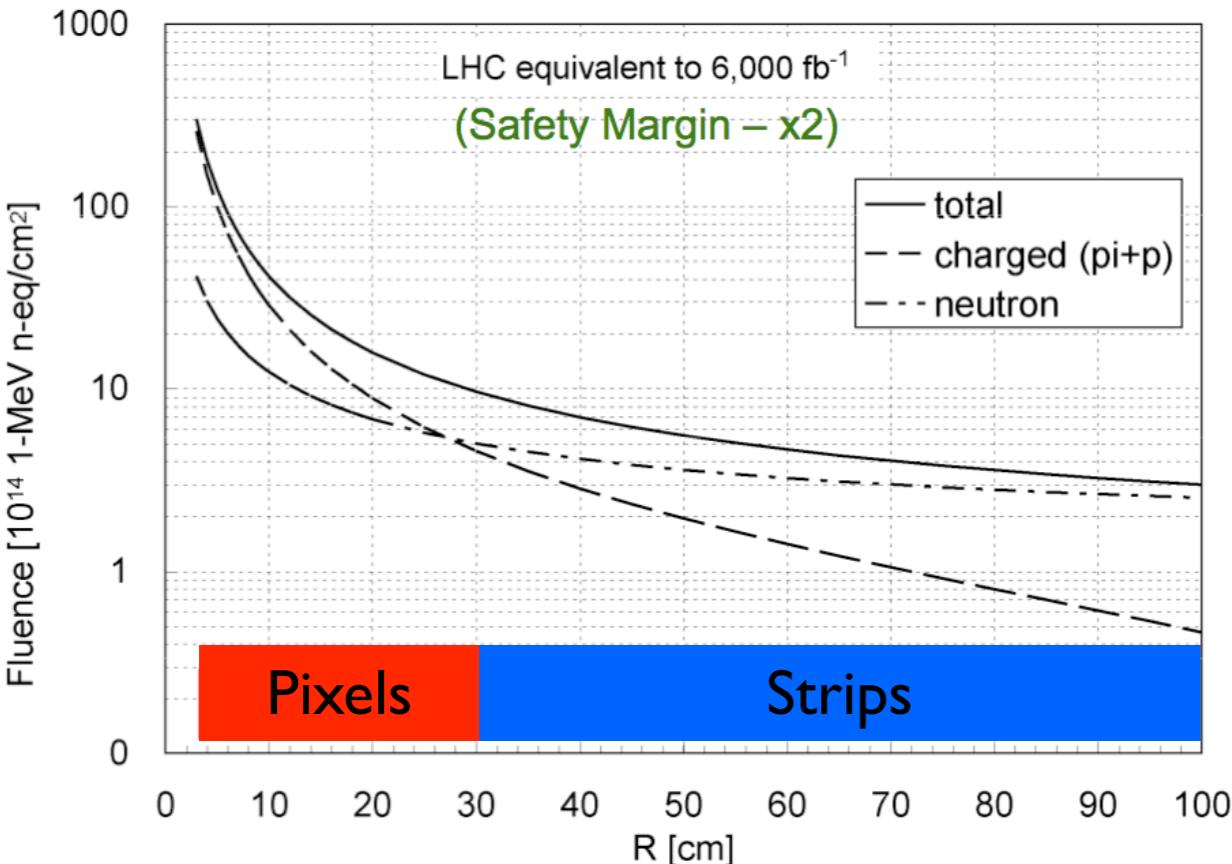


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Diamond Pixel Modules and BCM

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Motivation: ATLAS for sLHC: Layout & Fluences

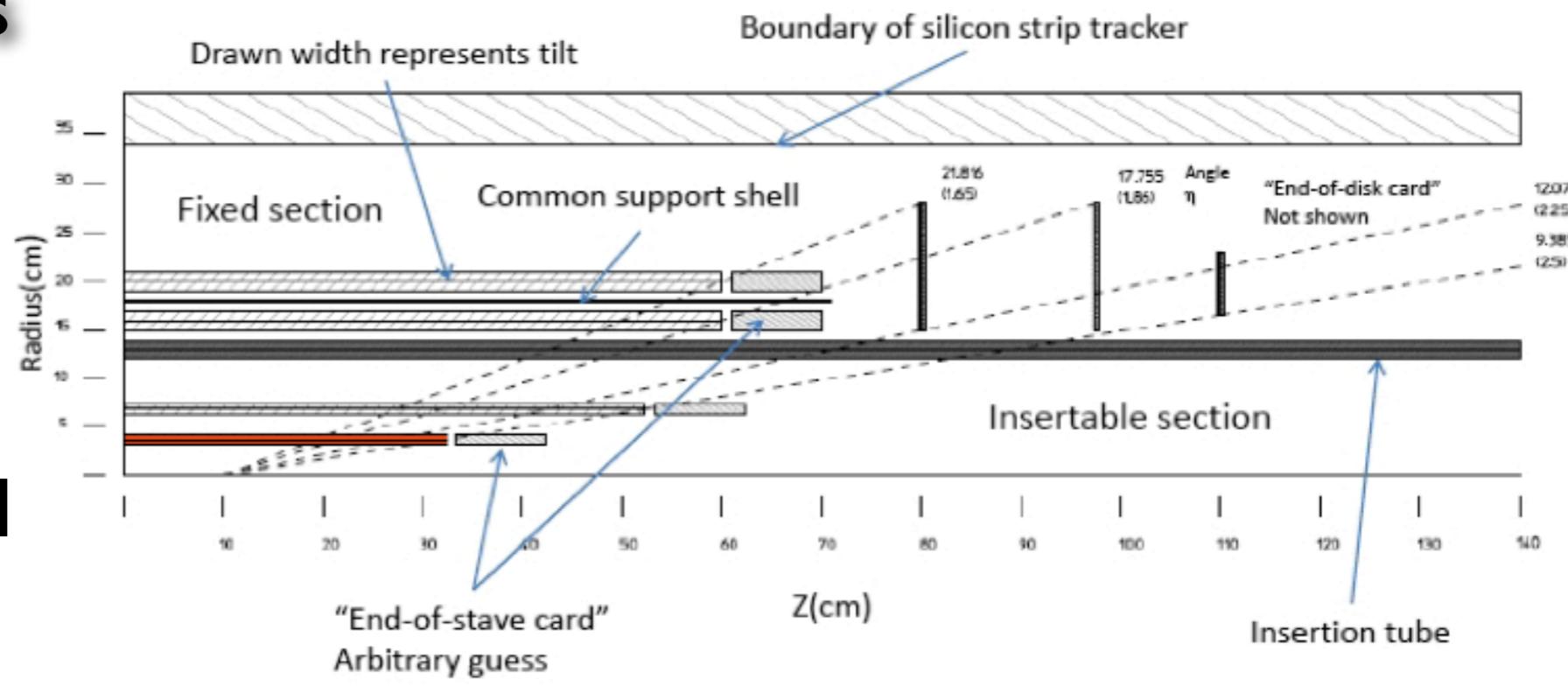


sLHC ATLAS Layout Snapshot

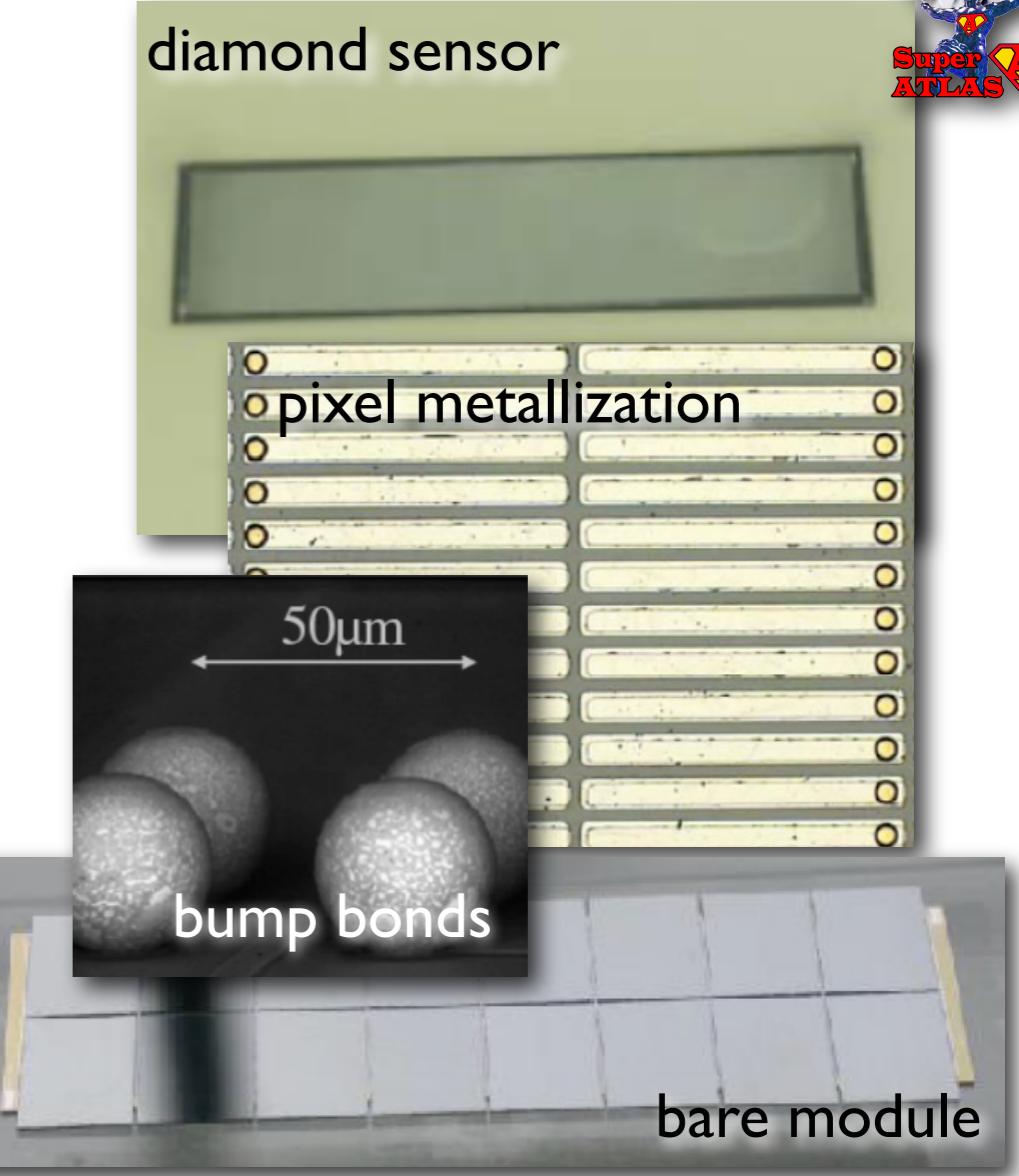
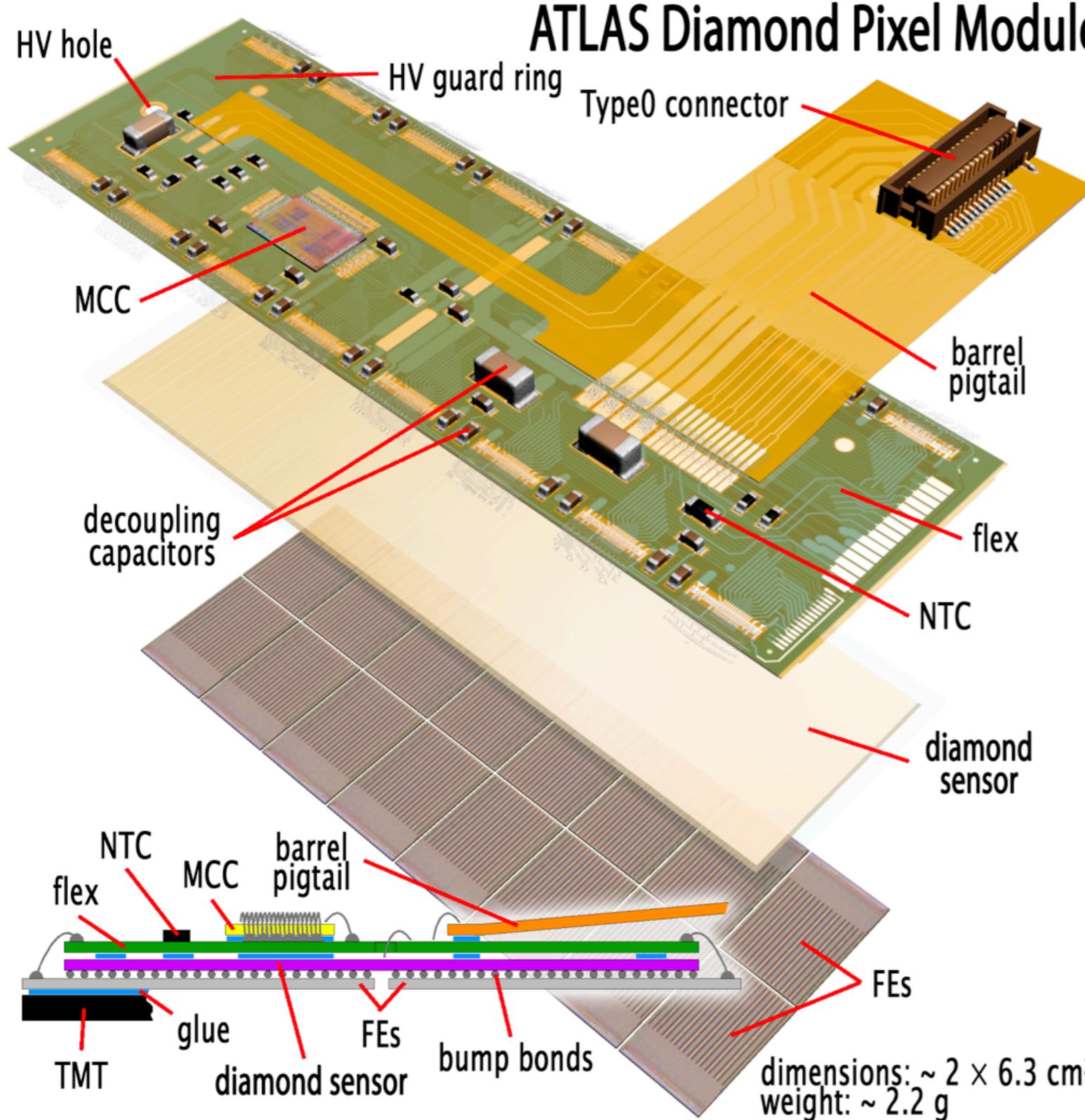
- 3 - 30 cm Pixels
- 30 - 100 cm strips
- Pixel layer I: ~ 60 cm long staves at $r \sim 3$ cm
- multiple of 0.12 m^2 sensor material in innermost layer
- $\text{NIEL} \sim 1.5 \times 10^{16} \text{ cm}^{-2} (3000 \text{ fb}^{-1})$

sLHC ATLAS Fluences

- below 25 cm charged particles dominate (90% π, k, p - 10% n)
- different inner pixel technologies ?



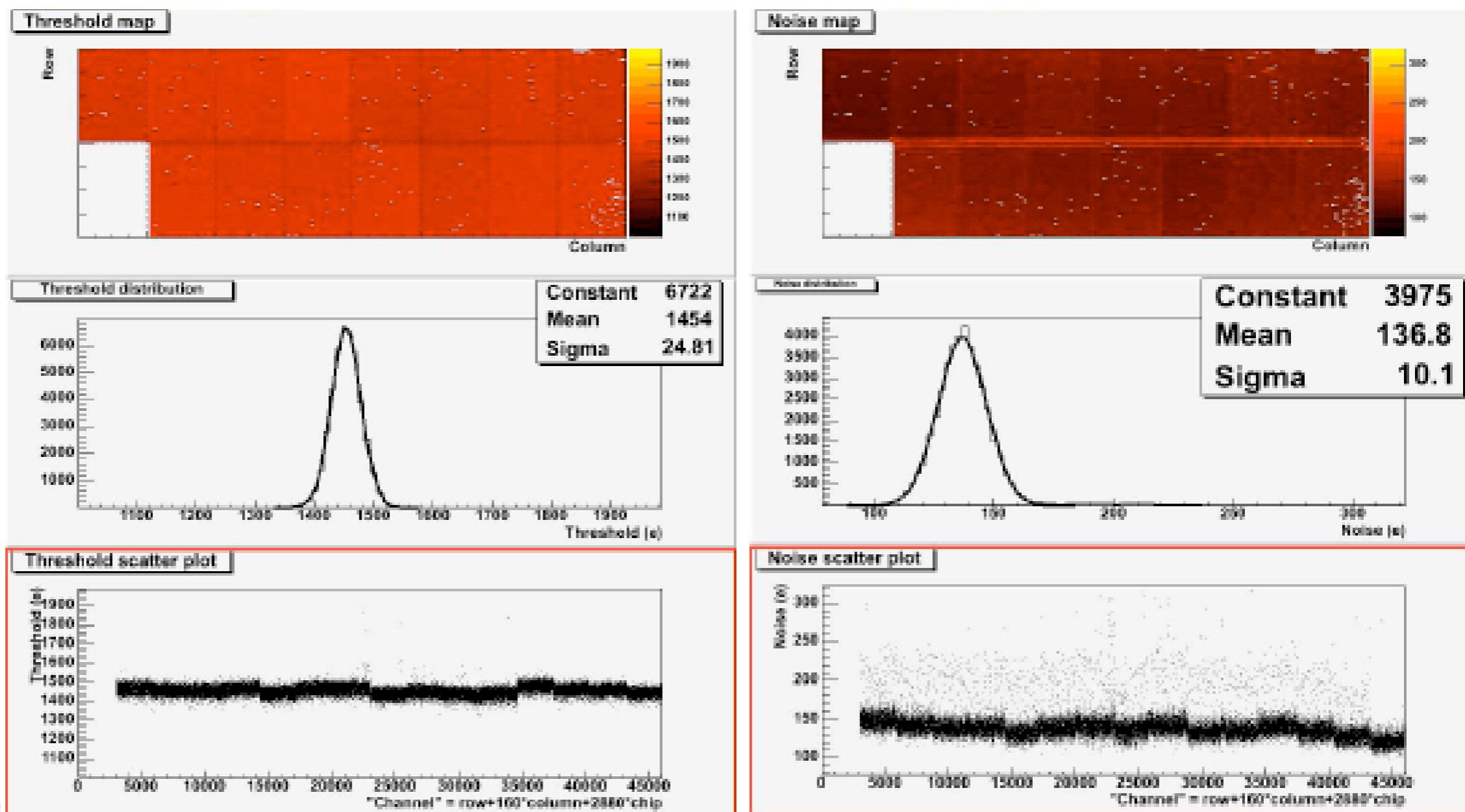
ATLAS pCVD Diamond Pixel Module



- 800 μm pCVD diamond
- 50×400(600) μm pixels
- 16 ATLAS FE-I3 chips
- active area: $61 \times 16.5 \text{ mm}^2$

Threshold and Noise

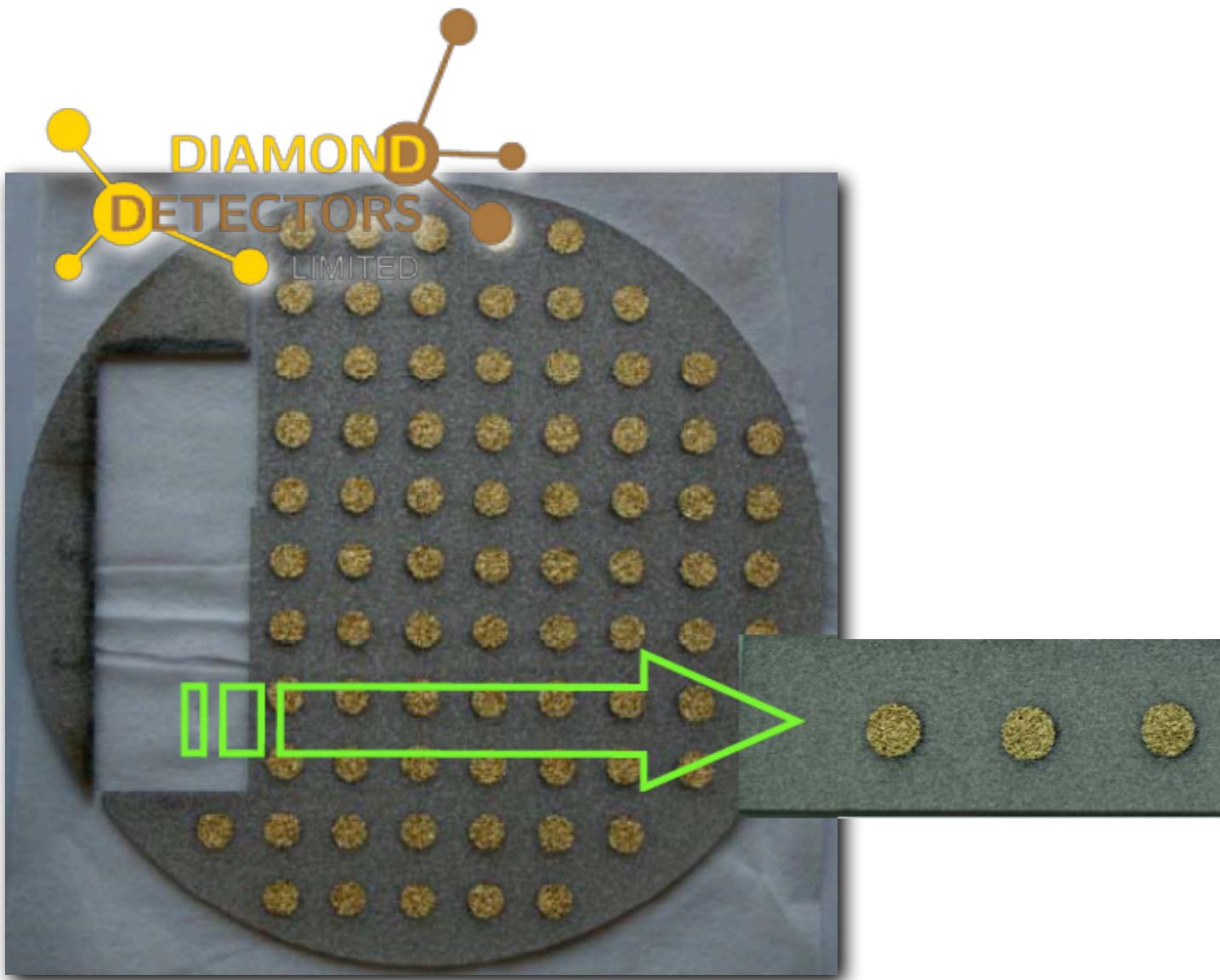
- excellent threshold and noise performance:
threshold: 1450 ± 25 e $^-$, noise: 137 ± 10 e $^-$ & overdrive 800 e $^-$
- no changes from bare FEs (1497 ± 26 e $^-$; 138 ± 8 e $^-$) to module
- “invisible sensor”: low capacitance C & leakage current I_{leak}



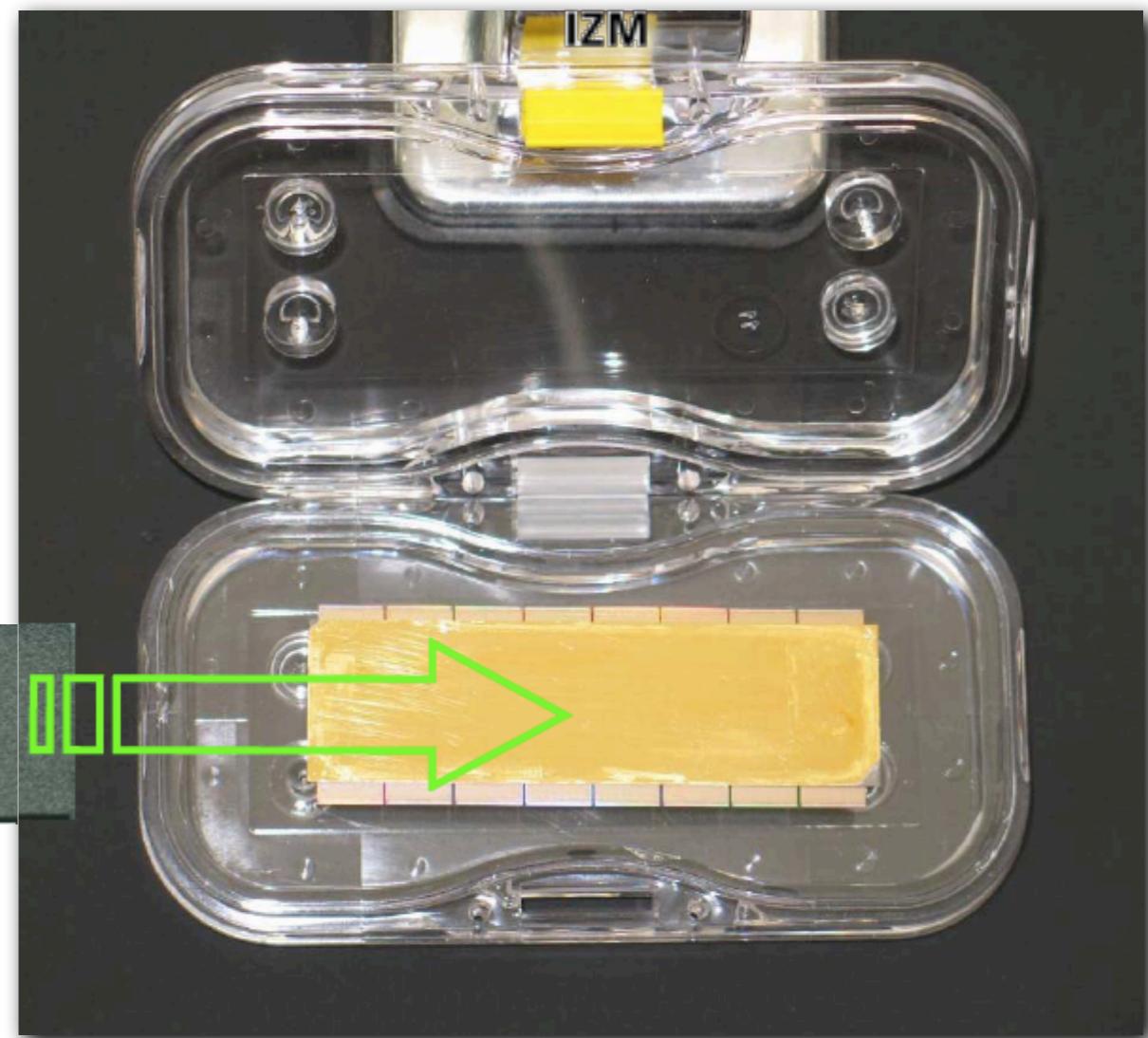
2nd full Pixel Module - Industrialization



- 1st full pCVD pixel module produced by OSU, IZM and Bonn
- 2nd module: 1st module fully build by Industry
- All steps from polished sensor to bump-bonding performed at IZM Berlin



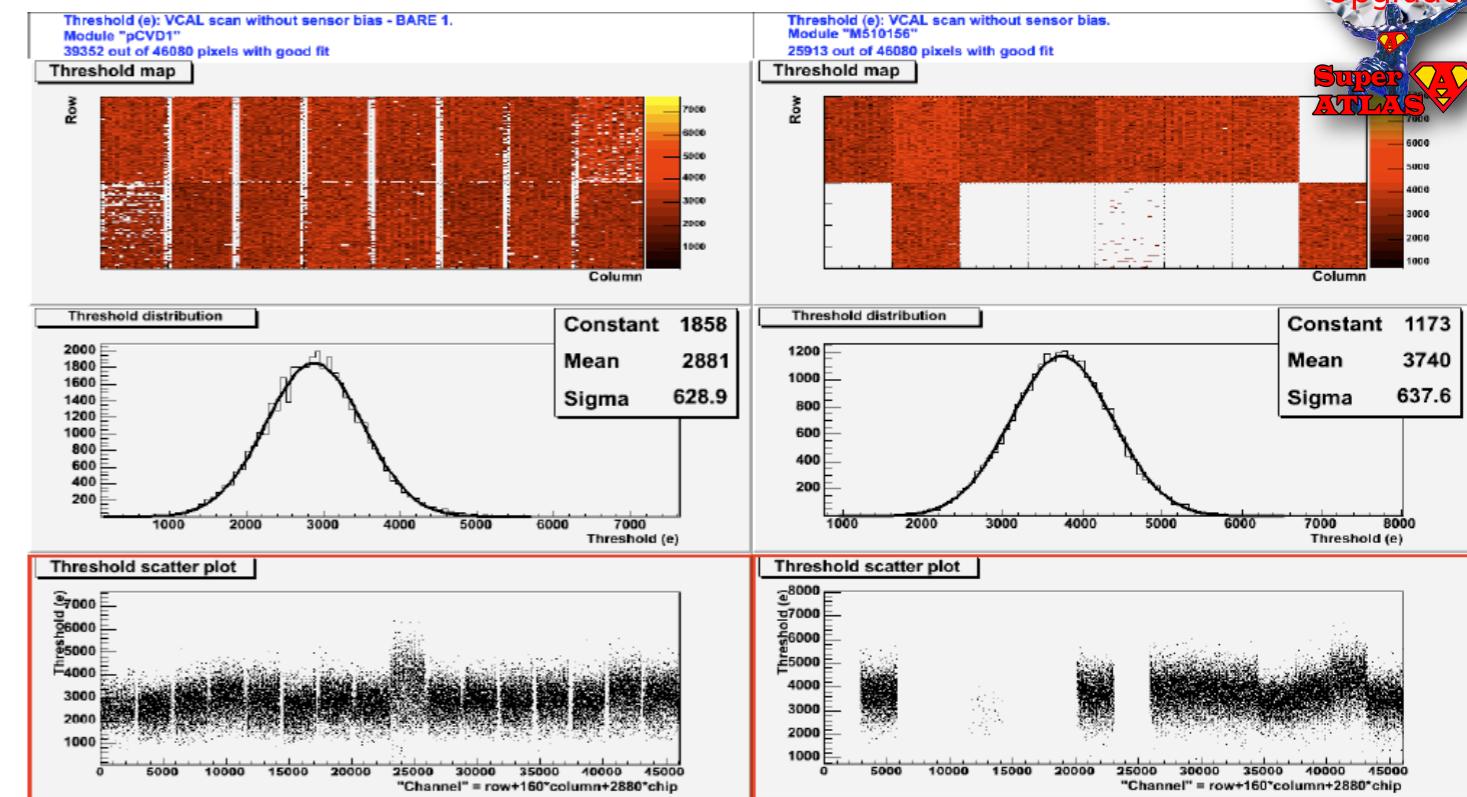
 **Fraunhofer**



Industrialization: Rework of Diamond Sensors

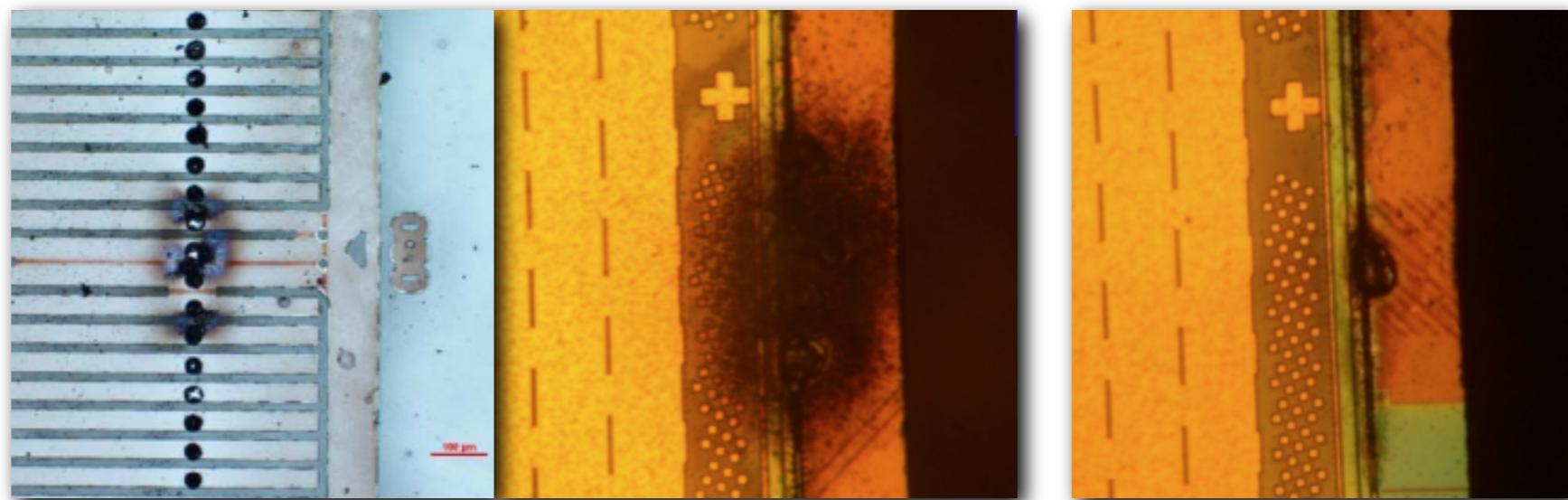


- diamond edge left metallized
- module shorted: 10V bias
- 7/16 FEs damaged
- reworked at IZM
- backside metallization redone
- module rim plasma etching
- all FEs replaced



before

after applying 10V



before rework

after rework



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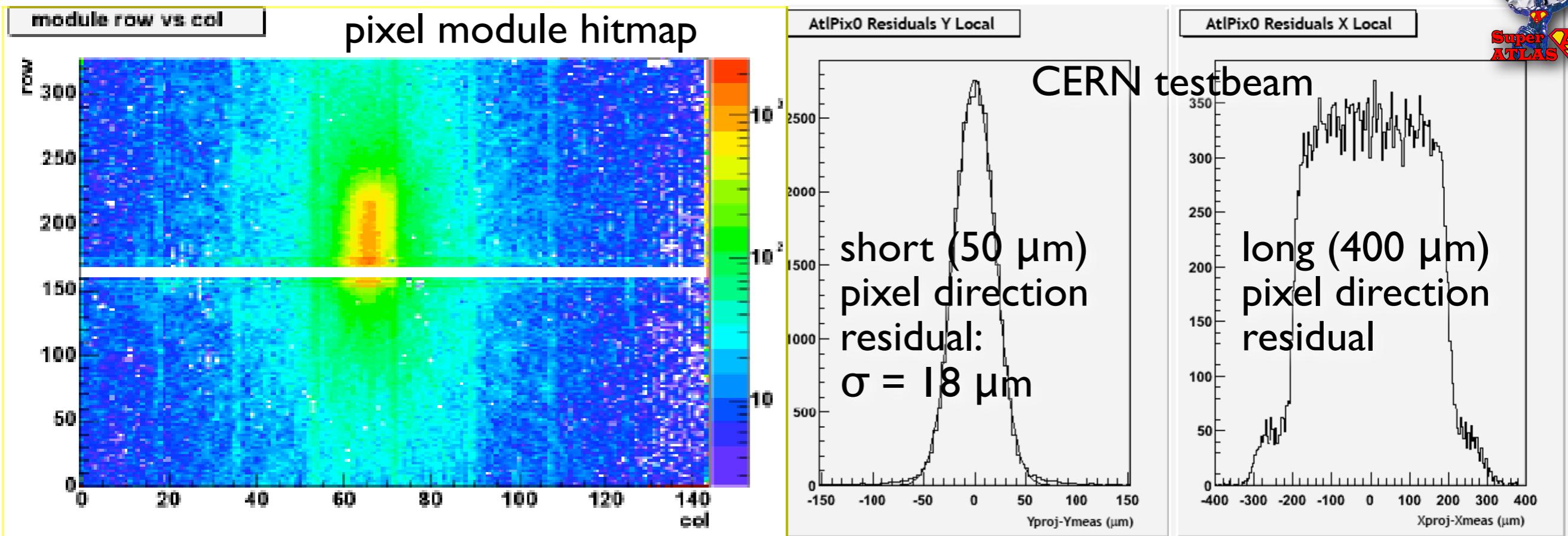
Diamond Pixel Modules and BCM

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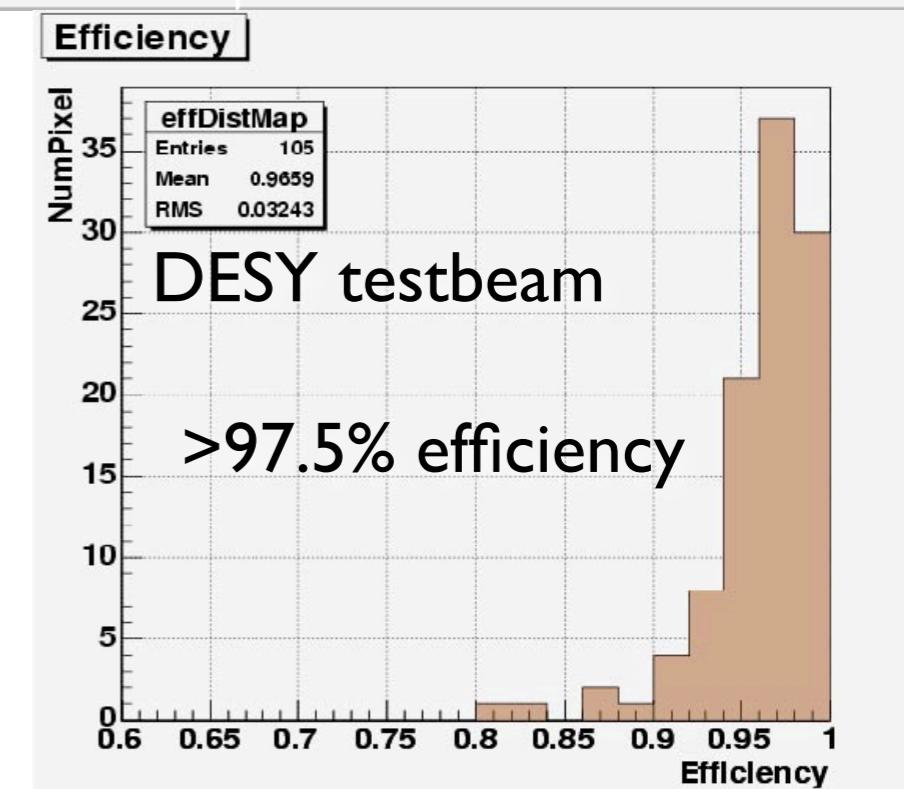
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pCVD Diamond Module: Resolution & Efficiency



- residuals show expected behavior:
 $18 \mu\text{m} \rightarrow$ unfold telescope resolution
 $\rightarrow 14 \mu\text{m}$ as expected from $50 \mu\text{m}/\sqrt{12}$
- 97.5% efficiency lower limit due to scattered tracks (4 GeV electrons)



TOT and Charge Collection



cut: I hit on each plane

threshold:
~ 1700 e⁻

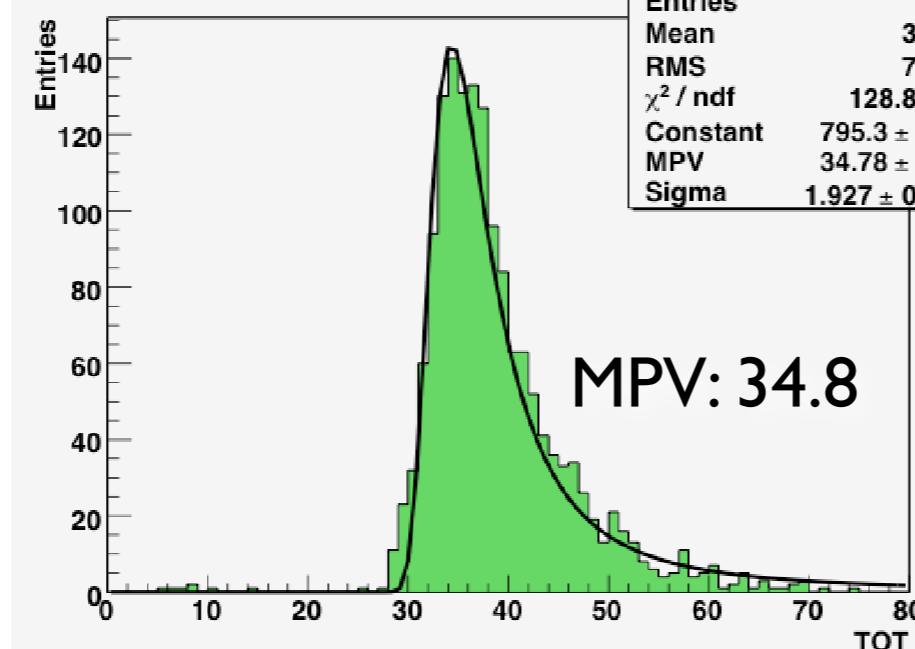
bias voltage:
- 400 V

bias voltage:
- 800 V

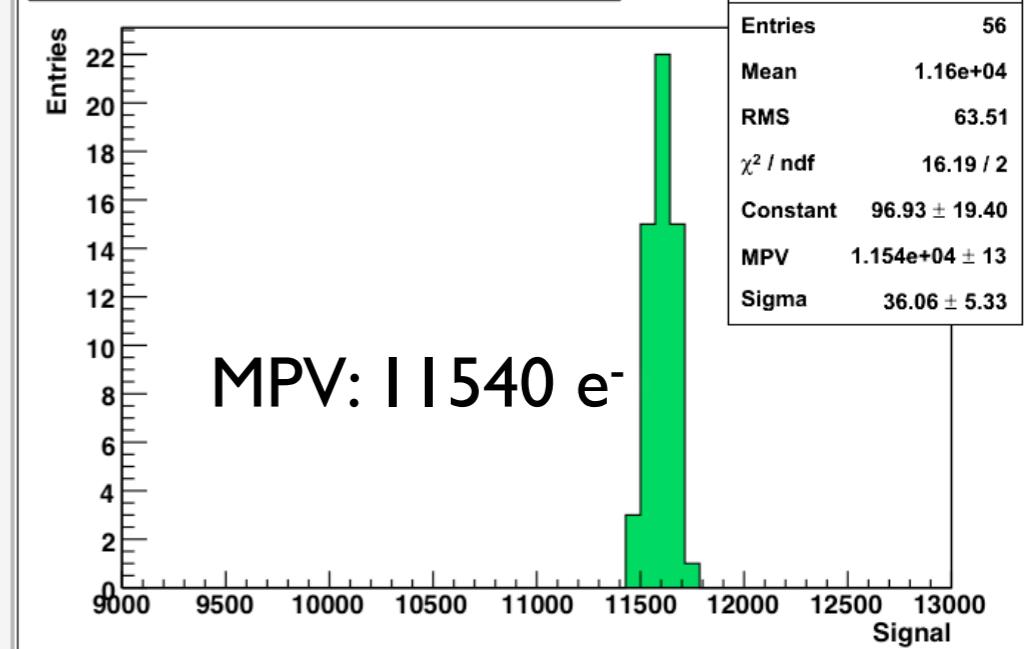
threshold:
~ 1470 e⁻

before irradiation

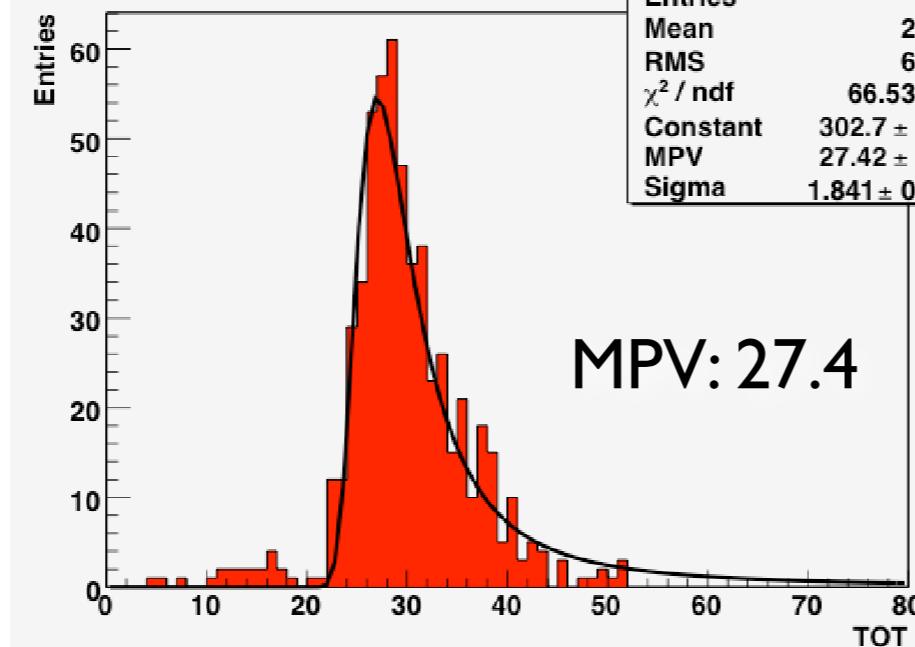
Oct. 06 - 30 TOT @ 10ke (run# 3294)



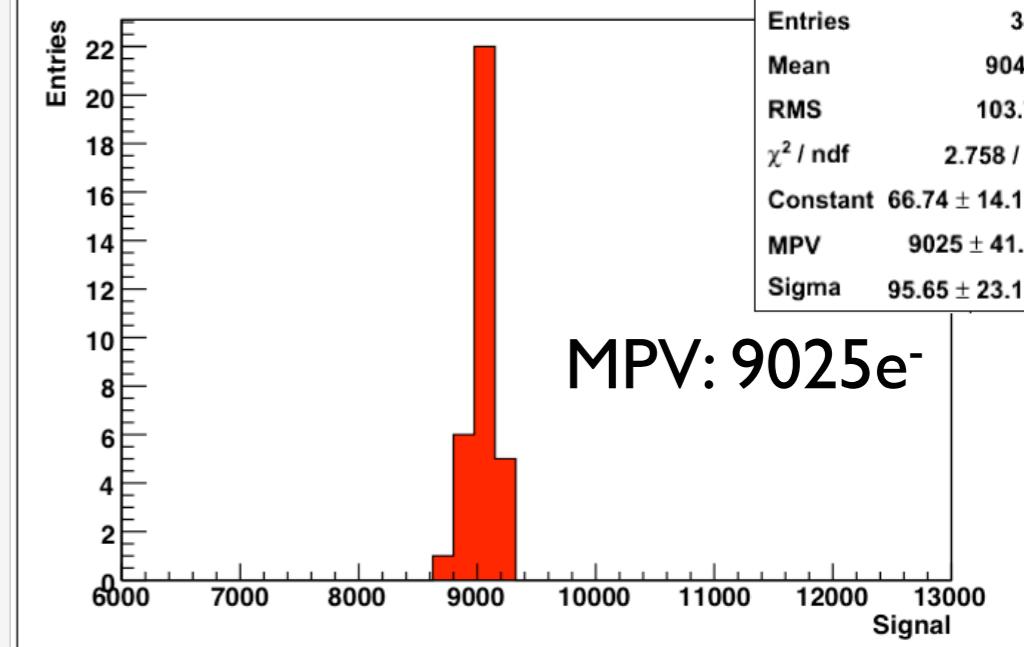
October 06 - MPV of charge collected



July 08 - 30 TOT @ 10ke (run# 9717)



July 08 - MPV of charge collected



after irradiation $0.7 \times 10^{15} \text{ p/cm}^2$



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Diamond Pixel Modules and BCM

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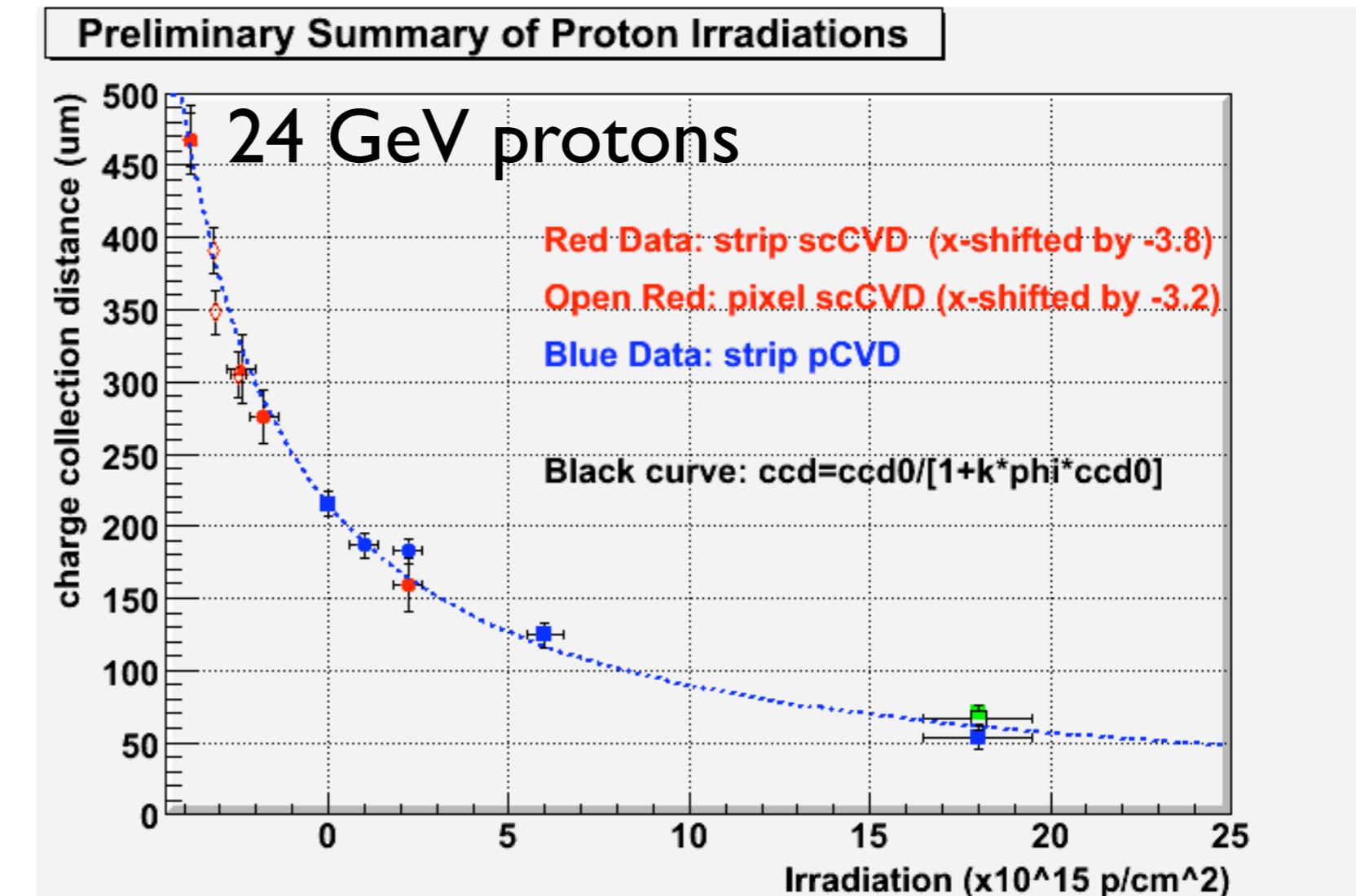
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Radiation Hardness

- studies performed with many pCVD & scCVD samples
- both follow curve:
 $I/ccd = I/ccd_0 + k\phi$
- diamond irradiated without FEs (pixelated with FEs)

Diamond Module Plans:

- damage curve for many particle types and energies
- produce & test:
 - 4: 16 FE-I3 modules
 - 20: 1 FE-I4 modules





ATLAS Beam Conditions Monitor (BCM)

Introduction to BCM:

- Motivation
- BCM in the ATLAS Inner Detector
- Diamond Detectors

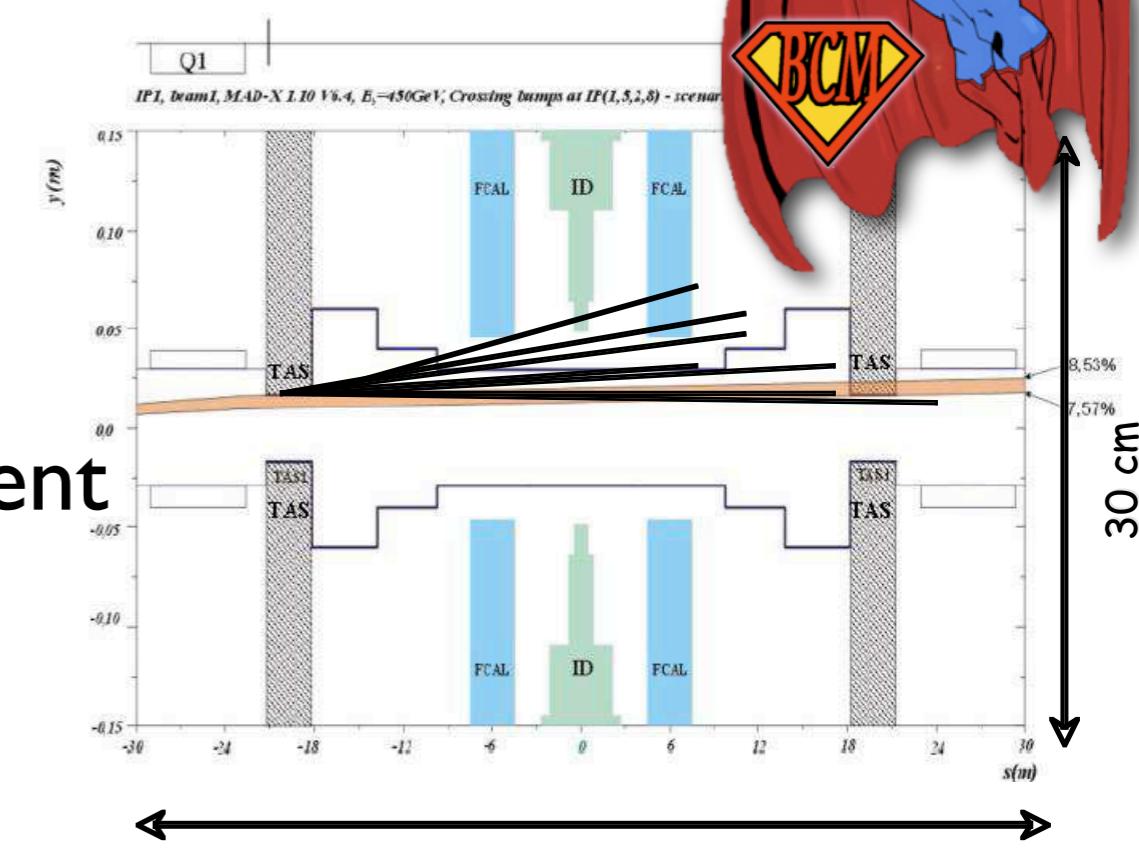
Results from 2009 LHC run:

- Beam Conditions Monitoring
- Bunch-by-Bunch Beam Conditions Monitoring
- Post Mortem Buffer
- 390 ps Beam Abort Diagnostic

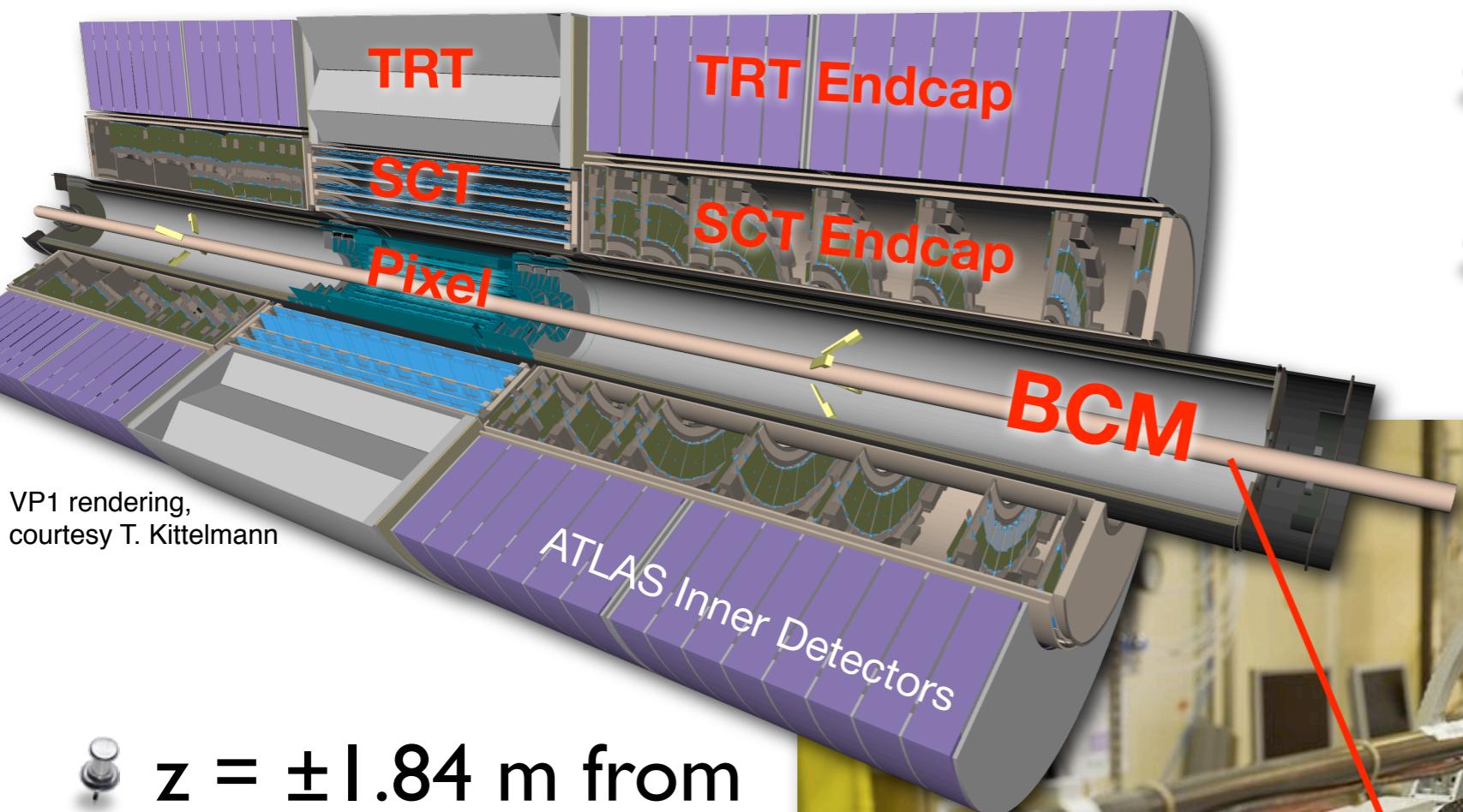




- SppS / LEP / RHIC / HERA / Tevatron experiences and ATLAS simulations teach: protect detectors from beam incidents
- Instantaneous beam conditions measurement to distinguish each bunch crossing between:
 - Normal collision
 - Beam gas (tiny effect); beam halo
 - Pilot beam loss
(5×10^9 p @ 450 GeV; 360 J)
 - Beam loss
- Magnets have \sim ms time constants
- Generate abort signals before incident
- Most probable scenario: pilot bunch scrapes TAS Cu collimators
($|l| = 1.8$ m; $z = \pm 18$ m) 5×10^{-3} Gy

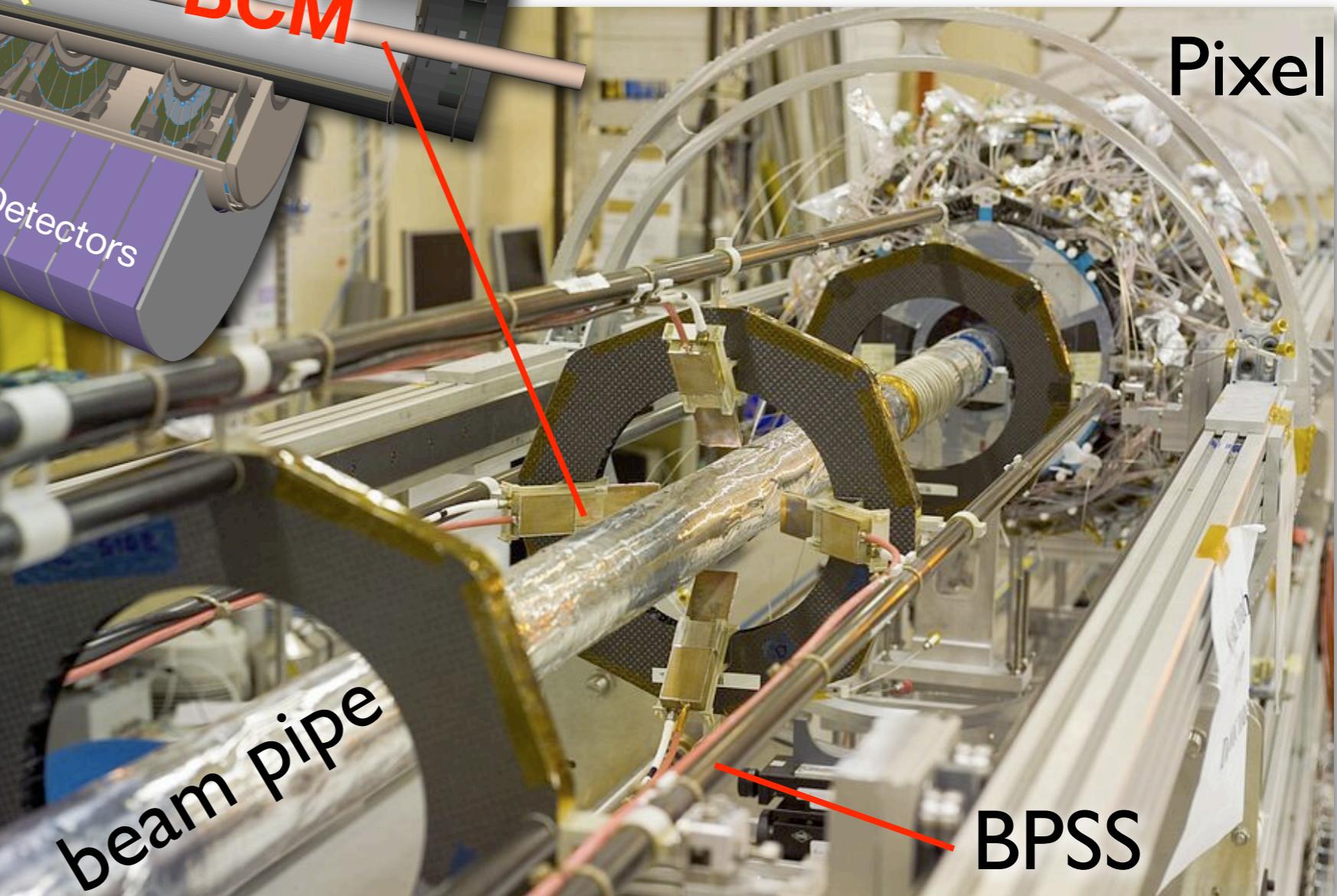


BCM in the ATLAS Inner Detector



- 4 detectors each side (C & A)
- Positions: X+, Y+, X-, Y-

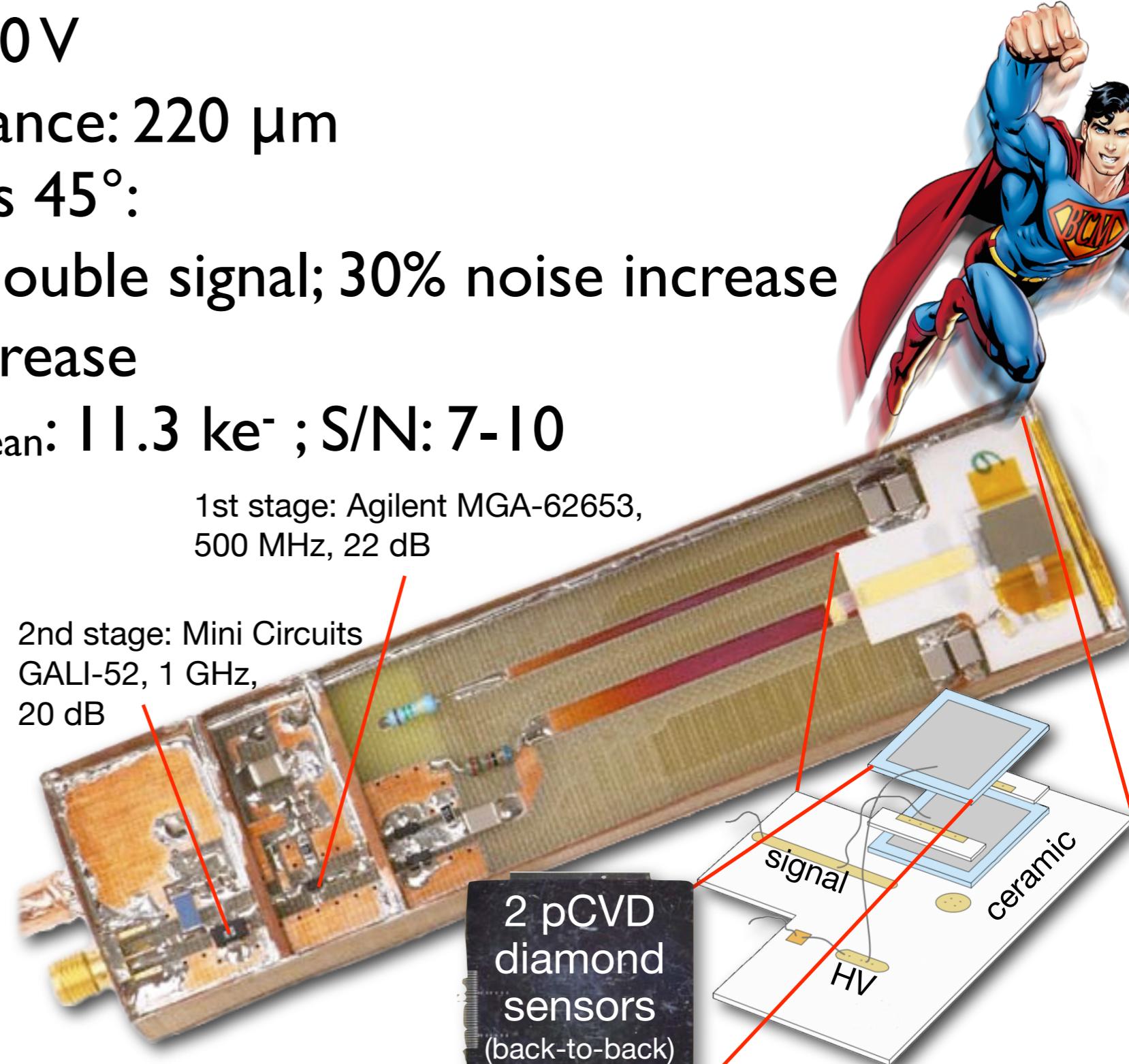
- $z = \pm 1.84$ m from interaction point
- Detectors at 5.5 cm radius from beam axis
- Installed on the Pixel Beam Pipe Support Structure



BCM Diamond Detectors



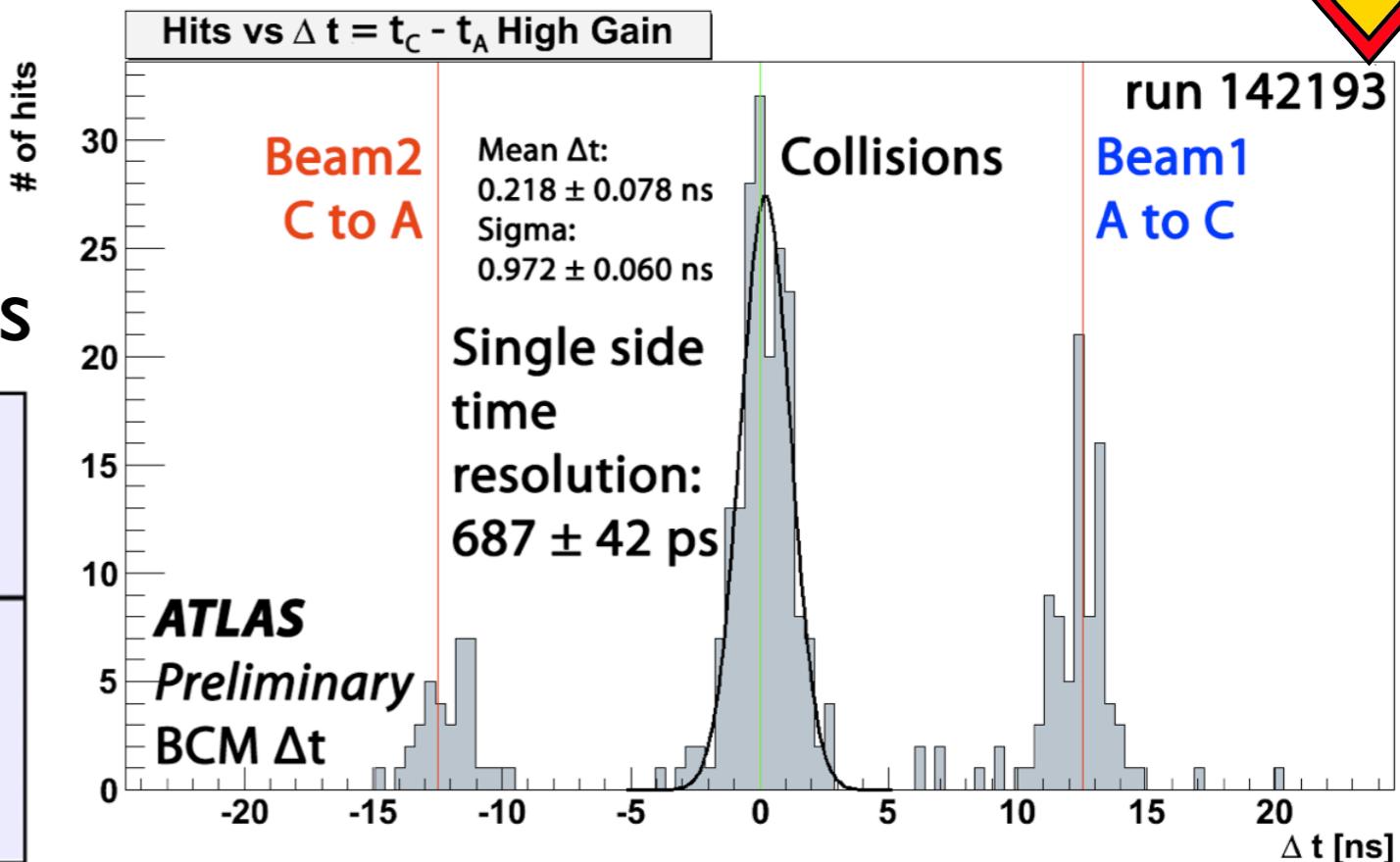
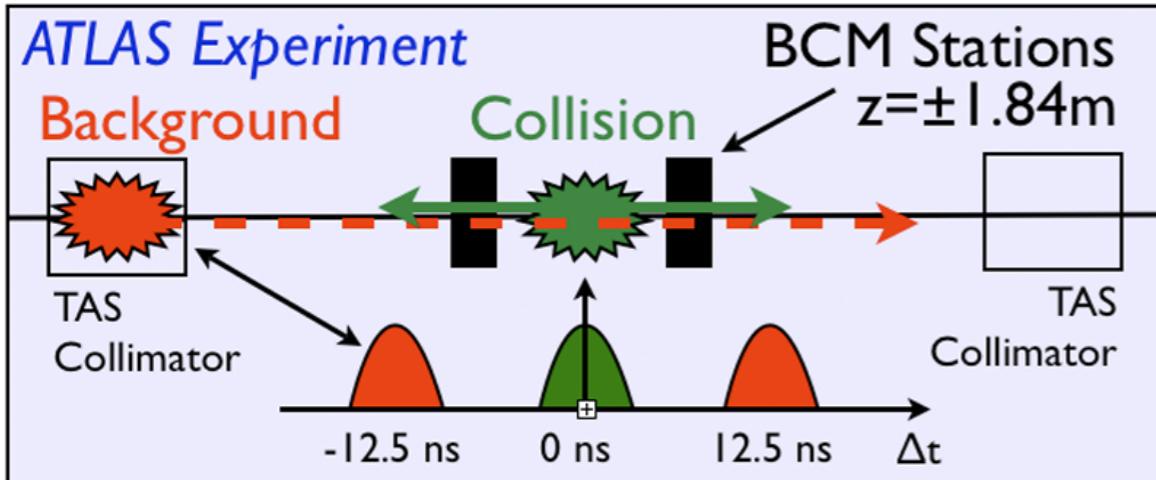
- pCVD (RD42) sensor: 10×10 (contacts: 8×8) $\text{mm}^2 \times 500 \mu\text{m}$
- V_{bias} : $1-2 \text{ V}/\mu\text{m} \rightarrow 1000 \text{ V}$
- Charge collection distance: $220 \mu\text{m}$
- 2 back-to-back sensors 45° :
 - Double sensor \rightarrow double signal; 30% noise increase
 - $45^\circ \rightarrow 41\%$ signal increase
- $Q_{\text{most prob.}}: 9.0 \text{ ke}^-$; $Q_{\text{mean}}: 11.3 \text{ ke}^-$; S/N: 7-10
- Readout: 2 thresholds (high and low gain) per detector
 - 2.56 GHz sampling (390 ps) with a Virtex4 FPGA data acquisition system



Beam Conditions Monitoring



- Measure Time-of-Flight to distinguish beam background from collisions



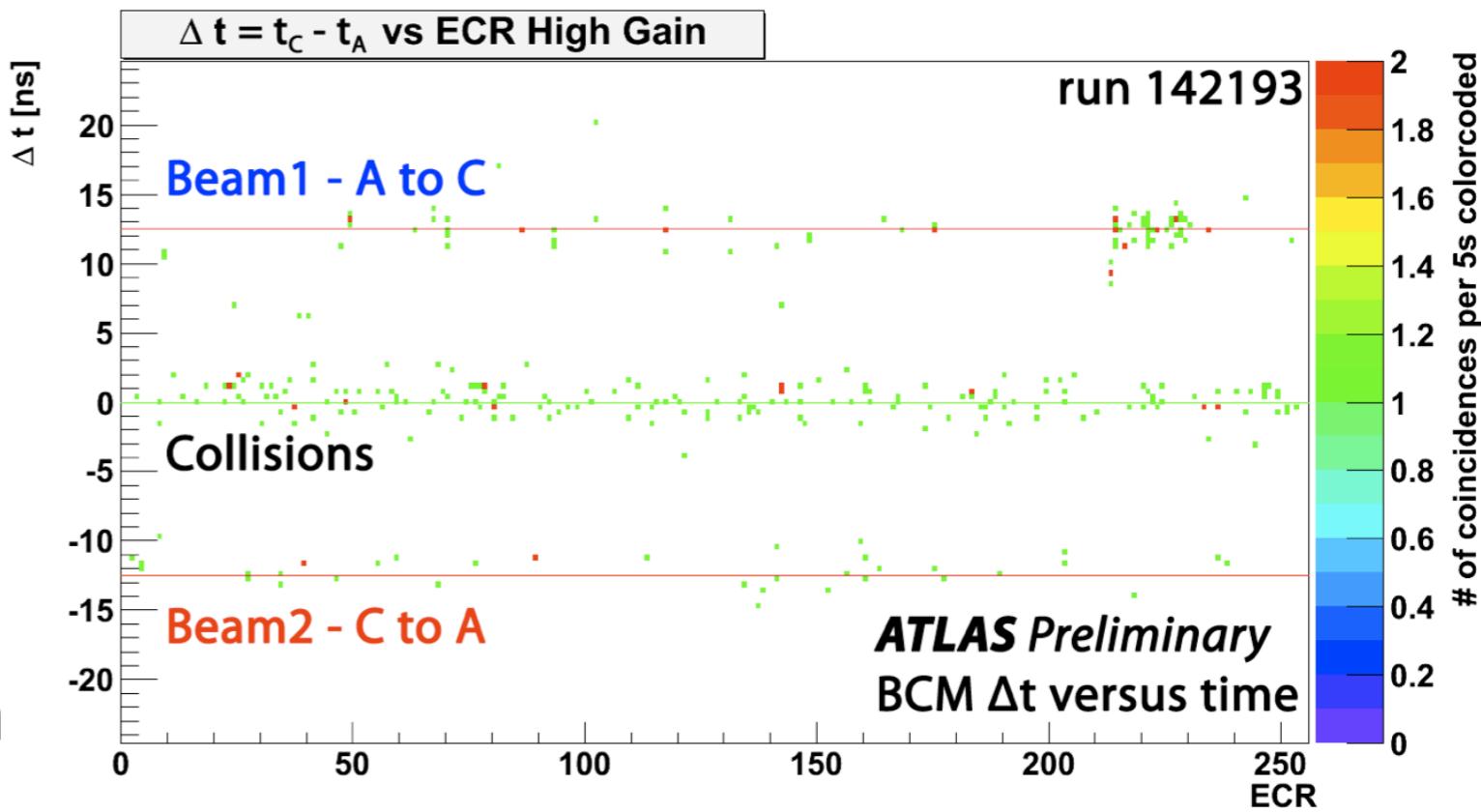
- Beam beam interactions

$\Delta t = 0\text{ ns}$

- Beam gas / beam halo / collimator scraping et al.

$\Delta t = \pm 12.5\text{ ns}$

- Excellent side to side and single side time resolution

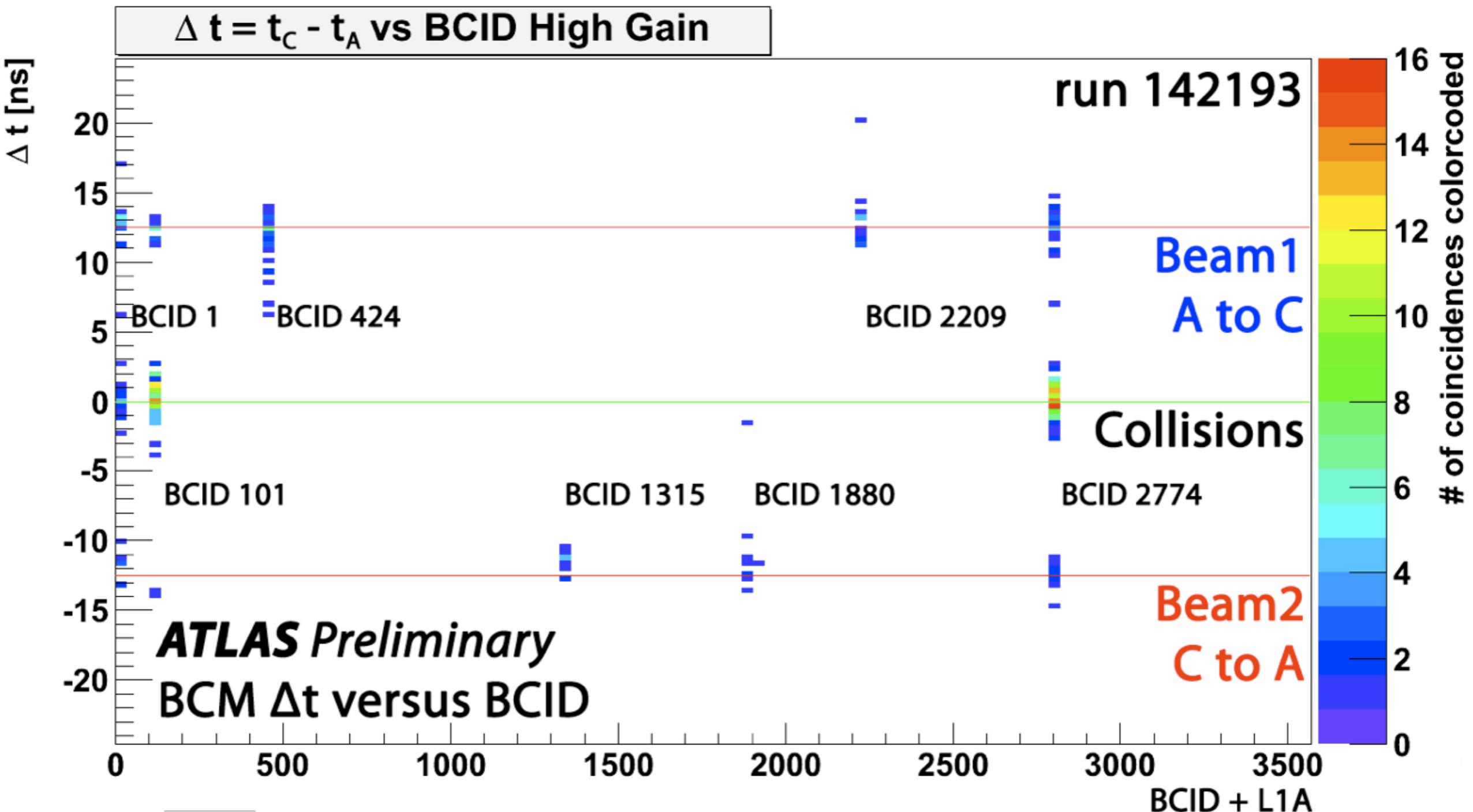


Bunch-by-Bunch Beam Conditions Monitoring



Colliding bunches in BCID 1, 101 & 2774

Single bunches 424, 1315, 1880 & 2209 collide in ALICE & LHCb



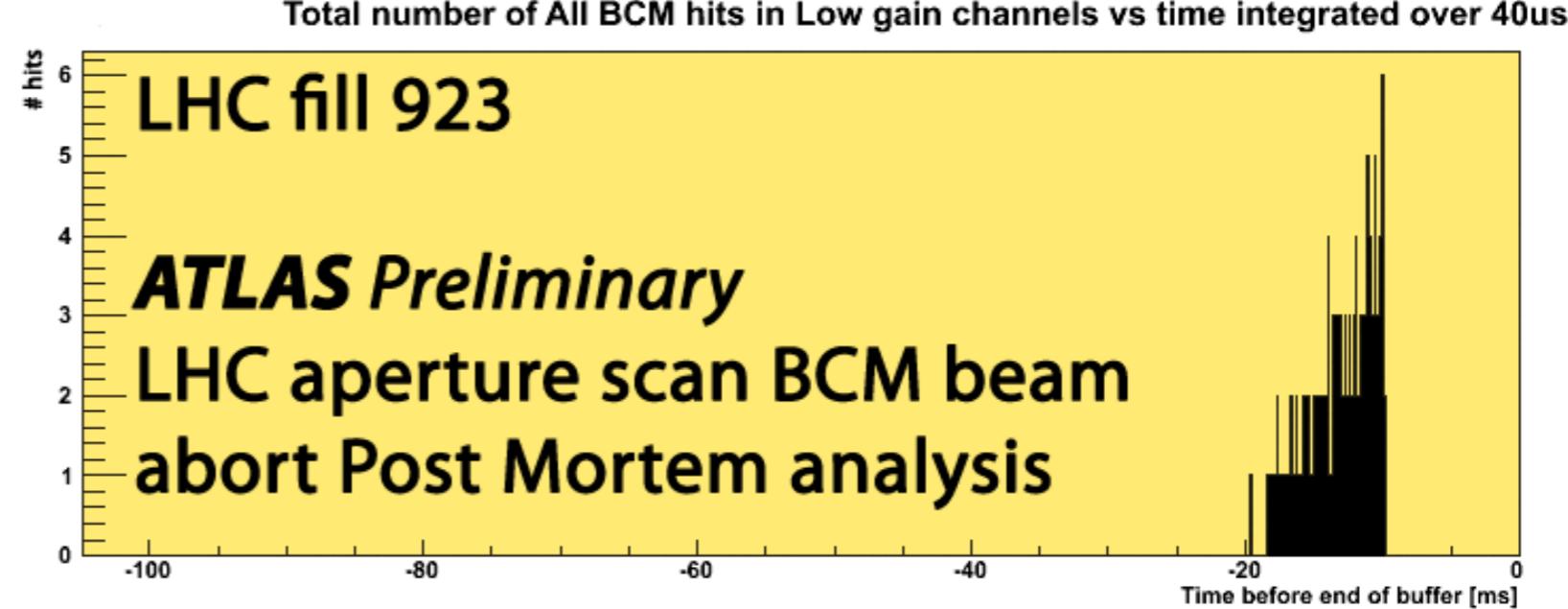
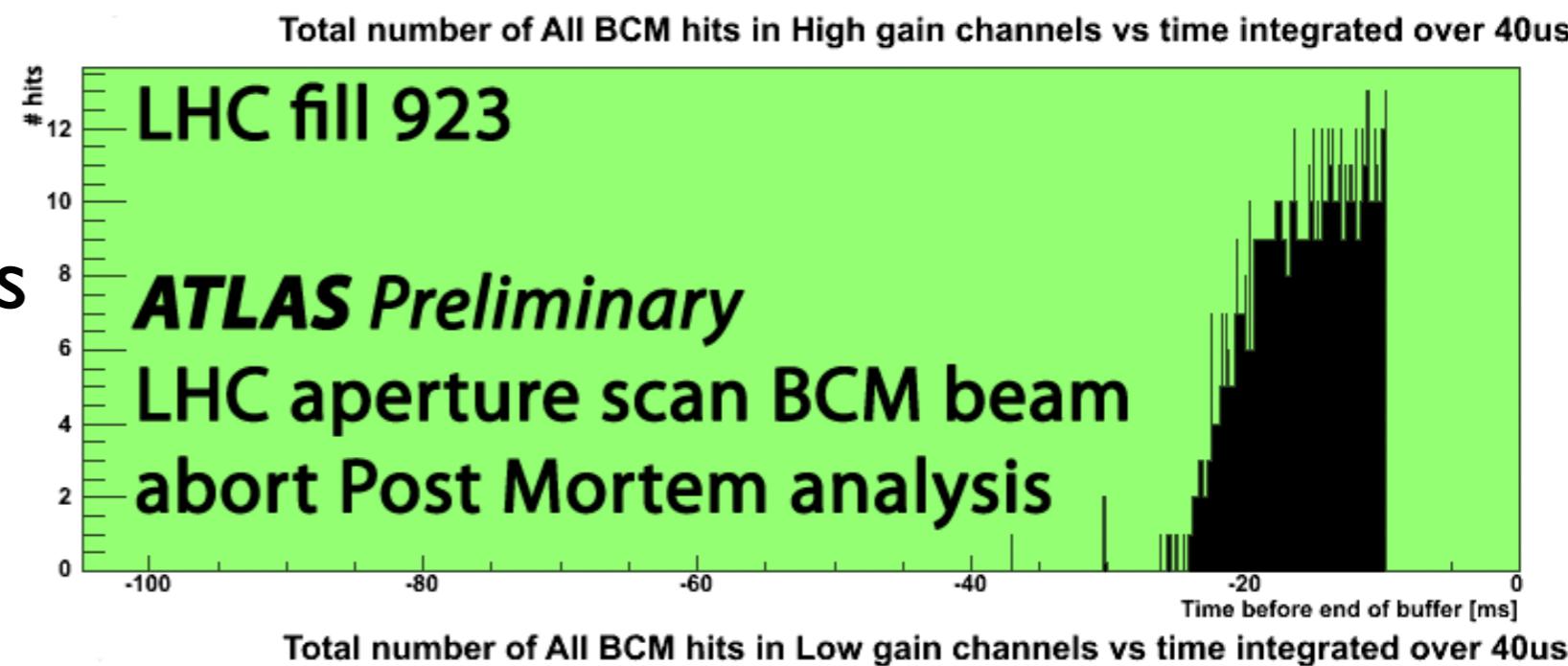
Post Mortem Buffer



- Circular buffer of raw data for 1177 LHC orbits (105 ms)
- Frozen 9 ms (~100 orbits) after LHC wide Post Mortem signal
- Allows to monitor evolution of beam losses in ATLAS before and after the beam abort
- Beam 2 horizontal aperture scan

Reduced sensitivity for this machine development measurement:

- Increased thresholds:
1 V (nominal 280 mV)
- Lowered bias voltage:
400 V (nominal 1 kV)
- BCM beam abort with last aperture step



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Diamond Pixel Modules and BCM

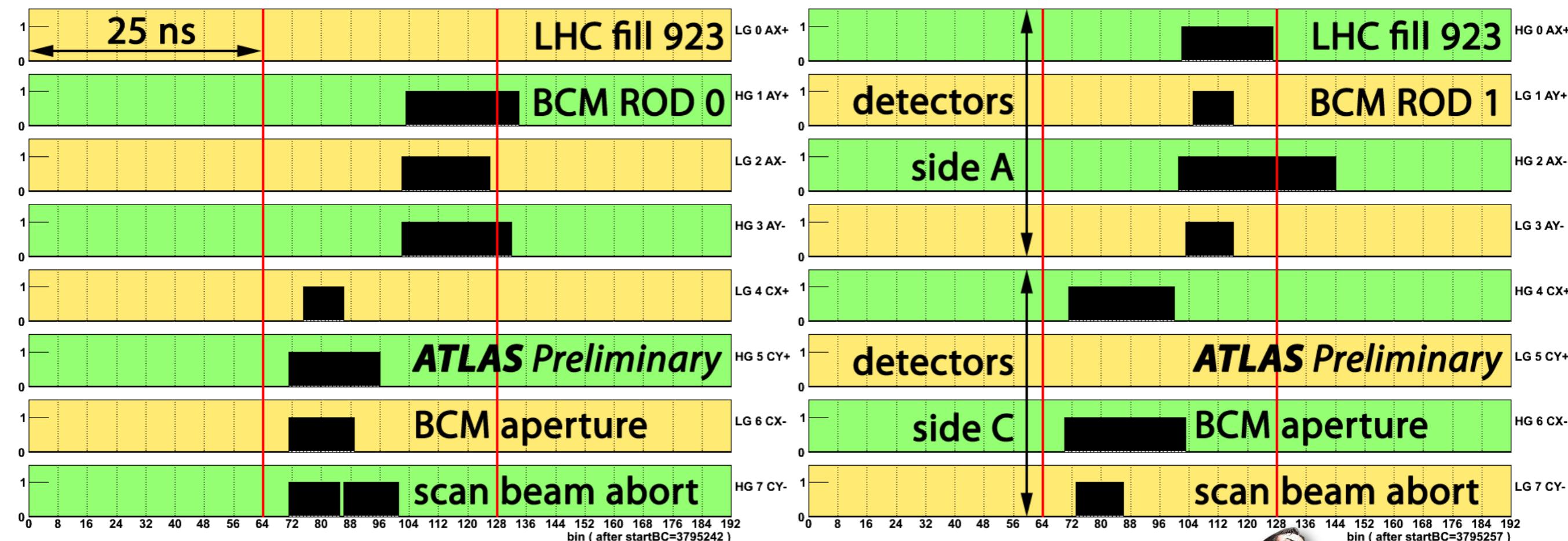
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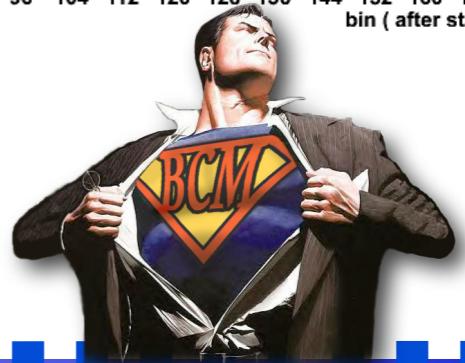
390 ps Beam Abort Diagnostic



- Post Mortem buffer allows identifying moment of beam abort
- Abort condition: 3 low + 3 high gain hits in 1 bunch crossing
- Due to higher effective threshold shorter low gain pulses
- 12.5 ns later A side pulses as expected for Beam 2 ($C \rightarrow A$)



- Timing allows to implement TOF beam abort condition for future



Diamond Pixel Modules:

- Industrialization of diamond pixel modules
 - Module #2 processed and rebuild, Module #3 being assembled
- Improved understanding of radiation hardness (RD42)
- Build & test O(10) assemblies with FE-I4 prototypes
- Diamonds are an option to be seriously considered at IBL and for the inner pixel layer at sLHC

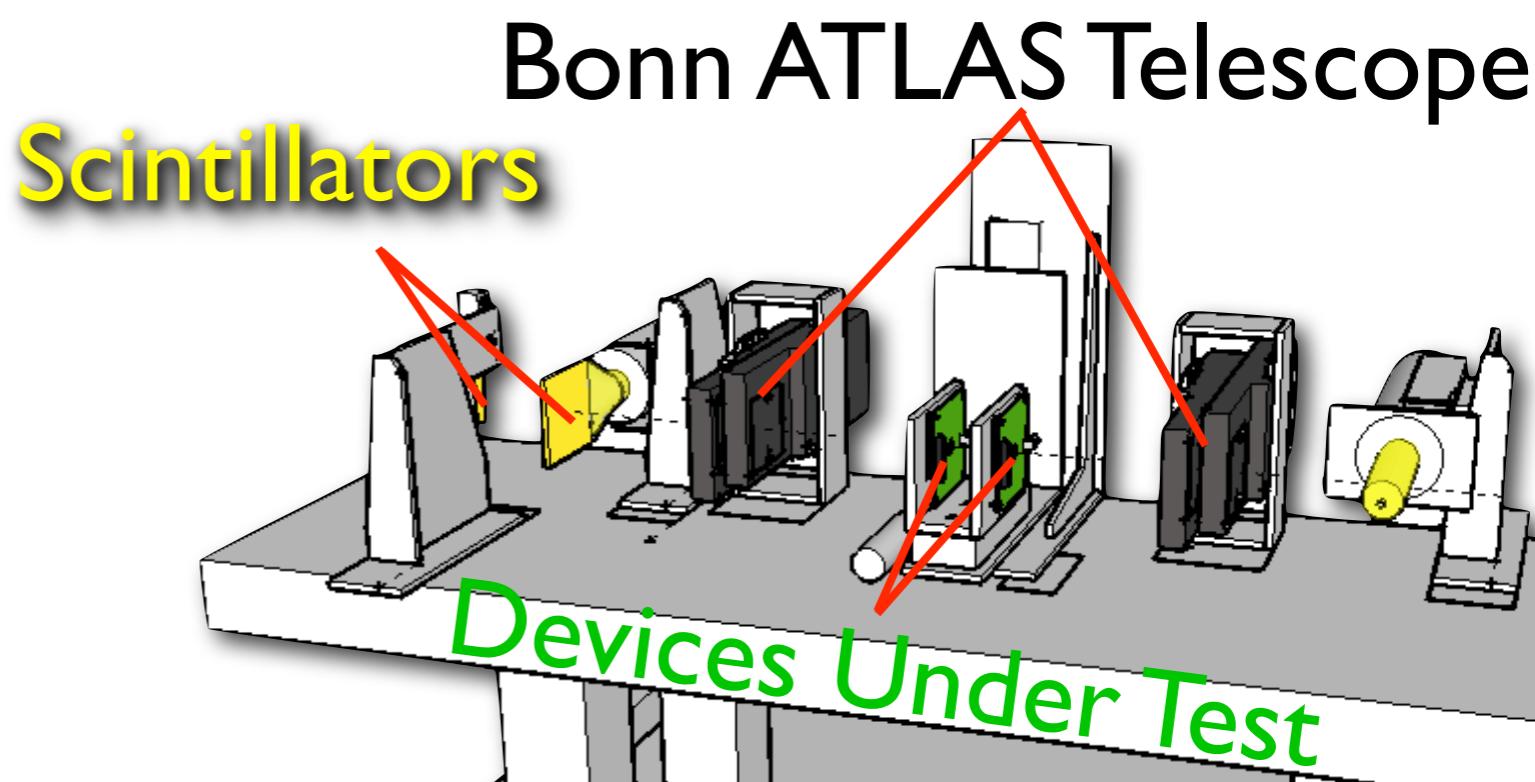
Beam Conditions Monitor:

- Excellent side to side and single side time resolution - but expected to become even better
- LHC fill structure observable
- Post Mortem buffer allows to monitor evolution of abort beam losses in ATLAS and provides beam abort diagnostics
- Timing sufficient to use TOF based beam abort algorithms soon

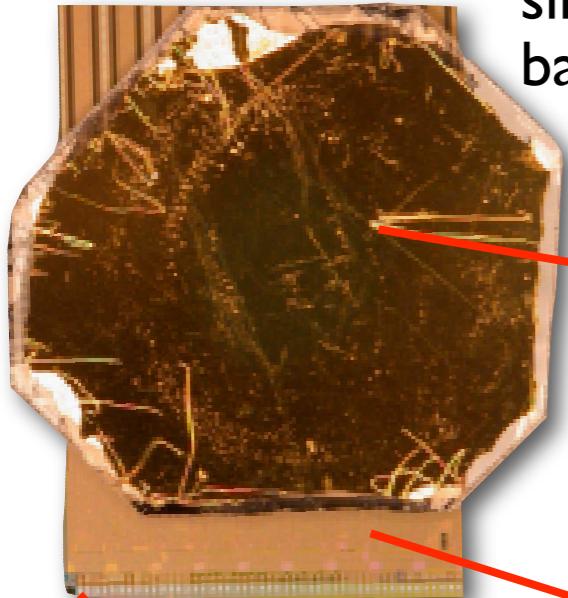
BACKUP slides

- characterization in the lab: source tests
- testbeams at CERN & DESY: pads, strips & pixels
- irradiation:
 - 24 GeV protons → Cern SPS
 - 70 MeV protons → Sendai
 - 25 MeV protons → Karlsruhe
 - Neutrons → Ljubljana
 - up to $\sim 18 \times 10^{15}$ p/cm²

- small & decreasing leakage current → no heating and thermal runaway
- ~no space charge → no V_{depl} increase
- charge trapping only relevant radiation damage effect in diamond
- operational consequences: charge loss and polarization



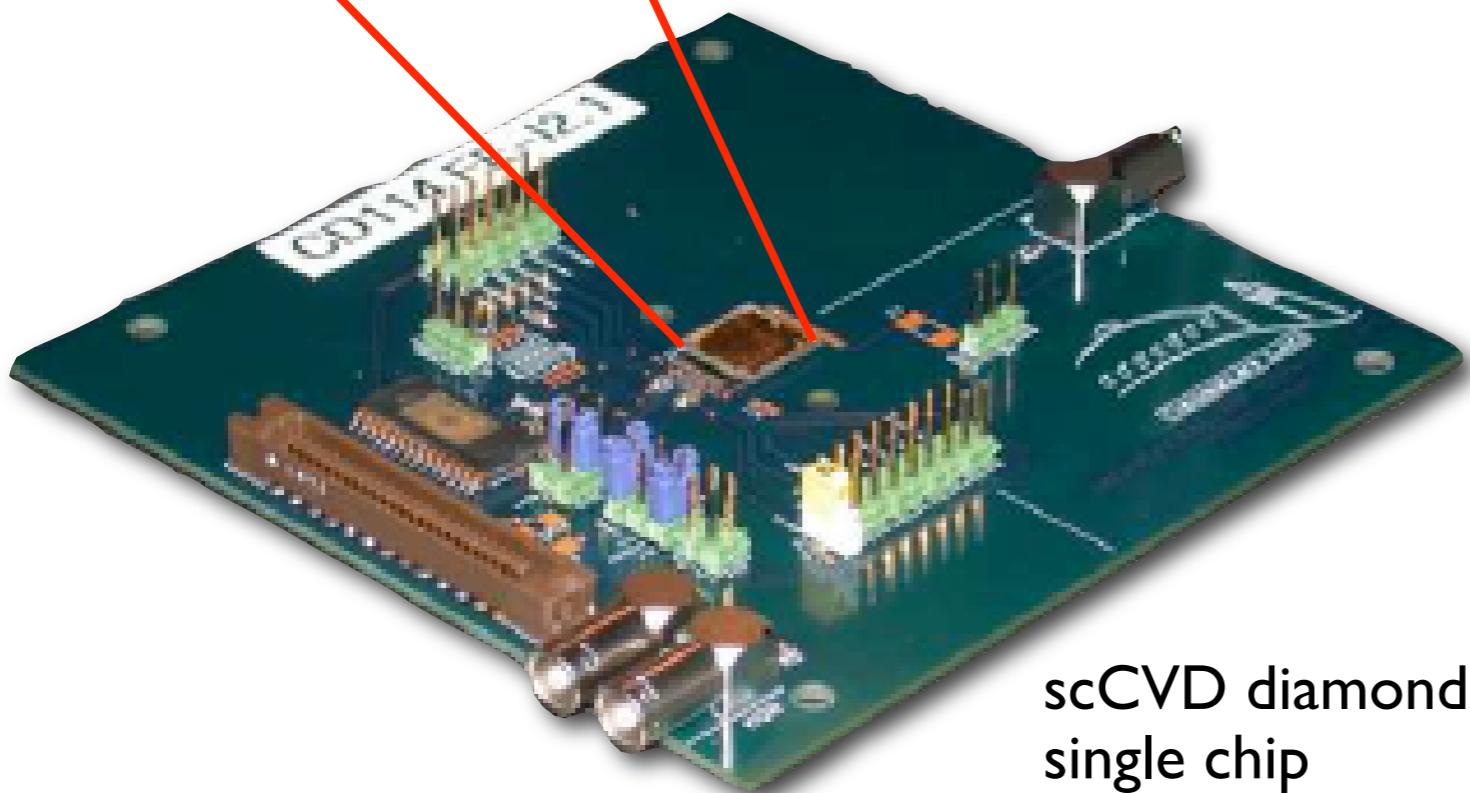
ATLAS scCVD Diamond Pixel Single Chip



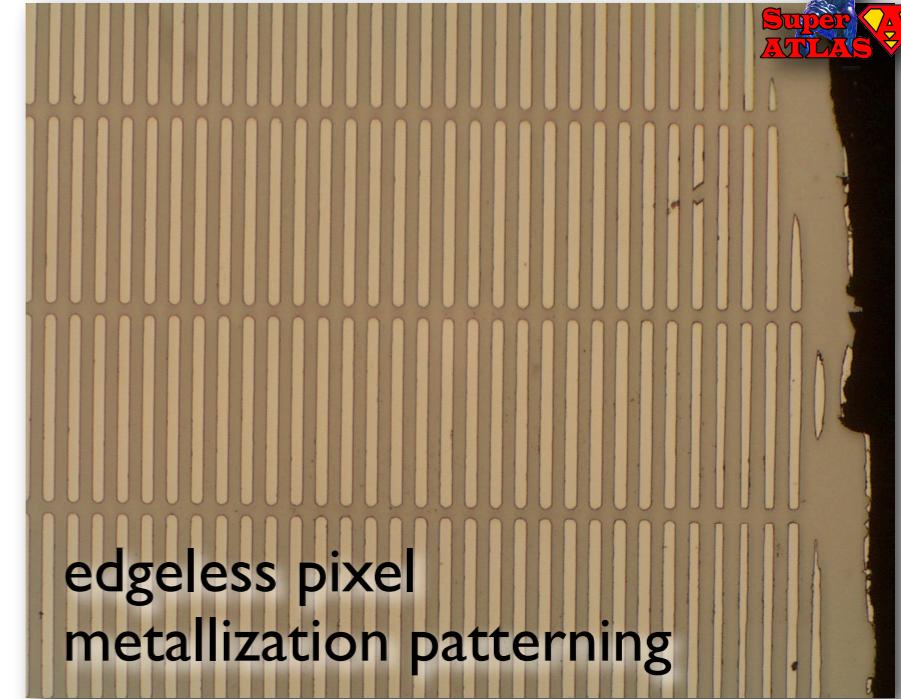
diamond
single chip
bare module

$395 \mu\text{m}$ thick $\sim 1 \text{ cm}^2$
scCVD diamond
single chip sensor

front-end electronics:
FE-I3



scCVD diamond
single chip
on FE test board



edgeless pixel
metallization patterning

- metallization at OSU
- bump-bonding at IZM of 2200 of the possible 2880 bump bonds
- tested at Bonn
- testbeams at CERN

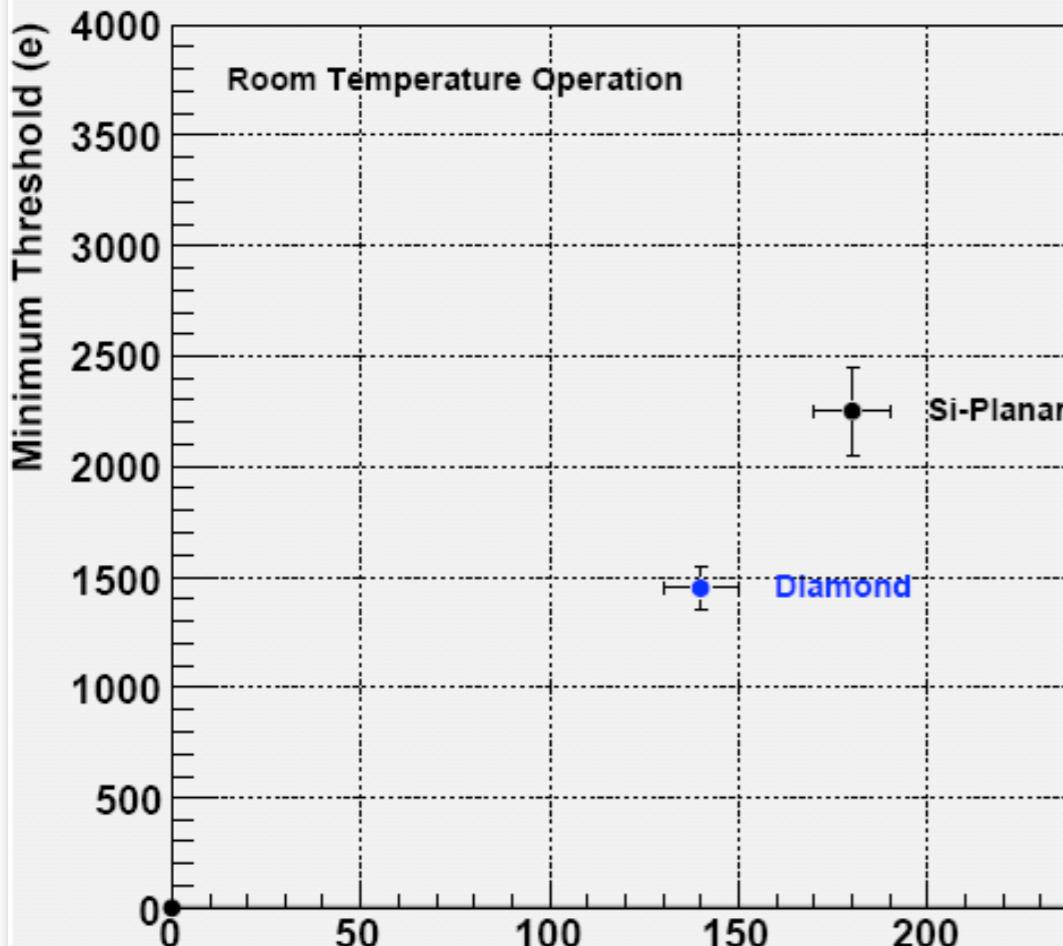


“Invisible Sensor” Advantages

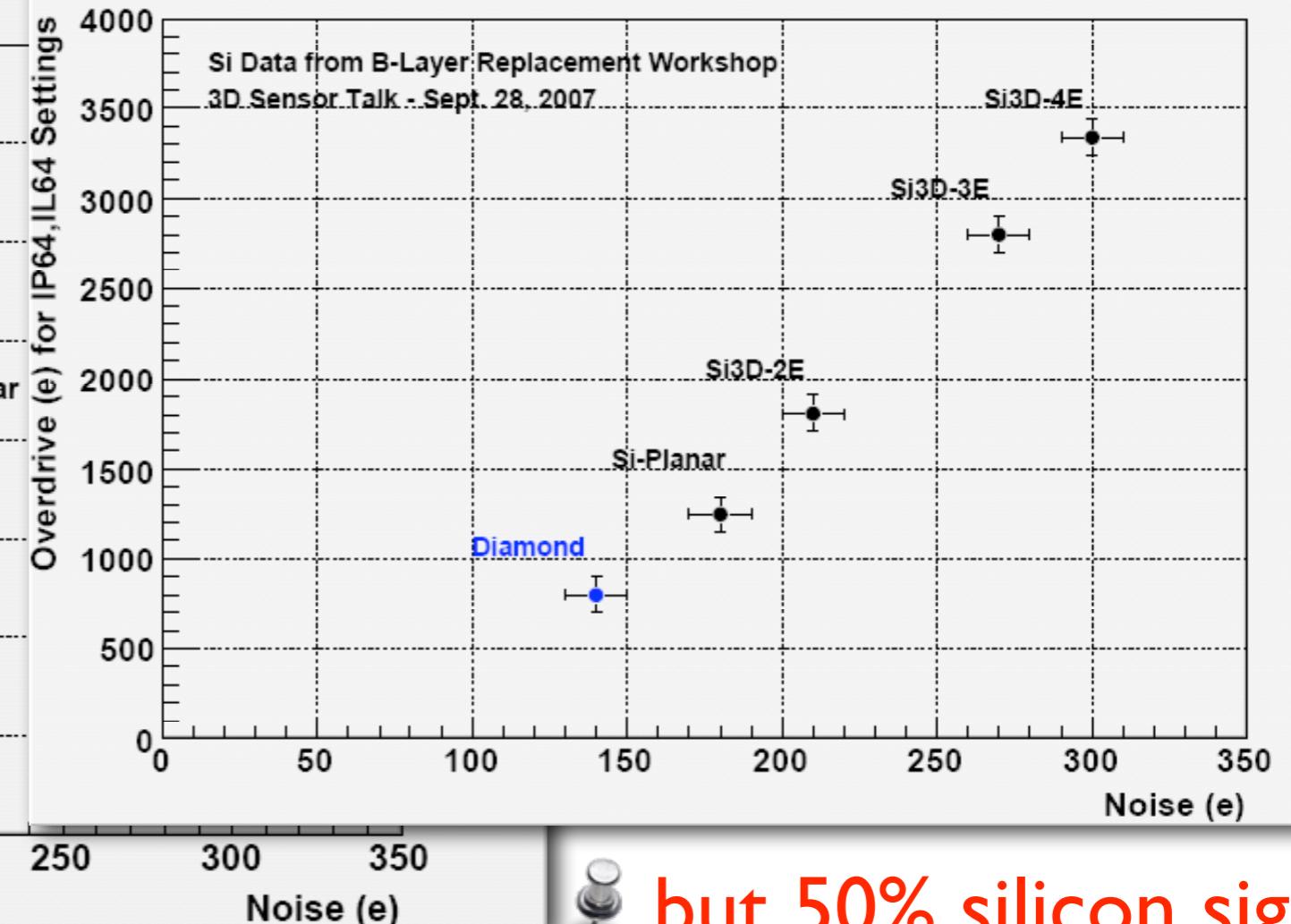
- “no” leakage current & $\sim 3x$ less capacitance
- both result in excellent noise performance:
 - low threshold
 - low noise
 - low time walk (overdrive)



Threshold versus Noise (Capacitance)



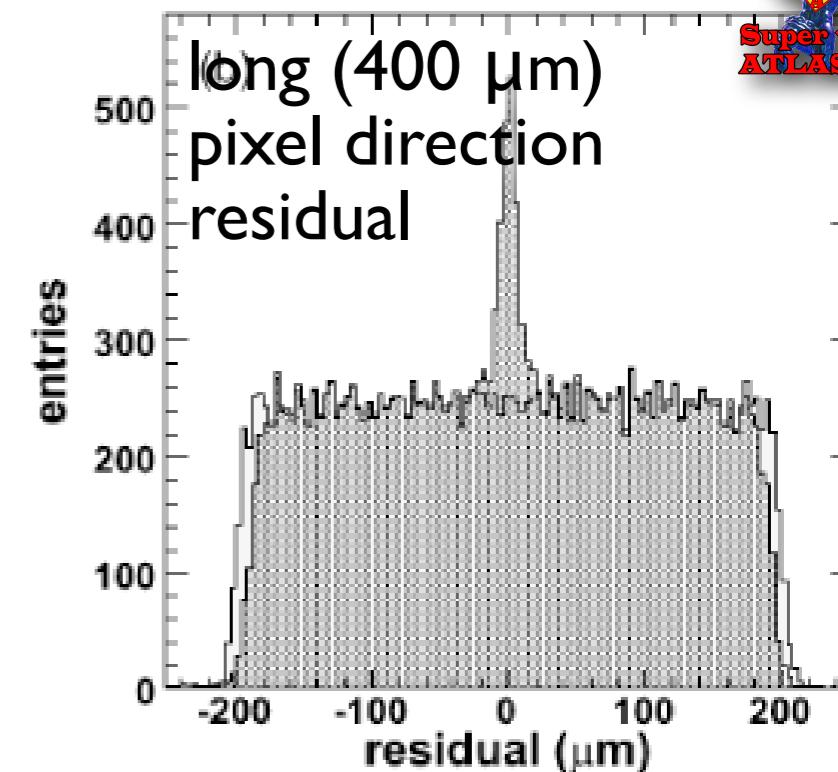
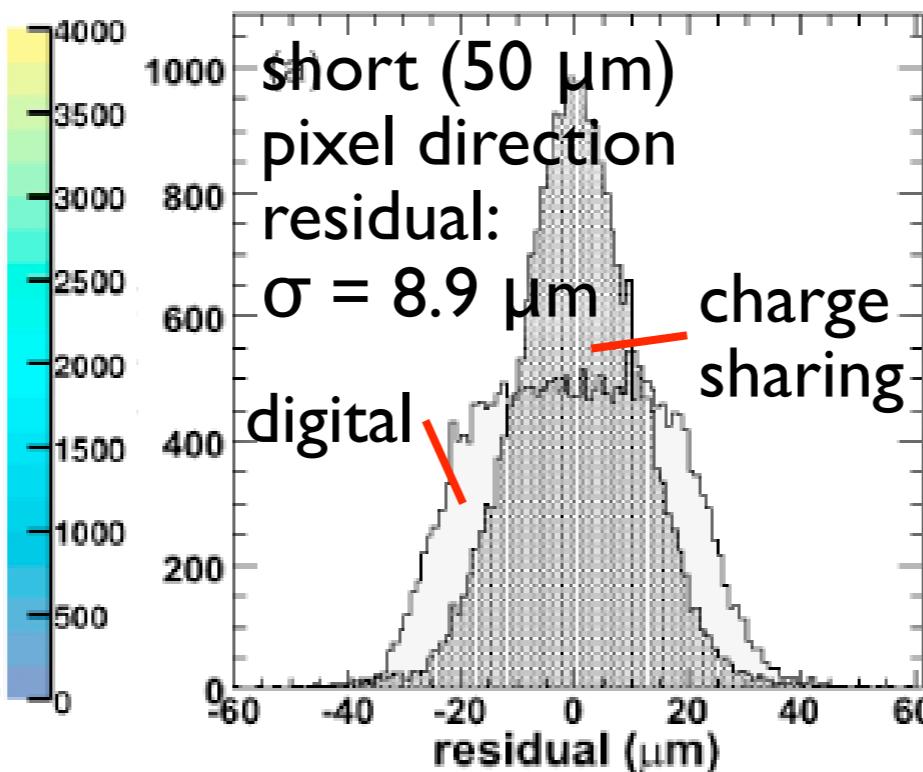
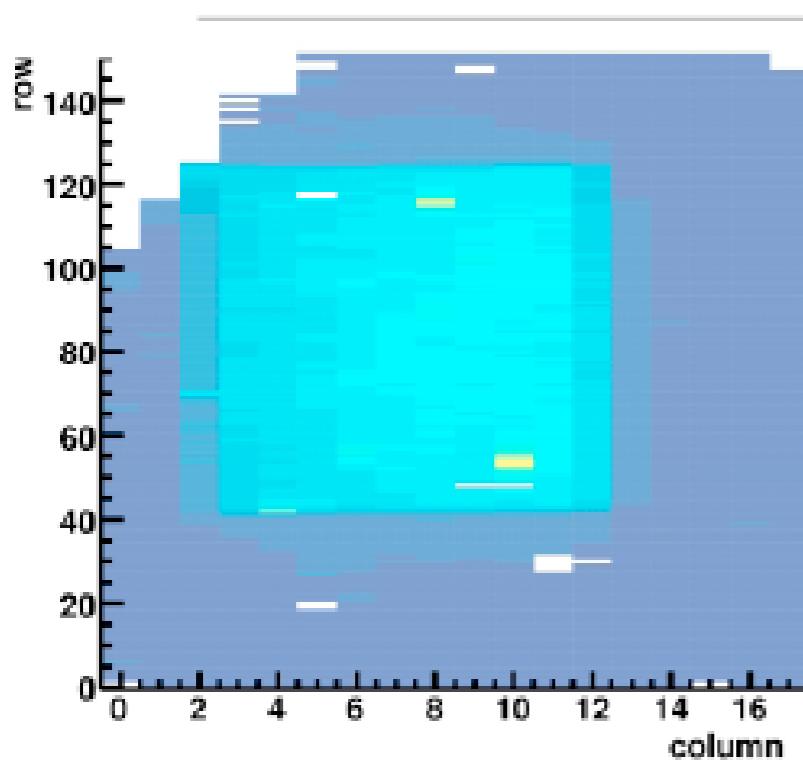
Overdrive versus Noise (Capacitance)



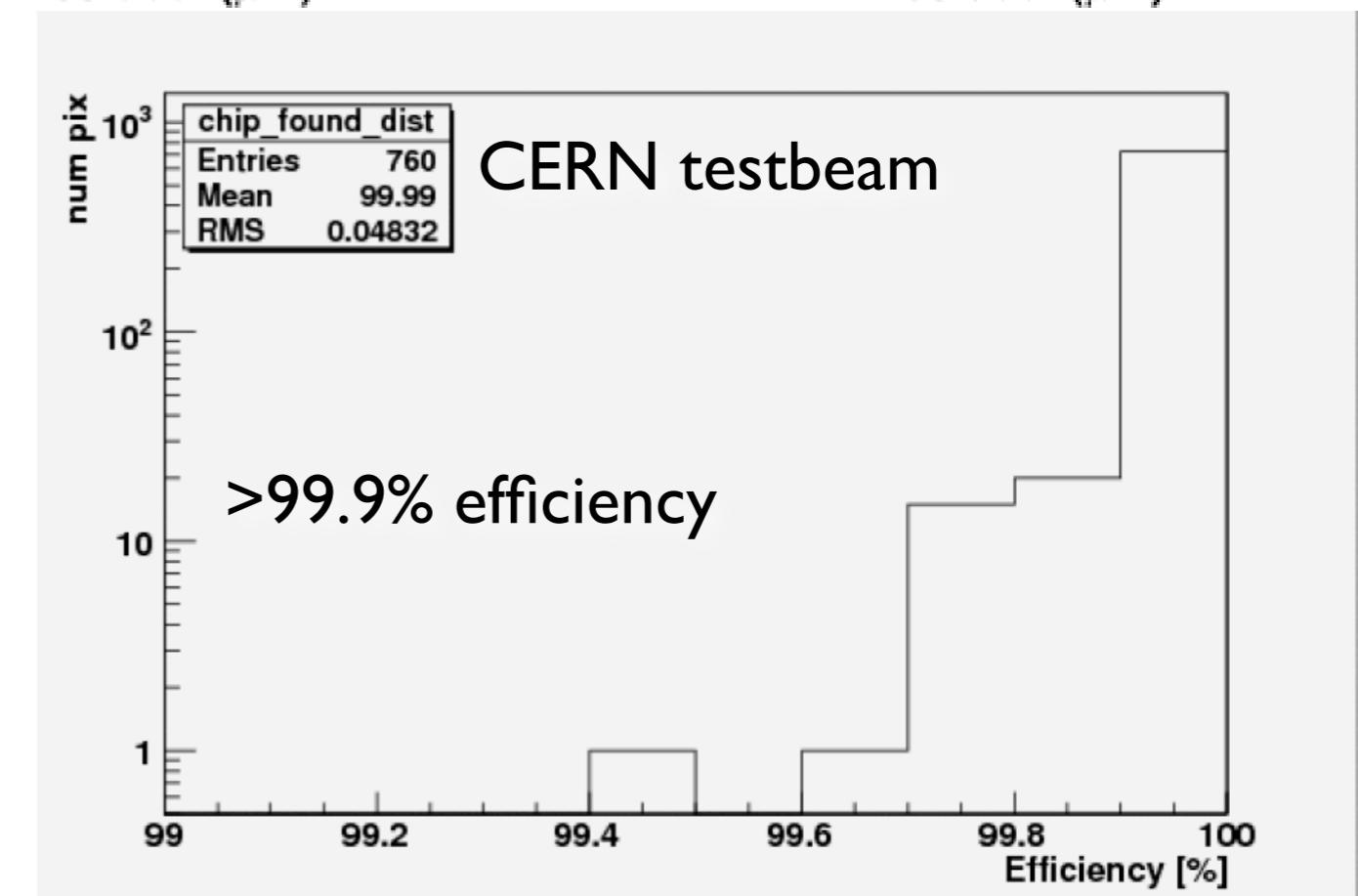
but 50% silicon signal



scCVD Diamond Single Chip Results



- 1 dead pixel
- 8 noisy pixels
- 12 FE damaged pixels
- excellent efficiency with 100 μm acceptance radius due to low thresholds charge sharing algorithms work excellent $\rightarrow 8.9 \mu\text{m}$



Charge Sharing



- extrapolated incident position of track on pixel with the beam telescope
- charge sharing as expected - no effect of bump bond - no bias grid dot as on silicon pixel modules

