

Pixelated 3D sensors for tracking in radiation harsh environments

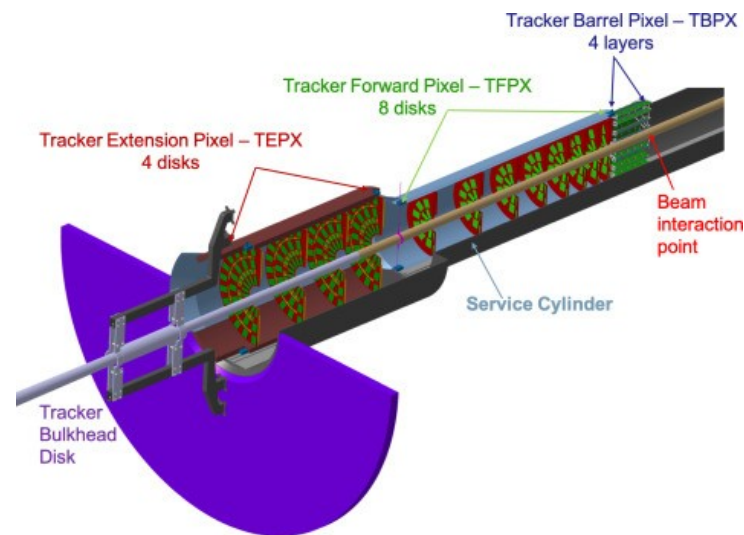
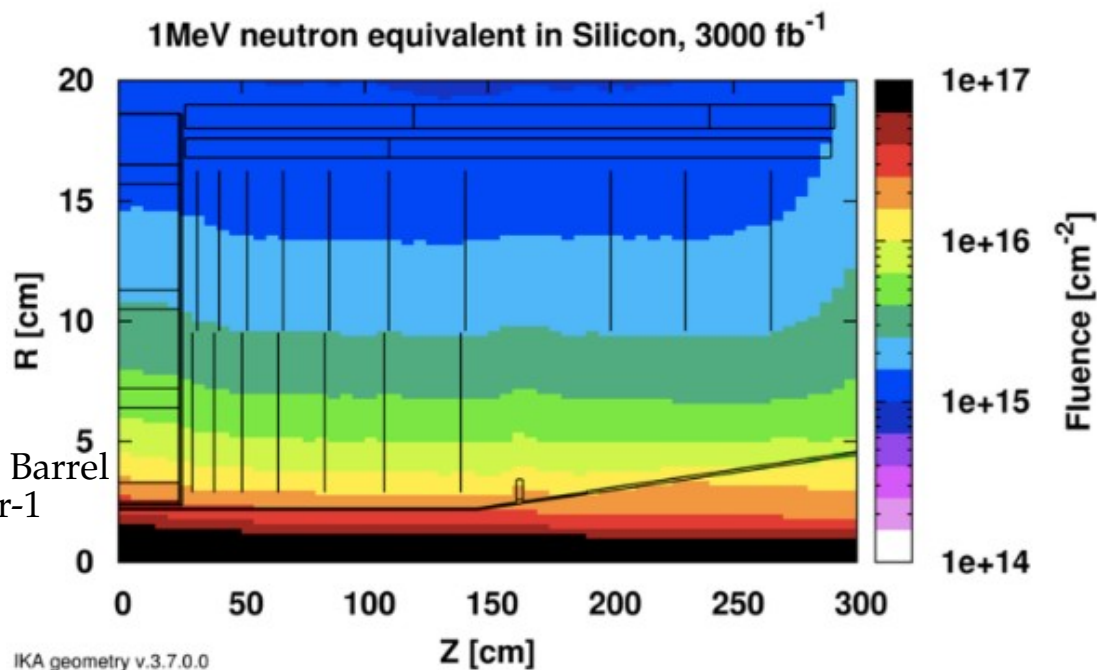


Jordi Duarte-Campderrós
on behalf of RD50 Collaboration



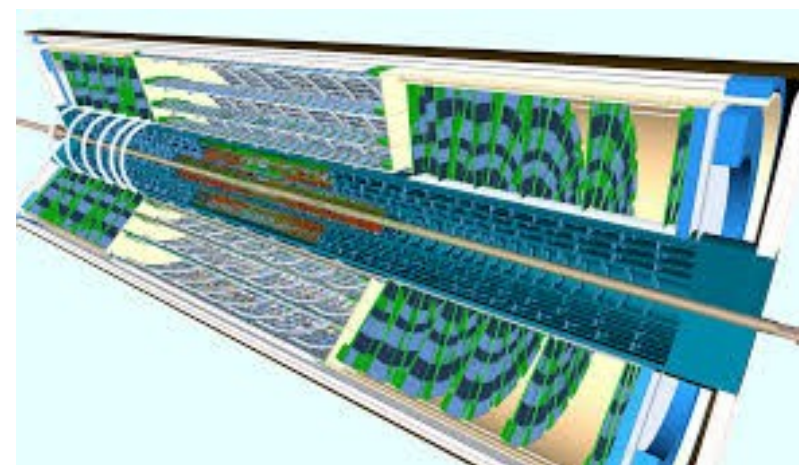
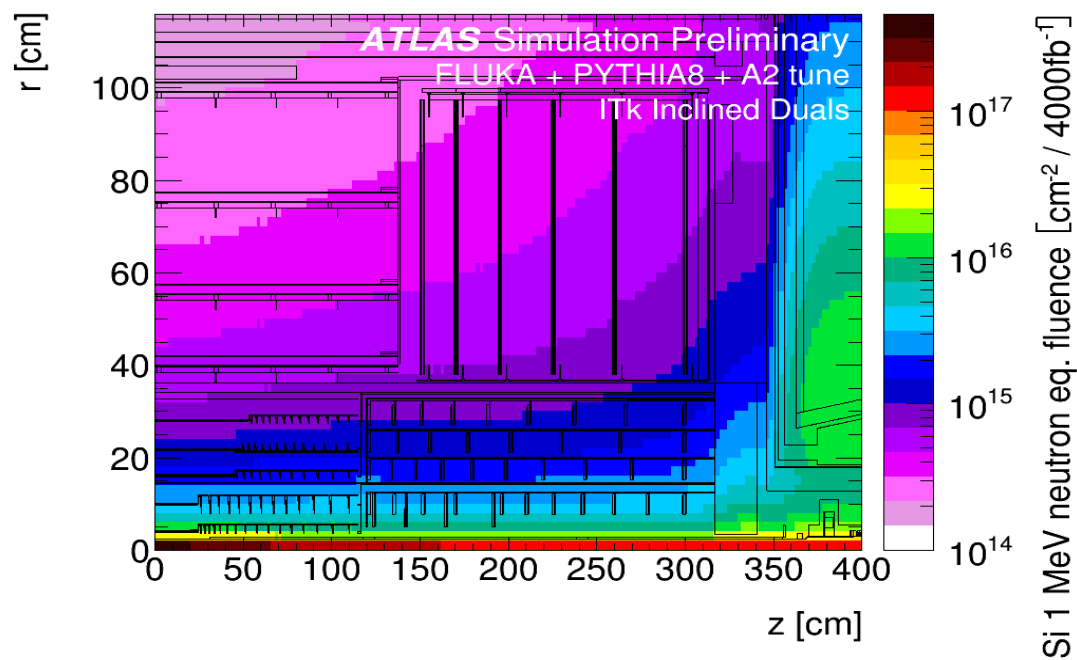
- High Luminosity LHC upgrade
→ very large particle fluences

CMS inner Tracker



- High Luminosity LHC upgrade
→ very large particle fluences

ATLAS



“Novel” technology, but well established
(*S. Parker et. Al. NIMA 395 (1997) 328*)

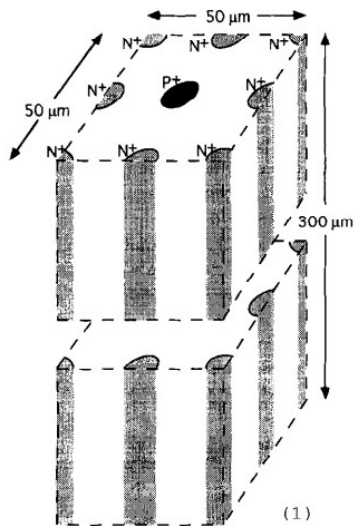
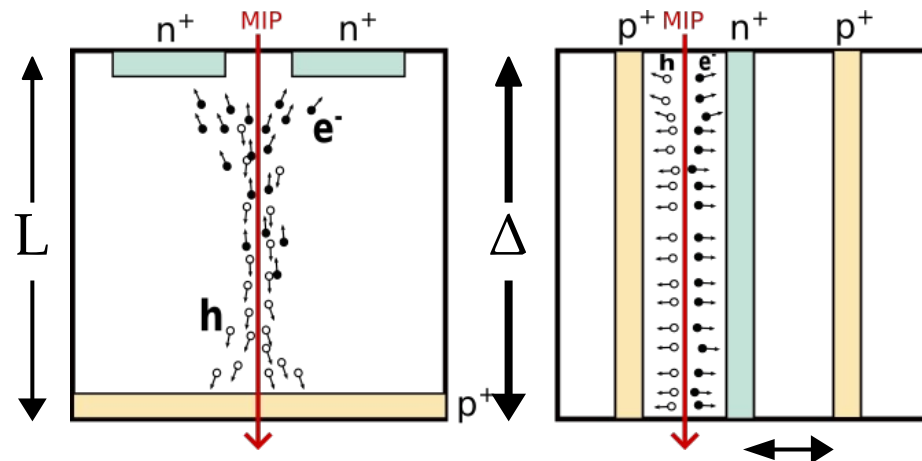
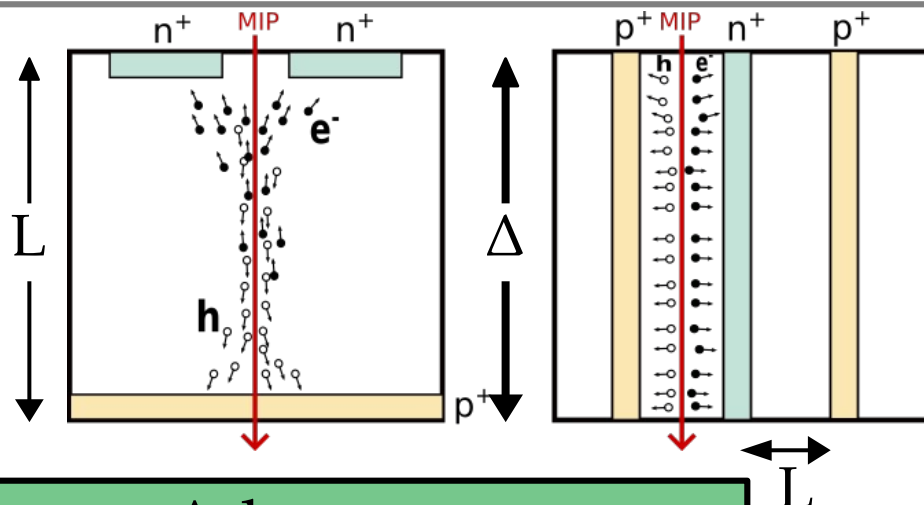


Fig. 1. Three-dimensional view of a typical cell.

- Main characteristic: Inter-electrode distance (L) **decoupled** from active sensor thickness (Δ)

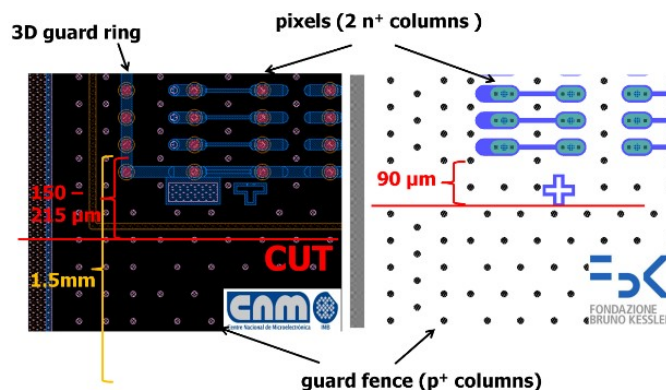
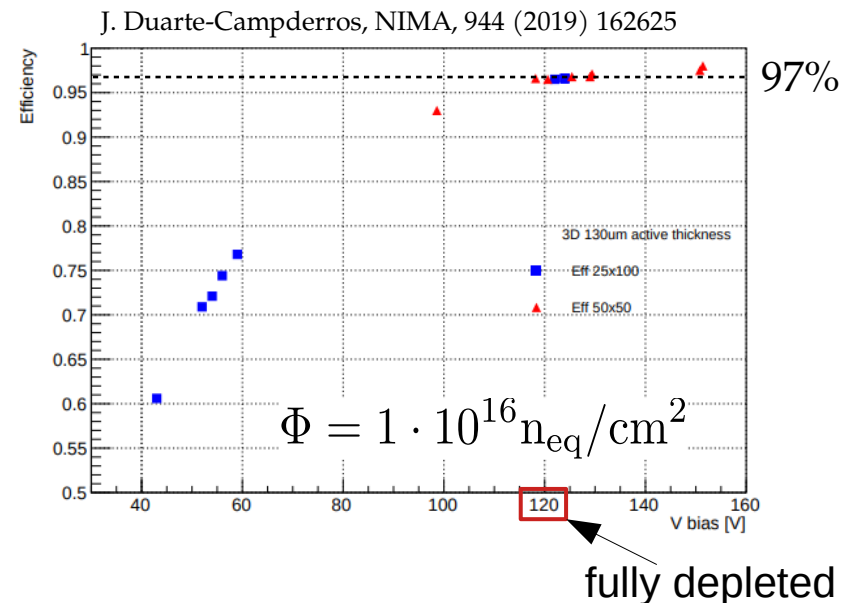


→ Fast response time and inherently radiation tolerant

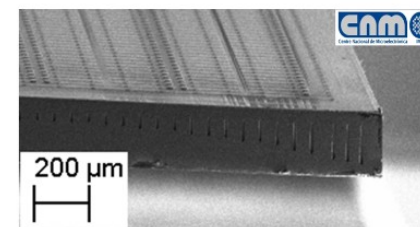


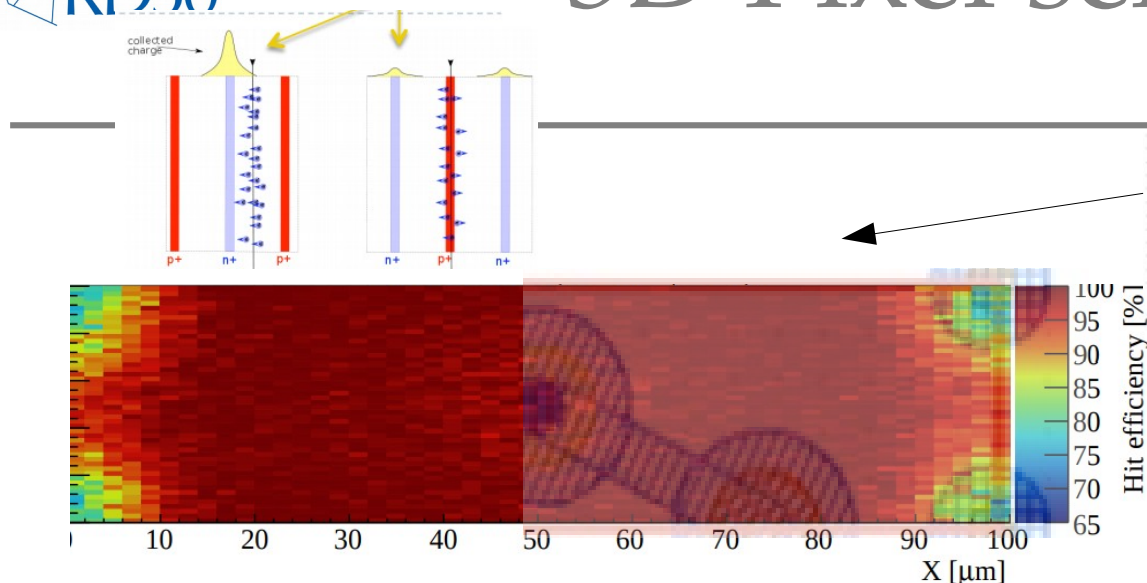
Advantages

- Low depletion voltage → **low power dissipation**
- Short charge collection distance
 - **Fast response**
 - **Less trapping probability after irradiation**
- Active/slim edges

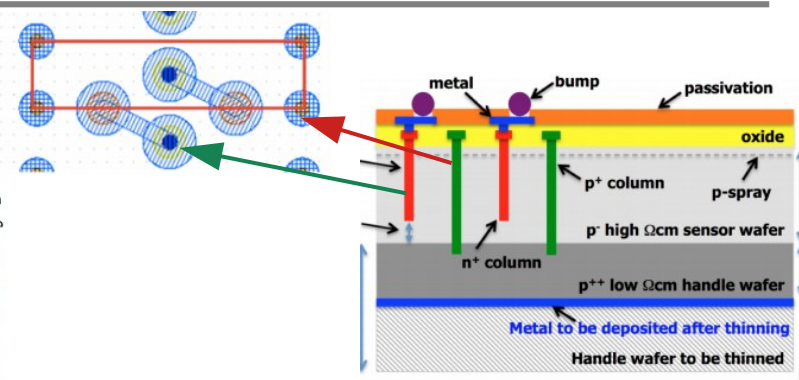


J. Lange et al. JINST 10 (2015) C03031

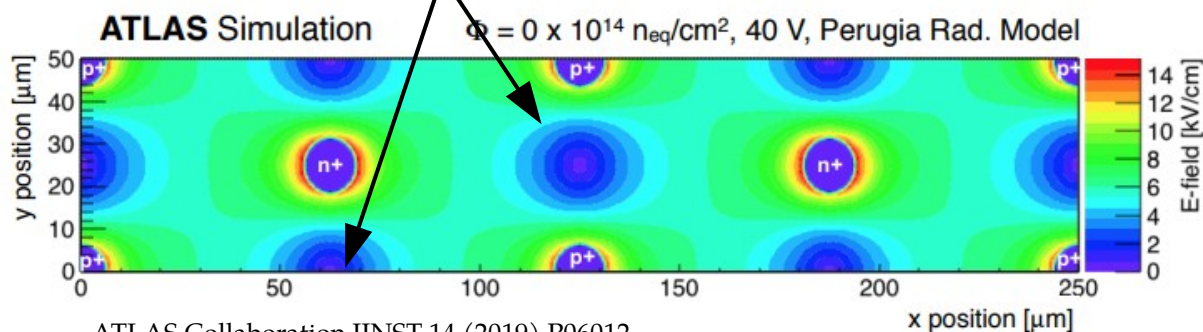




S. Terzo et al. JINST 14 (2019) 06, P06005



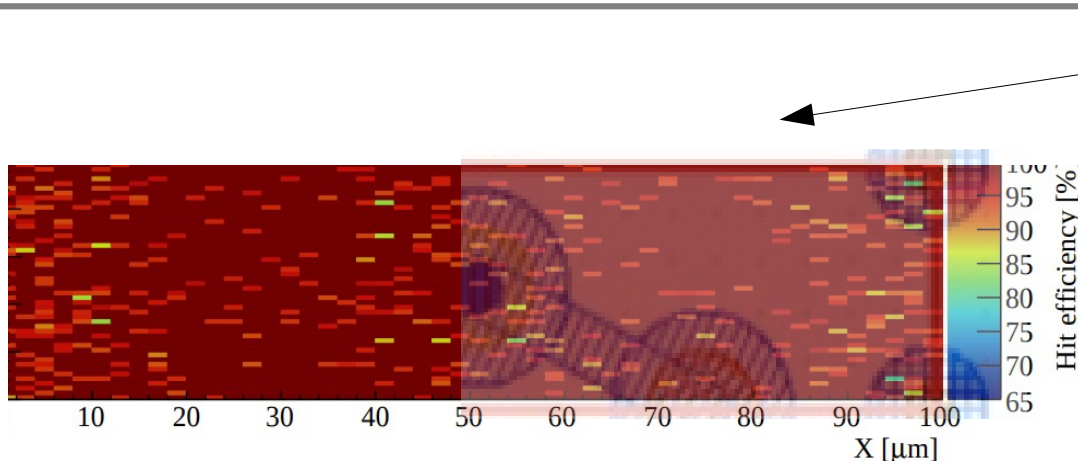
null points → delayed signal (diffuse first)



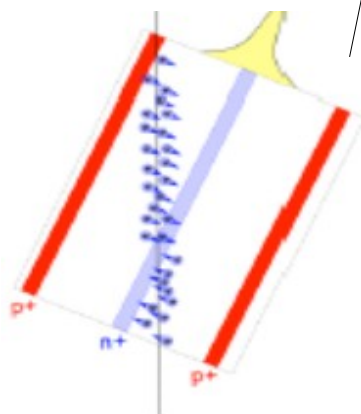
ATLAS Collaboration JINST 14 (2019) P06012

Drawbacks

- **Non uniform spatial response**
 - Charge losses inside electrodes
 - Low field regions between same type electrodes
- Higher capacitance than planar
 - Higher noise
- Complicated technology

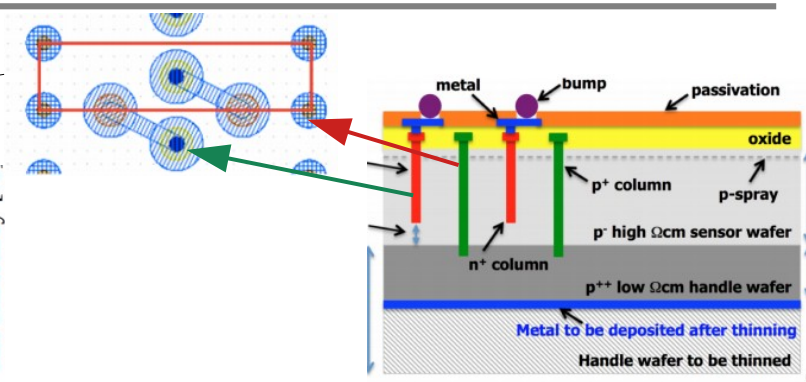


S. Terzo et al. JINST 14 (2019) 06, P06005



Recovers efficiency

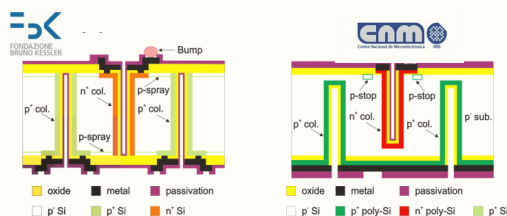
Tilting sensors



Drawbacks

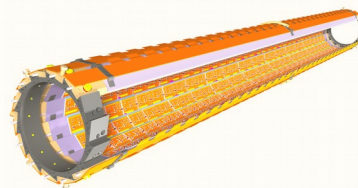
- ~~Non uniform spatial response~~
 - Charge losses inside electrodes
 - Low field regions between same type electrodes
- Higher capacitance than planar
 - Higher noise
- Complicated technology

LHC

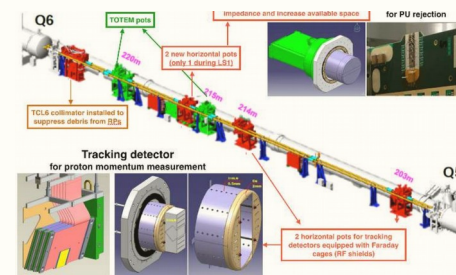


Double sided, n-in-p,
50 x 250 x 230 μm^3

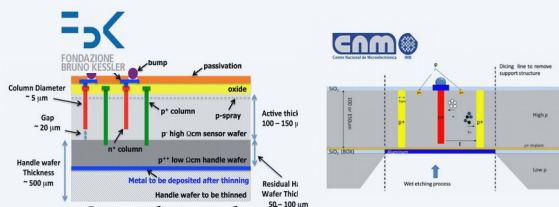
– ATLAS: IBL forward region (25% total IBL)



– CMS-TOTEM PPS

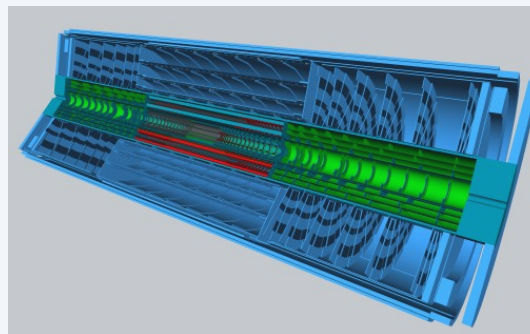


HL-LHC

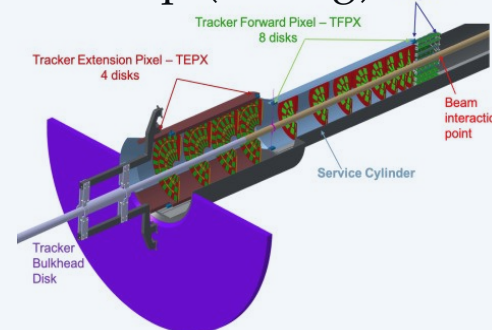


Single sided, n-in-p,
50x50x150/25x100x150 μm^3

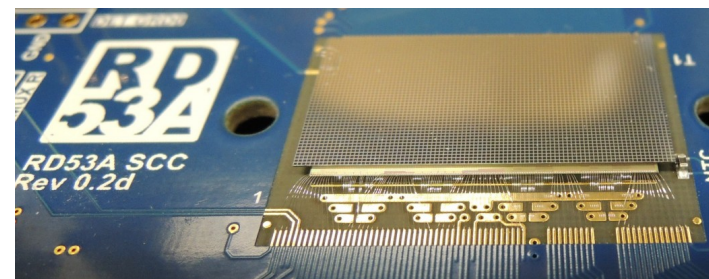
– ATLAS Upgrade
Innermost layer of the ITk



– CMS Upgrade
Being considered for Pixel
Barrel (Layers 1-2) and
Endcap (1st ring)

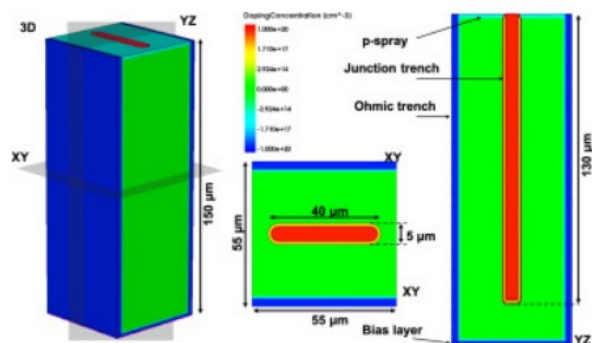


- Qualification and characterization of small-pitch 3D sensors for the HL-LHC experiments with (pre-)production chip(s) (**RD53A**) ITkPix/CROC



- Time performance for 3D pixel sensors G. Kramberger et al. NIMA, 934 (2019), p. 26
 - 3D-trenched electrodes: uniform fields

with 3D-geometr

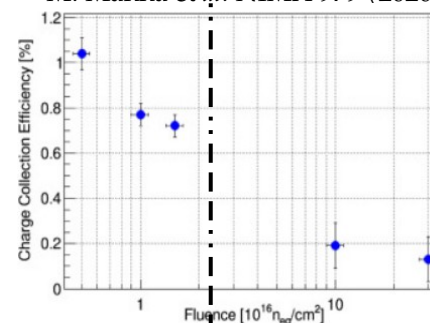


A. Lai et al. NIMA 981 (2020) 164491

[D03] 3D-trench Silicon Pixels with 20ps timing resolution

Adriano Lai (Universita e INFN, Ca...)

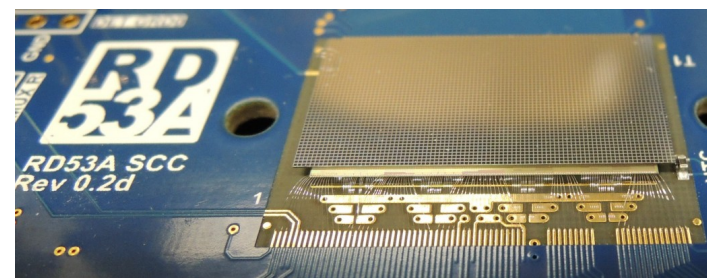
M. Manna et al. NIMA 979 (2020) 164458



HL-LHC lifetime expected fluence CMS IT innermost layer

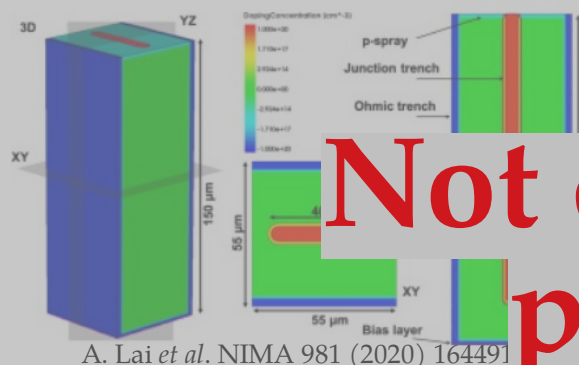
- 3D pixel sensors radiation hardness at extreme fluences $> 1 \times 10^{17} n_{eq}/cm^2$
 - “Sensor maintain function” at FCC expected irradiation levels

- Qualification and characterization of small-pitch 3D sensors for the HL-LHC experiments with (pre-)production chip(s) (**RD53A**) ITkPix/CROC



- Time performance for 3D pixel sensors G. Kramberger et al. NIMA, 934 (2019), p. 26

- 3D-trenched electrodes: uniform fields with 3D-geometry



A. Lai et al. NIMA 981 (2020) 164491

[D03] 3D-trench Silicon Pixels with 20ps timing resolution

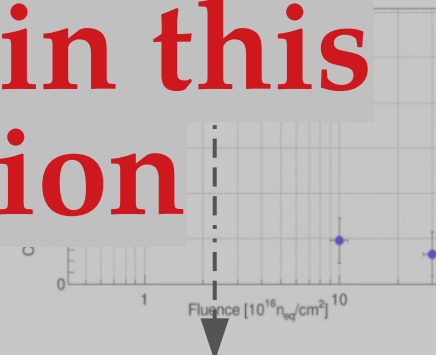
Adriano Lai (Universita e INFN, Ca...)

M. Manna et al. NIMA 979 (2020) 164458

Not covered in this presentation

- 3D pixel sensors radiation hardness at extreme fluences $> 1 \times 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2$

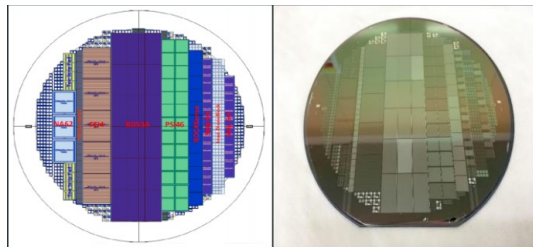
- “Sensor maintain function” at FCC expected irradiation levels



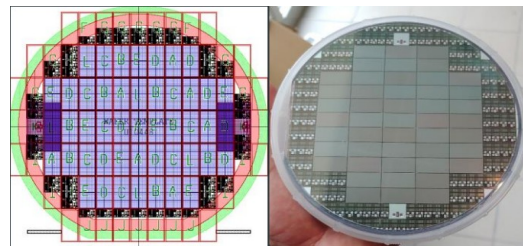
HL-LHC lifetime expected fluence CMS IT innermost layer

CNM/FBK 3D productions compatible with RD53A chip

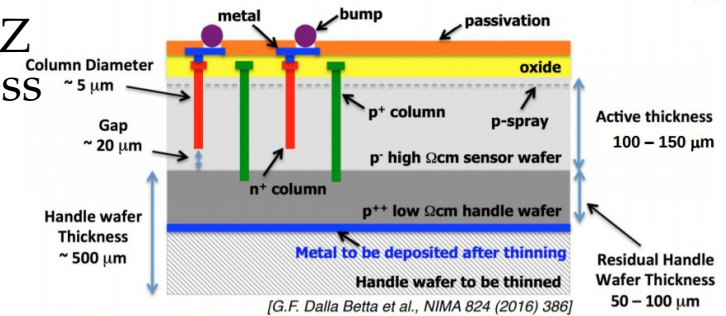
- FBK: Si-Si 6", DWB substrates:** p⁺⁺ low-resistivity CZ and high-resistivity FZ. DRIE for columns. SS process



(2nd 3D-SS) Batch with Mask Aligner lithography (FZ 130 μm thickness)

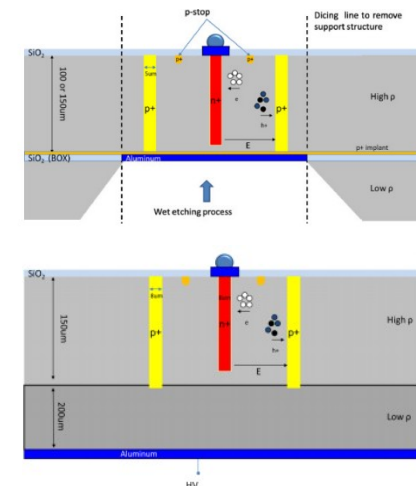
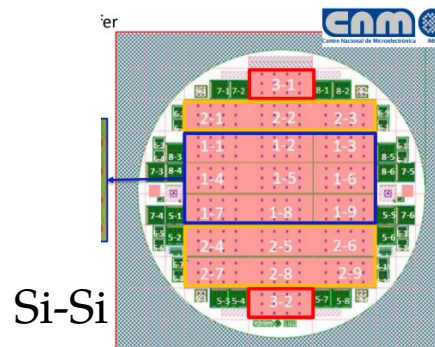
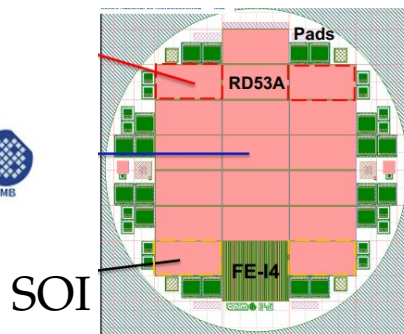


(3rd 3D-SS) Batch with Stepper lithography (FZ 150 μm thickness)



FONDAZIONE BRUNO KESSLER

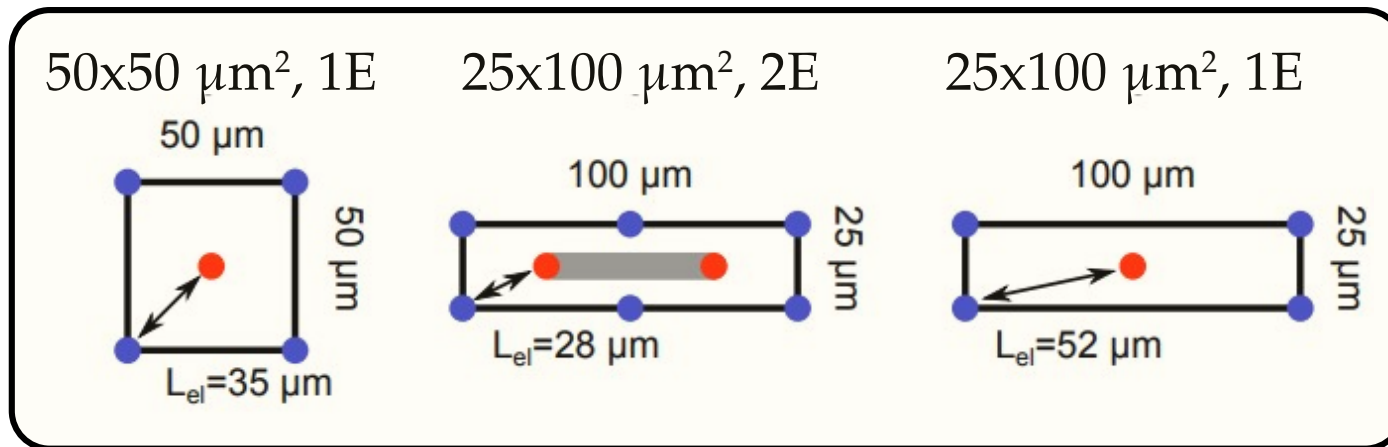
- CNM: SOI/Si-Si 4", substrates:** p⁺⁺ low-resistivity CZ and high-resistivity FZ, SS process



SIO

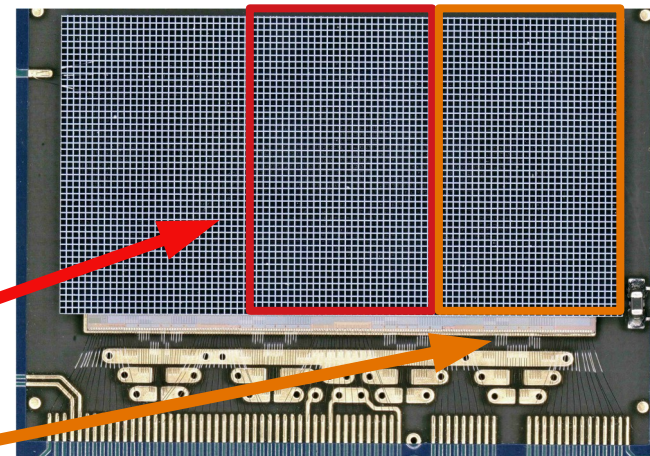
Si-Si

- ATLAS/CMS considered pixel geometries (CMS final decision by Q1/2021)
 - ATLAS choice: $25 \times 100 \mu\text{m}^2$ 1E barrel, $50 \times 50 \mu\text{m}^2$ rings

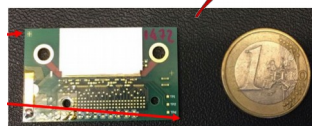


[2] https://cds.cern.ch/record/2287593/files/%20RD53A_Manual_V3-42.pdf

- **RD53A**^[2]: a demonstrator readout chip for HL-LHC upgrade of ATLAS and CMS
 - 65 nm CMOS technology
 - Not a production chip
 - Chip divided in regions with 3 different analog front ends
 - CMS choice **Linear AFE**
 - ATLAS choice: **Differential AFE**



- Sensor+RD53A mounted over adapters cards for readout

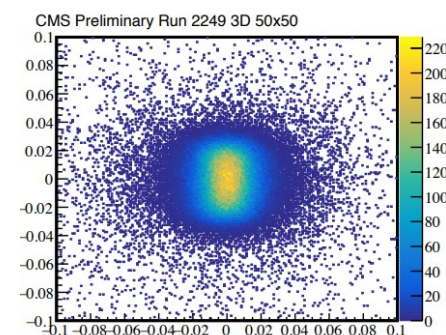
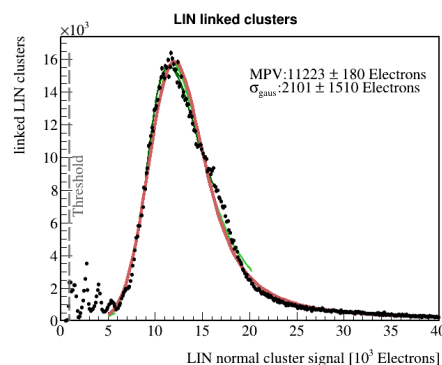
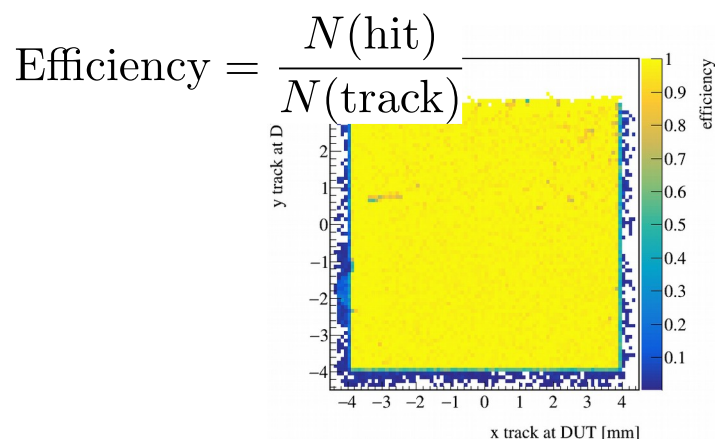
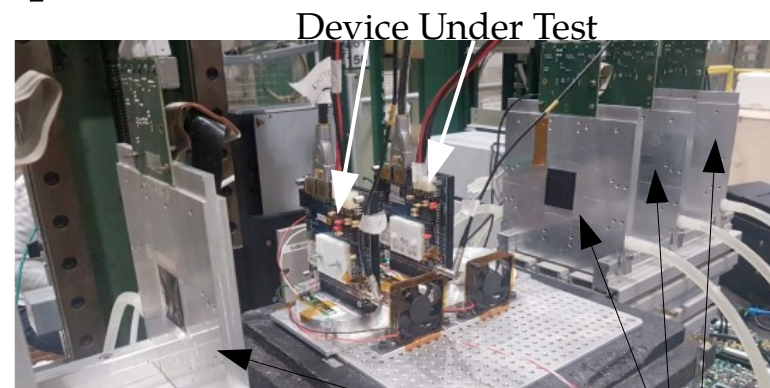
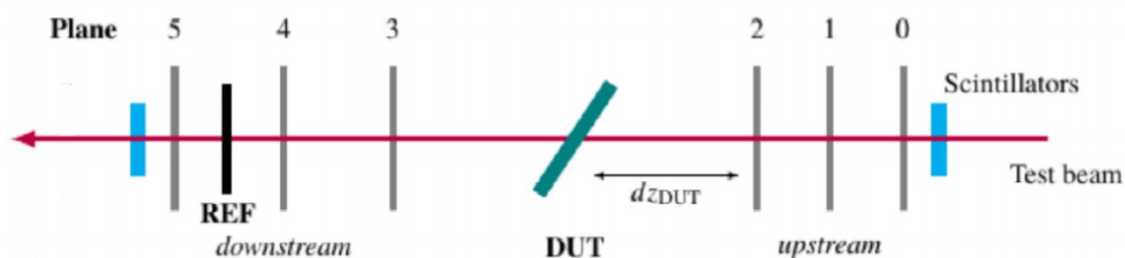


RICE card



Bonn SCC

- Test beams are used to characterize sensor performance under similar conditions than in the real experiment

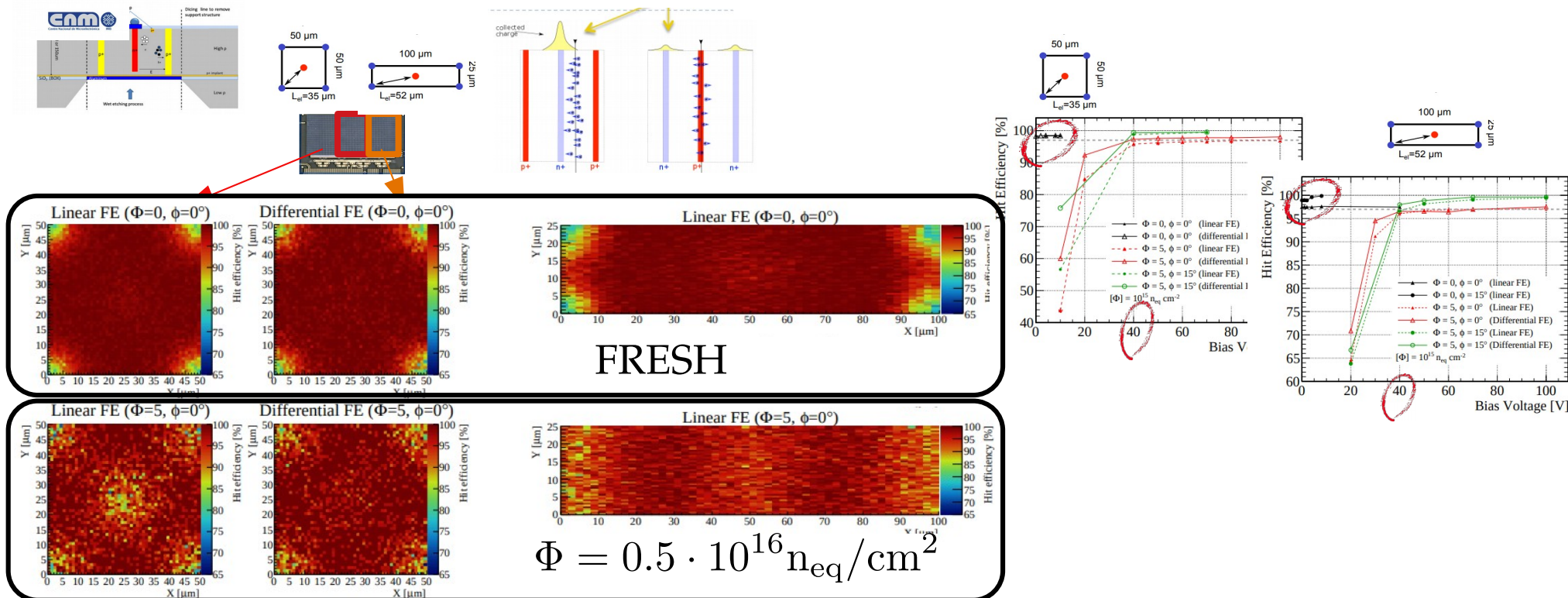


Telescope planes

Hit Efficiency

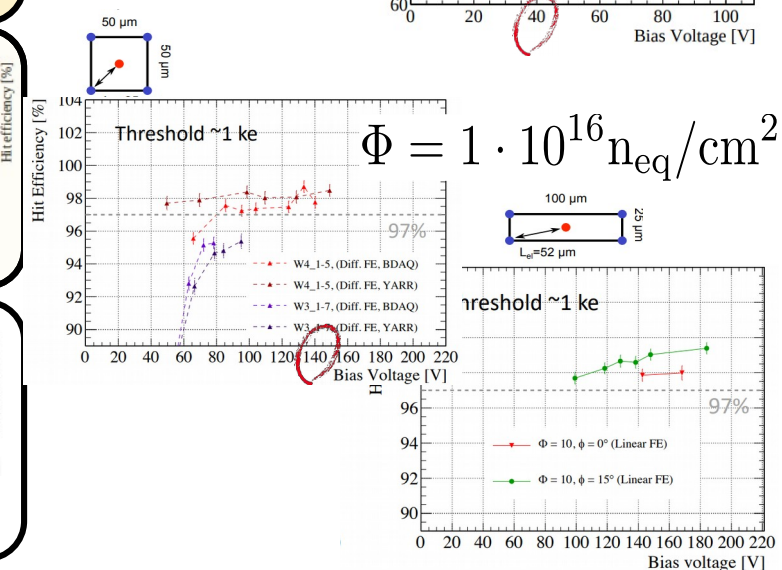
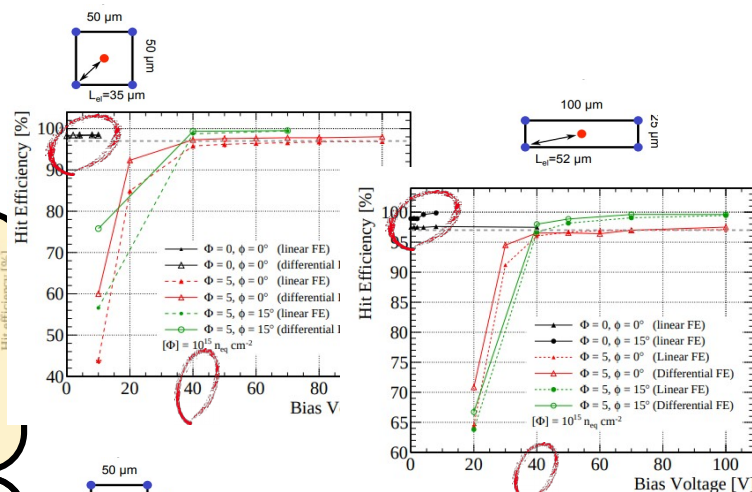
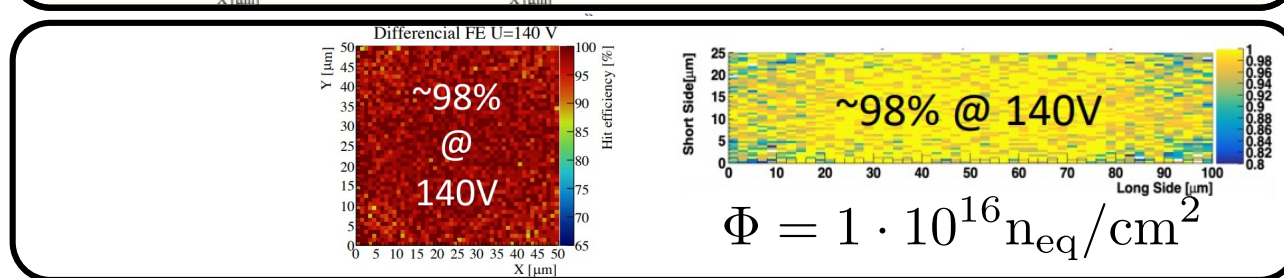
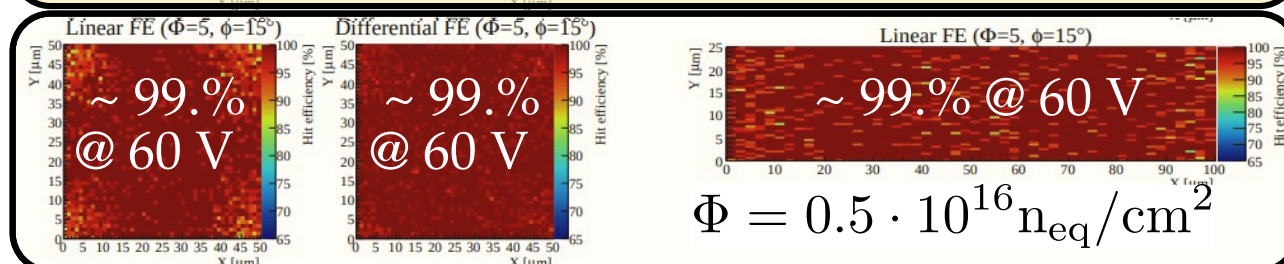
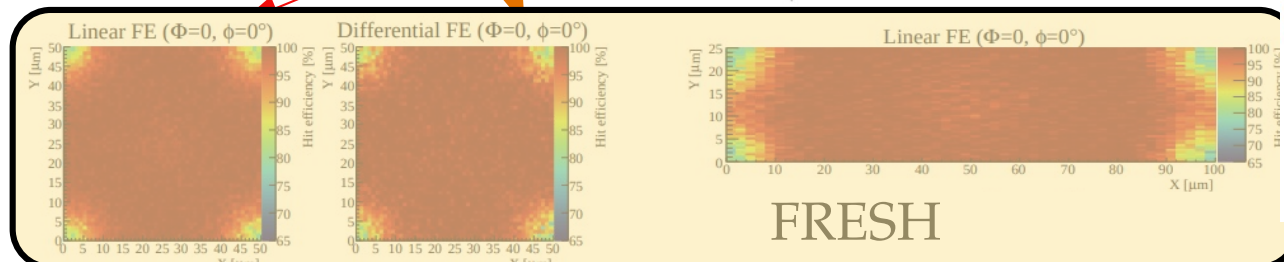
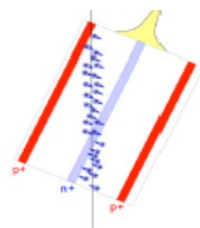
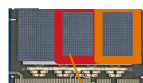
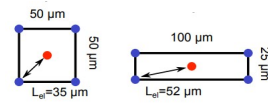
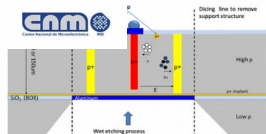
S. Terzo et al. JINST 14 (2019) 06, P06005

<https://indico.cern.ch/event/803258/contributions/3582778/attachments/1962445/3262150/204-terzo-hiroshima.pdf>



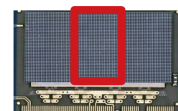
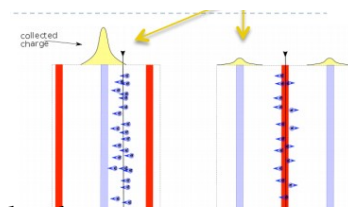
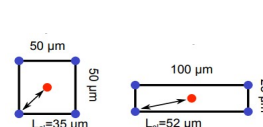
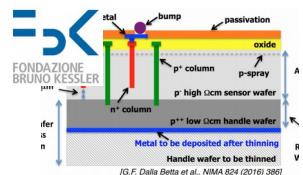
S. Terzo et al. JINST 14 (2019) 06, P06005

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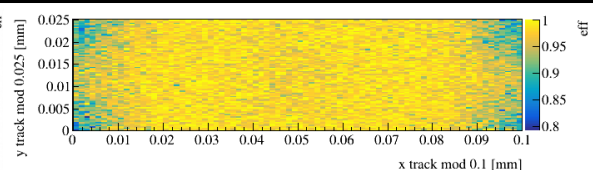
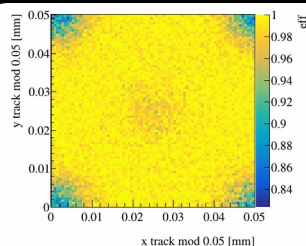
J.Duarte-Campderros et al. NIMA 944 (2019) 162625

https://indico.cern.ch/event/803258/contributions/3582883/attachments/1962451/3262153/300-Meschini-3D_Pixel_CMS.pdf

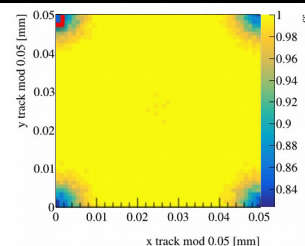


Mask Aligner, 130 μm thick

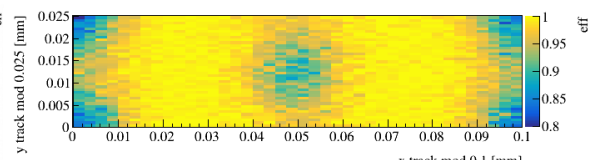
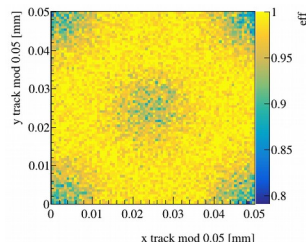
Stepper, 150 μm thick



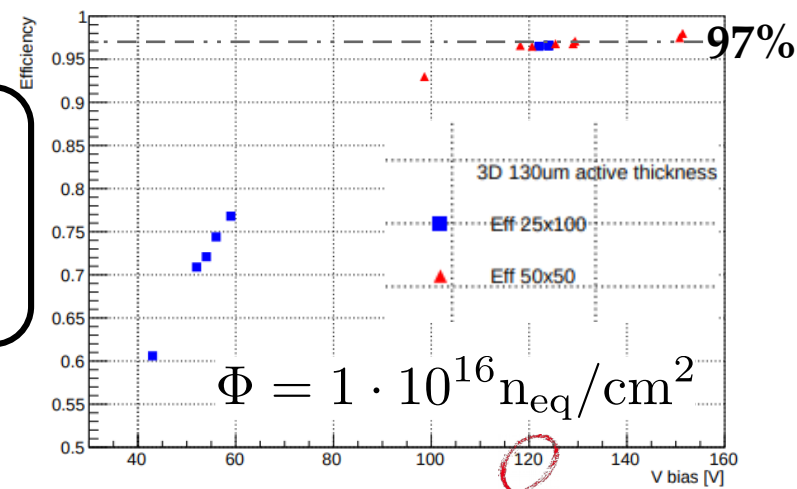
FRESH



- Efficiency > 98% (few V_{bias})
 - Tilted → > 99%

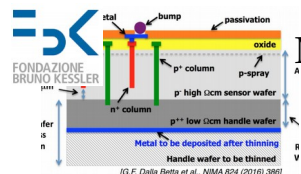


$$\Phi = 1 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$$

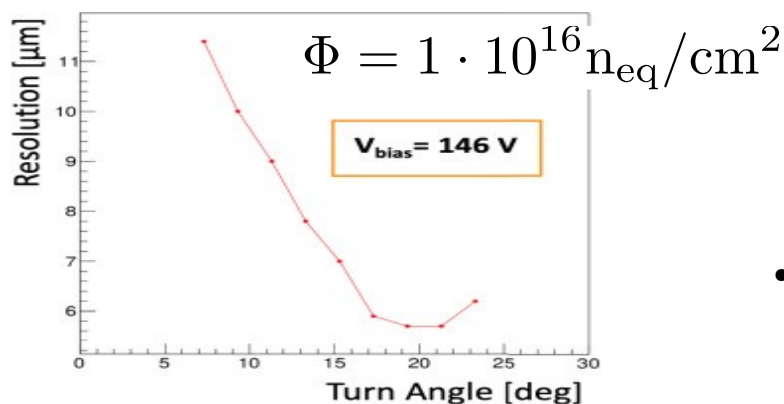
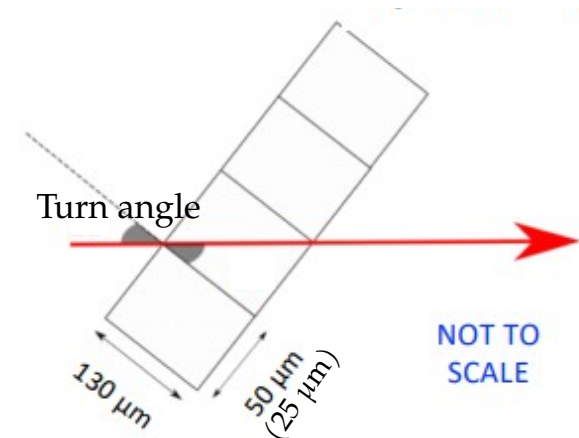
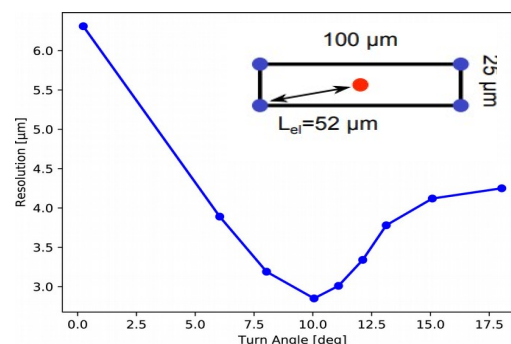
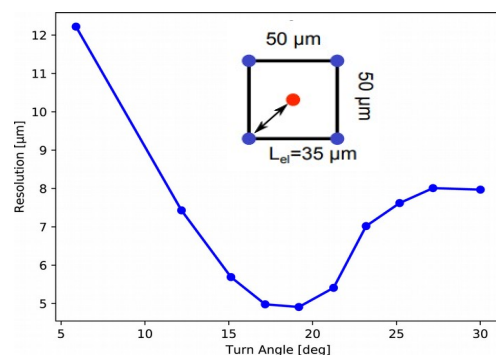


M. Meschini et al. NIMA 978 (2020) 164429

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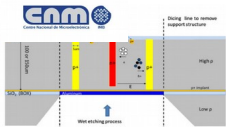


Mask Aligner, 130 μm thick

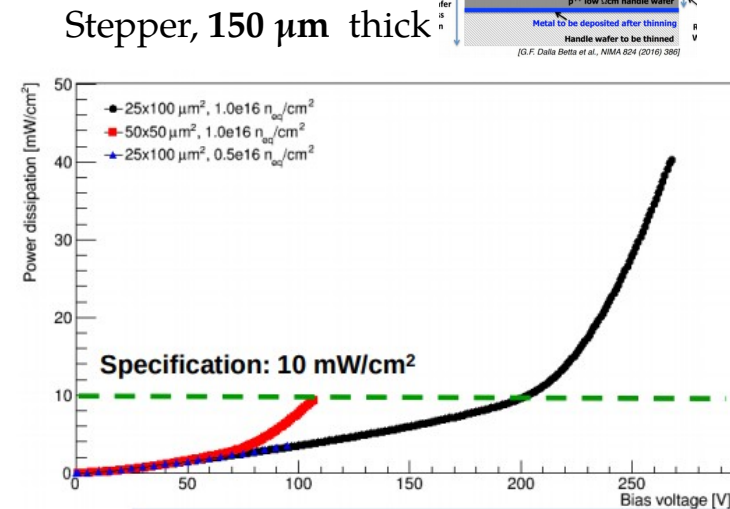
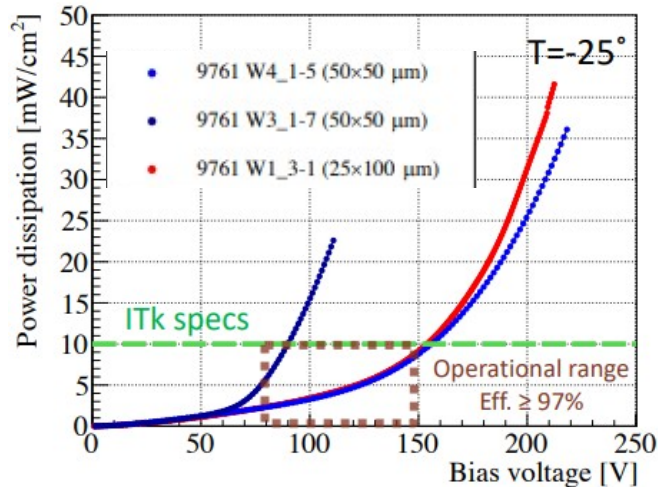
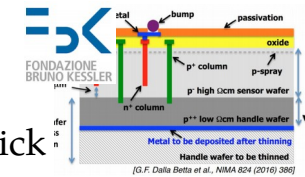


Resolution:

- ~ 5 μm (50 μm pitch)
- ~ 3 μm (25 μm pitch)
- Almost **no degradation** in resolution after irradiation



$$\Phi = 1 \cdot 10^{16} n_{eq}/cm^2$$



- Power dissipation below 10 mW/cm² for operational range
 - Fulfill ATLAS specs (CMS are less stringent)

- Small-pitch 3D pixel sensors bump-bonded to pre-production ROC (RD53A) have proven to have an **excellent radiation tolerance** up to $1 \cdot 10^{16}$ neq/cm²
 - High efficiency (> 97% normal incidence)
 - Maintain spatial resolution
 - Low operational bias voltages (40-140 V)
 - Low power dissipation (<10 mW/cm², @ -25 C)
 - Both 25x100 and 50x50 designs shows similar performance, in particular 25x100-1E is able to reach requirements (no need for 2E)
- **Comply with ATLAS/CMS baseline performance requirements**
- Samples irradiated to $2 \cdot 10^{16}$ neq/cm², to be tested in beam soon
- Preparing final radiation tolerance study with production ROCs (ITkPixV1 & CROC)