New developments in 3D-trench electrode sensors

Jixing Ye, Maurizio Boscardin, Matteo Centis Vignali, Francesco Ficorella, Omar Hammad Ali, Adriano Lai, Angelo Loi, Francesca Mattedi, Laura Parellada Monreal, Sabina Ronchin, Gian-Franco Dalla Betta

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FONDAZIONE BRUNO KESSLER

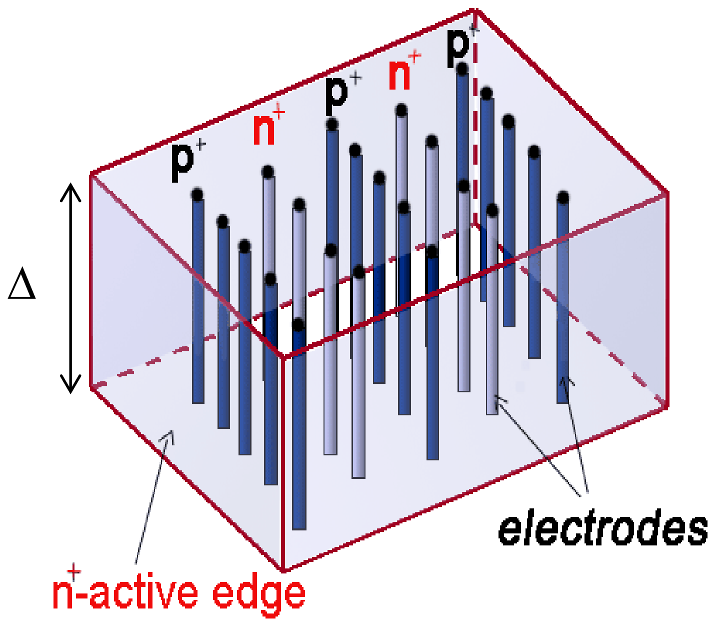
TimeSPOT

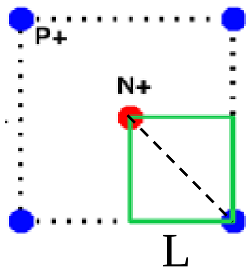
PIXEL 2024

Outline

- *Introduction - 3D Sensors*
- *3D-trench electrode sensors for timing:*
  - *Proof of concept*
  - *Test results (TIMESPOT)*
- *3D-trench electrode sensors – A new design:*
  - *Standard (STD) vs Dashed (DSH)*
  - *Electrical tests (AIDAInnova)*
- *Other ongoing efforts*
- *Conclusions*

Introduction - 3D sensors





Inter-electrode distance (L) and active substrate thickness (Δ) are decoupled → L<<Δ by layout

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

ADVANTAGES:

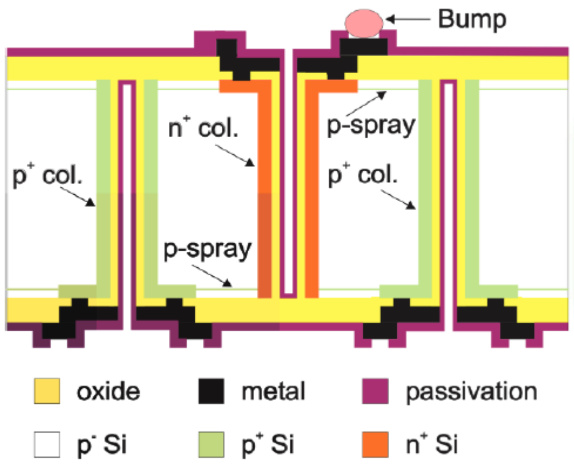
- *Low depletion voltage (low power diss.)*
- *Short charge collection distance:*
  - *Fast response*
  - *Less trapping probability after irr.*
- *Lateral drift → cell "shielding" effect:*
  - *Lower charge sharing*
  - *Low sensitivity to magnetic field*
- *Active edges*

Relatively low voltage (power) after strong irr.

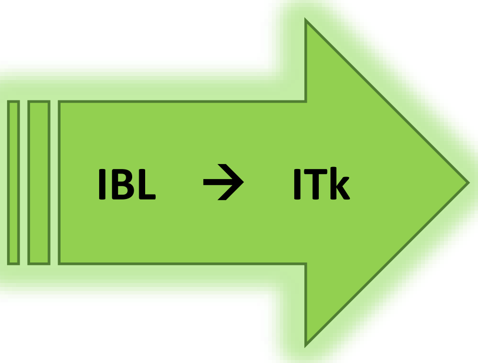
DISADVANTAGES:

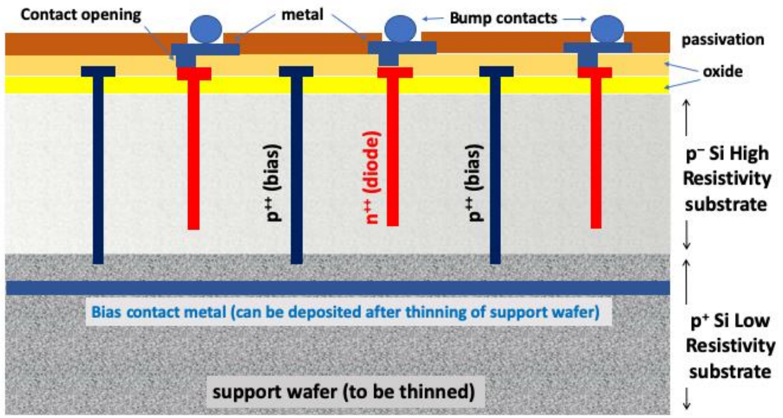
- *Non uniform spatial response (electrodes and low field regions)*
- *Higher capacitance with respect to planar (~3x for ~ 150 µm thickness)*
- *Complicated technology (cost, yield)*

Introduction - 3D sensors



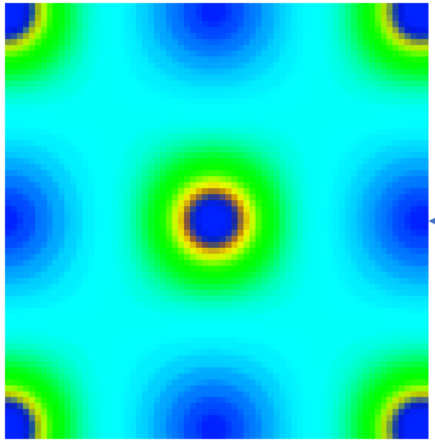
Schematic of 3D-DDTC for LHC



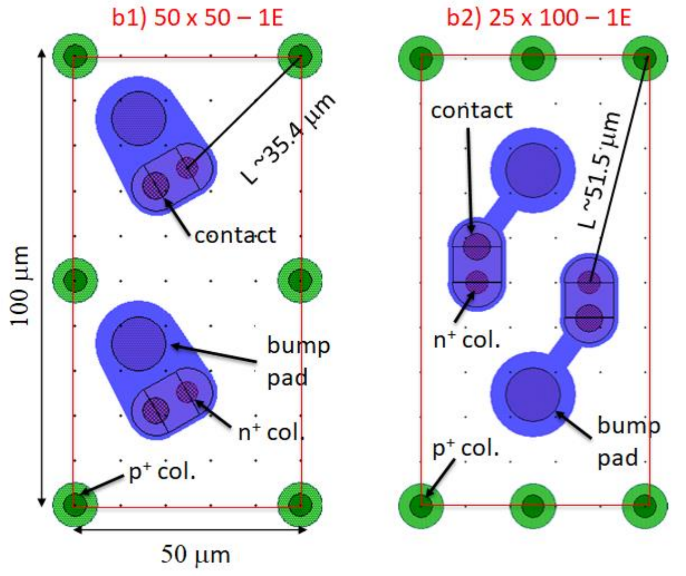


Schematic of 3D small-pitch pixels for HL-LHC

Though low field regions exist in columnar electrode 3D sensors, measurements show ***high hit efficiencies (>97%) after fluence of ~10^{16} n_{eq}/cm^2 for both layouts.***



Electric field@100 V

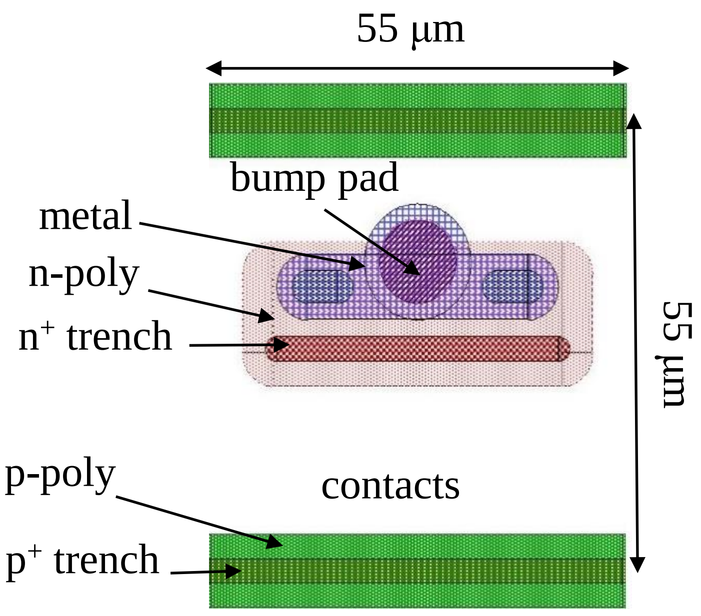


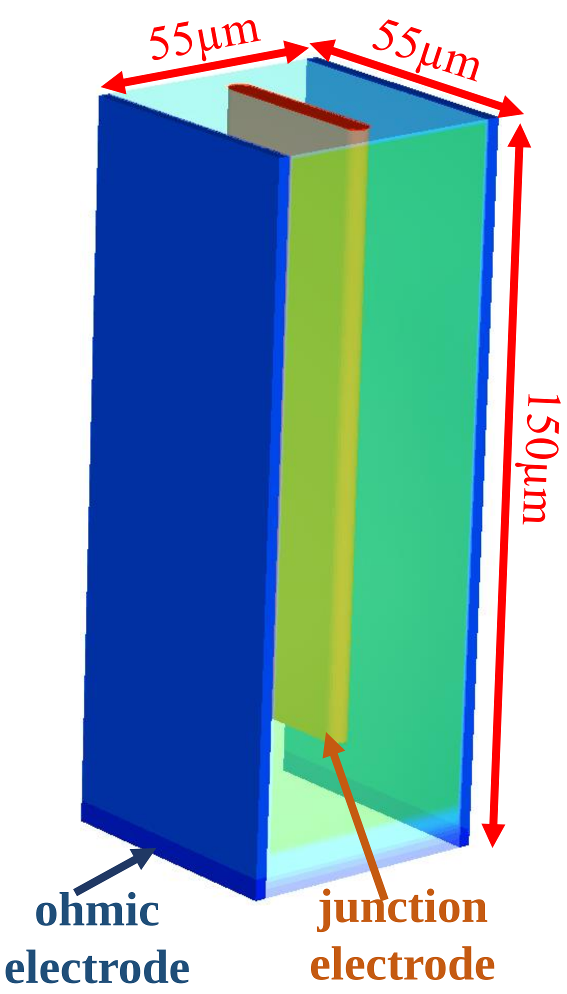
End-cap of L0 ***Central barrel of L0***

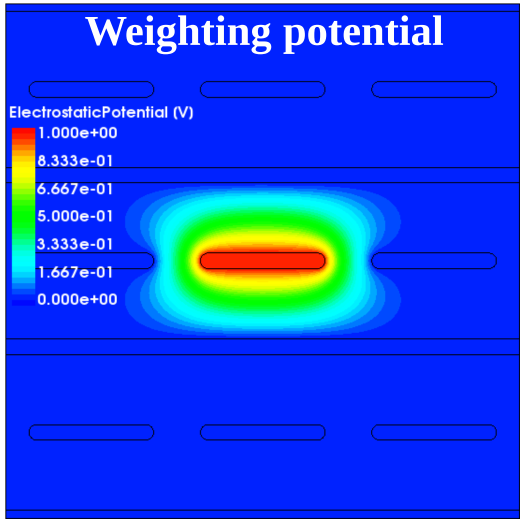
3D-trench electrode sensors for timing

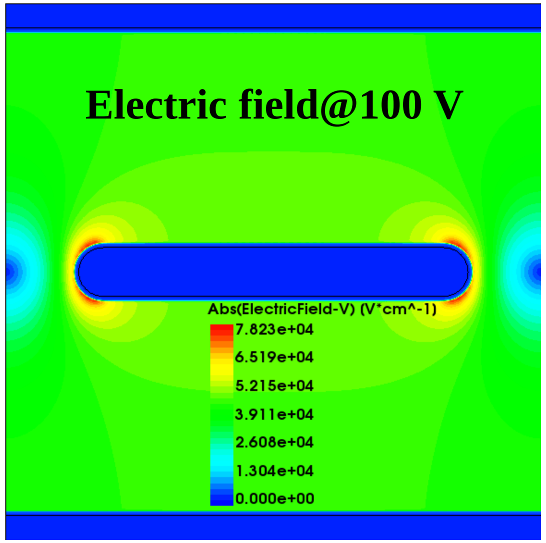
*Under the **TIME-SP**ace **O**perating **T**racker Project, 3D-Trenched sensors for tracking + timing have been developed for the first time.*

(INFN CSN5 Call Project, 2018-2021)

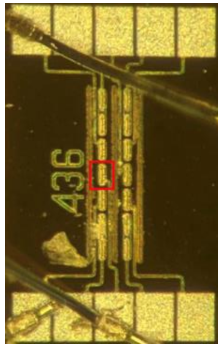


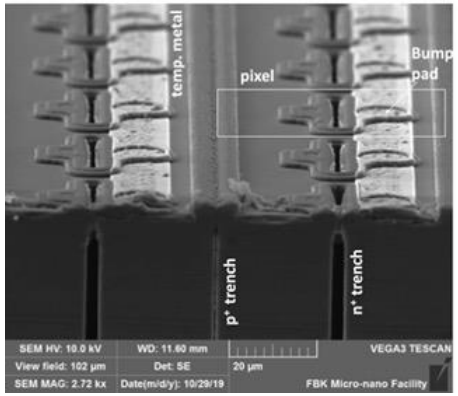


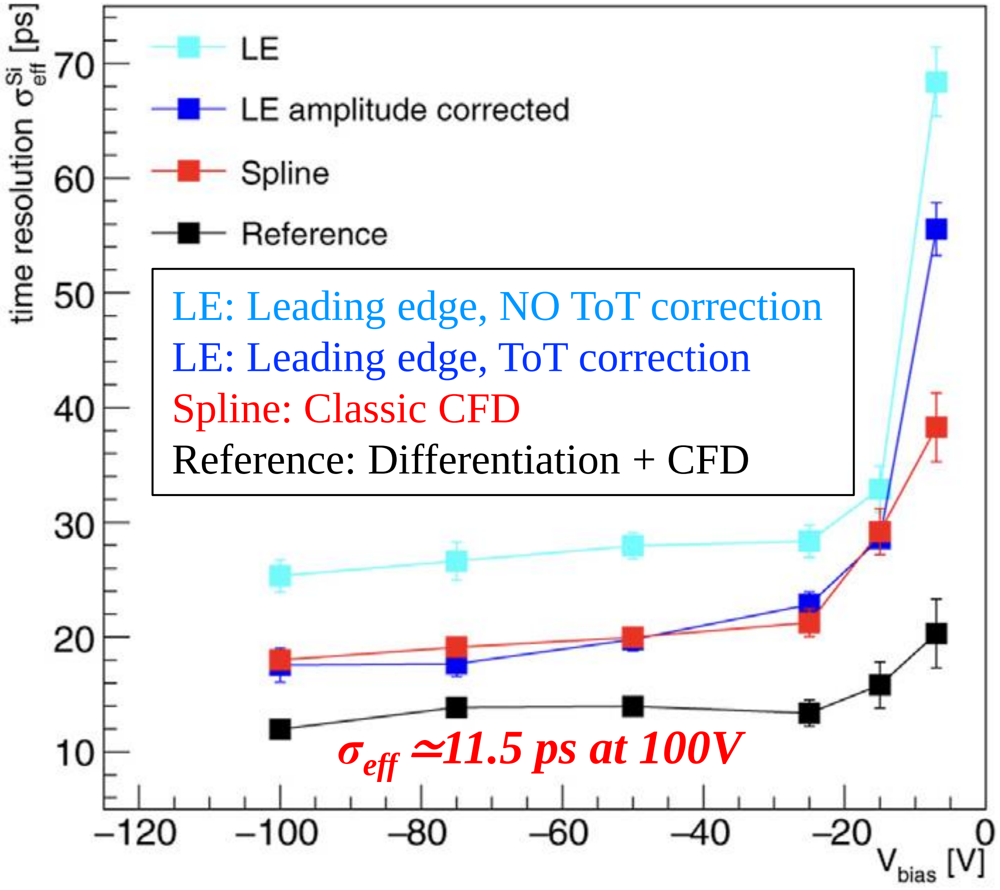




Timing measurements (single pixel @ a_{tilt}=0°, not irrad.)



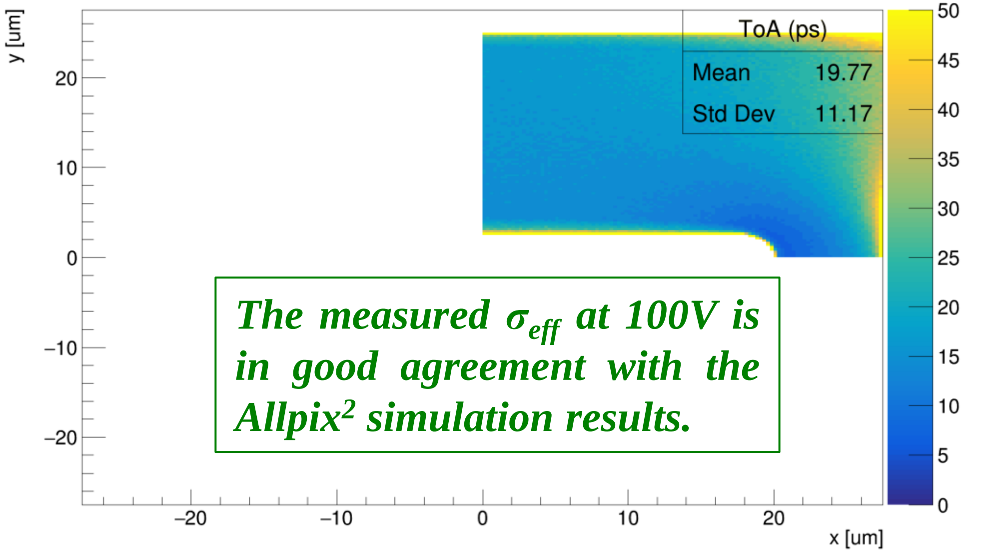




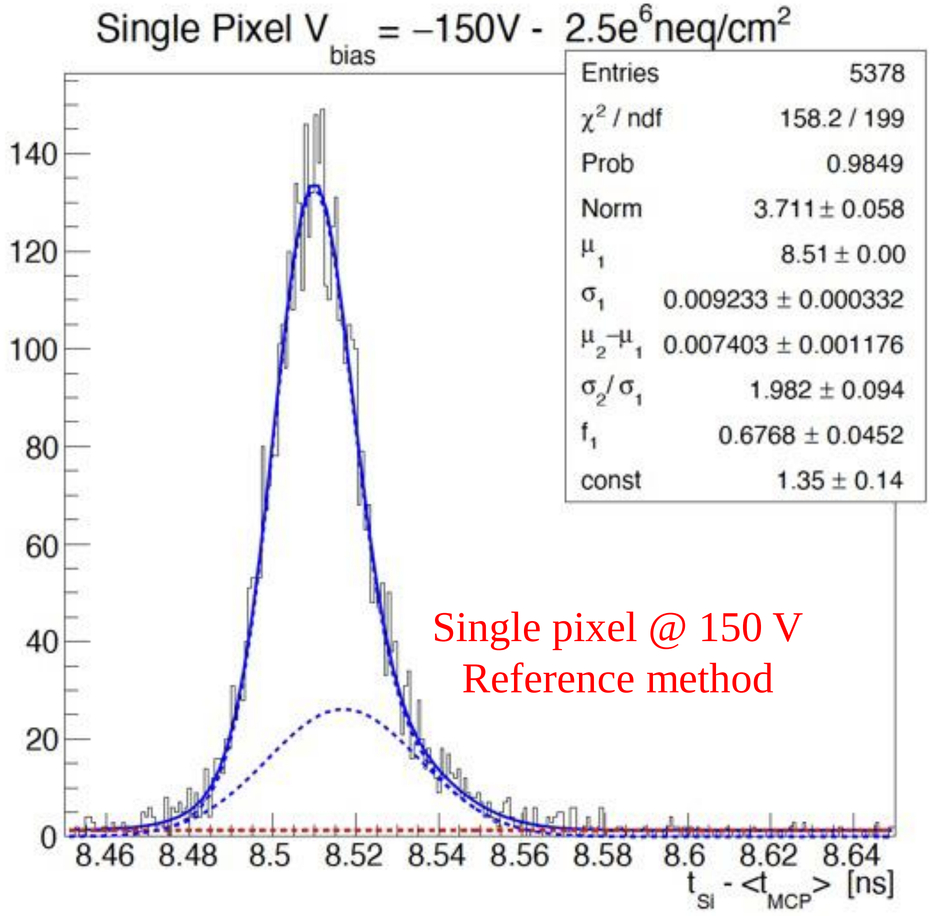
F. Borgato et al. Frontiers in Physics (2023) 1117575

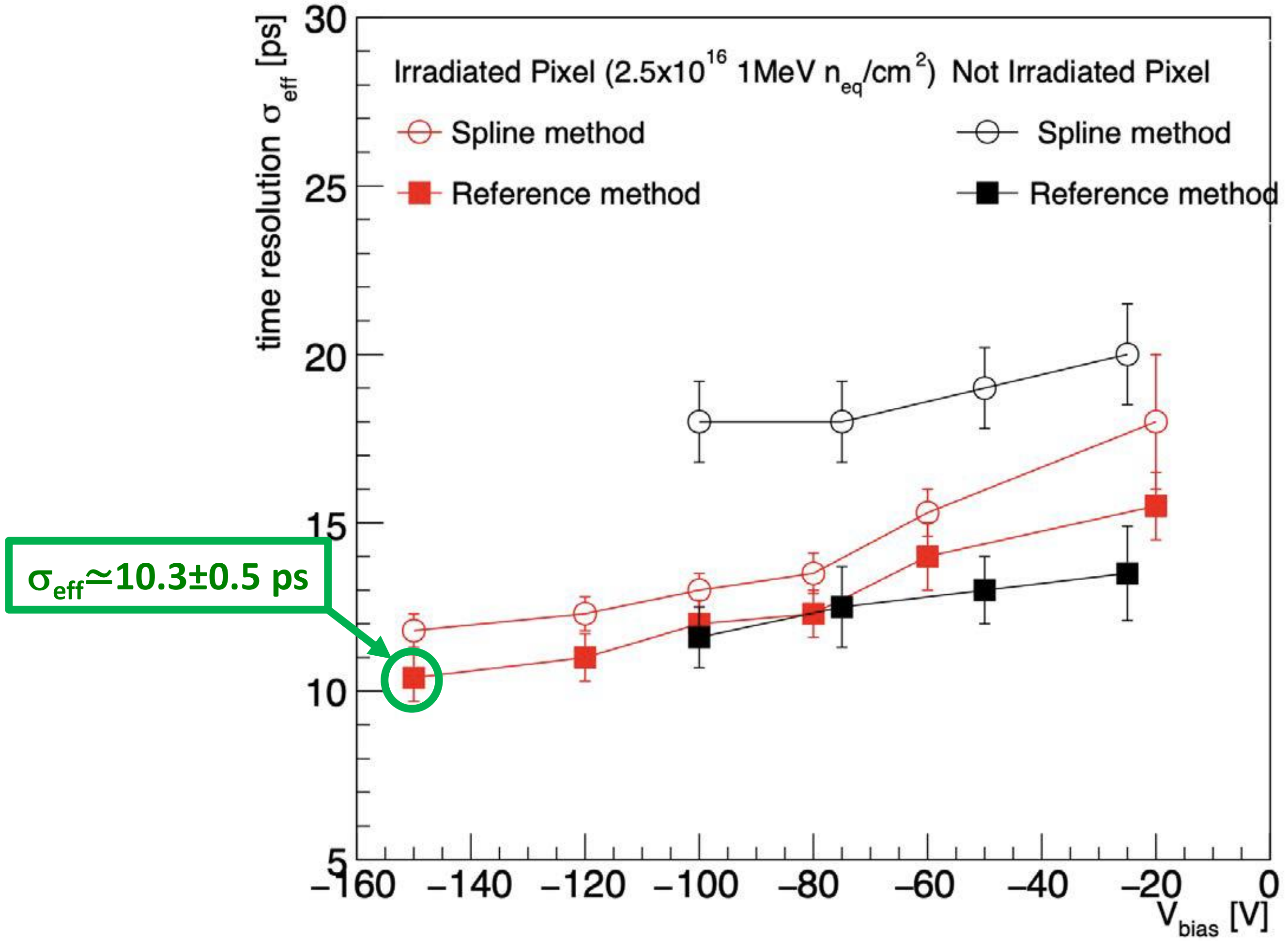
Monte-Carlo simulation based on Allpix^2:

1). Standard mobility models used;
2). Scan over a quarter of the pixel with a step-length of 0.25μm (12100 events in total).



Timing measurements (single pixel @ α_{tilt}=0°, irradiated)

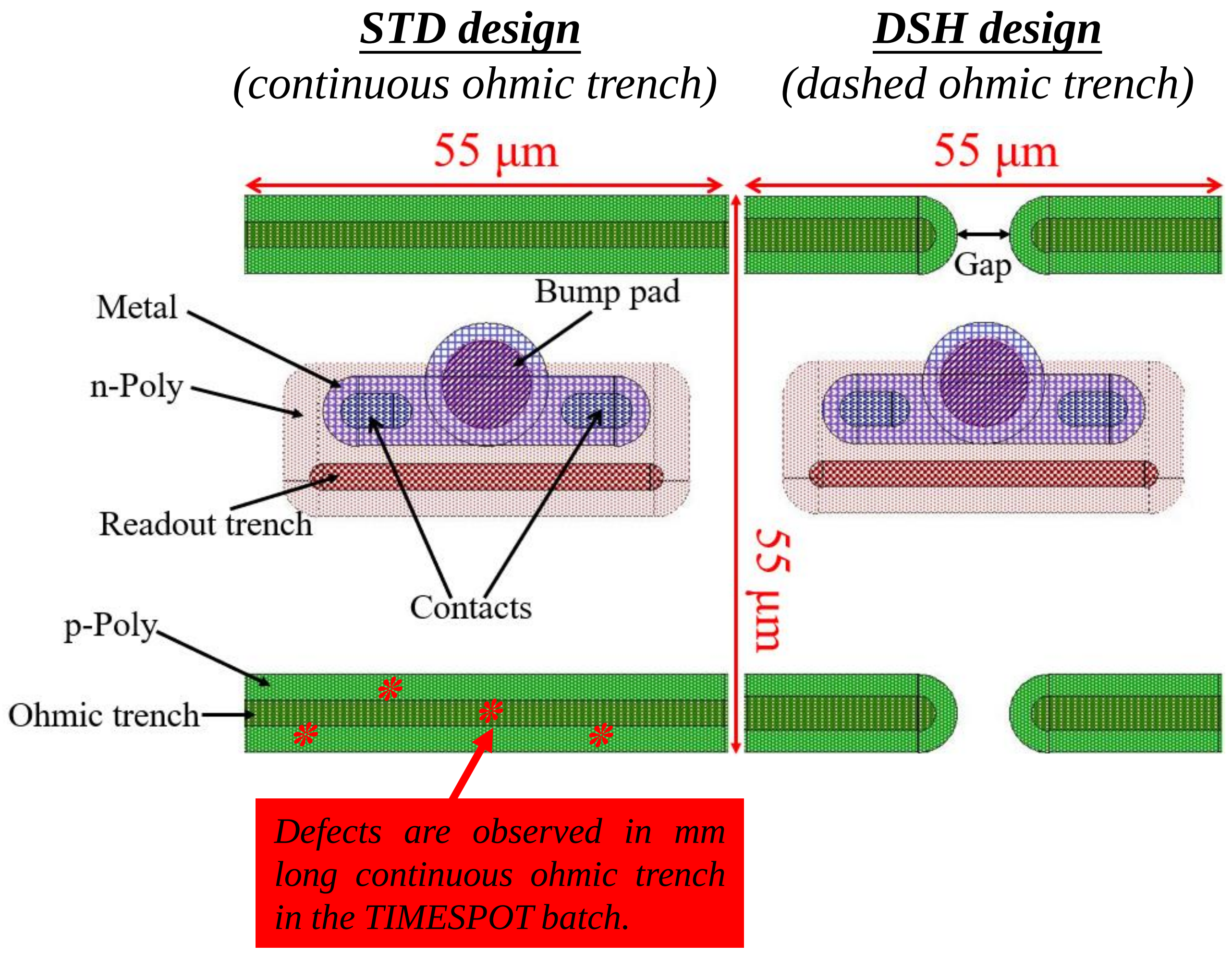




A. Lampis et al. JINST 18 (2023) C01051

3D-trench electrode sensors – A new design

- *3D-trench technology not yet mature*
- *Main aspects involved:*
  - *Trench etching*
  - *Trench filling*
  - *Planarization*
  - *Final passivation*
- *Further developments required to:*
  - *reduce defect density*
  - *increase device area*
  - *increase the device density on wafer while reducing the bow*



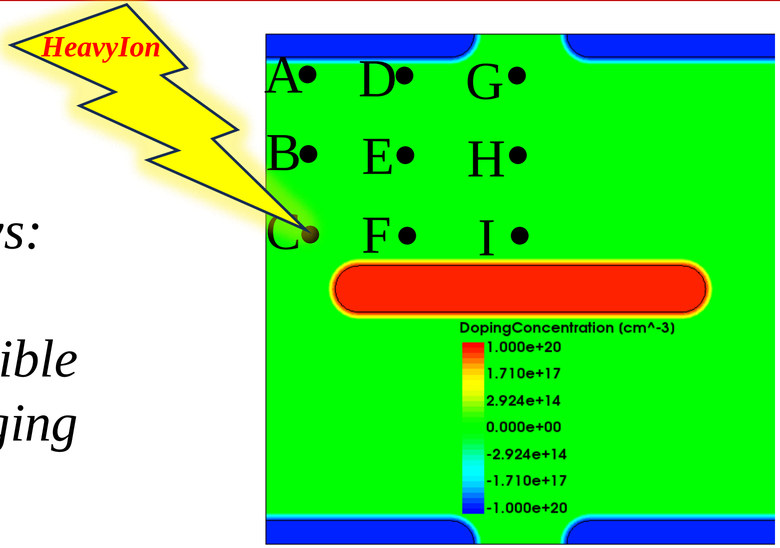
3D-trench electrode sensors – A new design

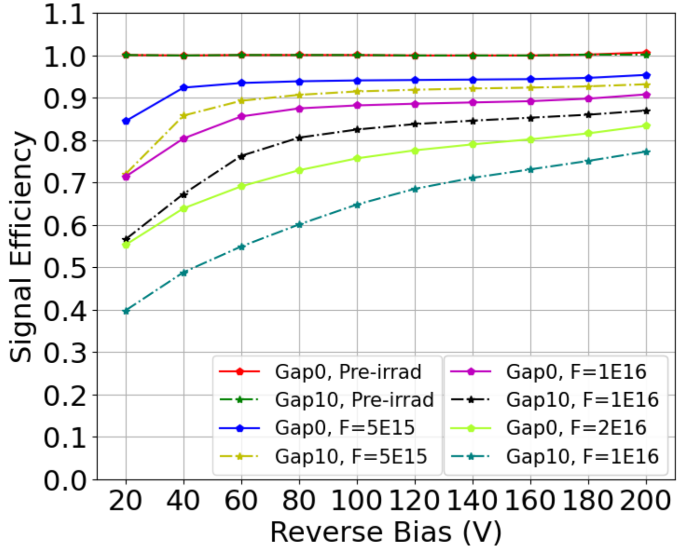
Transient TCAD simulation shows:

1). STD & DSH have negligible difference in the SE for impinging position A, B, C, D, E, and F;

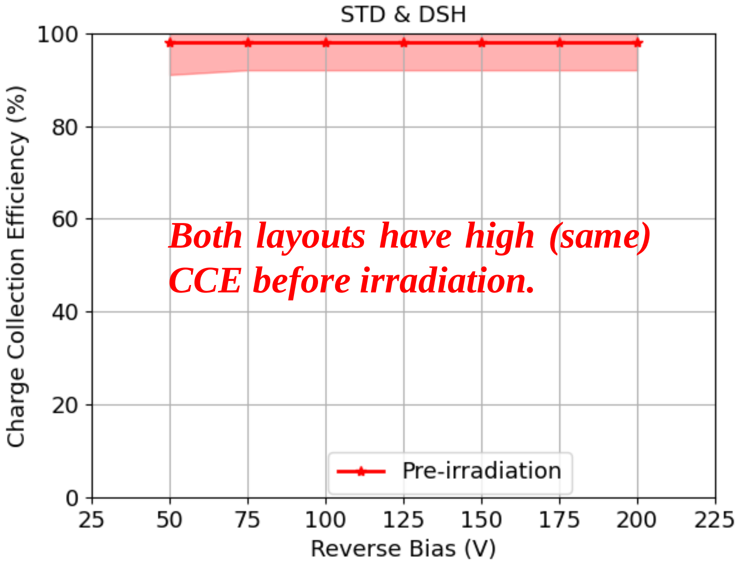
2). For impinging position G, H, I, the difference between the two designs decreases as the impinging position moves away from the gap, where the EF is less affected.

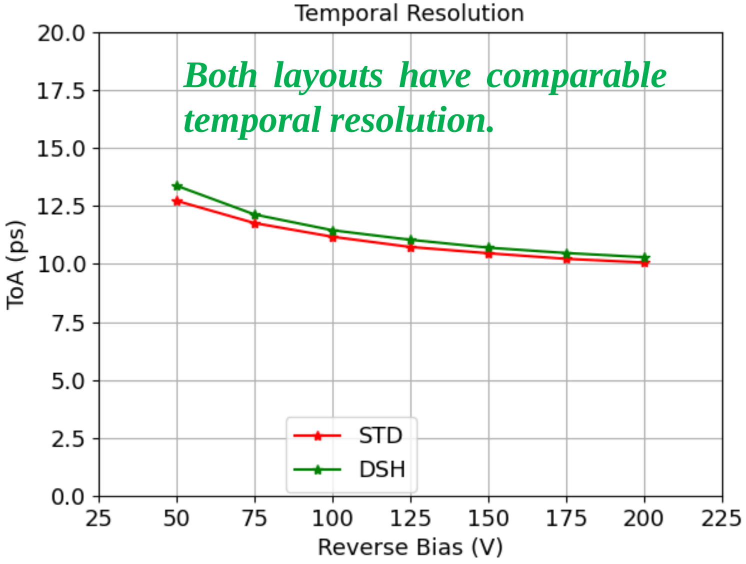
J. Ye et al., IWORID 2023





SE of Pos G





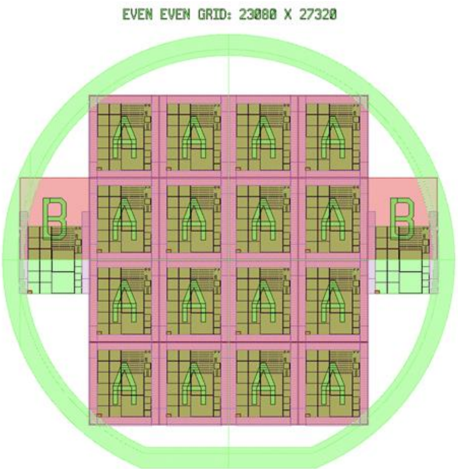
3D-trench electrode sensors – A new design

New batch including the STD and DSH has funded by

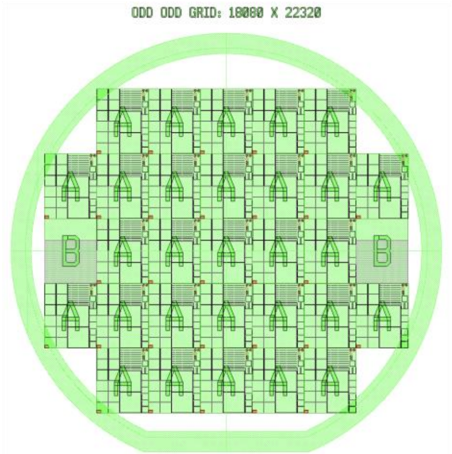
Fabrication done at FBK

Largely increased device density on wafer w.r.t TIMESPOT batches (11 shots);

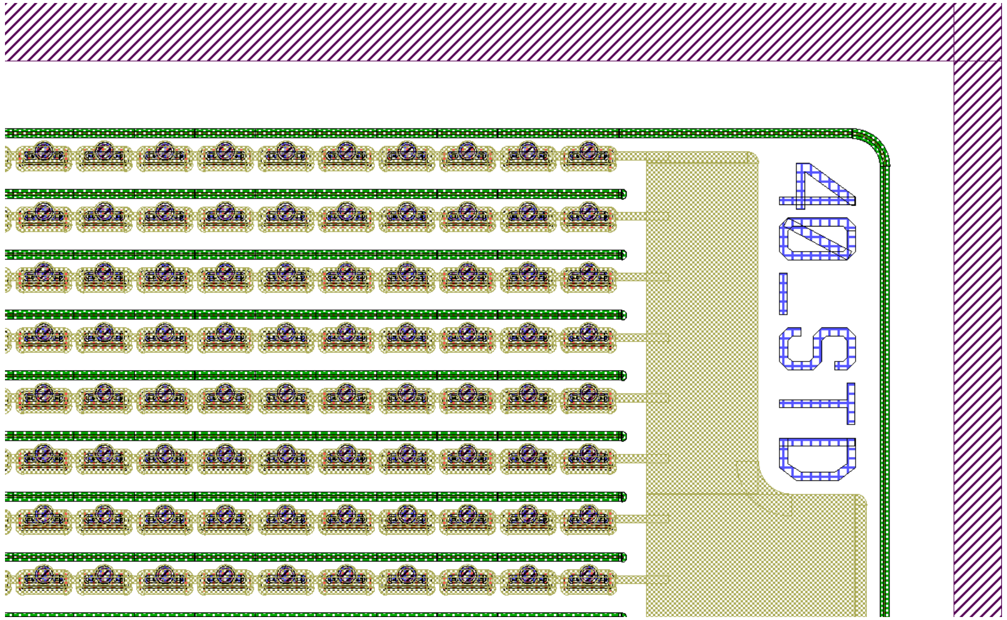
Bow under control (~max 20 μm).



18 shot exposure



29 shot exposure



Layout of 64×64 sensor (STD design)
Only the corner region is shown

3D-trench electrode sensors – A new design

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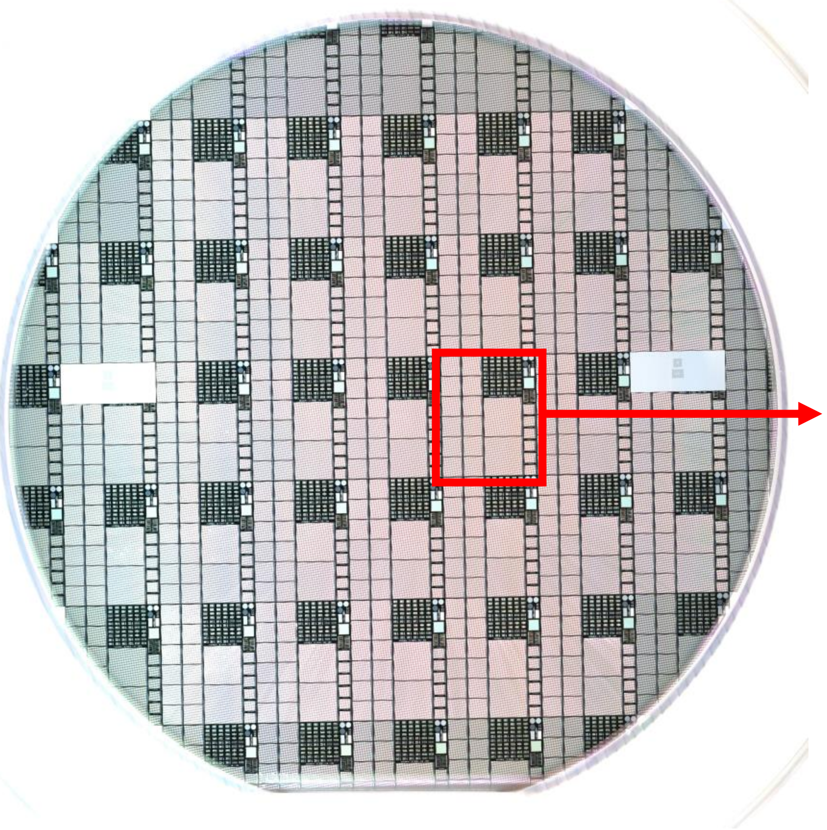
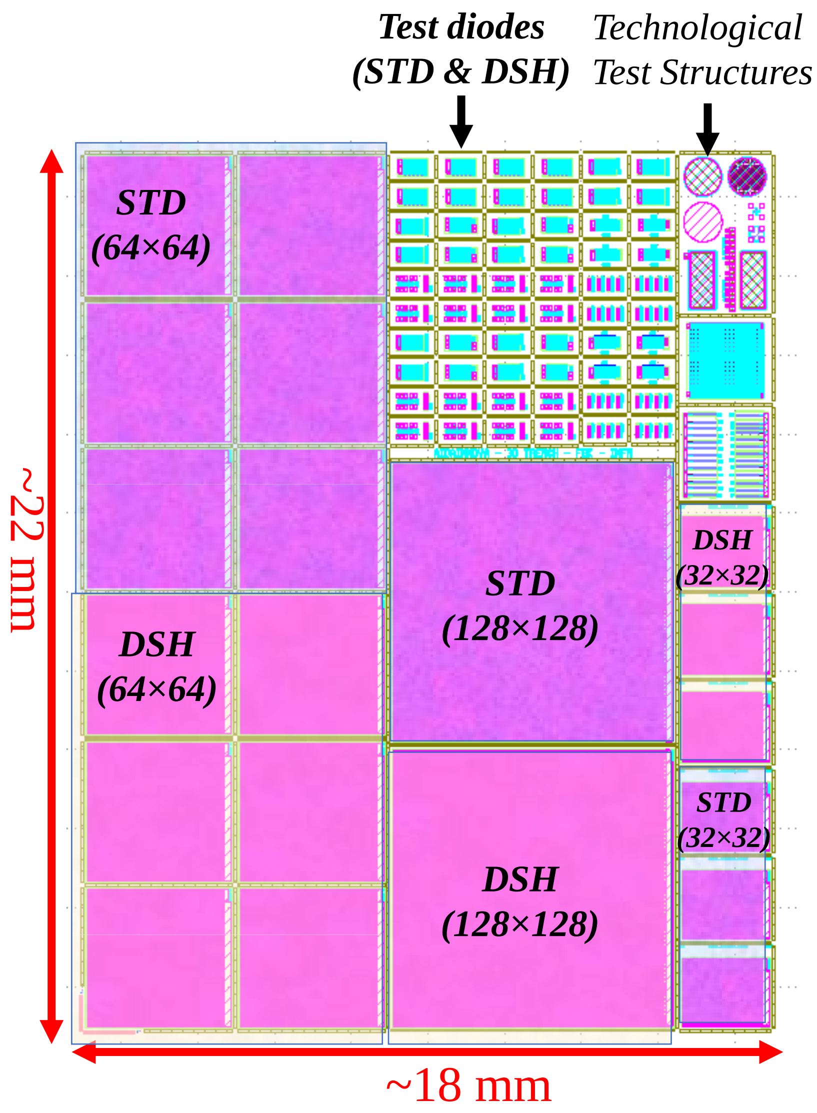
Fabrication based on
Stepper Lithography





To explore the ***full potential*** *of the reticle, the layout is arranged in a way such that it can host sensors with different sizes, including:*

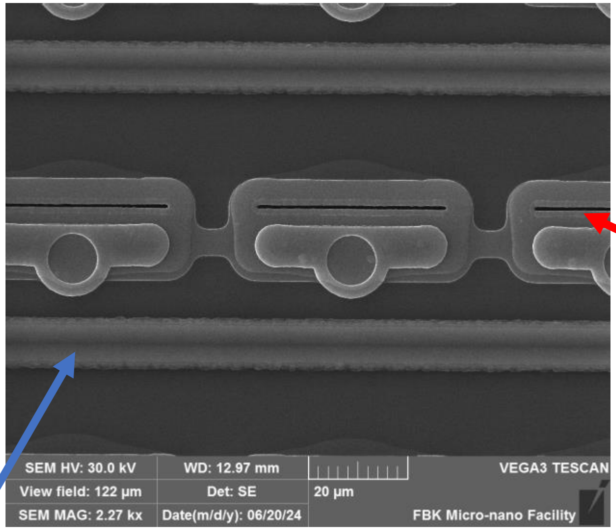
1) *6 STD & 6 DSH* ***64×64*** *sensors (pixel size: 55μm×55μm);*
2) *1 STD & 1 DSH* ***128×128*** *sensors;*
3) *3 STD & 3 DSH* ***32×32*** *sensors.*

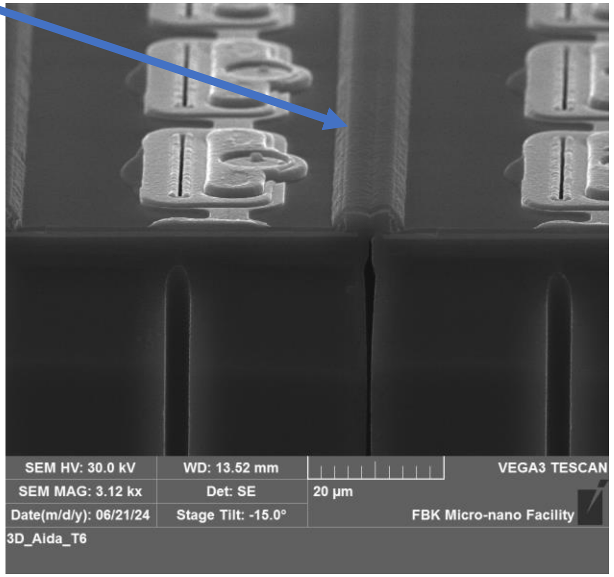
Test diodes ***(55 μm, 42 μm pitch, STD & DSH)***

- *Groups of individual pixels*
- *Strips*
- *Diodes*

Technological test structures.

3D-trench electrode sensors – A new design

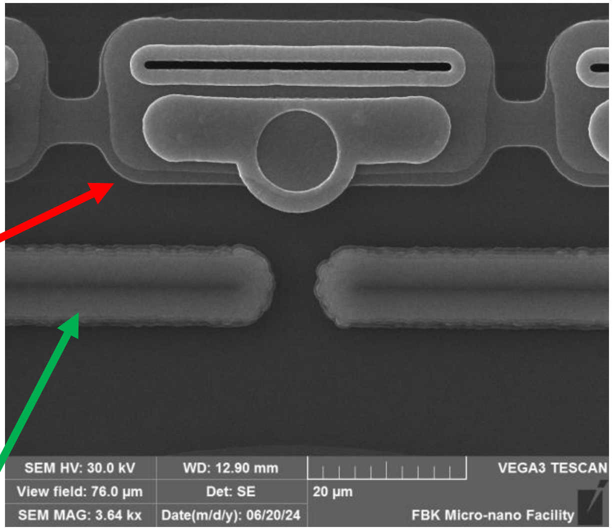


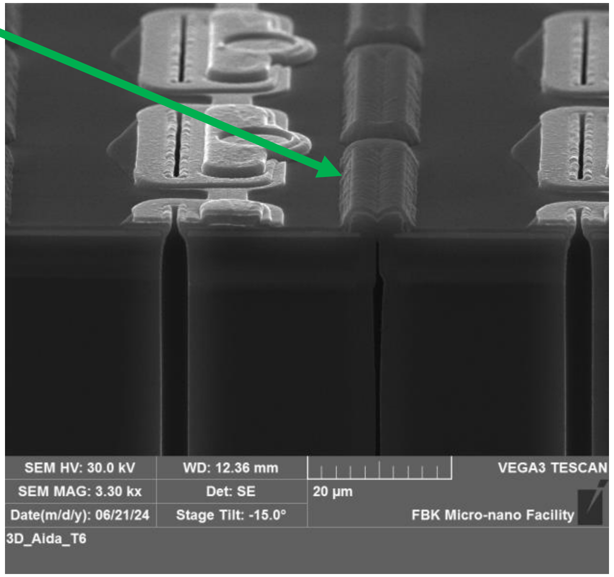


Long continuous ohmic trenches in the standard design.

Well defined junction trenches.

Dashed ohmic trenches in the new design.

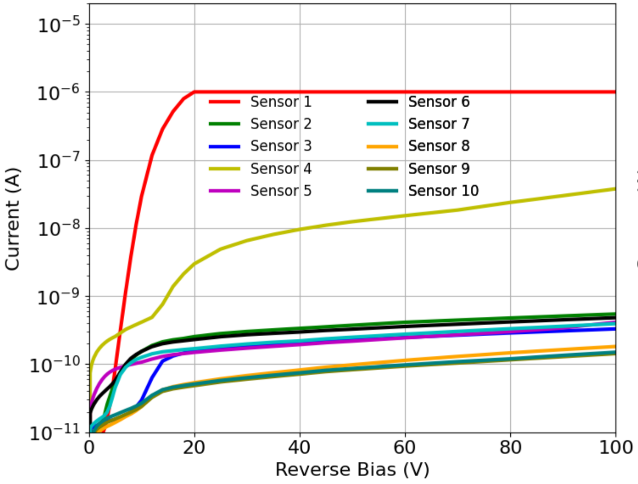




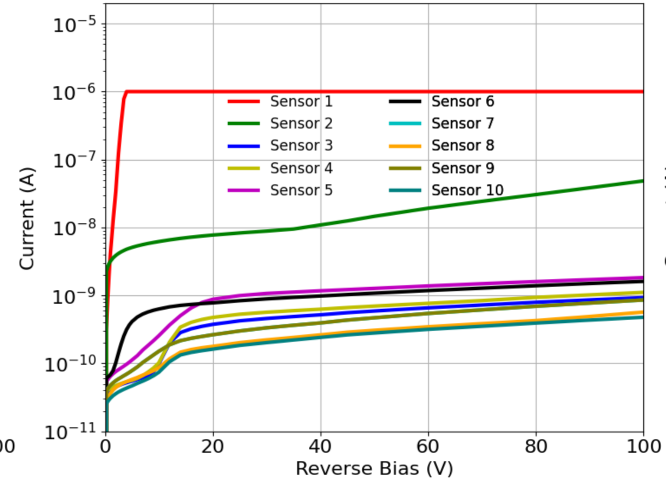
3D-trench electrode sensors – A new design

STD

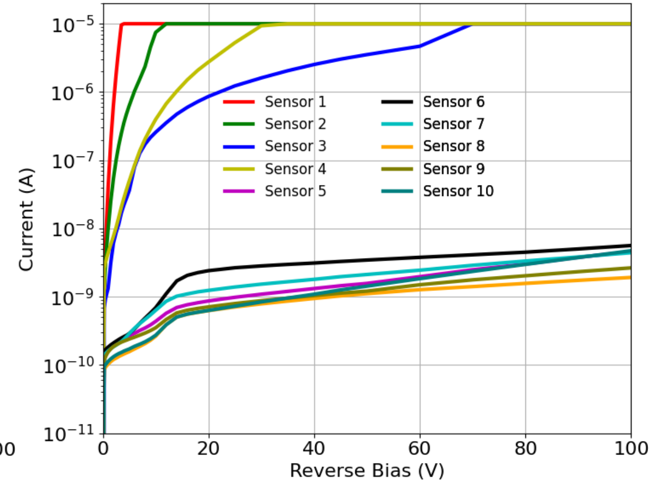
Sensor size = 32×32



Sensor size = 64×64

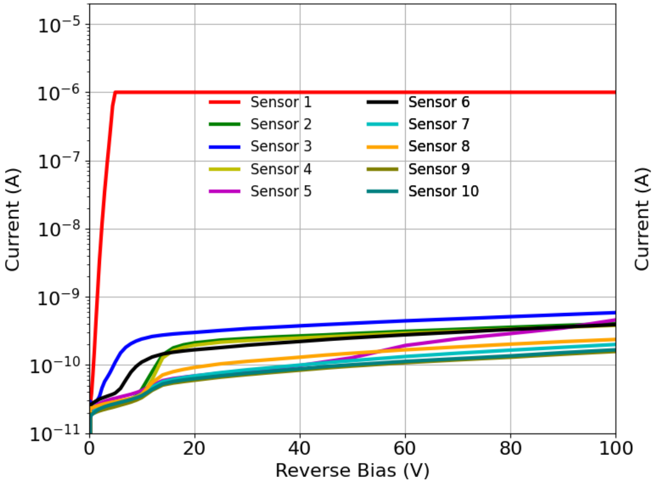


Sensor size = 128×128

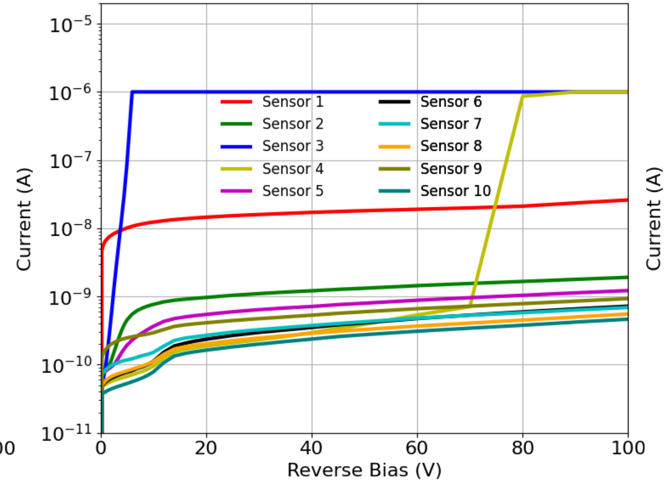


DSH

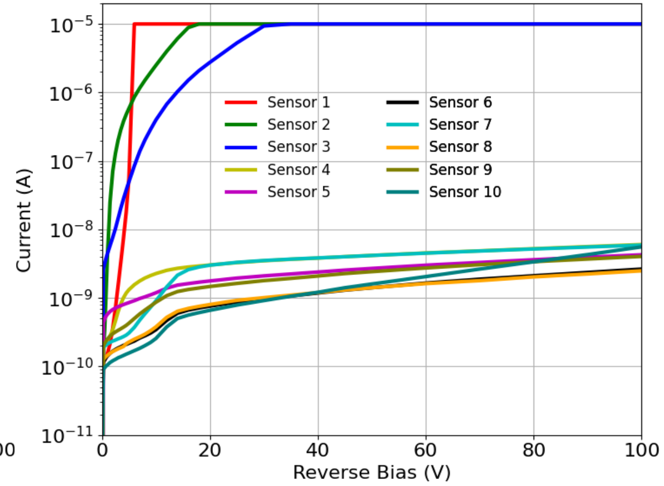
Sensor size = 32×32



Sensor size = 64×64



Sensor size = 128×128

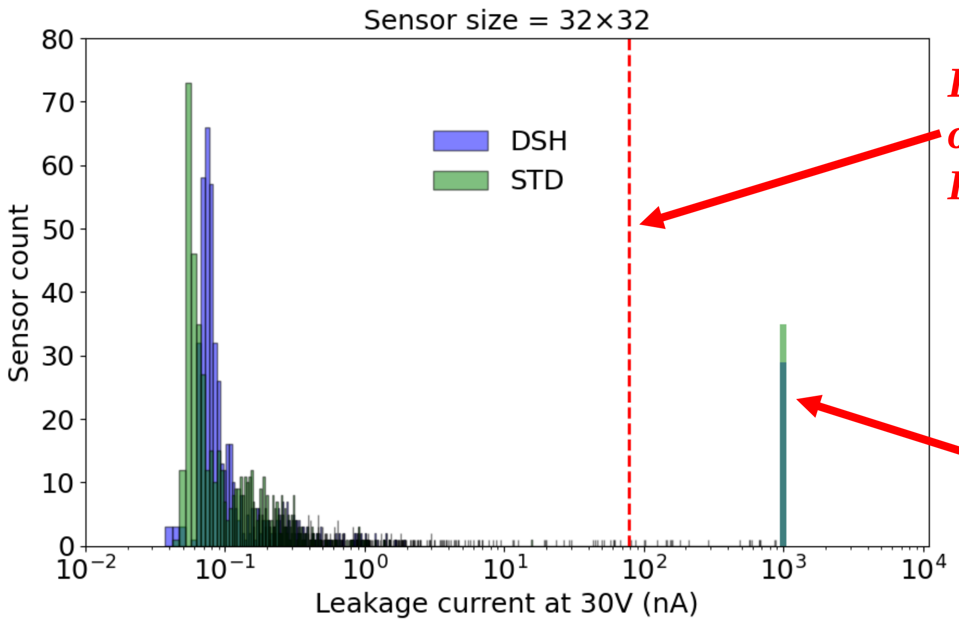


On-wafer electrical tests done at FBK to evaluate the quality of different sensors;

Most of the sensors have small leakage current, except for some sensors that experience early breakdown;

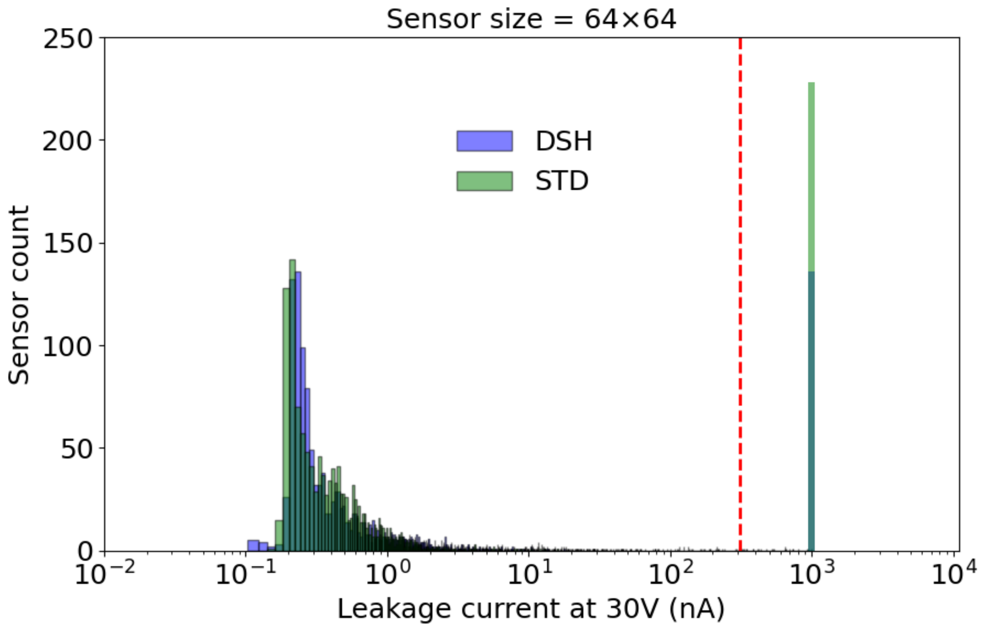
As the sensor size gets larger, more early breakdown sensors are observed.

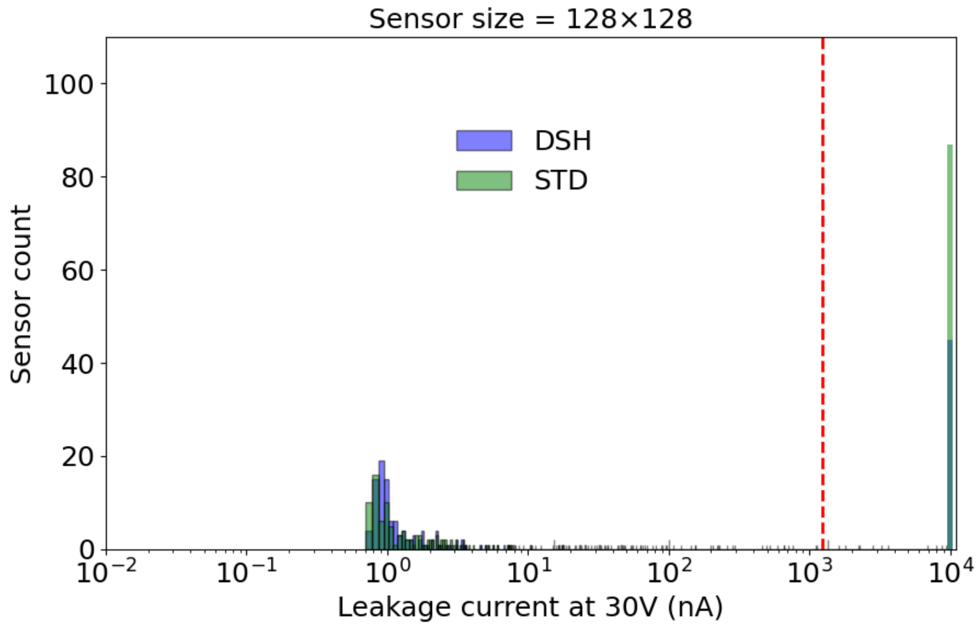
3D-trench electrode sensors – A new design



Leakage current at operation voltage $I(V_{op}) < 2.5\mu A/cm^2$

Leakage current at compliance





- *Small 3D trench-electrode sensors (32×32) have comparable (high) yield for both designs;*
- *The yield decreases as the sensor size gets larger, but the DSH has better yield compared to the STD;*
- *The fabrication technology has to be further improved for a better large-sensor yield;*
- *Best wafers selected for bump bonding (TIMESPOT & IGNITE ROCs).*

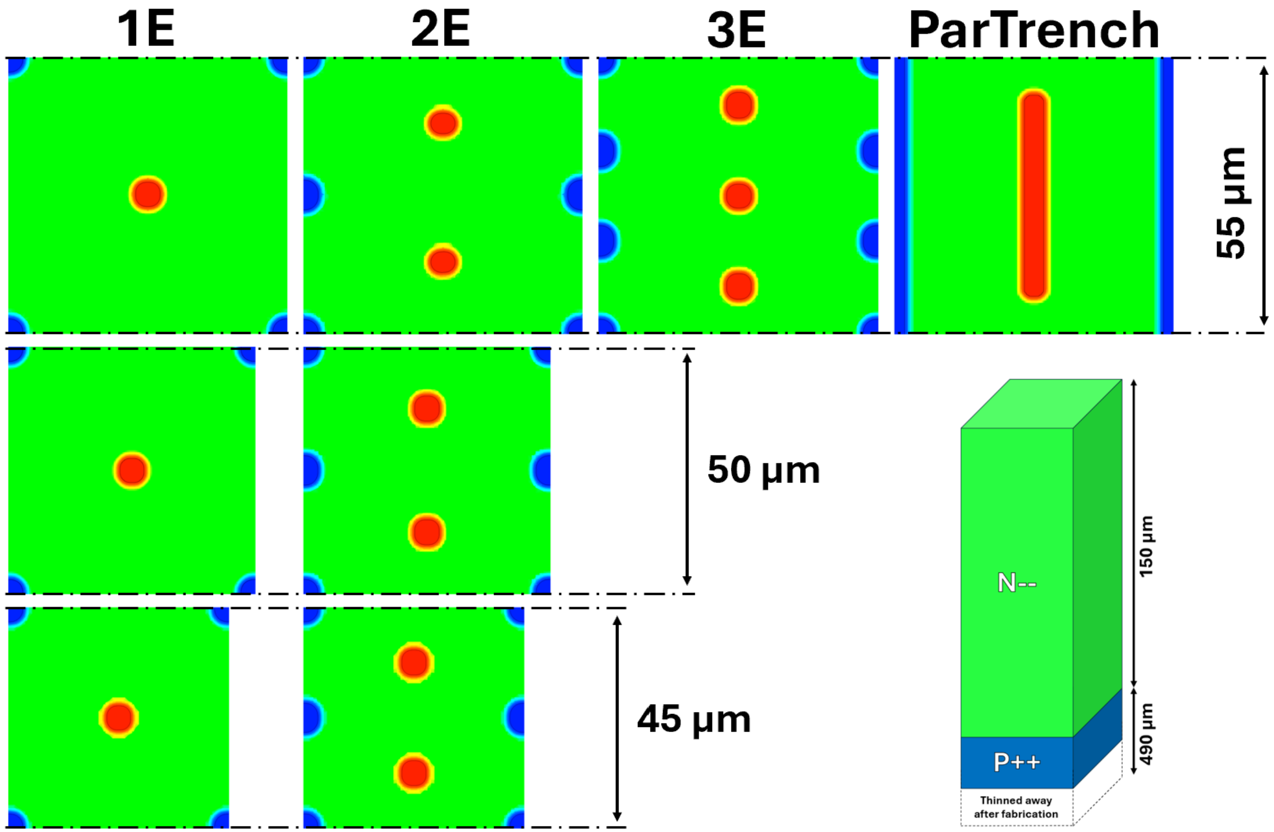
Other ongoing efforts

- *The intrinsic temporal resolution of 3D-trench sensors cannot be maintained in pixel implementations, due to the power constraints in the ROC*

- *3D-column sensor performance might be good enough for some applications, easing the fabrication complexity*

- *We are also studying 3D-column designs with different cell size (55 μm, 50 μm, and 45 μm) and electrode arrangements (1E, 2E, 3E)*

- *These designs will be implemented in a new batch funded by INFN CSN1 (LHCb).*



Other ongoing efforts

*More info from **Angelo Loi** during the **Poster Session***

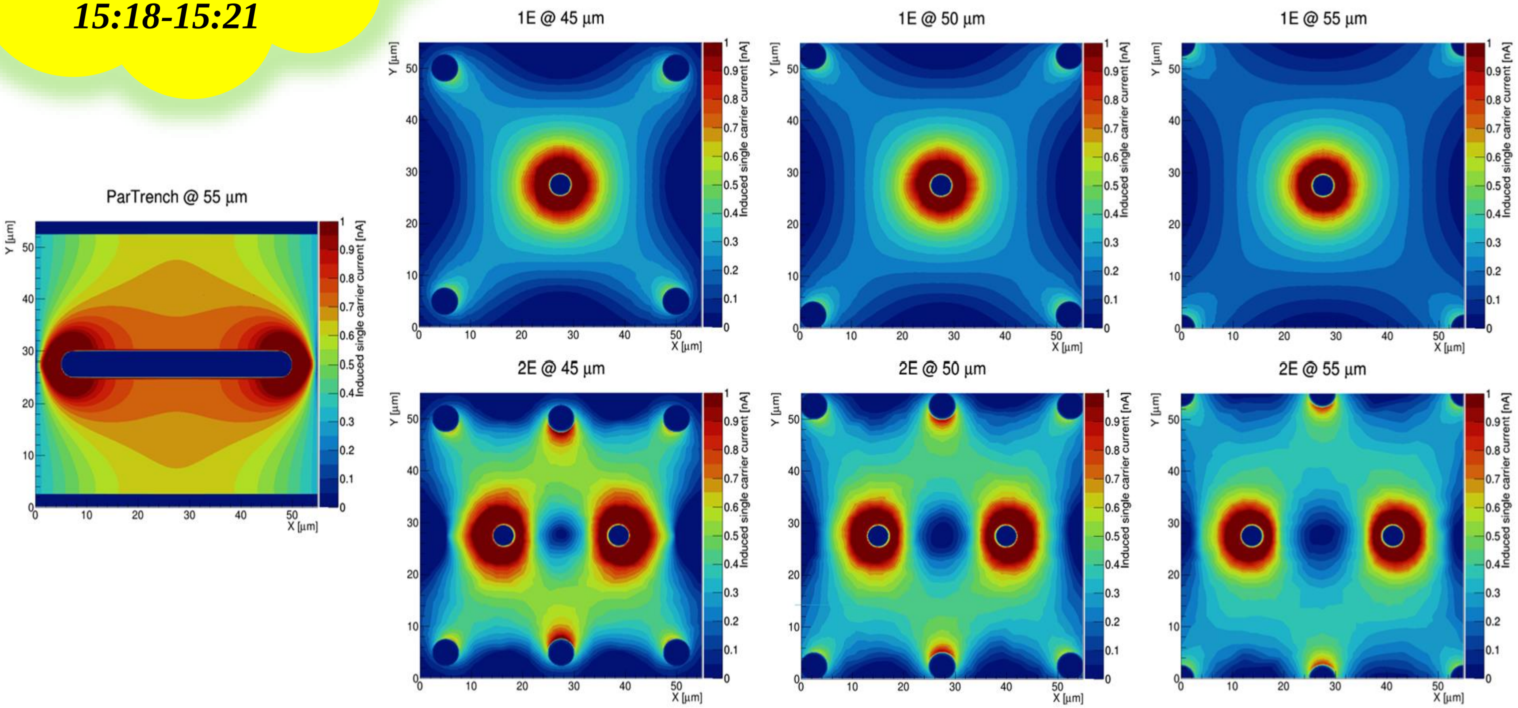
Thursday afternoon 15:18-15:21

Current induction on the readout electrode on different pixel sizes has been simulated, using Ramo Map approach:

$$i_k = -q\vec{v} \cdot \overrightarrow{E_Q}$$

Compared to 1E structures, all the 2E structures have higher induction current;

The 45×45-2E structure has the most intense induction current among the proposed geometries.



Conclusions

- *3D-trench electrode pixels are a promising candidate for future 4D tracking applications*
- *Excellent temporal resolution so far demonstrated on test structures with discrete, high-speed electronics:*
  - *~10 ps for 3D-trenched electrodes, also confirmed after large radiation fluences*
- *3D-trench electrode sensors with dashed ohmic electrodes have higher fabrication yield compared to the standard design, but the technology has to be optimized for large-area sensors.*
- *Functional characterization of samples from the AIDAInnova batch is in progress.*
- *Different 3D-column designs are also worth investigating (trade-off between intrinsic speed and capacitance/noise).*

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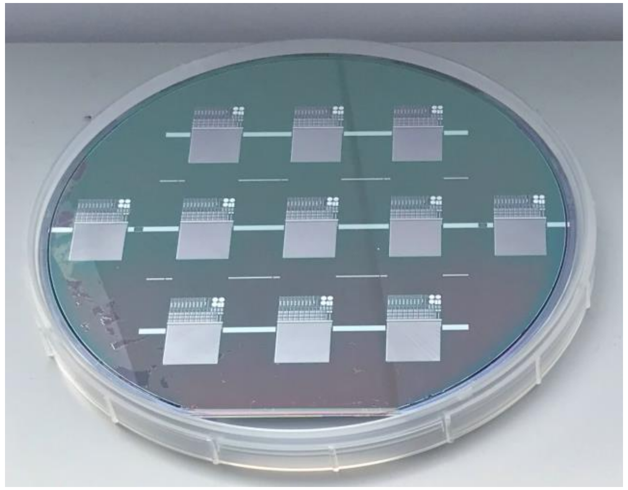
Acknowledgements

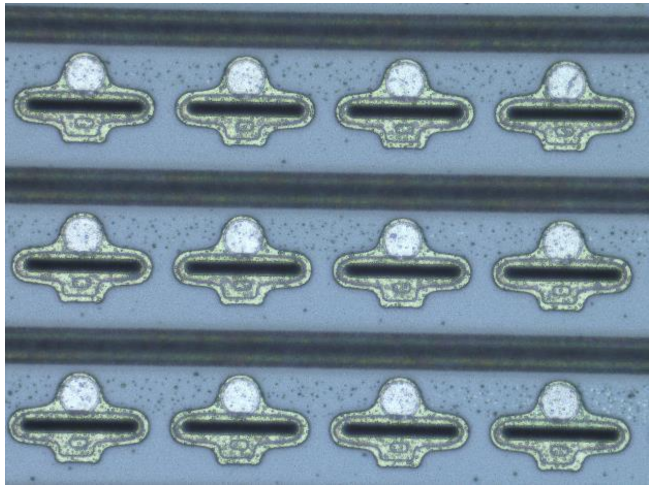
INFN Istituto Nazionale di Fisica Nucleare

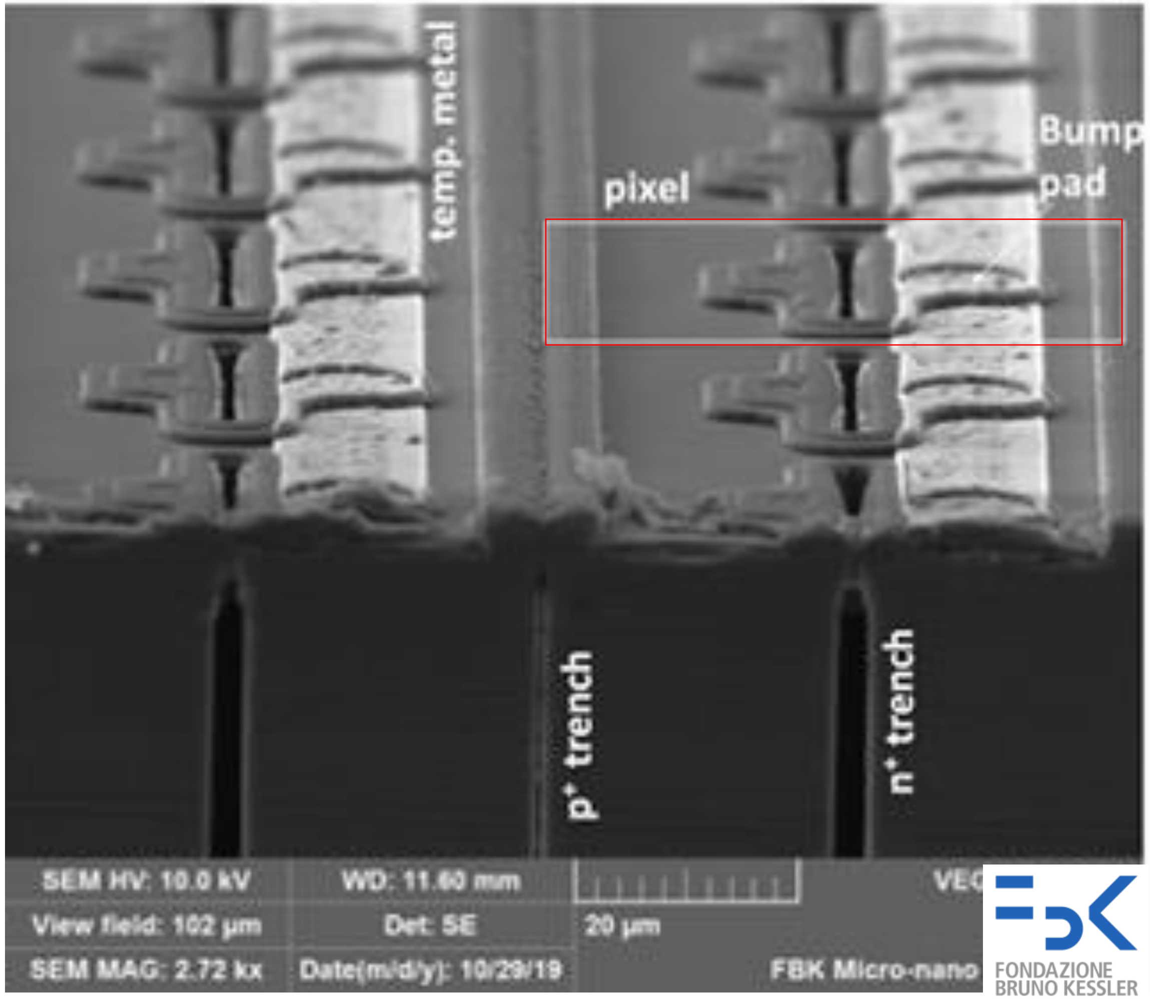
- *This work has received funding from:*
    - *the Italian National Institute for Nuclear Physics (INFN) through the Projects TIMESPOT (CSN5) and LHCb (CSN1)*
    - *INFN and FBK through the Framework Agreement MEMS4*
    - *the EC under Grant Agreement 777222, ATTRACT-INSTANT project.*
    - *the European Union's Horizon 2020 Research and Innovation programme under GA no. 101004761 (AIDAInnova)*
- *Special thanks to:*
    - *Sherwood Parker for inspiring this work, and Cinzia Da Via (Univ. Manchester, UK) for fruitful discussions*

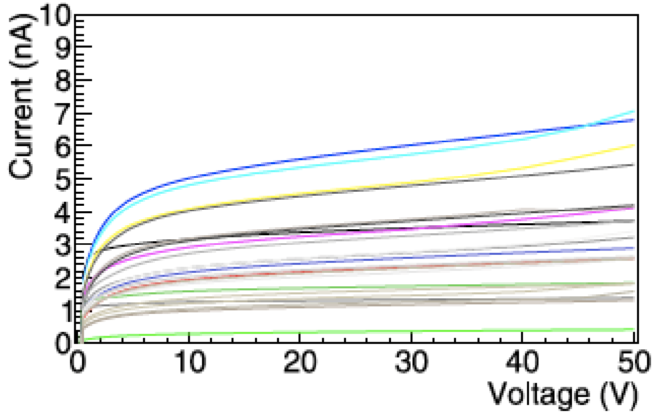
Thank you!

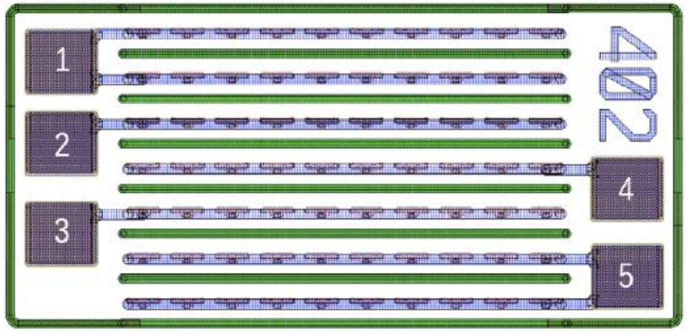
TIMESPOT sensors

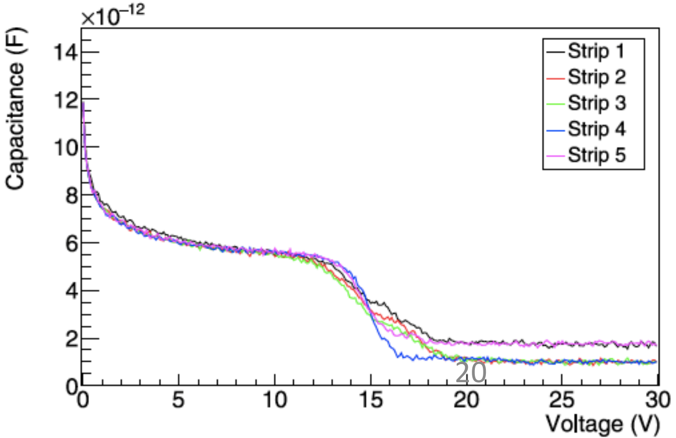






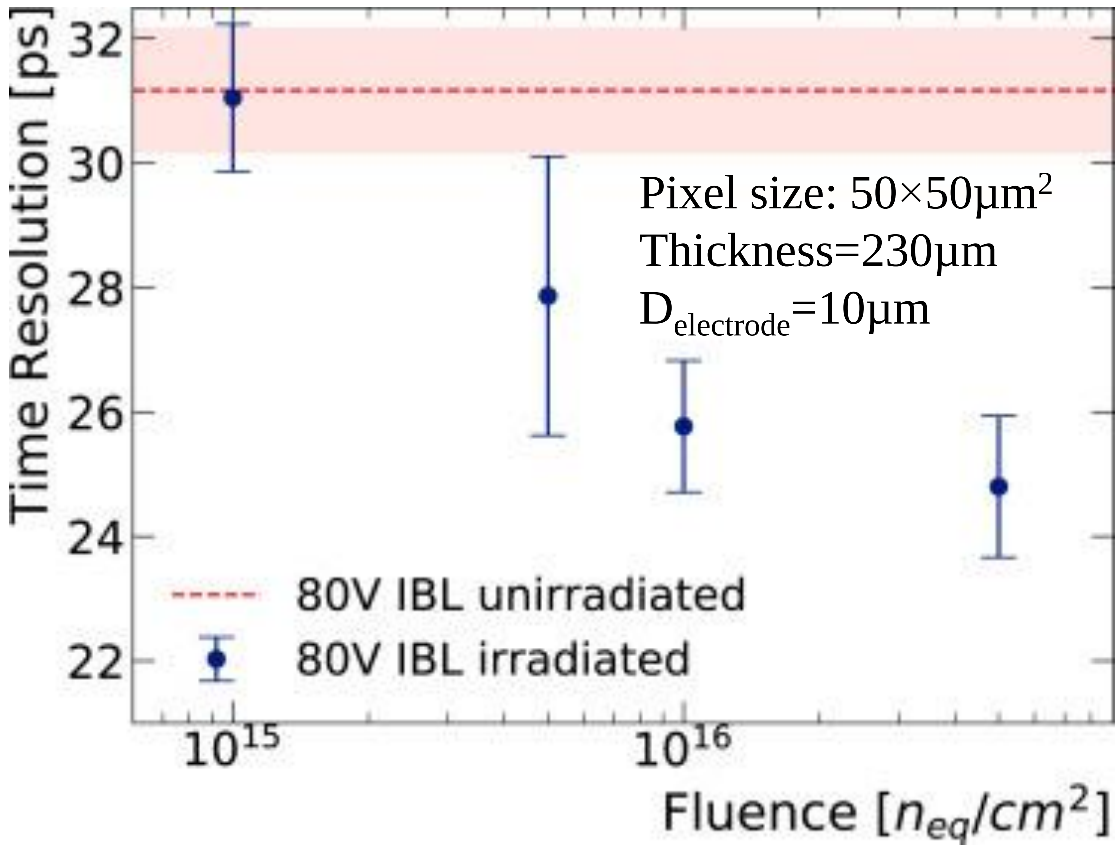






G. Forcolin et al., NIMA 981 (2020) 164437

Backup

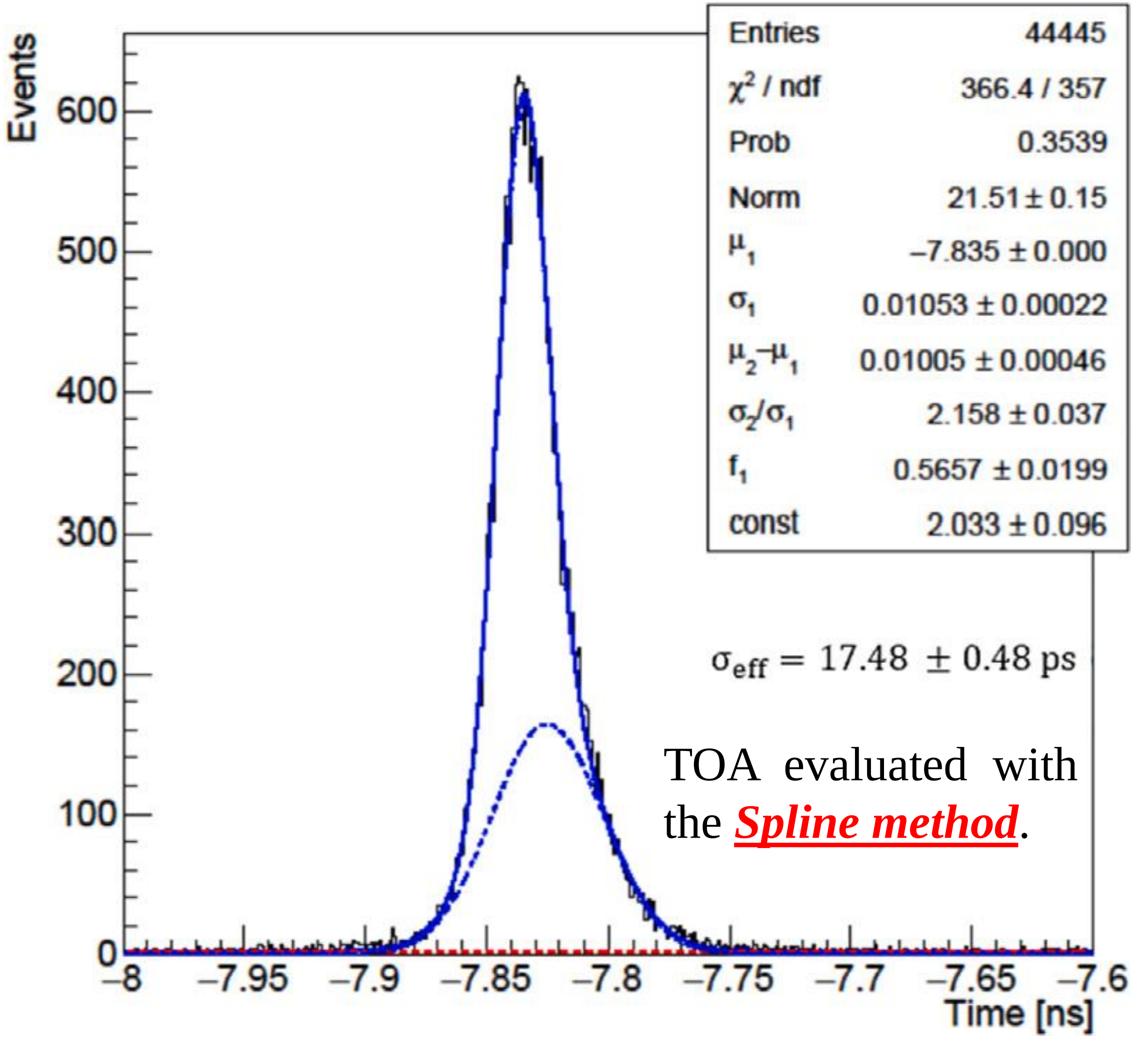


Measurements of IBL 3D sensors show an improved time resolution with increasing irradiation fluence, while maintaining almost the same bias voltage range.

The time resolution improved to about 25 ps after the highest measured fluence of 5×10^{16} n_{eq}/cm^2.

L. Diehl, et al. Nucl. Instrum. Methods A, (2024) 169517

Backup



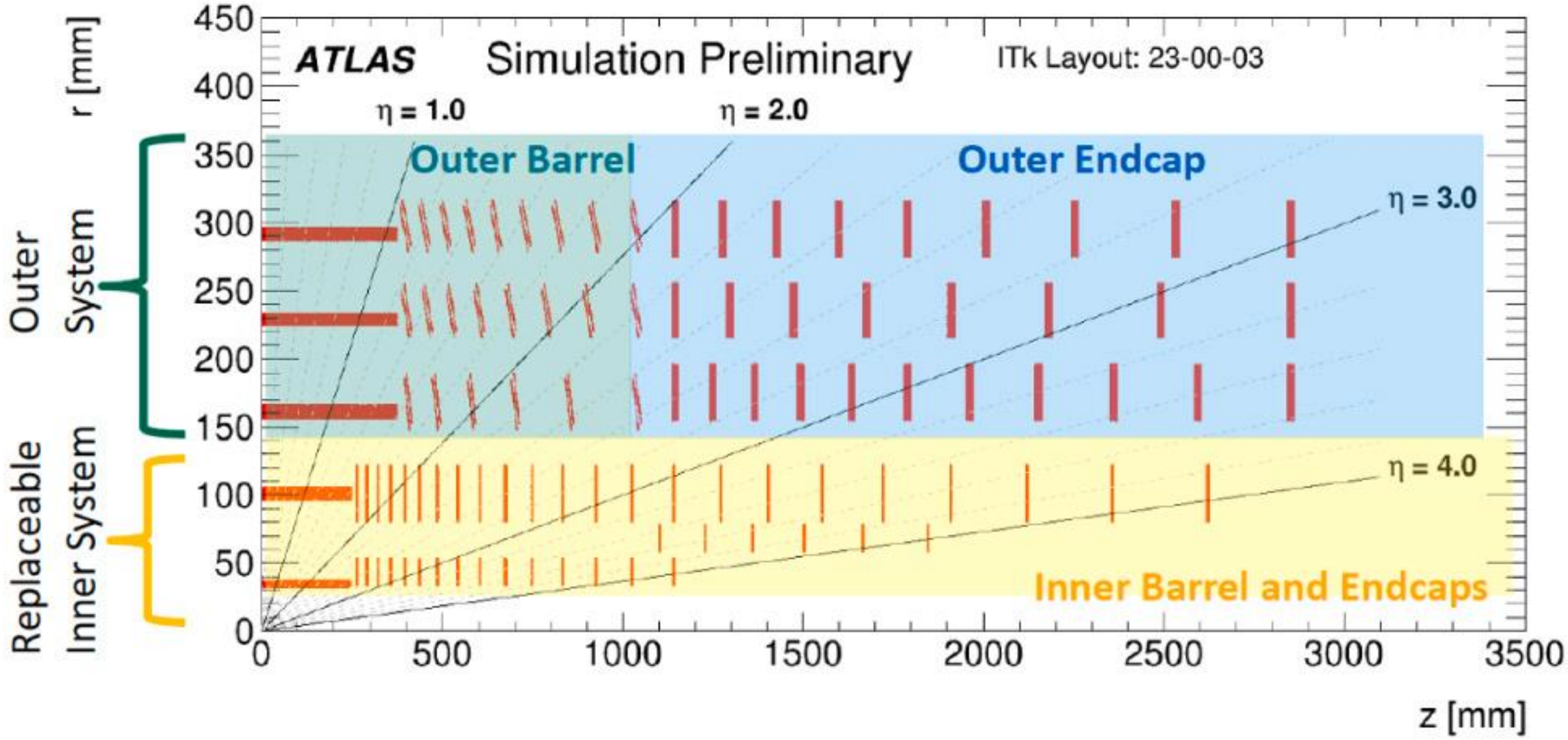
Time distribution of a 3D trench pixel irradiated at 1×10^{17} 1MeV n_{eq}/cm^2 at 250V.

The ToA distribution is comparable to the previously published 17.8 ± 1.0 ps for the non-irradiated sensor.

The irradiated sensor achieved a 95% efficiency at 20 degrees tilt, compared to 99% for the non-irradiated ones.

A. Lampis, et al. Nucl. Instrum. Methods A, (2024) 169984

Backup



C. Buttar, ATLAS ITk collaboration. Nucl. Instrum. Methods A, (2024) 169978.

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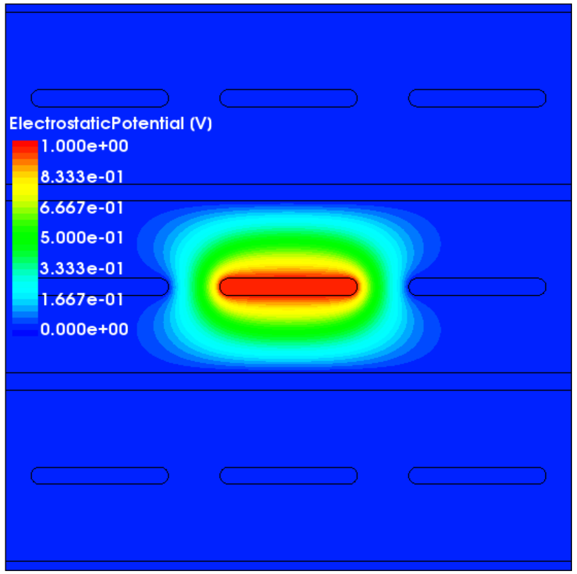
ElectrostaticPotential (V)
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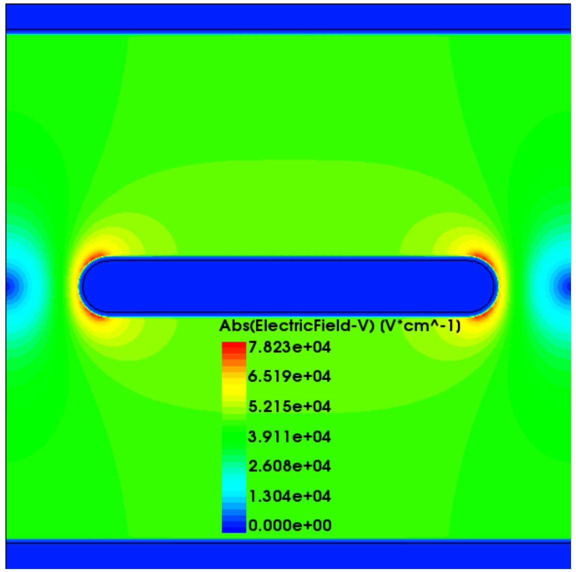
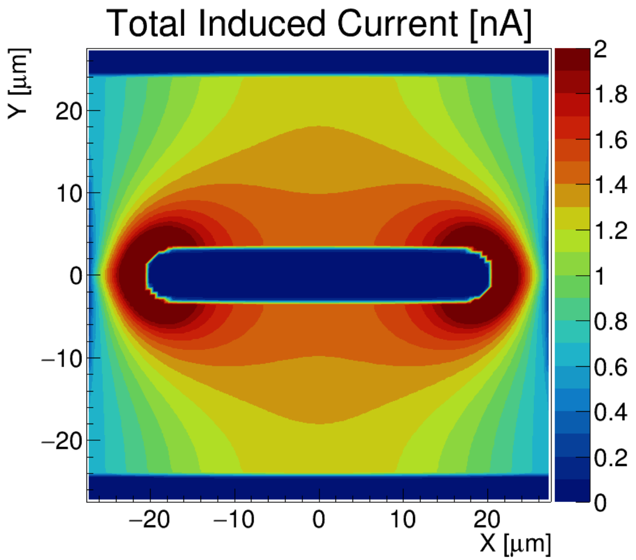
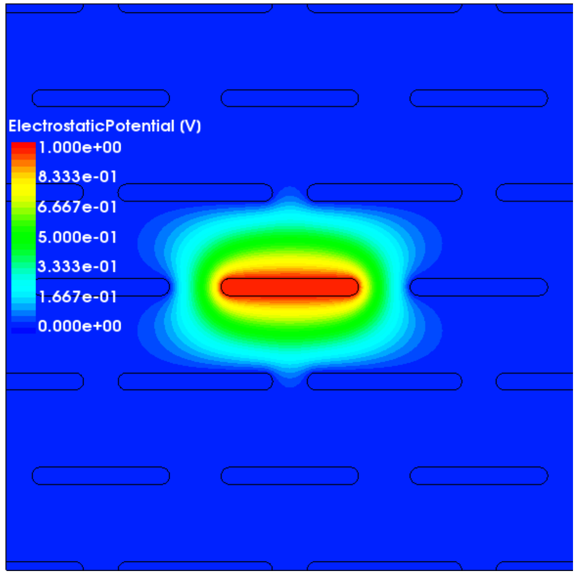
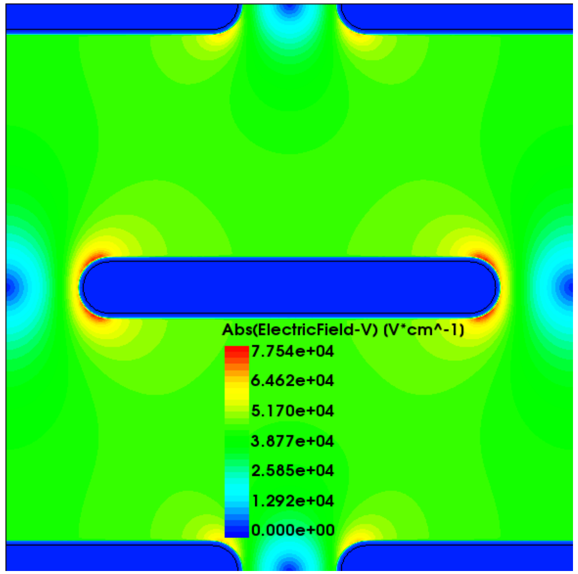
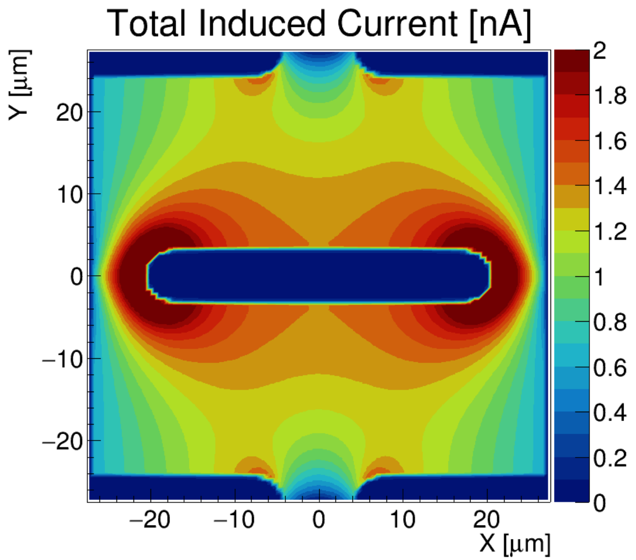
8.333e-01
6.667e-01
5.000e-01
3.333e-01
1.667e-01
0.000e+00


Abs(ElectricField-V) (V*cm^-1)
7.823e+04
6.519e+04
5.215e+04
3.911e+04
2.608e+04
1.304e+04
0.000e+00

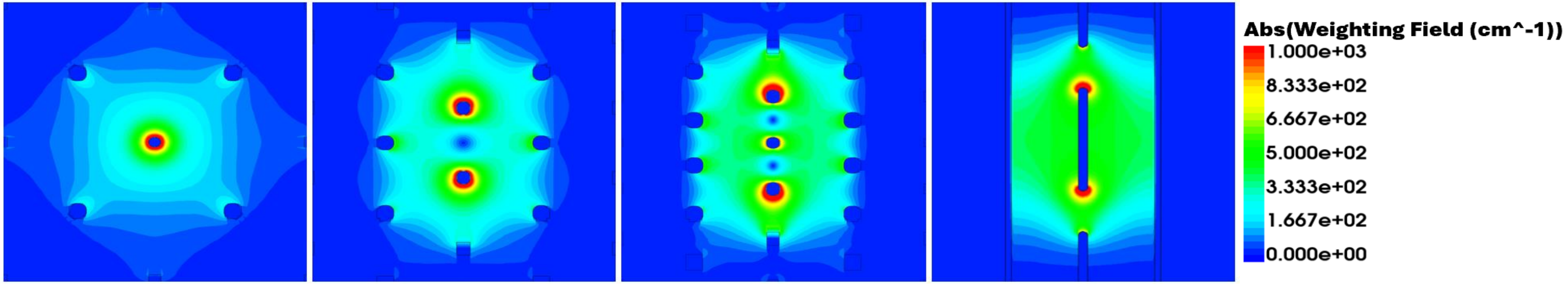

Total Induced Current [nA]
Y [µm]
X [µm]
20
10
0
−10
−20
−20
−10
0
10
20
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0


ElectrostaticPotential (V)
1.000e+00
8.333e-01
6.667e-01
5.000e-01
3.333e-01
1.667e-01
0.000e+00


Abs(ElectricField-V) (V*cm^-1)
7.754e+04
6.462e+04
5.170e+04
3.877e+04
2.585e+04
1.292e+04
0.000e+00


Total Induced Current [nA]
Y [µm]
X [µm]
20
10
0
−10
−20
−20
−10
0
10
20
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0

Backup


Abs(Weighting Field (cm^-1))
1.000e+03
8.333e+02
6.667e+02
5.000e+02
3.333e+02
1.667e+02
0.000e+00