3D Silicon Radiation Sensors

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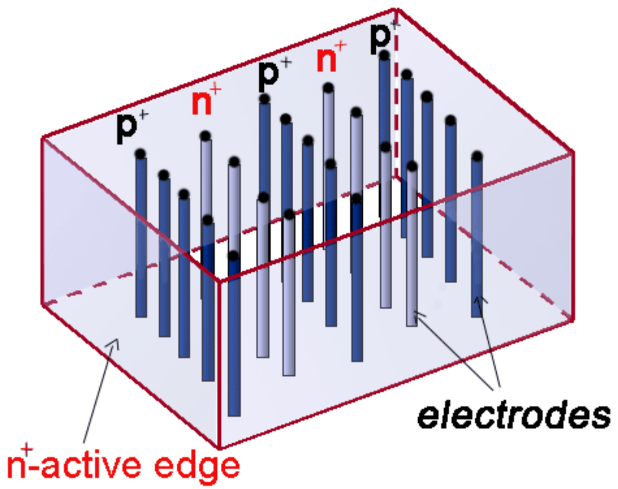
Outline

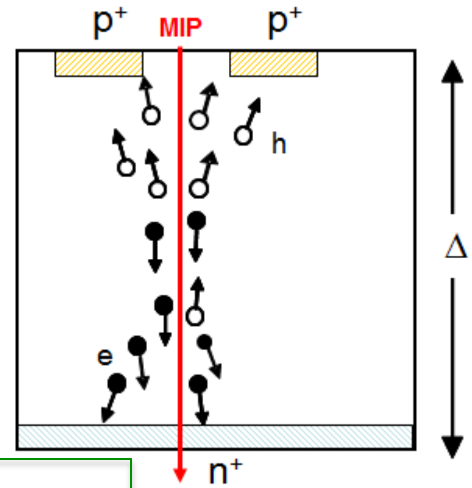
- Introduction
  - Overview of 3D sensors properties and technologies
- The ATLAS IBL project
- On going developments for HL-LHC
- 3D sensors for timing
- Conclusions

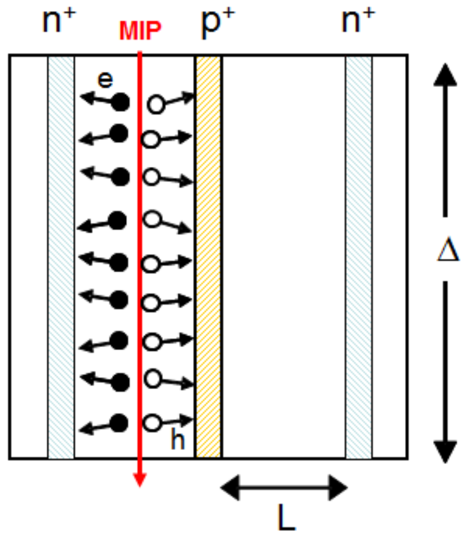
3D radiation sensors

S. Parker et. Al. NIMA 395 (1997) 328



Electrode distance (L) and active substrate thickness (Δ) are decoupled → L<<Δ by layout





ADVANTAGES:

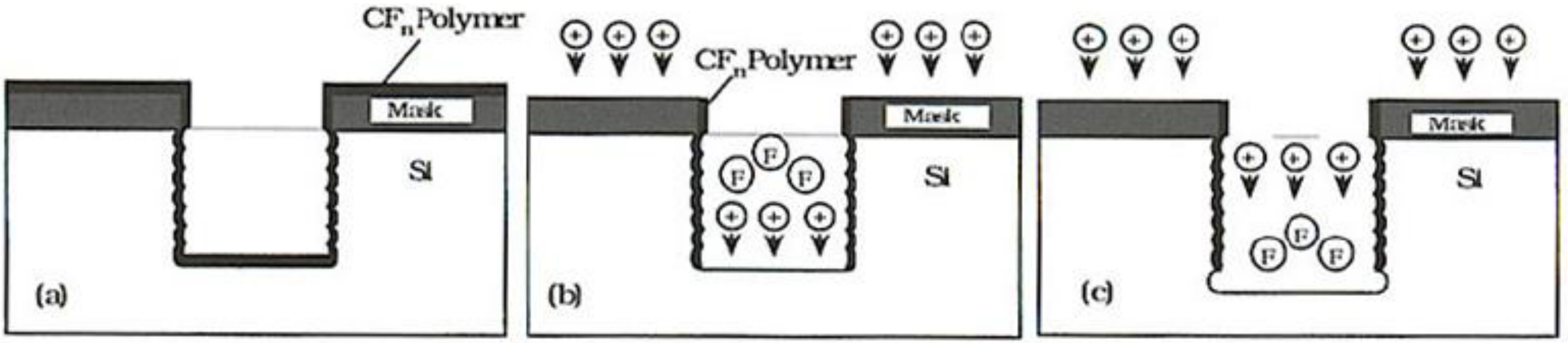
- Low depletion voltage (low power diss.)
- Short charge collection distance:
  - Fast response rise
  - Less trapping probability after irr.
- Lateral drift → cell "shielding" effect:
  - Lower charge sharing
  - Low sensitivity to magnetic field
- Active edges

→ **HIGH RADIATION HARDNESS**

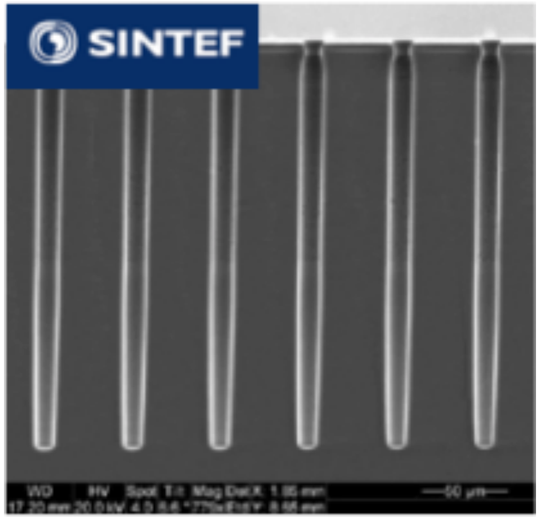
DISADVANTAGES:

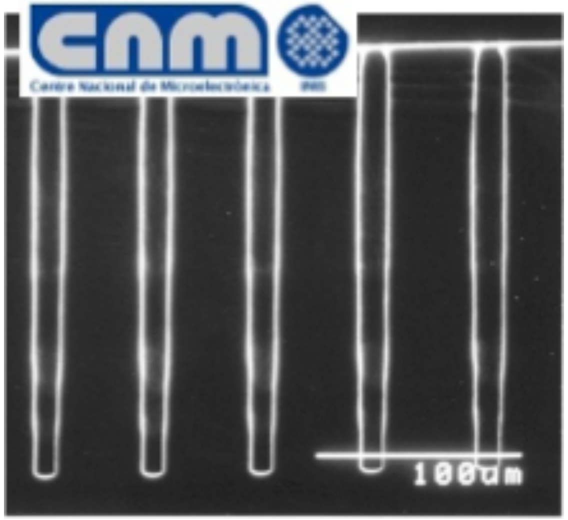
- Non uniform spatial response (electrodes and low field regions)
- Higher capacitance with respect to planar (~3-5x for ~ 200 μm thickness)
- Complicated technology (cost, yield)

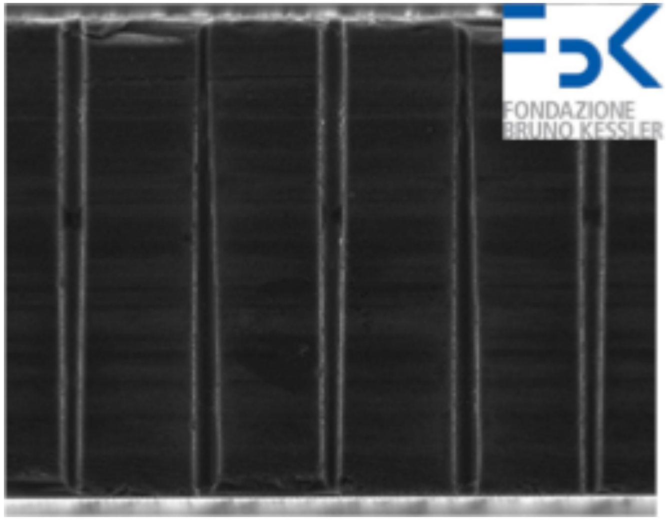
Key technology: DRIE by the Bosch process



- Alternating etch cycles (SF_6) and passivation cycles (C_4F_8)
- High aspect ratio (>20:1 or better for trenches) and good uniformity



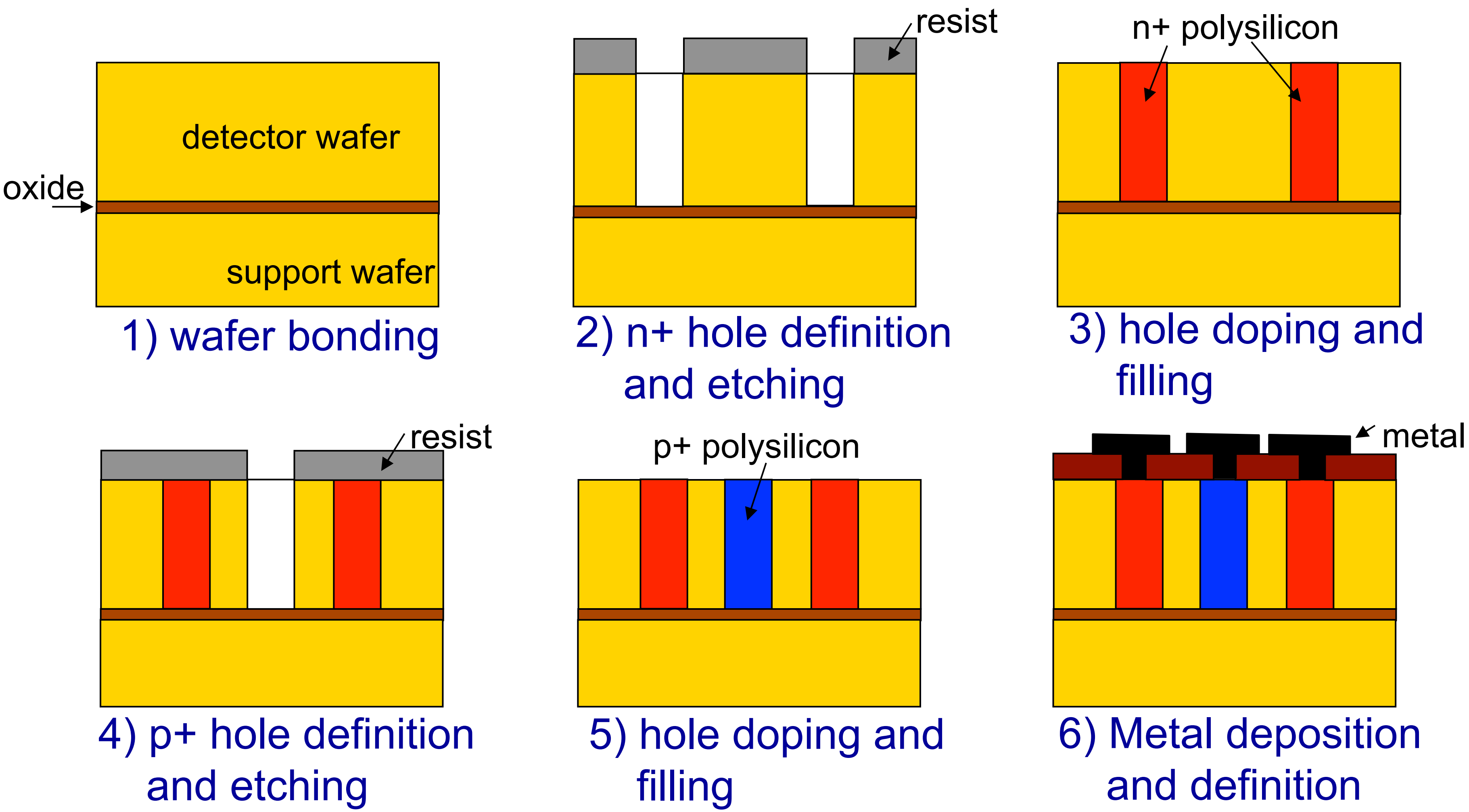




Original full-3D process

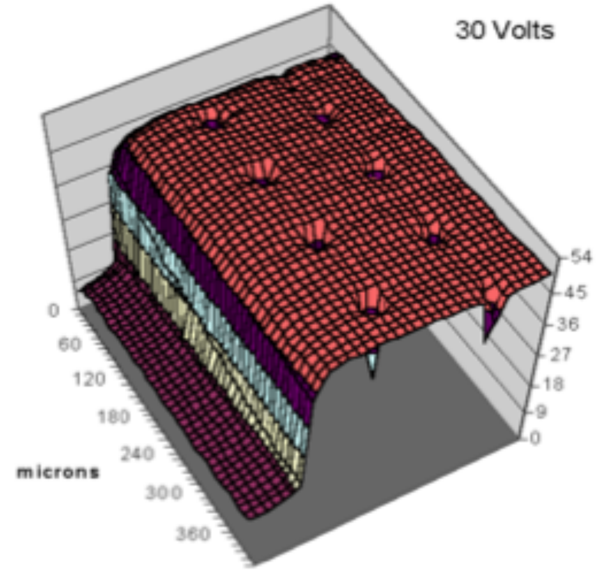
3D Consortium

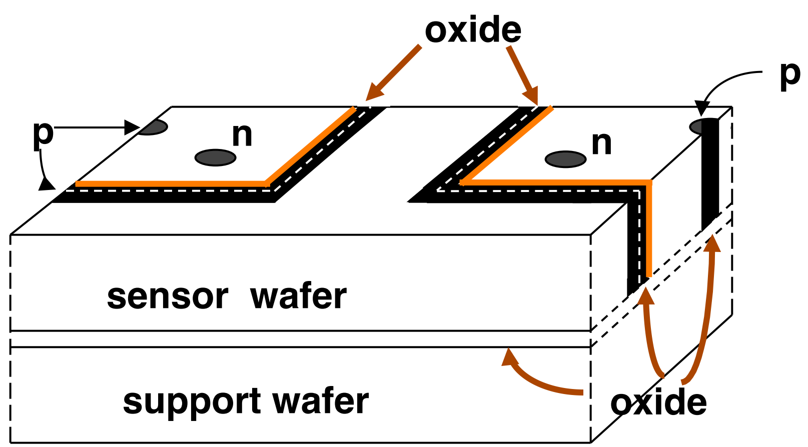
C. Kenney et al., IEEE TNS, vol. 46, n. 4 (1999) 1224
T.E. Hansen et al., JINST 4 (2009) P03010



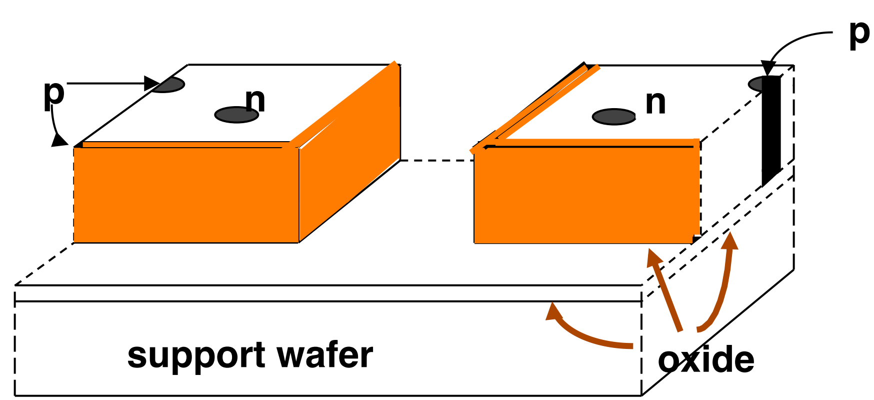
Active edges

- First introduced at Stanford as an extension of 3D sensor technology, later applied to planar sensors
- Cut lines are not sawed but etched with DRIE & doped as electrodes, arbitrary shapes possible
- Sensitivity up to a few μm from the physical edge, at the expense of additional process complication





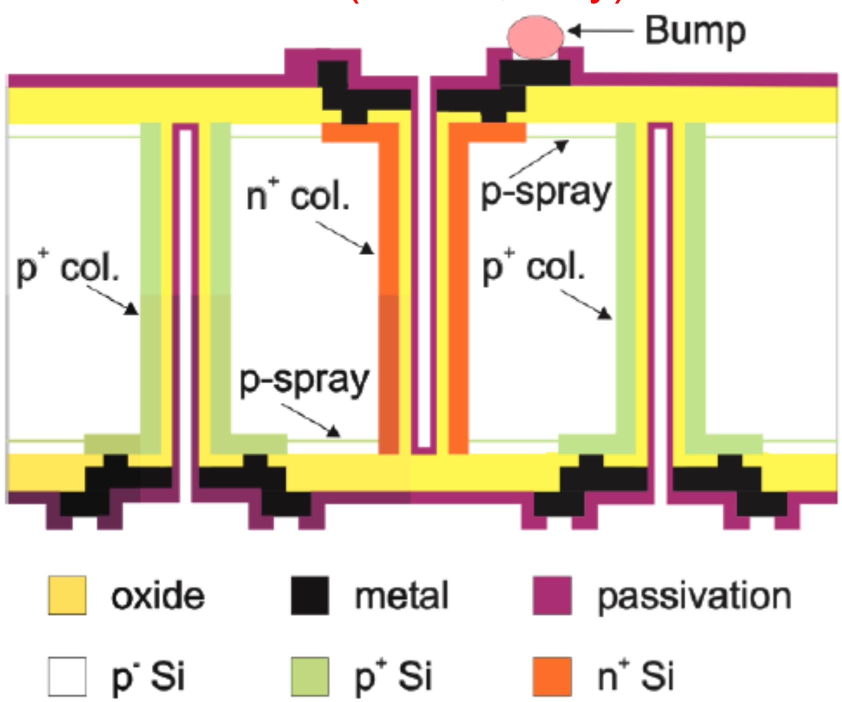
C. Kenney et al., IEEE TNS 48 (2001) 2405



C. Kenney et al., NIMA 565 (2006) 272

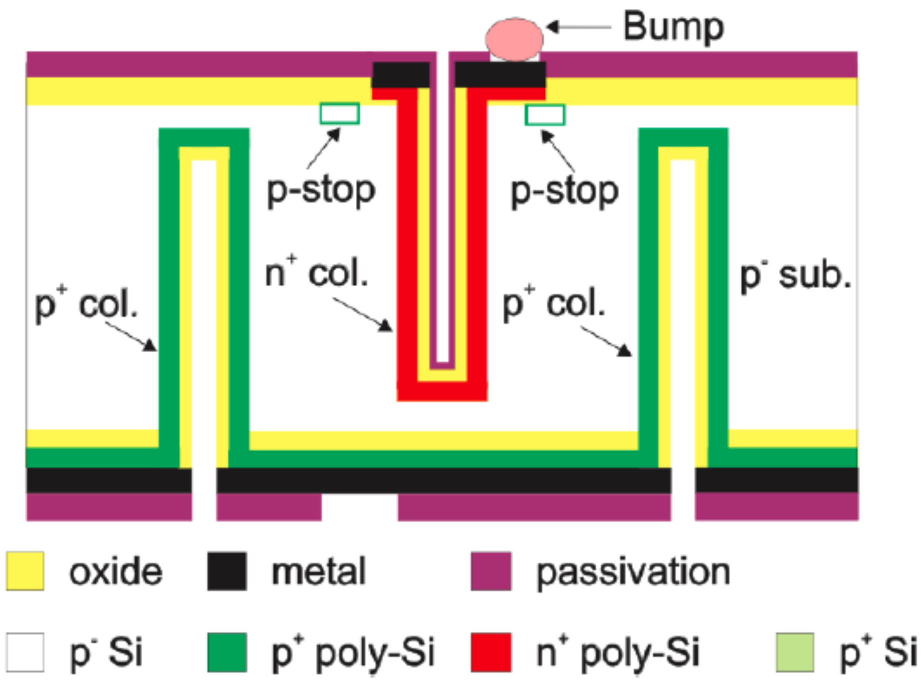
Double-sided 3D sensors

FBK (Trento, Italy)



A. Zoboli et. al., IEEE TNS 55(5) (2008), 2775
G. Giacomini, et al., IEEE TNS 60(3) (2013) 2357

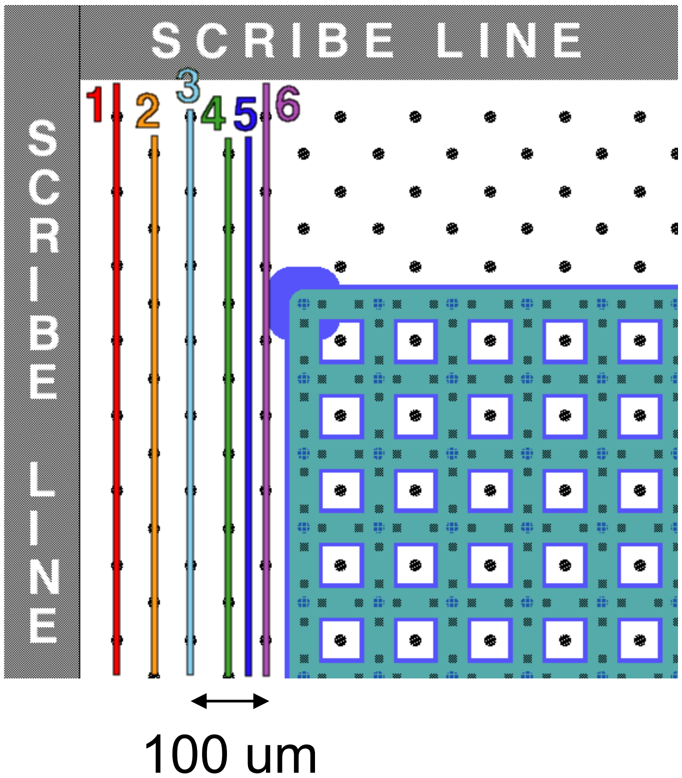
CNM (Barcelona, Spain)

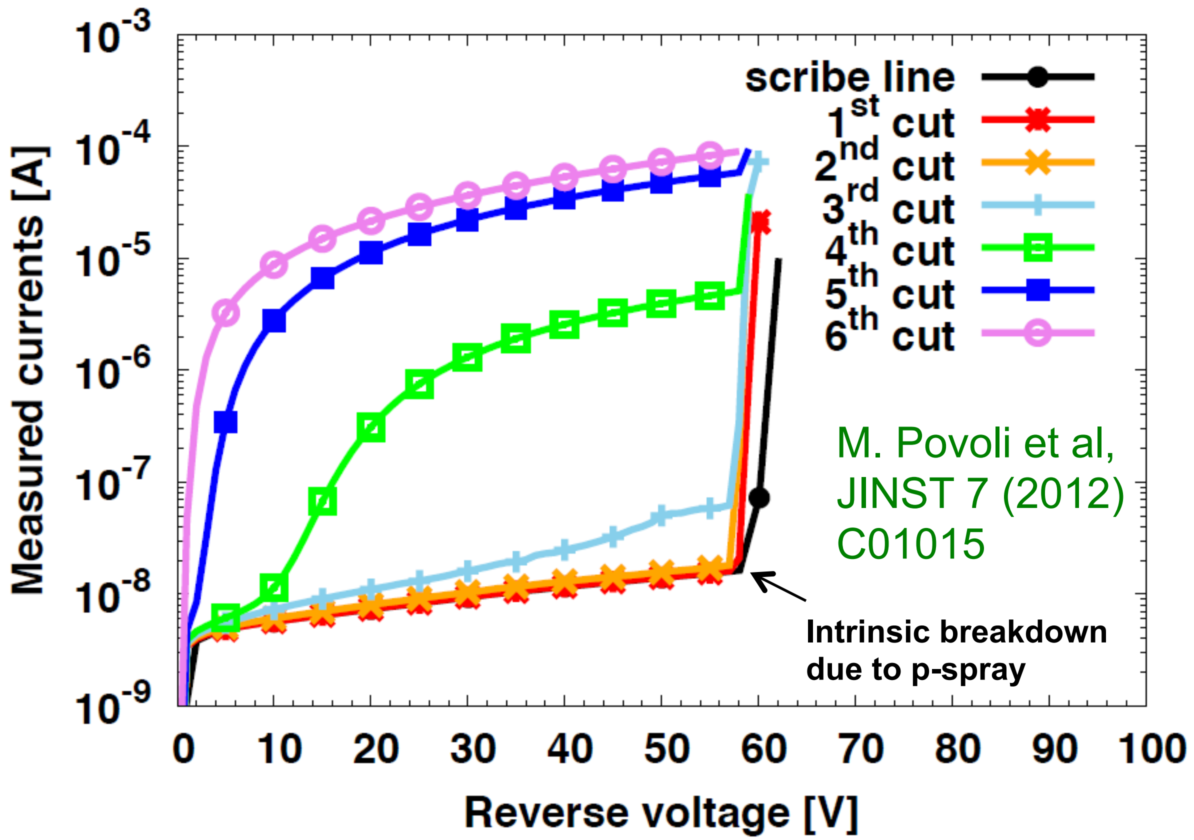


G. Pellegrini et. al. NIMA 592(2008), 38
G. Pellegrini et. al. NIMA 699(2013), 27

- Do not use support wafer → reduced process complexity
- Back-side accessible → Easier assembly within a detector system
- Active edge not feasible → Slim edge

Slim edge in double-sided 3D sensors





- Repeated cuts starting from scribe-line, each one closer to the active area (the 6th cut dices the last row of ohmic columns of the active area)
- Devices can be safely operated up to the 3rd cut (i.e., with only one row of ohmic columns beyond the active area)
  → There's room for design optimization (dead region < 100 micron)

3D Signal Efficiency: a comparison

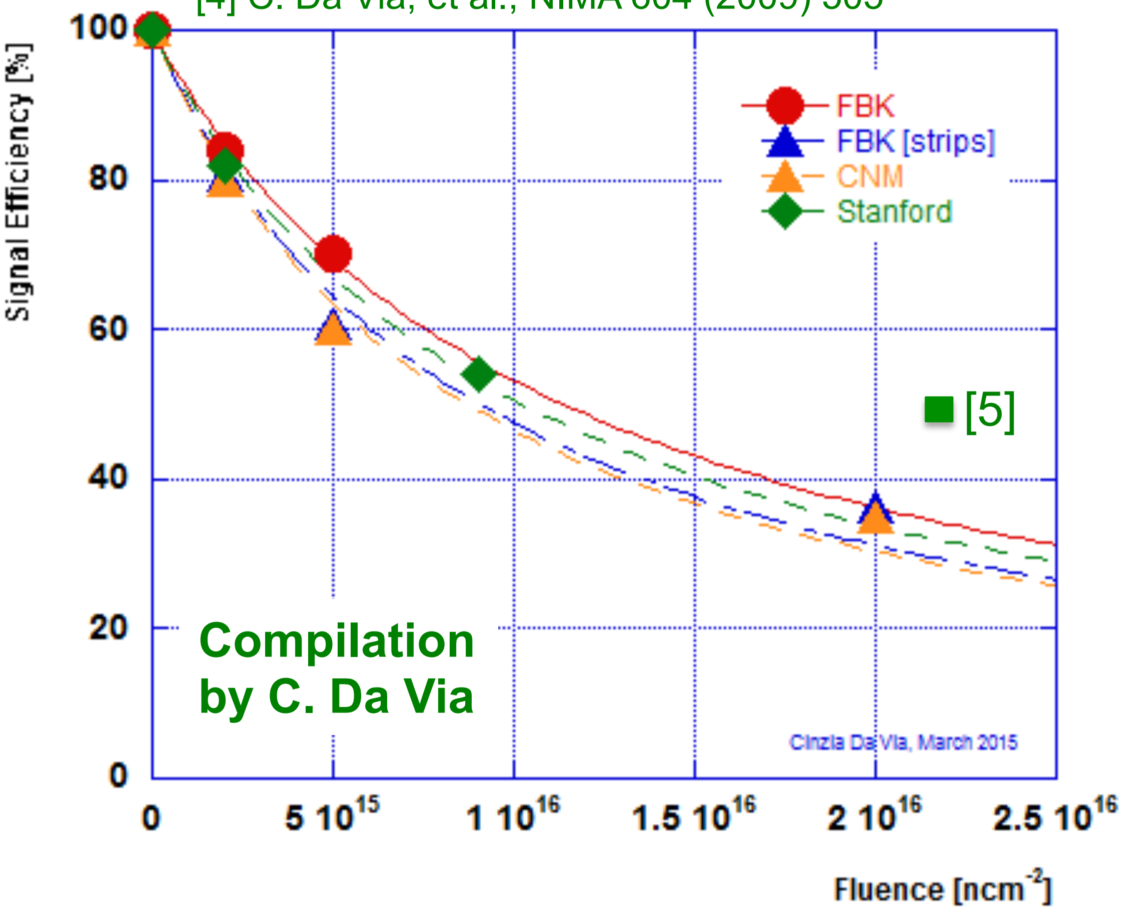
Data from:

[1] ATLAS IBL Collaboration, JINST 7 (2012) P11010

[2] G.-F. Dalla Betta, et al., NIMA 765 (2014) 155

[3] M. Koehler et al. NIMA 659 (2011) 272

[4] C. Da Via, et al., NIMA 604 (2009) 505



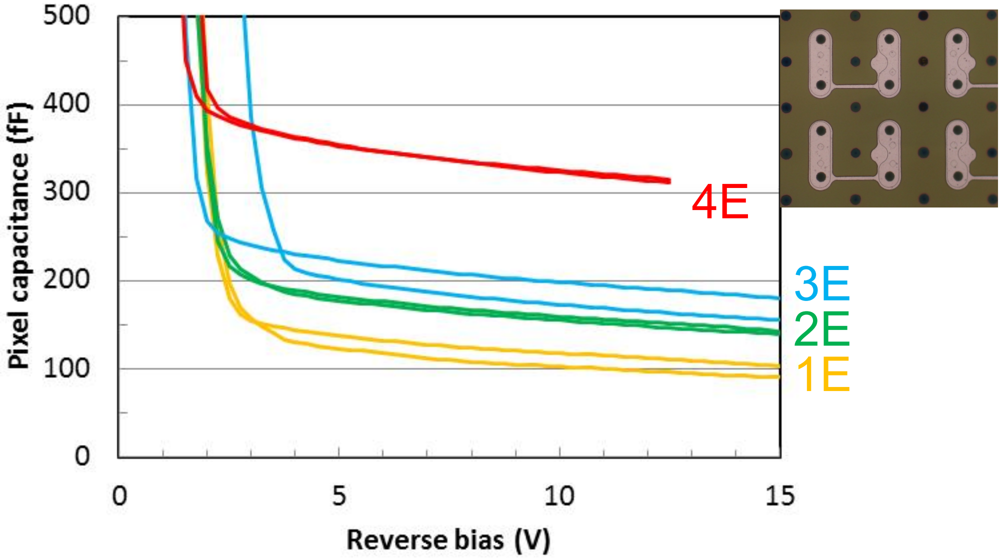
Signal Efficiency = Ratio of max. signal after irradiation and before irradiation

$$SE = \frac{1}{1 + 0.6L \frac{K_\tau}{v_D} \Phi}$$

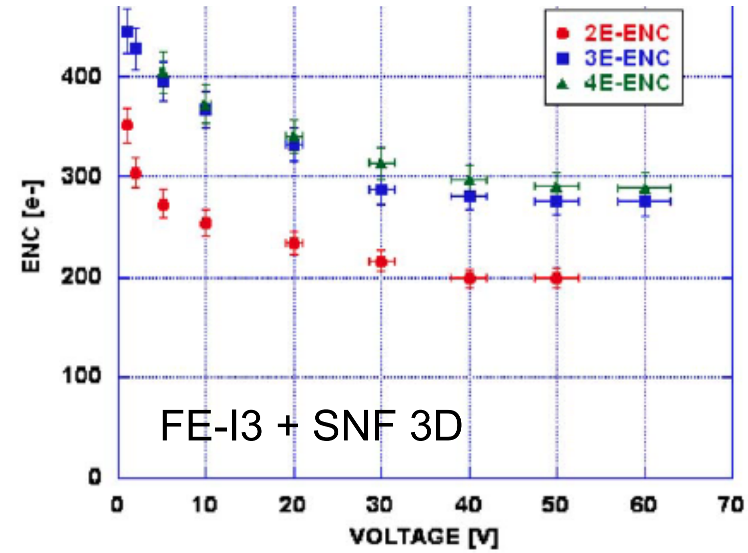
C. Da Via, S. Watts, NIMA 603 (2009) 319

[5] I. Haughton et al., NIMA 806 (2016) 425

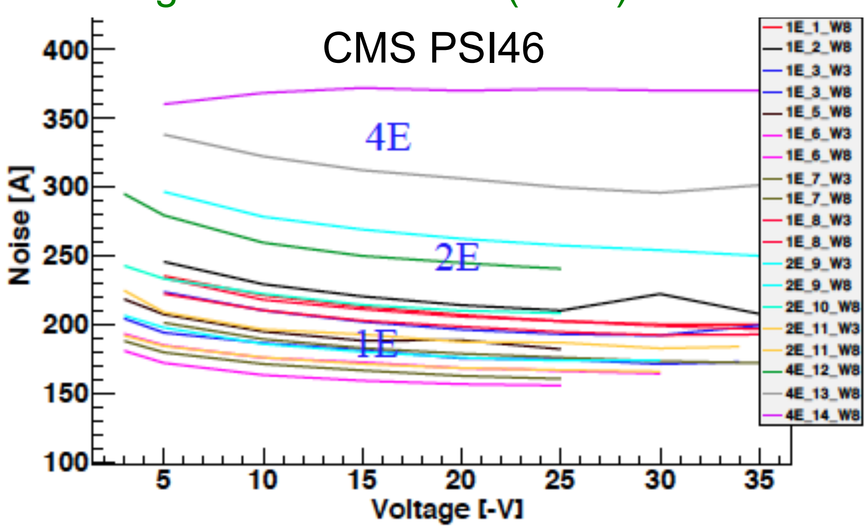
Capacitance and noise

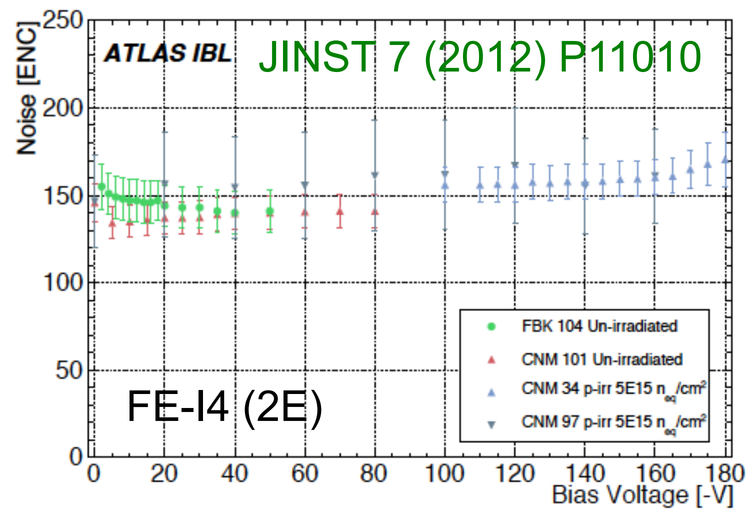


C. Da Via et al. NIMA 604 (2009) 505

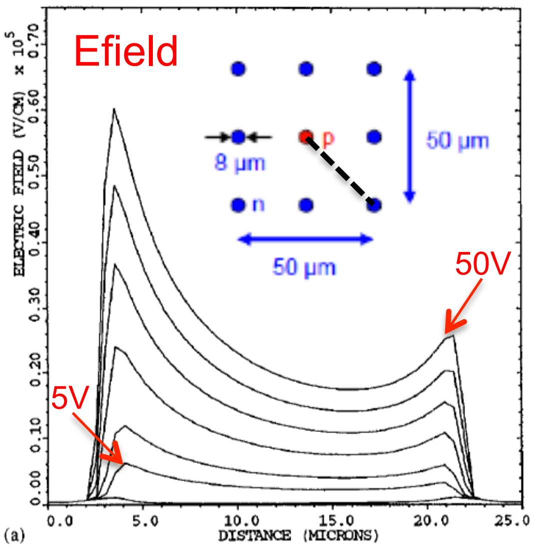


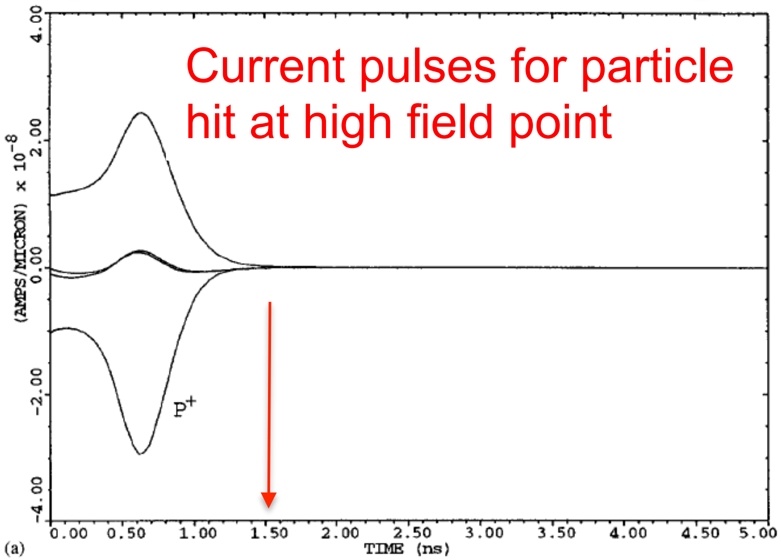
E. Alagoz et al. JINST 7 (2012) P08023

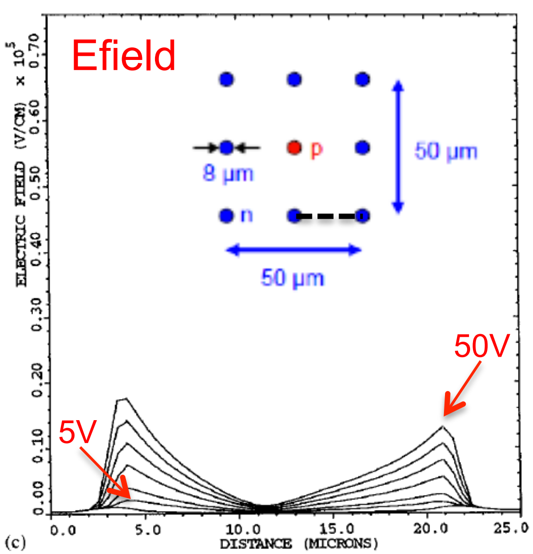


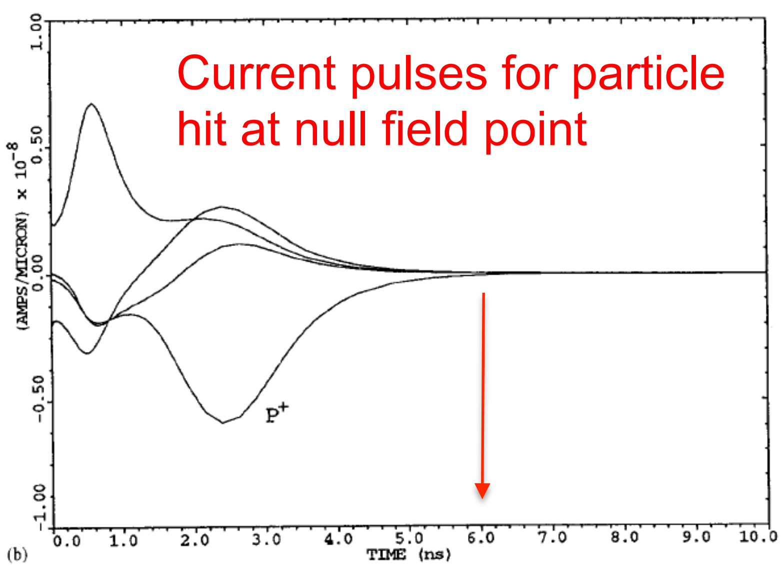


Null field points and delayed signals









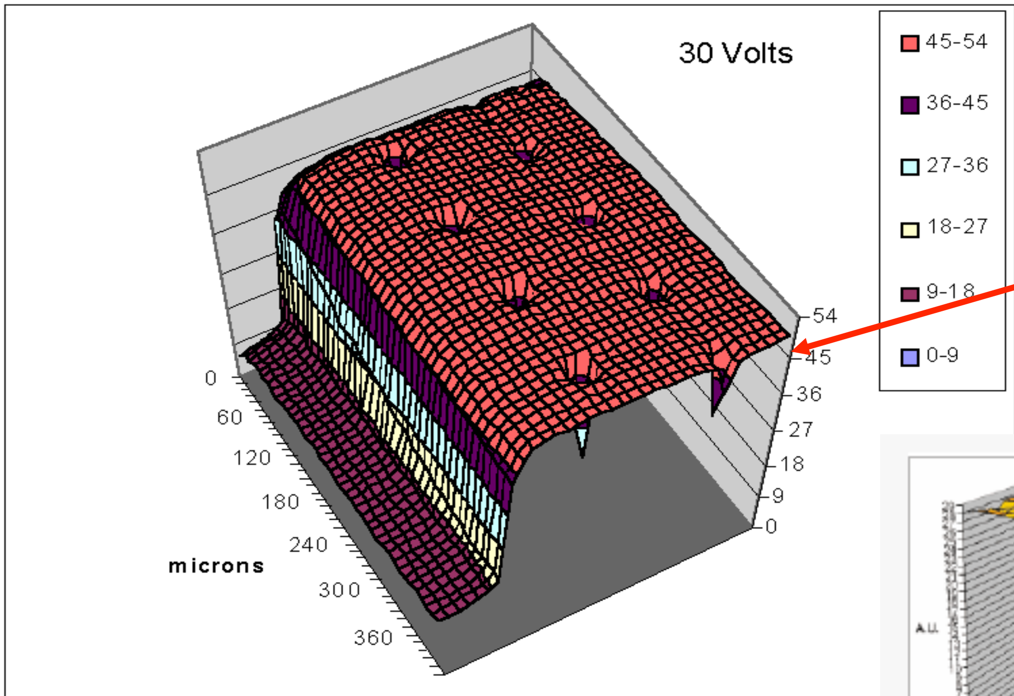
S. Parker et al. NIMA395 (1997) 328

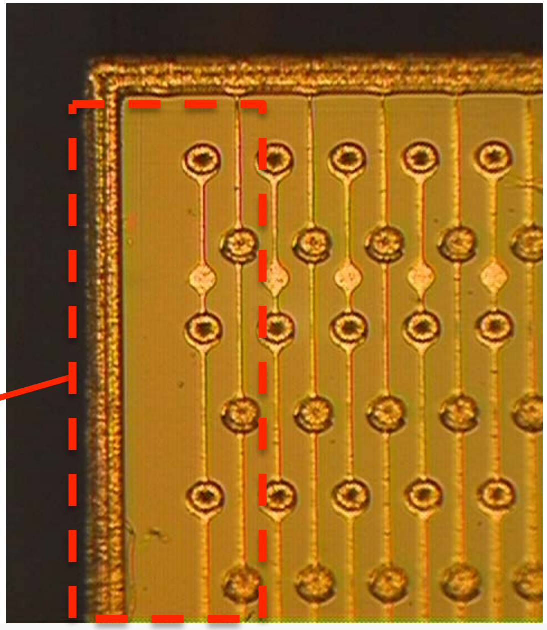
- 3D structure implies null field points in between columnar electrodes of the same doping type
- Carriers generated at null field points first have to diffuse before drifting, thus delaying signals
- This can be improved with trenched electrodes, but at the expense of higher capacitance and reduced geometrical efficiency

Poly-Si electrode inefficiency

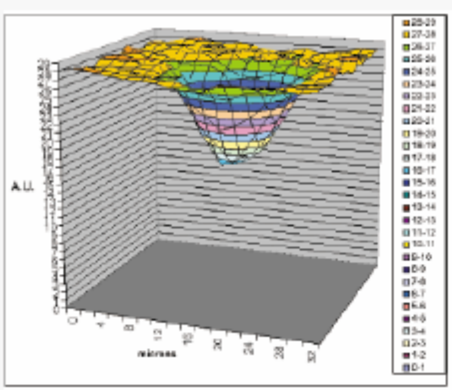
J. Hasi, PhD thesis, Brunel, 2004

Electrode response using 12 keV X-ray beam (ALS at LBNL), beam size ~ 2μm



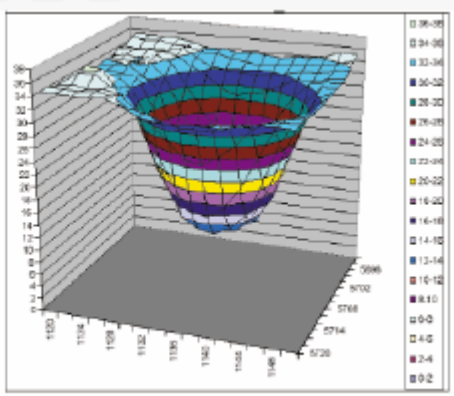


- Diffusion, lifetimes (poly-Si grain sizes)
- Oxide barrier effect at the interfaces …
  - → Replace $POCl_3$ with PH_3
  - → Replace BBr_3/O_2 with B_2H_6



N – Electrode

Signal Reduction 43%



P – Electrode

Signal Reduction 66%

Outline

- Introduction
  - 3D sensors and related technologies
- The ATLAS IBL project
- On going developments for HL-LHC
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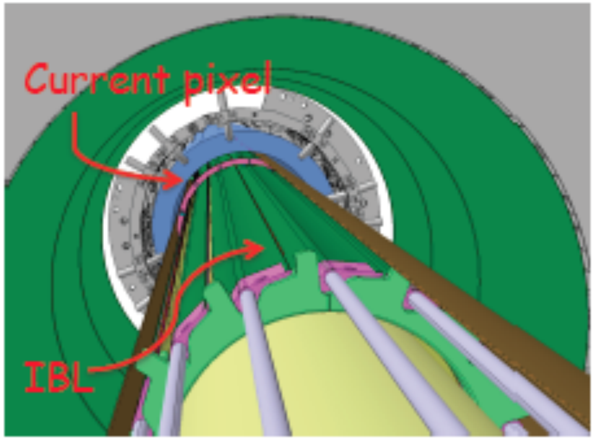
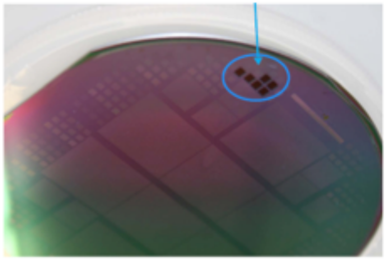
The ATLAS 3D Sensor Collaboration

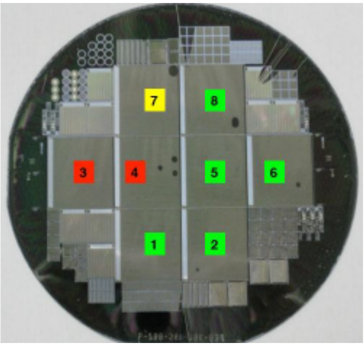
- Approved by CERN in 2007 for the "Development, Testing and Industrialization of Full-3D Active-Edge and Modified-3D Silicon Radiation Pixel Sensors with Extreme Radiation Hardness".
- It includes 18 Institutions and 4 processing facilities: SNF, SINTEF, CNM, and FBK.
- Major efforts devoted to the Insertable B-Layer (IBL) of the ATLAS detector at LHC:
  - First application of 3D sensors in a High Energy Physics experiment
  - First medium volume production accomplished in due time and with reasonably good yield

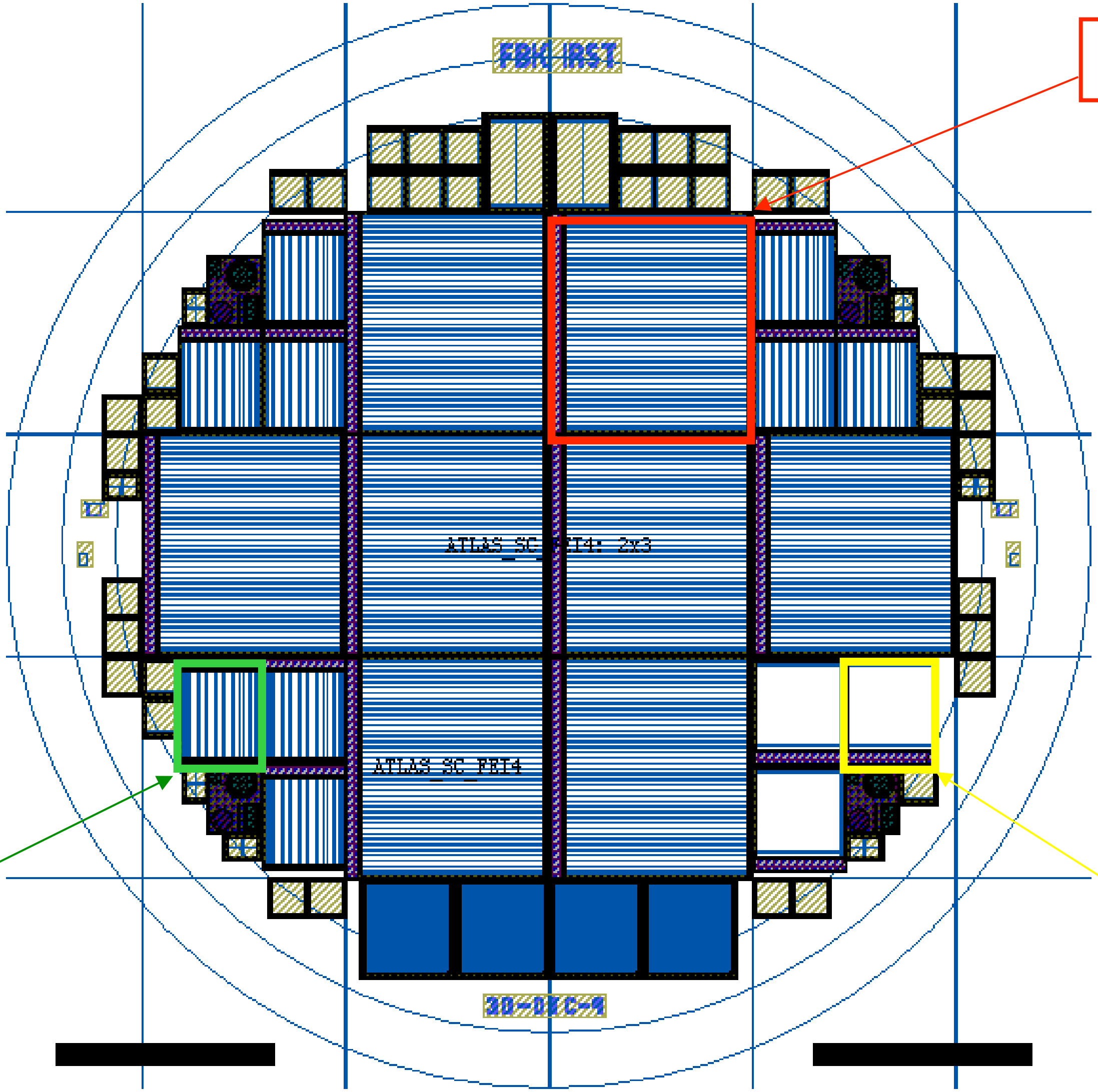


ATLAS IBL 3D common floor-plan

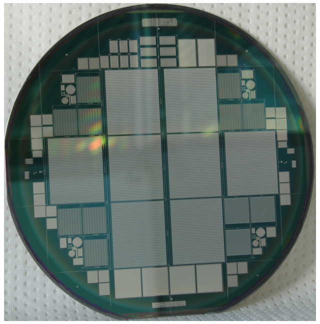
Test structures at the periphery

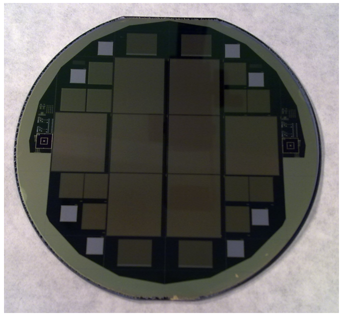






FE-I4 (8x)





CMS (3x)

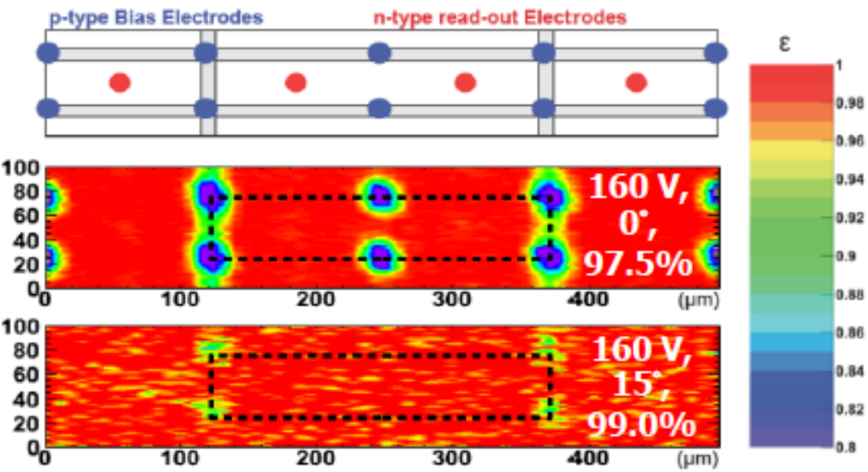
FE-I3 (9x)

IBL 3D Performance – Radiation Hardness

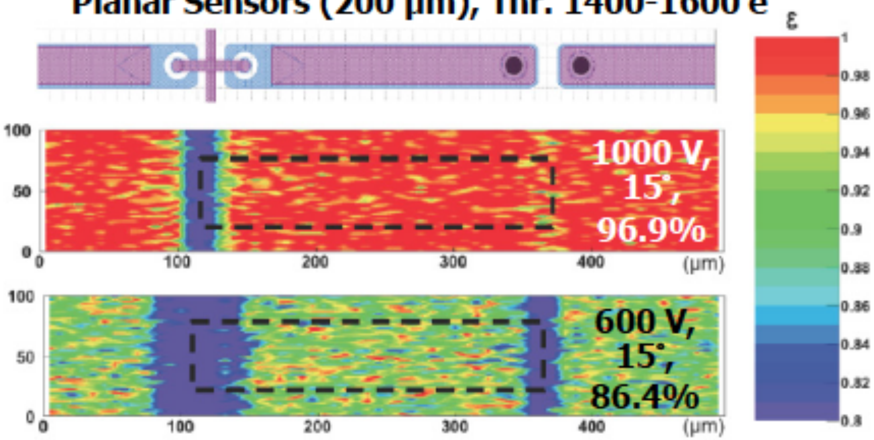
J. Lange, PIXEL 2015

Sub-Pixel Efficiency at 5x10^{15} n_{eq}/cm^2

CNM 3D Sensors (230 µm), Thr. 1500 e



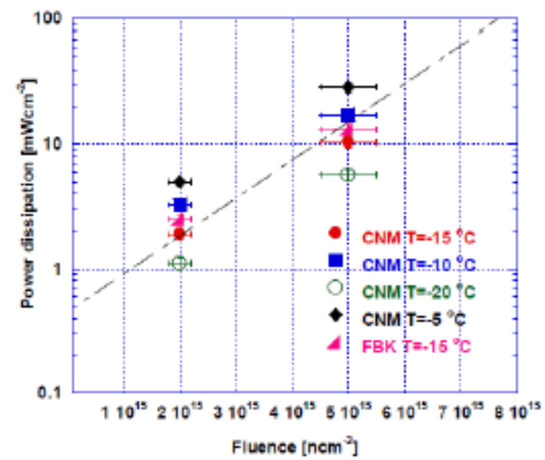
Planar Sensors (200 µm), Thr. 1400-1600 e



ATLAS IBL Coll., JINST 7 (2012) P11010

- Radiation hardness tested up to 5x10^{15} n_{eq}/cm^2
- 3D sensors
  - **Fully efficient at 160 V** and 15° angle
  - Mean efficiency 1-2% lower at normal incidence due to columns
  - Power dissipation <15 mW/cm² at T=-15° C
- Planar sensors
  - Need 1000 V for similar efficiency
  - Power dissipation ~90 mW/cm² at T=-15° C

→ operational advantage for 3D sensors



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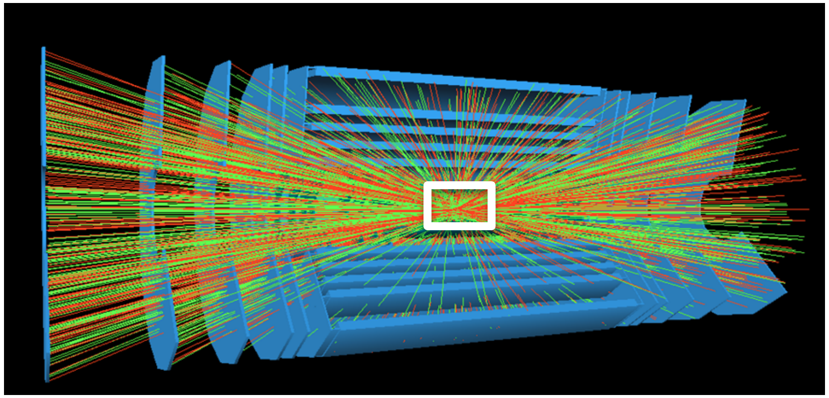
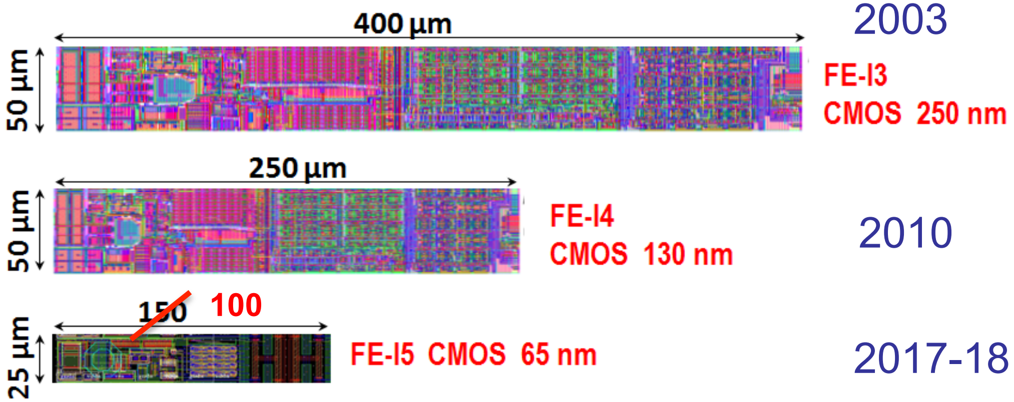
Pixel Roadmap LHC → HL-LHC

N. Wermes, 9th TN Workshop (Genova, 2014)



ATLAS roadmap → Pixel Size



Increased luminosity requires

- higher hit-rate capability
- increased granularity
- higher radiation tolerance
- lighter detectors

Next ROC generation (RD53 65 nm)

50x50 μm² and 25x100 μm² pixels

$C_{DET} \leq 100$ fF

$I_{leak} \leq 10$ nA/pixel (no amp. comp.)

Threshold: ~1000 electrons

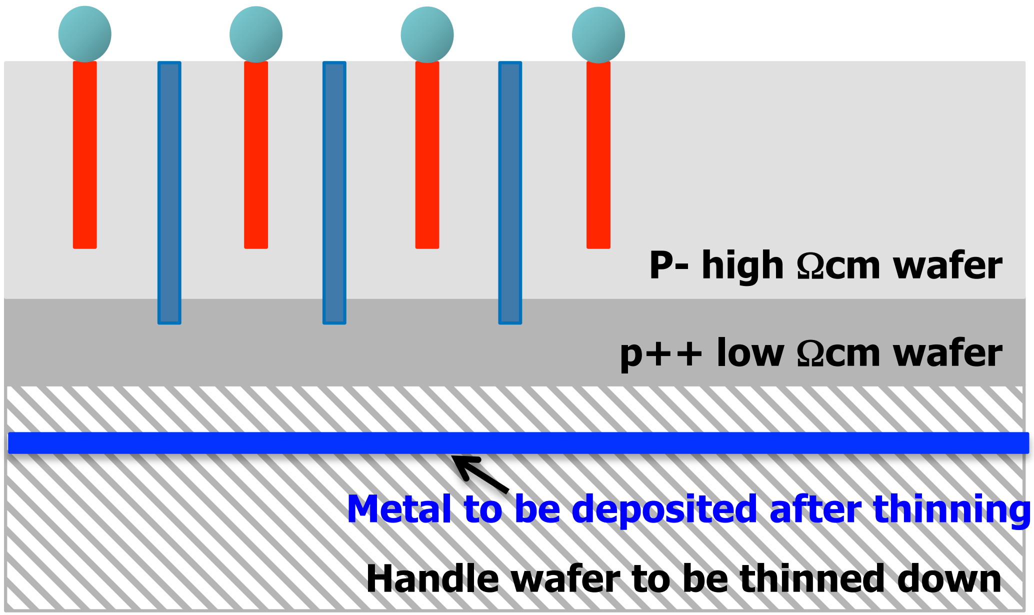
Implications for 3D sensors

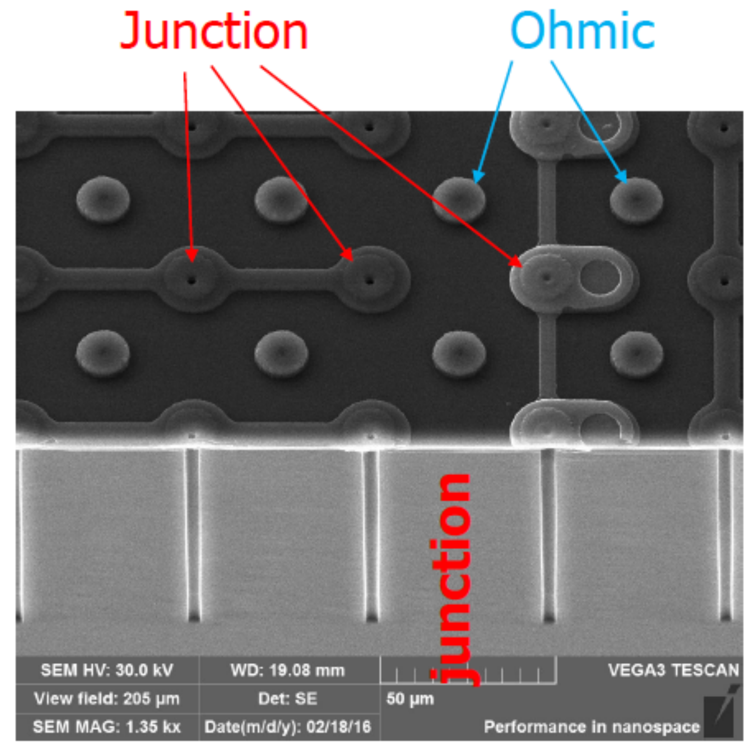
Modified technology/design for:

- thinner sensors
- narrower electrodes
- reduced electrode spacing
- very slim (or active) edges

- HL-LHC ATLAS and CMS Pixel TDR: 2017
- 3D pixels are an option for the innermost layers

New 3D pixels: fabrication



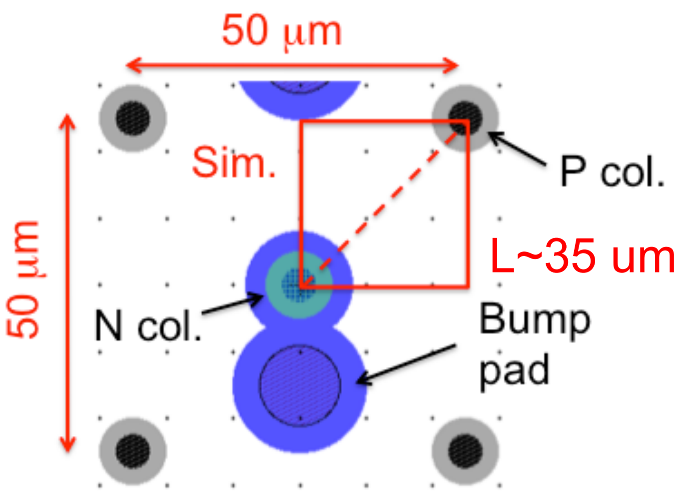


- Thin sensors on support wafer (SiSi)
- Ohmic columns/trenches depth > active layer depth (for bias)
- Junction columns depth < active layer depth (for high V_{bd})
- Reduction of hole diameters to ~5 um
- Holes (at least partially) filled with poly-Si

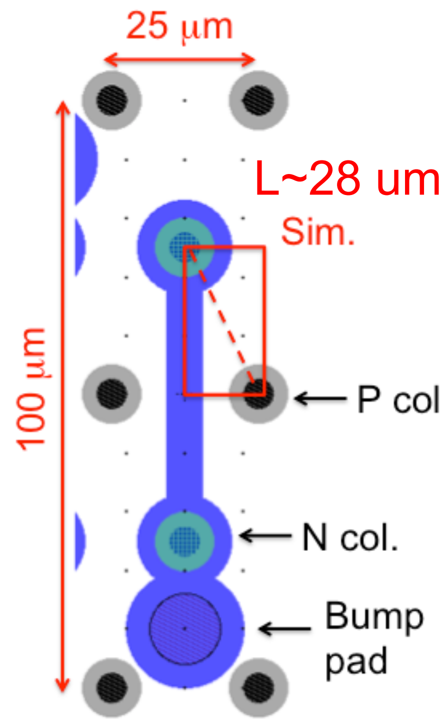
INFN-FBK "RD_FASE2" Project (CSN1)

New 3D pixels: design and simulations

50 x 50

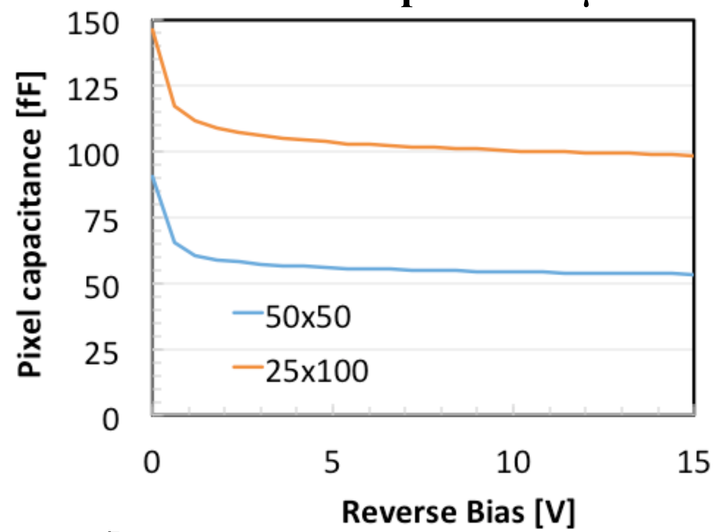


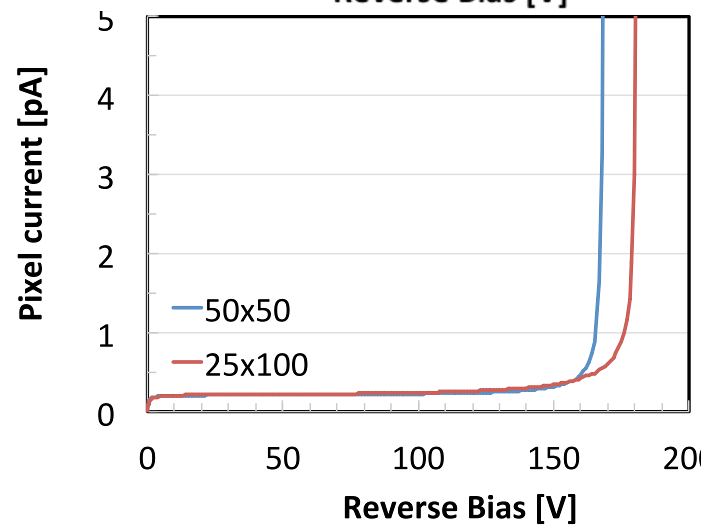
25 x 100



All designs assuming a column diameter of 5 µm

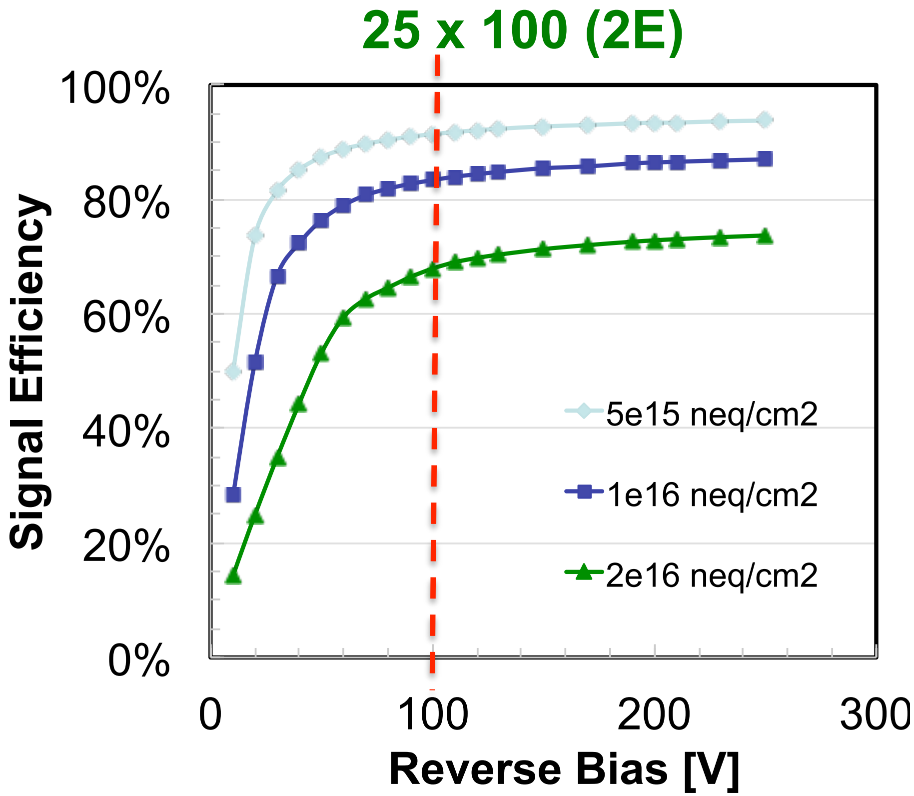
Thickness = 150 µm
N+ col. depth = 130 µm

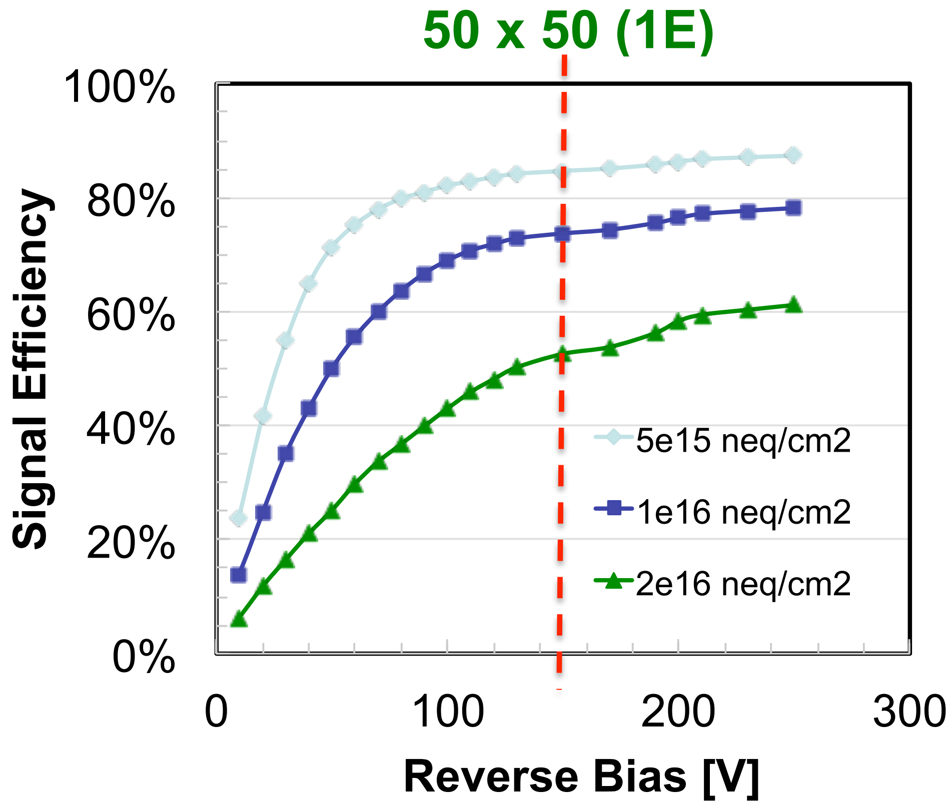




- 50x50 design safe, 25x100 is difficult … too little clearances (new ideas for bump pad to be tested)
- Capacitance compatible with RD53 specs
- Initial breakdown voltage high enough

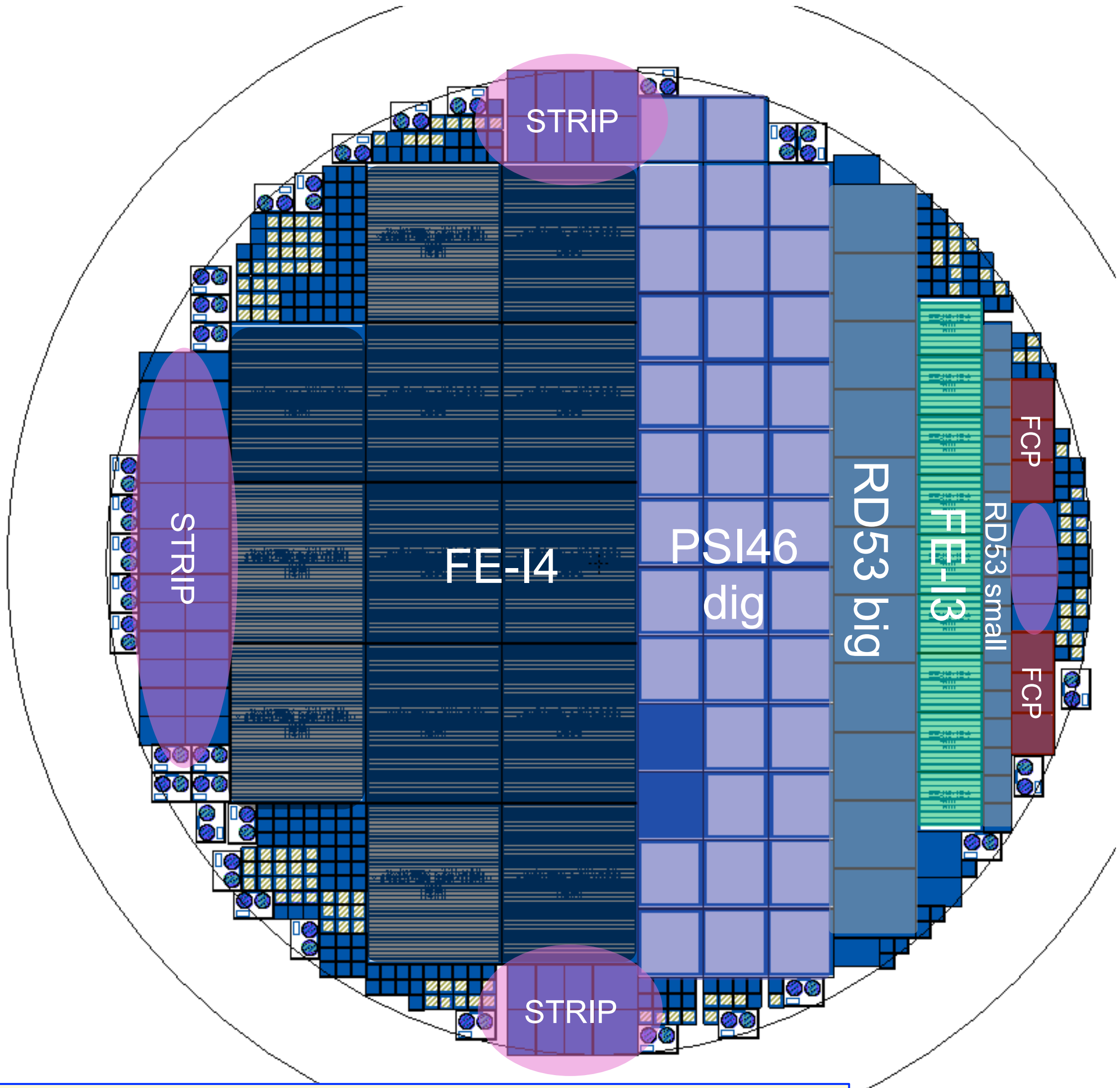
Simulated signal efficiency (preliminary)





- New 3-trap level "Perugia" model D. Passeri et al. (doi:10.1016/j.nima.2015.08.039)
- 1 μm thick (~2d) slice, with MIP vertical hits at many different points
- 20-ns integration of current signals → normalization to injected charge → average
- Higher Signal Efficiency at lower V_{bias} in 25x100 (2E), as expected due to smaller L

3D Pixel Wafer Layout

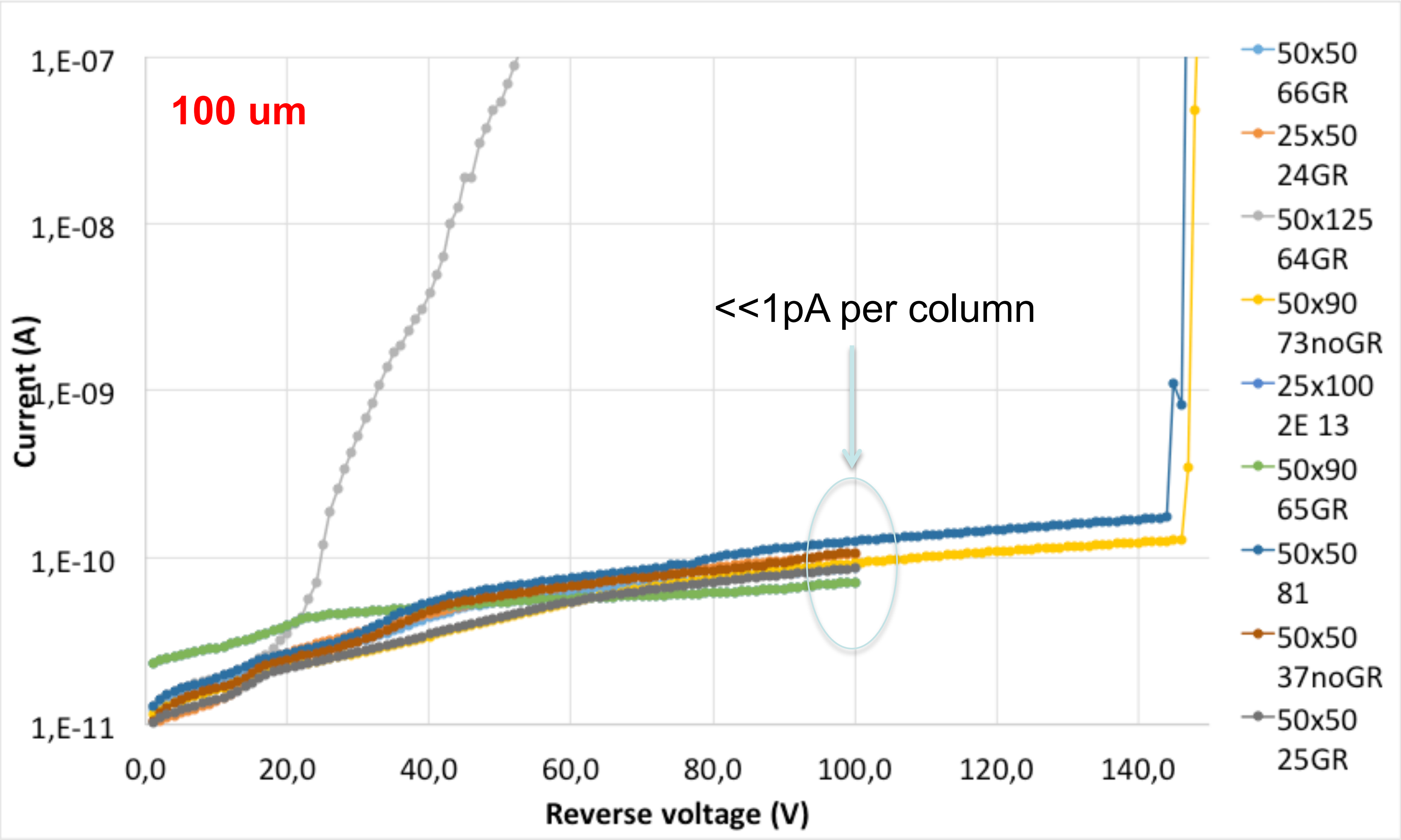


Many different pixel geometries and pitch variations:

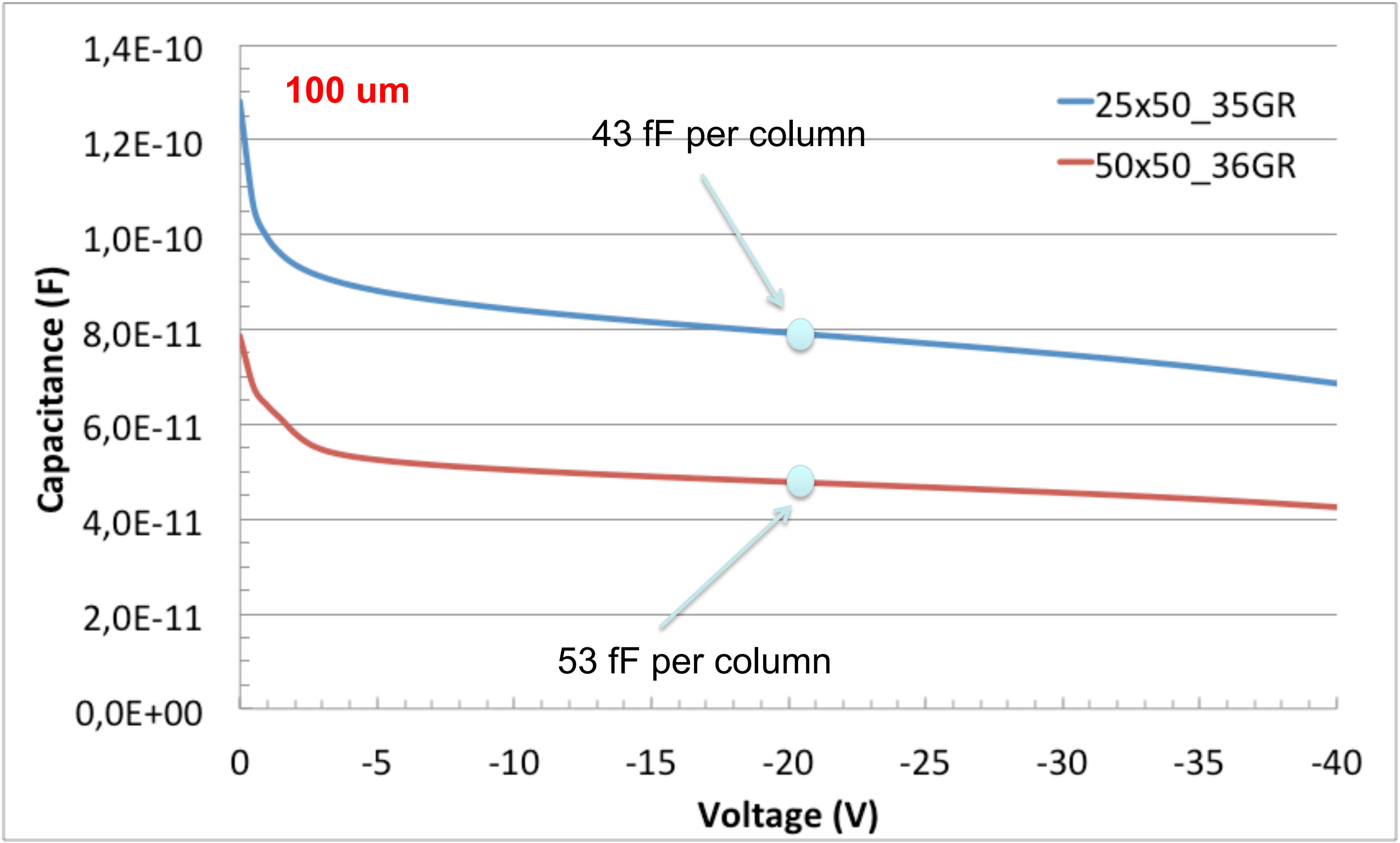
- FE-I4
  - 50 x 250 (2E) std
  - 50 x 50 (1E)
  - 25 x 100 (1E and 2E)
  - 25 x 500 (1E)
- FE-I3
  - 50 x 50 (1E)
  - 25 x 100 (1E and 2E)
- PSI46dig
  - 100 x 150 (2E and 3E) std
  - 50 x 50 (1E and 2E)
  - 50 x 100, 100 x 100 (2E + 4E)
  - 50 x 100, 100 X 150 (2E + 6E)
  - 25 x 100 (1E and 2E)
- FCP
  - 30 x 100 (1E)
- RD53
  - 50 x 50 (1E)
  - 25 x 100 (1E)
  - 25 x 100 (2E)

+ Test structures (strip, diodes, etc)

Preliminary results (1): W48 diode IV

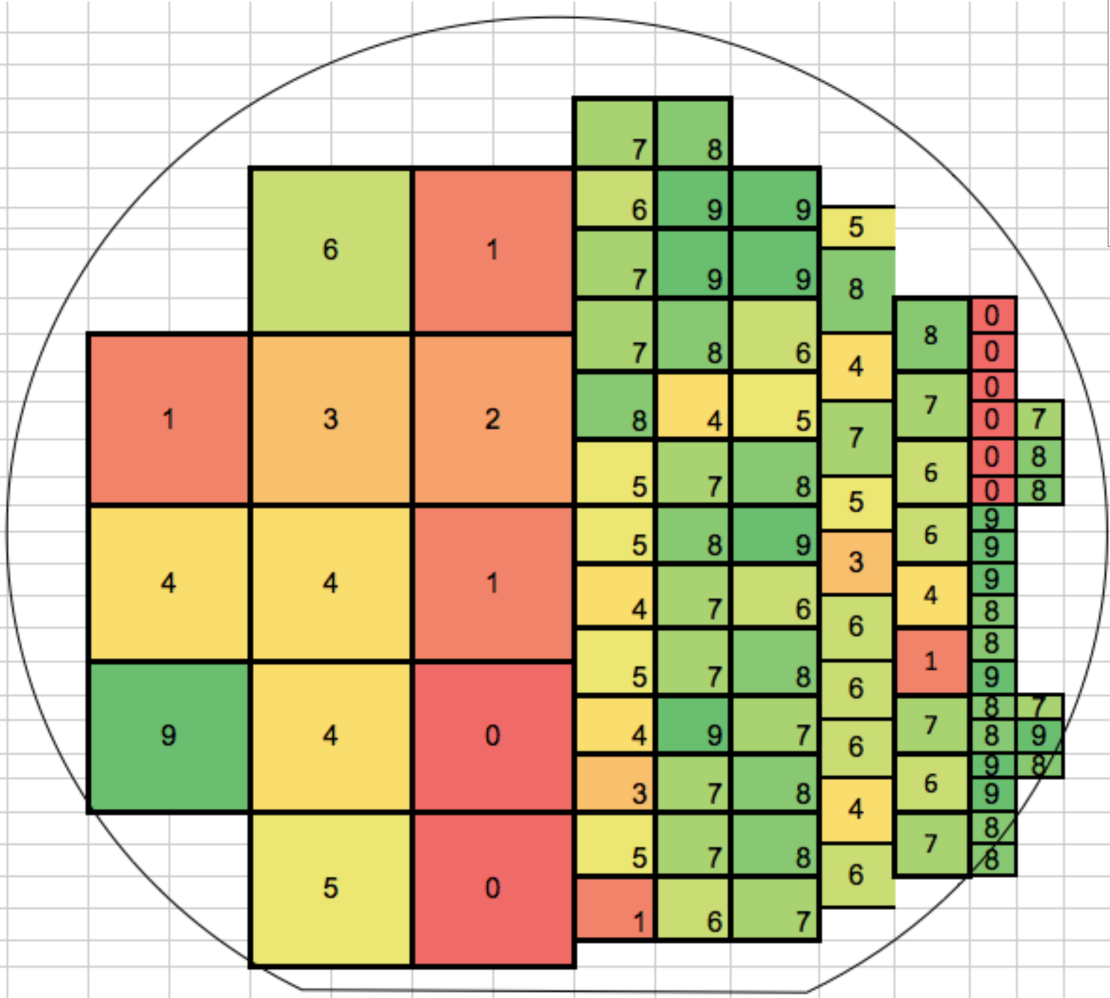


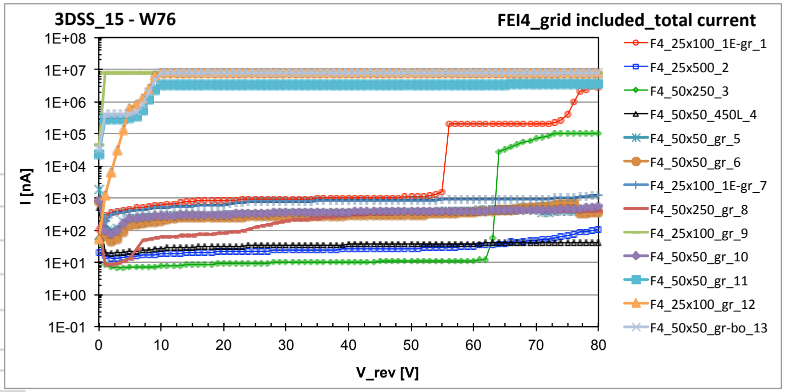
Preliminary results (2): W48 diode CV



Automatic tests

Numbers of good detectors per type on 9 wafers





- Good electrical characteristics in terms of leakage current, breakdown voltage and capacitance, in good agreement with simulations
- Process Yield ~38% on large sensors (FEI4), >60% on all others
- Best two wafers (76&78) at Selex for bump bonding

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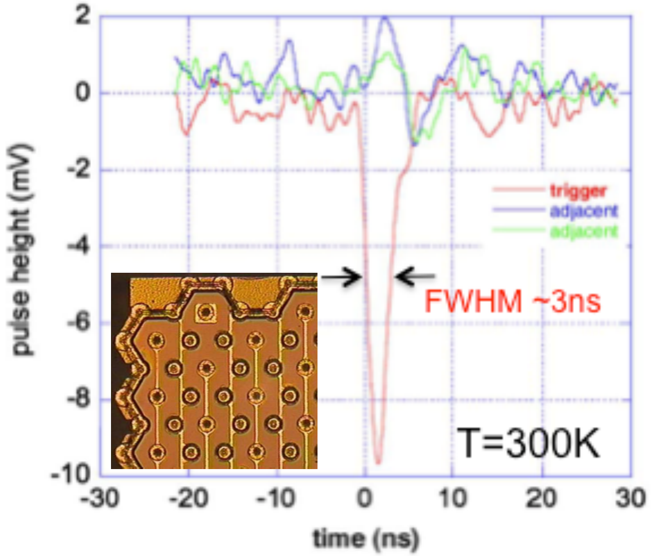
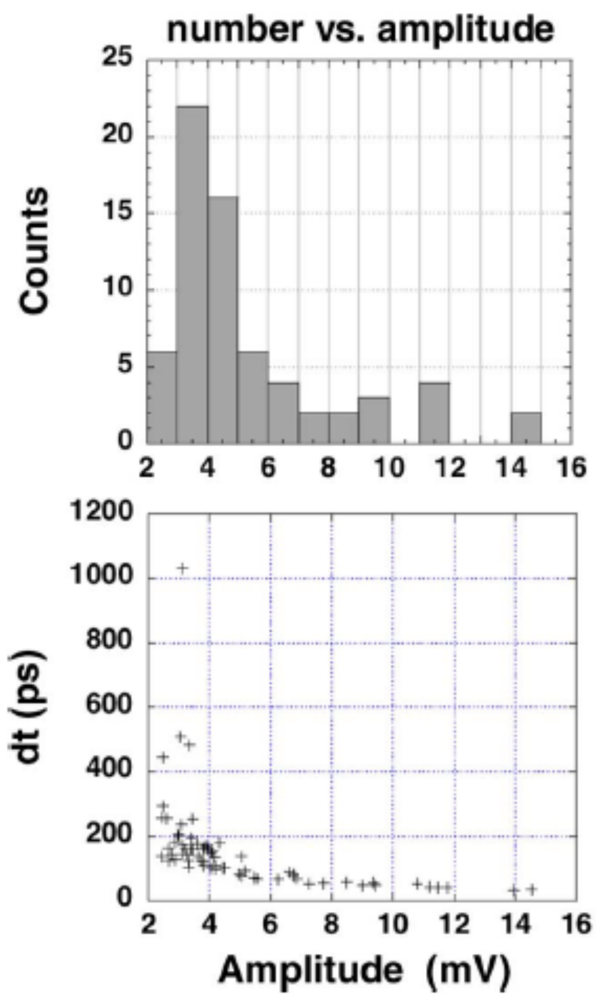
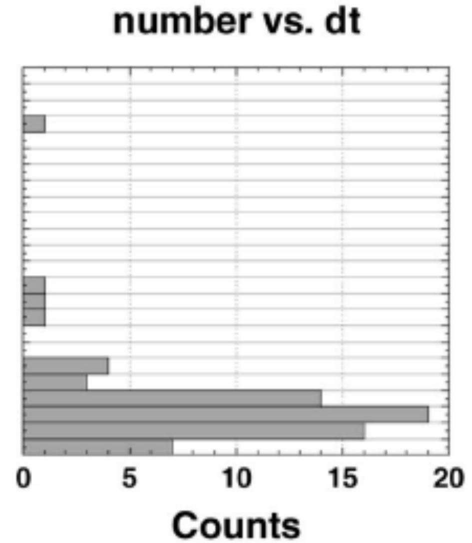
Timing with 3D

So far tested with hex-cell 3D's (L=50μm) & fast current amplifier

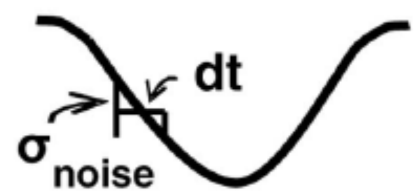


S. Parker et al. IEEE TNS 58(2) (2011) 404

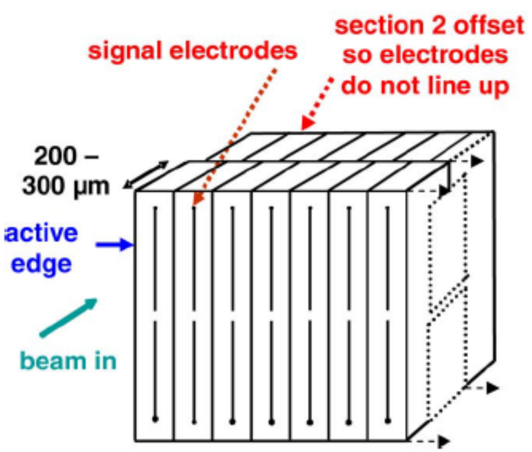




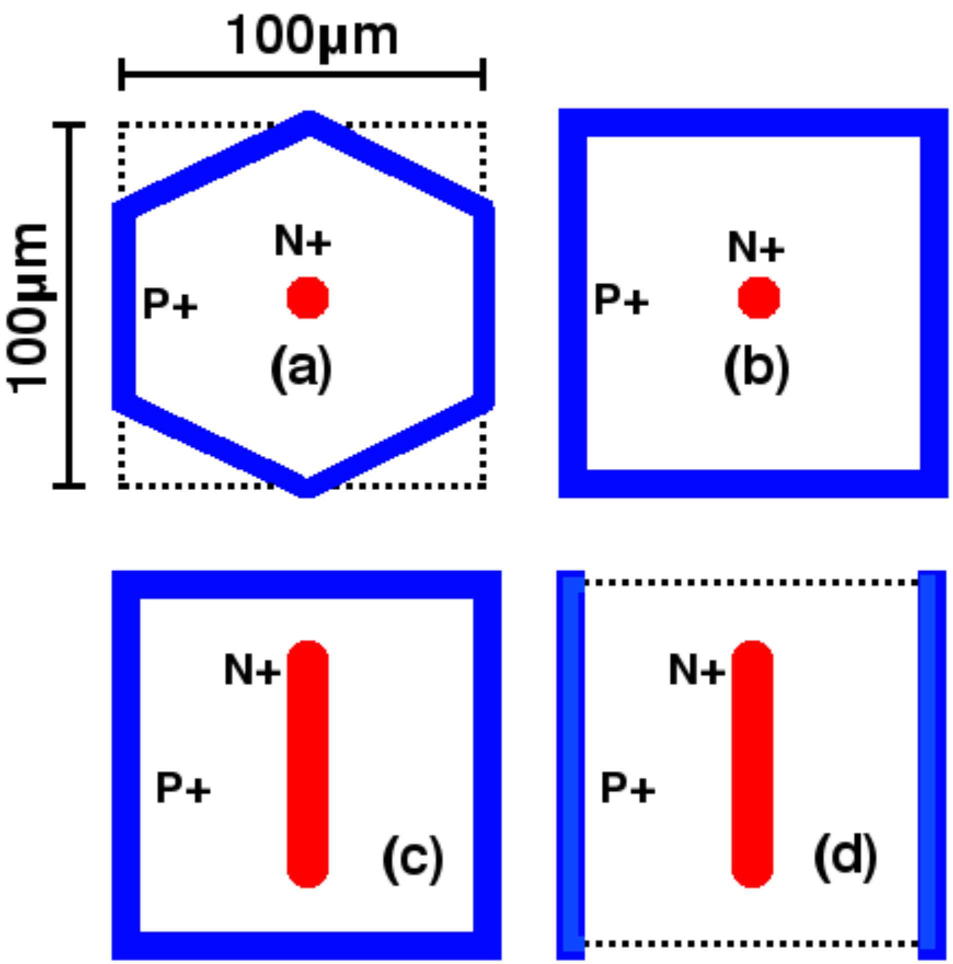
- Off-line analysis of recorded waveforms
- Timing resolution from 177 ps to 31ps
- Limited by front-end noise

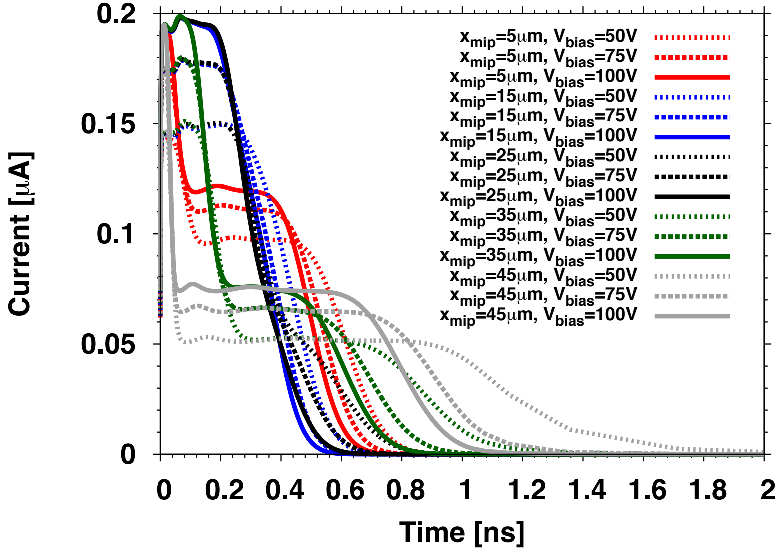


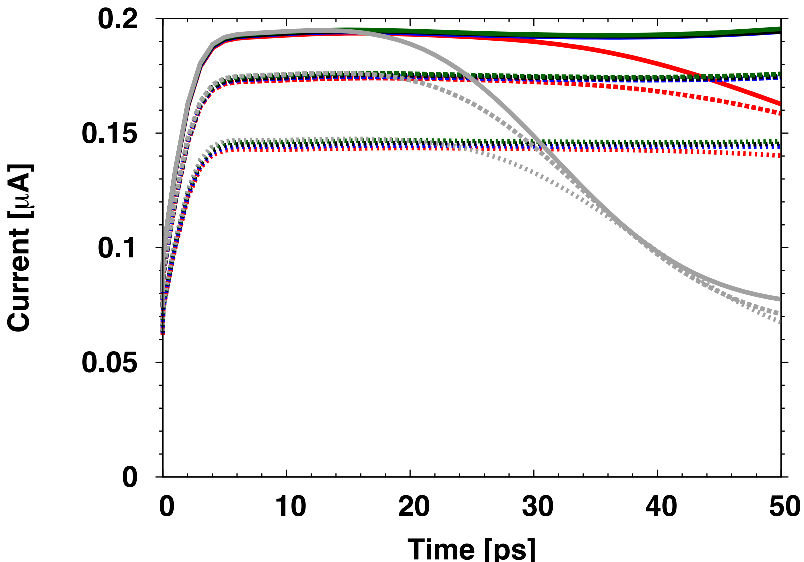
Best choice: trenched detectors



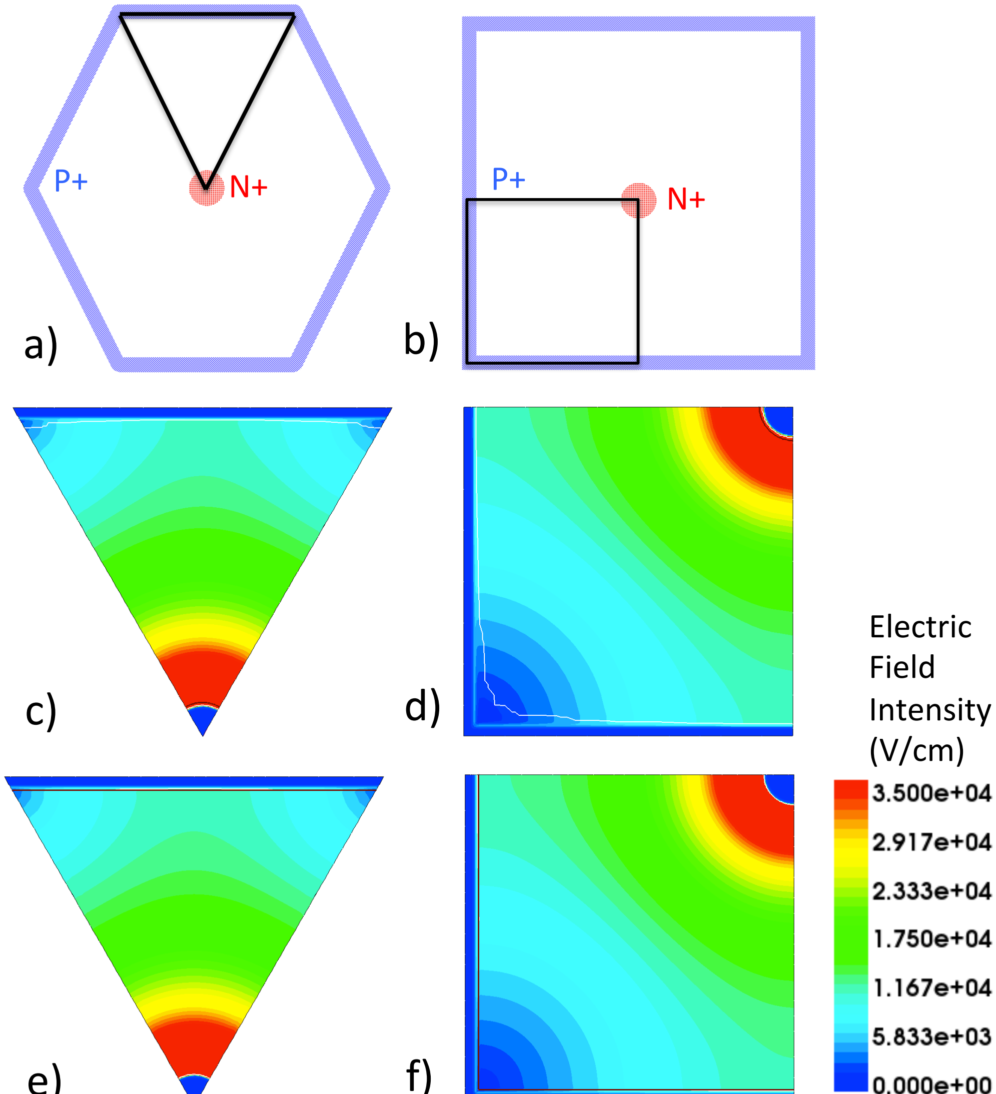
New Trenched-3D pixels for timing (1)

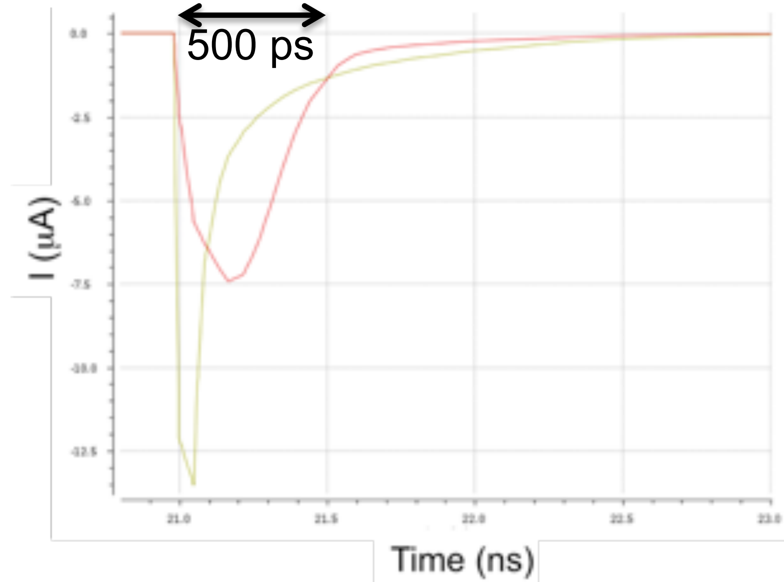


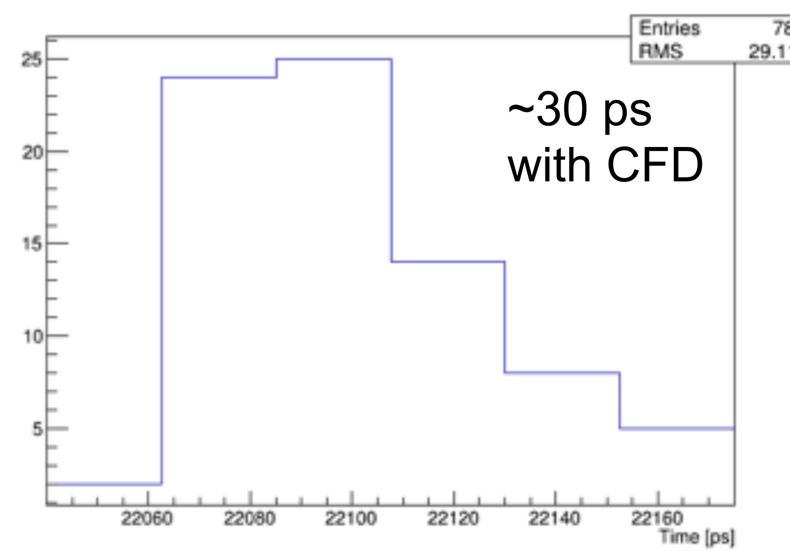




New Trenched-3D pixels for timing (2)







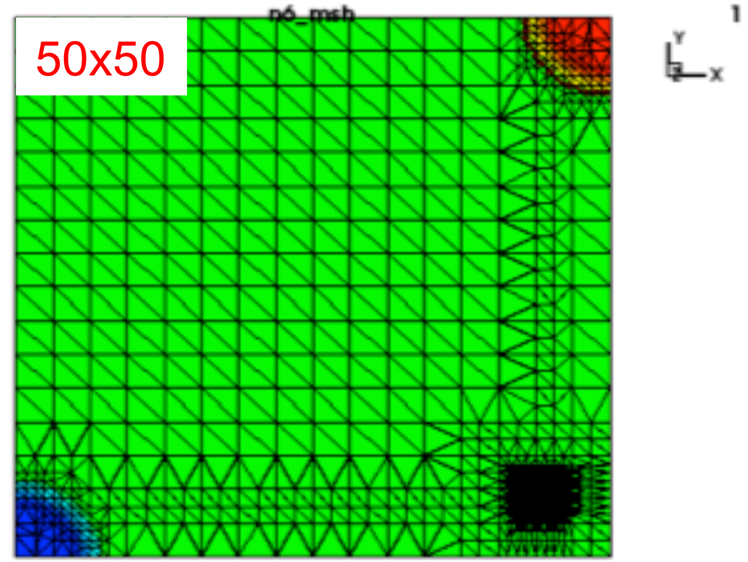
Conclusions

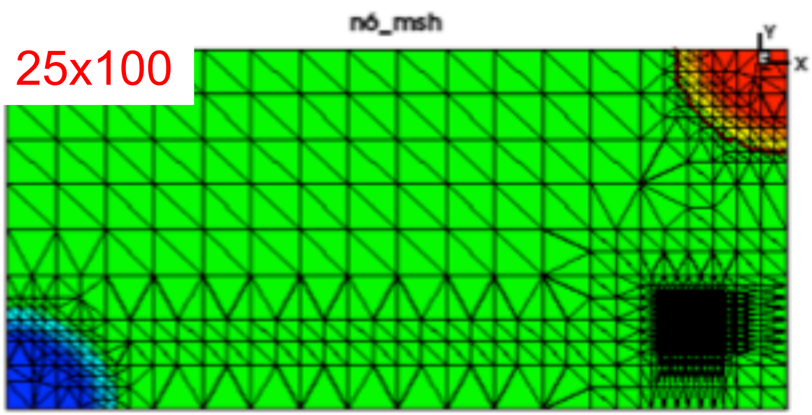
- Very impressive progress has been recently achieved in 3D radiation sensors, boosted by the ATLAS IBL project:
  - Experimental confirmation of superior radiation tolerance with relatively low power dissipation
  - Demonstration of medium volume productions
- These accomplishments paved the way for using 3D sensors in pixel detector upgrades at HL-LHC, for which a new generation of 3D pixels is being developed
- Despite their significant potential, 3D sensors fast signal properties have so far not been exploited.
- An R&D effort in this direction is worth, and it can partially benefit from on-going technological developments

Back-Up Slides

CCE simulation approach

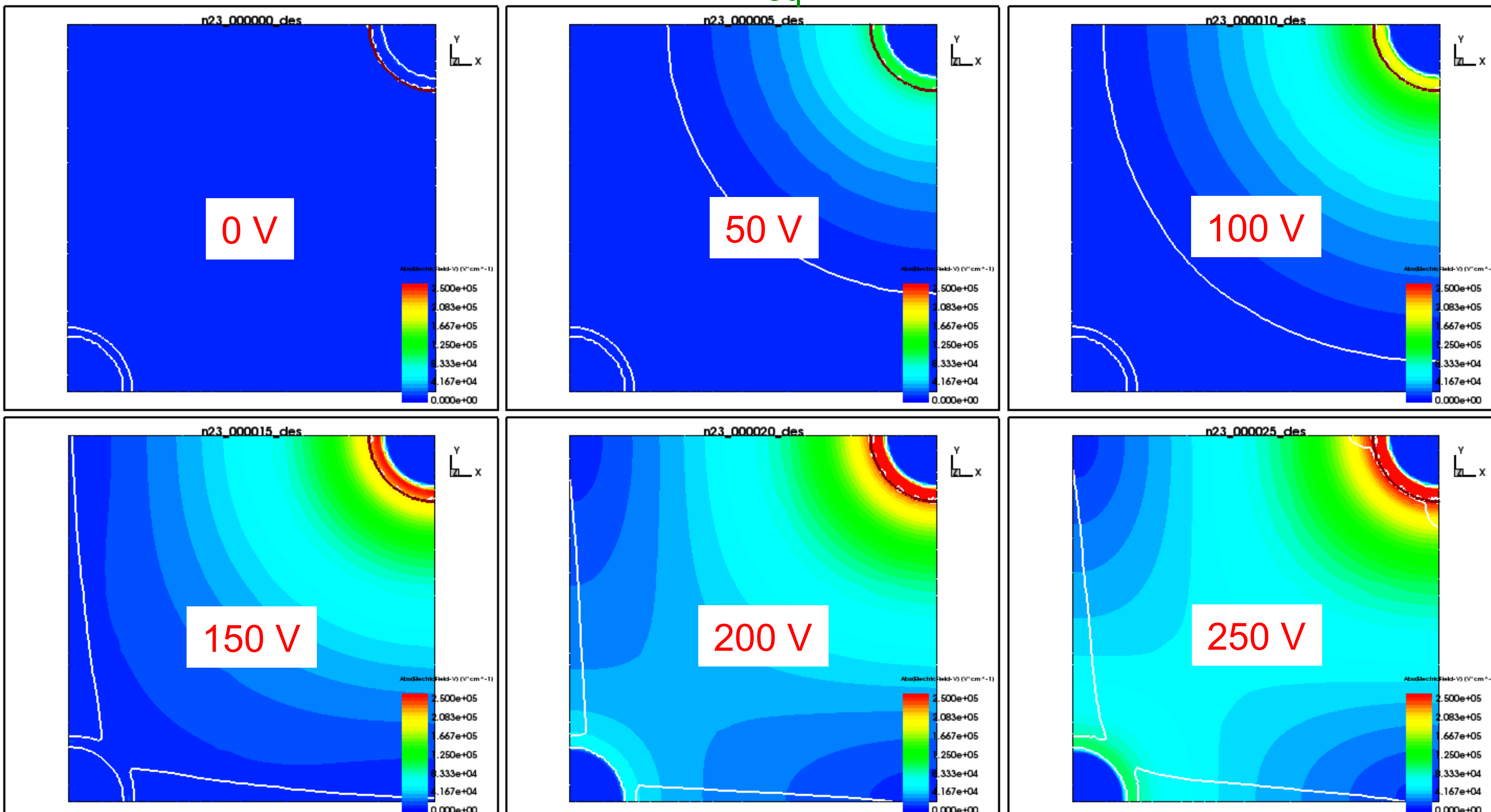
- Simplified simulation domain (~2d):
  1 μm thick slice (1/4 or 1/8 of pixel)
- MIP (heavy ion model): vertical hits at several different positions evenly distributed and representing different electric field values
- Impact ionization model not active
- Avoiding boundaries: no charge sharing
- 20-ns integration of current signals
- Normalization to injected charge
- Repeat at different bias voltage
- Average charge over all hit positions





50x50: electric field 2d (preliminary)

$2x10^{16}$ n_{eq}/cm^2



Charge multiplication by design in 3D sensors

Exploiting high fields in thin 3D structures with small inter-electrode spacing

M. Povoli et. al., To be published