Recent 3D detector measurement results

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With co-authors for synchrotron studies with the Diamond light source synchrotron (J. Marchal, N. Tartoni, E. N. Gimenez et al.) and from CERN pion beam studies with Medipix and LHCb colleagues (R. Plackett, P. Collins, M. Gersabeck et al.)

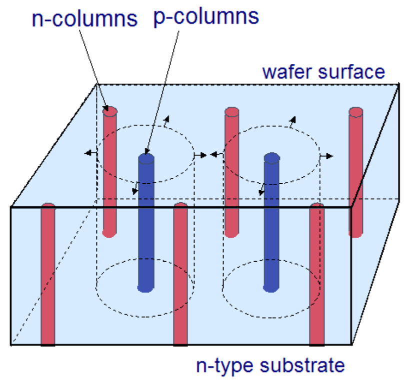
Outline

- Introduction: 3D detectors fabricated at IMB-CNM
- 3D strip detectors
  - Irradiation and annealing behaviour
  - Lab tests: charge collection in 3D strips
  - High bias operation
  - Test beam at SPS CERN
- 3D Medipix
  - Test beam at Diamond synchrotron
  - Test beam at SPS CERN
- Conclusions

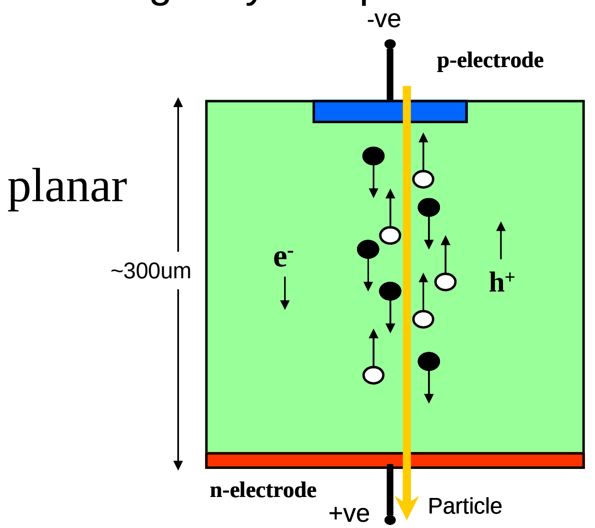
3D detectors

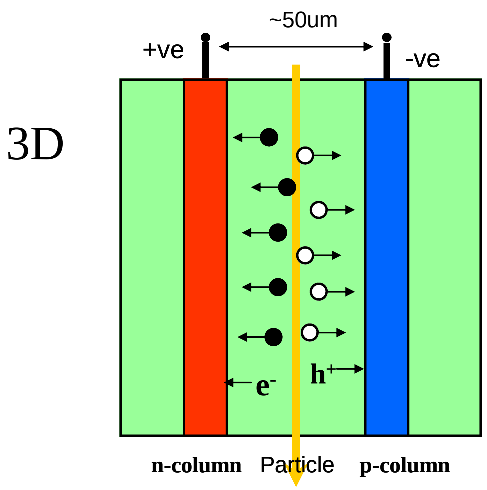
- 3-d array of p and n electrodes that penetrate into the detector bulk
- Lateral depletion
  - Maximum drift and depletion distance set by electrode spacing (<< wafer thickness)
  - Reduced charge sharing due to E-field shape: higher signal in one pixel
  - Fast collection time: reduced charge trapping
  - Reduced depletion voltage
- Technologically complex - micromachining

Rad hard



First proposed by Parker *et al.* Nucl. Instr. Meth. A, 395 (1997)



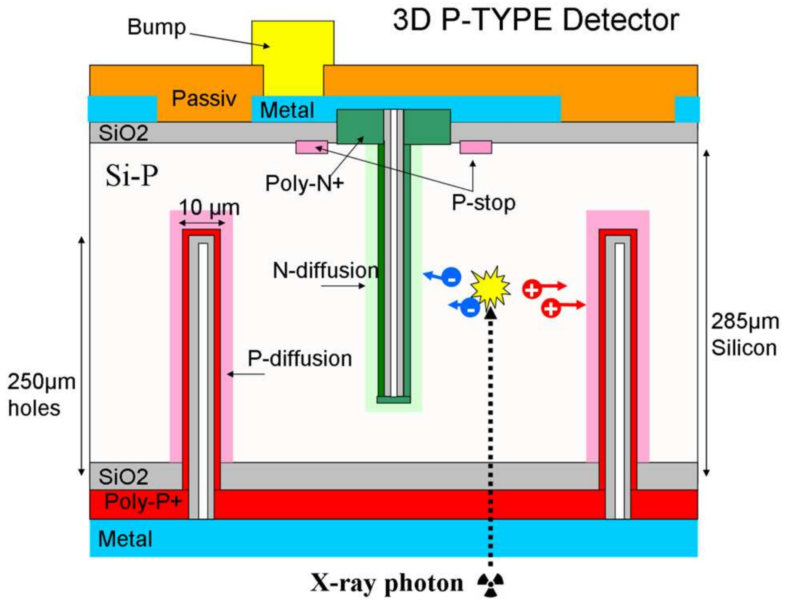


Double-sided 3D at CNM

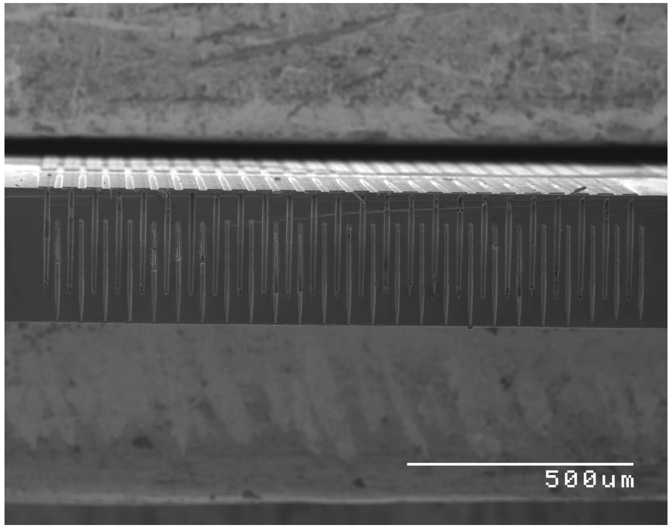
- Columns etched from opposite sides of substrate and don't pass through full thickness
- All fabrication done in-house
- ICP is a reliable and repeatable process (many successful runs)

Electrode fabrication:

1. **ICP etching of the holes: Bosch process, ALCATEL 601-E**
2. **Holes partially filled with LPCVD poly**
3. **Doping with P or B**
4. **Holes passivated with TEOS SiO_2**

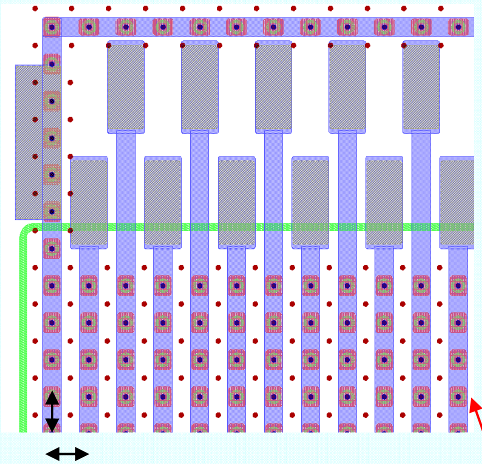


Hole aspect ratio 25:1
10µm diameter, 250µm deep
P- and N-type substrates, 285µm thick

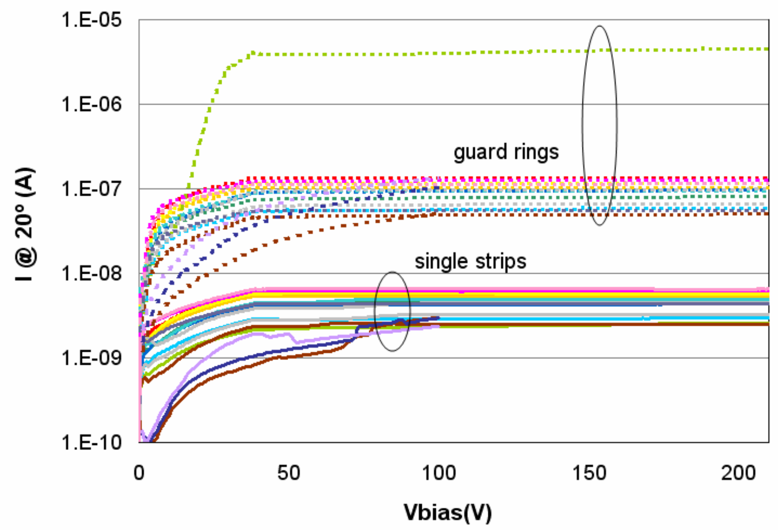


Devices designed by Glasgow Uni&CNM, fabricated at CNM

3D strip detectors



Leakage current of p-type 3D strip detector



50 strips
DC coupled
50 electrodes/strip
4mm long strips
n+ strips/p- bulk/p+ back contact

Before irradiation, T = 20ºC

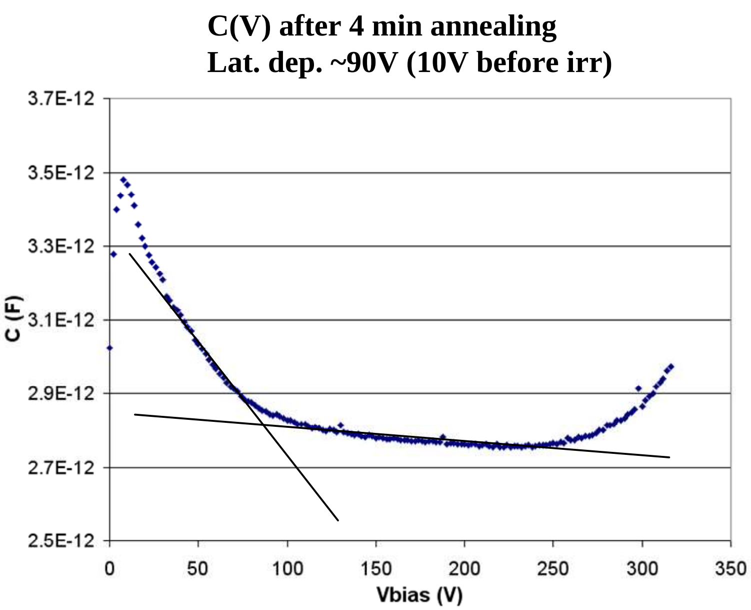
Backside biased, strip and guard ring grounded

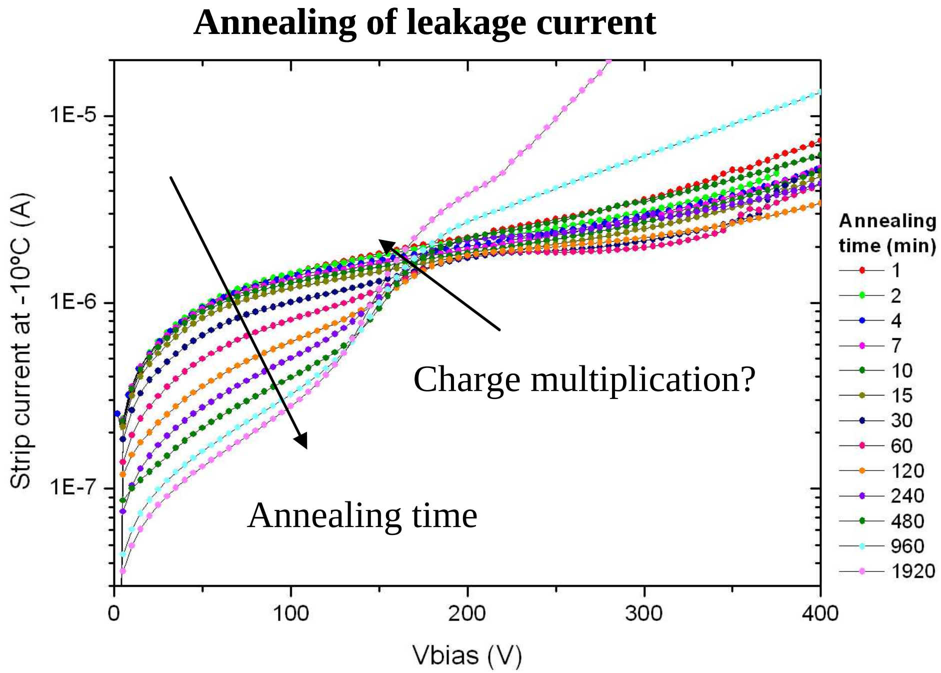
- V_{FD} ~ 40V, I = 40–120 pA/column
- Only 2 detectors, of 19 tested, bad (not shown)
  - Breakdown at less than 5V (catastrophic defect?)
  - All others work far beyond full depletion

3D detectors are mainly a candidate for the sLHC pixel layers, but it is still interesting to study 3D strip detectors because testing is much easier!

Irradiation and annealing

- P-type strip detector irradiated in FZK Karlsruhe with 26 MeV protons to 1E16 1MeV n_{eq}/cm2
- Accelerated annealing at 80ºC
  - Acceleration factor of 7400 for the reverse annealing with respect to RT
- Tested at -10ºC in probe station



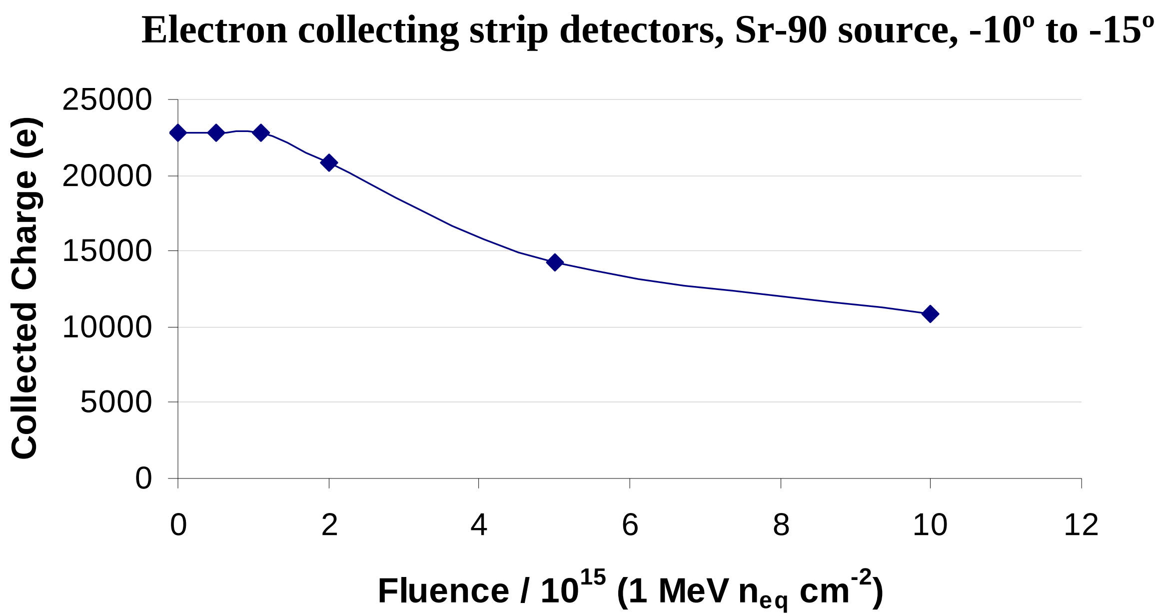


Two competing effects in I-V curves:

⇨ Annealing of leakage current at low V.

⇨ From ~200V: Charge multiplication? More pronunced and earlier for longer annealing time

ALIBAVA lab tests: Collected charge for irradiated devices

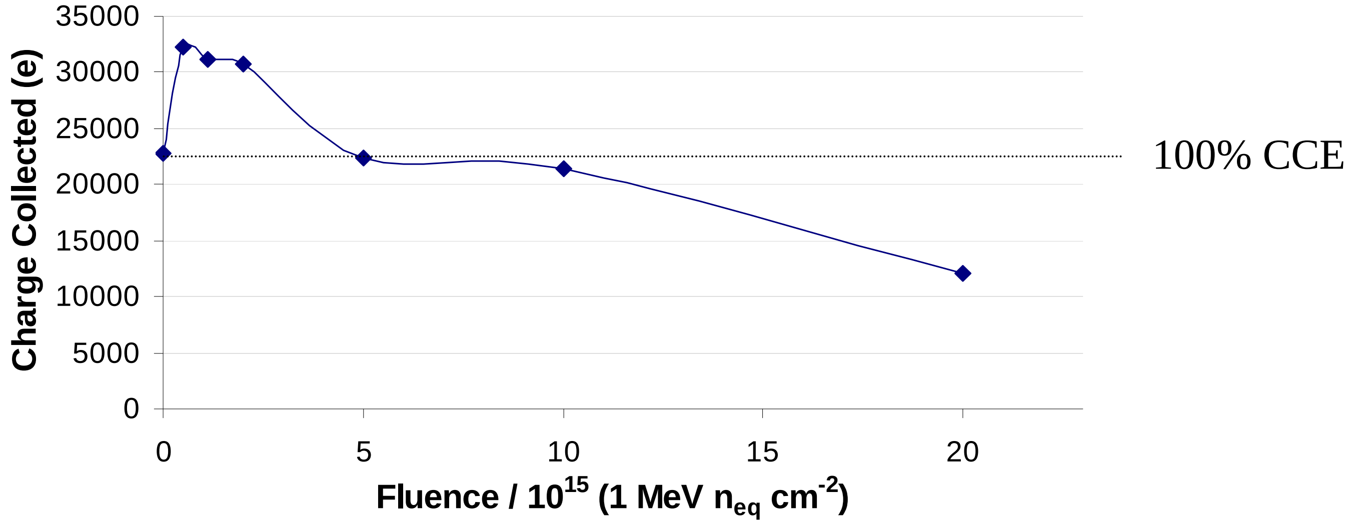


- ALIBAVA system: Beetle front end (LHCb), LHC speed bi-polar amplifier (25ns peaking time), full analogue readout
- Detectors glued to ceramic base boards with RC pitch adaptors from VTT/Helsinki Institute of Physics
- 150V except non-irradiated sample, 18V

Calibration with planar strip detector: n- bulk 300 µm thick, 1 cm long AC coupled p+ readout strips (hole collection), 80 µm pitch
Plateau value taken as full charge collection in planar device

High bias operation

Bias voltage applied maximum possible before excess current or noise, typically 250 to 350V

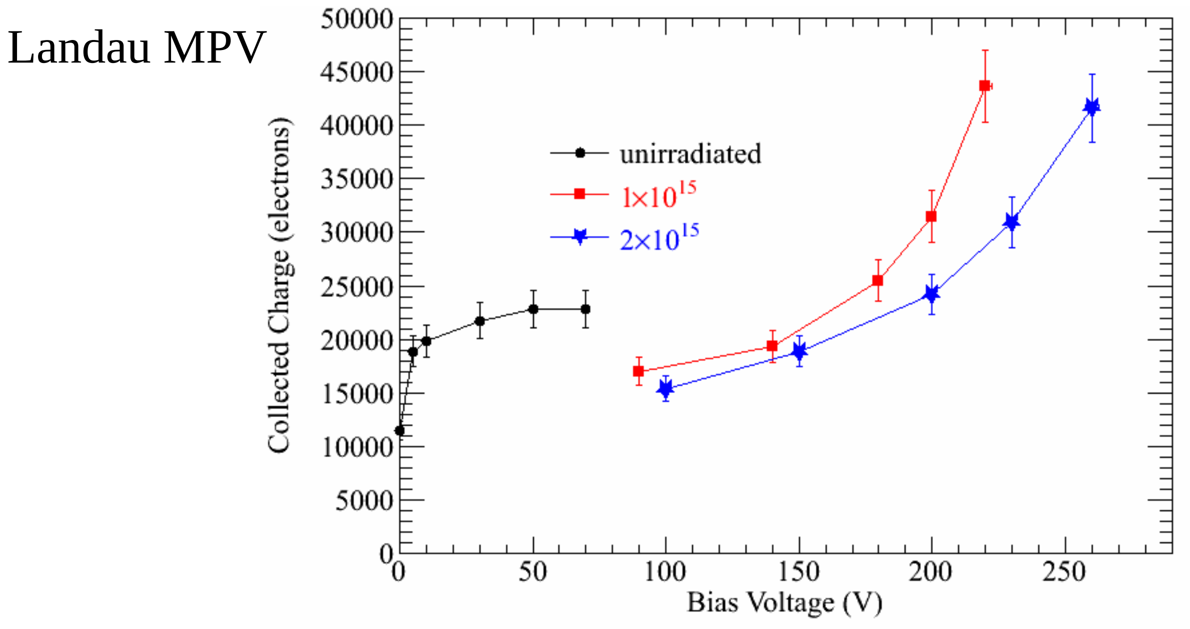


- Increased CCE for high fluences > 5×10^{15}, close to 100% CCE for 10^{16} n_{eq}/cm^2
- More than 100% CCE for fluences 0.5 to 2×10^{15} n_{eq}/cm^2!
  - Strong charge multiplication
  - Also observed in heavily irradiated planar devices with kV bias

For comparison with planar devices: **I. Mandic et al., "Measurement of anomalously high charge collection efficiency in n+p strip detectors irradiated by up to 10^{16} n_{eq}/cm^2" Nucl. Instr. Meth. A 603(3), 2009**

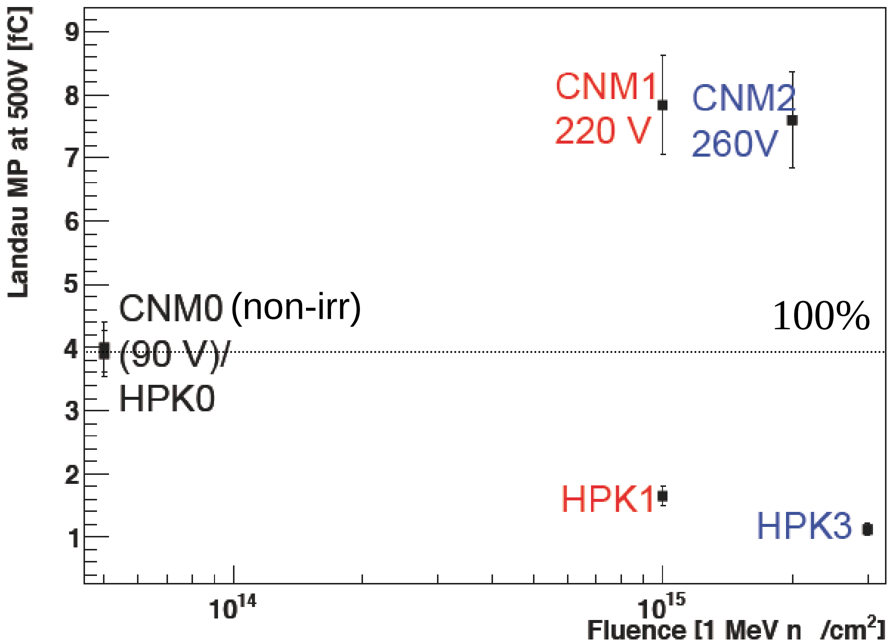
Strip testbeam work

CNM 3D p-type strip detectors tested with Silicon Beam Telescope with CMS readout (APV25 front end, analogue readout) and 50 ns shaping at CERN SPS (225GeV pions), -15ºC.



- Charge collected in testbeam is very close to lab tests
- Irradiated devices: increasing signal above ~150 V. Strong charge multiplication seen.
- For 10^{15}: ~100% CCE at 150V, ~140% CCE at 200V, ~200% CCE at 220V

Strip testbeam work – comparison with planar



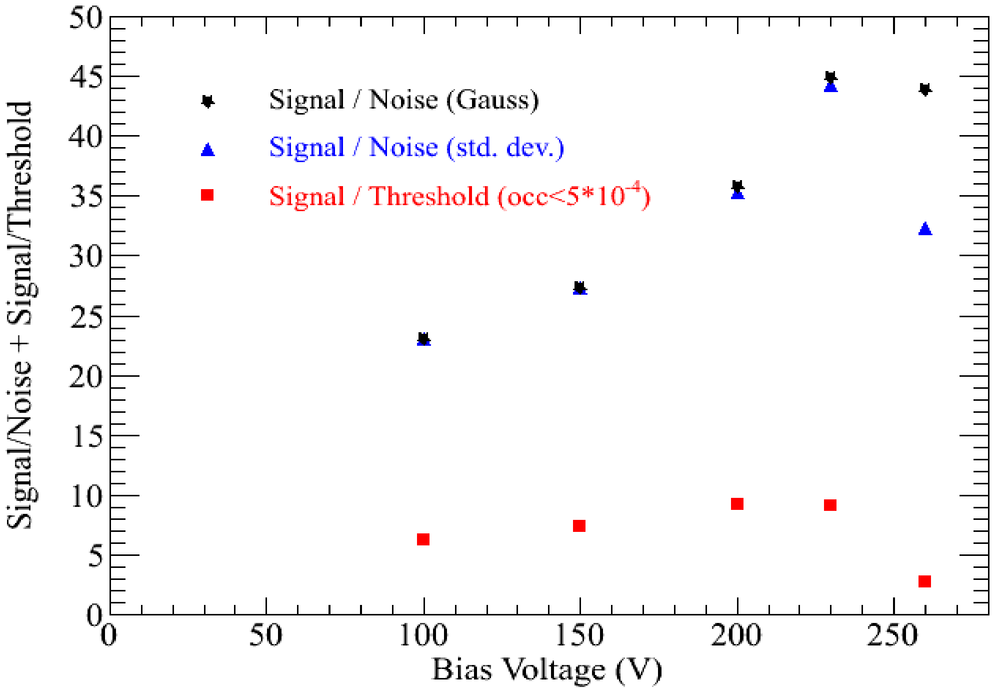
Comparison with Hamamatsu (HPK) planar strip sensors tested in same test beam, same readout, at <u>500V</u>

Data normalised to 320µm thickness

- Irradiated planar sensors far from being depleted at 500V
- Noise level for the planar sensors is ≈ 0.1 fC
- At highest fluence just enough signal left for measurements of planar sensors, SNR≈10

Signal to noise/signal to threshold

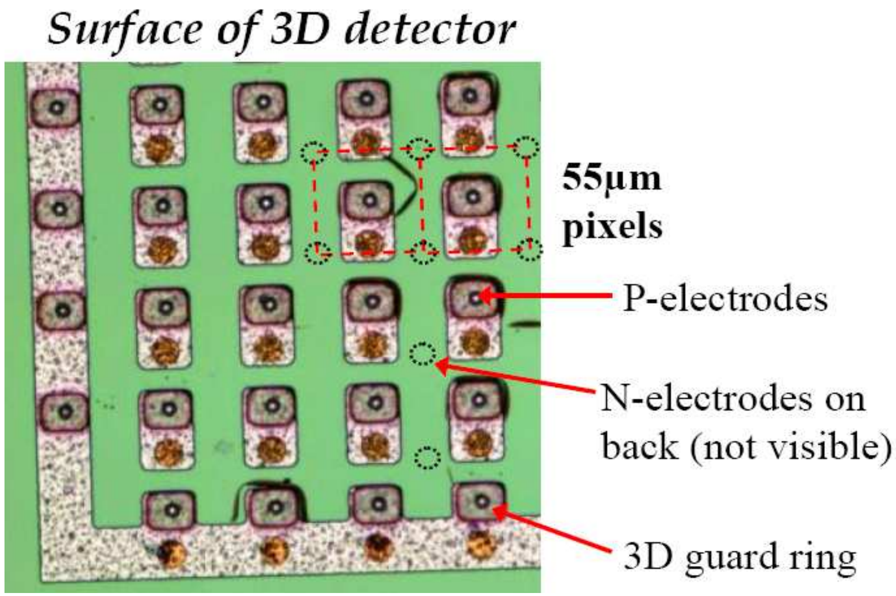
- Need high S/N ratio but for binary systems (e.g. ATLAS) S/T even more important criterion
  - Threshold required to keep the noise occupancy below a certain limit must be increased strongly when charge multiplication is present
- Test beam had large common mode that could not be reduced completely
  - Noise measurements performed in the lab with Beetle-based ALIBAVA readout
- Charge multiplication beneficial for S/T and S/N up to certain point



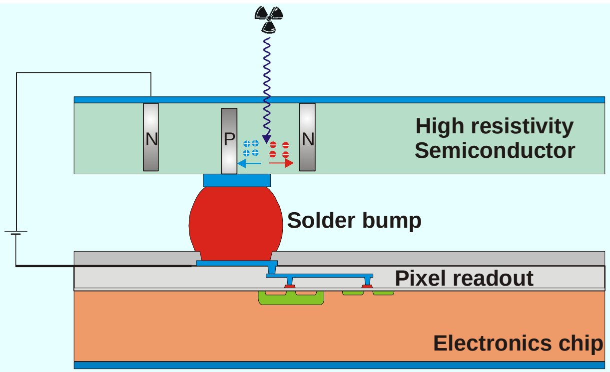
$2x10^{15}$ 1MeV n_{eq}/cm^2

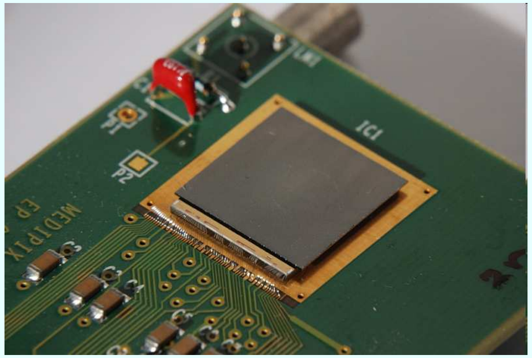
-26ºC

Medipix2 3D detectors



- Medipix and Timepix electronics
  - 65k single-photon counting pixel array
  - 55 x 55 µm square pixels
  - Electron or hole collection
  - 100ns shaping time
  - Counting device with counter on each pixel
    - Each photon hit is compared to a pair of adjustable thresholds
    - Pixel counts no. of accepted hits during acquisition time
  - Timepix allows time over threshold to be recorded
    - Only one photon per frame is recorded in this mode

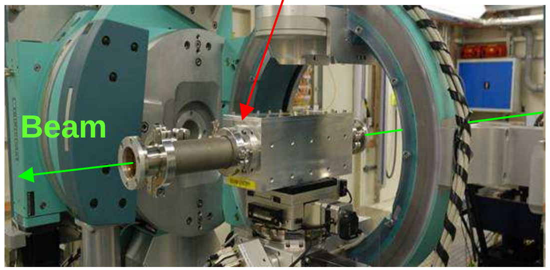


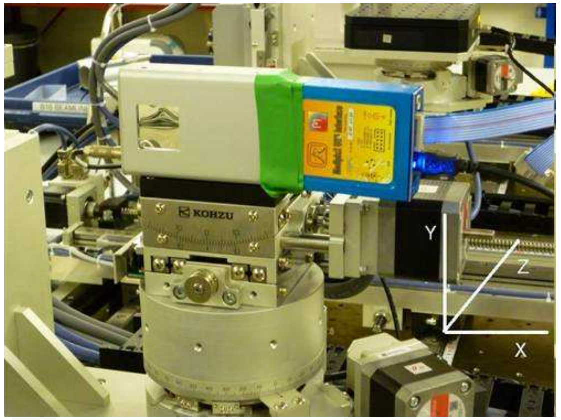


Double sided 3D sensors compatible with standard pixel read out electronics. High voltage on the back of the pixels like in planar devices.

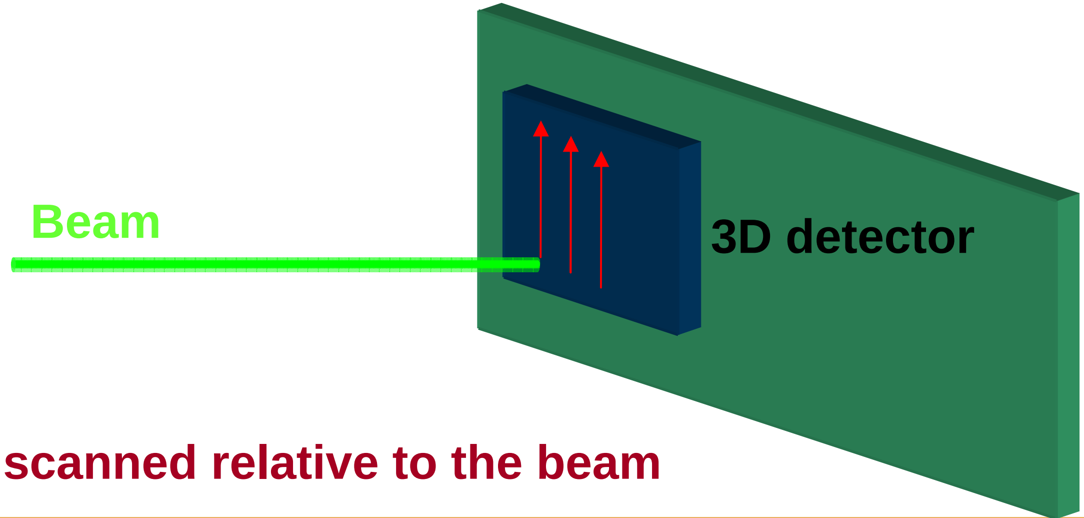
X-ray beamline at Diamond

Compound refractive lens



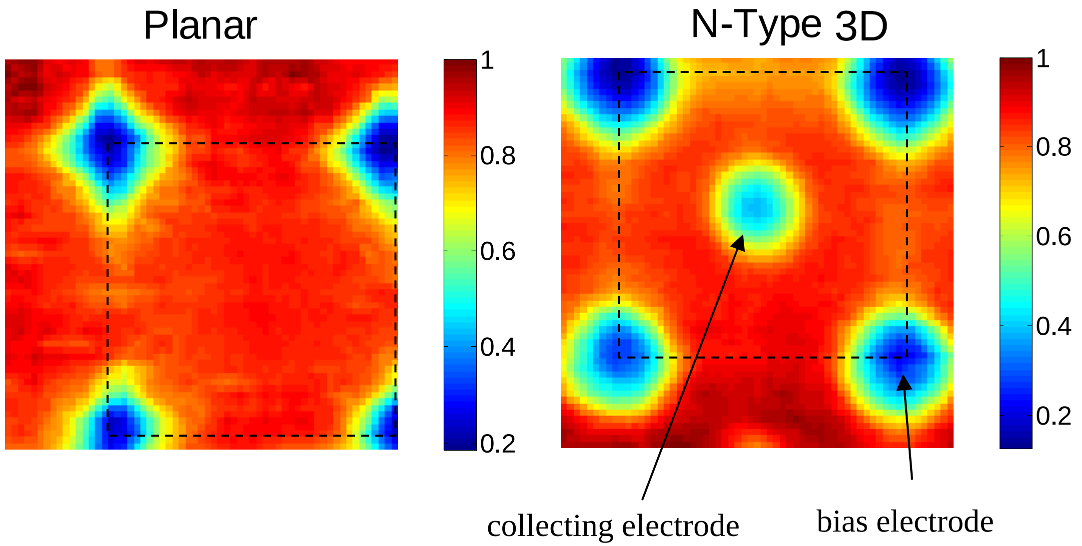


- B16 test beamline at the Diamond Synchrotron
- Monochromatic X-ray beam of 14.5keV
- Microfocussed beam size FWHM were measured as:
  - 4.5±0.3 µm in x
  - 6.7±0.3 µm in y
- Six degrees of freedom, 0.1µm translational and 5µrad rotational
- Alignment of 0.3º in x and 0.9º in y



Detector substrate raster scanned relative to the beam

Pixel maps and X-ray detection efficiencies (Medipix mode – counts above threshold)



- 77.5µm square pixel maps (55µm pixel), background subtracted, interpolated and normalised to the highest count.
- 2.5µm steps
- THL ~ 50% of beam energy

Inefficiencies	Centre	Corners*
Planar	0%	7%
3D N –Type	3%	7%
3D P –Type	4%	7%

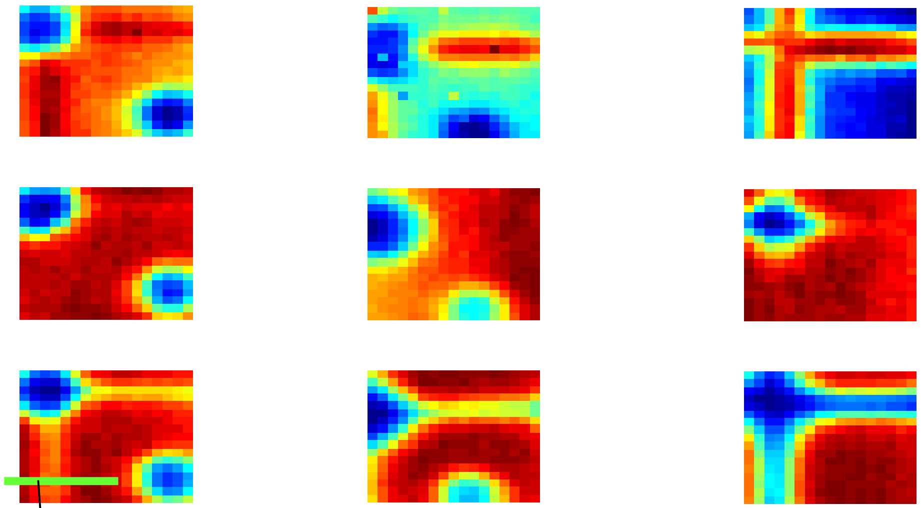
***efficiencies at the corners due to electrodes structures and charge sharing**

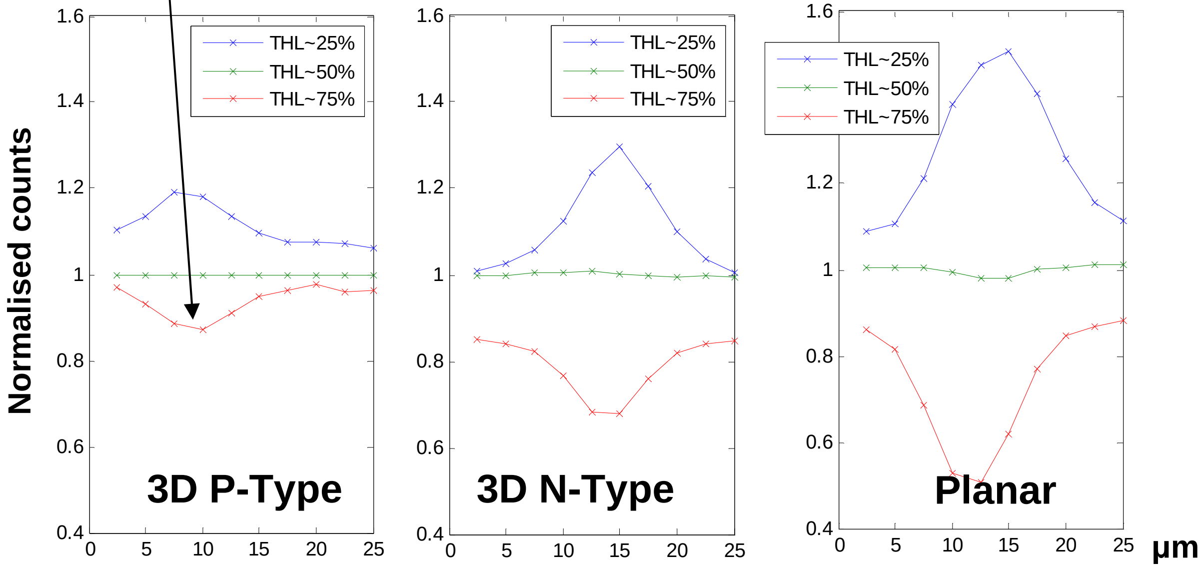
Charge Sharing

THL~25%

THL~50%

THL~75%



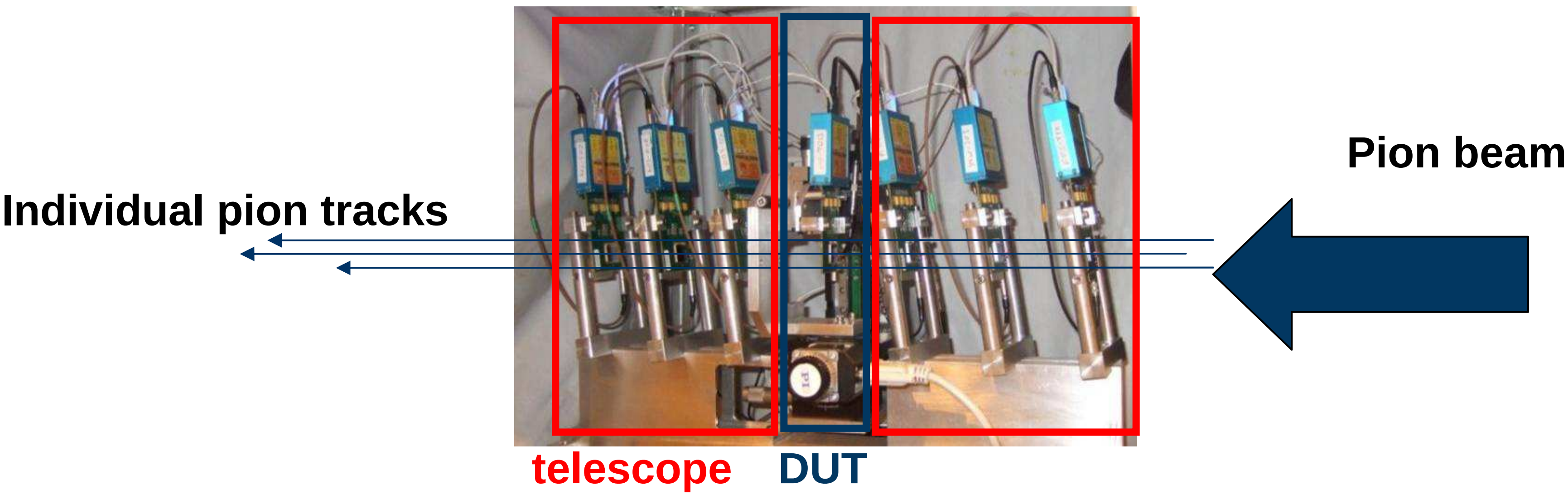


Reduced level of over and under counting in 3D

MIP beam test of 3D Medipix2

Medipix & LHCb

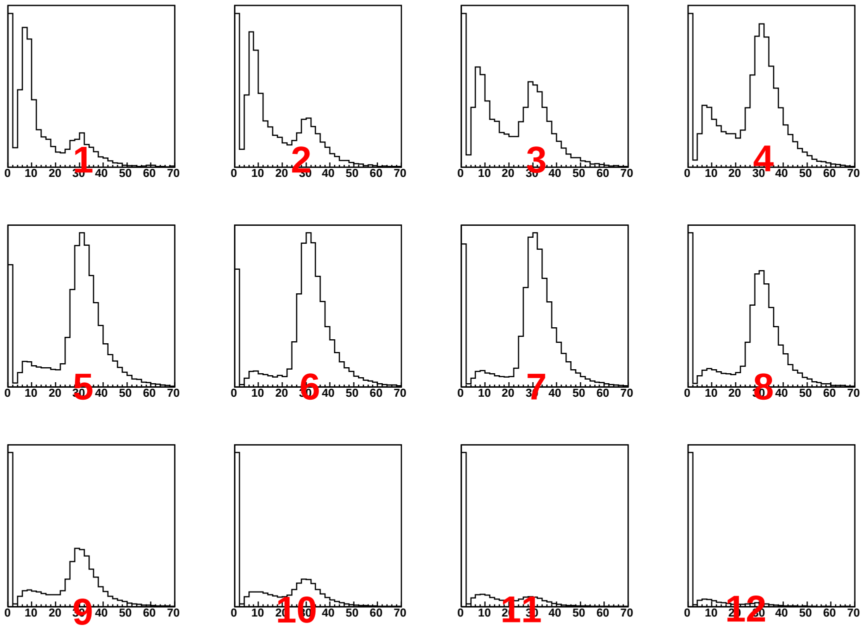
- Secondary 120 GeV pion beam from SPS
- 4 Timepix, 2 Medipix planes in telescope
- DUT: double sided 3D N-type sensor from CNM/Glasgow, Timepix mode (Time Over Threshold)
- Expected track extrapolation error < 3 μm

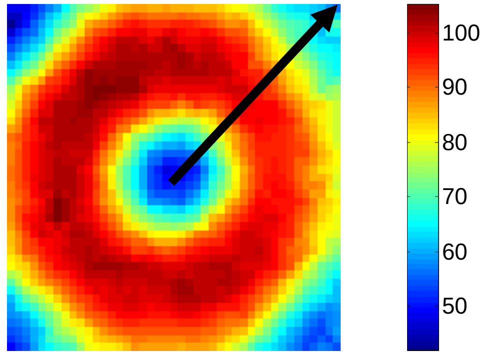


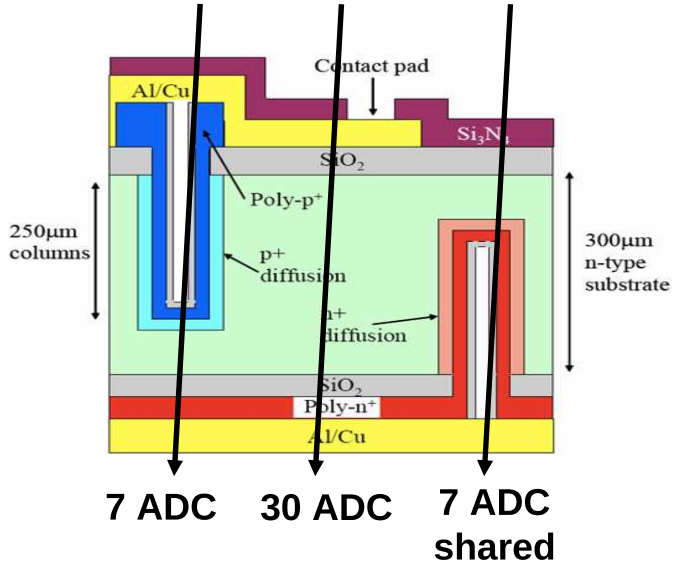
Charge efficiency

Measurements at 0º angle (normal incidence)

1-12 show ADC counts (TOT) in pixel at positions along cross section from center (junction) to the corners (ohmic, shared)



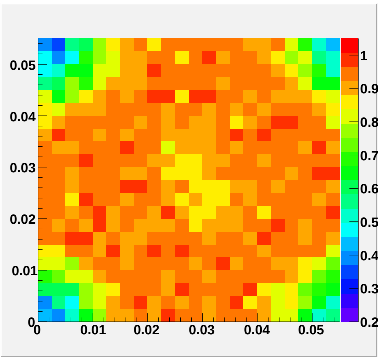




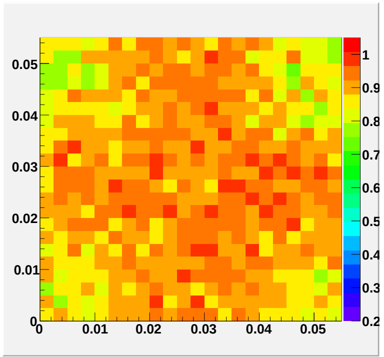
Peaks seen at ~7 and ~30 ADC counts

Detection efficiency with angle (preliminary)

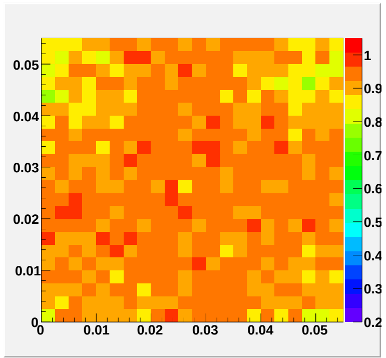
0º



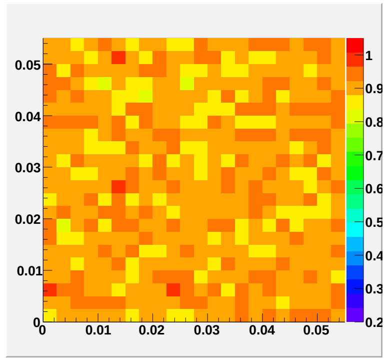
2º



4º



10º



- Absolute efficiency (Medipix mode, counts above threshold)
- Threshold just above noise level
- Efficient if hit in 3x3 pixel array around intercept point

For a detailed analysis of the Medipix Diamond and CERN testbeams see **G. Stewart's poster "3D Detector Analysis from testbeams at the Diamond Synchrotron and CERN SPS"**

For simulations of charge multiplication: **J.P Balbuena, "Simulation of charge multiplication in 3D detectors"**

Conclusions

3D irradiated strip sensors:

- Evidence of charge multiplication in testbeam and lab tests
- Both signal to noise and signal to threshold ratio can be increased up to a certain point, but they decrease with very strong multiplication
- Charge multiplication could possibly improve the performance of irradiated 3D detectors, but more experiments and simulations needed.

3D Medipix2/Timepix

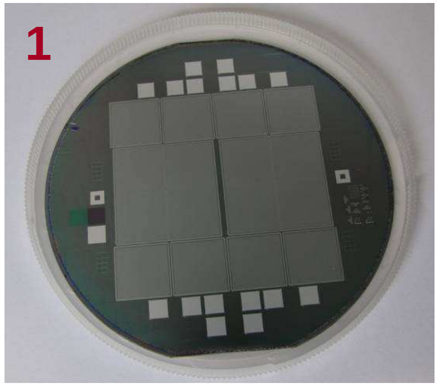
- 3D detector shows less charge sharing than the planar equivalent
- Charge collection observed from both inter-column and column-back plane regions
- Charge loss inside the electrodes
- As the detector is rotated the signal equalises across the detector
- Trade-off between efficiency and charge sharing/radiation hardness in 3D devices

- Double sided 3D suitable for pixels with short edges (~10um) -> tiling
- Technology ready for small-medium production (e.g. IBL)

Future 3D work at IMB-CNM

- New run of 3D-Medipix3, standard (2 cm^2) and quad area (16 cm^2). Collaboration with Diamond Light Source and Glasgow Uni (1)
- Irradiation and test beams with Medipix (Timepix) detectors for LHCb VELO upgrade.
- ATLAS pixels FE-I3 and new FE-I4 fabrication, irradiation and test beam. For the IBL, in the framework of the ATLAS 3D Collaboration (http://test-3dsensor.web.cern.ch/test-3dsensor/). (2)
- Design and fabrication of CMS pixels: single chips and 8x2 module. In collaboration with PSI. (3)
- Design and fabrication of 3D strip detectors for TOTEM (CERN) (4)

1



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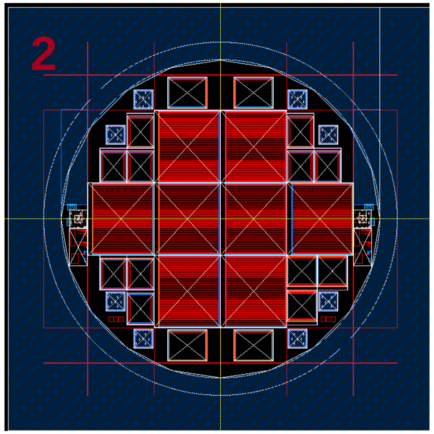

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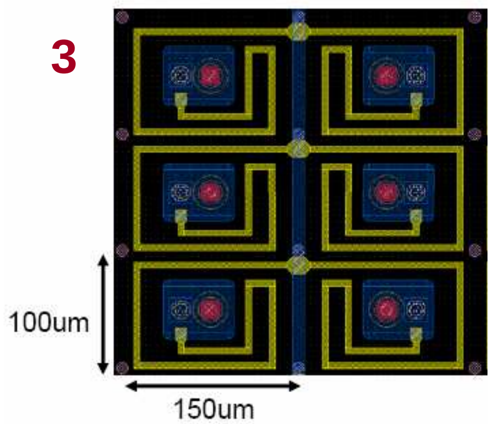

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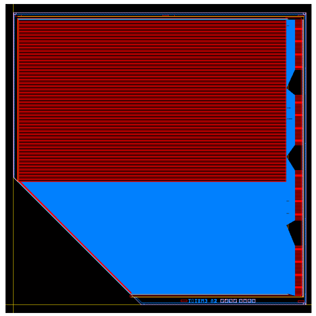

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