Charge collection efficiencies of 3D detectors irradiated at SLHC fluences and testbeam operation results

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

Part of this work has been conducted in the framework of RD50 Collaboration

Outline

Introduction

- Motivation
- CNM Double-sided 3D detectors

Annealing studies

- Electrical characterization

Alibava system

- Set-up and calibration

Charge collection in strip 3D

- Response to Sr-90 electrons
- High bias operation

Test beam measurements

- Diamond light source synchrotron (Medipix2)
- Test beam at SPS CERN (Timepix)
- Test beam of irradiated strip detectors (preliminary)

Future work and Summary

Radiation-hard detectors for the (s)LHC

ATLAS Forward Physics programme (≈2012)

- Fluence ~ **1 x 10^{15} 1MeV neq/cm2**

Inner pixel layer (IBL) replacement for ATLAS (≈ 2014)

- Fluence of **4.4 x 10^{15} 1MeV neq/cm2**

Super-LHC GPD pixel detectors (≈ 2017)

- 10 * luminosity upgrade on present LHC
- Fluence up to ~ **1 x 10^{16} 1MeV neq/cm2**

LHCb VELO upgrade (≈ 2016)

- Integrated fluence ~ **1 x 10^{16} 1MeV neq/cm2**

Design fluences for ATLAS sensors (includes 2x safety factor) **:**

Innermost Pixel Layer ~ 5cm radius :**1.6 x 10^{16} 1MeV neq/cm^2** = 500 Mrad

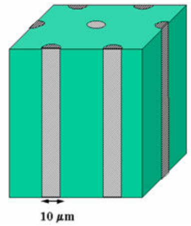
Outer Pixel Layers ~ 30cm radius: 3 x 10^{15} 1MeV neq/cm^2 = 150 Mrad

3D Detectors

Array of electrode columns passing through substrate
Electrode spacing << wafer thickness (e.g. 10μm:300μm)
Benefits:

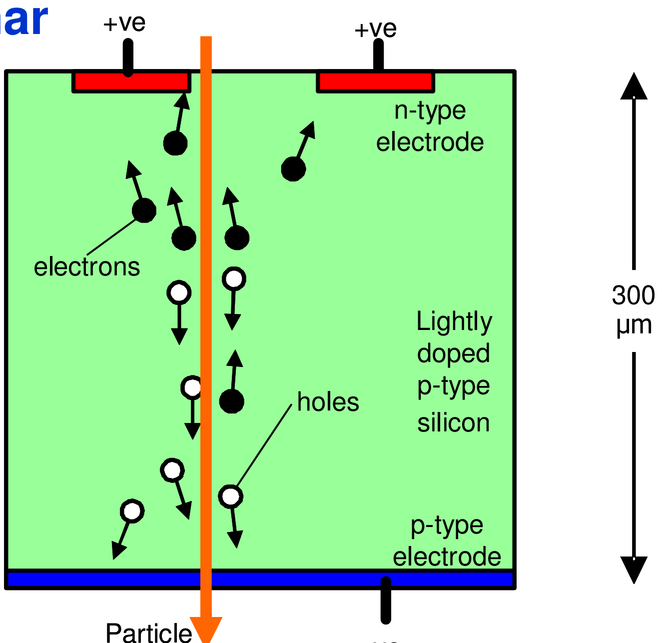
- Low full depletion voltage
- Fast collection times → Reduced charge trapping
- Reduced charge sharing due to E-field shape → Higher signal in one pixel

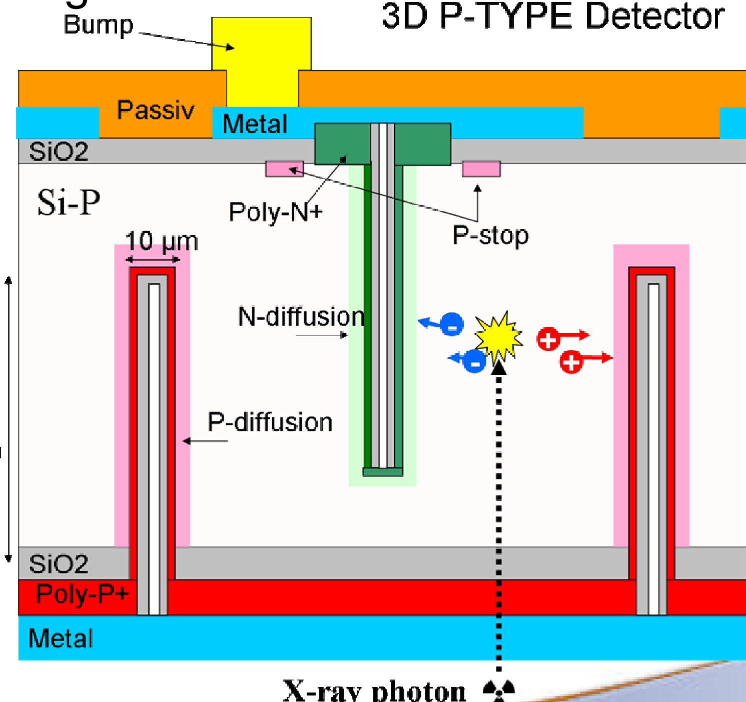
More complicated fabrication - micromachining



First proposed by Parker *et al.* Nucl. Instr. Meth. A, 395 (1997) 328

Planar



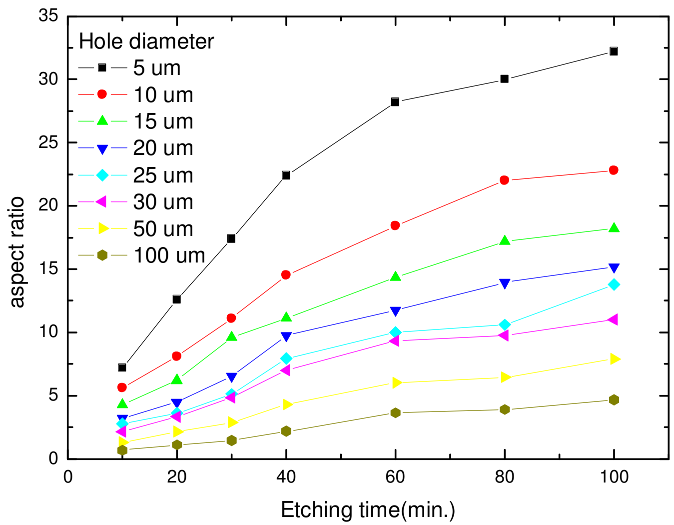


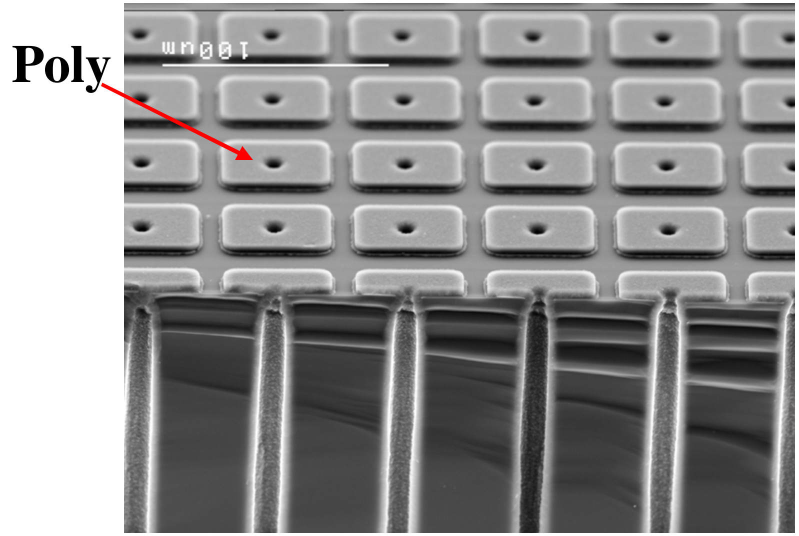
Double sided 3D

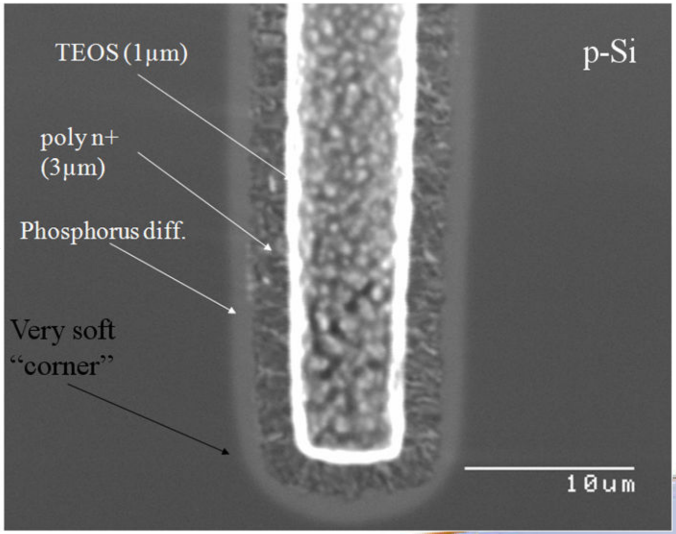
G. Pellegrini et al. NIMA Volume 592, Issues 1-2, 11 July 2008, Pages 38-43

3D Electrodes

Hole aspect ratio up to 25:1 (columns are 10µm diameter, 250µm deep)







Electrode fabrication:

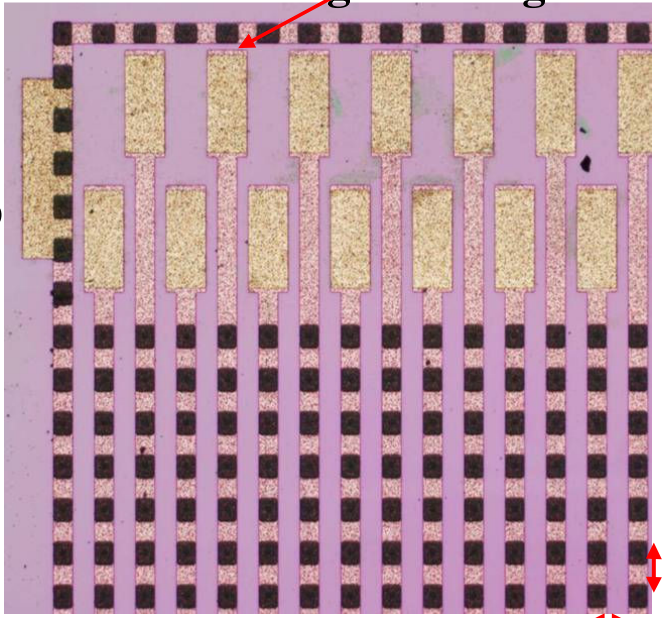
1. **ICP etching of the holes: Bosch process, ALCATEL 601-E**
2. **Holes partially filled with 3 µm LPCVD poly**
3. **Doping with P or B**
4. **Holes passivated with 1 µm TEOS SiO_2**

CNM Double-sided 3D fabrication runs

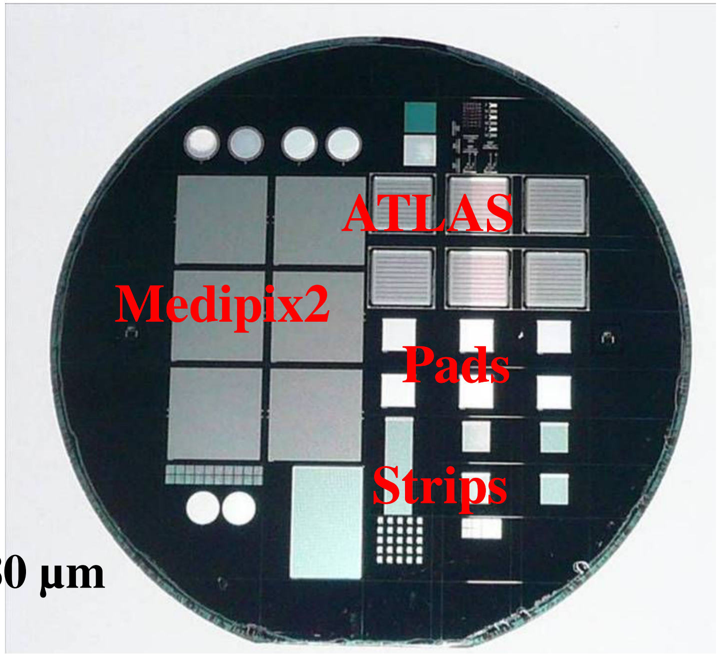
- Hole aspect ratio 25:1
- 10µm diameter, 250µm deep
- p-type and n-type substrates 285µm thick.
- Only one guard ring 10um wide

Devices designed at Glasgow & CNM
Fabricated at CNM

50 strips
DC coupled
50 electrodes/strip
4mm long strips



CNM 3D-wafer



4 inch wafer

Devices

- **n^+ strips**
- **p^- bulk**
- **p^+ back contact**

ICP is a reliable and repeatable process (many test runs always successful).
Yield: Strip detectors = 88%. ATLAS pixels = 50%

Irradiations

Short strip detectors

- Electron collecting,
  n^+ readout columns

Irradiated at Karlsruhe with 26 MeV protons. Irradiated cold but not biased.

No intentional annealing

- max 5 days RT

Detectors glued to Ceramic base boards

- RC pitch adaptors from VTT/Helsinki Institute of Physics

Fluence (1 MeV neq/cm^2)

- **5E14**
- **1E15**
- **2E15**
- **5E15**
- **1E16**
- **2E16**

26 MeV protons scaled to
1 MeV neutron equivalent fluence
with a hardness factor of 1.85

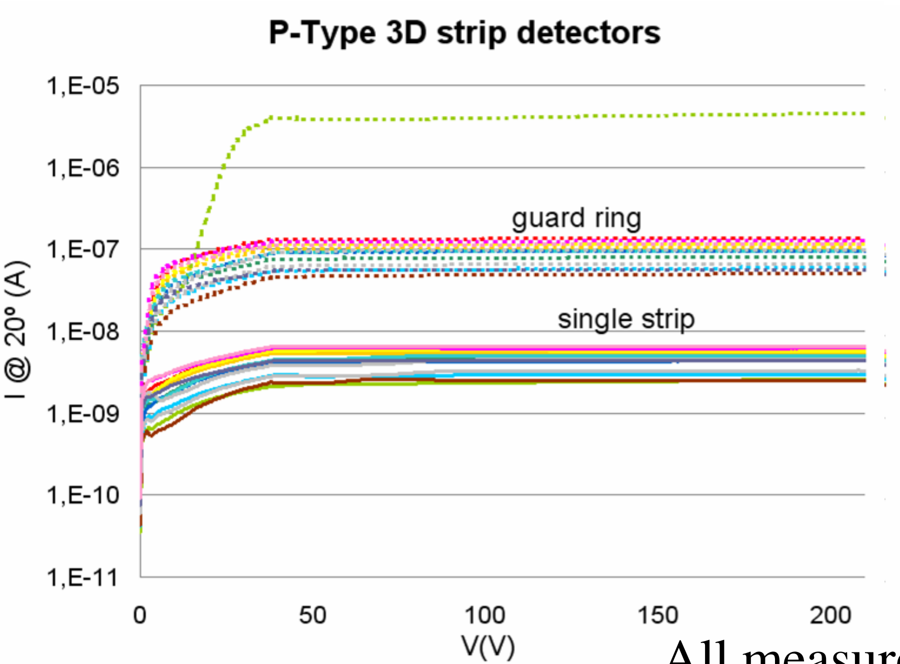
Strip detectors

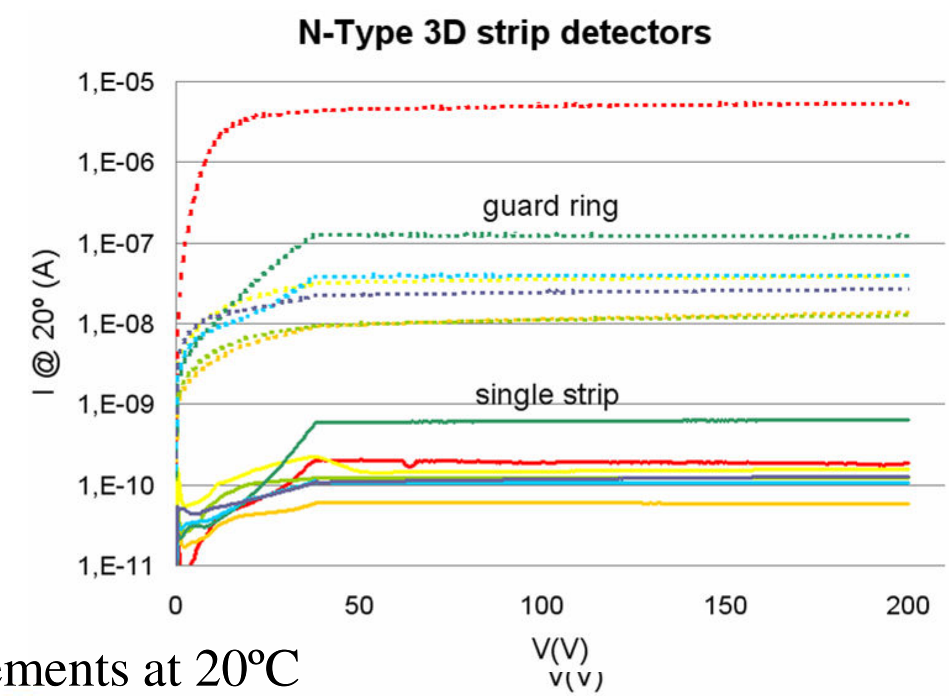
P-type

- VFD ~ 40V
- 2 – 6 nA/strip, very homogeneous between wafers
- Only 2 detectors (of 16 tested) with breakdown < 50V -> yield 87.5%

N-type

- VFD ~ 10V
- 0.1 – 0.6 nA/strip
- Currents less homogeneous and stable than in the ptype
    - Beneficial effect of p-stops in the ptype sensors or effect of dopant profiles?
- 3 detectors (of 10) with BD < 50V -> yield 70%





All measurements at 20ºC

R8

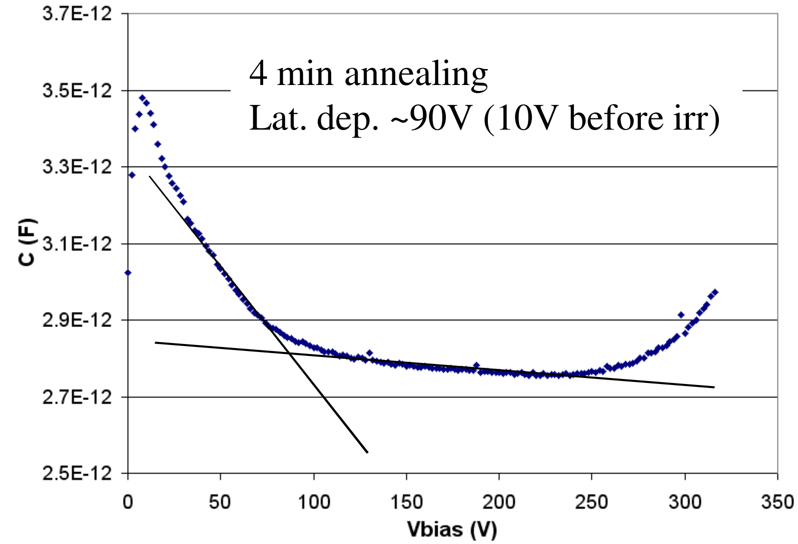
Irradiation and annealing studies

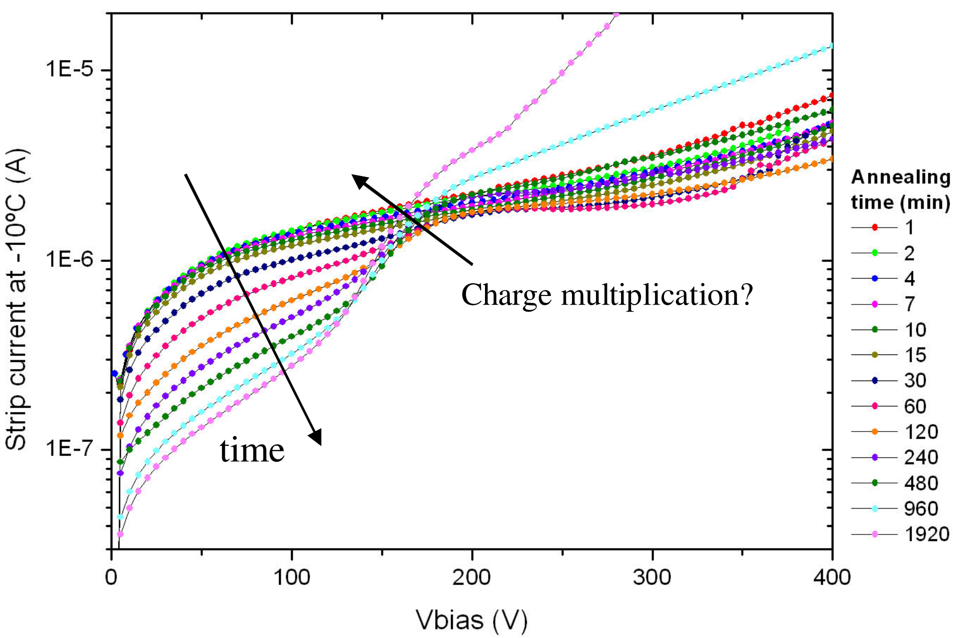
P-type strip detector irradiated with 26 MeV protons to 1E16 neq/cm²

Tested at -10ºC in probe station

Accelerated annealing at 80ºC

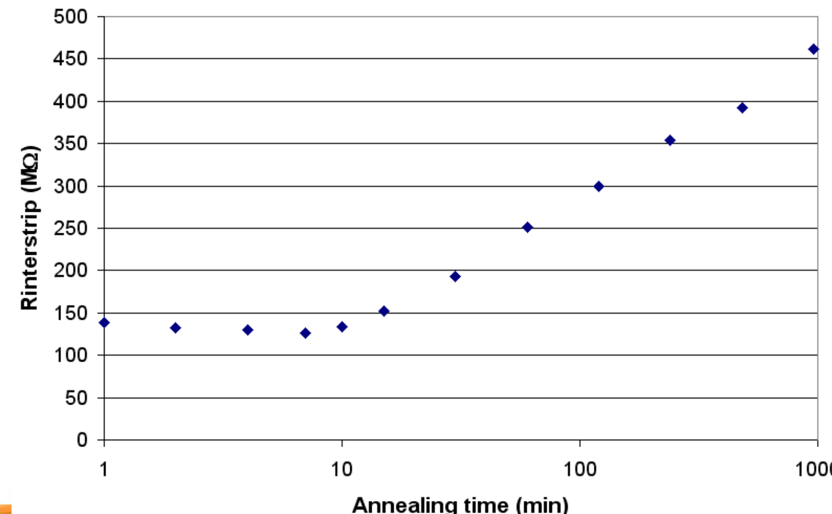
- Acceleration factor of 7400 for the reverse annealing with respect to RT





Annealing of interstrip resistance at 100V

Non-irradiated sensor @20º: ~100GΩ



Slide 9

R8 This is very interesting.
I wonder if a "real" semi-conductor expert should look at this. Maybe Erermin?
Richard, 2/11/2010

Alibava system - Hardware

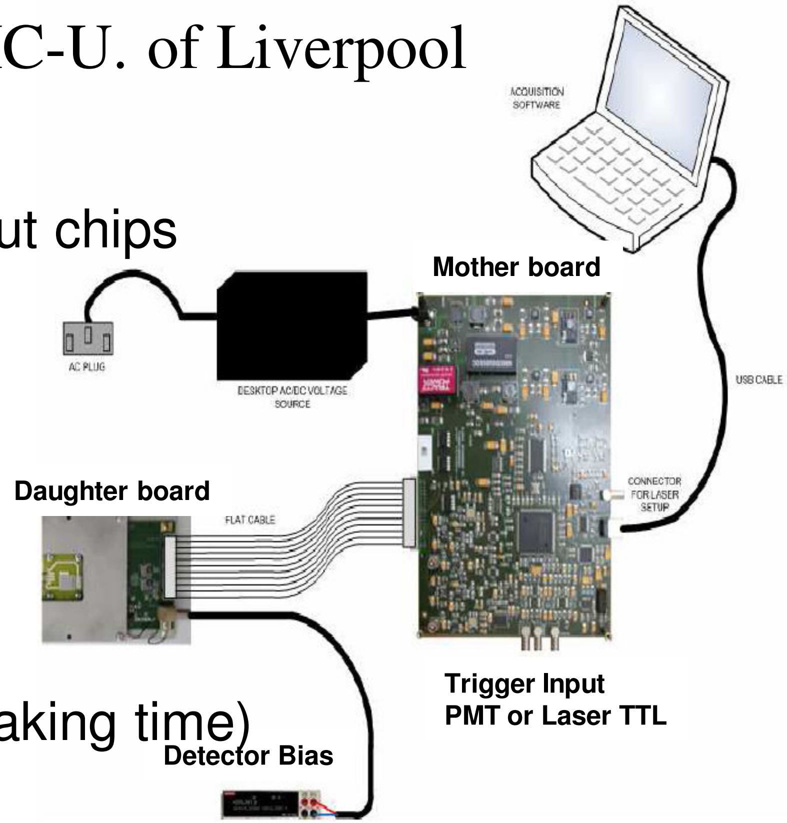
CNM-IFIC-U. of Liverpool

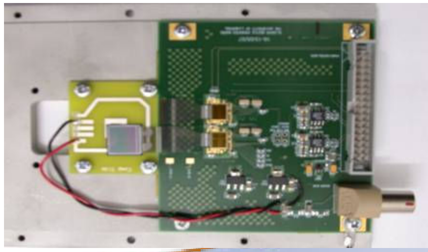
Mother Board
- Control Beetle chips
- Trigger on PMT signal
- Process analogue data from readout chips
- Communicate with a PC via USB.

Daughter board
- Two Beetle readout chips
- Re-bondable fan-ins
- H.V. filter operational to 1kV

Beetle front end (from LHCb)
- LHC speed bi-polar amplifier (25ns peaking time)
- Full analogue readout

Rest of hardware
- Collimated Sr-90 source above the detector
- Scintillator with PMT trigger below the detector
- Everything in a freezer with dry air and monitoring

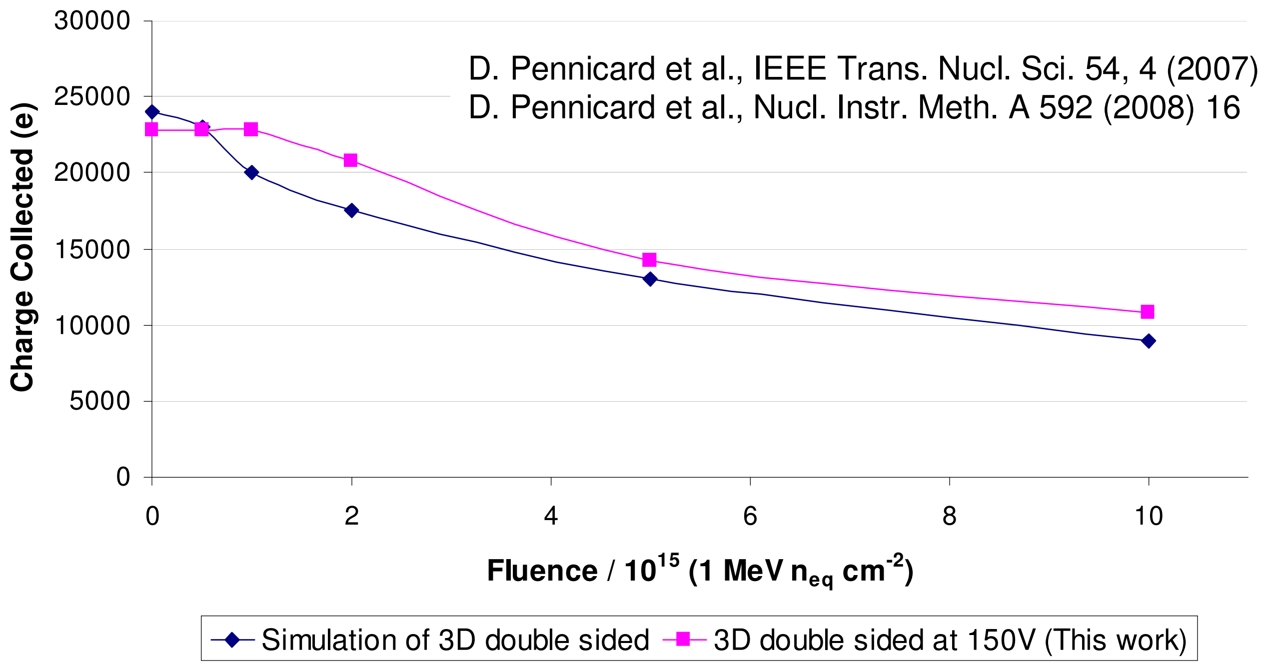




R.Marco et al, IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 56, NO. 3, JUNE 2009

Collected charge for irradiated devices

Electron collecting strip detectors



Bias Voltage fixed at 150V for all irradiated samples

Non-irradiated sample biased at 18V

Detector's ceramic based board temperature between -10℃ to -15℃

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

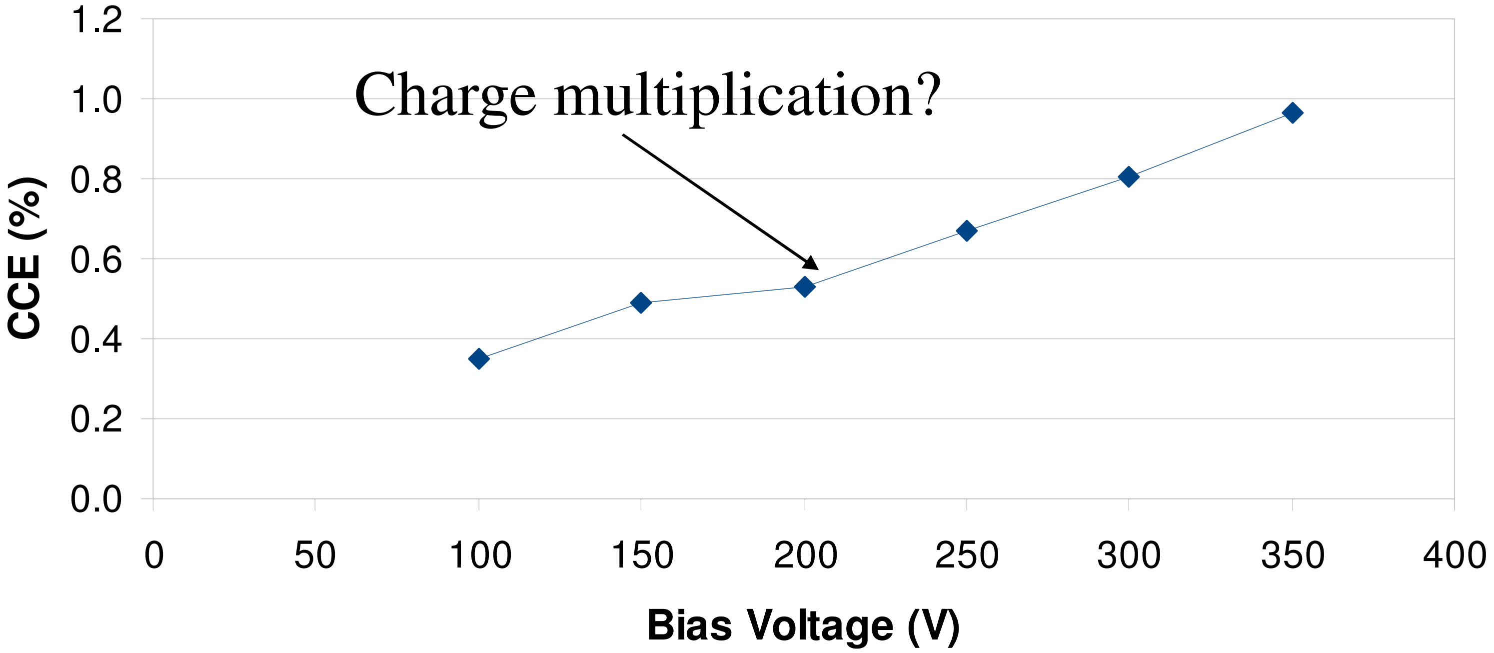
Slide 11

R10

I would make a clearer note that this both data and simulation.
I would make it clear that the Pennicard references are for the simulation only
Richard, 2/11/2010

CCE with increasing bias voltage

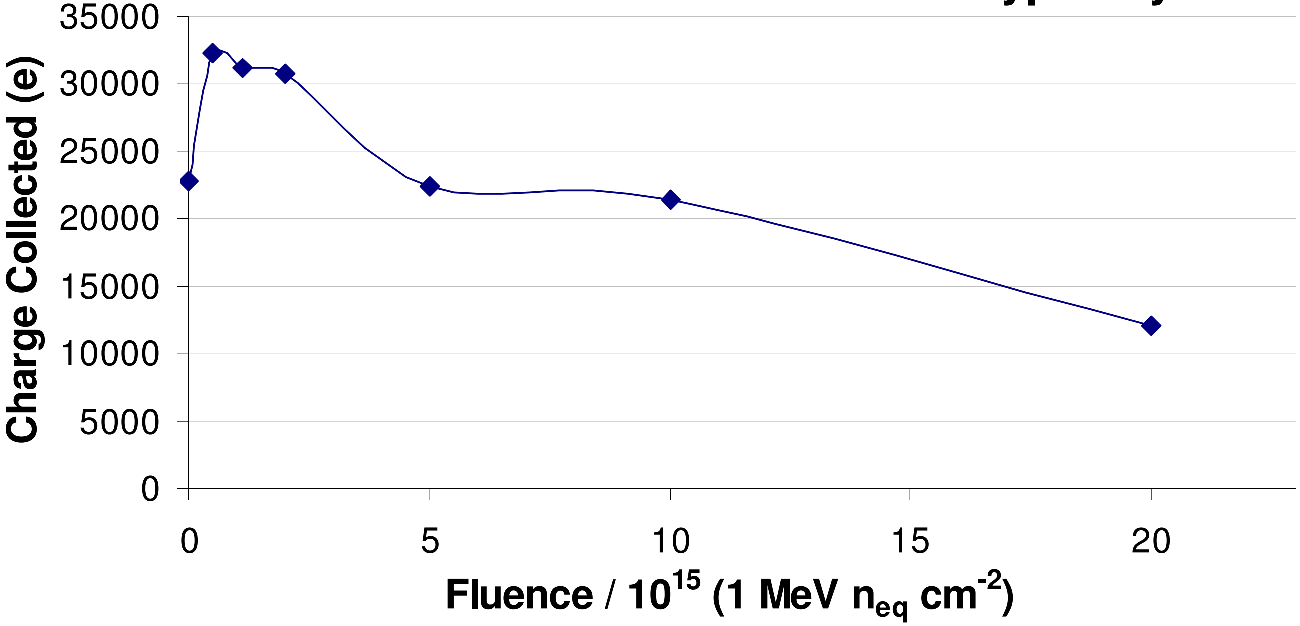
Detector response after a fluence of 1×10^{16} 1 MeV n_{eq} cm^{-2}



For comparison with planar devices: I. Mandic et al. NIMA Volume 603, Issue 3, 21 May 2009, Pages 263-267

High bias operation

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



- Increased CCE for high fluences > 5 x 10^{15}

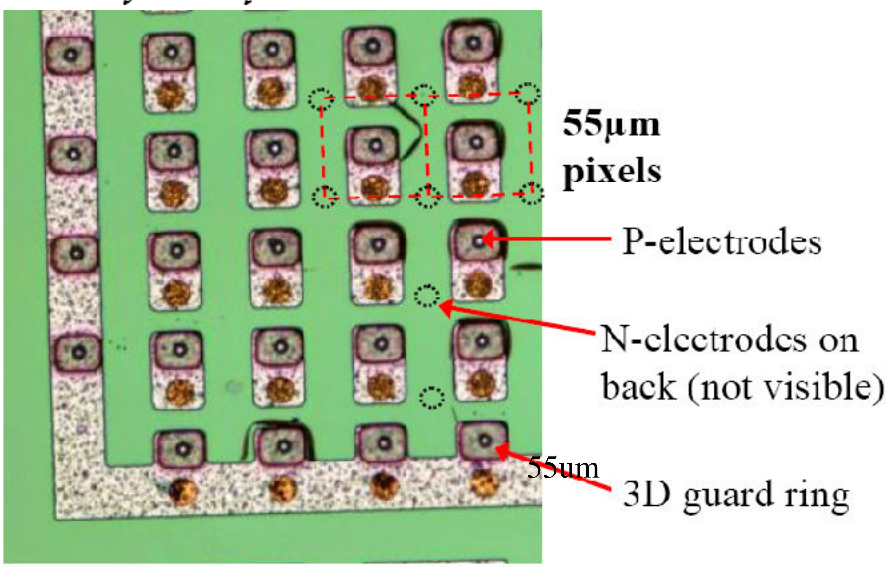
  Close to 100% CCE for 10^{16} 1 MeV n_{eq} cm^{-2}

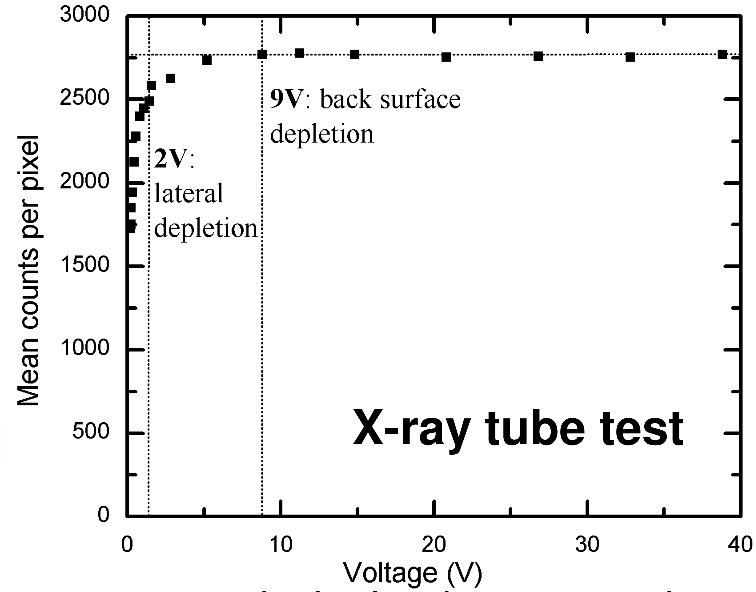
- More than 100% CCE for fluences 0.5 to 2 x 10^{15} 1 MeV n_{eq} cm^{-2} !!
- Possible charge multiplication observed (?)

  Observed in heavily irradiated planar devices with kV bias

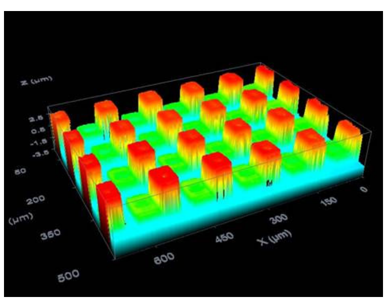
Medipix 2 – 3D

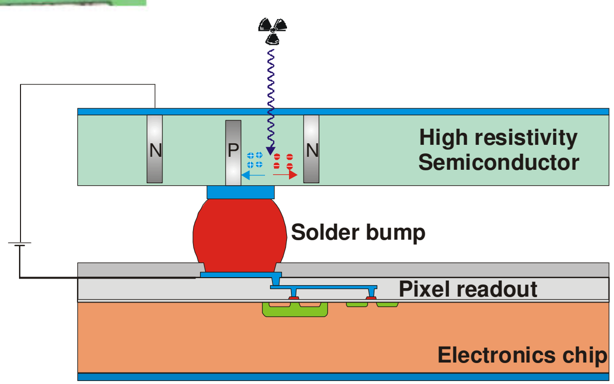
Surface of 3D detector





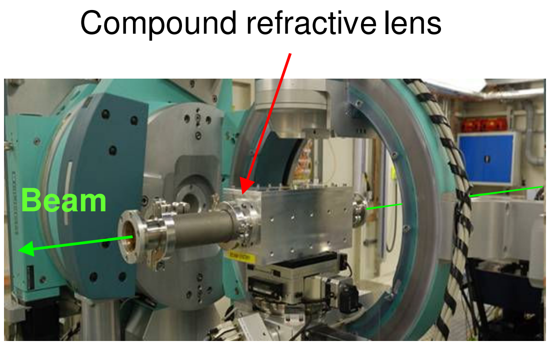
- 65k single-photon counting pixel array
- Square pixel size of 55µm
- Area=1,4 x 1,4 cm^2
- Electron or hole collection
- Threshold equalisation
- Count rate of ~100kHz
- Readout in 300μs
- High dynamic range

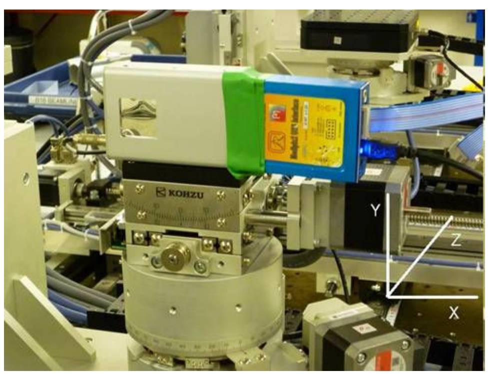




3D double side compatible with standard pixel read out electronics.
High voltage on the back of the pixels like in planar devices.

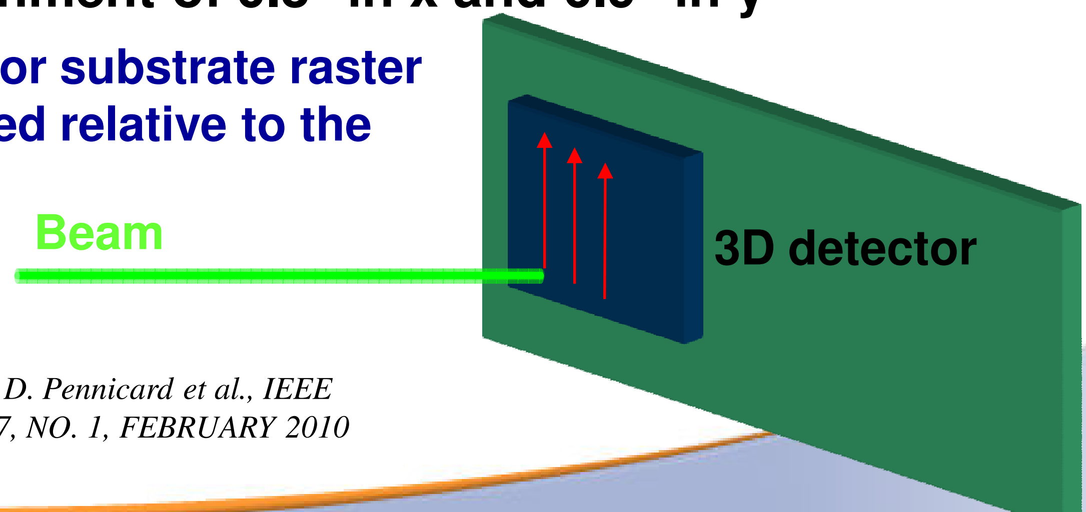
X-ray Beamline Set-up





- B16 Test beamline at the Diamond
- Monochromatic X-ray beam of 14.5keV
- 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 0.3^{o} in x and 0.9^{o} in y

Detector substrate raster scanned relative to the beam

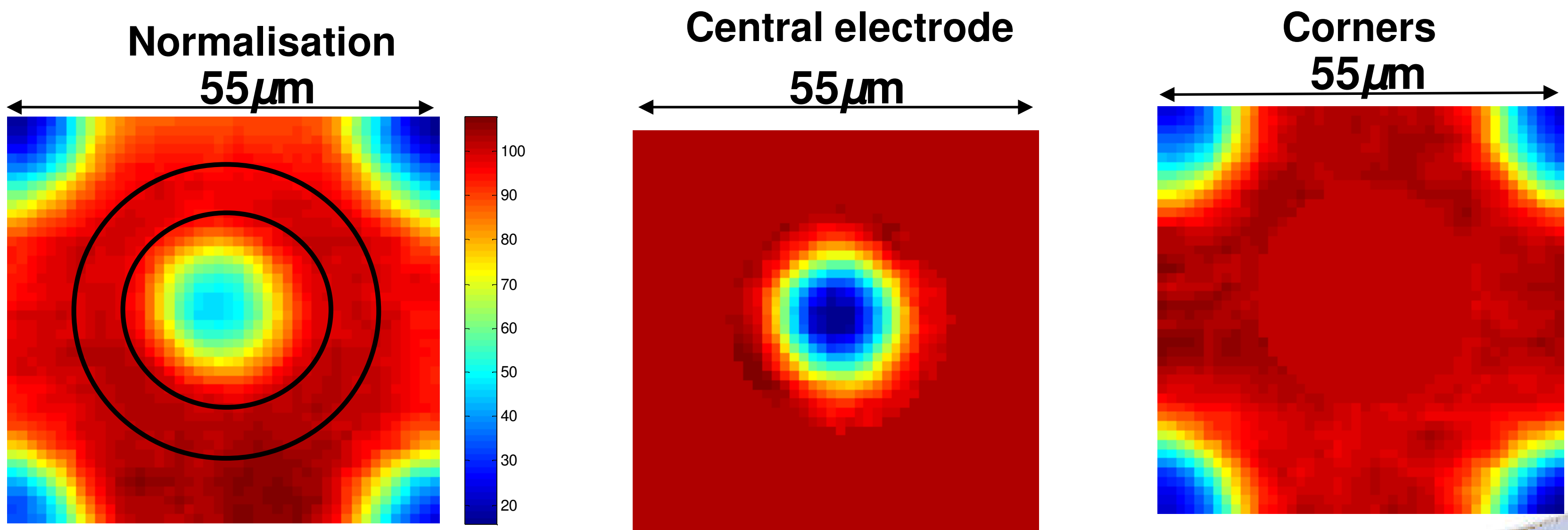


Synchrotron Tests of a 3D Medipix2 X-Ray Detector, D. Pennicard et al., IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 57, NO. 1, FEBRUARY 2010

Detection Efficiencies

THL ~ 50% of beam energy

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



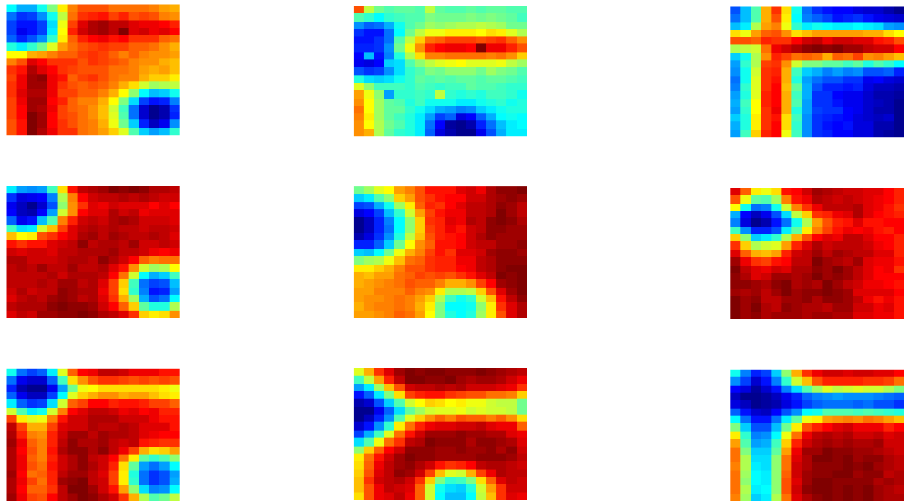
***efficiencies at the corners due to electrodes structures and charge sharing**

Charge Sharing

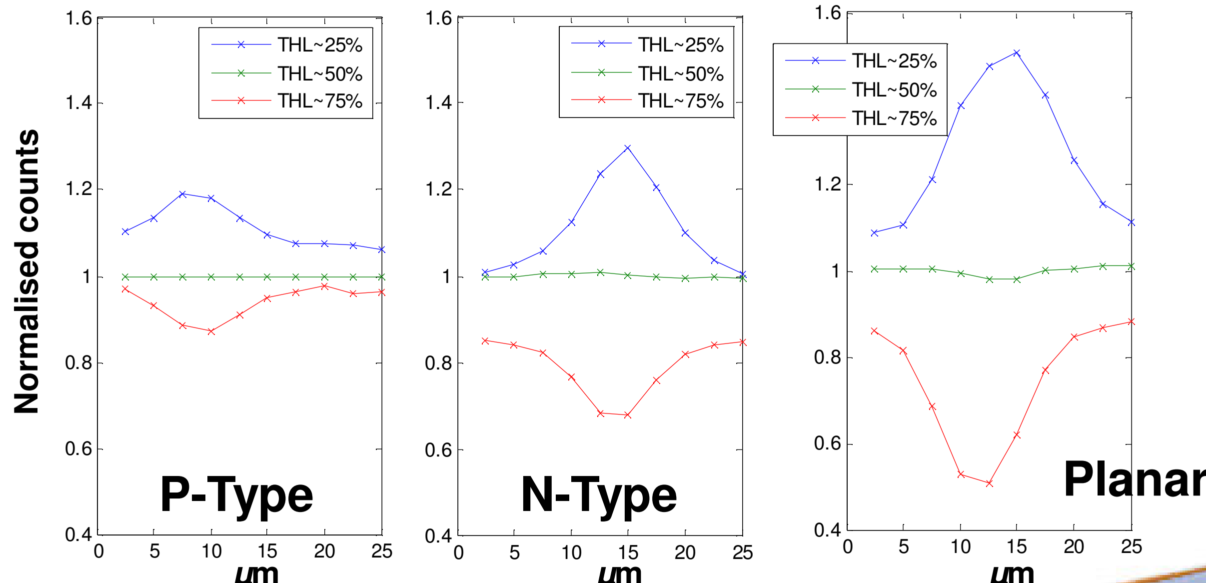
THL~25%

THL~50%

THL~75%



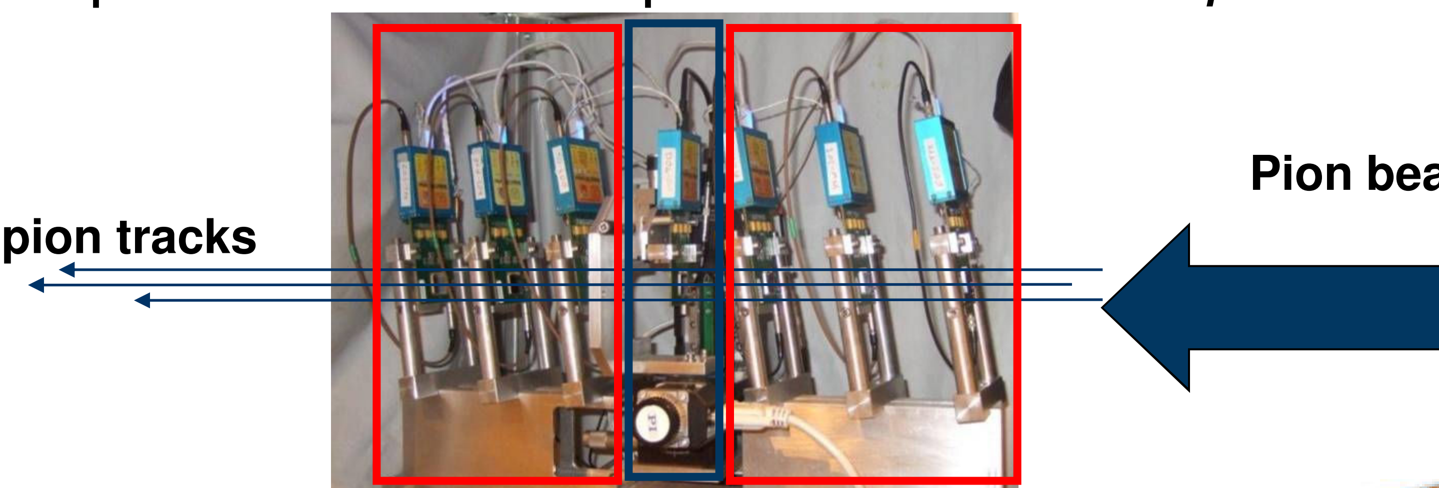
Reduced level of over counting and under counting in 3D



MIP beam from SPS

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
- Expected track extrapolation error: < 3 μm



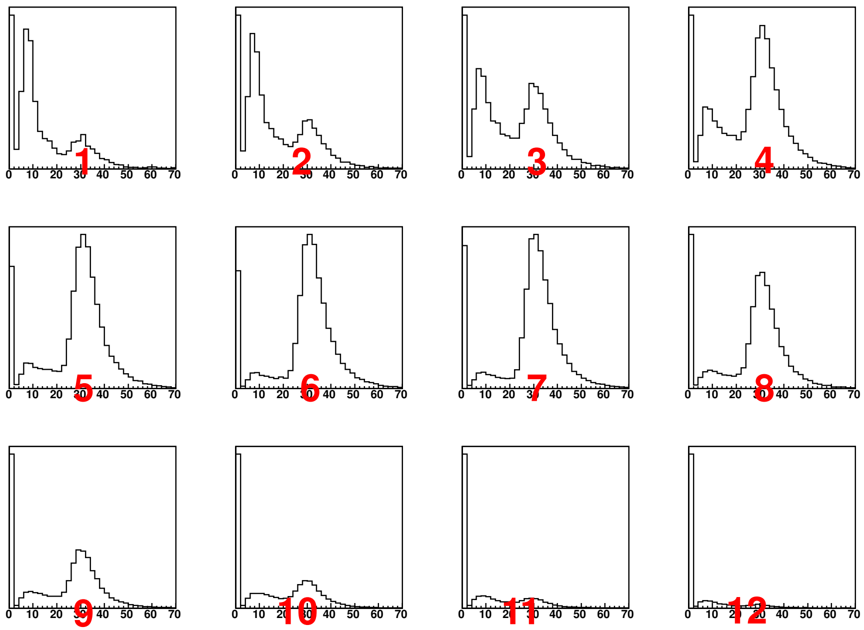
Slide 18

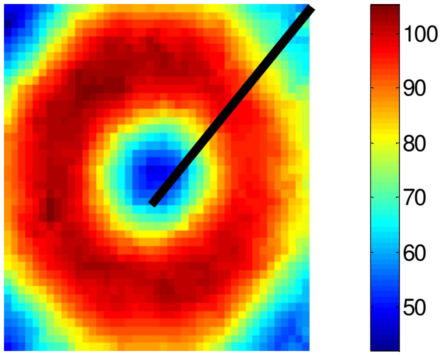
R11 MIP beam test from SPS of 3D Medipix2 assembly

Is there room for a longer title as above?
Richard, 2/11/2010

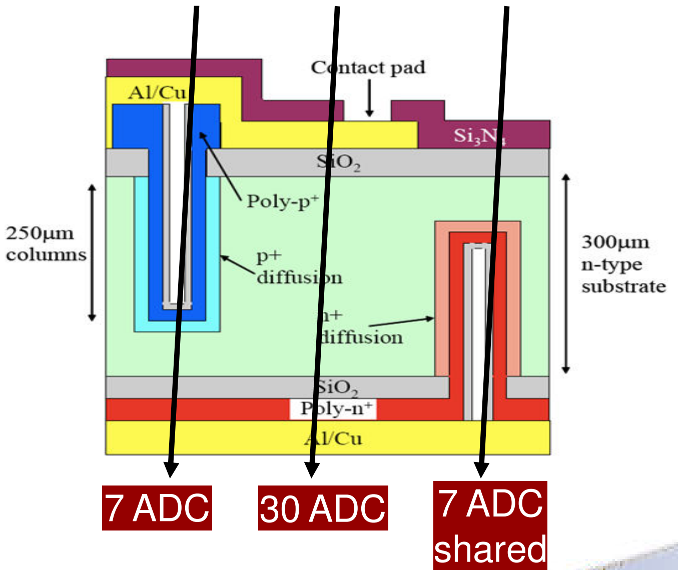
Efficiency – TOT Mode (Energy Spectra)

1-12 show ADC counts at positions along cross section from centre to the corners





Peaks seen at ~7 and ~30 ADC counts

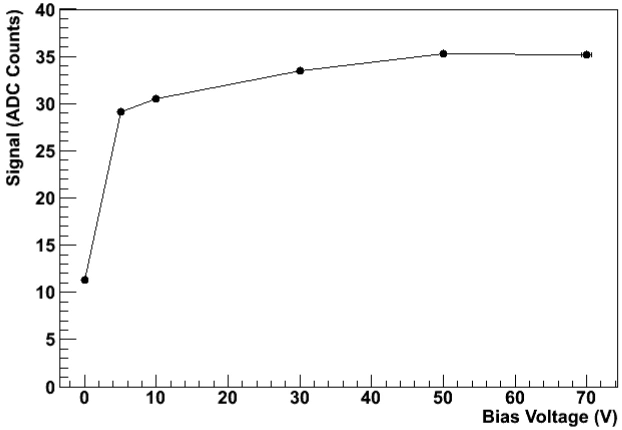


Measurements at 0º. No true with tilting
On going analysis with scans to 10º.

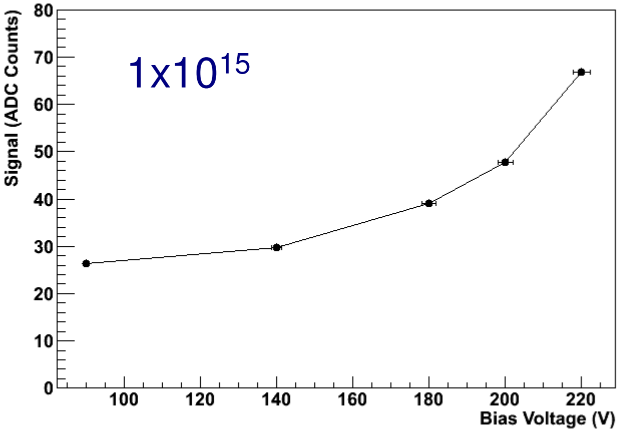
Strip testbeam work

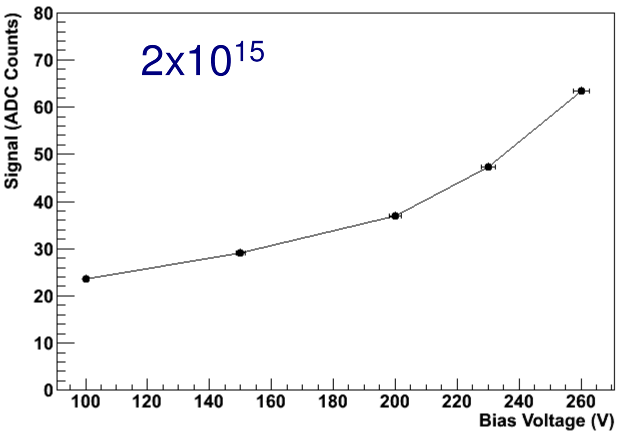
Planar and 3D strip detectors tested with Silicon Beam Telescope (SiBT) with CMS readout (APV25 front end chip) and 50 ns shaping last summer at CERN.

unirradiated



Preliminary





- 1×10^{15}: max. signal ~70 ADC
- 2×10^{15}: max. signal ~65 ADC
- Charge collected in testbeam is very close to lab tests
- e.g. for 1×10^{15} : 100% cce at 150V, 140% cce at 200V
- Strong charge multiplication seen!

Summary

- Post irradiation CCE, measured at 150V:
  - CCE of 62% : 14000 e^- after $5x10^{15}$
  - CCE of 47% : 11000 e^- after $1x10^{16}$
- Charge collection agrees well with simulation prediction
- Double sided 3D suitable for pixels with “short edges” (~10um)-> tiling
- Sufficient charge for ATLAS upgrade scenario
- Operation at -10°C to -15°C is fine
- 3D detectors tested in test beam conditions.
- Technology ready for small-medium production.
- Charge multiplication to be studied, is the same for n-type detectors ?

Double side processing demonstrated to be very reliable and repeatable.

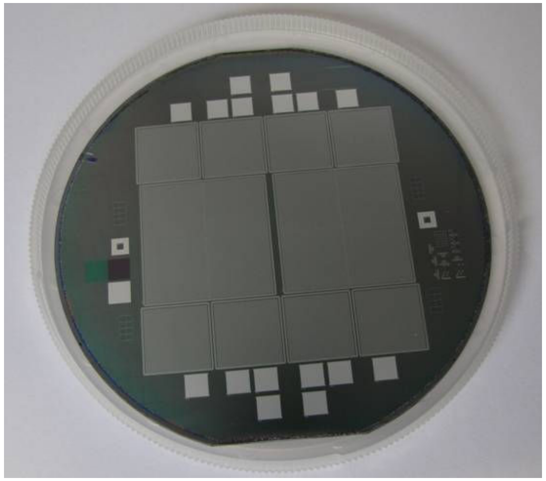
Yield =(number of tested good sensors)/(number of wafers started x number of sensors per wafer) **~ 50% (but not all detector tested and comparing different geometries)**

Slide 21

R13 Do you want to add that with higher biases (but still only 300V) charge multiplication observed and approximatley 100% cce possible after 1E16.
might be worth noteing that noise might also increase in charge multiplication region.
Richard, 2/11/2010

Future Work

- Irradiation and test beams with Timepix detectors for LHCb VELO upgrade.
- Atlas pixels, FE-I3 and new FE-I4 fabrication and irradiation for Insertable B-Layer and testbeam. In the framework of the Atlas 3D collaboration (**http://test-3dsensor.web.cern.ch/test-3dsensor/**).
- New Medipix3 already fabricated, standard ($2cm^2$) and quad area ($8cm^2$).



Backup slide

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