Diamond Pixel Detectors and 3D Diamond Devices

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For the RD42 Collaboration

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The 2016 RD42 Collaboration

127 Participants

The 2016 RD42 Collaboration

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127 Participants

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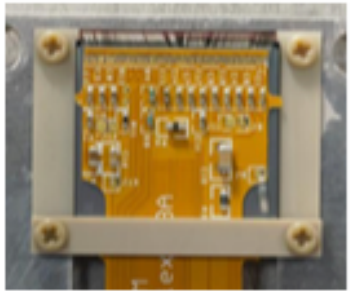
31 Institutes

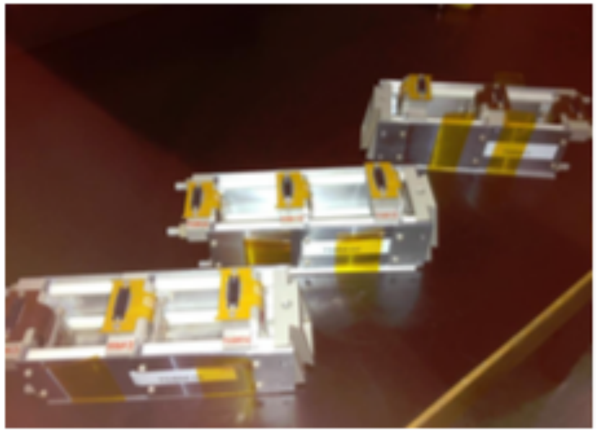
The RD42 Program

- Characterization of diamond as sensor material (irradiation, test beams)
  - **scCVD**: expensive and limited area (very pure, high CCD)
  - **pCVD**: less expensive but more intrinsic charge traps
- Constantly improving sensor material in collaboration with vendors:
  - 300-325 μm charge collection distance in production (Q > 10ke)
  - 400 μm charge collection distance in sight
- Supporting of existing machine/experiment devices (BCMs, BLMs, lumi)
- Development of diamond detectors:
  - for the LHC (BLMs)
  - for upgrade to HL-LHC experiments (3D diamond devices)

Diamond Beam Monitor in ATLAS

- DBM: pixel detectors in ATLAS with tracking capabilities
- Total production: 45 diamonds (500 µm thickness) read out with FE-I4B
- Modules assembled at CERN
- Installed during LS1

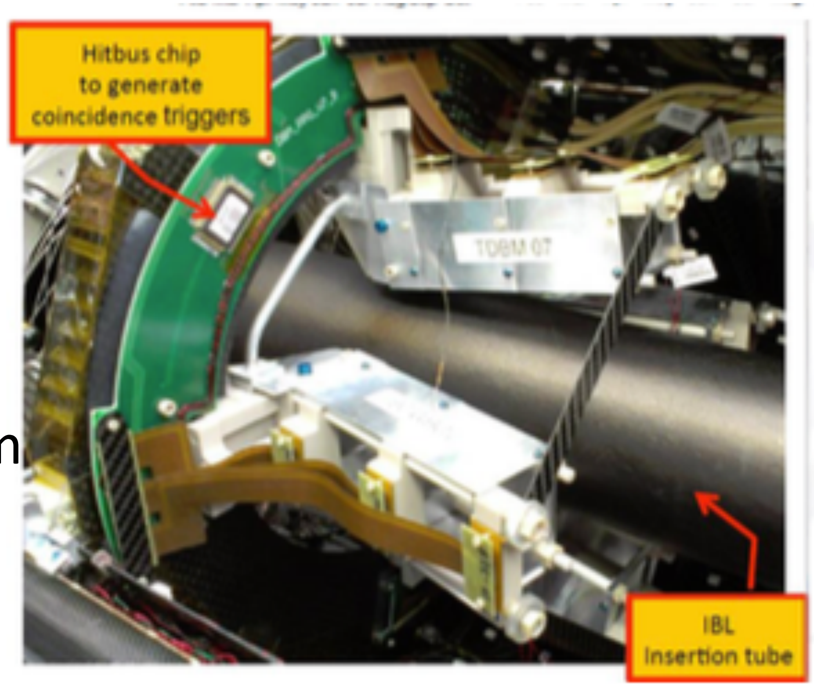




8 telescopes
(2 with Si)
symmetric
around ATLAS IP:

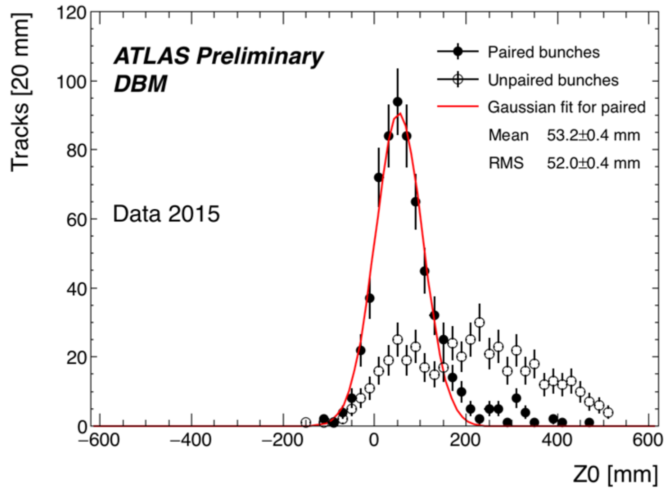
$854<|z|<1092$ mm

$3.2<|\eta|<3.5$



Diamond Beam Monitor: Data

- Use hits from the three modules for reconstructing tracks
- Can discriminate between IP and background particles
- Final alignment still to be done
- Loss of modules in 2 electrical incidents in 2015
  -> now in re-commissioning phase

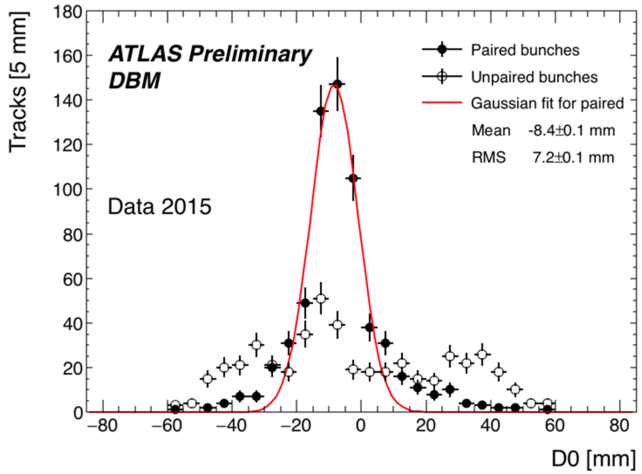


Run of July 2015
clear separation:

Collisions:

vs

Background:



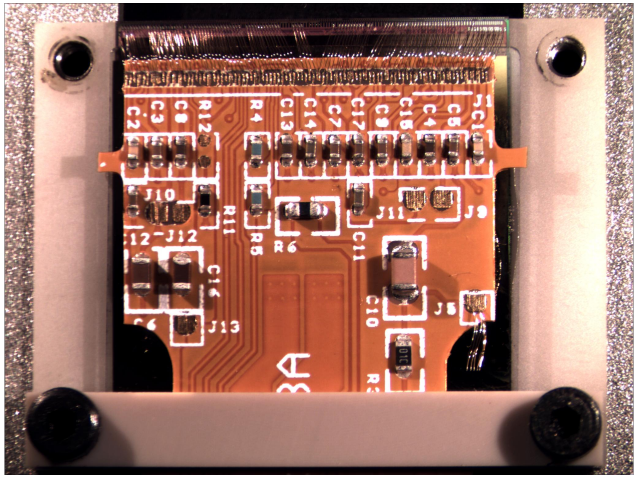
Longitudinal distance of the projected particle tracks to the interaction point

Radial distance of the projected tracks of the closest approach to the interaction point

DBM test beam

- Test beam campaigns at CERN SPS to study the DBM characteristics:
- Lower charge from diamond necessitates low threshold operation of FE chip
- Developed a new tuning algorithm for FE-I4B not using Pulser DAC: Threshold Baseline Tuning

MDBM-120

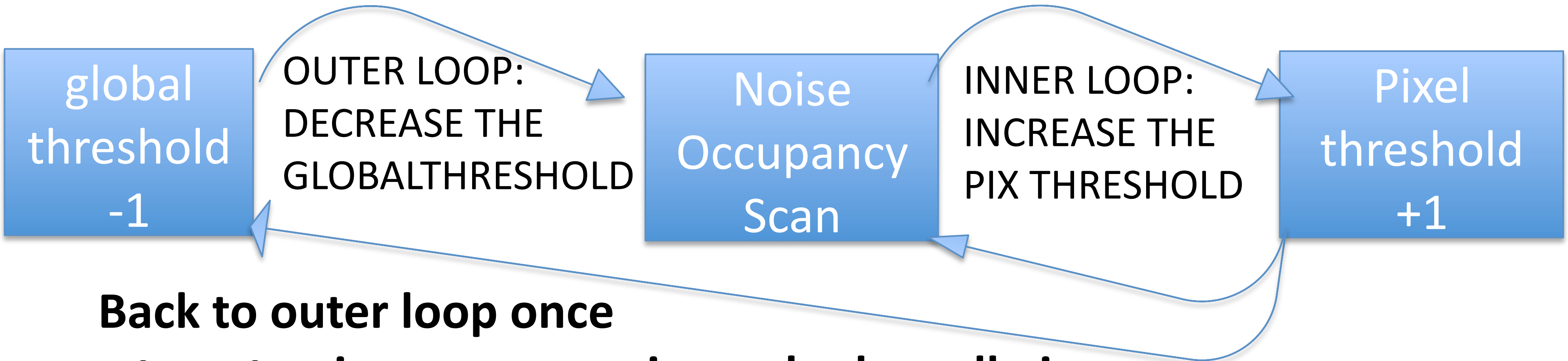


Tuning	Method	Threshold Value
Standard ATLAS	Pulser DAC	~ 3-4 ke (Si)
Optimal DAC	Pulser DAC	~ 1.5-2.2 ke (Diamond)
Threshold Baseline	Noise Occupancies	~ 1 ke (Diamond)

Threshold Baseline Tuning

- Developed by University of Bonn
- Algorithm based on noise occupancy scans
- Initial Condition:
  - -> Set global threshold (GDAC) to a rather high value
  - -> Set pixel thresholds (TDAC) to lowest possible value

Algorithm Loop:

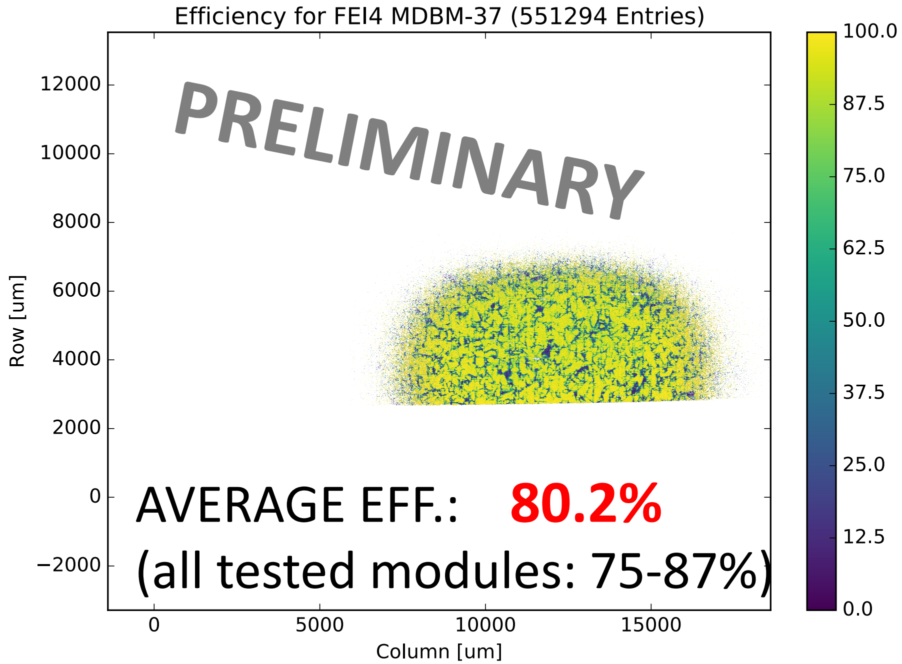


Back to outer loop once
a target noise occupancy is reached on all pix

DBM Test Beam: Efficiencies

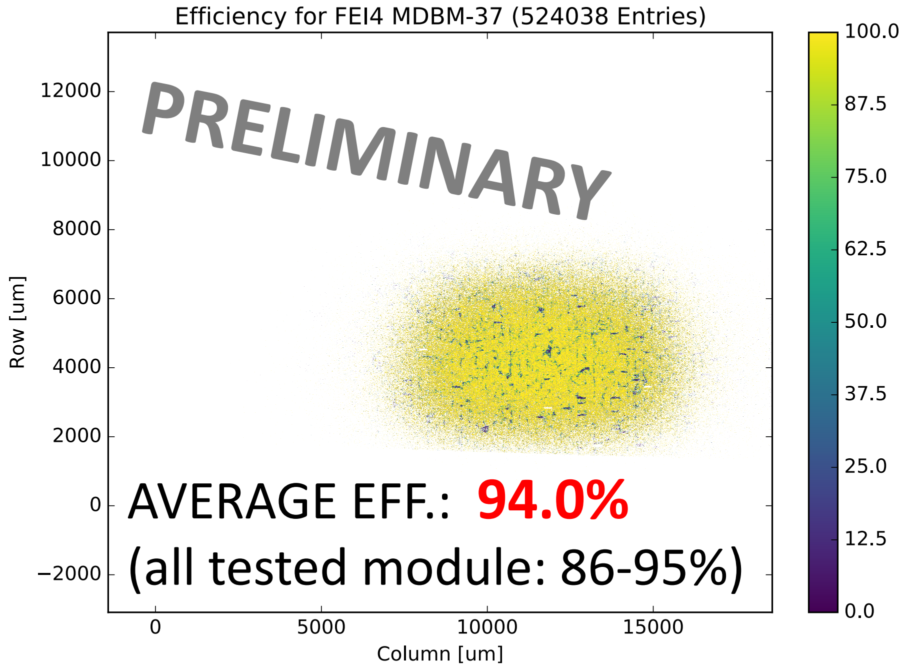
OPTIMAL DAC TUNING

THRESHOLD ~1.5-2.2 ke



THRESHOLD BASELINE TUNING

THRESHOLD ~1 ke



- Average efficiency of planar Silicon: 97.5% (cross-checks on-going)
- Applicable to ATLAS-IBL (for Si sensors after irradiation)
- Diamond can reach reasonable efficiency!

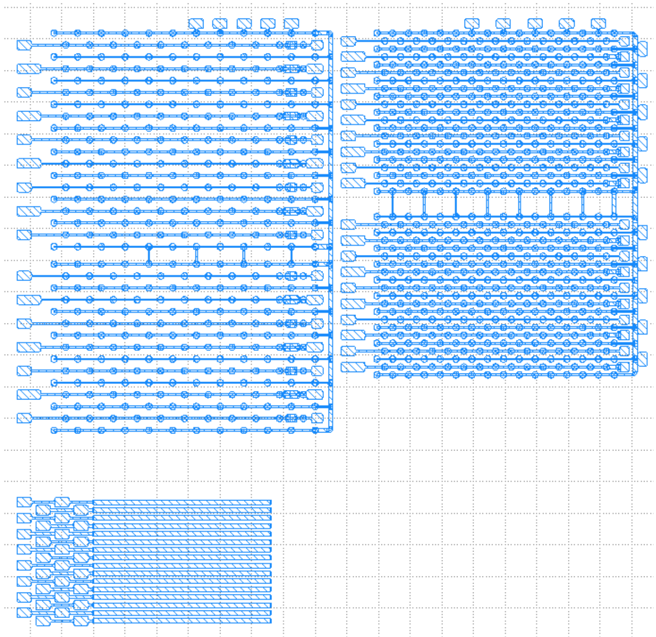
3D pCVD Diamond Sensor

Metallization pattern:

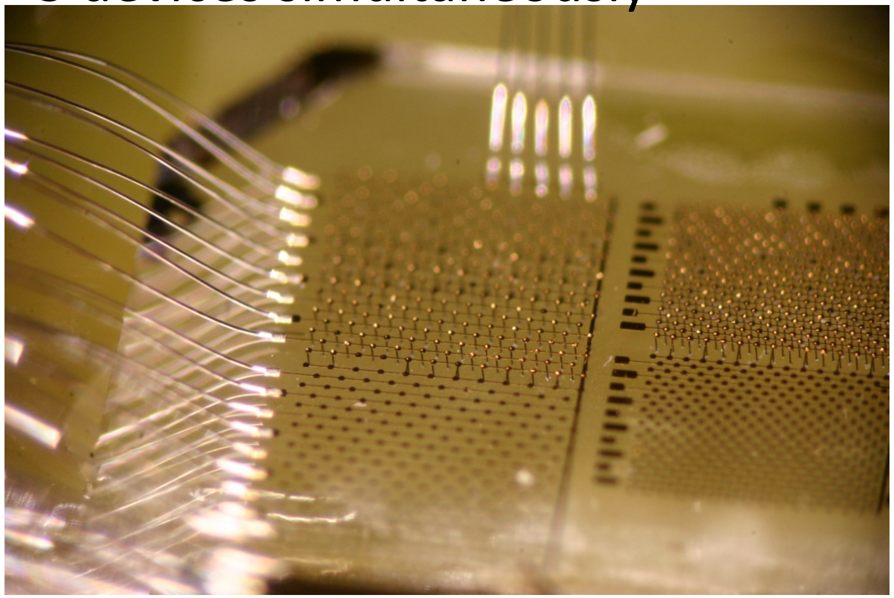
3D

Phantom
(NO electrode in the bulk)

Strip



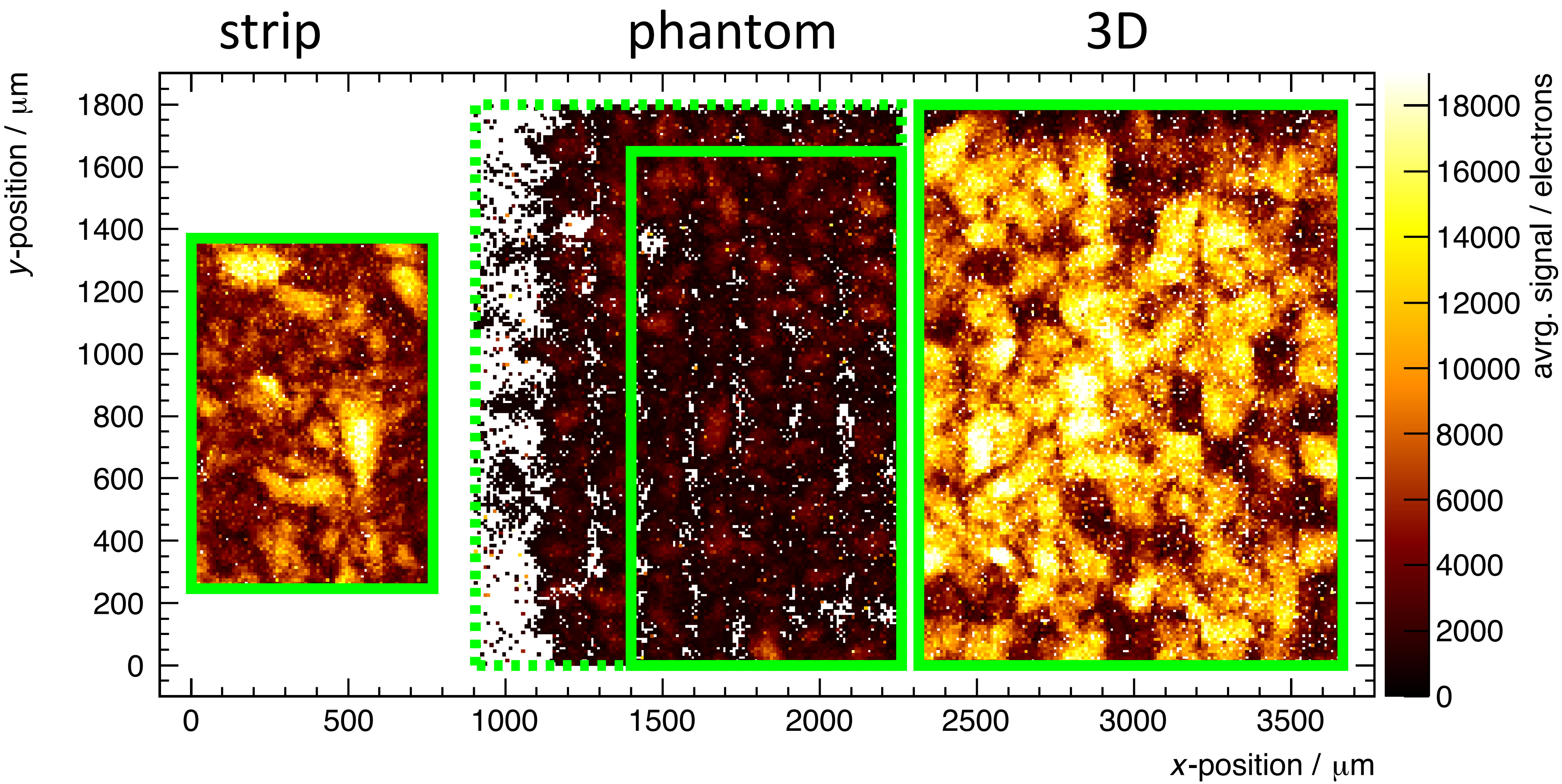
Same electronic read-out:
3 devices simultaneously



- **First 3D** pCVD diamond device:
  - Compare pCVD strip detector at 500 V with 3D (and phantom) at 60 V
  - Same metal mask on top and bottom for 3D (and phantom)
    - -> increase the probability of connecting columns (amorphous carbon)

3D Diamond Sensor: Signal

- Measured signal: visually 3D gives more charge that planar strip

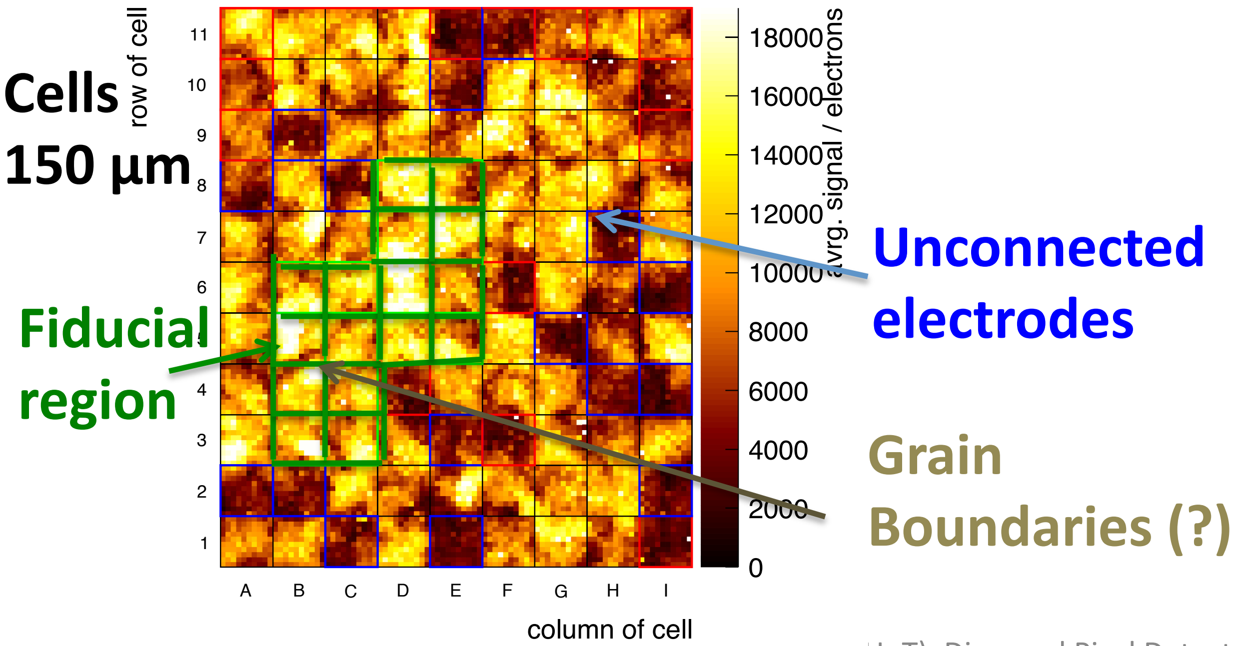


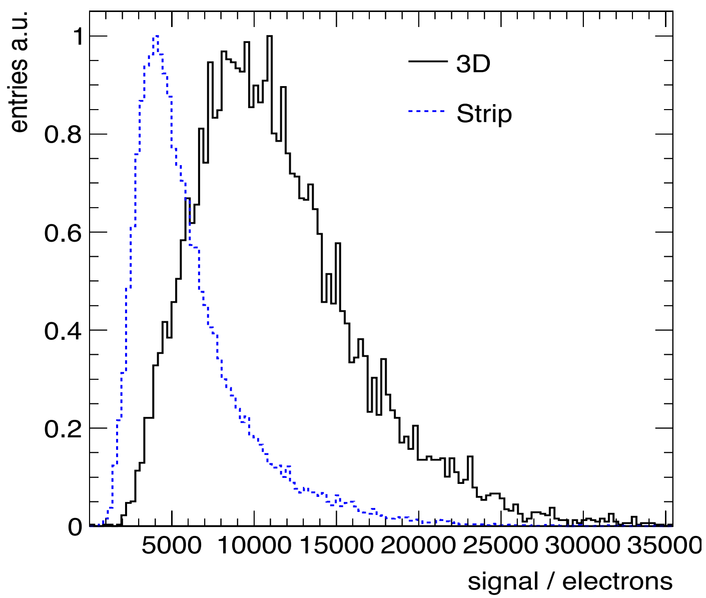
3D Diamond Sensor: Charge Collection

- Measured signal (diamond thickness 500 μm):

- Planar Strip average charge: 6,900e or ccd = 192 μm
- 3D average charge: 13,500e equivalent to ccd = 350-375 μm

-> For the first time collect >75% of the average charge



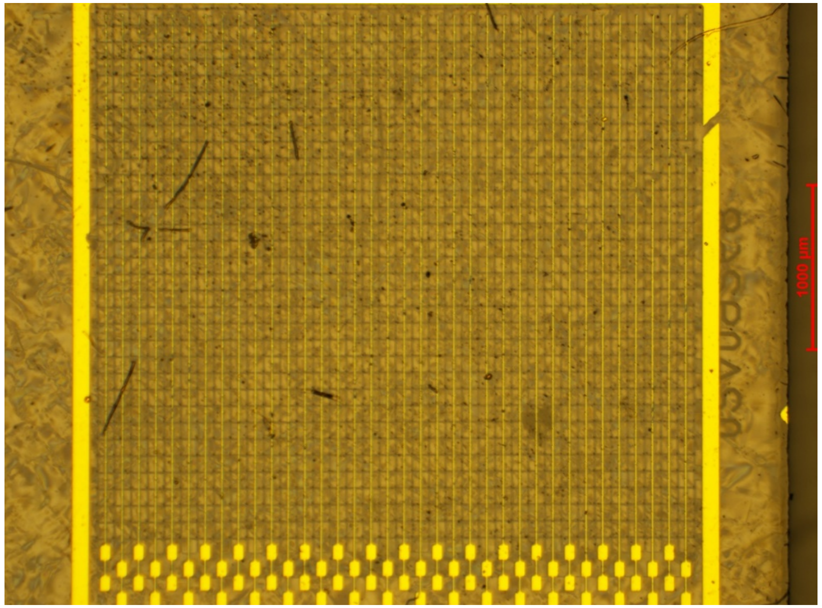


Large 3D diamond sensors

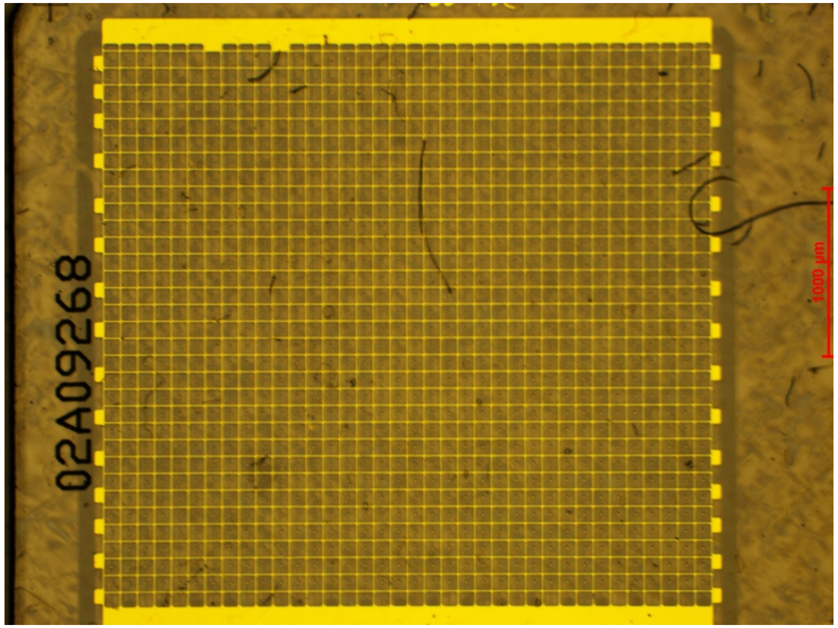
- In May 2016 we tested the first full 3D in pCVD (1cm^2) (no phantom, no strip) with dramatic improvements:

1. An order of magnitude more cells (1188 vs 99)
2. Smaller cell size (100 µm vs 150 µm)

Readout side



Bias side



Large 3D diamond sensor: Results

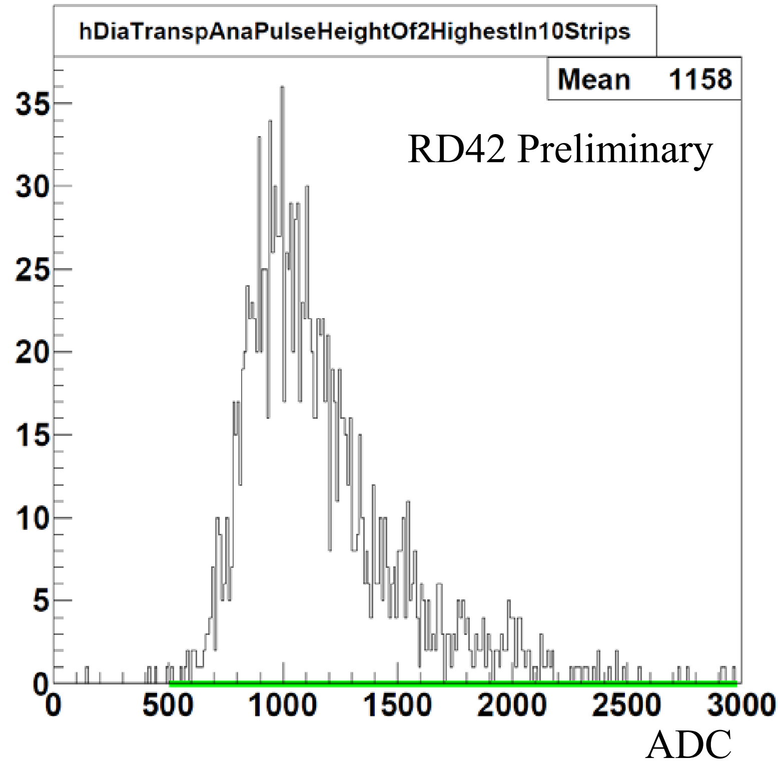
Preliminary results of full 3D pCVD device:

- First plot of 3D collected charge in small "good" region

- Largest signal in pCVD diamond:

  > 85% of released charge collected

- Full analysis in progress



Conclusions

- RD42 collaboration is testing the diamond material characteristics

  -> Production and material capabilities are increasing

- DBM is being re-commissioned in ATLAS:

  -> 2015 data analysis showed good collisions/background discrimination

  -> New tuning algorithm used in DBM test beam with promising efficiencies

- 3D pCVD detector prototypes made great progress:

  -> first time more than 75% of charge collected at 60 V bias

  -> scale up worked; smaller cells worked: more than 85% of charge collected

OUTLOOK: build a 3D diamond pixel detector

Back-up Material

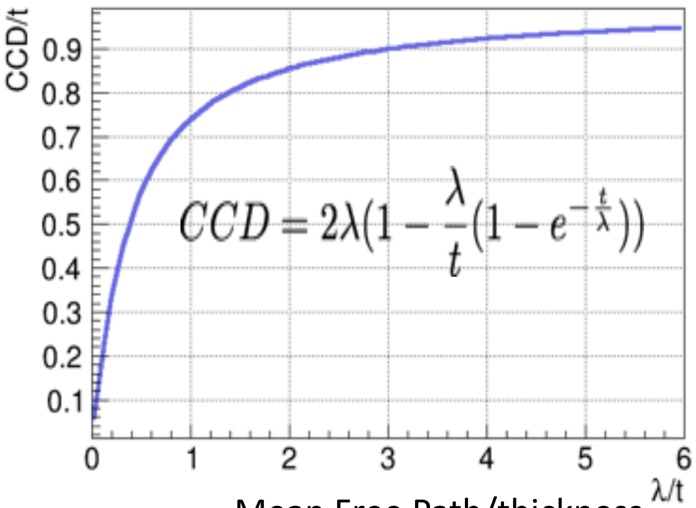
Si vs C

		silicon [a]		natural diamond [b]	
proton number	[ ]	14		6	
atomic number	[ ]	28.0855	[9]	12.011	[9]
lattice constant	[Å]	5.4310	[10]	3.5668	[10]
mass density	[$\mathrm{g\,cm^{-3}}$]	2.329	[10]	3.515	[10]
cohesive energy	[eV/atom]	4.63	[11]	7.37	[11]
melting point	[K]	1685	[10]	4100 [(c)]	[10]
band gap	[eV]	1.124	[10]	5.48	[10]
relative dielectric constant [d]	[ ]	11.9	[10]	5.7	[10]
resistivity	[Ωcm]	20×10^3 [(e)]		$> 10^{13}$	[11]
	[Ωcm]	5×10^{11} [(f)]	[3.2.3]	$> 10^{14}$ [(g)]	[3.2.3]
breakdown field	[V/μm]	30		1000	
electron mobility	[$\mathrm{cm^2\,V^{-1}\,s^{-1}}$]			1500..	[12]
		1450	[10]	..2400	[13]
hole mobility	[$\mathrm{cm^2\,V^{-1}\,s^{-1}}$]			1000..	[12]
		≈ 440	[10]	..2100	[13]
electron saturation velocity	[cm/s]			2×10^7	[13]
hole saturation velocity	[cm/s]			10^7	[13]
thermal expansion coefficient	[$\mathrm{10^{-6}K^{-1}}$]	2.59	[10]	0.8..1.0	[14]
thermal conductivity	[$\mathrm{W\,cm^{-1}\,K^{-1}}$]	1.4		20..23	[14]
energy to create *eh*-pair	[eV]	3.6	[15, 16]	13	[13, 17]
radiation length	[cm]	9.4	[9]	12.03	[3.75]
specific ionization loss	[MeV/cm]	3.9	[3.3.1]	6.2	[3.3.1]
ave. no. of *eh*-pairs/*mip*	[pairs/100 μm]	9000	[3.3.5]	3600	[11]
ave. no. of *eh*-pairs/*mip*	[pairs/300 μm]	27000	[3.3.5]	11850	[3.3.5]

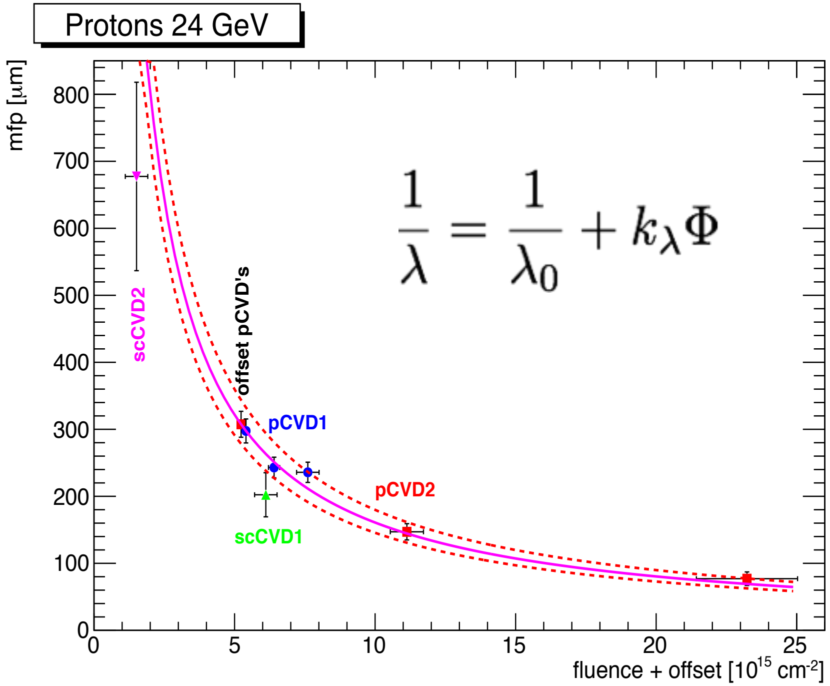
Radiation hardness of diamond

$k_{24\ GeV\ p} \sim 0.62 \pm 0.07 \times 10^{-18}\ \mu m^{-1} cm^{-2}$

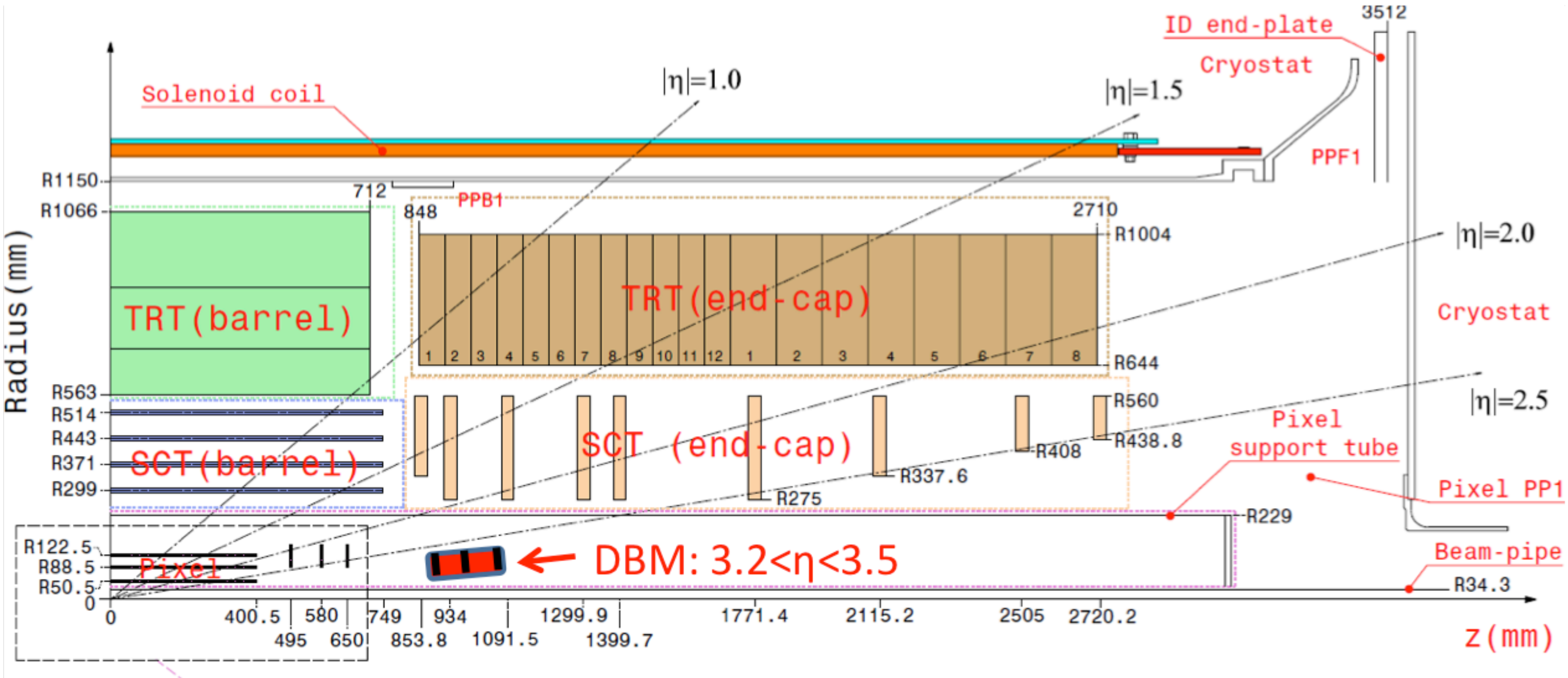
particle	energy	relative k
proton	24 GeV	1
	800 MeV	2.0 (was 1.7)
	70 MeV	2.7
	25 MeV	4.2
pion	300 MeV/c	2.9



Mean Free Path/thickness



DBM in ATLAS



ID end-plate
3512
Cryostat
Solenoid coil
|η|=1.0
|η|=1.5
PPF1
R1150
712
PPB1
R1066
848
2710
R1004
|η|=2.0
Radius (mm)
TRT (barrel)
TRT (end-cap)
Cryostat
1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8
R644
R563
R560
|η|=2.5
R514
Pixel
R443
SCT (end-cap)
R438.8
support tube
R371
SCT (barrel)
R408
R299
R337.6
R275
Pixel PP1
R229
R122.5
R88.5
Pixel
DBM: 3.2<η<3.5
Beam-pipe
R50.5
R34.3
0
0
400.5
580
749
934
1299.9
1771.4
2115.2
2505
2720.2
495
650
853.8
1091.5
1399.7
z (mm)

DBM tunings

Standard Threshold Tuning:

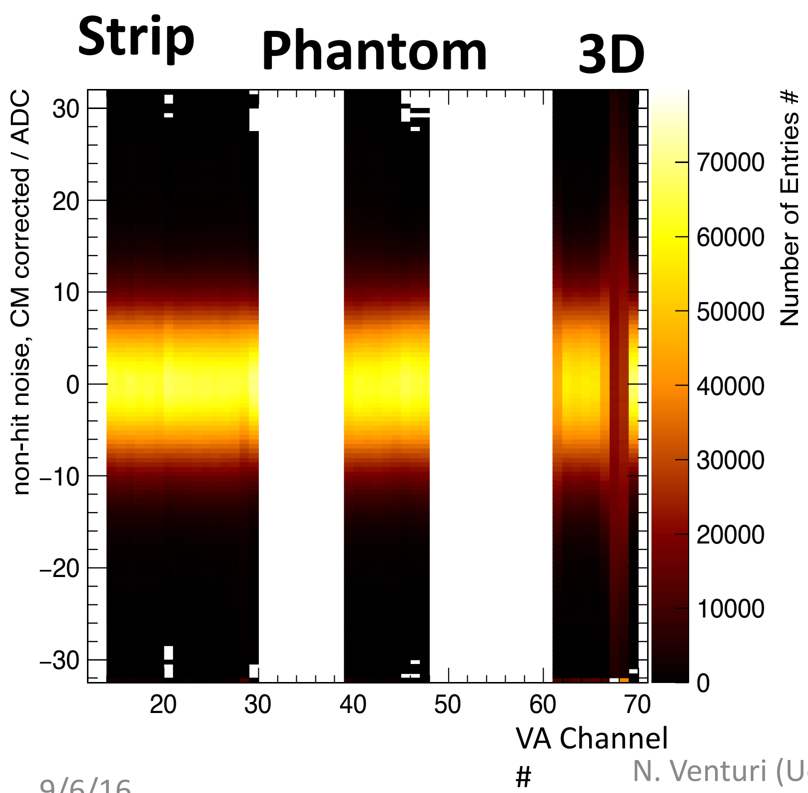
- Using internal pulser for charge injection
- Tuning of threshold and feedback
- Threshold 15 PulserDAC ≈ 1500e (rather low threshold)
- Gain 150 PulserDAC ≈ 9000e at 8ToT (high gain, low feedback)

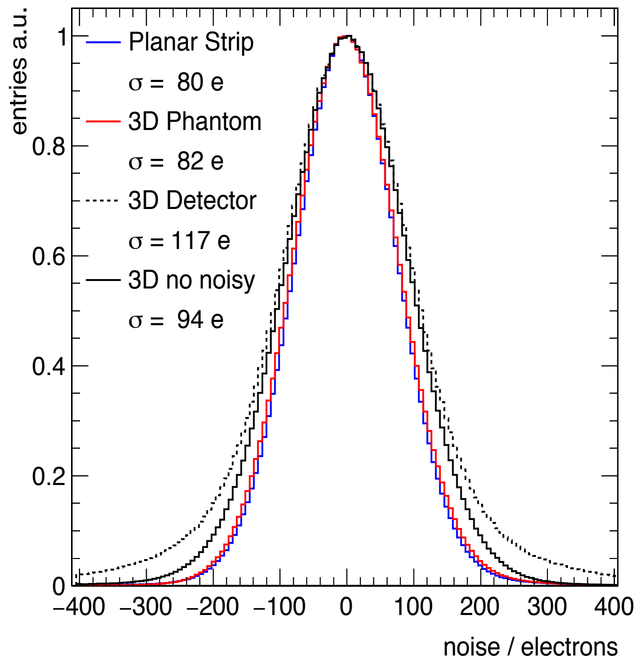
NEW Threshold baseline tuning:

- No PulserDAC used, based on individual pixel noise occupancy
- Threshold estimated to be ≈ 900e (Calibration with Si-modules)
- Pixel and global feedback current is kept at their default values

3D Device in pCVD Diamond

- Measured noise:
  - Strip: 88e
  - Phantom: 92e
  - 3D no noisy strip: 104e





3D CVD diamond sensor