University of Glasgow

Old title: 3D pixel devices; design, production and characterisation in test beams

Characterisation of Glasgow/CNM double-sided 3D sensors

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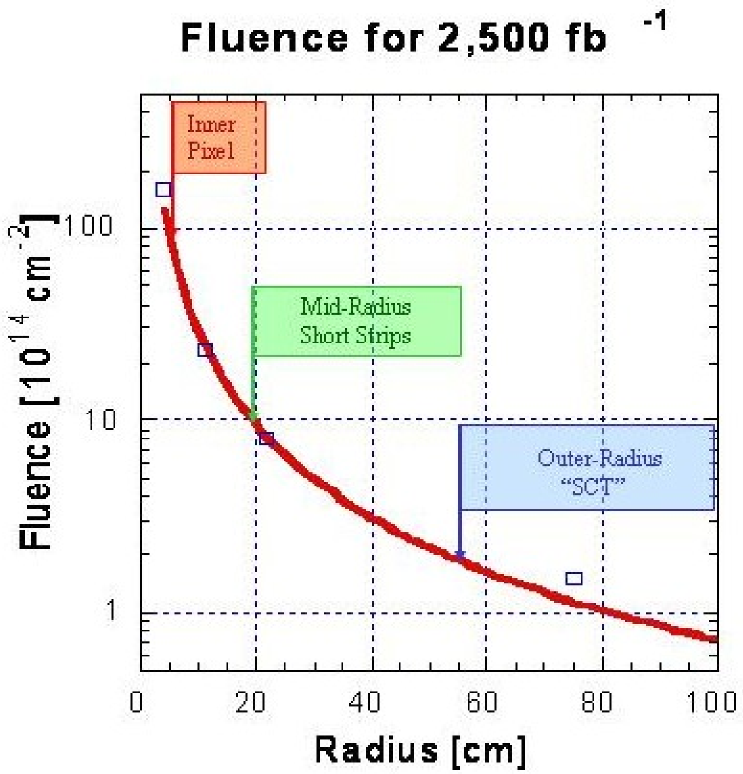
TIPP, Chicago, June 2011.

Motivation for radiation hard sensors



- Fact of 10 luminosity upgrade of LHC to HL-LHC to extend physics programme
- Radiation damage increase in proportion to integrated luminosity
- Need to optimise silicon detector design to survive

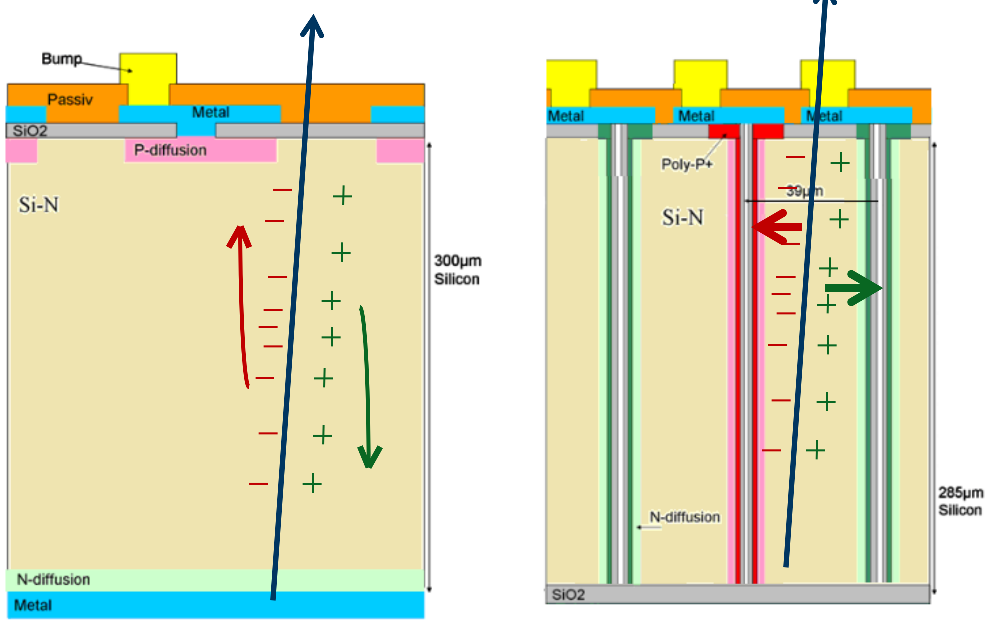
#203: Silicon Detectors for High Luminosity Colliders. RD50 Status Report. Ulrich Parzefall

- **Radiation hardness requirements (including safety factor of 2)**
  - **2×10^{16} n_{eq}/cm^2 for the innermost pixel layers**
  - **1×10^{15} n_{eq}/cm^2 for the innermost strip layers**

3D sensors

- **Greater signal charge** due to faster collection time (less trapping)
- **Reduced power consumption** due to lower depletion voltages
- **Reduced charge sharing**
- Active edge technology: large-area tiled 'edge-less' detectors

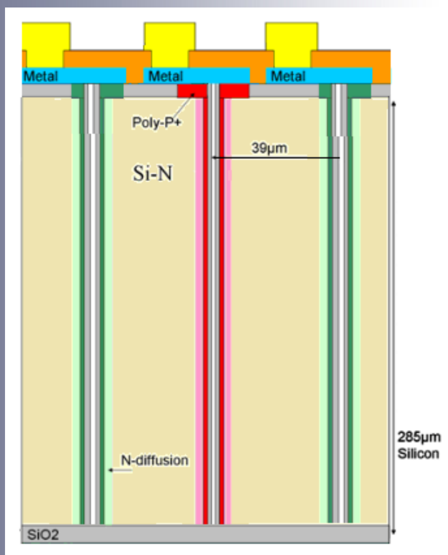
Planar 3D



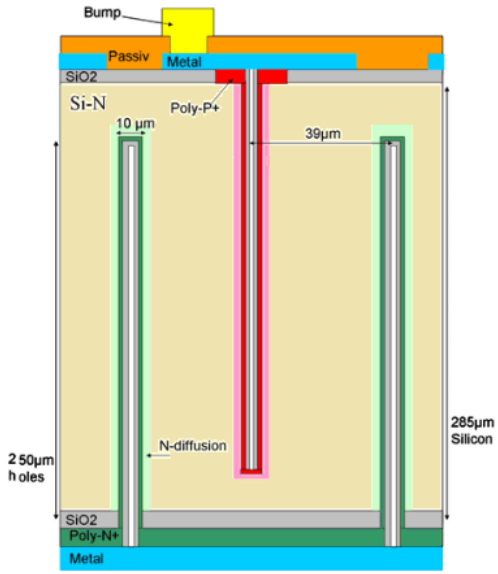
Drawbacks

- increased complexity, **yield** issues
- areas of **inefficiency**

Double sided 3D sensors



3D



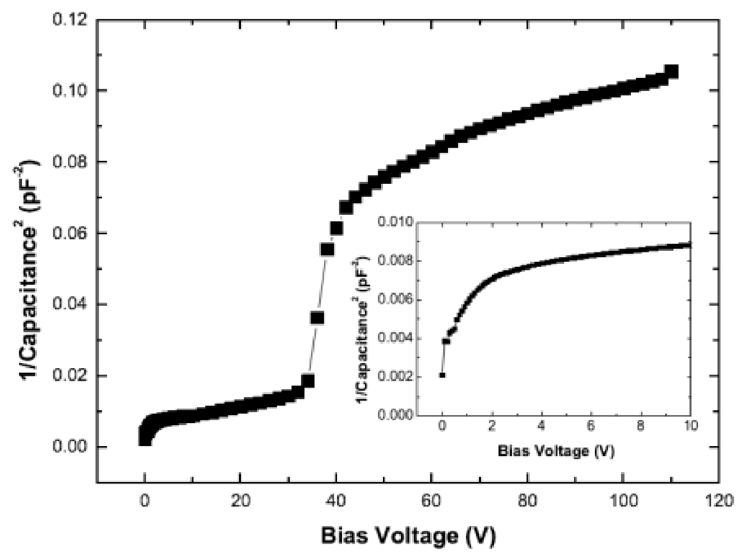
Double-sided 3D

<u>Double depletion</u>

Lateral depletion ~4V

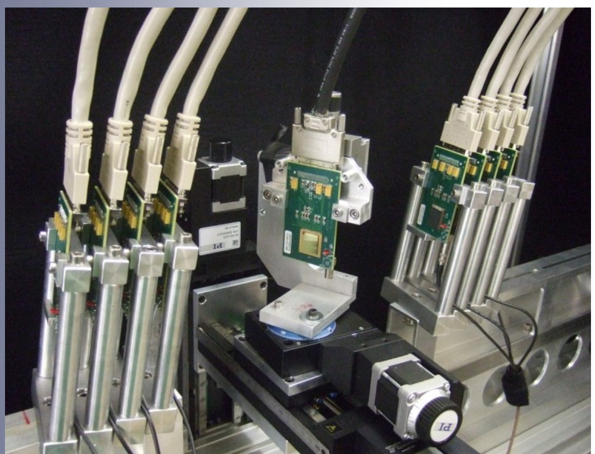
Full depletion~40V

- Reduce fabrication complexity
- Increase yield
- All regions of sensor have active Silicon

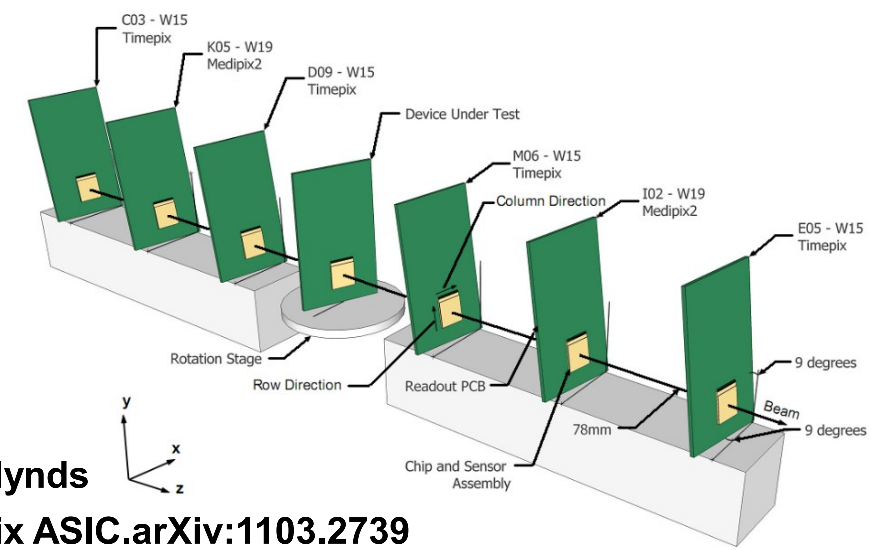


Precision scans of a 3D pixel cell

Timepix Telescope



- **TimePix/Medipix chips: 256*256 55μm square pixels**
- **Energy deposition provided by Time over Threshold in TimePix**
- **120 GeV pion beam from SPS**
- **Device under test (DUT): double sided 3D N-type pixel sensor**
- **DUT on high resolution rotational and translational stage**



For more details on telescope see

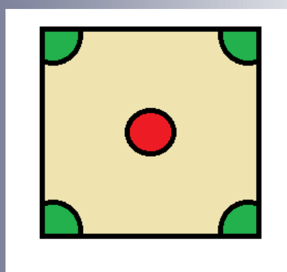
- **# 147 - The LHCb VELO upgrade. Daniel Hynds**
- **Charged Particle Tracking with the Timepix ASIC.arXiv:1103.2739**

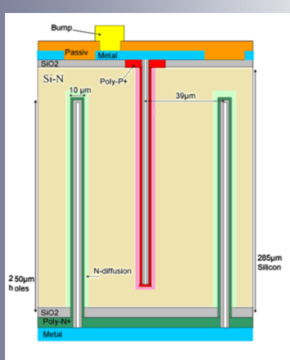
Precision scans of the Pixel cell response of double sided 3D Pixel detectors to pion and X-ray beams. 2011 JINST 6 P05002

University of Glasgow

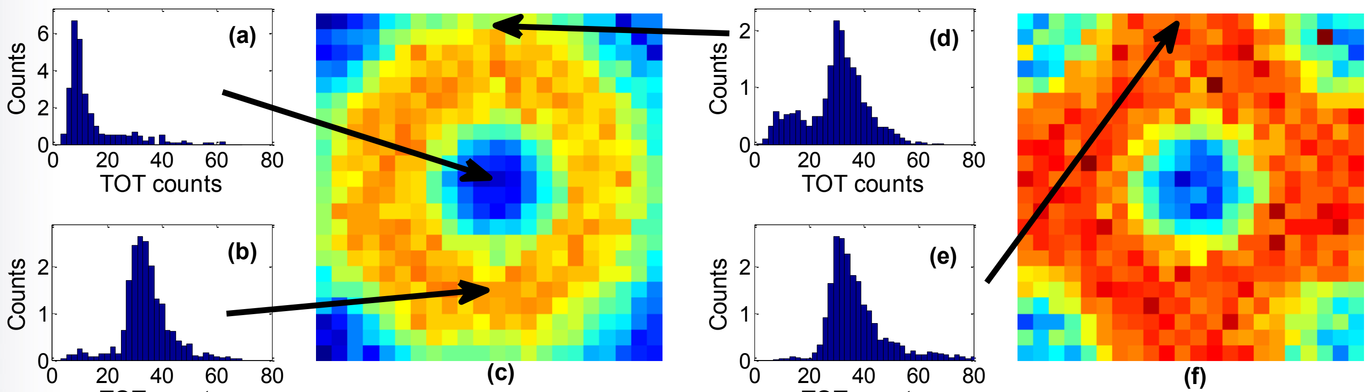
Precision scans: Charge deposition

Timepix Telescope





Mean energy deposited mapped onto pixel cell



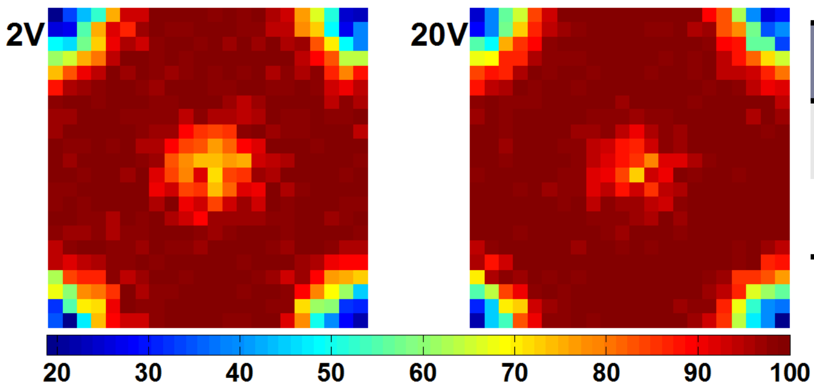
Single pixel response

Seed and nearest neighbours

- Area removed from columns exhibits standard Landau shape
- Charge deposition full/column ration = 35/285μm ratio
- Full cluster energy reconstruction

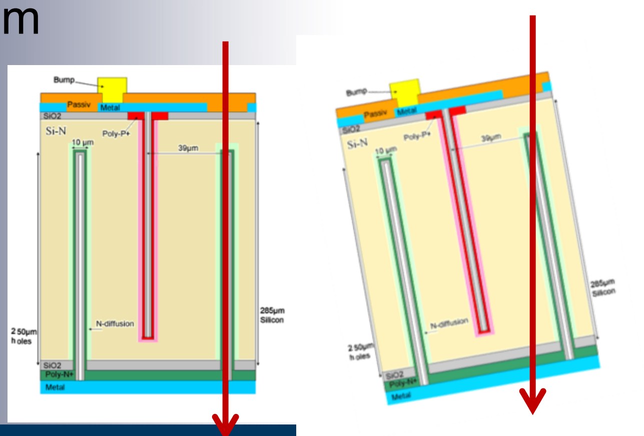
Precision scans: Efficiency

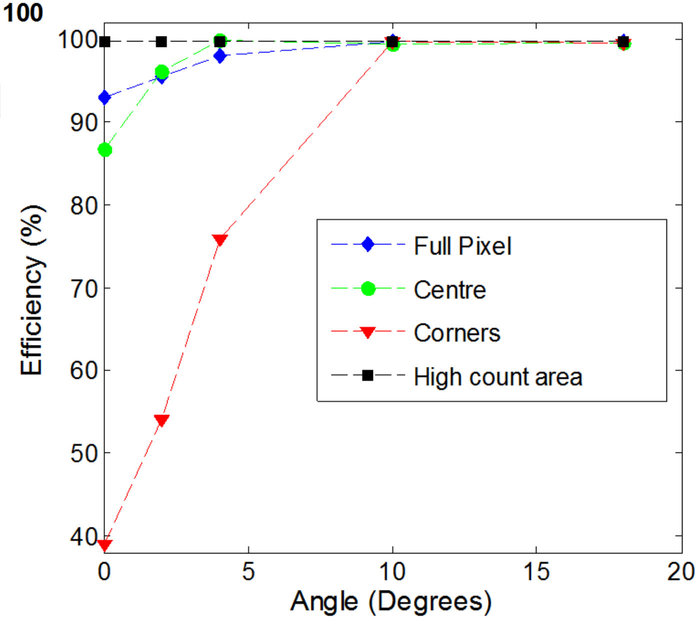
Timepix Telescope

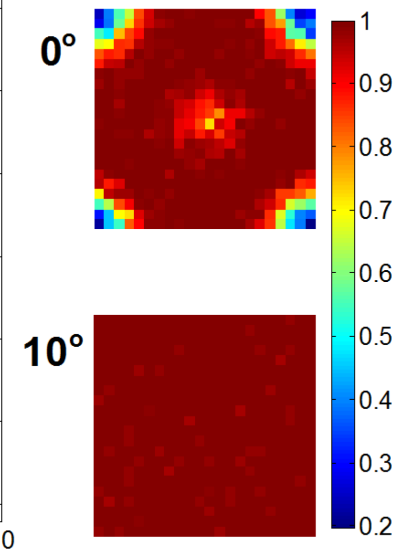


Voltage	Corner	Centre	Ring	Pixel
2V	35.6	79.1	99.1	91.2
20V	39.1	86.7	99.7	93.0

Full efficiency, **99.8±0.5%**, reached at an angle of **10°** to the incident beam







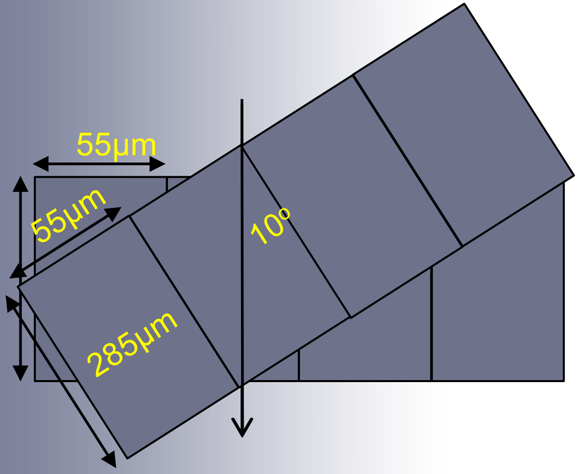
Precision scans: Spatial resolution

Timepix Telescope

Binary resolution = 55μm / √12 = 15.9μm

	3D		Planar *	
Degrees	0^o	10^o	0^o	10^o
Spatial resolution	15.8±0.1	9.18±0.1	10.15±0.1	5.86±0.1

Resolutions shown can be and have been improved with eta corrections and the removal of track extrapolation error

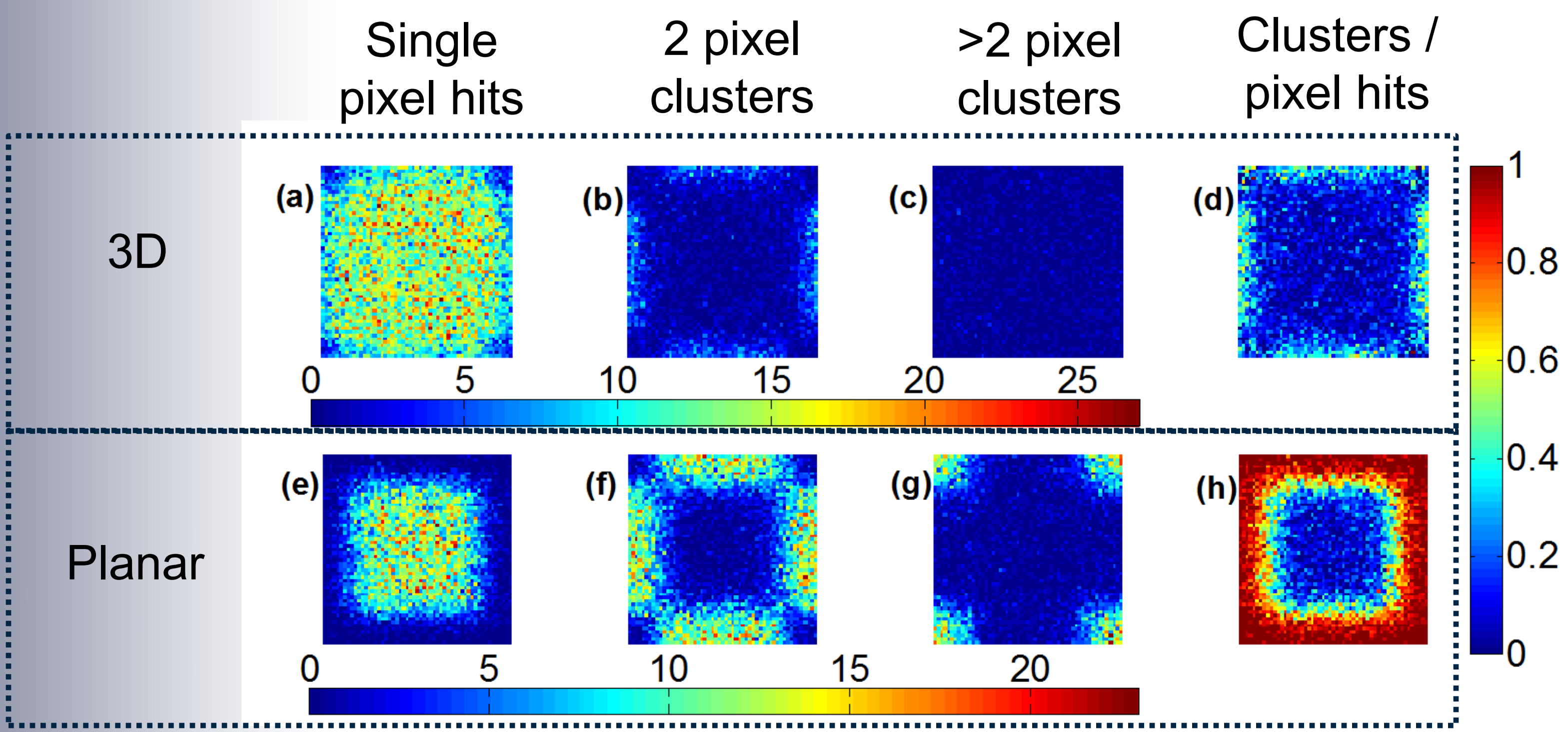


- Hits that only affect one pixel have limited resolution
- Tilting the sensor means all tracks charge share
- Can use ToT information in centroid, CoG calculations
- Maximum spatial resolution at 10^o *

**** Charged Particle Tracking with the Timepix ASIC. arXiv:1103.2739***

Precision scans: Charge sharing

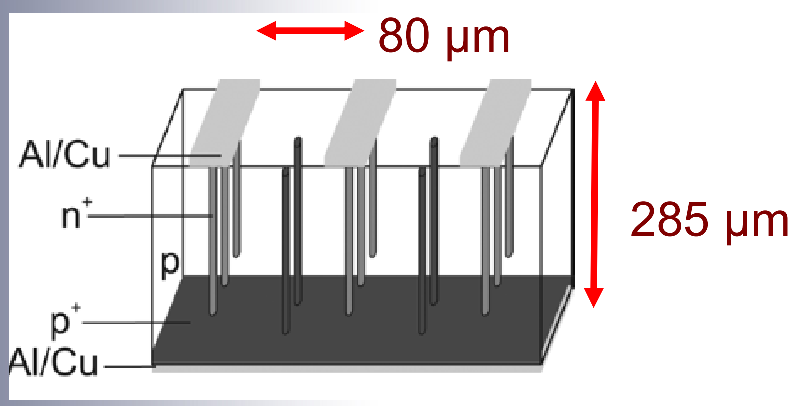
Timepix Telescope

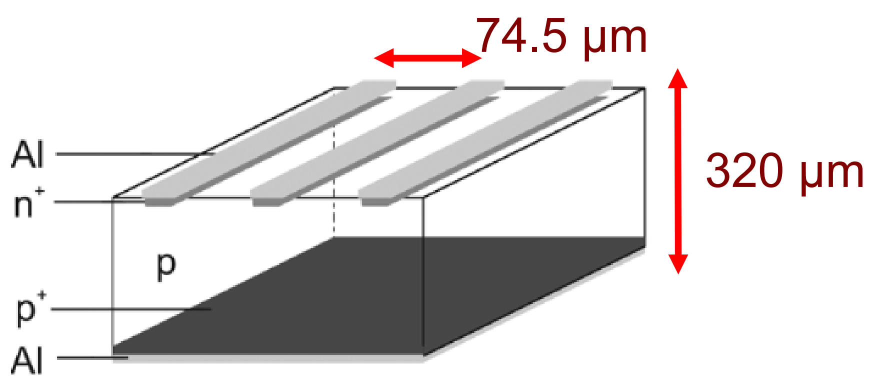


59% of incident particles multiple pixel hits in the **planar** sensor.
14% of incident particles multiple pixel hits in the **3D** sensor.

Strip devices

Electrical measurements





0.5 1,2,5,10,20 x10^{15} 1 MeV n_{eq} cm^{-2} (±20%)

Karlsruhe Institute of Technology, -20°C, 26 MeV protons

3D devices

P-stop isolation before and after irradiation to 10x10^{15}

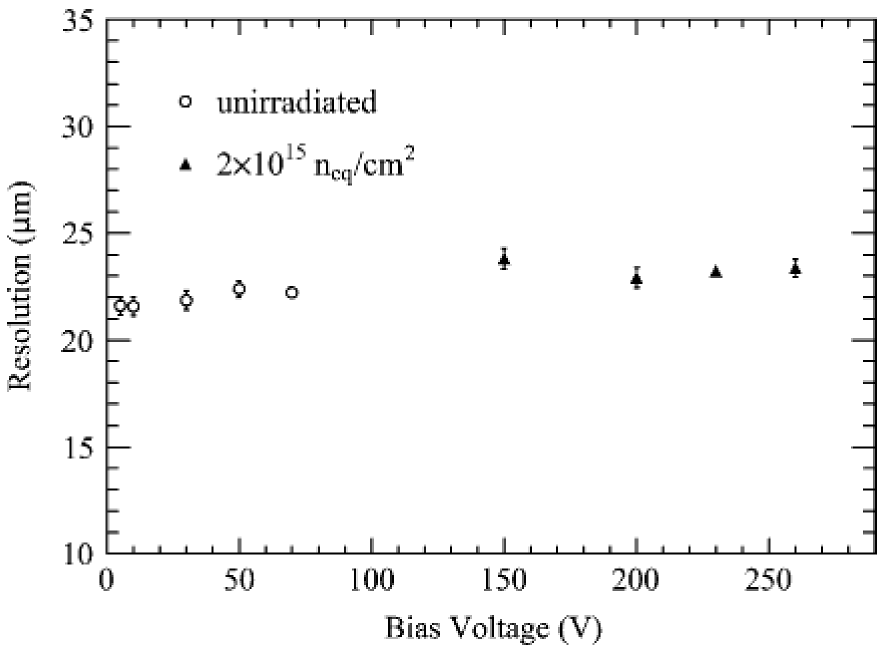
Inter-strip resistance 100MΩ

Leakage current scales as expected

Fluence (1x10^{15} 1MeV n_{eq} cm^{-2})	Lateral depletion voltage (V)
0	4
0.5	15 ± 5
5	100 ± 10
10	145 ± 10

Spatial resolution

Silicon Beam Telescope



- Resolution before and after irradiation close to binary resolution
- Summer 2011 – highly irradiated sensors in TimePix Telescope

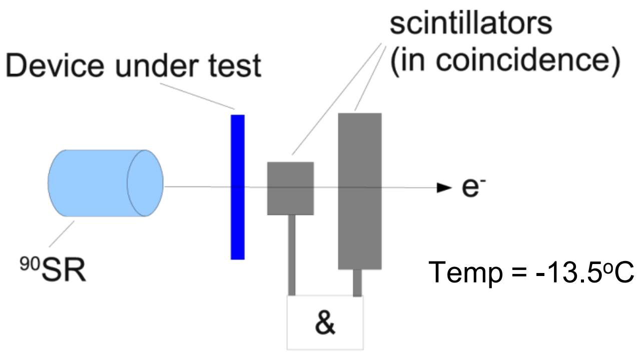
3D binary resolution = 74.5µm / √12 = 23.1µm

The spatial resolutions contain telescope alignment error

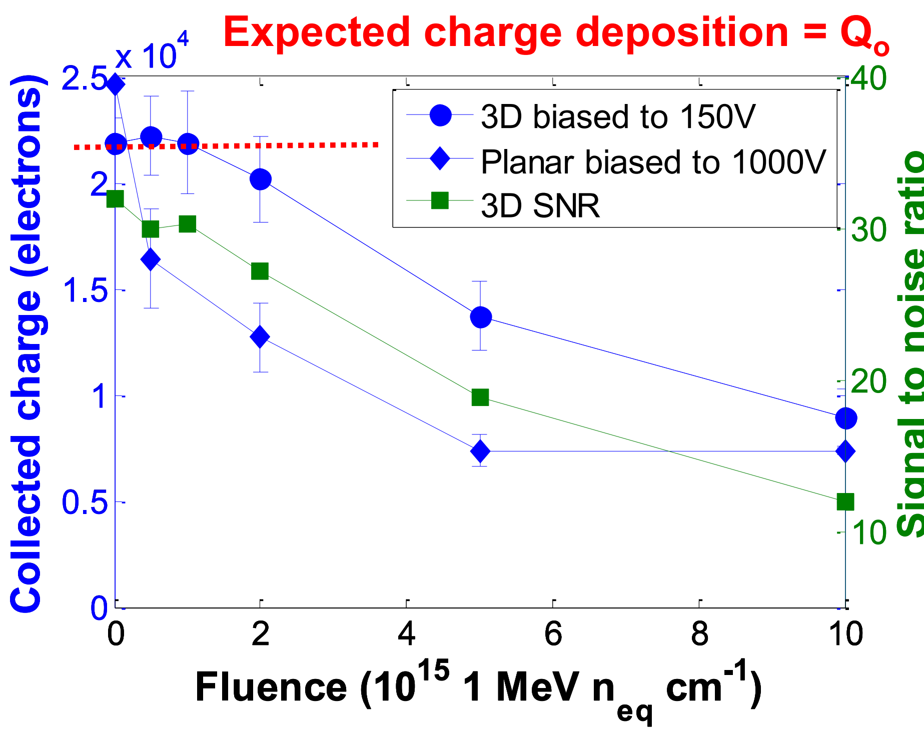
Beam Test Measurements With Planar and 3D Silicon Strip Detectors Irradiated to sLHC Fluences. Submitted to IEEE Trans. Nucl. Sci., DOI 10.1109/TNS.2011.2126598

Charge collection efficiencies (150V)

Sr-90 electrons



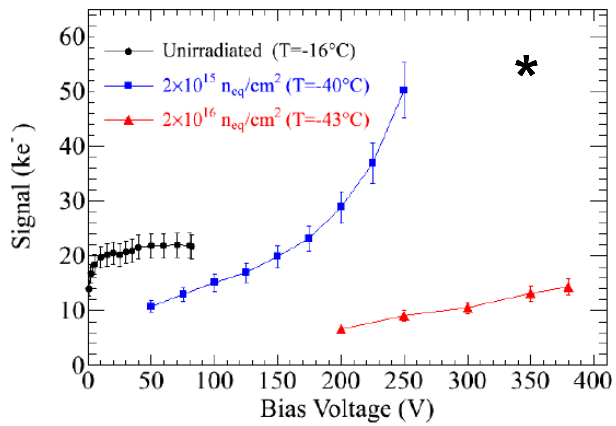
- Large charge collection at high fluences and modest voltages
- 3D charge collection of 47% of Q_o @10^{16} fluence at 150V
- This has been simulated using TCAD without any high field effects present and shows very good agreement
- Noise is constant giving a signal to noise value of >10 @ 10^{16} fluence at 150V
- Compared to planar sensor higher charge collected
- Planar charge collection, 30% of Q_o @10^{16} fluence at 1000V

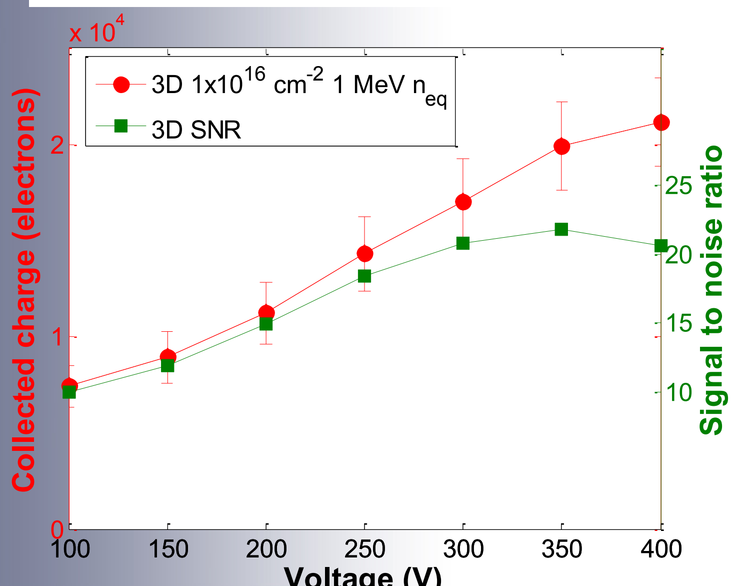


Charge collection studies and electrical measurements of heavily irradiated 3D Double-Sided sensors and comparison to planar strip detectors. R. Bates et al., submitted to IEEE

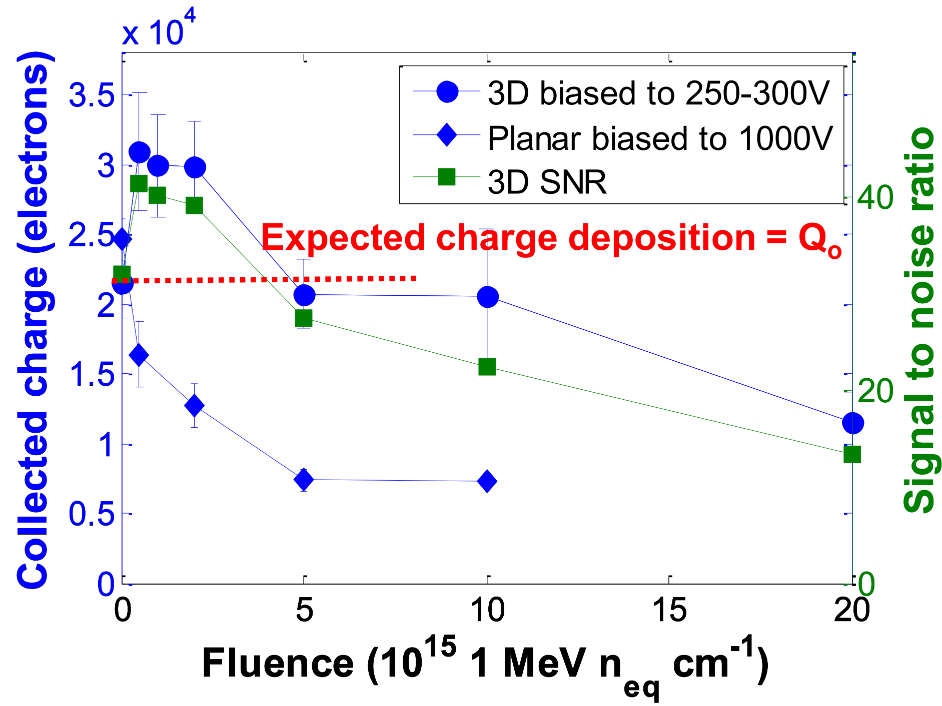
Charge collection efficiencies (~250-300V)

Sr-90 electrons





Charge multiplication through impact ionisation

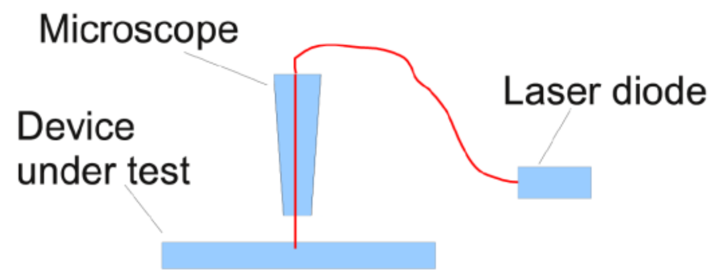


- 52% of Q_o collected at 20×10^{15} 1MeV n_{eq} cm^{-1}
- Charge Multiplication when bias >150V (10^{15})
- Noise ~ constant until > 250V
- 3D Signal >> Planar Signal (higher voltage)

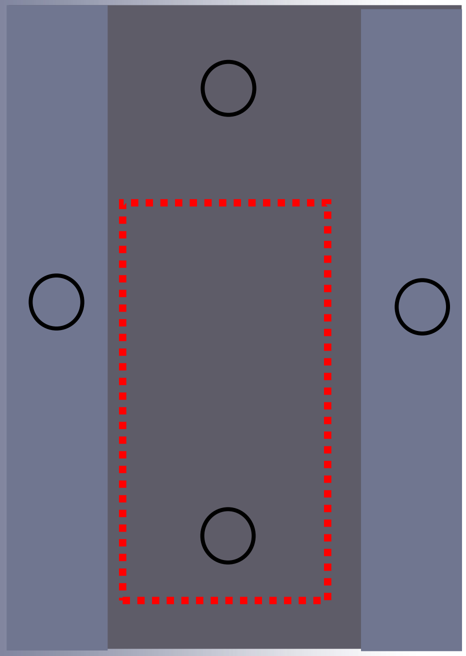
** M. Koehler et al., 6th Trento Workshop 2011*

Mapped CCE with scanned laser

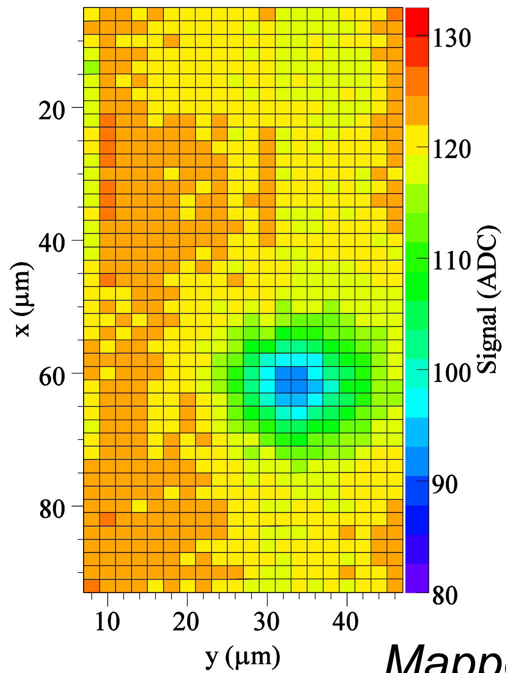
Laser scanning



Experimental setup:
- Space-resolved relative signal
- Motorised x-y stages, 4μm laser spot scanned in 2μm steps
- IR laser, 974 nm wavelength, absorption length: ~90μm (in Si, T=-20°C)



Scanned area



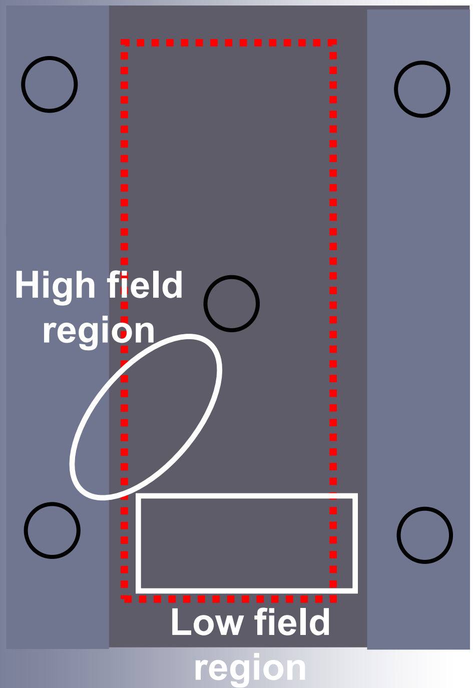
- 3D un-irradiated @ 77V
- p+ column evident
- Uniform charge collection outside of column position

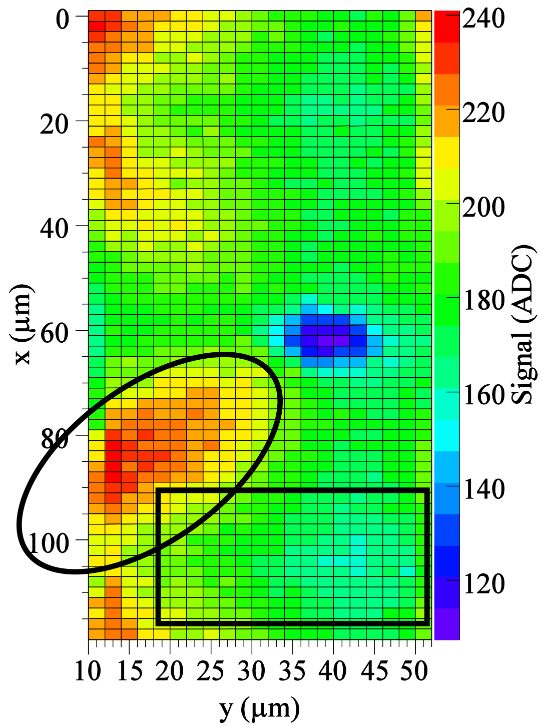
Mapped charge collection response

Mapped CCE with scanned laser

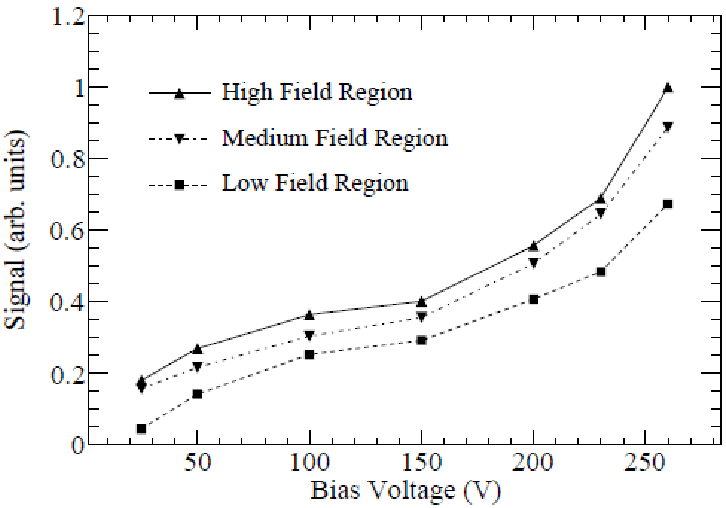
Laser scanning

Bias:260V
Fluence: 2×10^{15} 1 MeV n_{eq} cm^{-2}
Sr-90 measured ~137% of Q_o collected





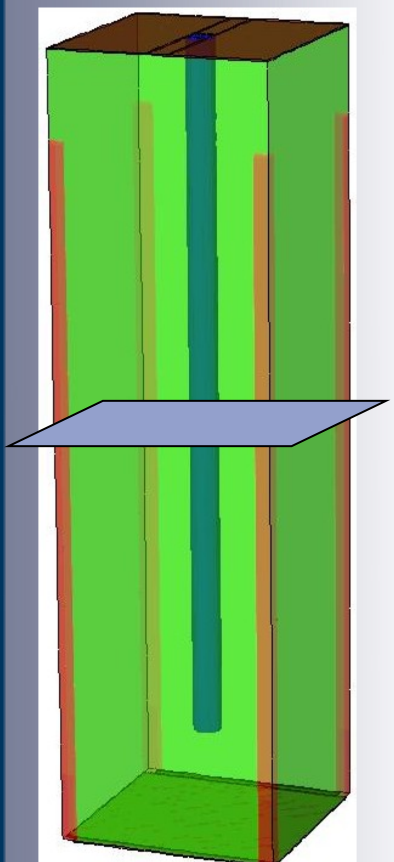
- p+ column evident
- Non-uniform charge collection outside of column position
- Area of low charge collection between the n+ contacts were a low field is present, greater probability of charge trapping

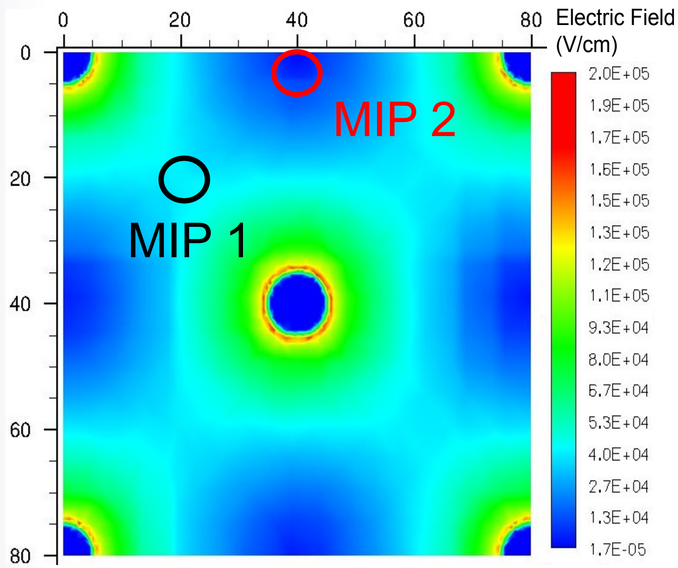


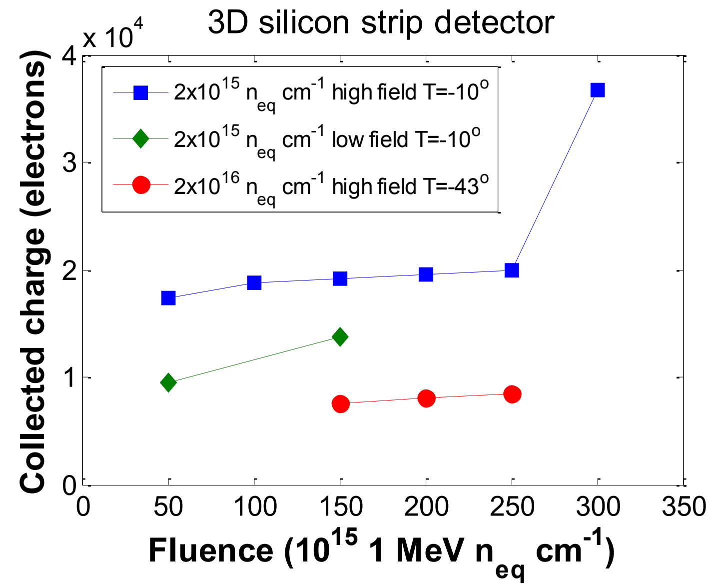
Charge Multiplication - simulations

TCAD

V_{bias} = 300 V | Fluence = $2\cdot10^{15}$ n/cm^2 | T = -10ºC







- Charge multiplication occurs along column length
- Work on-going on low field region

Conclusions

Timepix Telescope

Electrical measurements

Sr-90 electrons

Laser scanning

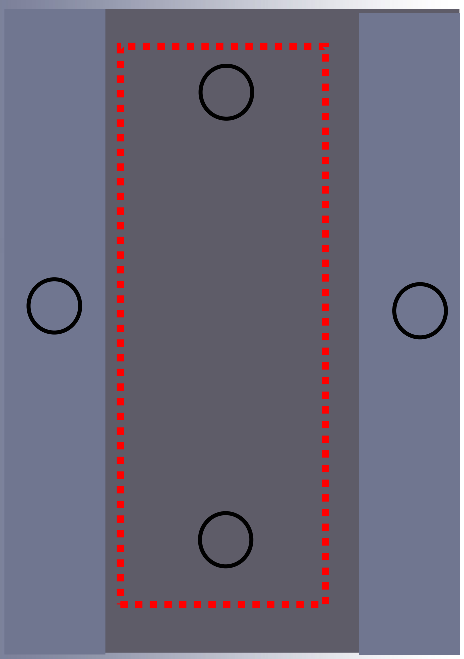
TCAD

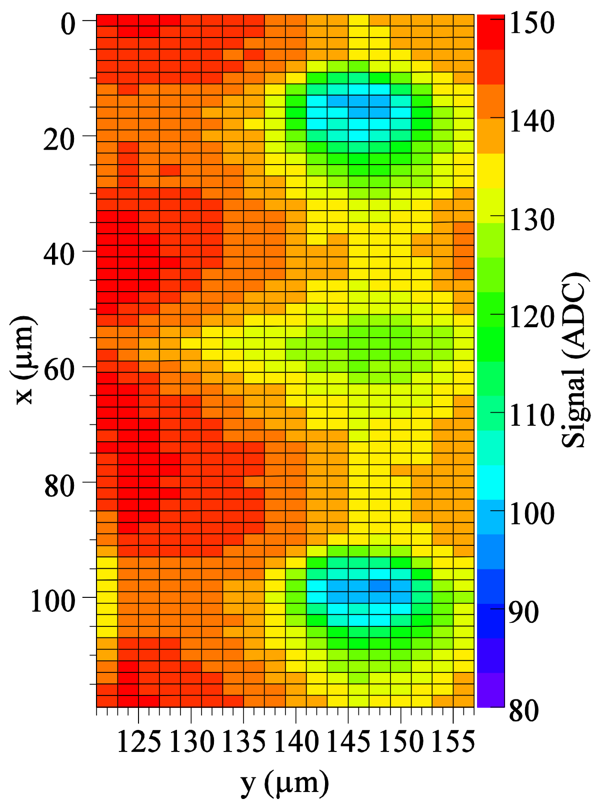
- Precision scans of the pixel performed, charge deposition mapped
  - Full charge collection from 35*μm* active Si above column
- High efficiency across pixel matrix
  - 93.0±0.5% @ 0°, **Full pixel efficiency, 99.8±0.5%,** at an angle of 10°
- Large decrease in charge sharing compared to planar
  - MIPs that create clusters in sensor: 59% in planar, 14% in 3D
- Good electrical performance after irradiation
  - inter-strip resistance of 100MΩ
- Higher collected charge at modest voltages for 3D
  - **47% of Q_o collected in 3D @150V, 30% in planar @1,000V**
- Charge multiplication in 3D irradiation device.
- Spatially resolved laser scanning uniform charge collection after irradiation
- Simulations can predict charge multiplication in irradiated devices

Mapped CCE with scanned laser

Laser scanning

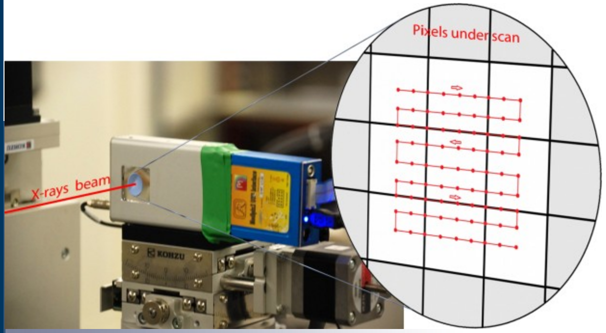
Bias:150V
Fluence: $1x10^{15}$ 1 MeV n_{eq} cm^{-2}
Sr-90 measured ~100% of Q_o collected



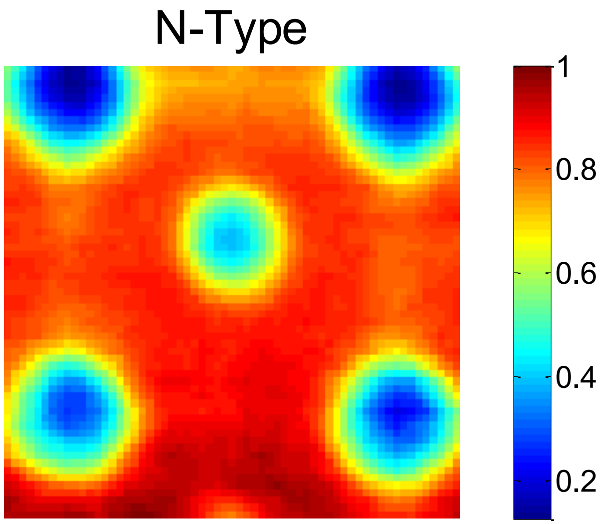


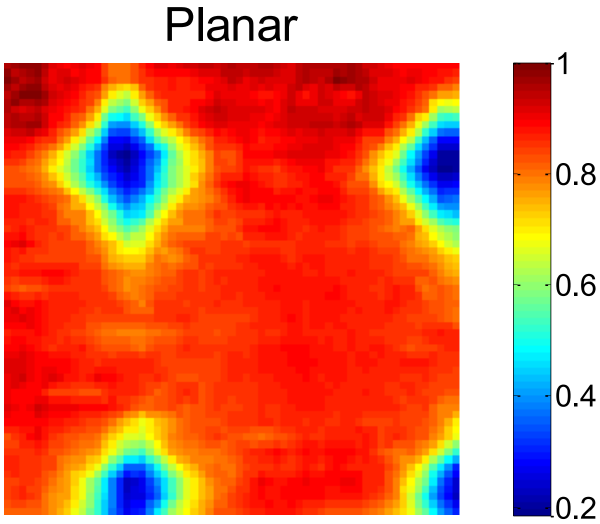
- Two p+ columns evident
- Non-uniform charge collection outside of column position
- Area of low charge collection between the n+ contacts were a low field is present
- Low field areas have greater probability of charge trapping

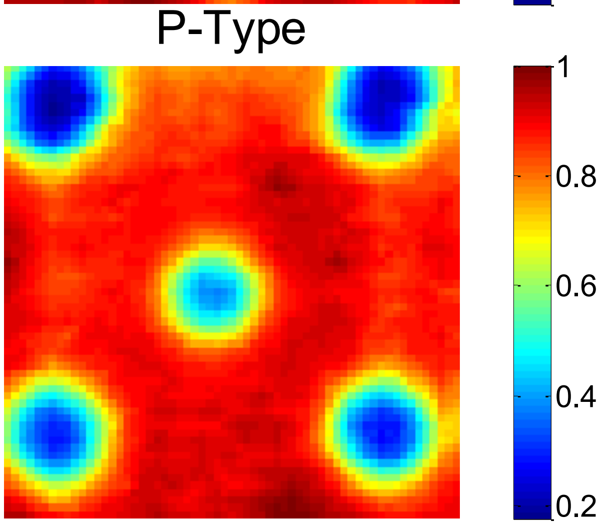
X-ray test beam: Pixel Maps



- **77.5μm square scans**
- **2.5μm steps**
- **Background subtracted**
- **Interpolated**







University of Glasgow

TCAD model physics used

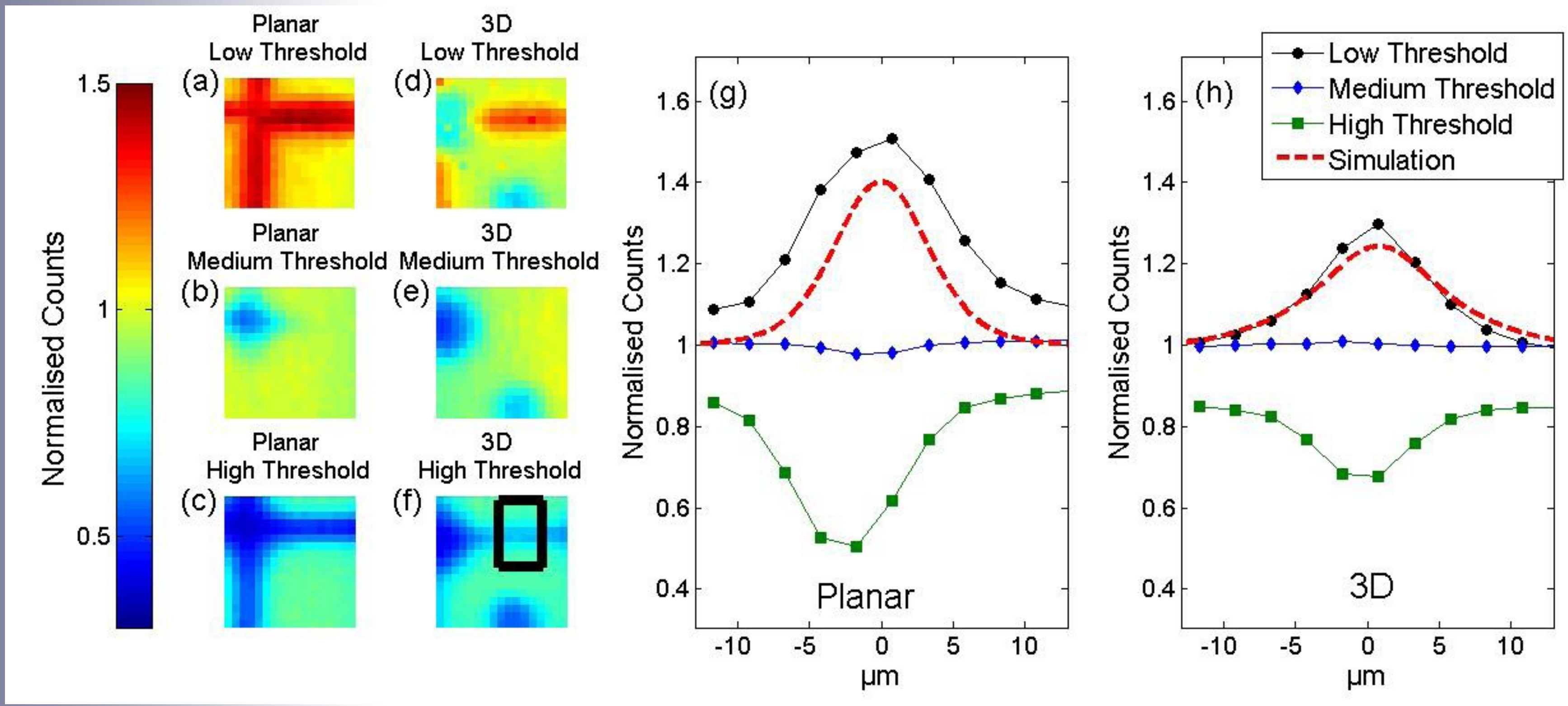
Physics	Model
Mobility	Doping dependance, High Electric field saturation
Generation and Recombination	Doping dependant Shockley-Read-Hall Generation recombination, Surface recombination model
Impact ionization	University of Bologna impact ionization model
Tunneling	Band-to-band tunneling, Hurkx trap-assisted tunneling
Oxide physics	Oxide as a wide band gap semiconductor for mips (irradiated), interface charge accumulation
Radiation model	Acceptor/Donor states in the band gap (traps)

P-TYPE RADIATION DAMAGE MODEL

Defect's energy (eV)	Introduction rate (cm^{-1})	Electron capture cross-section (cm^{-2})	Hole capture cross-section (cm^{-2})
$E_c - 0.42$	1.613	2.e-15	2e-14
$E_c - 0.46$	0.9	5e-15	5e-14
$E_c - 0.10$	100	2e-15	2.5e-15
$E_v + 0.36$	0.9	2.5e-14	2.5e-15

J.P. Balbuena et al., 6th Trento Workshop 2011

X-ray test beam: Charge Sharing



Precision scans of the Pixel cell response of double sided 3D Pixel detectors to pion and X-ray beams. 2011 JINST 6 P05002

SI Beam Telescope

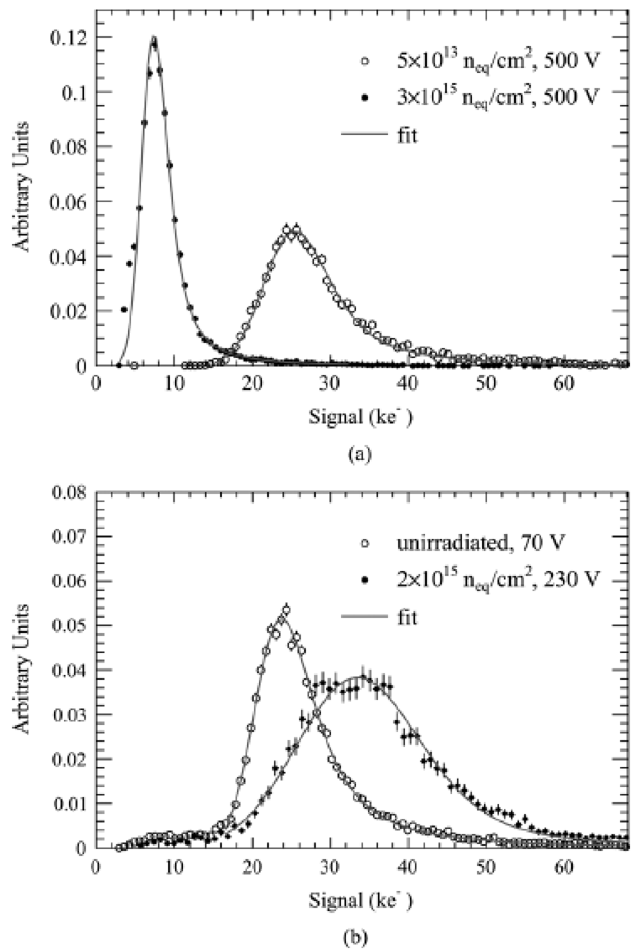


Fig. 2. Normalized signal distributions for different irradiation fluences (a) measured with planar detectors and (b) measured with 3D detectors. The fit superimposed is a convolution of a Landau function and a Gaussian.

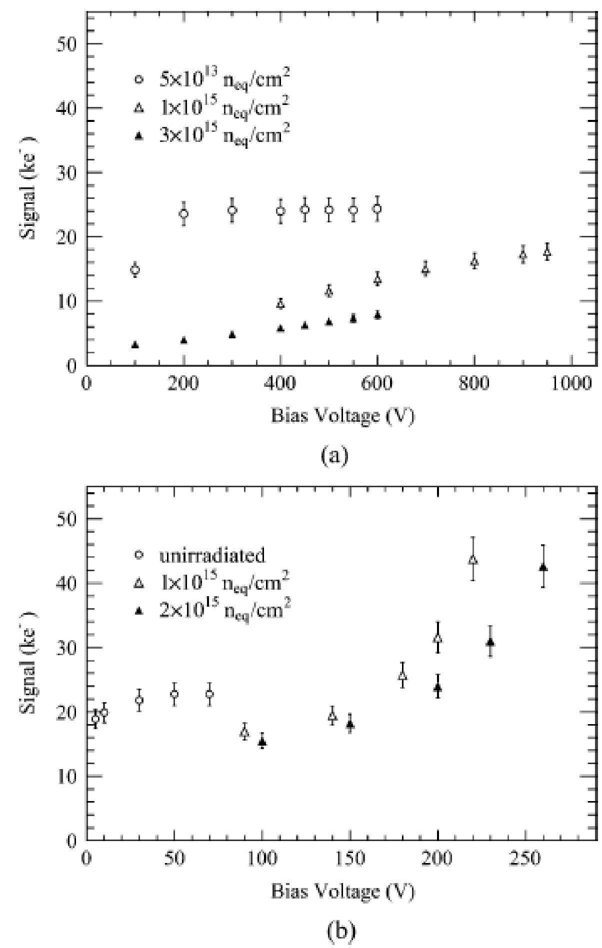


Fig. 3. Signal as a function of the applied bias voltage for different irradiation fluences (a) measured with the planar sensors and (b) measured with the 3D sensors. The errors are dominated by a systematic contribution due to the calibration uncertainty.

Beam Test Measurements With Planar and 3D Silicon Strip Detectors Irradiated to sLHC Fluences. Submitted to IEEE Trans. Nucl. Sci., DOI 10.1109/TNS.2011.2126598

Irradiated devices: double depletion

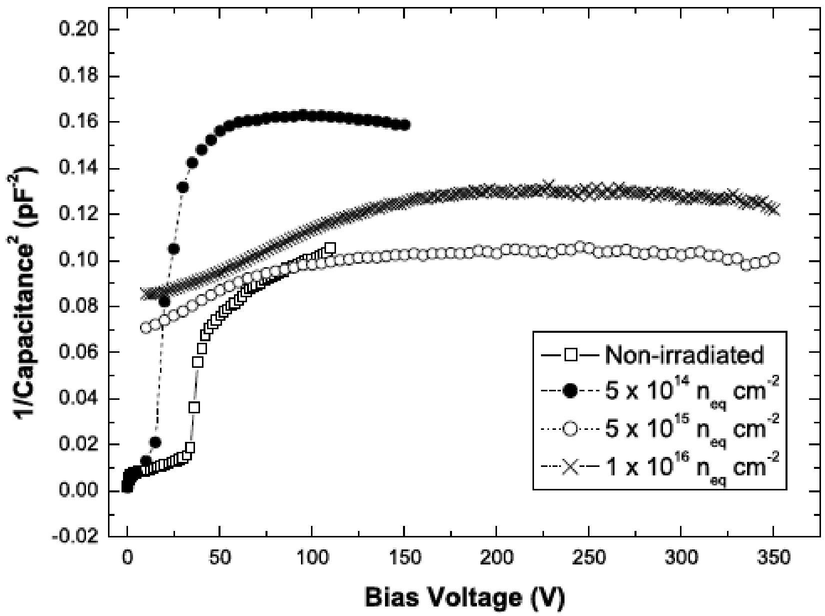


Fig. 6. Strip to back plane capacitance as a function of bias voltage measured after four different irradiation levels, namely; 0, 0.5, 5 and 10 x 10^{15} cm^{-2} 1 MeV n_{eq}. The four curves are labeled on the figure.

Charge collection studies and electrical measurements of heavily irradiated 3D Double-Sided sensors and comparison to planar strip detectors. R. Bates et al., submitted to IEEE