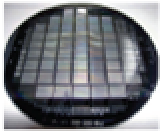
University of Glasgow

The Stanford Nanofabrication Facility



SINTEF

FONDAZIONE BRUNO KESSLER

MTLab
MicroTechnologies Laboratory

3D detectors

Richard Bates

School of Physics and Astronomy, University of Glasgow, U.K.

With many contributions from colleagues working as part of ATLAS 3D, ATLAS IBL and RD50

Vertex 2011, Rust, June 2011.

cnm
Centre Nacional de Microelectrònica IMB

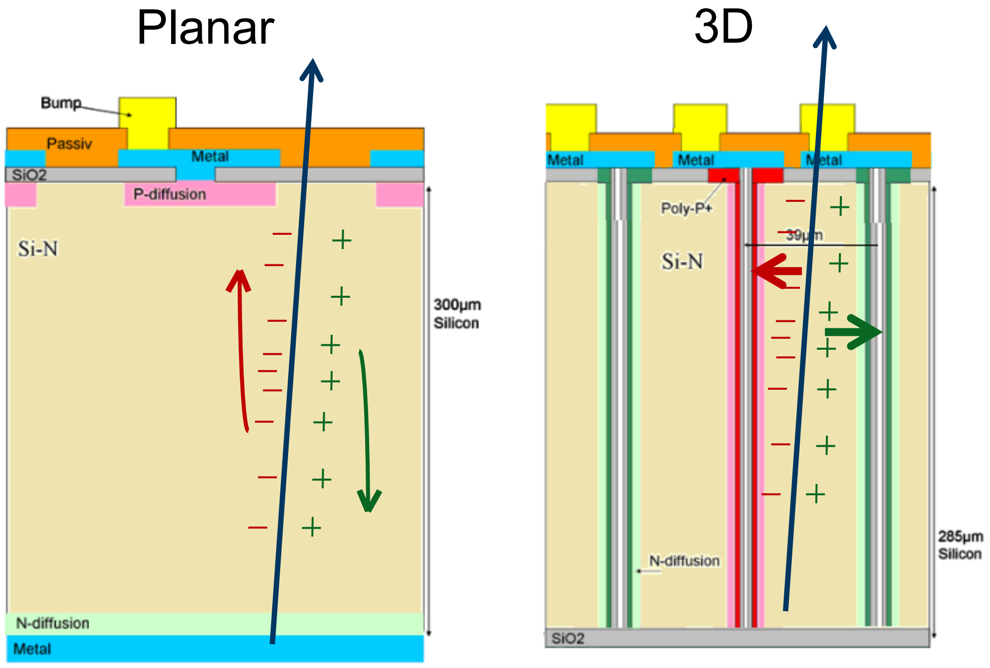
Contents

- Designs
- ATLAS IBL campaign
- Test Beam activity
- Irradiation hardness
- Modelling

3D detector designs

3D sensors

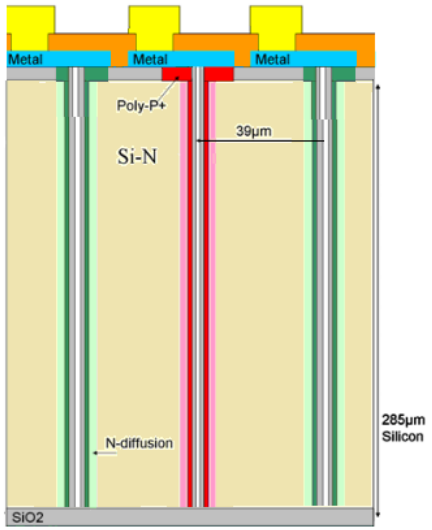
- **Greater signal charge** due to faster collection time (less trapping)
- **Reduced power consumption** due to lower depletion voltages
- **Reduced charge sharing**
- Active edge technology: large-area tiled ‘edge-less’ detectors



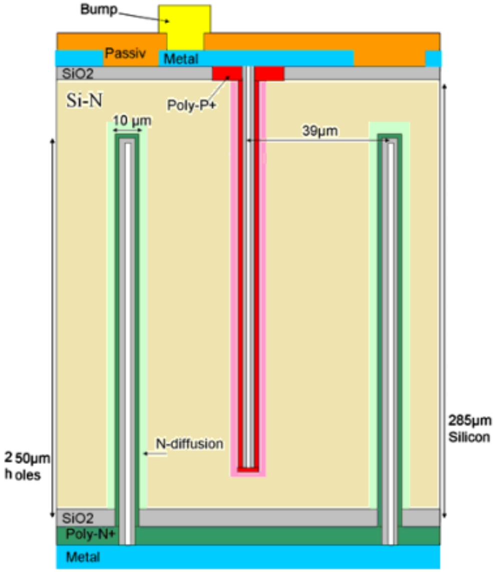
Drawbacks

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

3D sensor designs



Single side full 3D



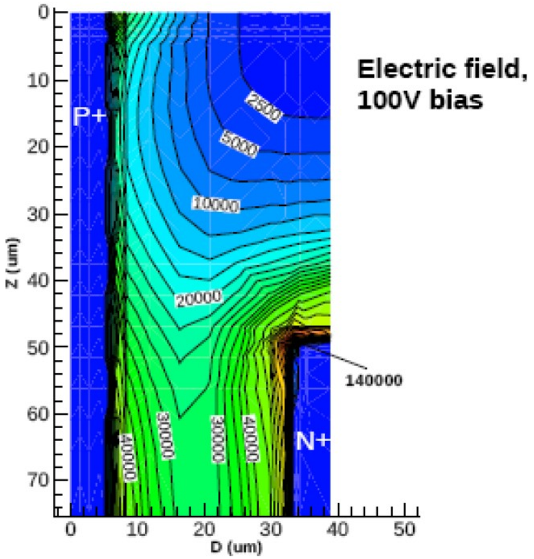
Double-sided 3D

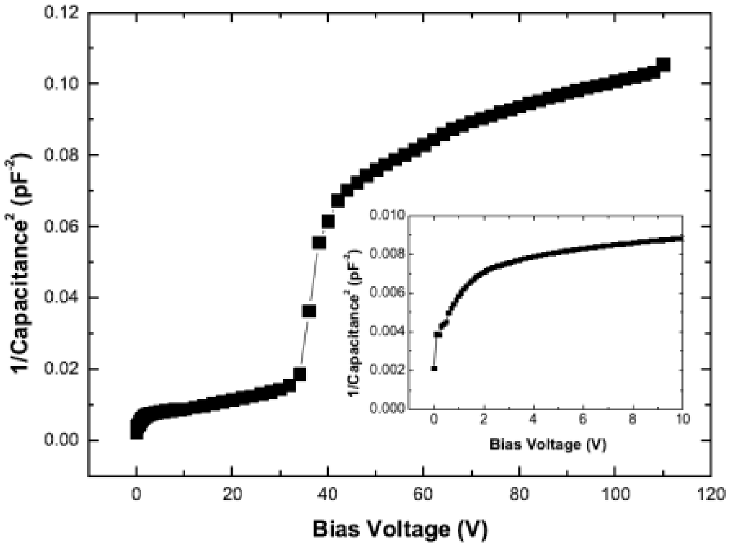
- Reduce fabrication complexity
- Increase yield
- All regions of sensor have active Silicon

__Double depletion__

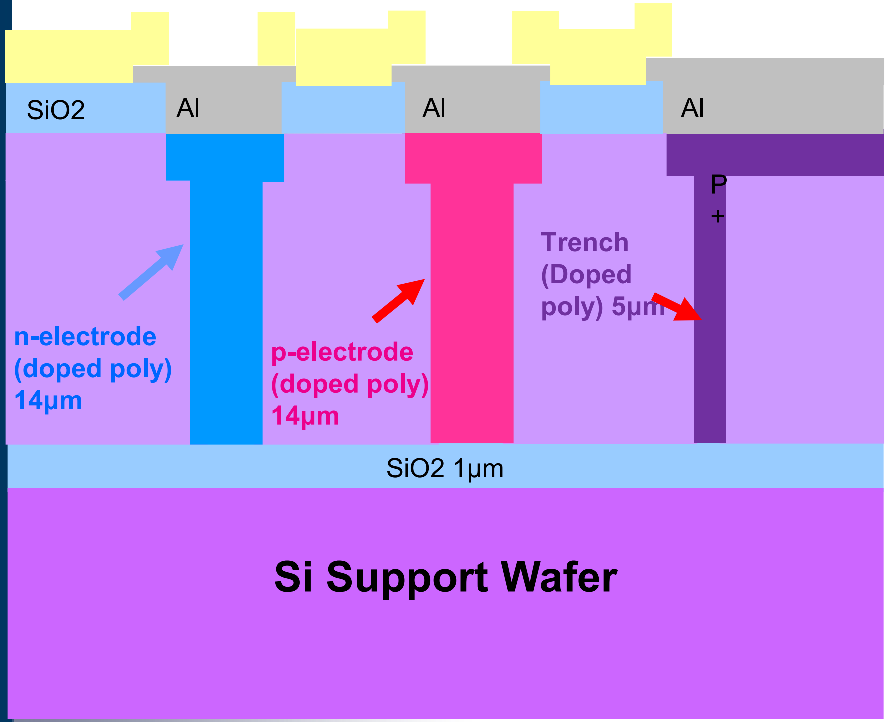
Lateral depletion ~4V

Full depletion~40V





Full 3D



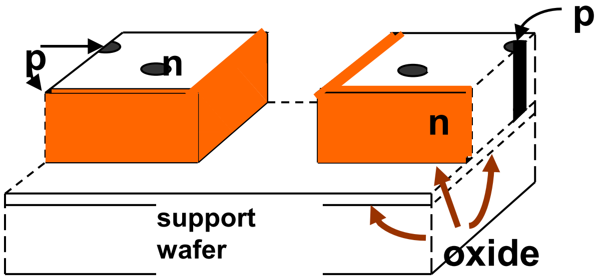
Advantages

- Uniform and high fields throughout device
- Sensitive electrodes
- Active edges

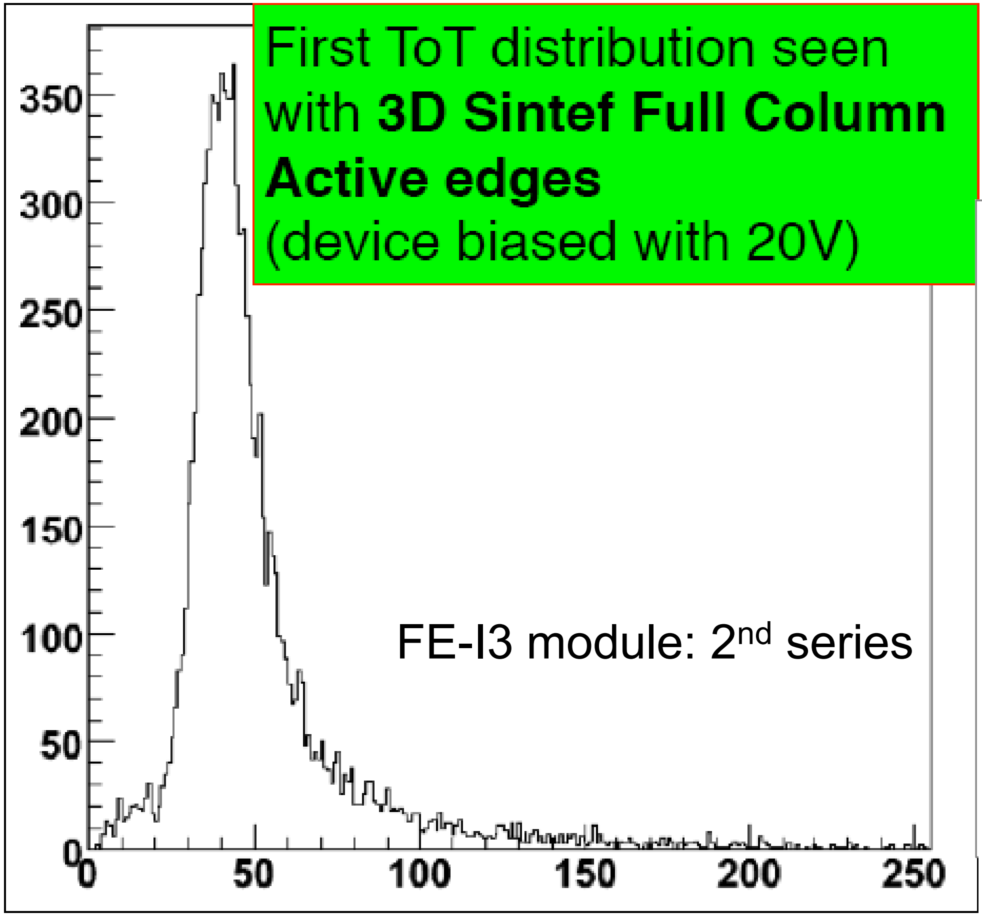
Complexities

- Support wafer
  - Wafer bonding
- Holes filled with polysilicon
  - Extra stress in the wafer
  - Careful about voids
- Surface isolation on both sides

- **Active edges**
  - **- by C. Kenney in 1997**
- **The edge is an electrode**!
- Must use silicon support wafer
- Dead volume at the Edge < 2 microns! Essential for
  - Large area coverage
  - Forward physics



ATLAS FE-Ix sensors from SINTEF



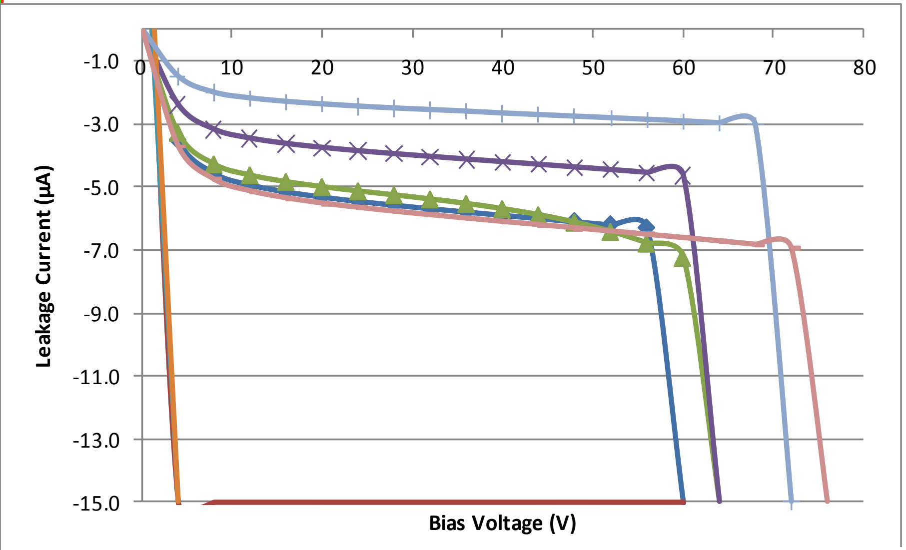
First ToT distribution seen with **3D Sintef Full Column Active edges** (device biased with 20V)

FE-I3 module: 2nd series

Results taken by Alessandro La Rosa and Philippe Grenier

IV of FE-I4: 3rd series

Area ~ 2.05 x 1.9 cm^2



- **Used temporary metal that shorts all pixels**
- **Current for the entire sensor including the active edge**
- **Sensors on other wafers seem to have a lower V_{bk}**
- **2/3 of sensors have V_{bk}>40V (V_{fd} = 15V)**

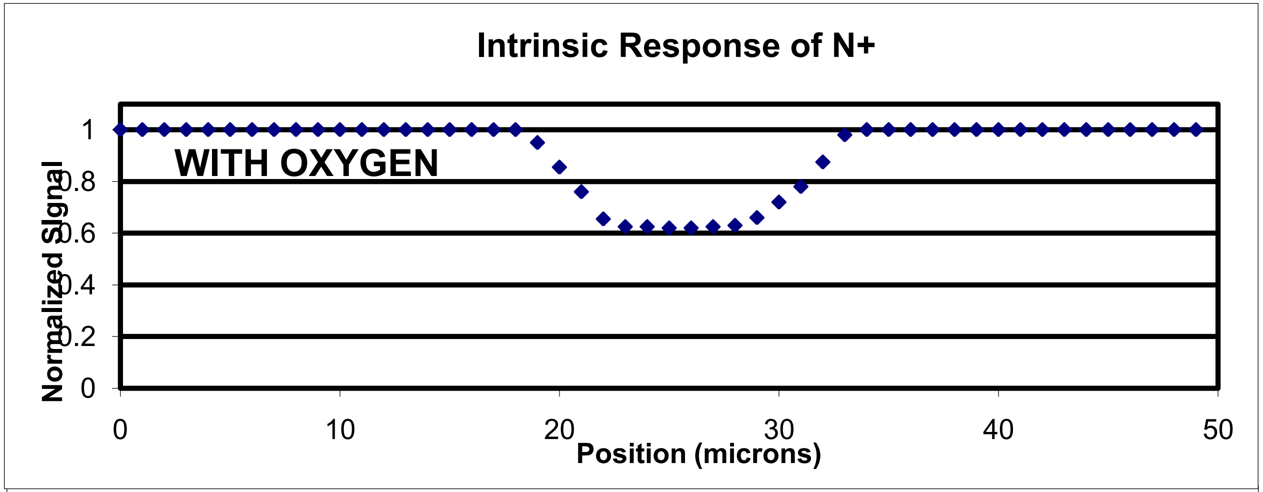
X-RAY STUDIES OF ELECTRODE RESPONSE

Data showing the response of electrodes using to a 2um wide X-ray beam

*** C. Kenney, J. Hasi (SLAC)**

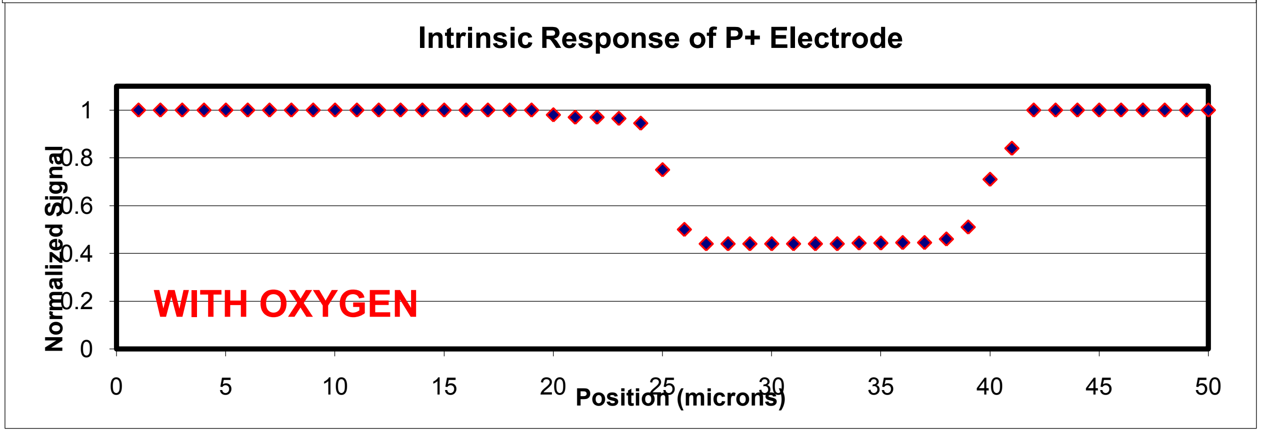
N+ electrode
efficiency about 60%

POCL3


Intrinsic Response of N+

P+ electrode efficiency about 42%

BBr3 + O2

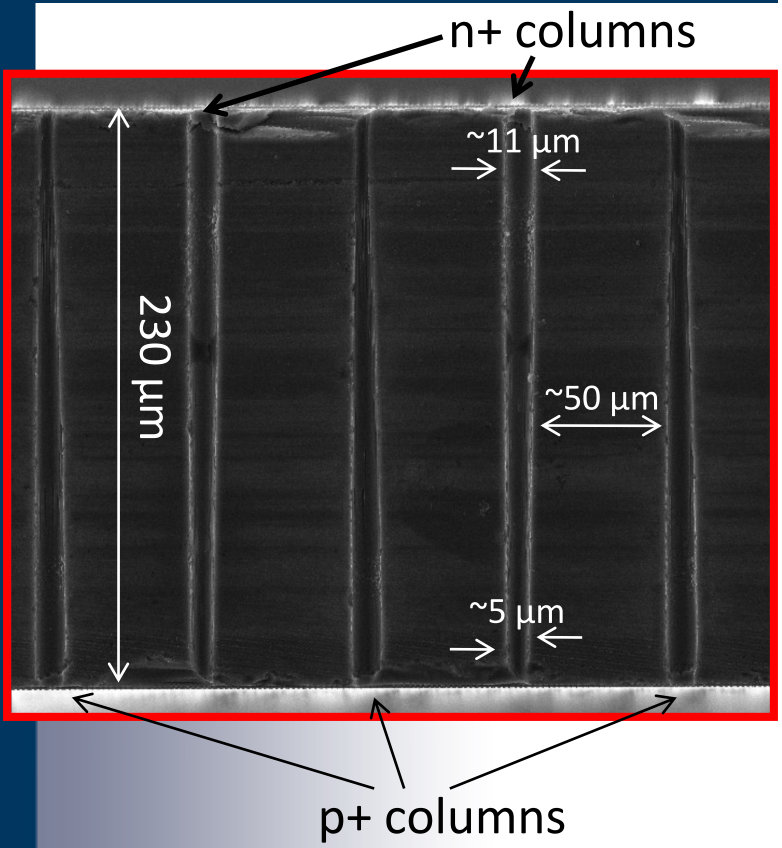

Intrinsic Response of P+ Electrode

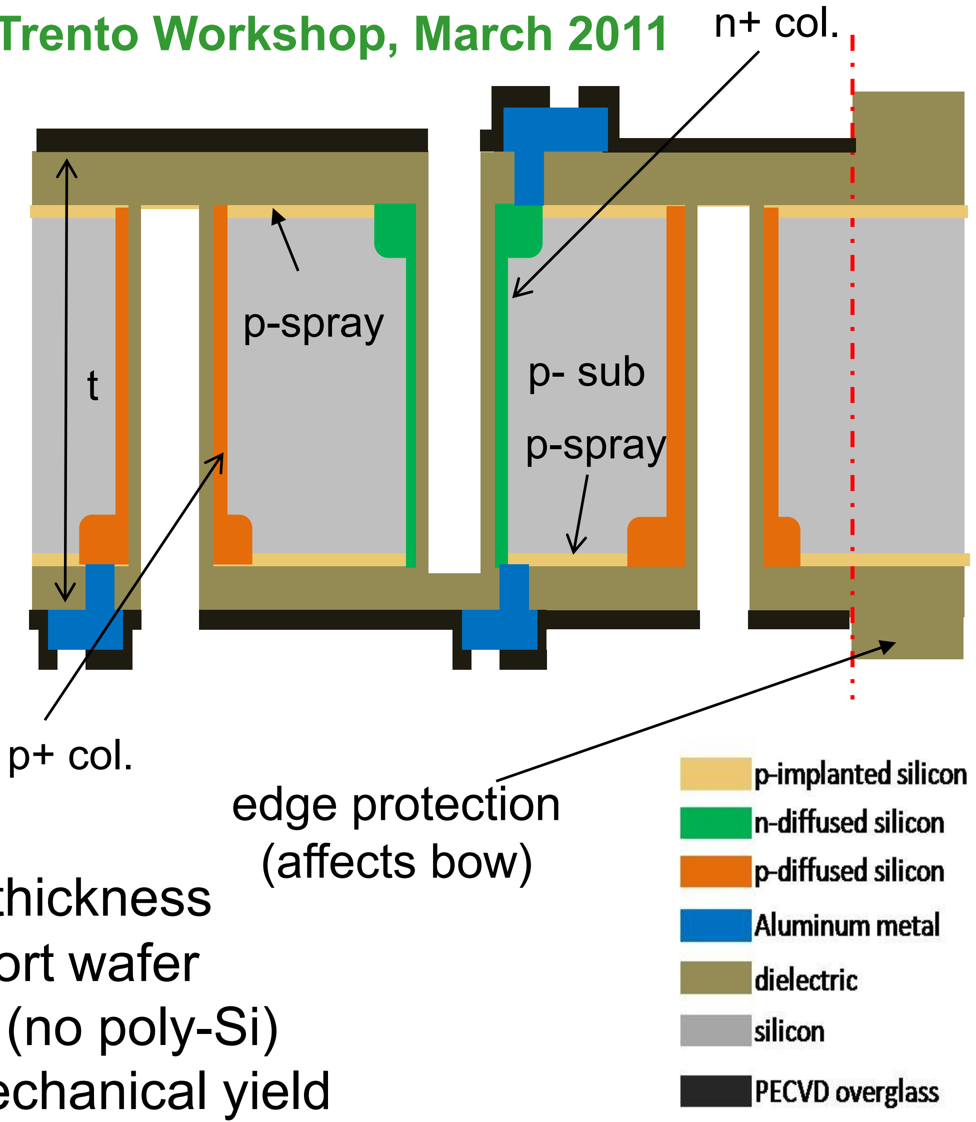
Oxygen trapping!
Replace POCL3 with PH3
Replace BBr3/O2 with B2H6

Done in Sintef Run 3

3D-DTC with passing through columns at FBK

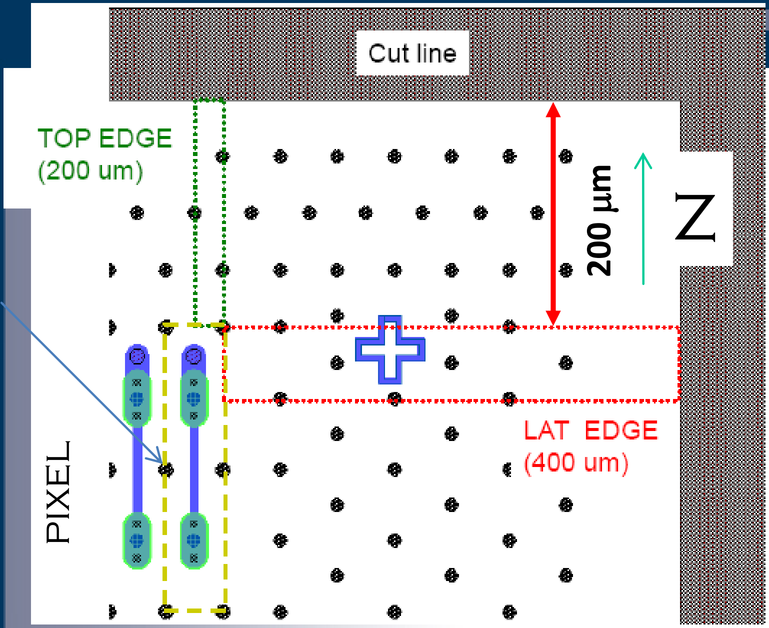
E. Vianello, et al.,
6th Trento Workshop, March 2011

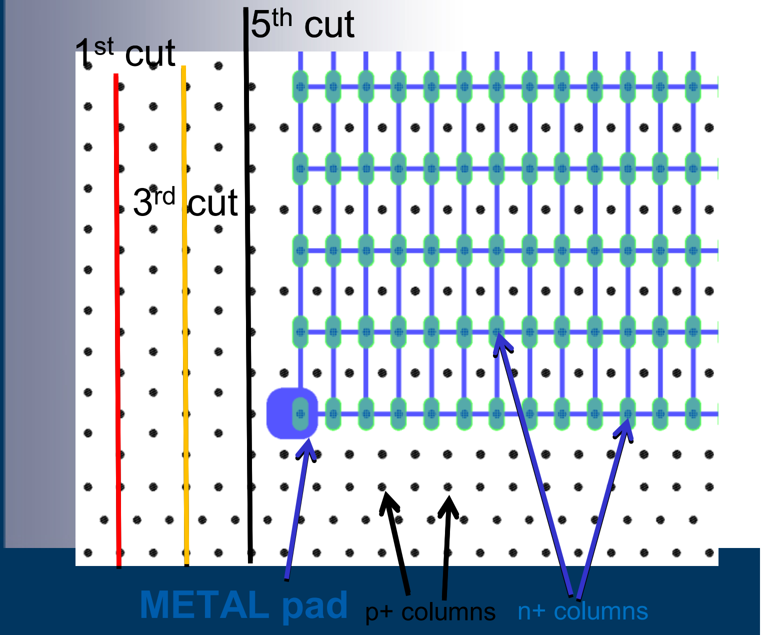




- Column depth equal to the wafer thickness
- Full double side process, no support wafer
- Holes (~11 µm diam.) are “empty” (no poly-Si)
- Edge protection to improve the mechanical yield

Slim Edge in 3D-DTC

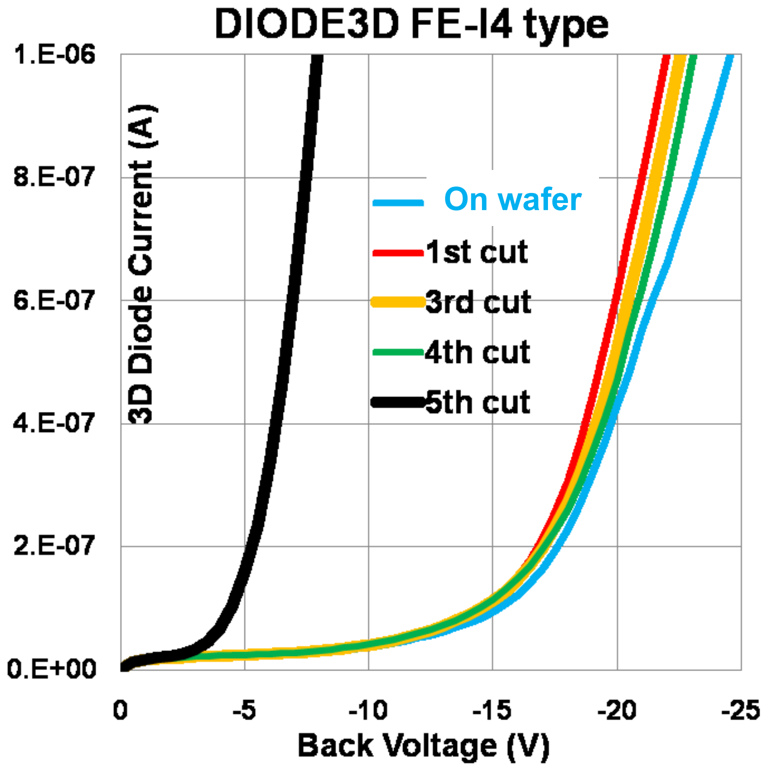




- Multiple ohmic column fence stops the depletion region spreading from the pixel to before it reaches the cut line

•Several dicings at different distances from the n+ pixels, to check the extension of the depleted region

→ **Safe**



G.-Giacomini et al., 6th Trento Workshop, 2-4 March 2011 (http://tredi.fbk.eu)

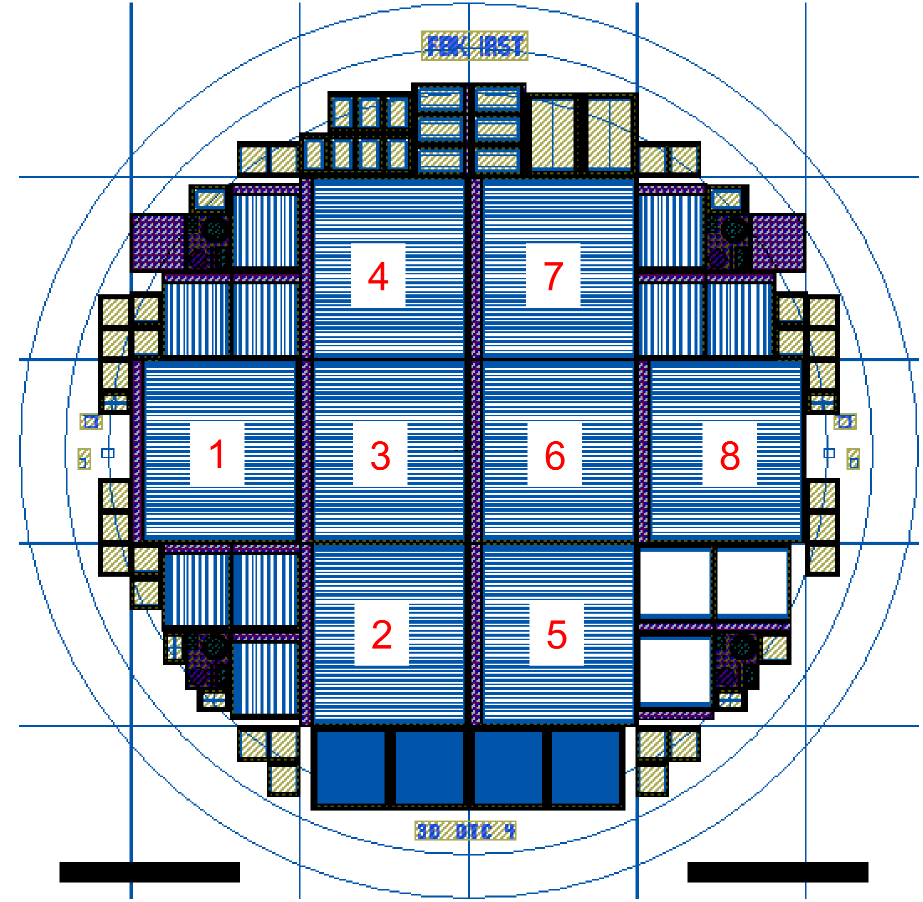
IBL campaign

Wafer layout for ATLAS IBL 3D sensors

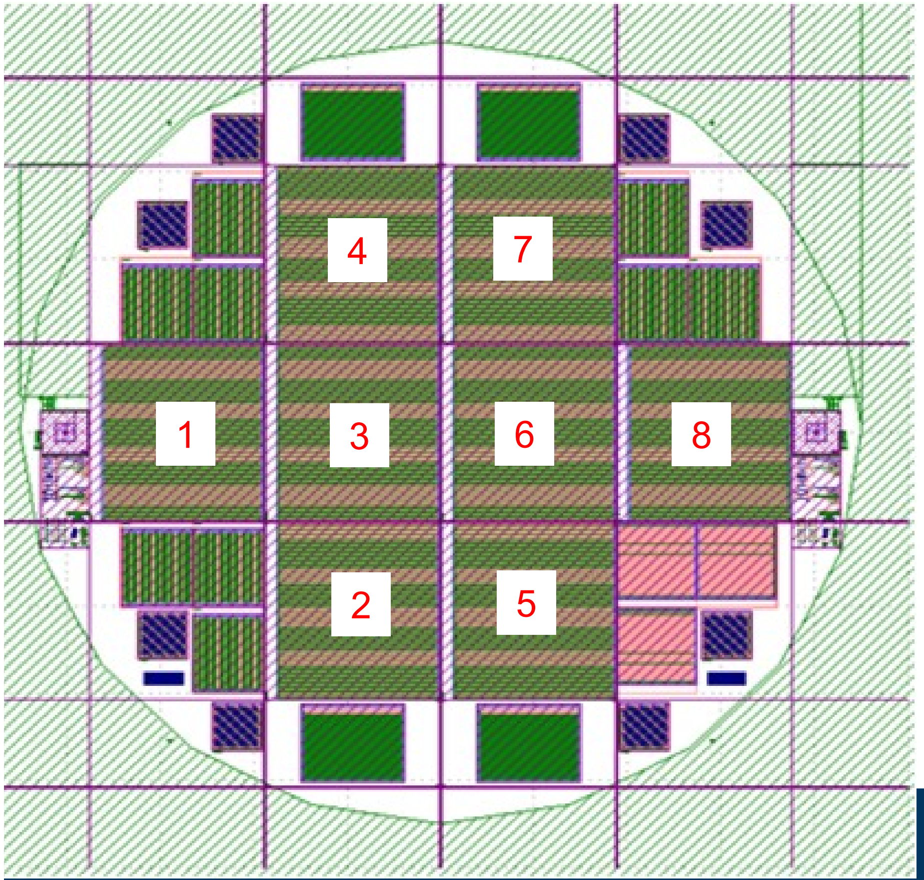
Layout from G.-F. Dalla Betta (University of Trento), G. Pellegrini (CNM)

- Common core: FE-I4 (8x), FE-I3 (9x), CMS (3x)
- Foundry-specific test structures at the periphery

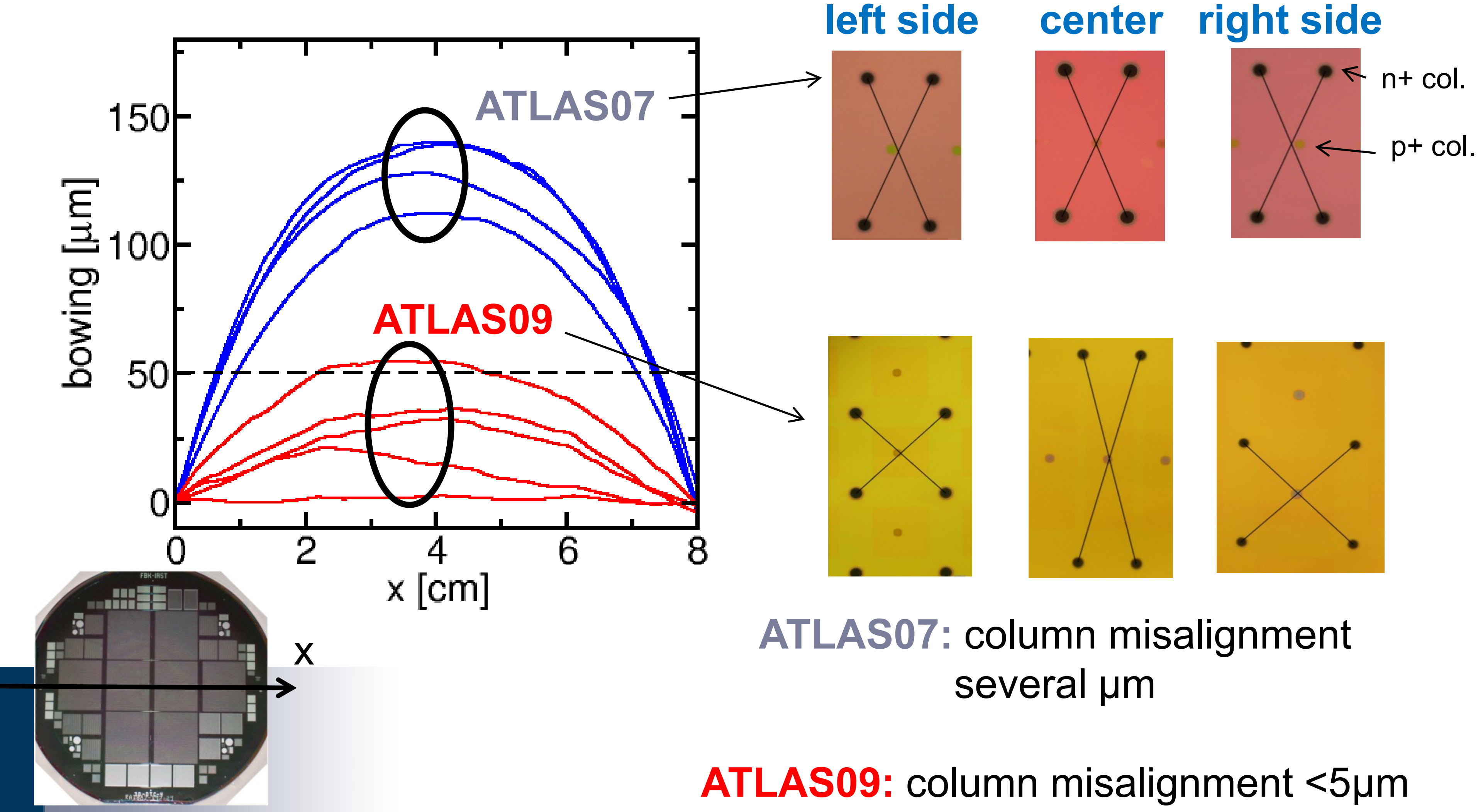
FBK Trento



CNM Barcelona



Wafer bow on FBK wafers

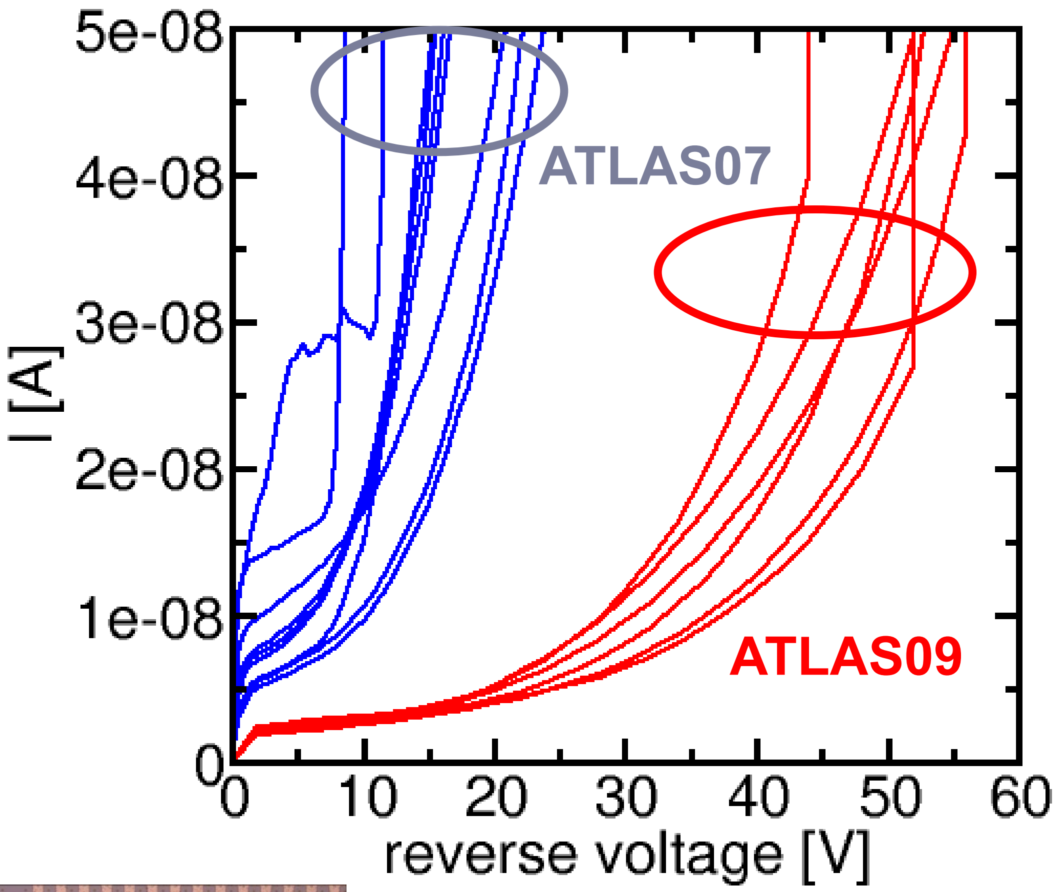


ATLAS07: column misalignment several μm

ATLAS09: column misalignment <5μm

G.F. Dalla Betta, et al.,
IBL General Meeting, CERN, June 8, 2011

I-V curves of 3D diodes



Old process (ATLAS07)

Bow > 100µm

→high mechanical stress

→ high leakage current

High p-spray dose

→ low breakdown voltage (~20V)

Optimized process (ATLAS09)

Bow < 50µm

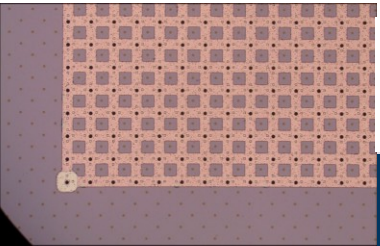
→reduced mechanical stress

→ low leakage current

(<10pA per pixel)

Optimized p-spray dose →

breakdown voltage ~40-50V



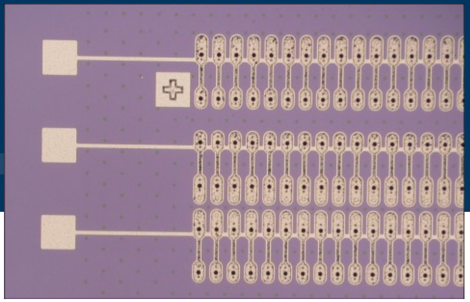
area~9.36mm^2

columns 40x40

E. Vianello, et al.,

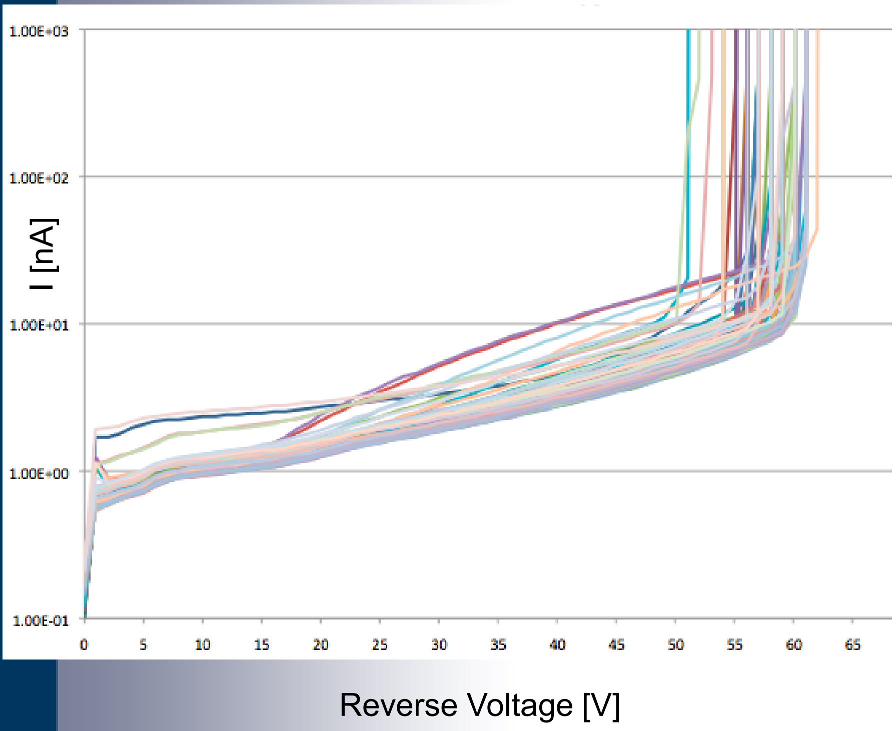
ATLAS 3D Processing Meeting, May 19th 2011

FBK I-V curves of FEI4 pixel sensors (measured with temporary metal)

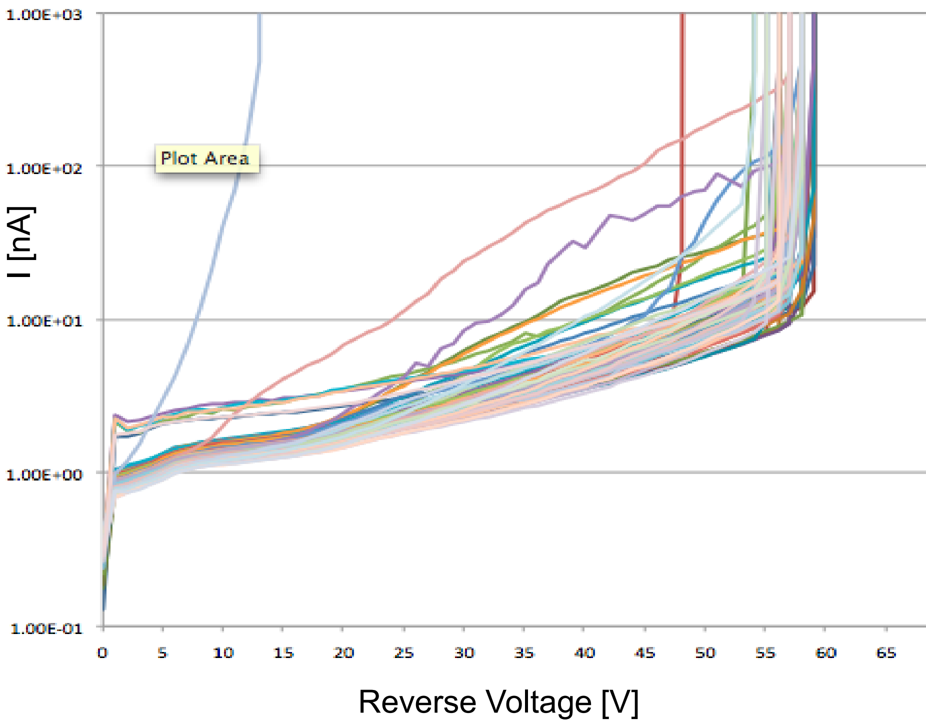


Each IV curve is measured on metal strip shorting 336 pixels

Good sensor



Bad sensor

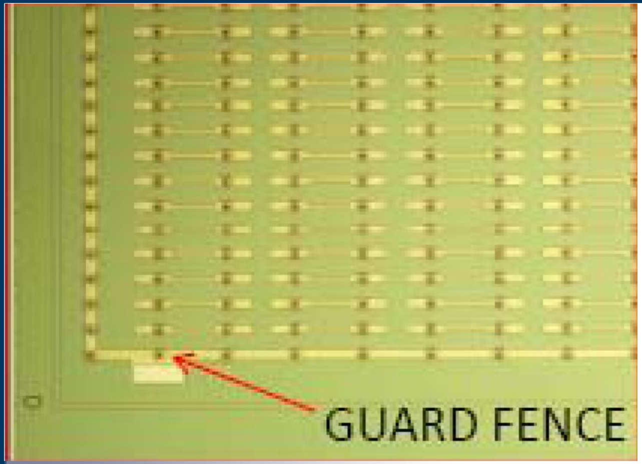


- Uniform behaviour of the 80 strips in terms of current and breakdown
- Normalized leakage current: ~5pA per pixel

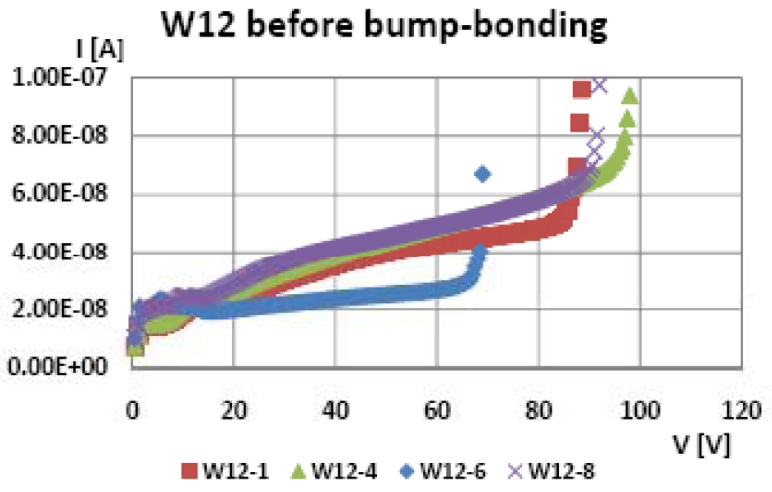
Only 1 strip does not work !
Defect density is very low…

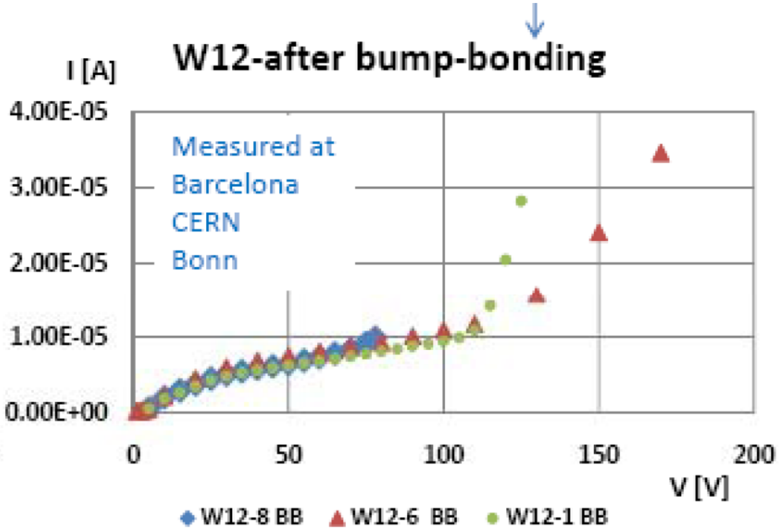
G.F. Dalla Betta, et al.,
IBL General Meeting, CERN, June 8, 2011

CNM I-V curves of FEI4 pixel sensors



- For QA I-V measured on the guard fence
- I-V after Bump bonding shows
  - Higher current as for whole sensor
  - Higher V_{bk} as stress removed
  - Correlation with guard fence current

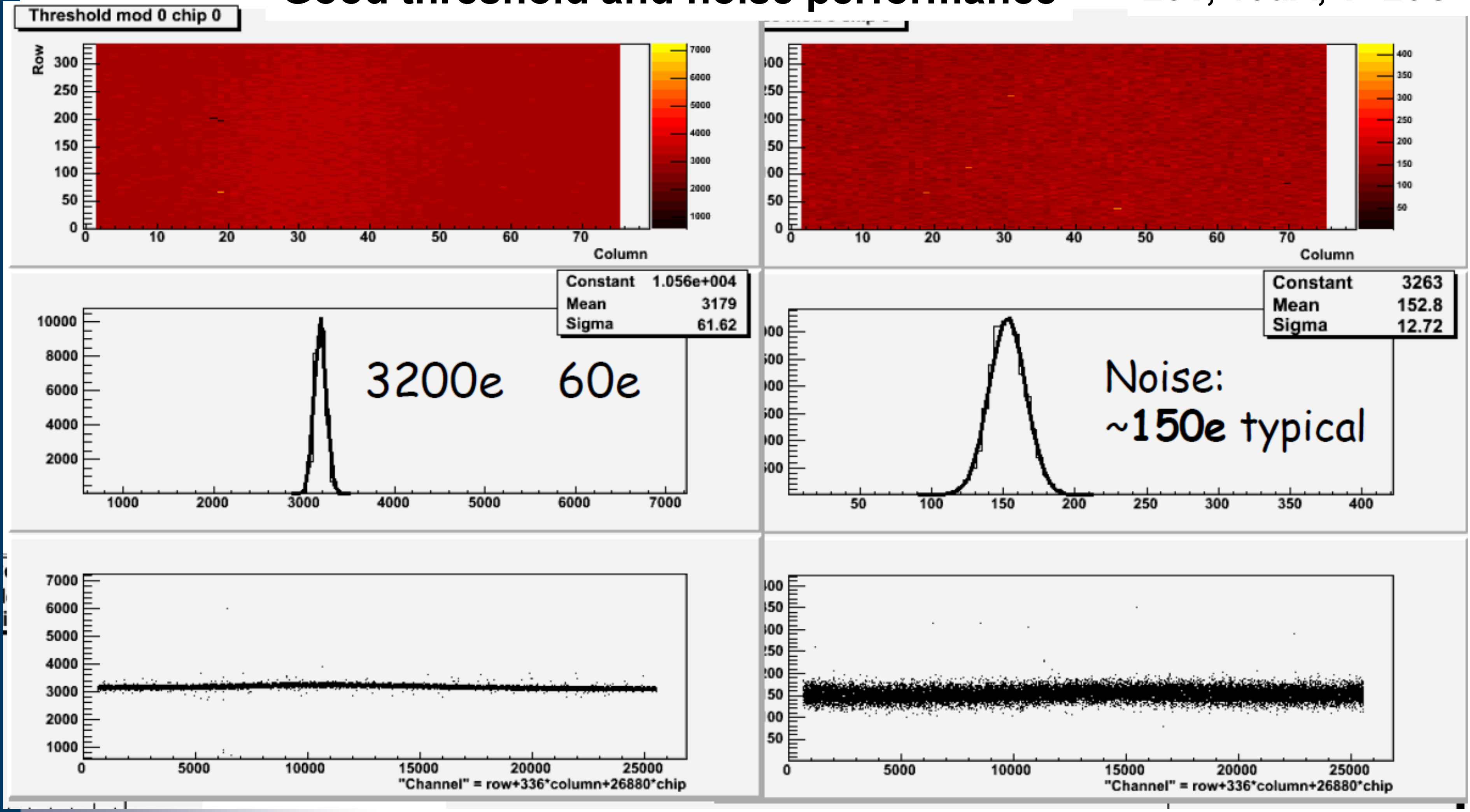




FE-I4 3D before irradiation

Good threshold and noise performance

20V, 10uA, T=20C

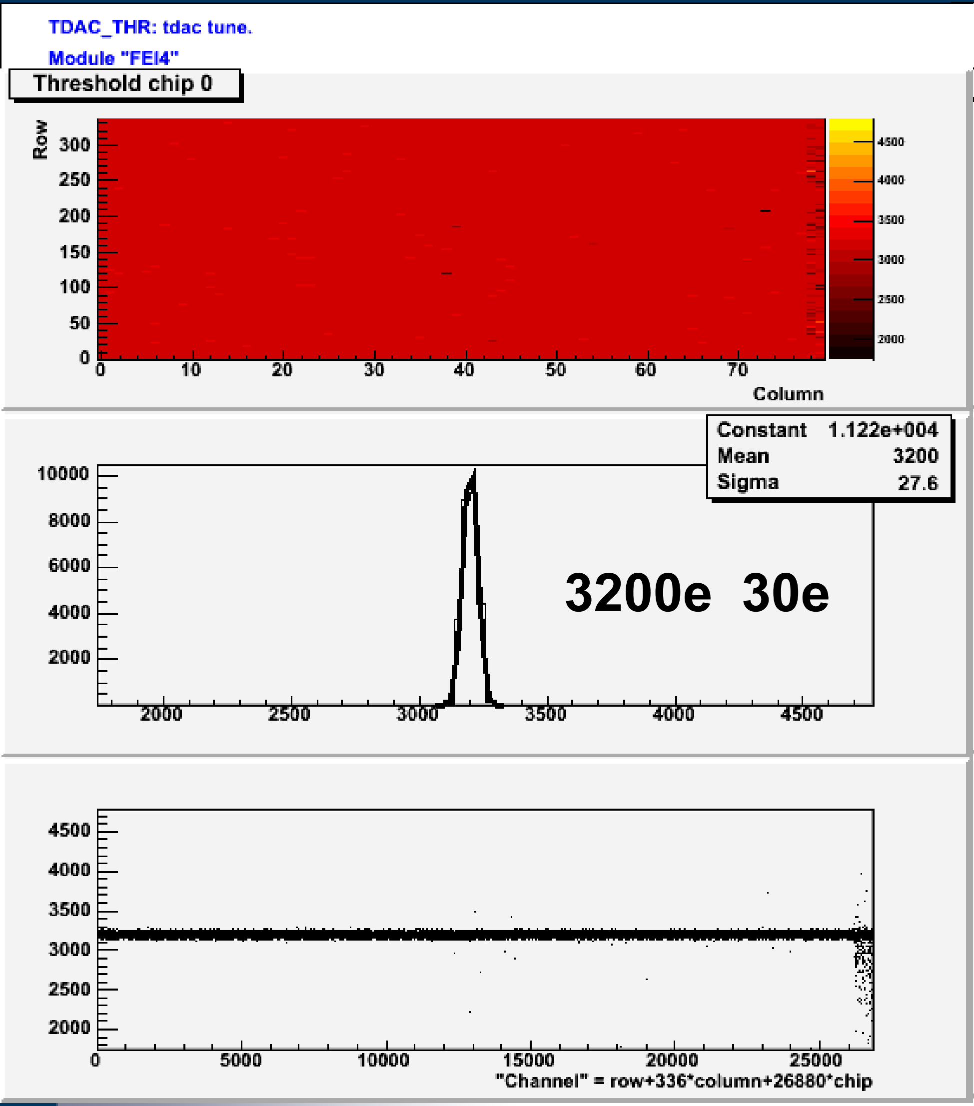


3200e 60e

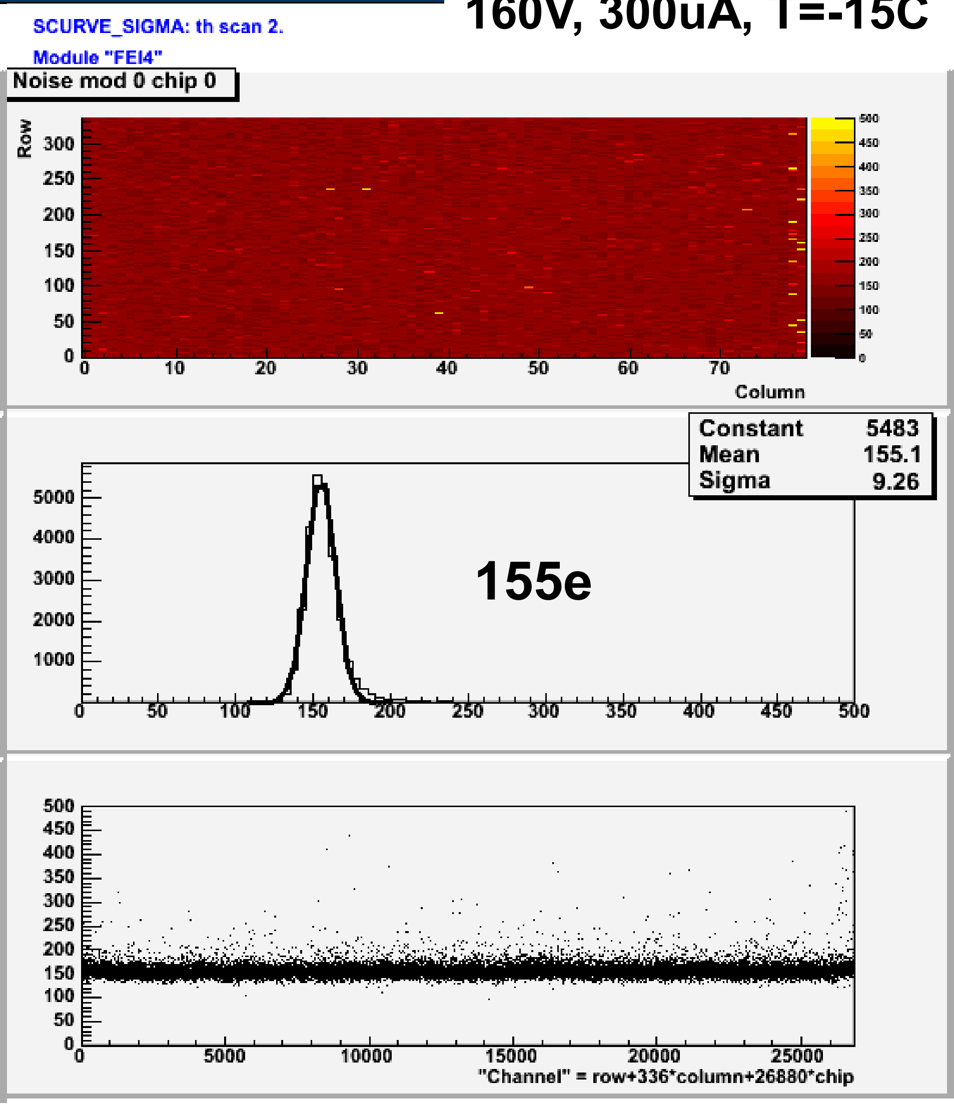
Noise:
~150e typical

FE-I4 3D after 5×10^{15} 1MeV n_{eq} – reactor neutrons

160V, 300uA, T=-15C



3200e 30e

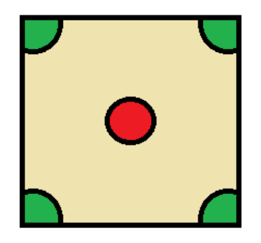


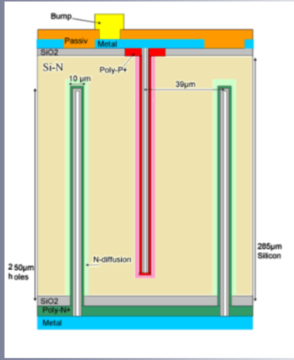
155e

Test beams analysis

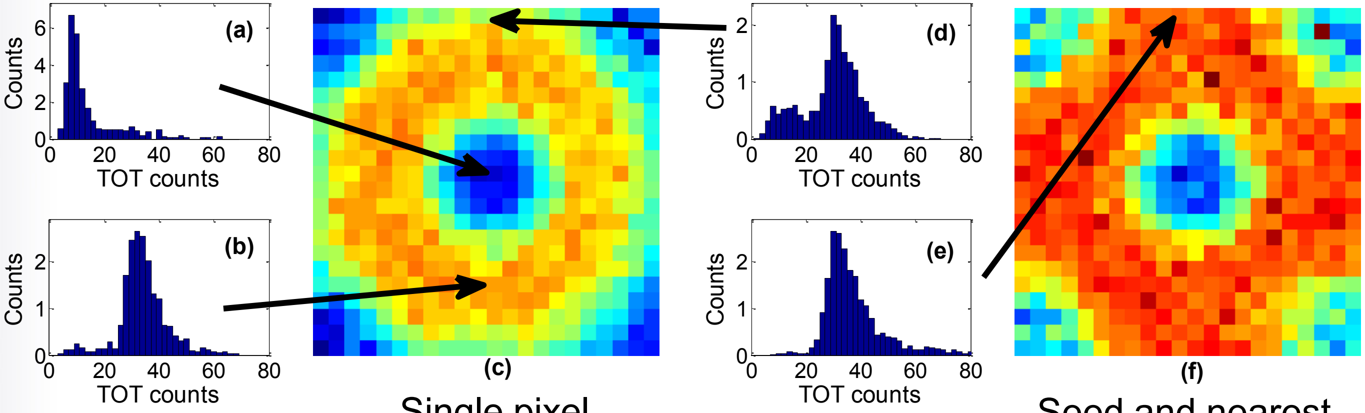
Precision scans: Charge deposition

Timepix Telescope





Mean energy deposited mapped onto pixel cell



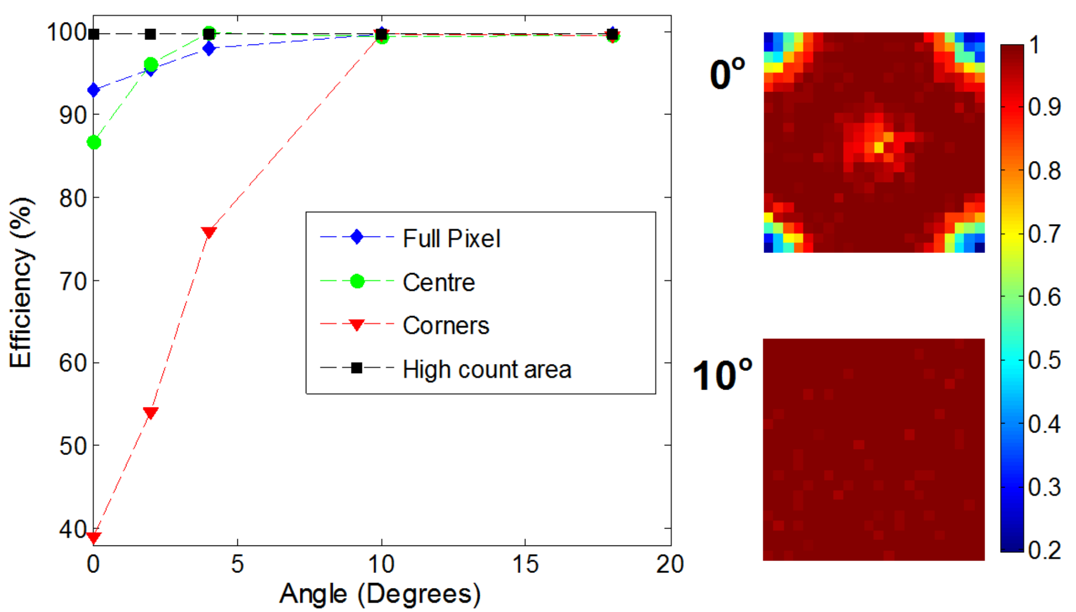
Single pixel response

Seed and nearest neighbours

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

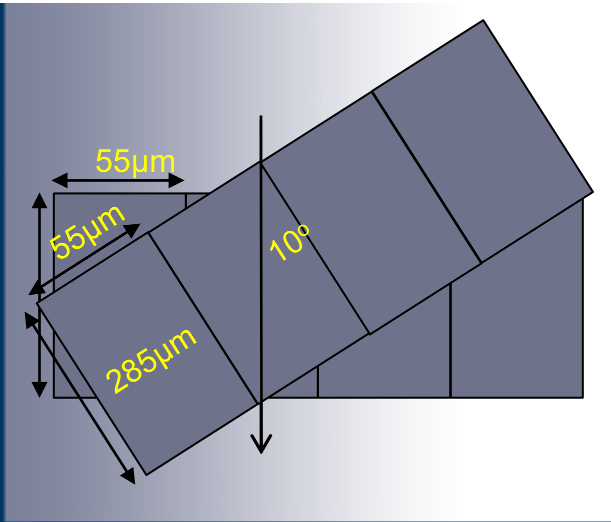
Precision scans of the Pixel cell response of double sided 3D Pixel detectors to pion and X-ray beams. 2011 JINST 6 P05002

Precision scans: Efficiency & Spatial resolution



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

Binary resolution
= 55μm / √12 = 15.9μm



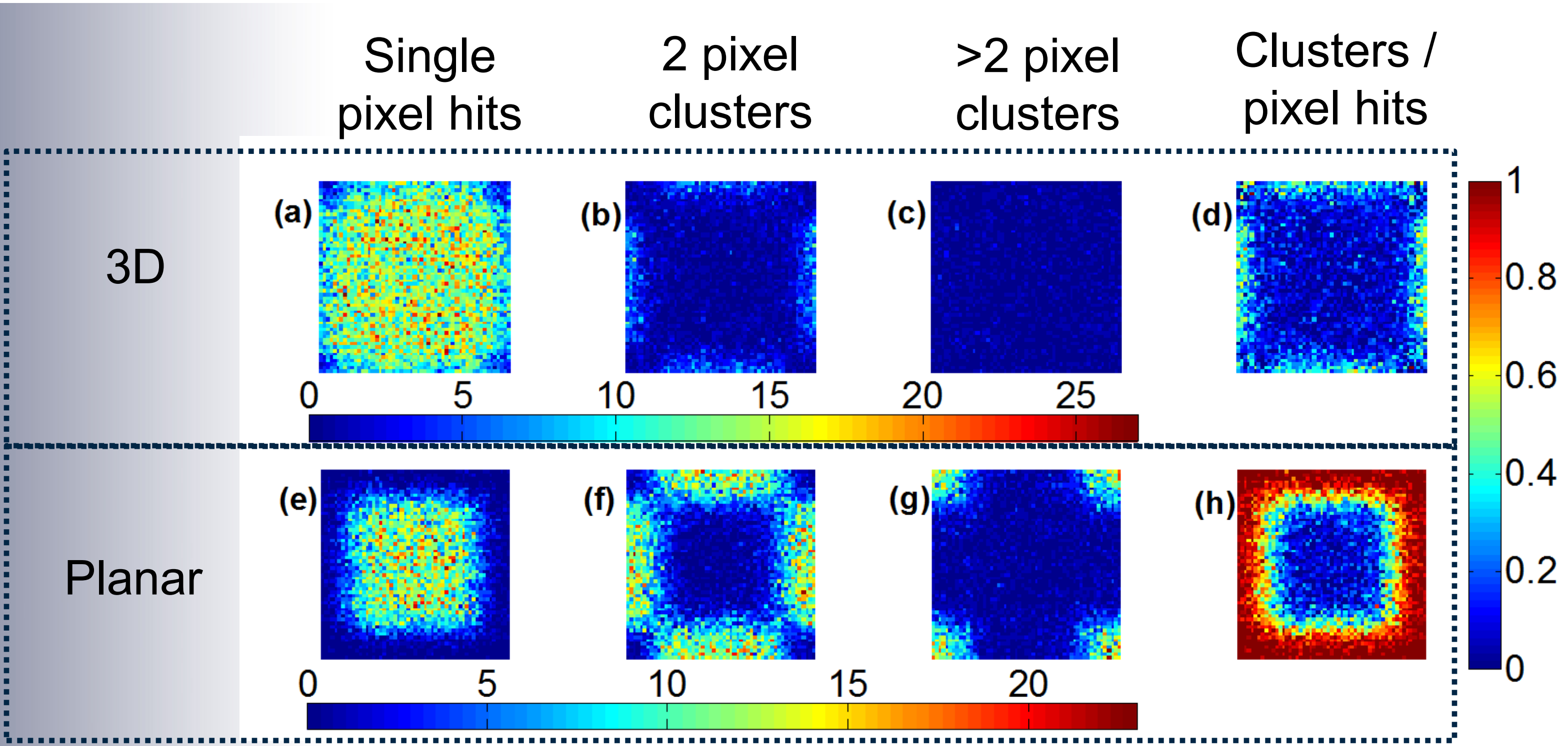
	3D		Planar *	
Degrees	0°	10°	0°	10°
Spatial resolution	15.8±0.1	9.18±0.1	10.15±0.1	5.86±0.1

- 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° *

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

Precision scans: Charge sharing

Timepix Telescope

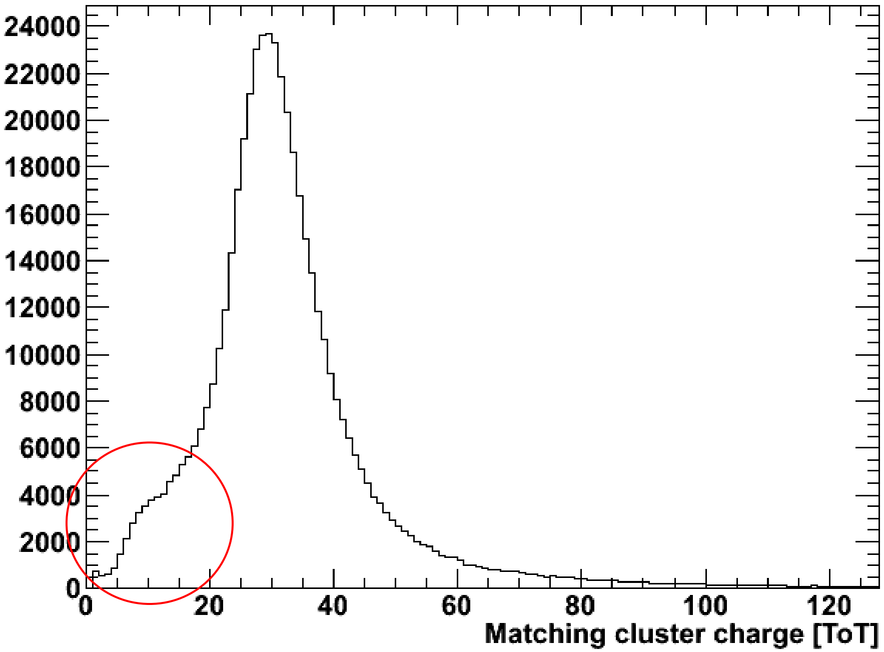


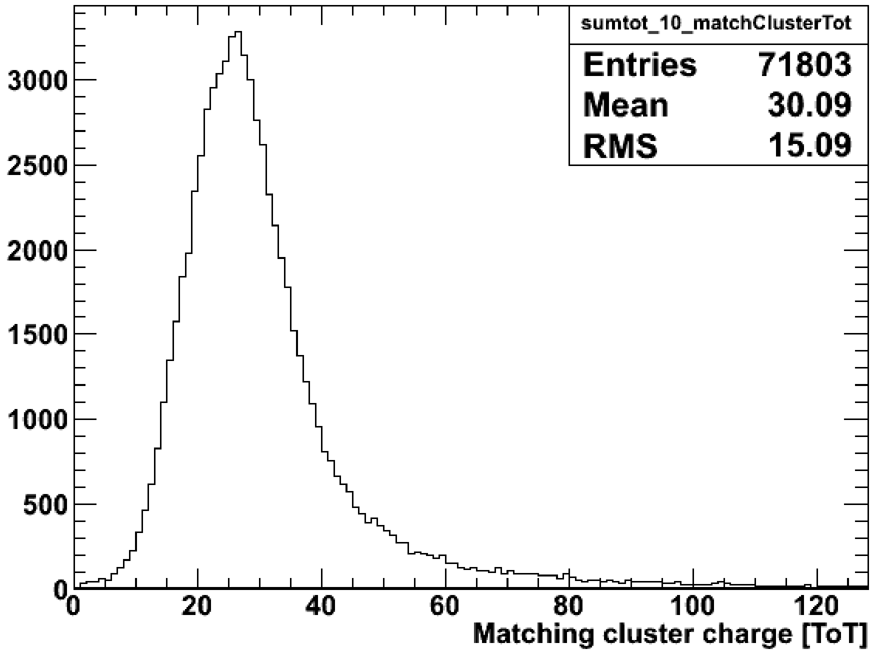
59% of incident particles multiple pixel hits in the **planar** sensor.
14% of incident particles multiple pixel hits in the **3D** sensor.

FE-I3 Test beam pulse height spectra

Normal incidence

15deg incidence

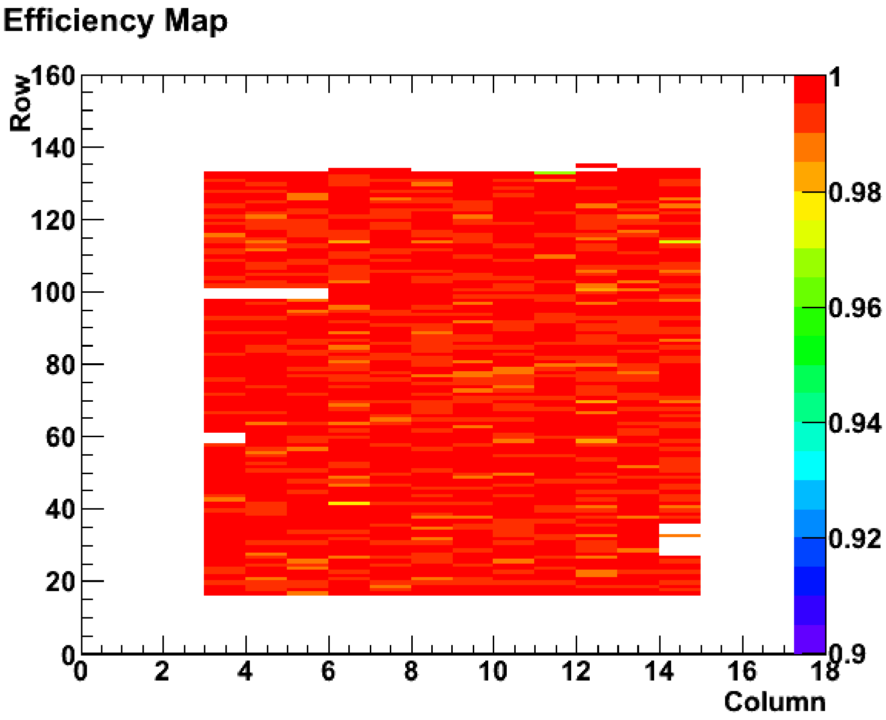




Low charge due to lost charge in the electrode

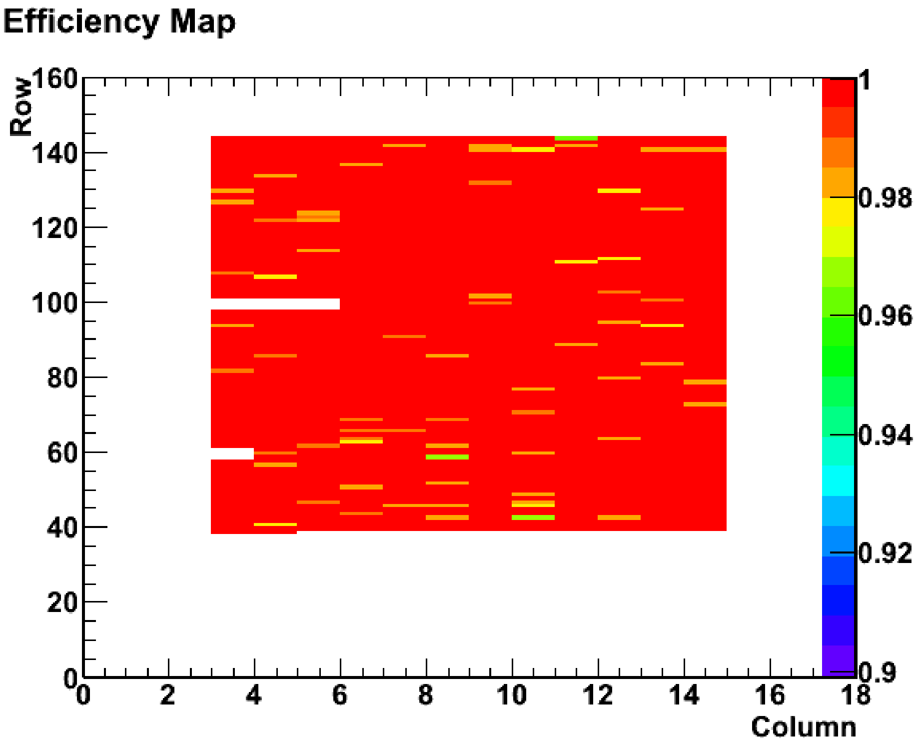
FE-I3 Test beam efficiency

Normal incidence



Efficiency = 99.53%

15deg incidence



Efficiency = 99.88%

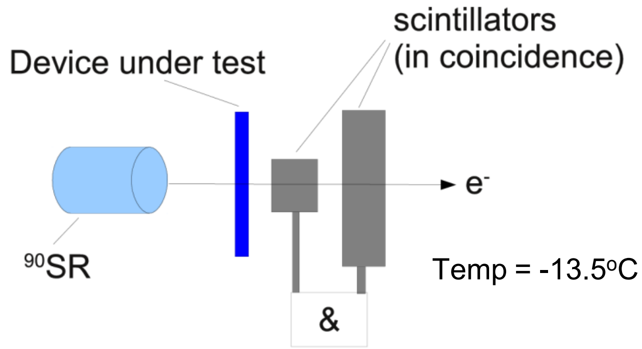
- Lower efficiency at normal incidence due to lost hits in pixel columns

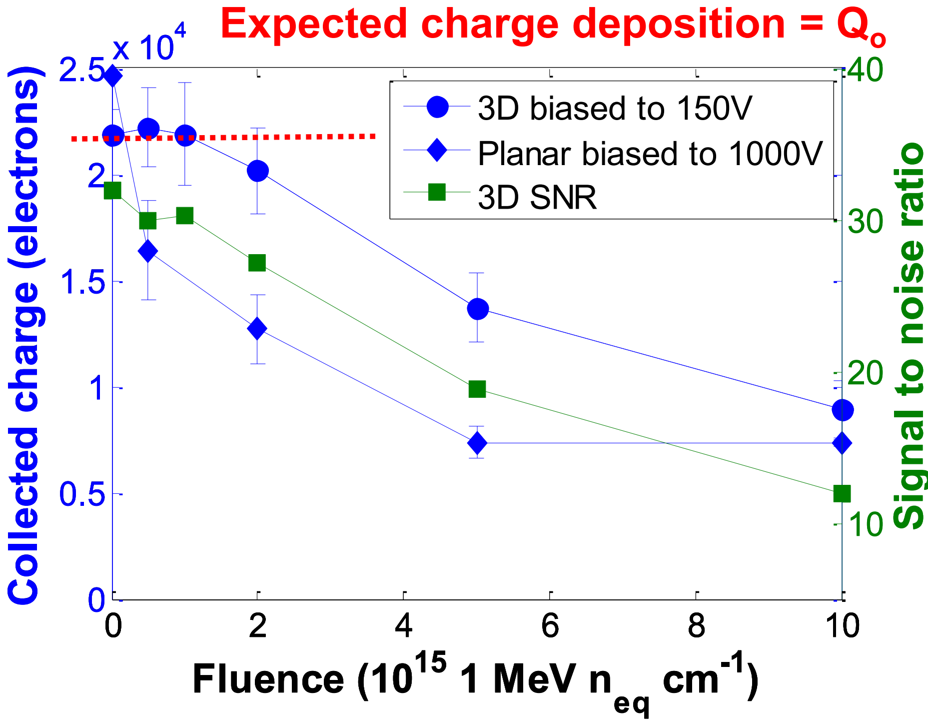
Radiation hardness studies

Charge collection efficiencies (150V)

Sr-90 electrons

- Use 4mm long strip device with 80um pitch
- 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

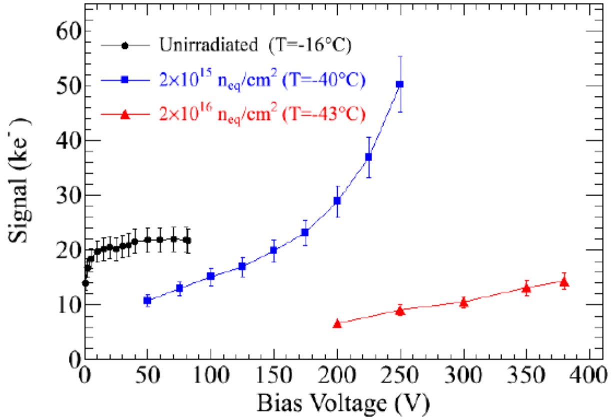


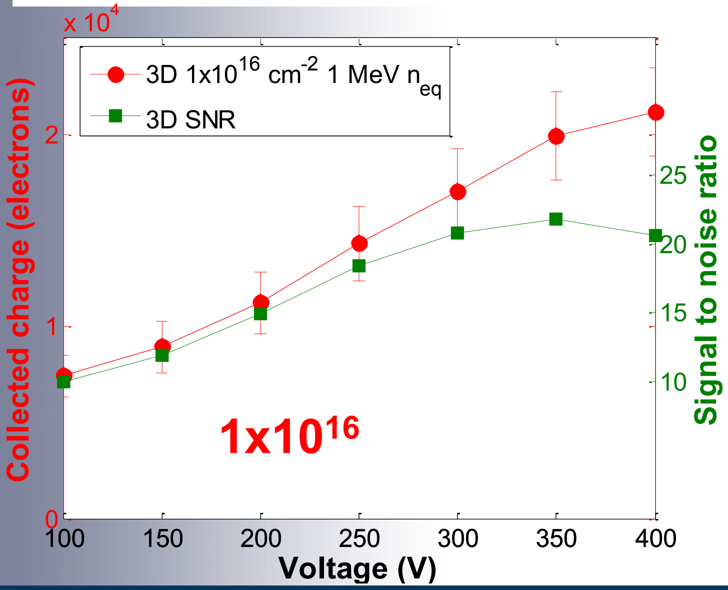


Charge collection studies and electrical measurements of heavily irradiated 3D Double-Sided sensors and comparison to planar strip detectors. R. Bates et al., submitted to IEEE

Charge collection efficiencies (~250-300V)

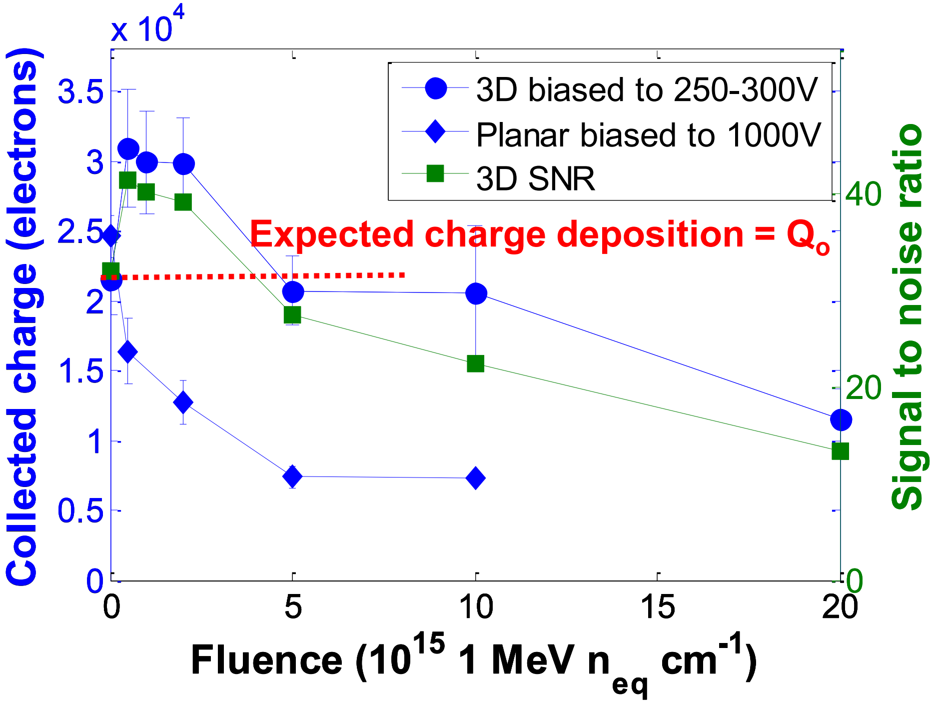
Sr-90 electrons





$1x10^{16}$

Charge multiplication through impact ionisation



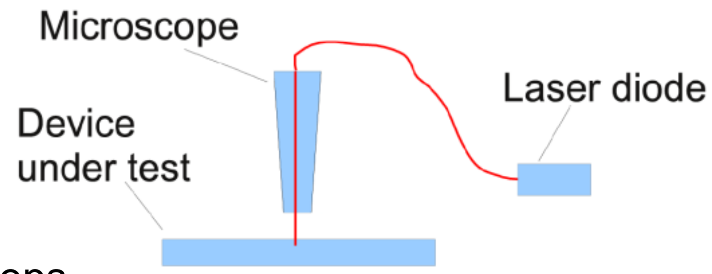
Expected charge deposition = Q_o

- 52% of Q_o collected at $20x10^{15}$ 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

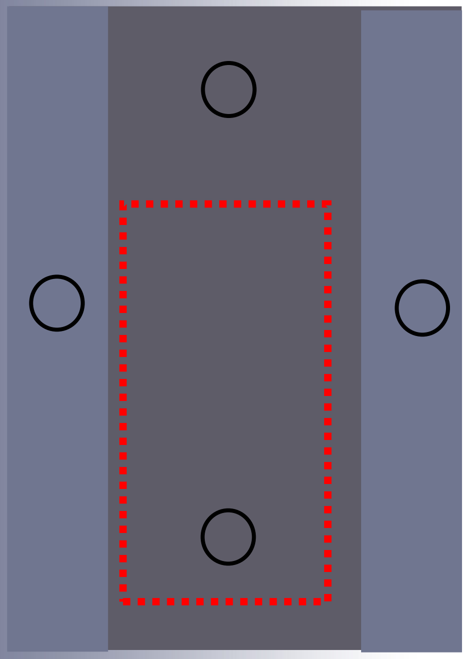
Mapped CCE with scanned laser

Laser scanning

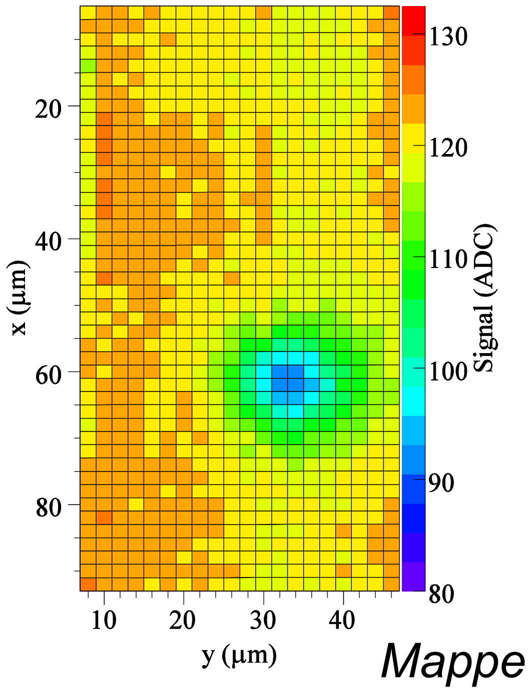


Experimental setup:

- 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



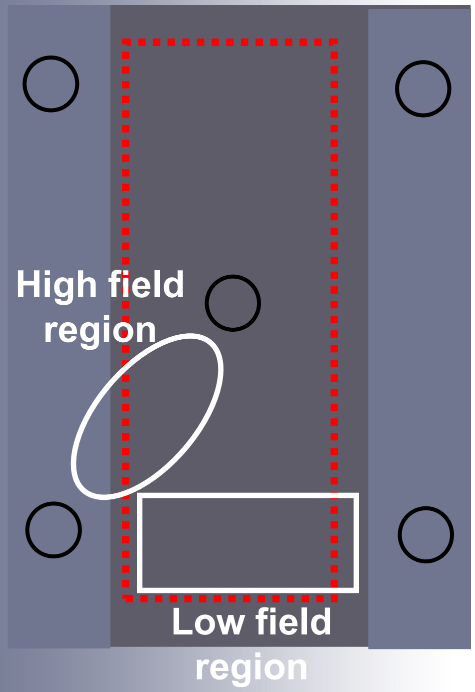
- 3D un-irradiated @ 77V
- p+ column evident
- Uniform charge collection outside of column position

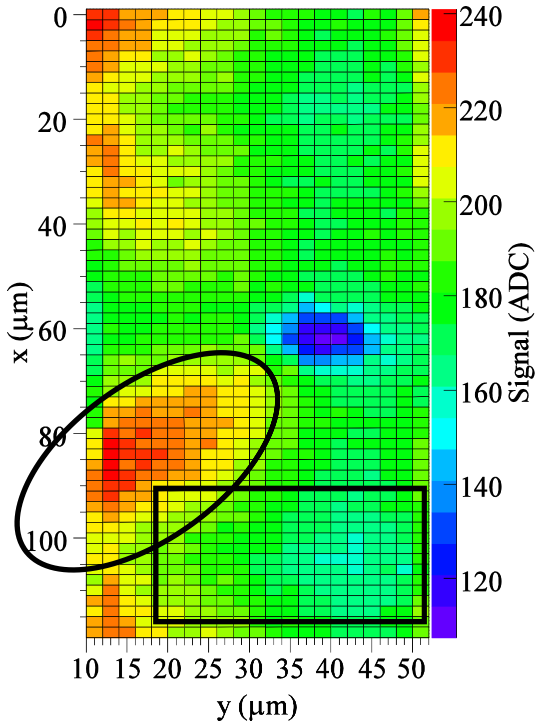
Mapped charge collection response

Mapped CCE with scanned laser

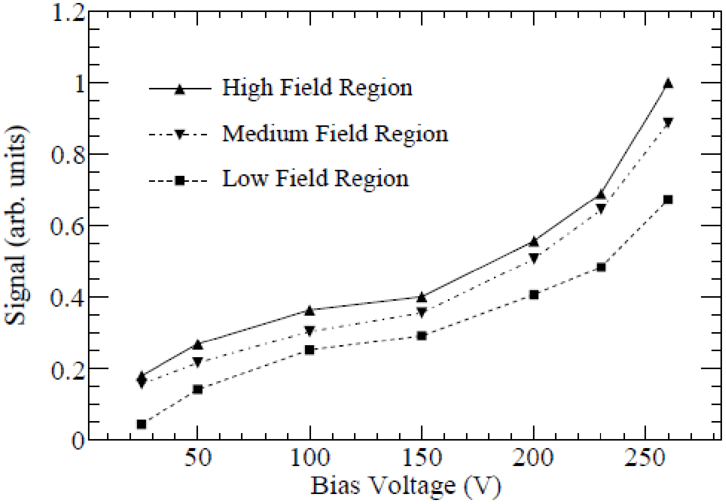
Laser scanning

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

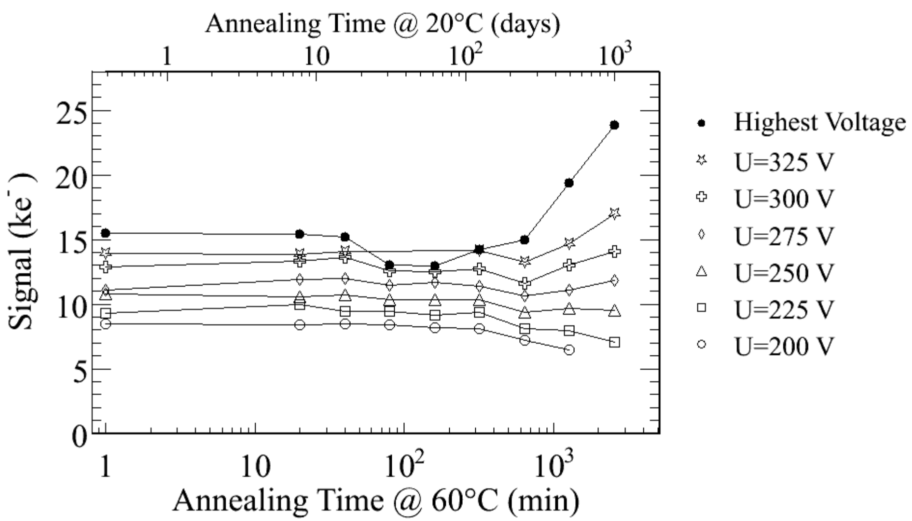


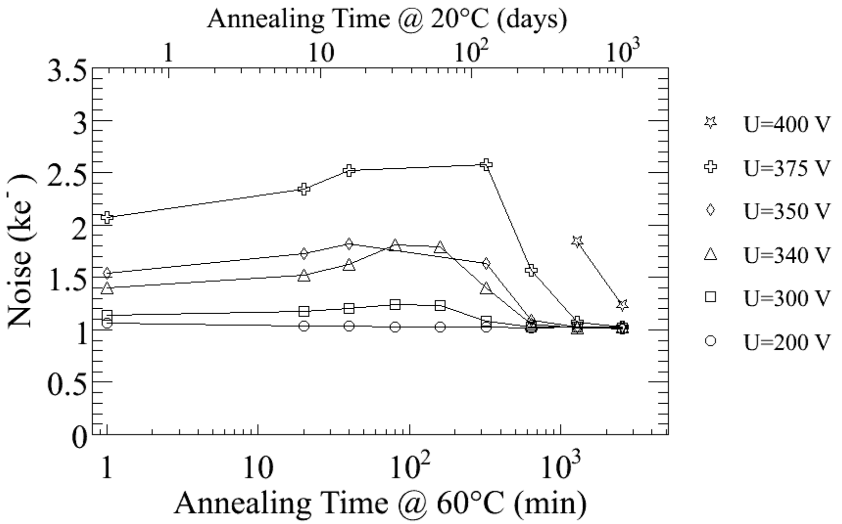


- p+ column evident
- Non-uniform charge collection outside of column position
- Area of low charge collection between the n+ contacts were a low field is present, greater probability of charge trapping



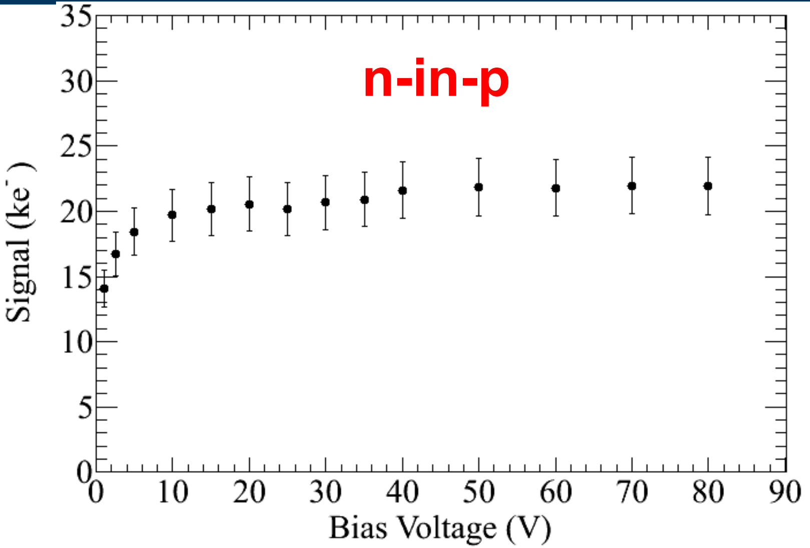
Annealing after $2x10^{16}$ 1MeV n_{eq} 26MeV protons

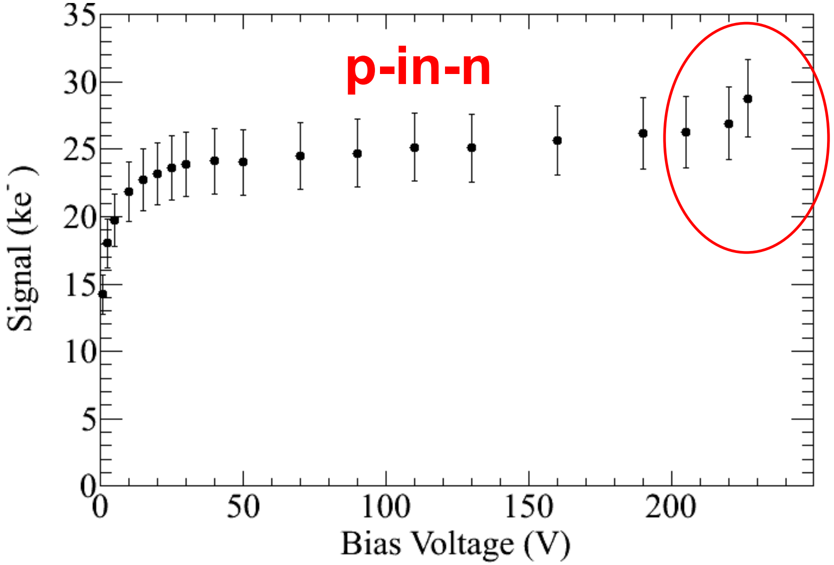




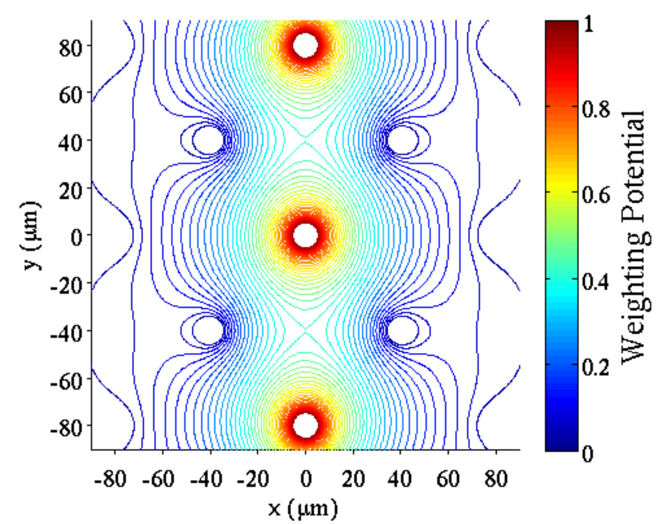
- Signal flat with annealing
  - increases after long annealing times
- Noise increases up to ~80 min (at 60°C),
  - Long annealing decreases strongly
- Long annealing extremely beneficial for S/N ratio

Charge multiplication before irradiation



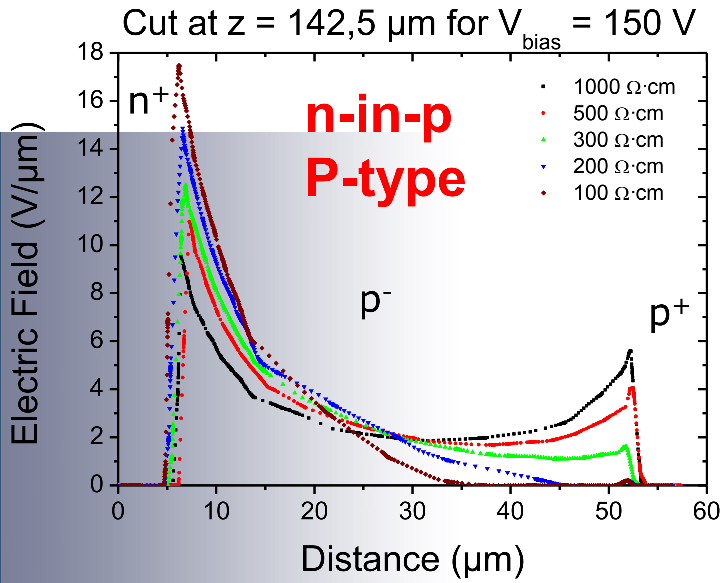


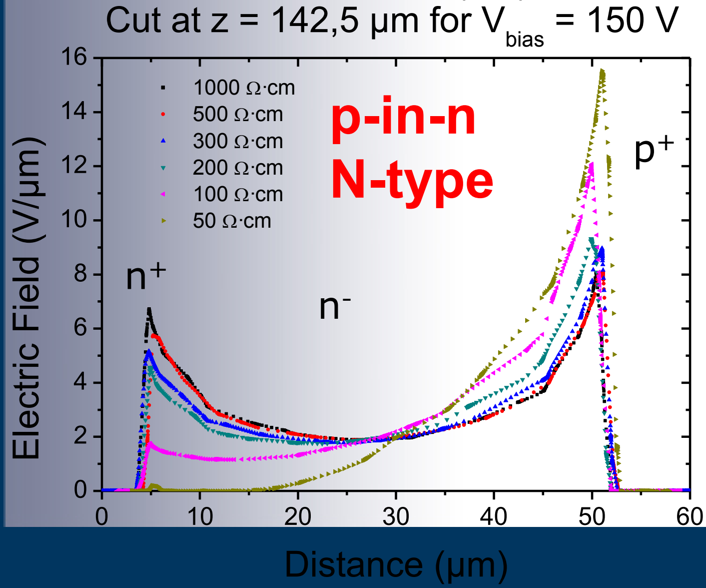
Lower breakdown due to p-stop



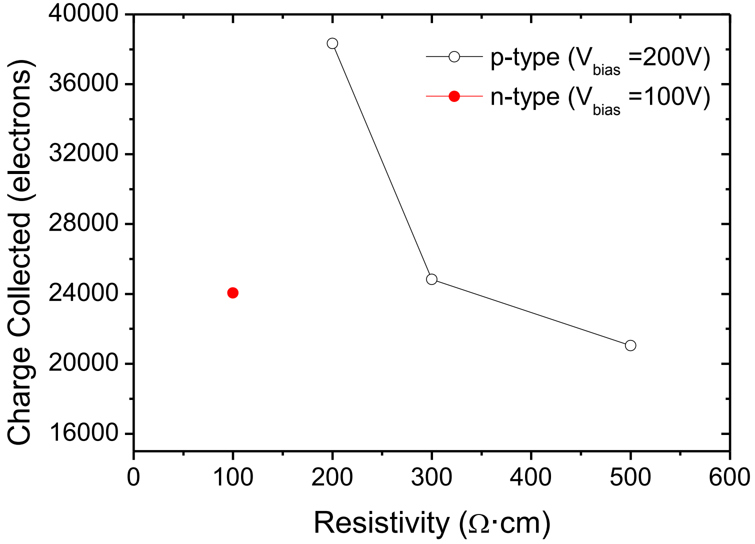
- **25% enhancement of signal at 230V**
- **Weighting potential → electrons and holes contribute ≈ to signal**
- **Electron multiplication at ohmic junction will result in charge multiplication**

Simulation of charge multiplication before irradiation





Collected charge from a mip

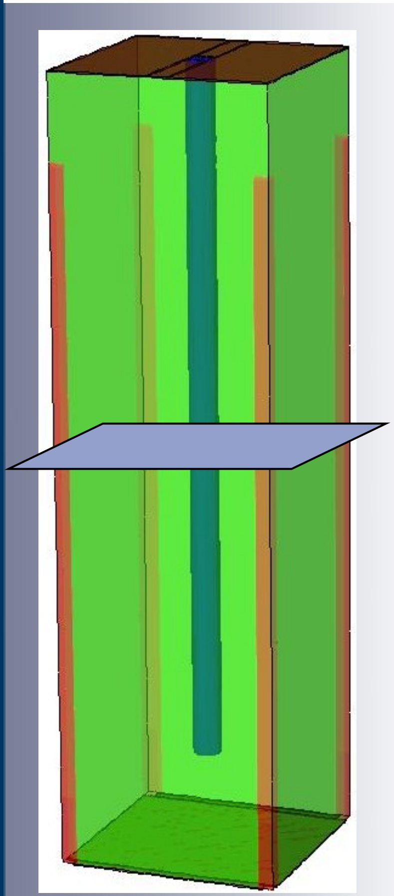


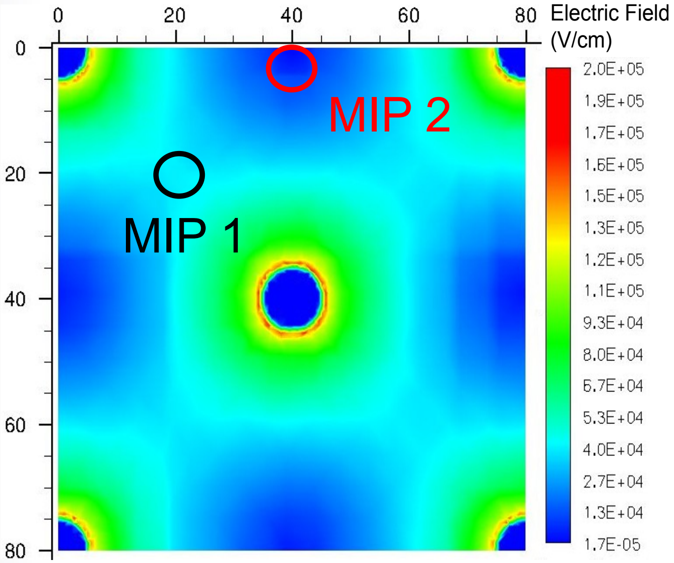
- Fields at junction can be high enough for charge multiplication in both n & p type devices
- Selection of doping density and bias voltage to allow full depletion and charge multiplication

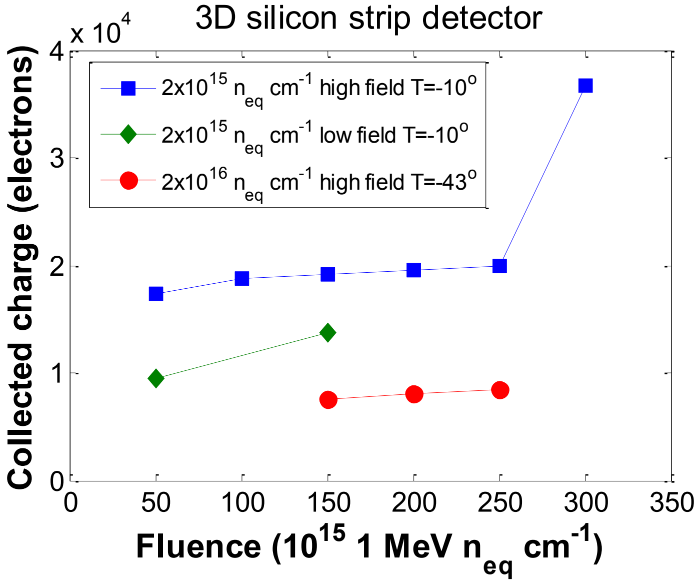
Charge Multiplication - simulations

TCAD

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







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

NSS 2011 -"Simulations of charge multiplication effect in 3D-DDTC silicon strip detectors"

Conclusions

Device production

Test beam analysis

Sr-90 electrons

Laser scanning

TCAD

- Device technology well developed
  - IBL pre-production going well
- Precision scans of the pixel performed, charge deposition mapped

  - Full charge collection from 35*μm* active Si above column
- High efficiency across pixel matrix

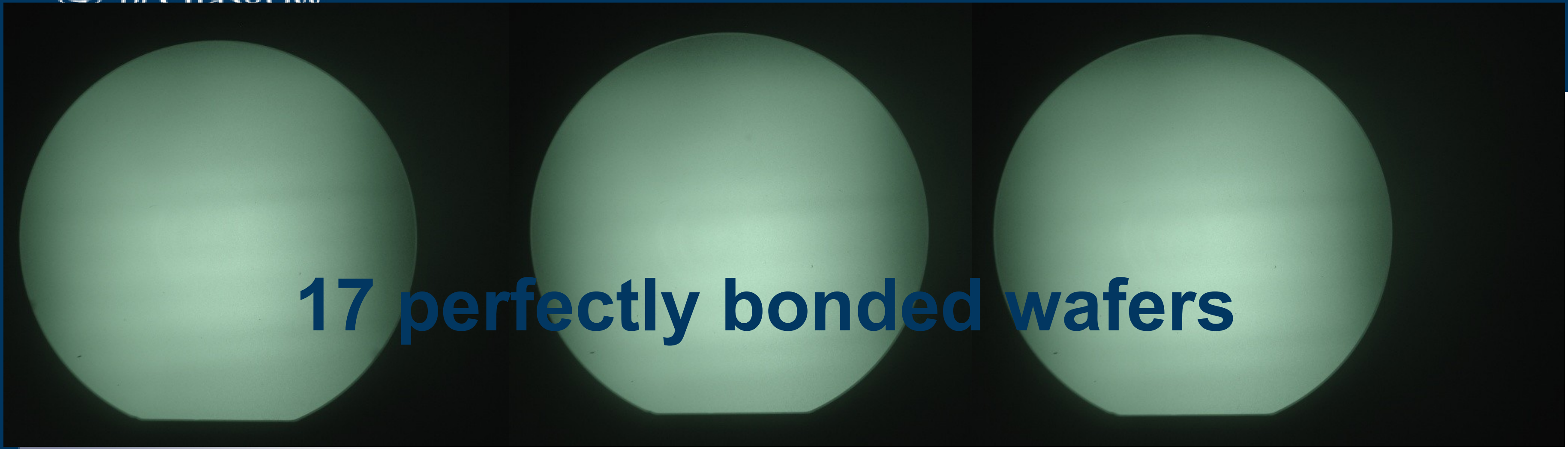
  - 93.0±0.5% @ 0^o, **Full pixel efficiency, 99.8±0.5%,** at an angle of 10^o
- Large decrease in charge sharing compared to planar
  - MIPs that create clusters in sensor: 59% in planar, 14% in 3D
- Higher collected charge at modest voltages for 3D

  - **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 non & irradiated devices

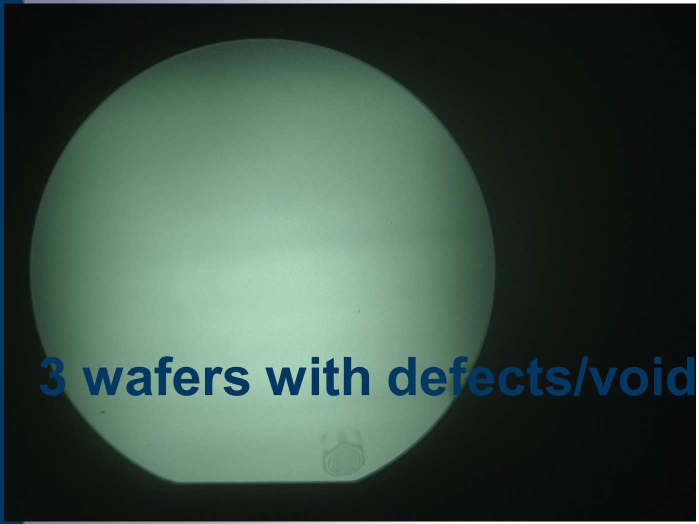
Back-up slides

Some process issues with full 3D

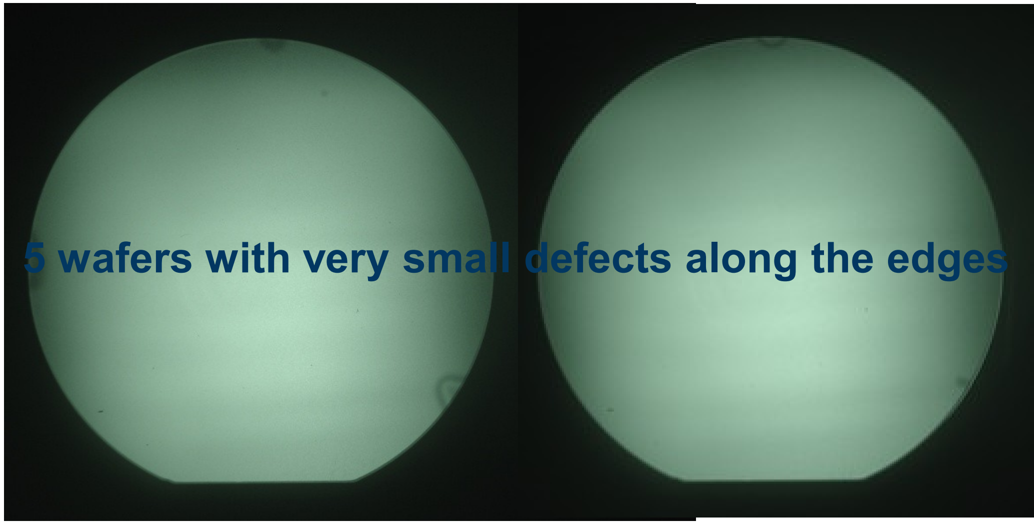
Bonding results from latest batch



17 perfectly bonded wafers

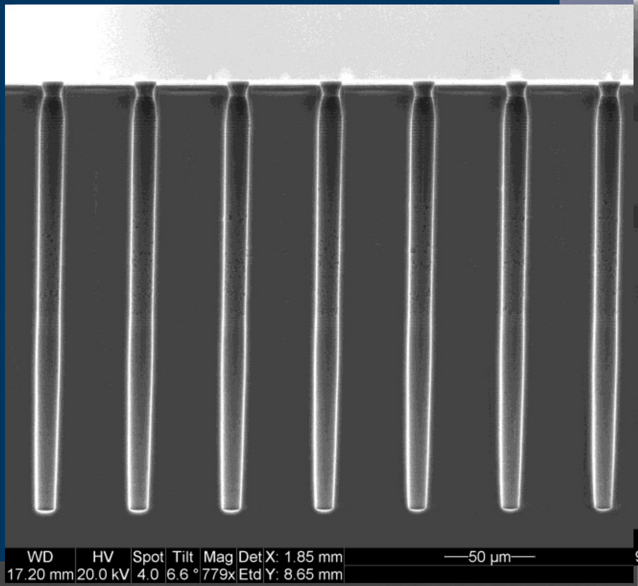


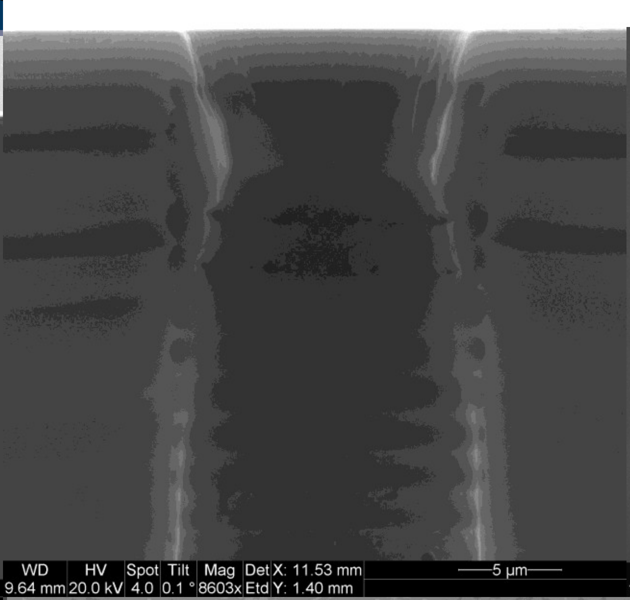
3 wafers with defects/voids

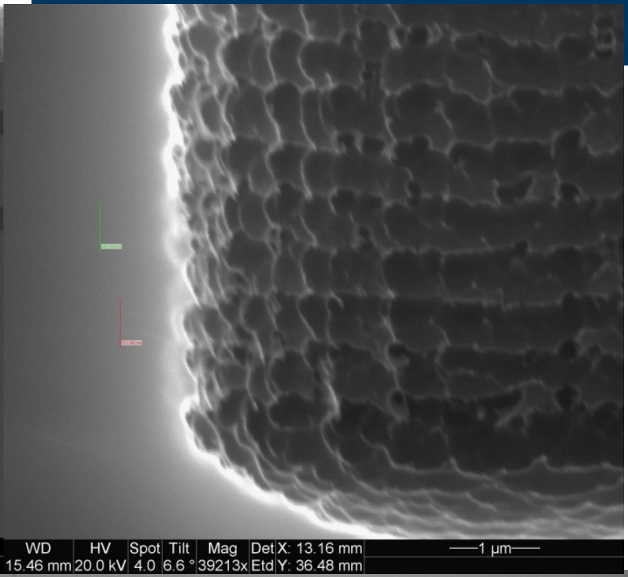


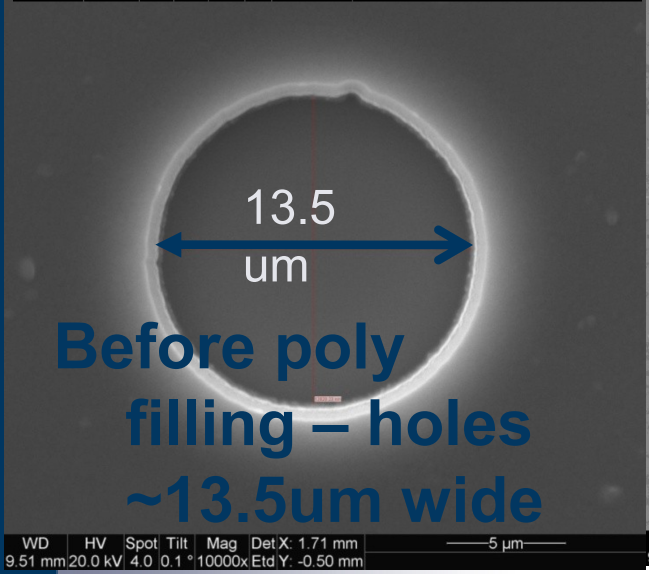
5 wafers with very small defects along the edges

DRIE and polyfilling results – 3rd

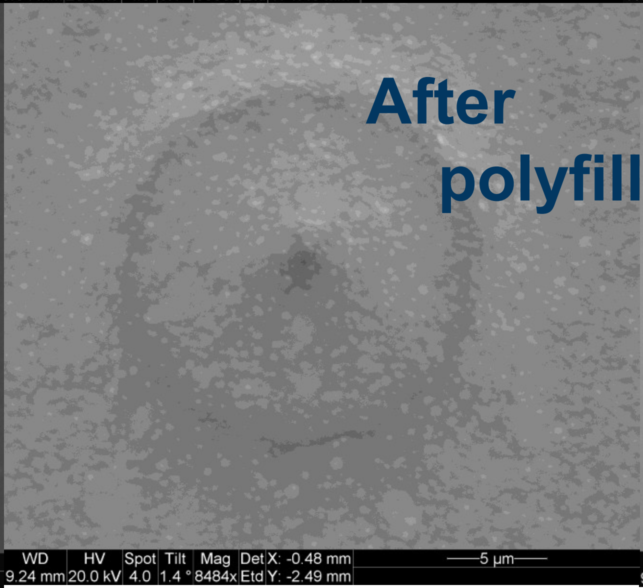




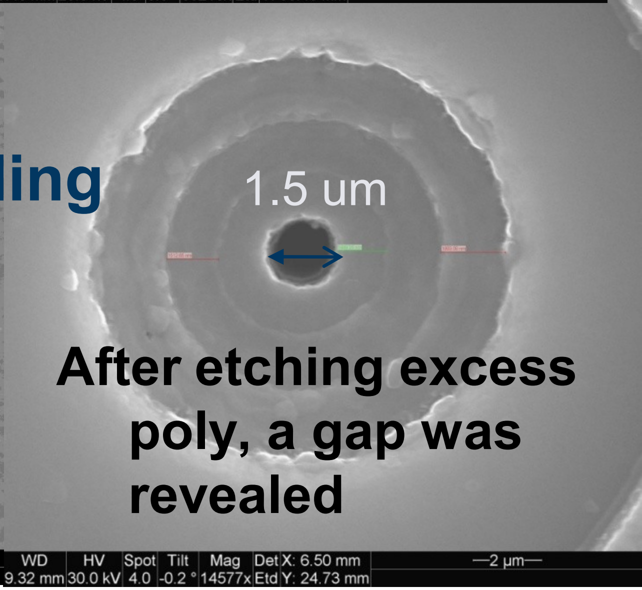




Before poly filling – holes ~13.5um wide

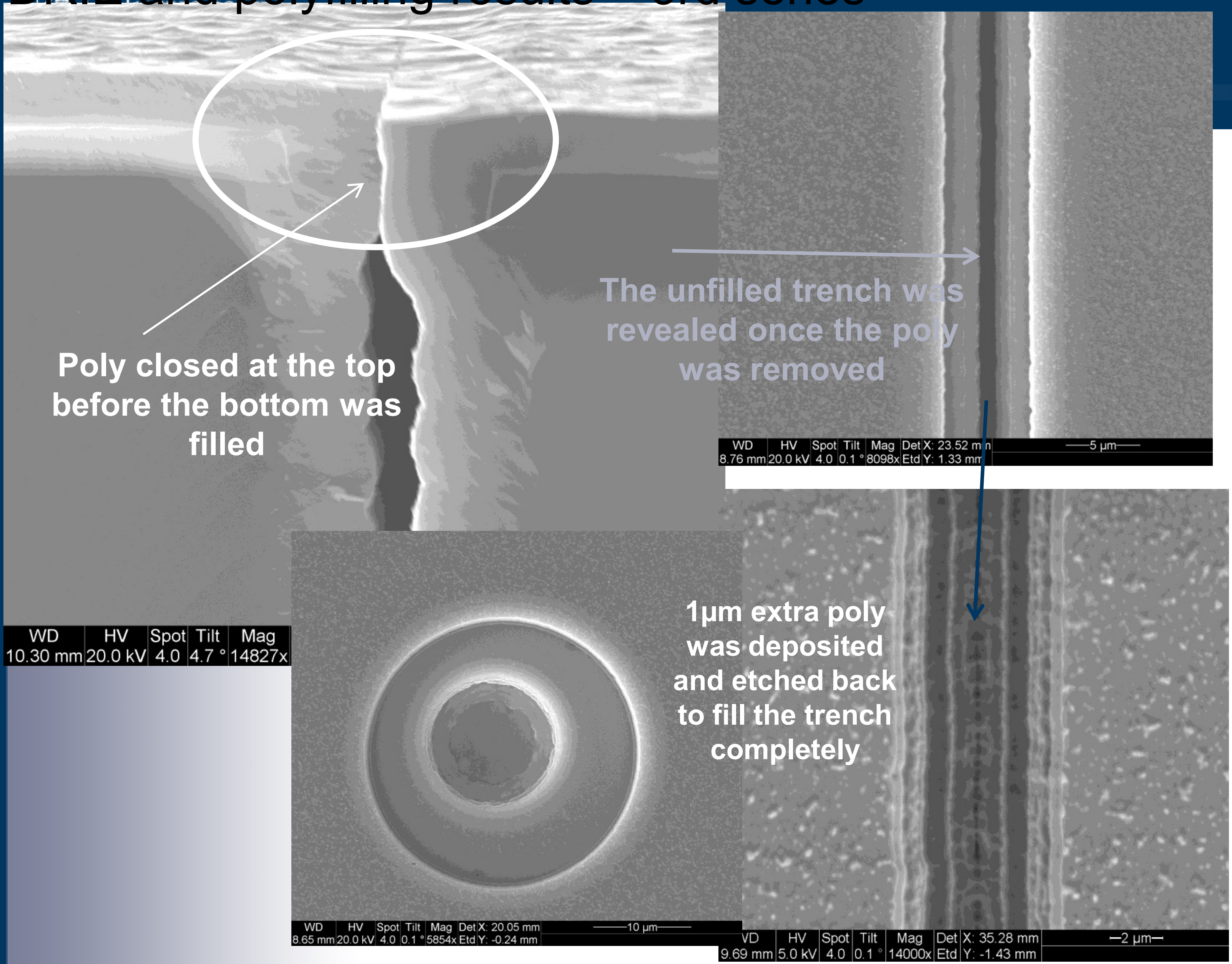


After polyfilling



After etching excess poly, a gap was revealed

DRIE and polyfilling results – 3rd series

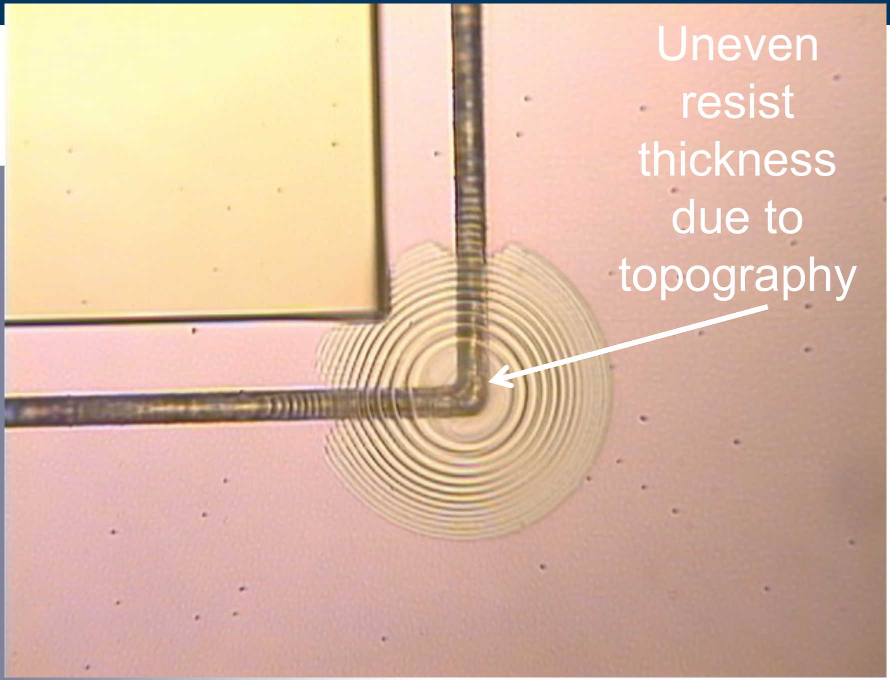


Poly closed at the top before the bottom was filled

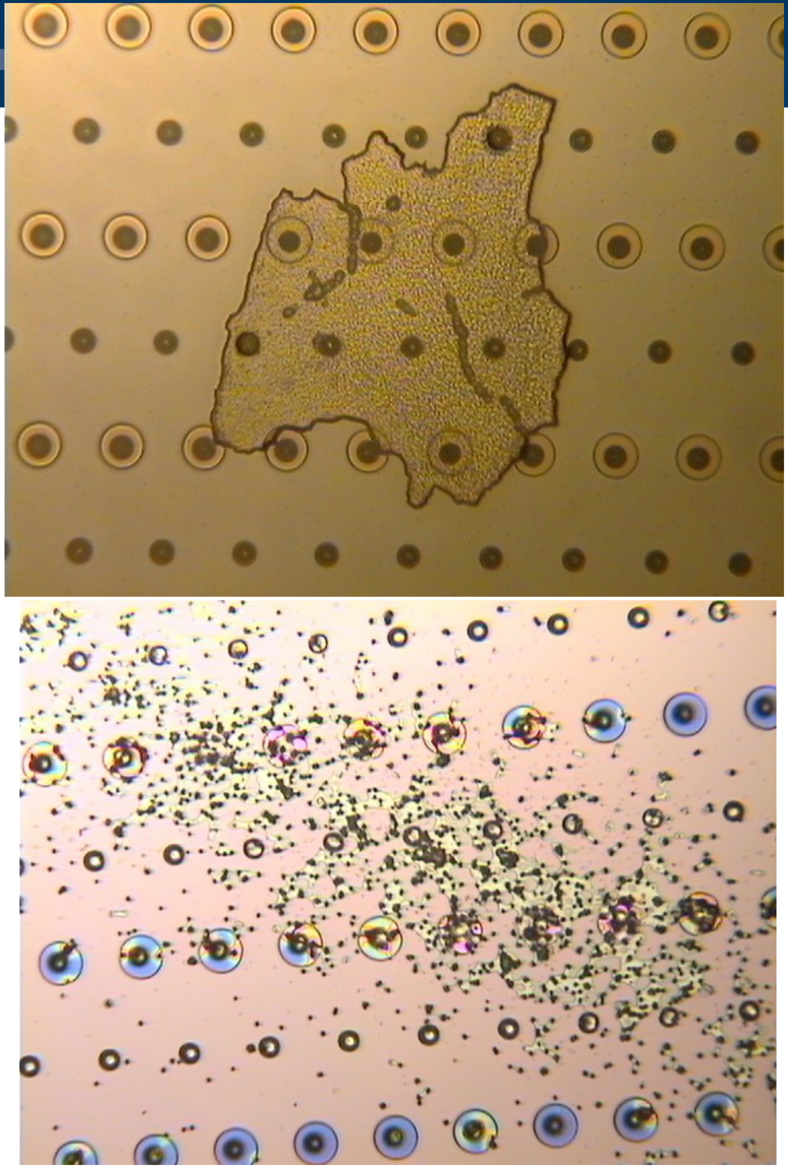
The unfilled trench was revealed once the poly was removed

1µm extra poly was deposited and etched back to fill the trench completely

Further Yield Factor Observed

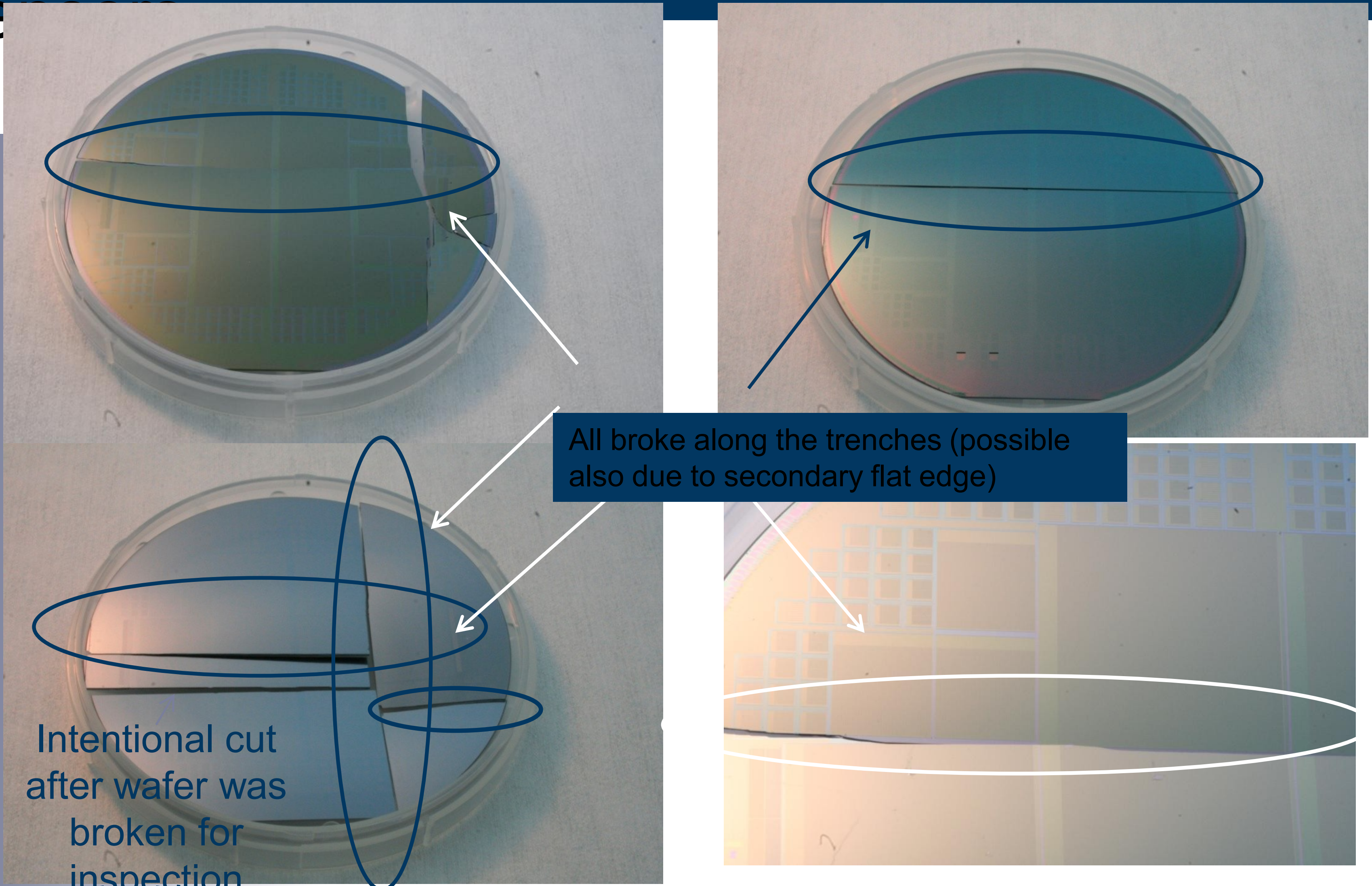


Uneven resist thickness due to topography



- Poly residue
  - Risks of short circuits
  - But overetch would destroy electrodes
- Topography makes litho difficult
- Chemical mechanical polishing could help

Yield factor when processing larger FE-I4 se

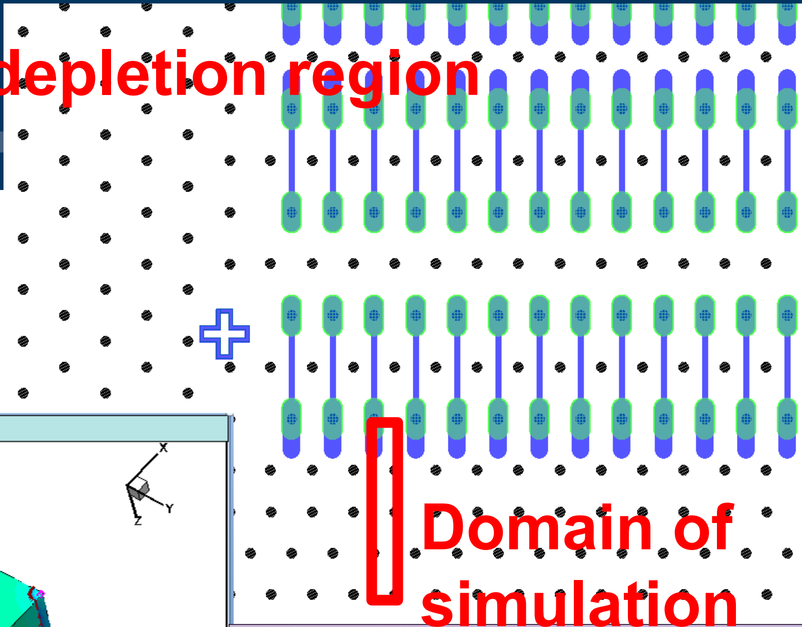


All broke along the trenches (possible also due to secondary flat edge)

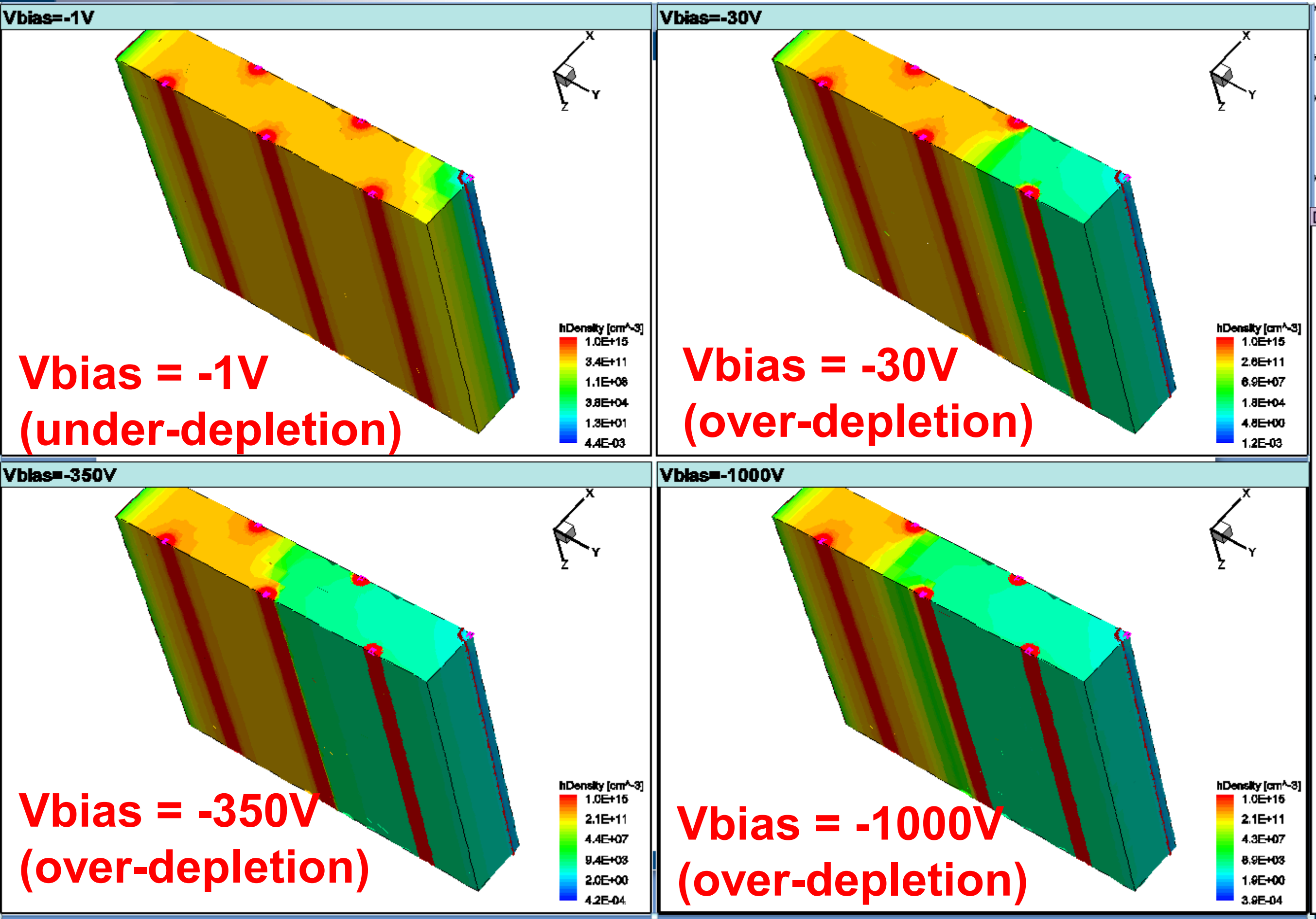
Intentional cut after wafer was broken for inspection

Simulation of guard fence

Simulation of the depletion region



Domain of simulation

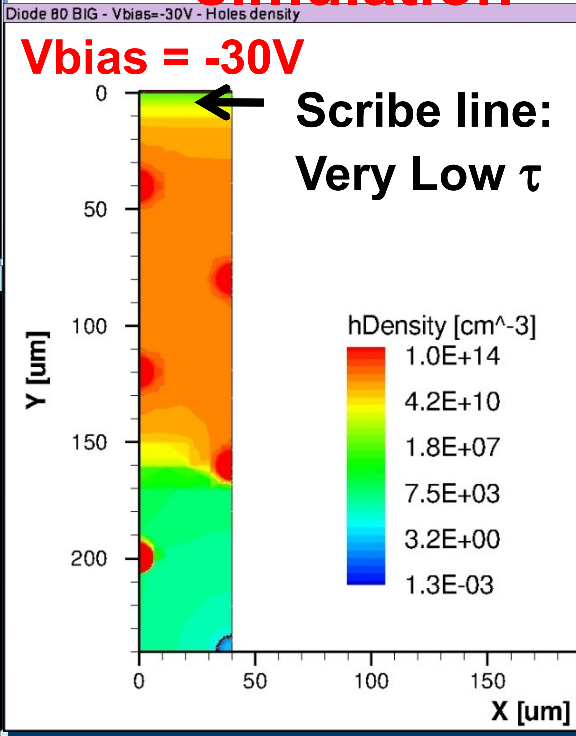


Vbias = -1V (under-depletion)

Vbias = -30V (over-depletion)

Vbias = -350V (over-depletion)

Vbias = -1000V (over-depletion)



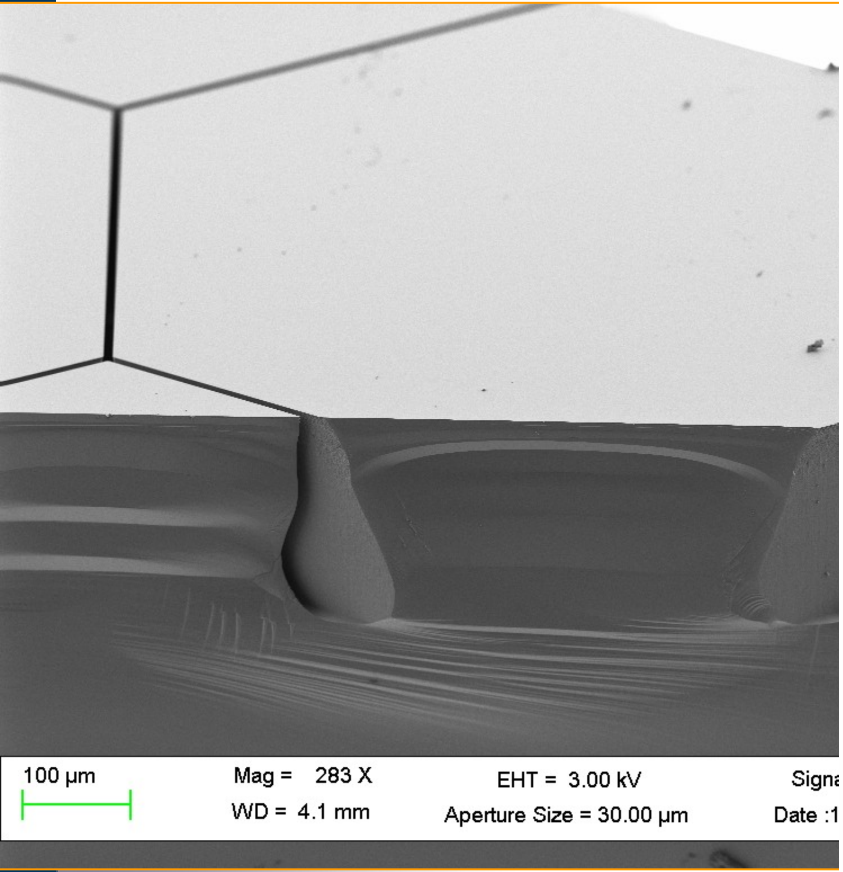
Vbias = -30V

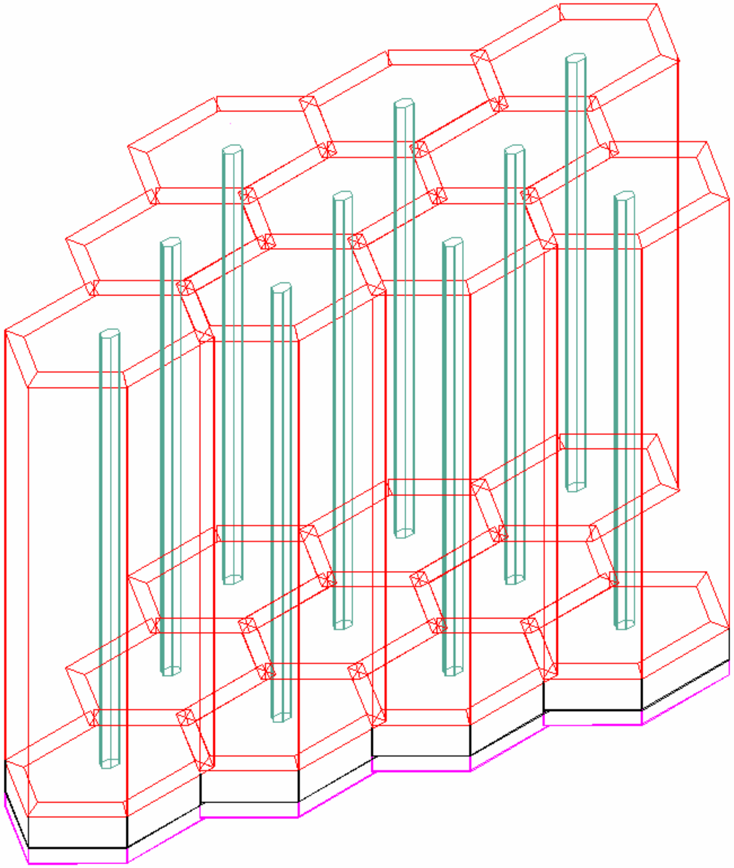
Scribe line: Very Low τ

Other 3D structures

Trenched 3D

Concept of the new Independent Coaxial Detector Array (ICDA), proposed by Zheng Li (BNL)



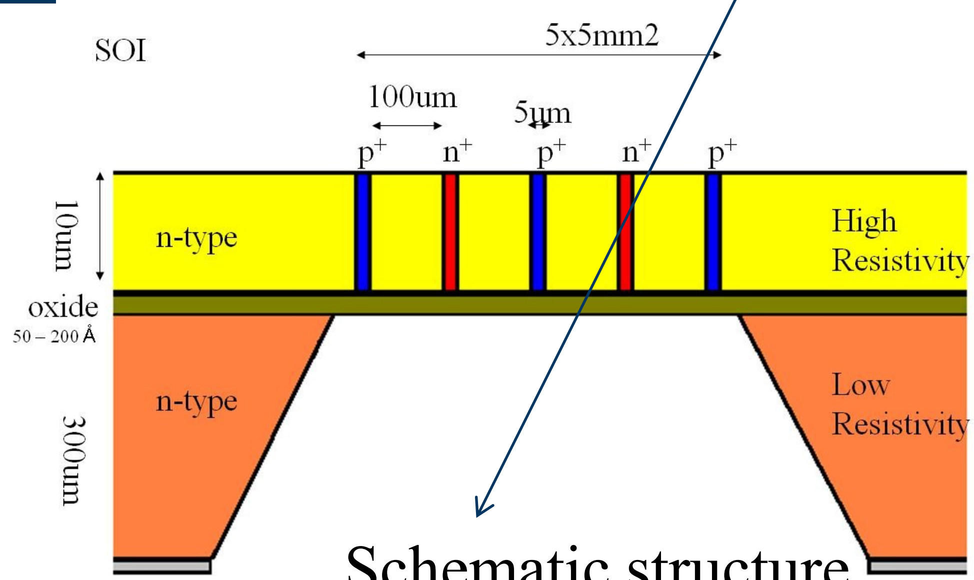


Test runs already done

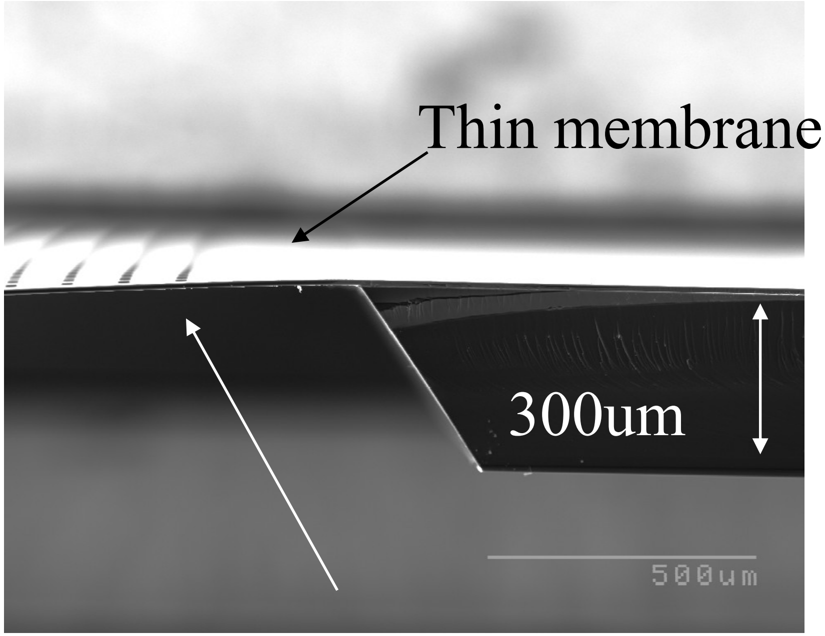
Fabrication run started

Thin 3D detectors

Tracking of ions is possible



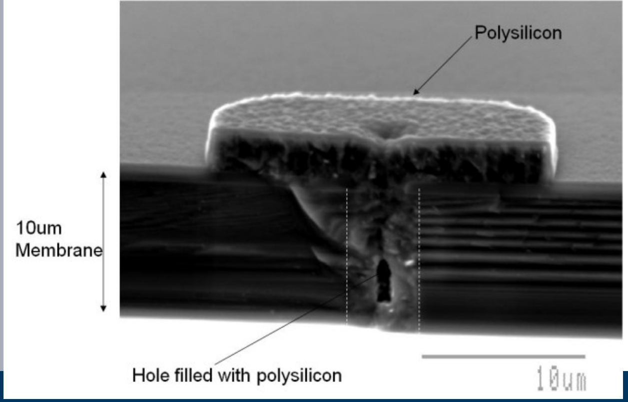
Schematic structure



Thin membrane

300um

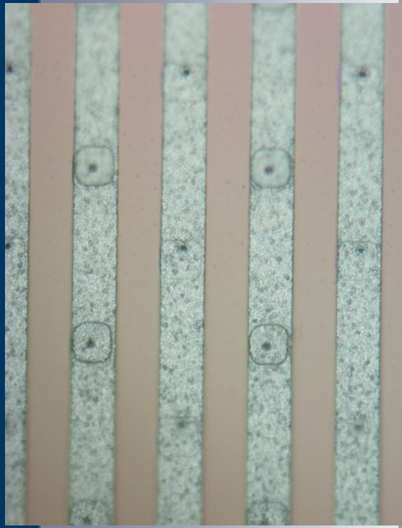
Etched backside

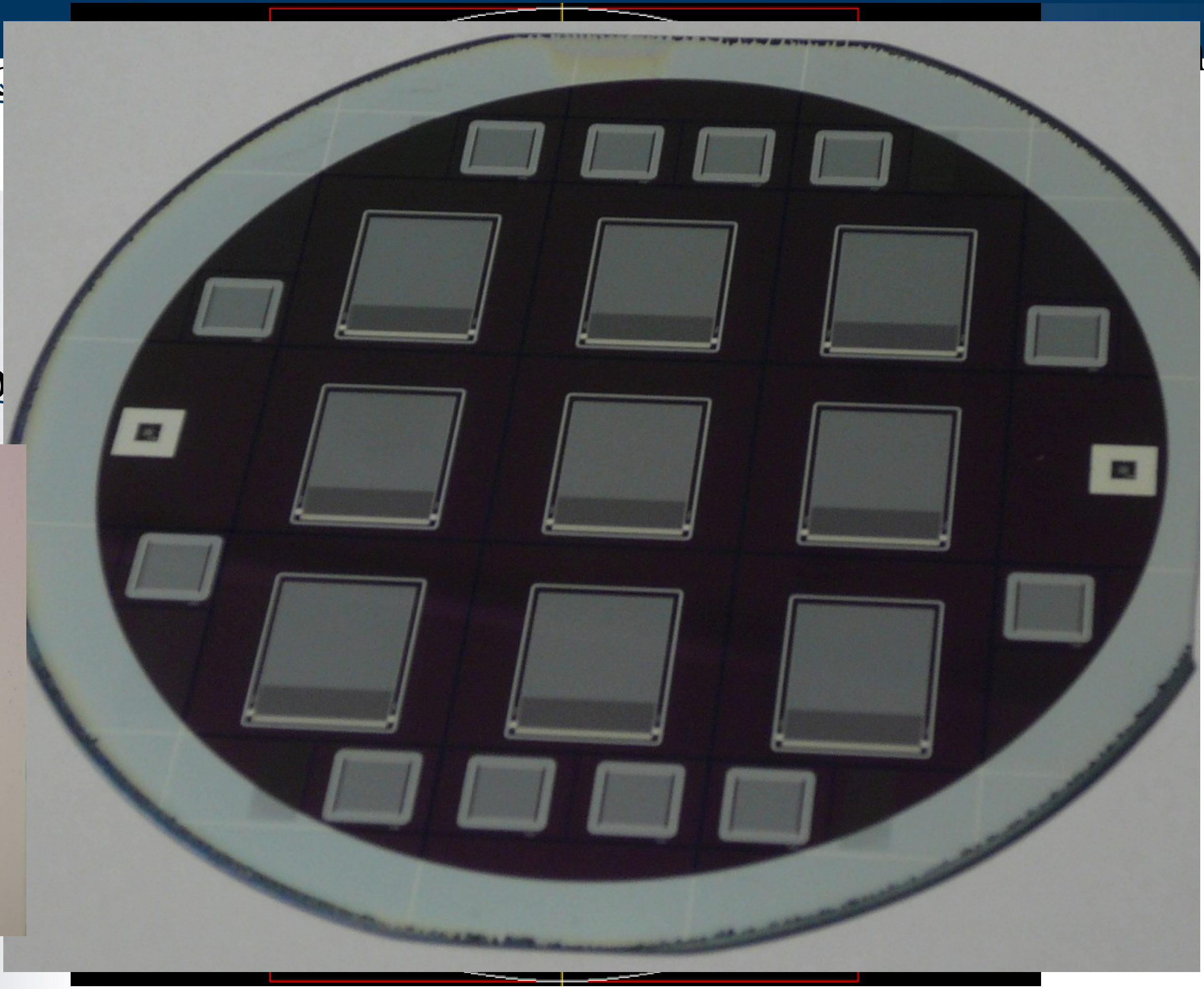


Thick pa

in pads

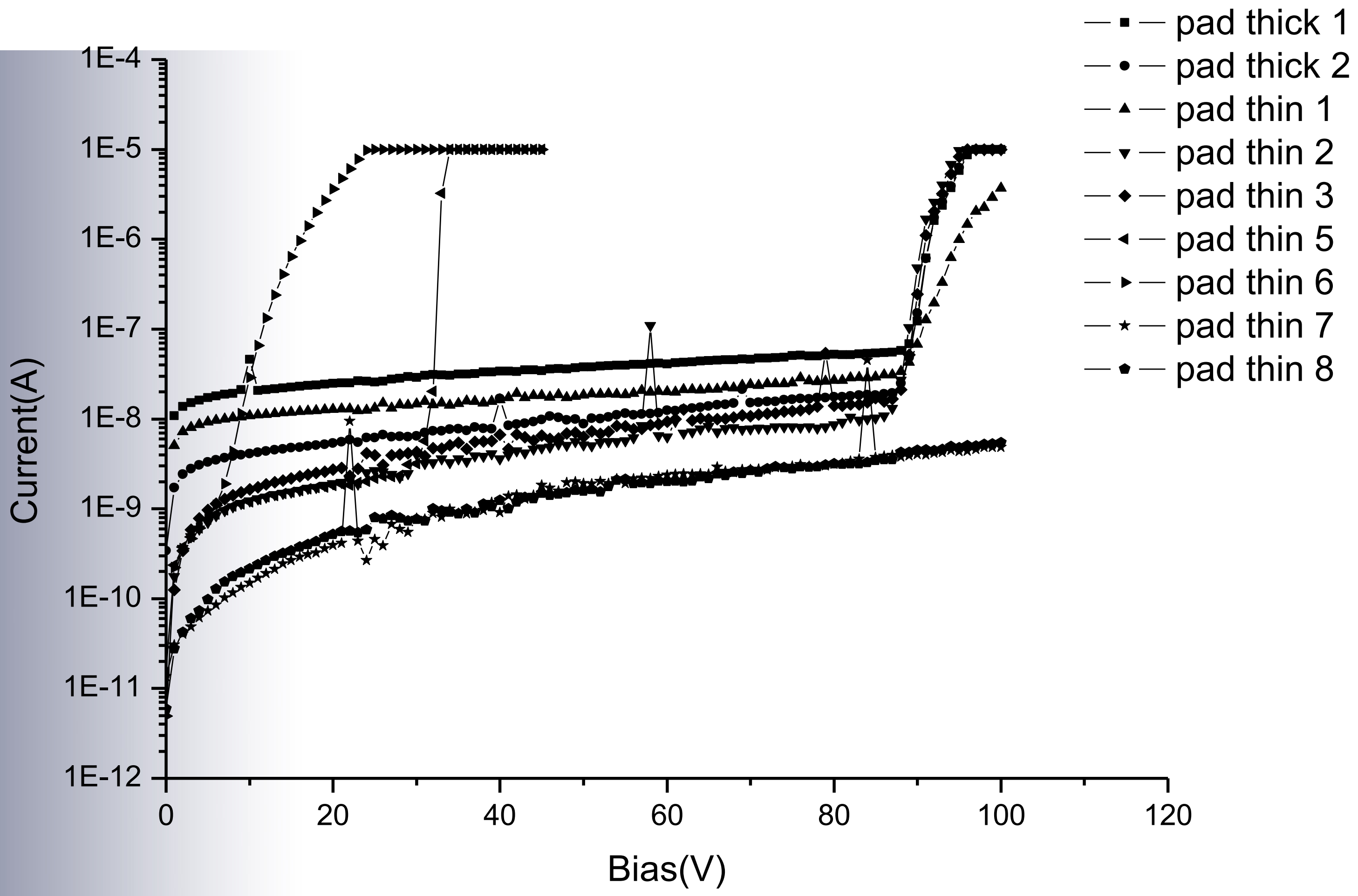
Thin strip



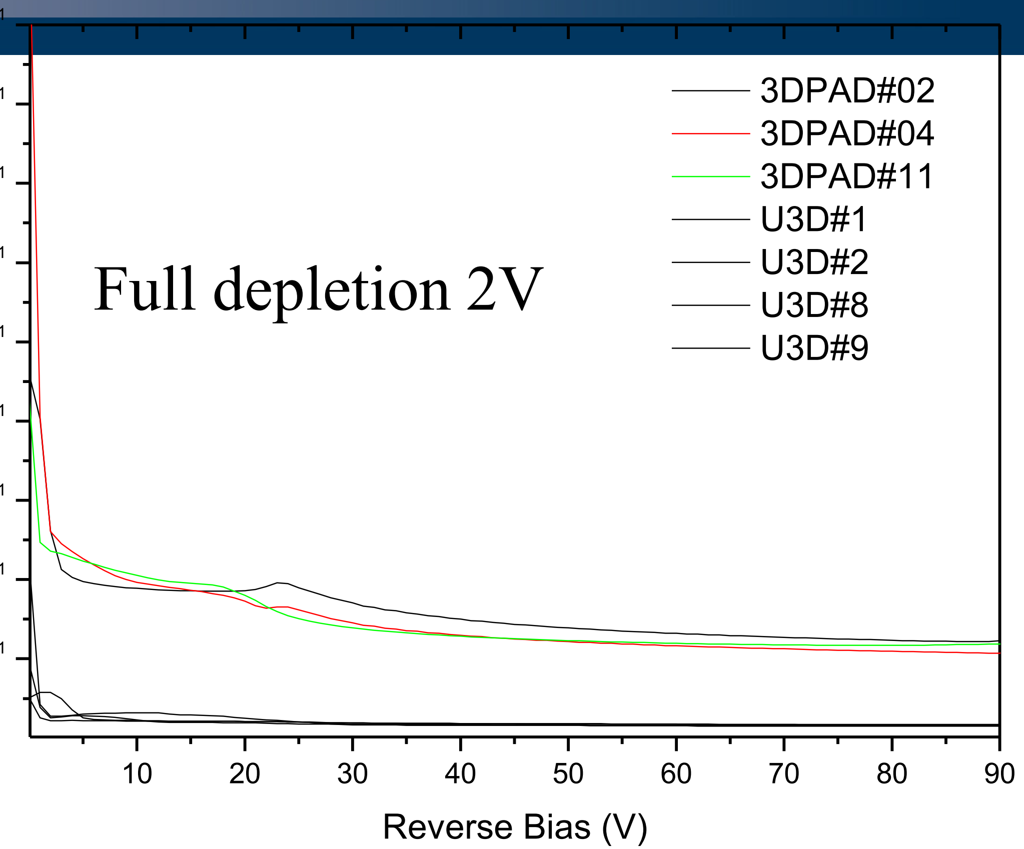


4 wafers fabricated and all working

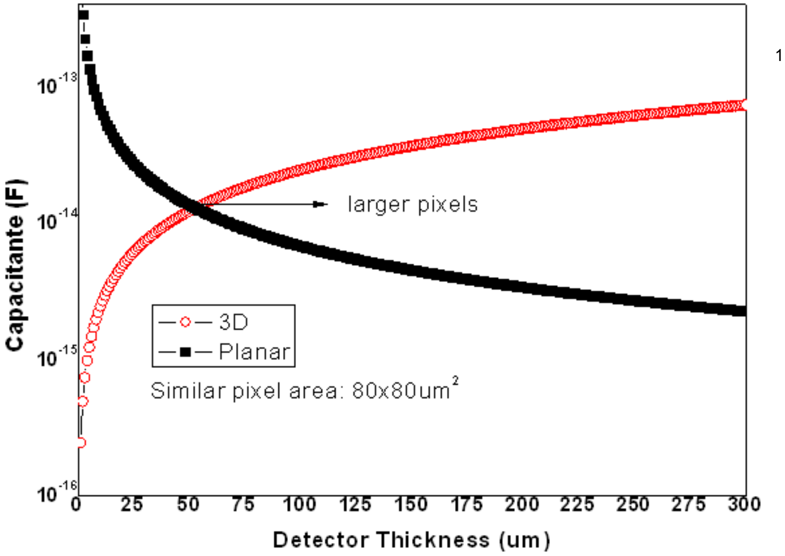
I-V characterization



CV mesurements



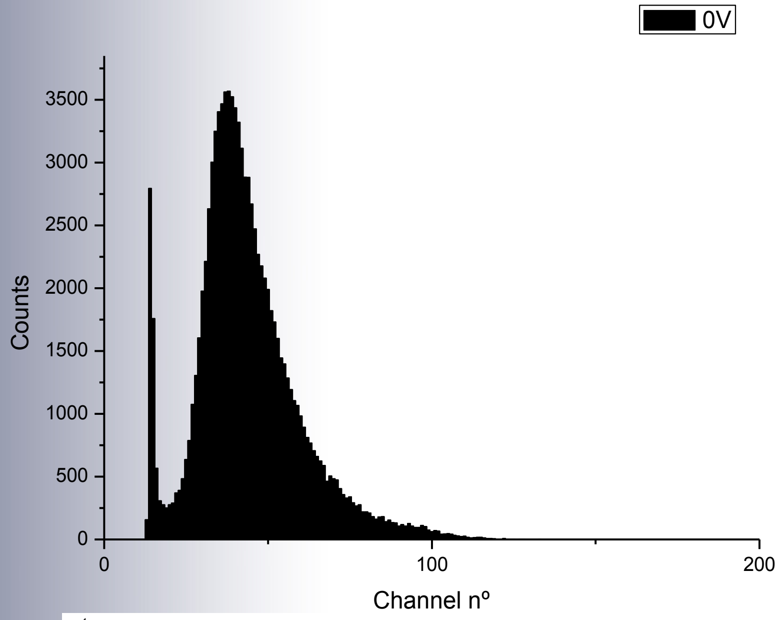
Full depletion 2V

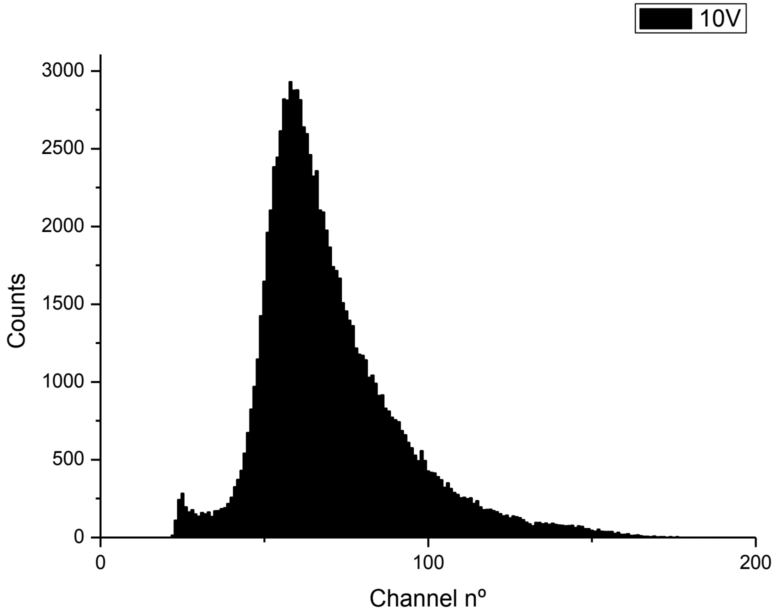


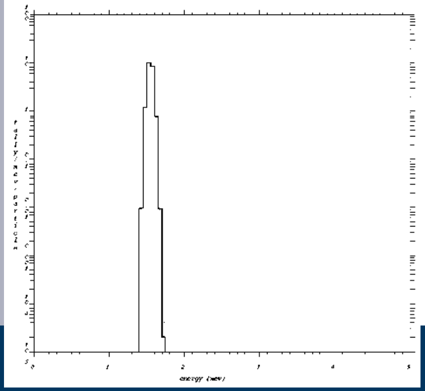
Capacitance of thin 3D is smaller than thin planar

Alpha particles

Alpha particles measured from an Am source.
Particles do not stop but deposit 1,5MeV in 10um Si



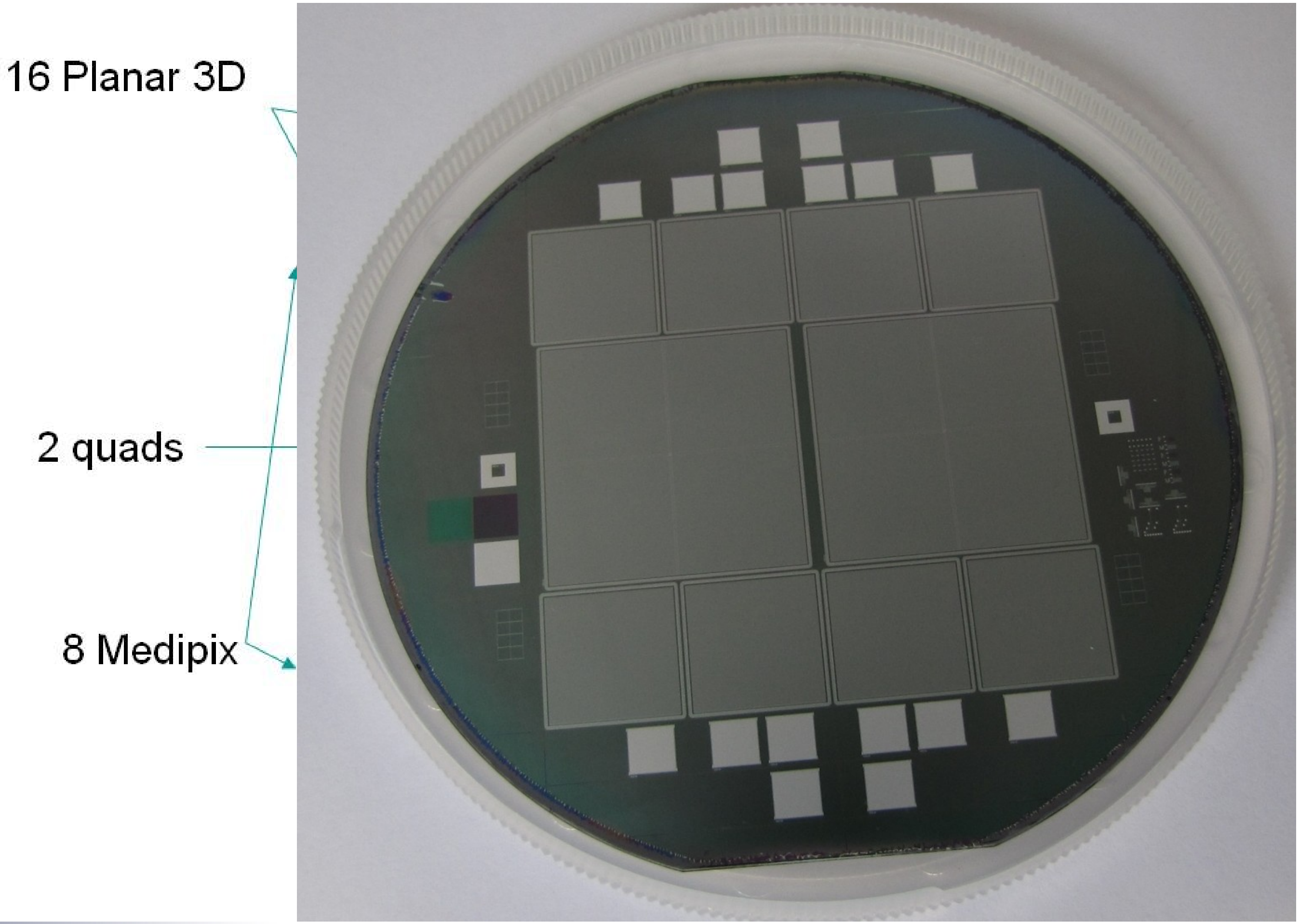




Preliminary simulation

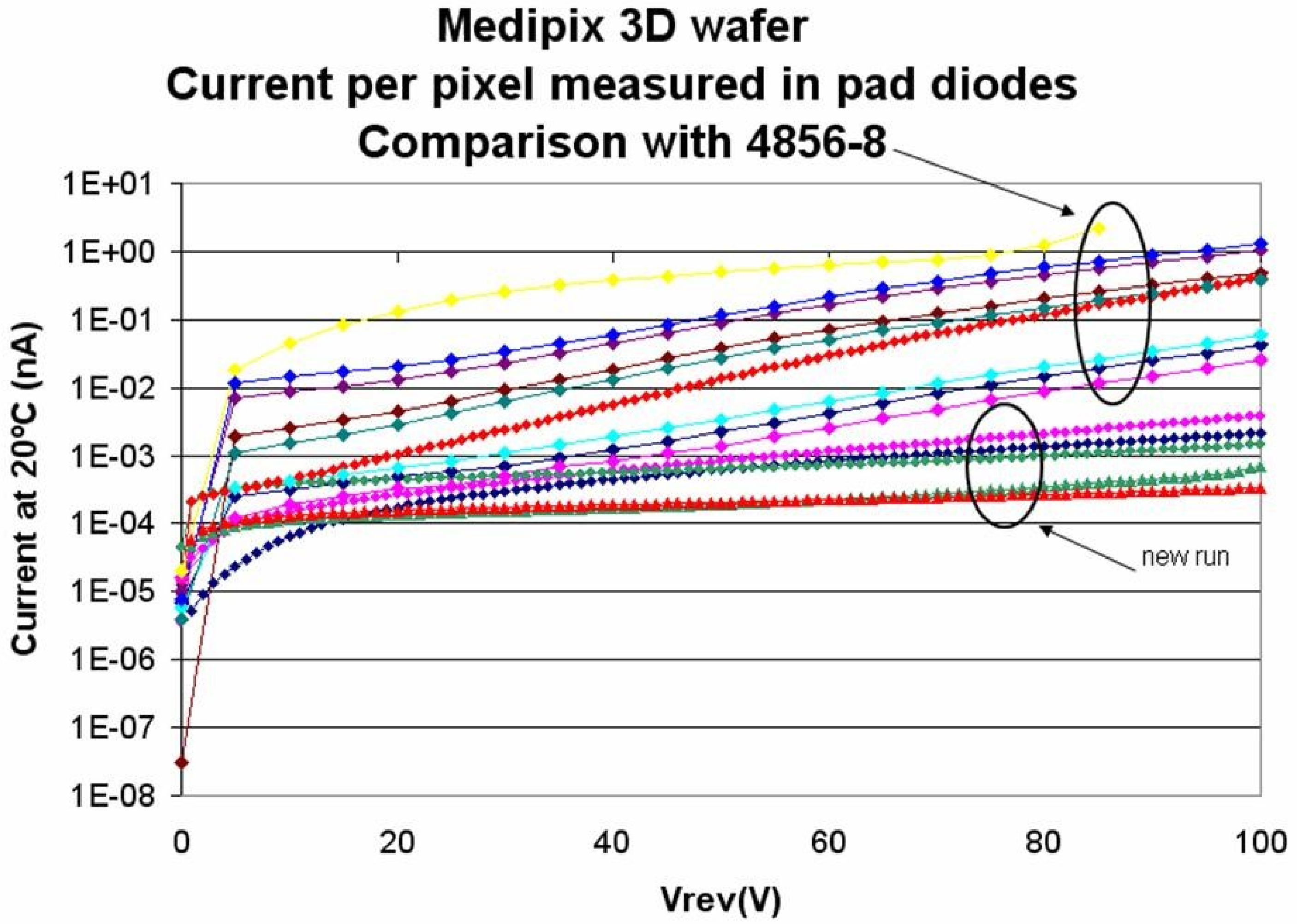
MCNPX, 10e6 alphas (5MeV), threshold 100KeV

3D pixel detectors for Medipix3 chip



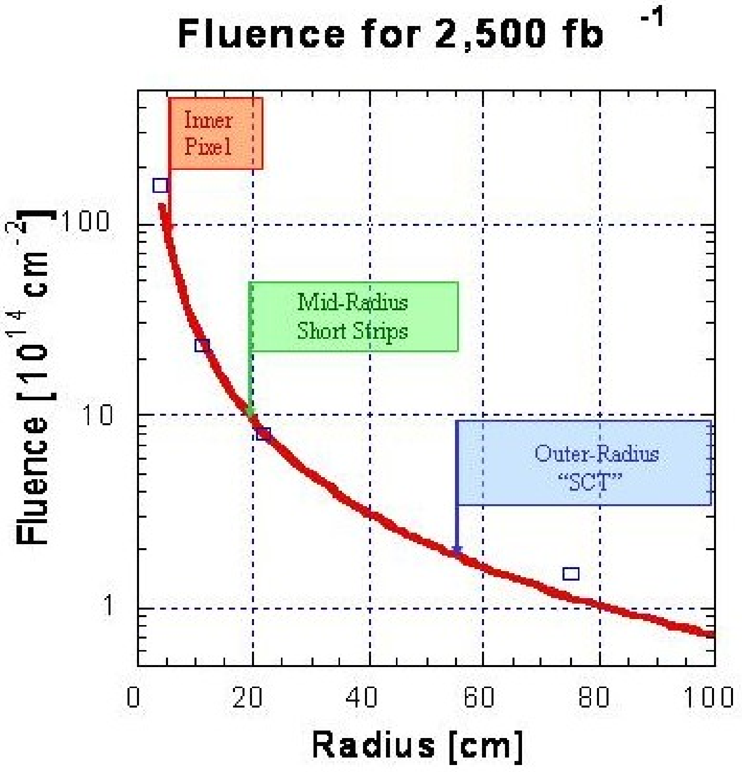
Second fabrication run 6 out of 10 wafers finished.
Double sided 3D detectors 285um thick.

Characterizations



90x90 pixels

Motivation for radiation hard sensors

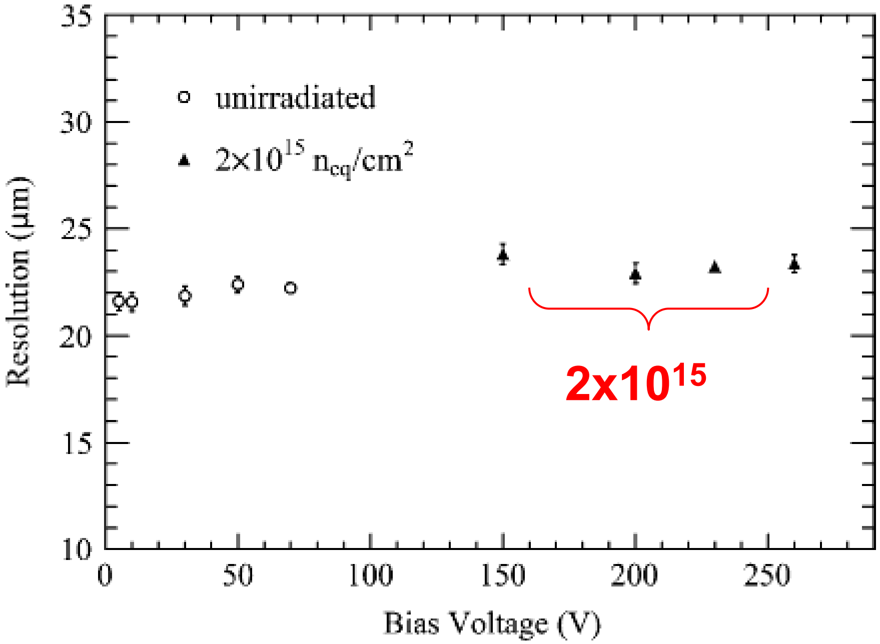


- Factor of 10 luminosity upgrade of LHC to HL-LHC to extend physics programme
- Radiation damage increase in proportion to integrated luminosity
- Need to optimise silicon detector design to survive

- **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**

80um pitch 3D strips: 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 and have not had any eta correction applied

Beam Test Measurements With Planar and 3D Silicon Strip Detectors Irradiated to sLHC Fluences. Nuclear Science, IEEE Trans. Nucl. Sci., Vol. PP, Issue 99, pgs. 1 - 7

SI Beam Telescope

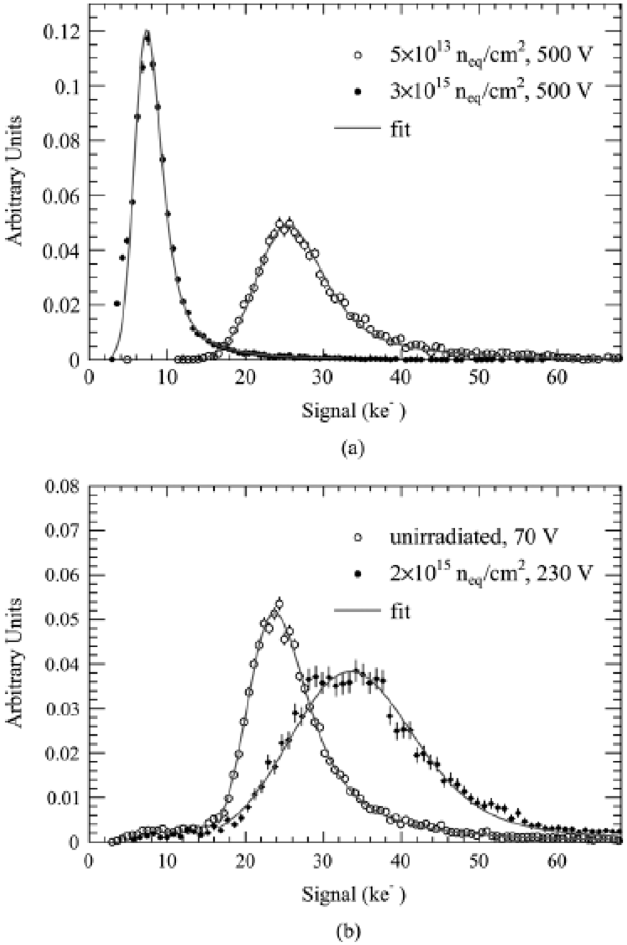


Fig. 2. Normalized signal distributions for different irradiation fluences (a) measured with planar detectors and (b) measured with 3D detectors. The fit superimposed is a convolution of a Landau function and a Gaussian.

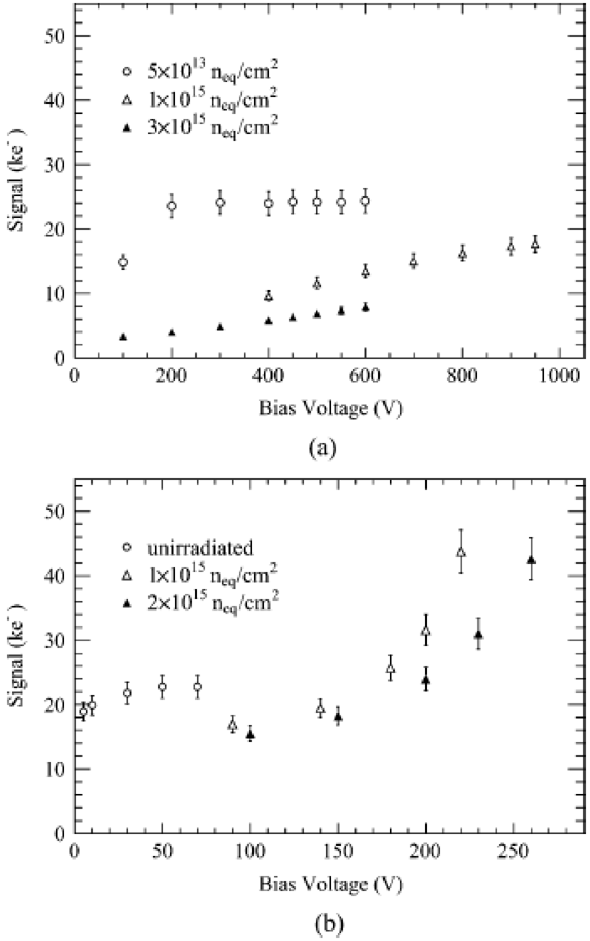
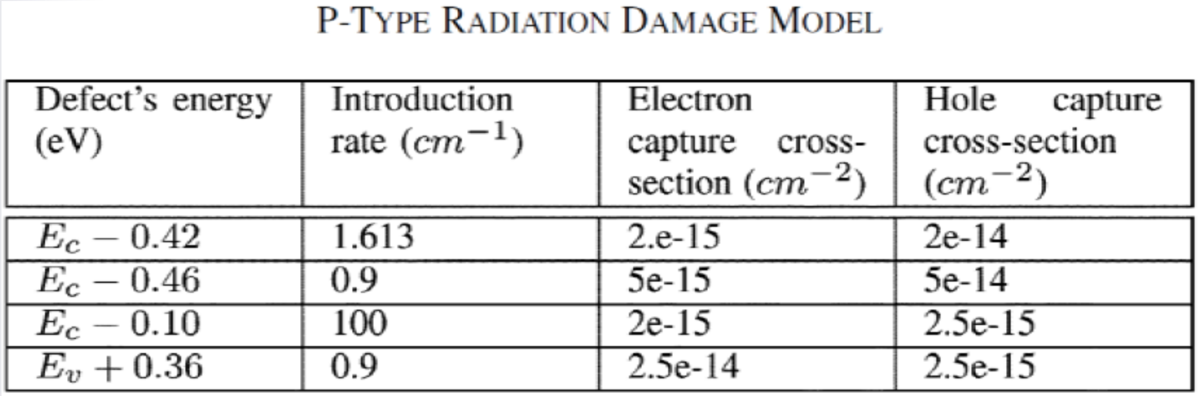


Fig. 3. Signal as a function of the applied bias voltage for different irradiation fluences (a) measured with the planar sensors and (b) measured with the 3D sensors. The errors are dominated by a systematic contribution due to the calibration uncertainty.

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

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

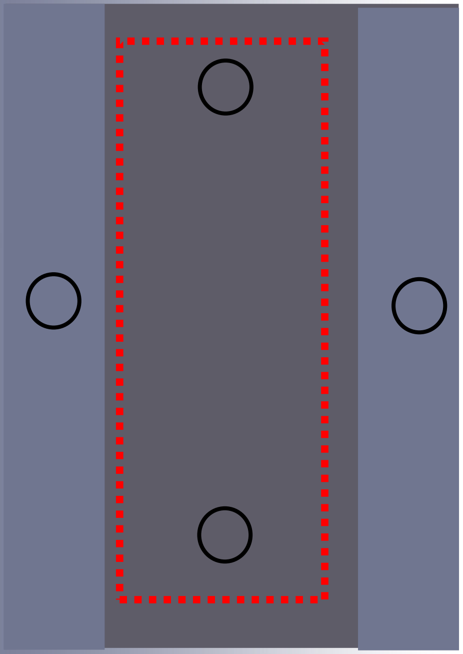
Defect's energy (eV)	Introduction rate (cm^{-1})	Electron capture cross-section (cm^{-2})	Hole capture cross-section (cm^{-2})
$E_c - 0.42$	1.613	2.e-15	2e-14
$E_c - 0.46$	0.9	5e-15	5e-14
$E_c - 0.10$	100	2e-15	2.5e-15
$E_v + 0.36$	0.9	2.5e-14	2.5e-15

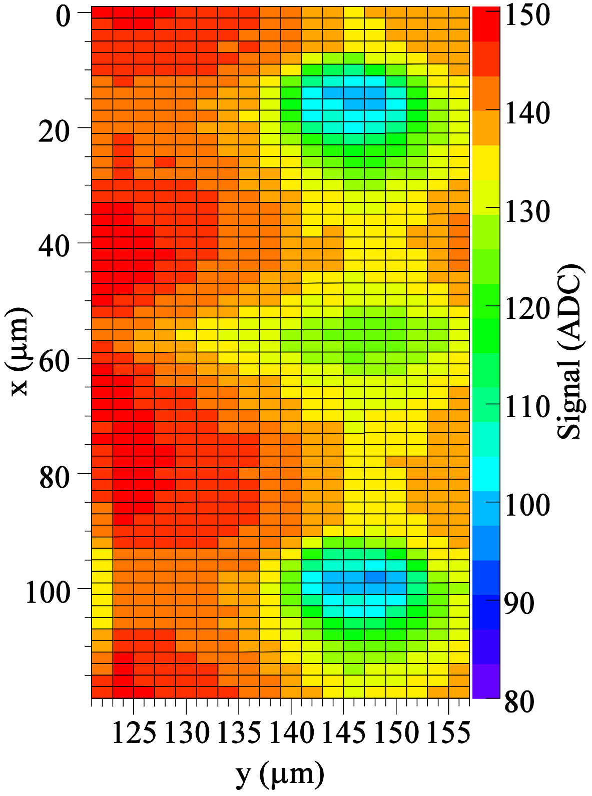
J.P. Balbuena et al., 6th Trento Workshop 2011

Mapped CCE with scanned laser

Laser scanning

Bias:150V
Fluence: 1×10^{15} 1 MeV n_{eq} cm^{-2}
Sr-90 measured ~100% of Q_o collected

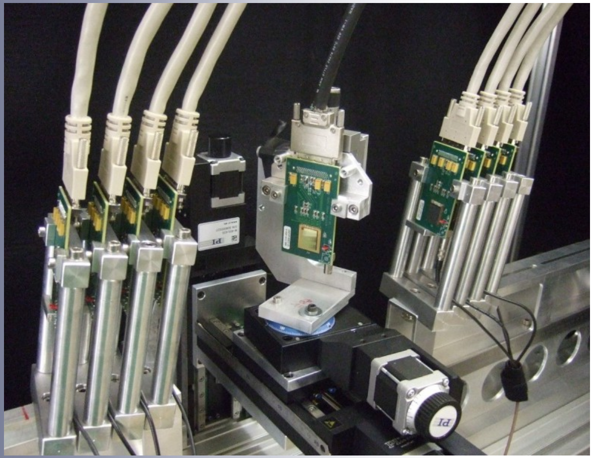




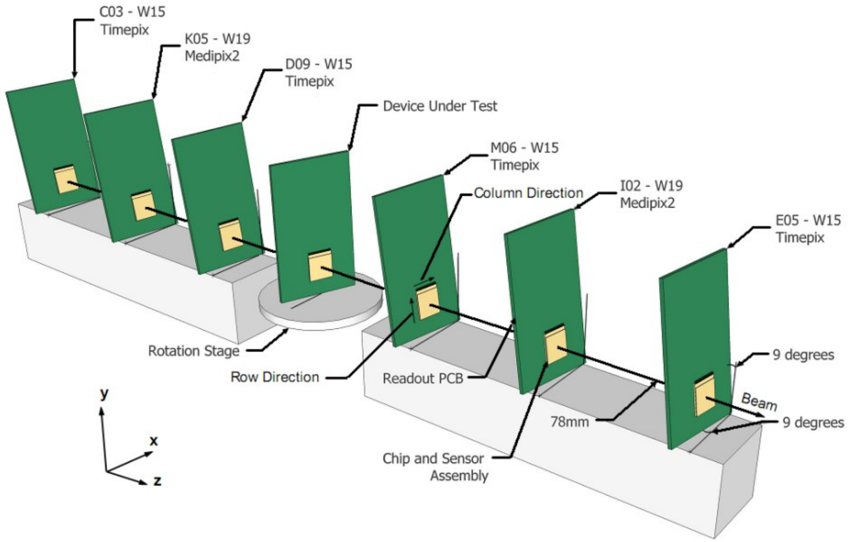
- Two p+ columns evident
- Non-uniform charge collection outside of column position
- Area of low charge collection between the n+ contacts were a low field is present
- Low field areas have greater probability of charge trapping

Precision scans of a 3D pixel cell

Timepix Telescope



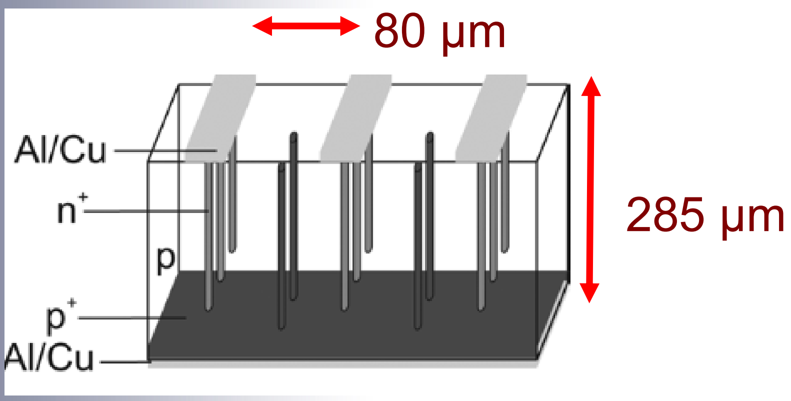
- TimePix/Medipix chips: 256*256 55µm square pixels
- Energy deposition provided by Time over Threshold in TimePix
- 120 GeV pion beam from SPS
- Device under test (DUT): double sided 3D N-type pixel sensor
- DUT on high resolution rotational and translational stage



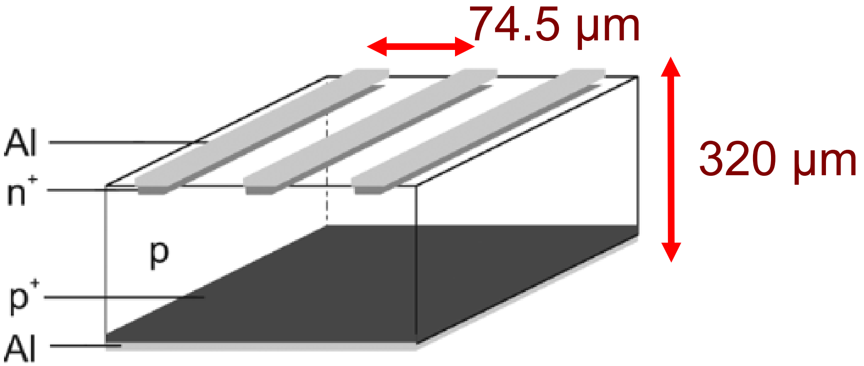
Strip devices

Electrical measurements

3D



Planar



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

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

3D devices

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

Inter-strip resistance 100MΩ

Leakage current scales as expected

FE-I4 pre-production runs

- 8 sensors per wafer
- Pre-production of 736 sensors by December 2011
- Production sensors : 400 ready in Jan 2012

- Yield
  - Difficult to define due to low stats
  - Better than 50%

	March	April	May	June	July	August	Sept	Oct	Nov	Dec	Jan	Feb	March
FBK A07-A09		**64**											
FBK A10					**176**								
FBK A11						**176**							
FBK A12											**200**		
FBK A13												**200**	
FBK A14													**200**
CNM Q1	**24**												
CNM P1								**192**					
CNM P2										**192**			
CNM P3											**200**		
CNM P4												**200**	
CNM P5													**200**