Timing performance of 3D pixel detectors

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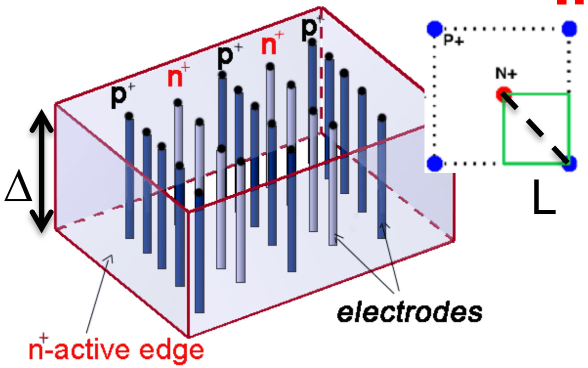
Outline

- Introduction: 3D Sensors
- Timing with 3D sensors
- Results:
  - 3D-columnar sensors
  - 3D-Trenched sensors (TIMESPOT)
- Ongoing developments
- Conclusions

Introduction: 3D Sensors



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

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

High radiation hardness at relatively low voltage (power)

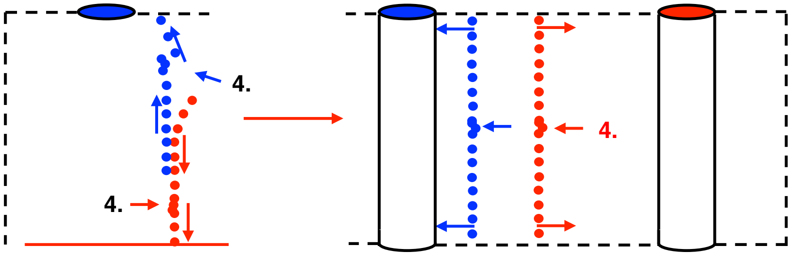
ADVANTAGES:

- 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

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)

Timing: Planar vs 3D



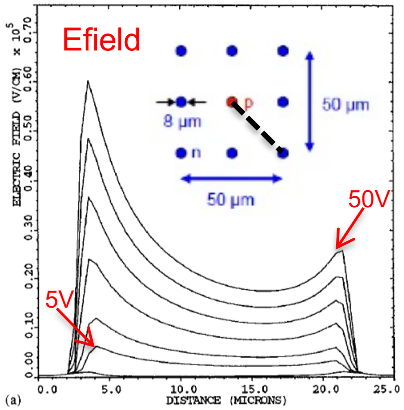
S. Parker et al. IEEE TNS 58(2) (2011) 404

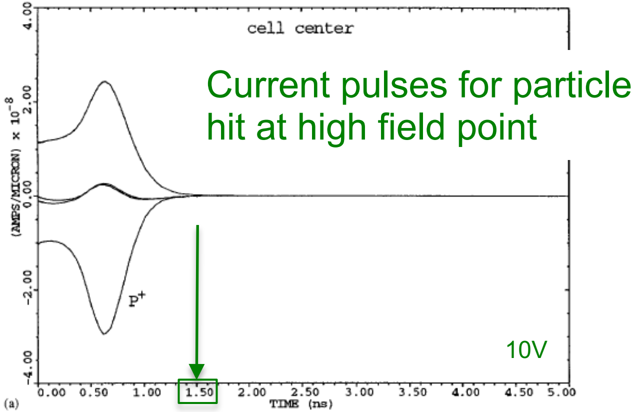
1. 3D lateral cell size can be smaller than wafer thickness, so
2. in 3D, field lines end on electrodes of larger area, so
3. most of the signal is induced when the charge is close to the electrode, so planar signals are spread out in time as the charge arrives, whereas
4. Landau fluctuations along track arrive sequentially and may cause secondary peaks

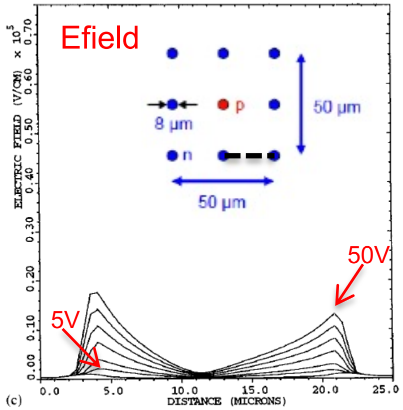
1. shorter collection distance
2. higher average fields for any given maximum field (price: larger electrode capacitance)
3. 3D signals are concentrated in time as the track arrives
4. Landau fluctuations (delta ray ionization) arrive nearly simultaneously

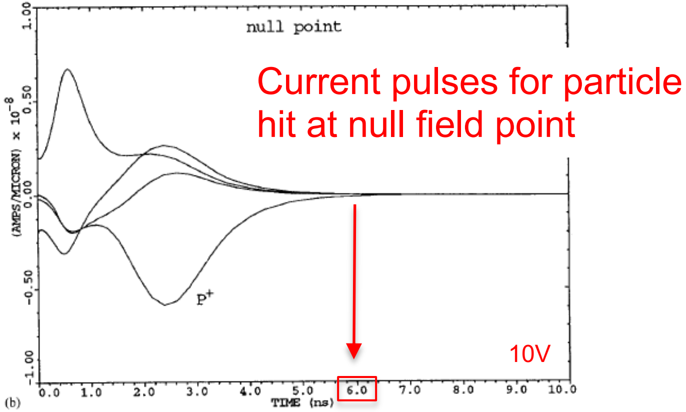
Null field points and delayed signals

S. Parker et al. NIMA395 (1997) 328





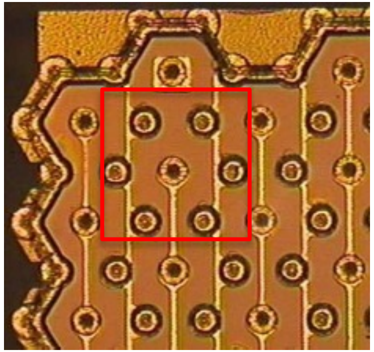


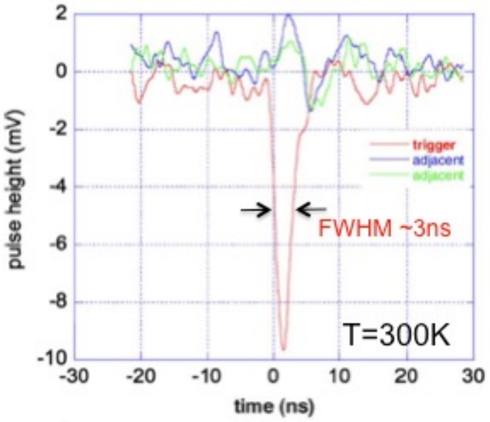


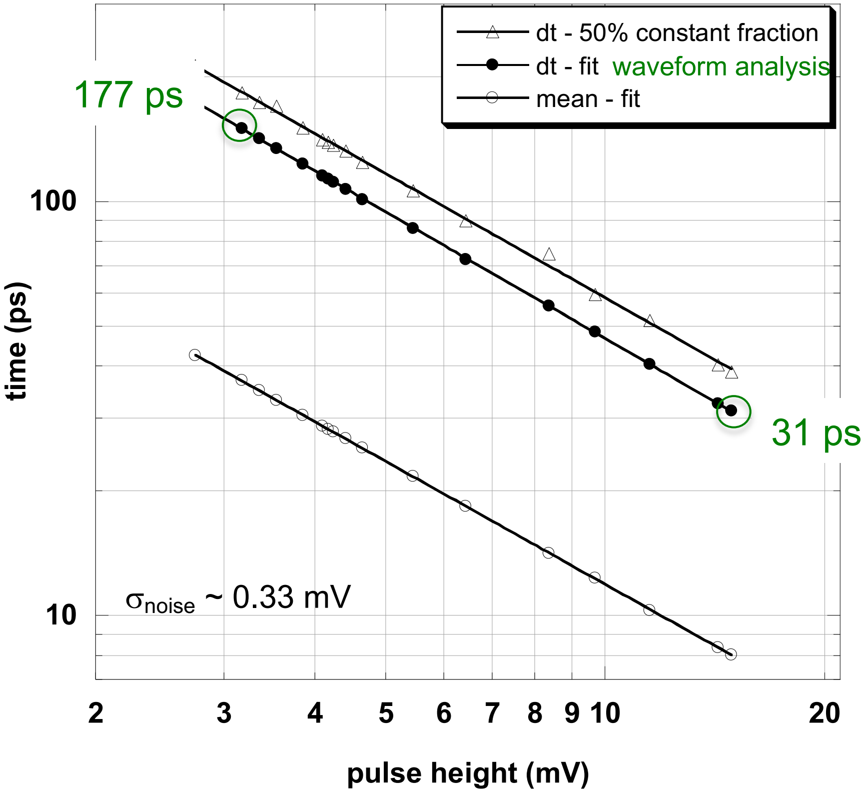
- 3D structure can potentially yield very fast signals of the order of 1 ns
- But electric field is not uniform, and null field points are present: signals are delayed due to initial diffusion
- Moreover, electrodes are (almost) dead regions
- These aspects can be improved with dedicated designs

An early study of speed with 3D

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



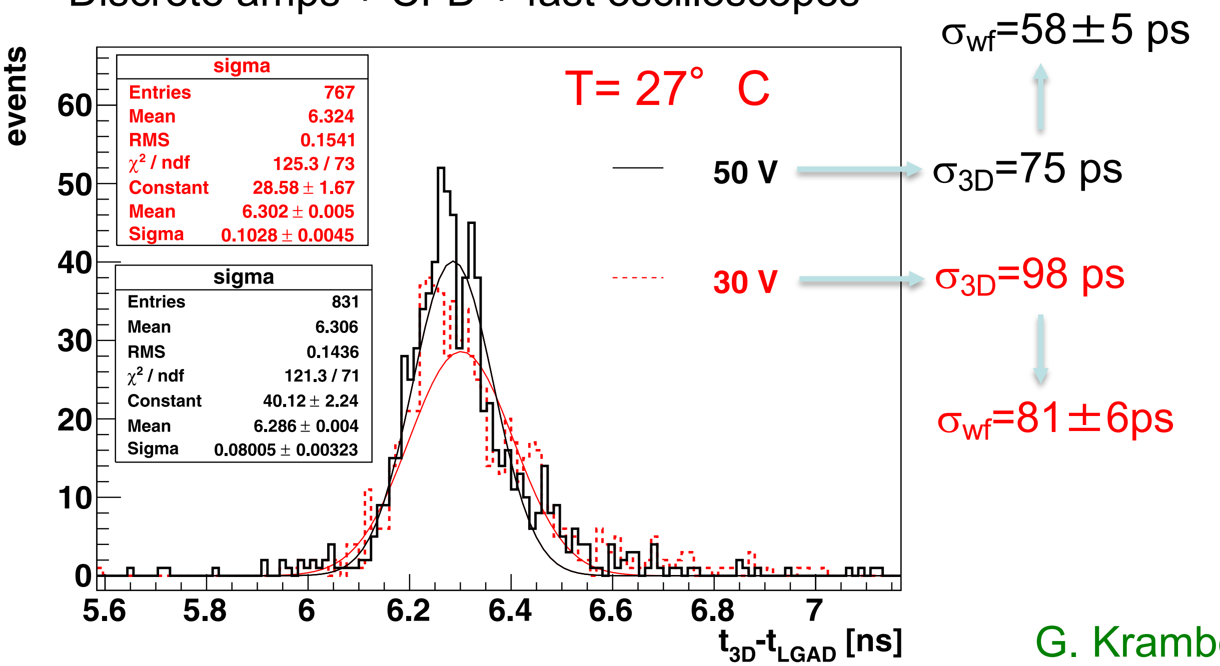


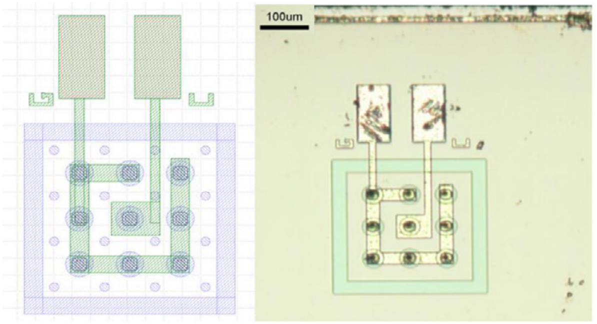


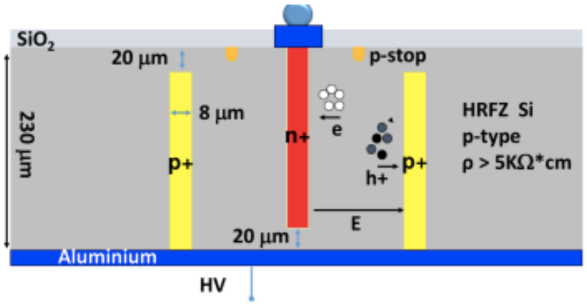
- Initially tested with ^{90}Sr source on hex-cell strip 3D's from SNF (L=50 μm) & fast current amplifier
- Despite several non-idealities (e.g., large capacitance, low bias, uncollimated source), promising results were obtained

Increasing interest in 3D pixels for timing

- CNM 50x50 μm^2 single cells DS-3D (230 and 285 μm thick) tested by several groups
- Beta source setups, with LGADs as reference
- Discrete amps + CFD + fast oscilloscopes



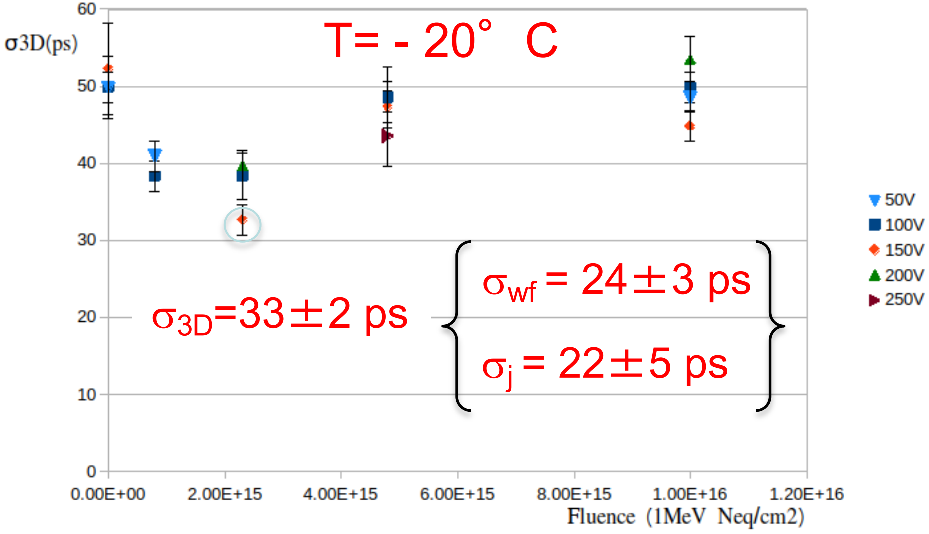




G. Kramberger et al., NIMA 934 (2019) 26

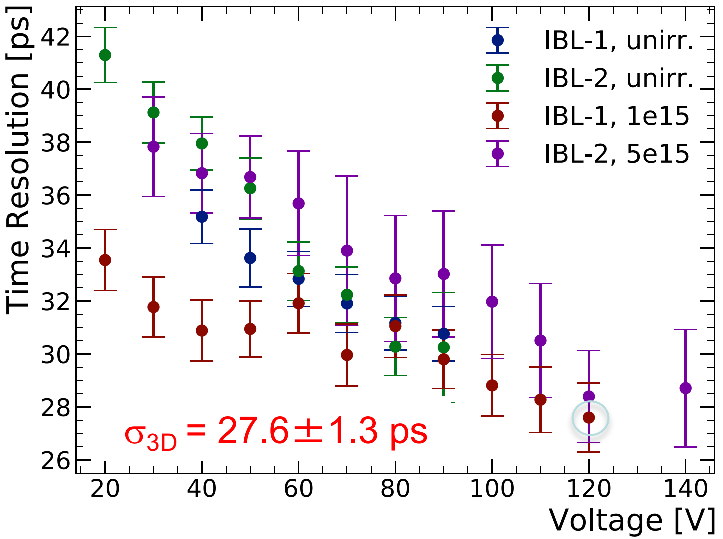
Neutron irradiated samples

- Same type of test structures from CNM, very similar beta source setups
- Best result ~27 ps timing resolution



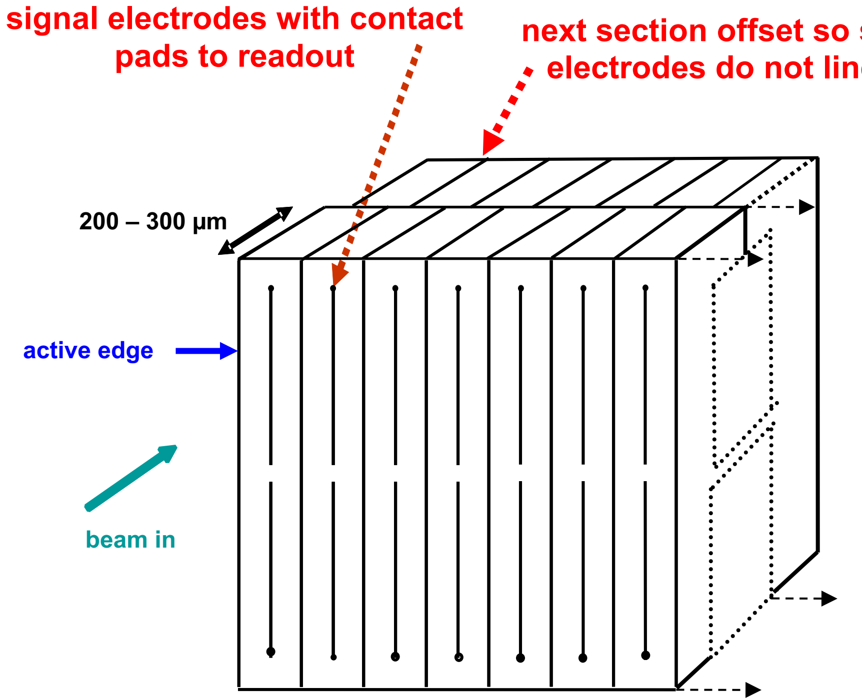
C. Betancourt et al., MDPI Instruments 6 (2022) 12

T= - 18.5° C



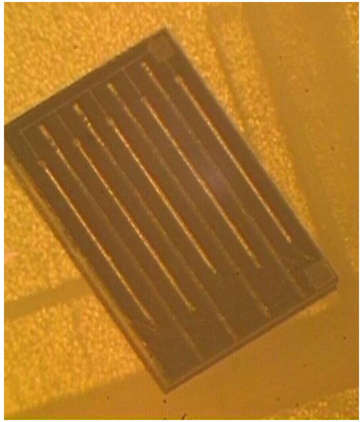
L.-Diehl. et al., NIMA 1046 (2022) 167691
L.-Diehl. et al., JINST 17 (2022) C12003

3D Trenched-electrode sensors



Schematic diagram of multiple plane arrangement in an active-edge 3D trench-electrode detector.
Other offsets (⅓, ⅔, 0, ⅓, ⅔ ..etc.) may also be used.

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



Benefits from trench electrodes

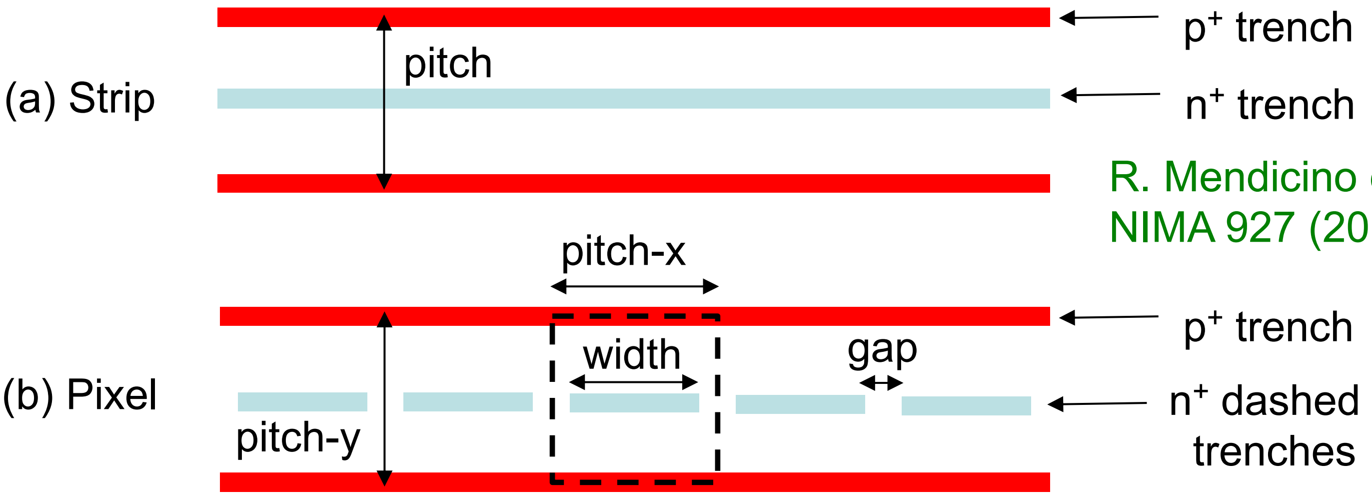
- High average field / peak field
- More uniform electric and weighting field distributions

Possible issues

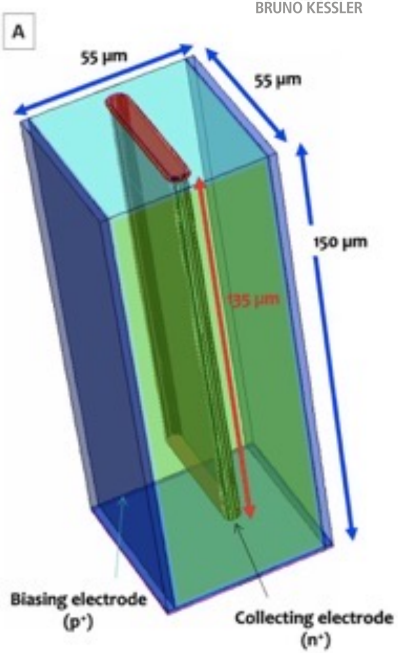
- Fabrication complexity
- Higher electrode capacitance
- Larger dead volumes

TIME-SPace Operating Tracker (INFN CSN5 Call Project, 2018-2021)

3D-Trenched sensors for tracking + timing have been developed for the first time



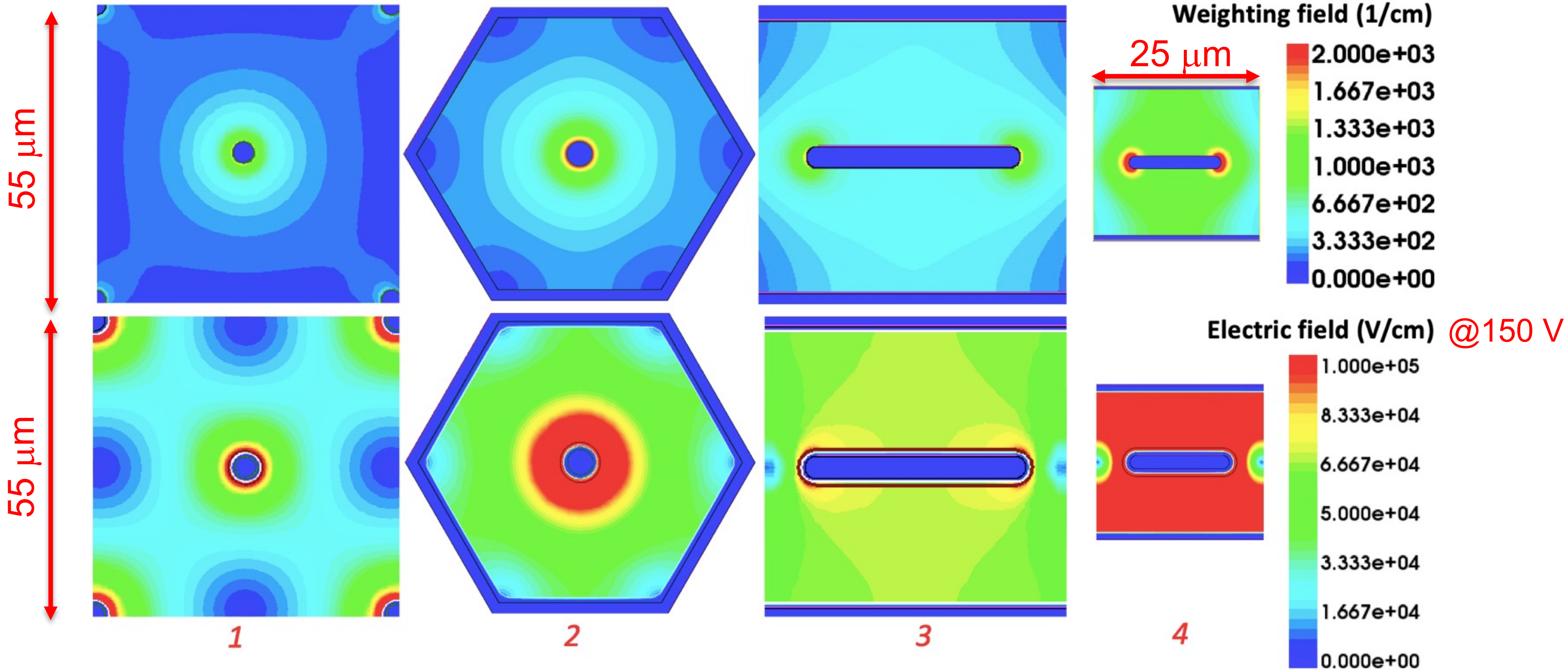
R. Mendicino et al., NIMA 927 (2019) 24



- Pixel design was optimized by simulations

Simulations (1): TCAD

A. Loi , PhD Thesis, Univ. Cagliari, 2020



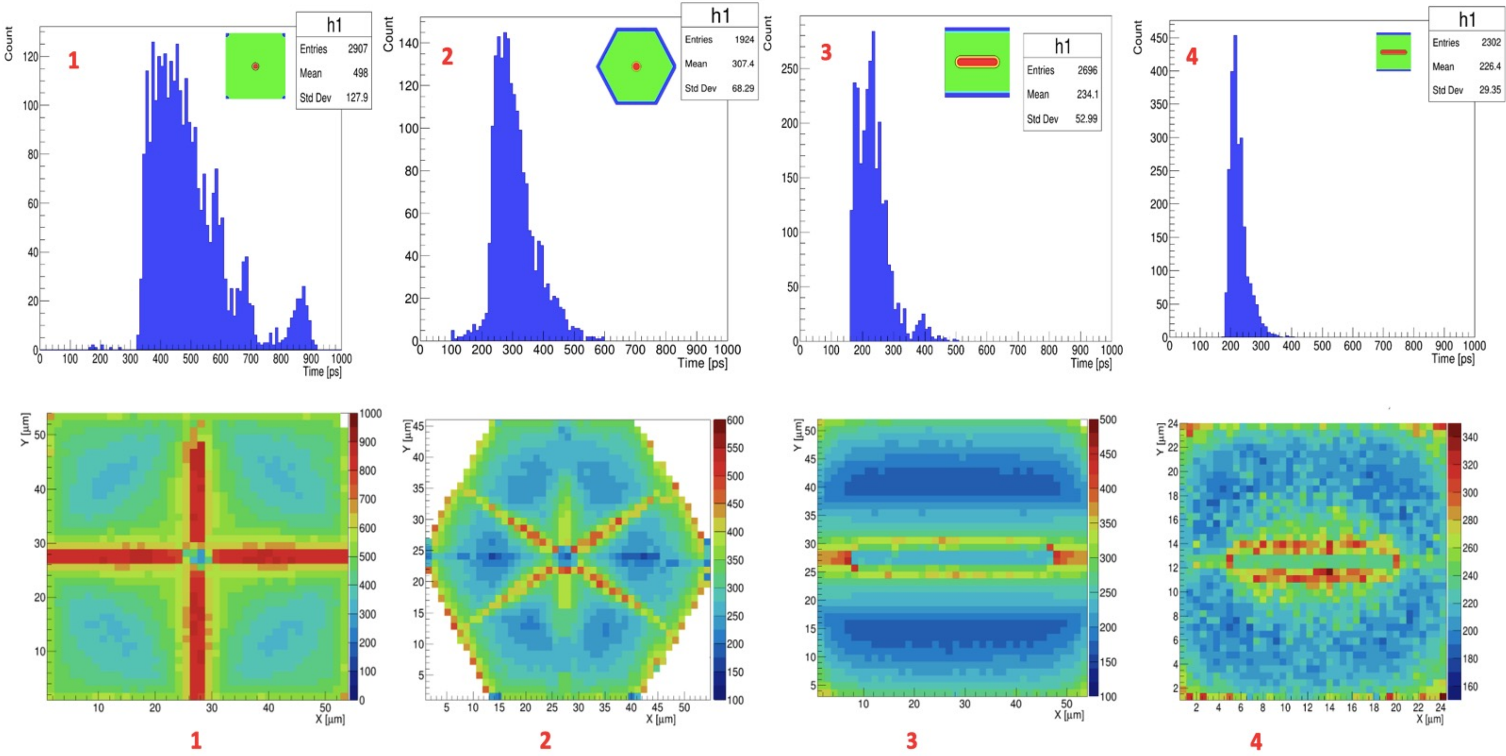
Simulations (2): TCoDe

A. Loi et al., JINST 16 (2021) P02011

- Input from TCAD and Geant4, solves drift/diffusion + Ramo current induction

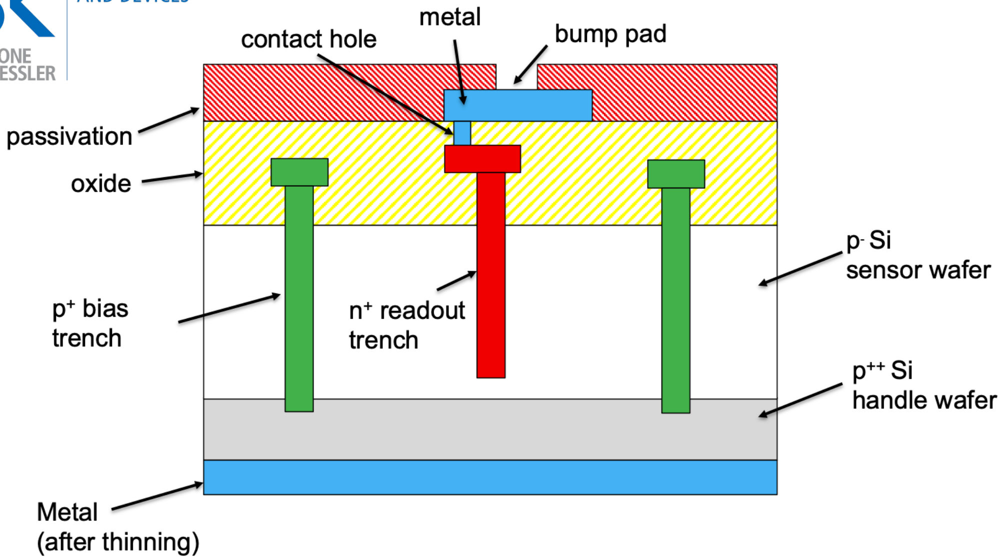
Distributions of charge collection times (ps)

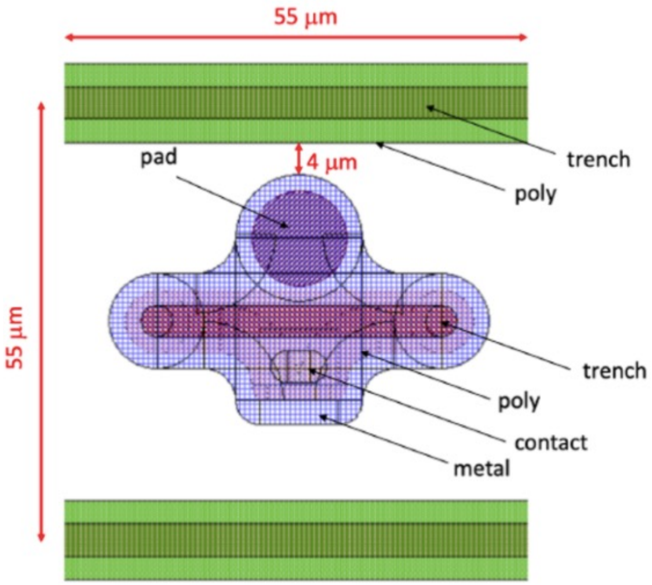
Maps of charge collection times (ps)



Pixel: from schematic to layout

FBK SENSORS AND DEVICES FONDAZIONE BRUNO KESSLER

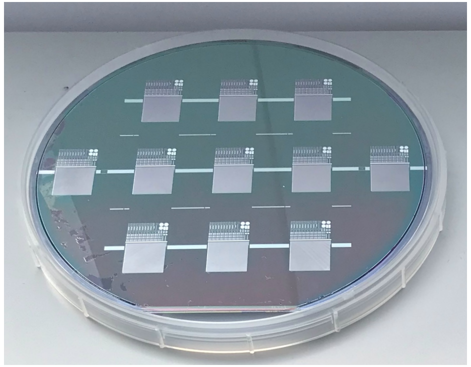


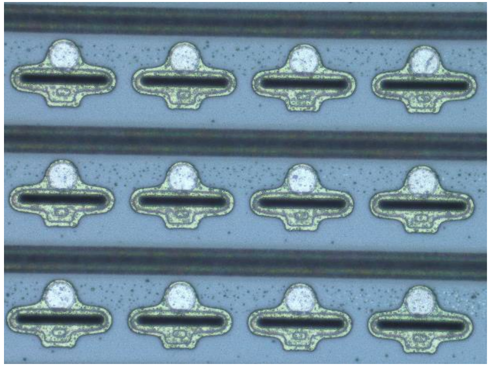


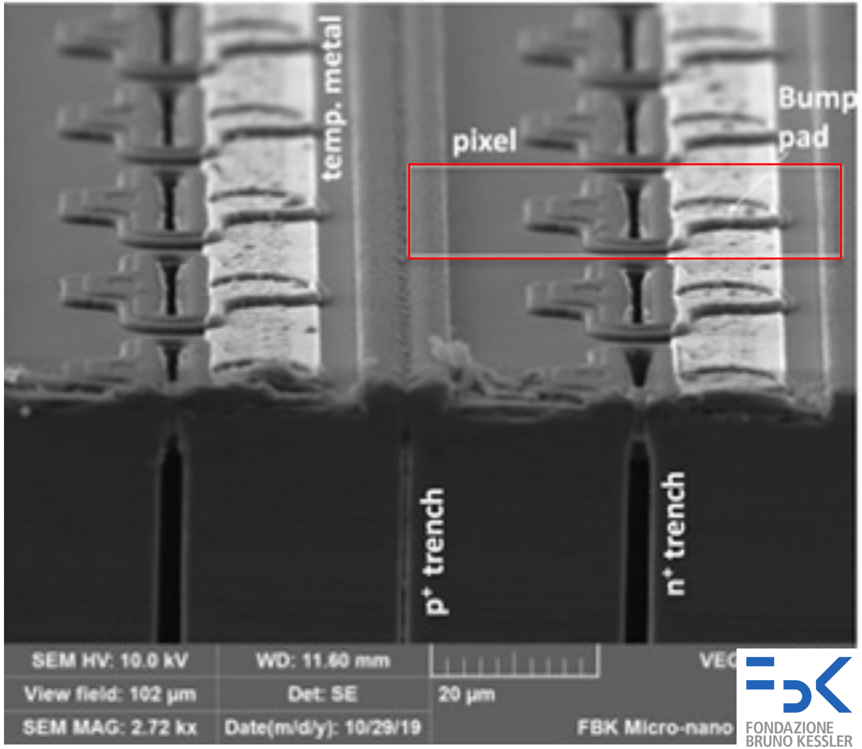
- FBK adapted to trenches the 3D-column single-sided tech. on SiSi-DWB substrates
- Stepper lithography used for better alignmment and detail definition

M. Boscardin et al., Front. Phys. 8 (2021) 625275

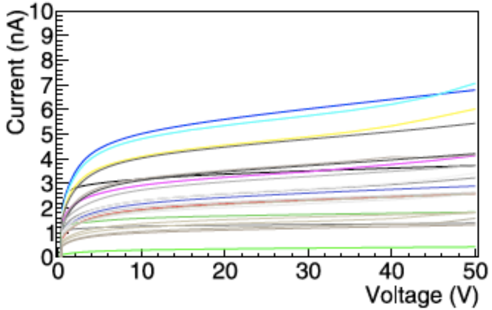
TIMESPOT sensors

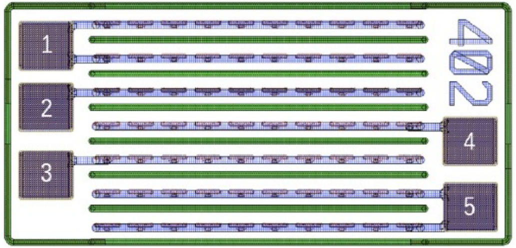


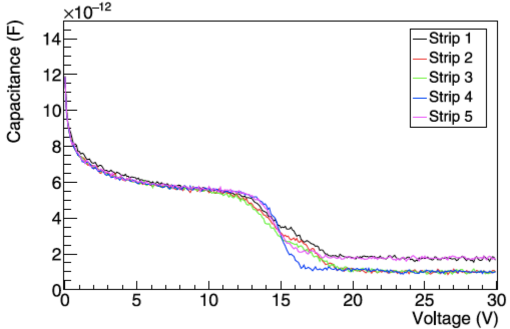




G. Forcolin et al., NIMA 981 (2020) 164437



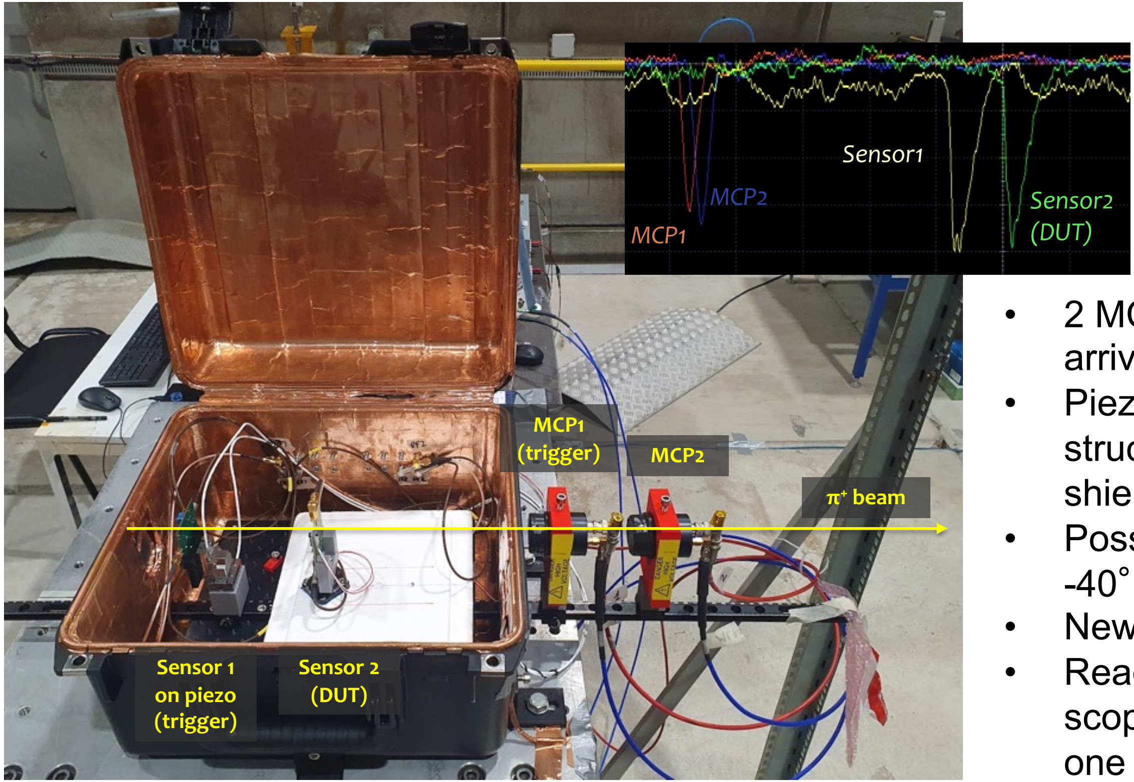


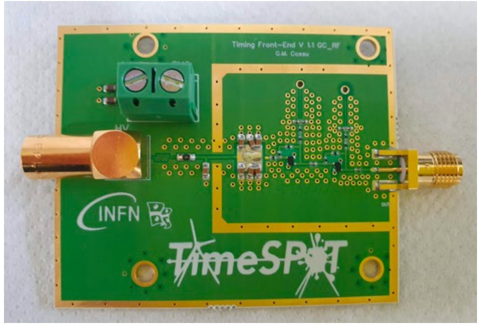


Beam test @ CERN SPS/H8 (2021-2022)

π^+ beam, 180 GeV/c

A. Lai, Vertex 2022

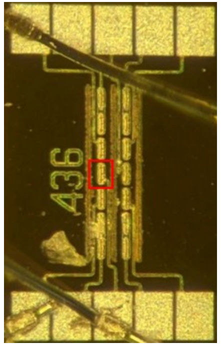


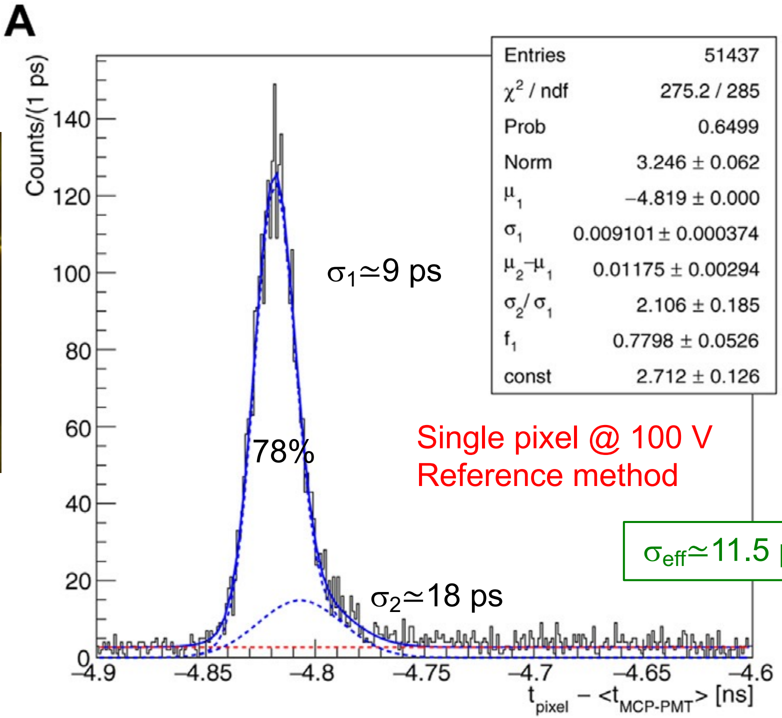


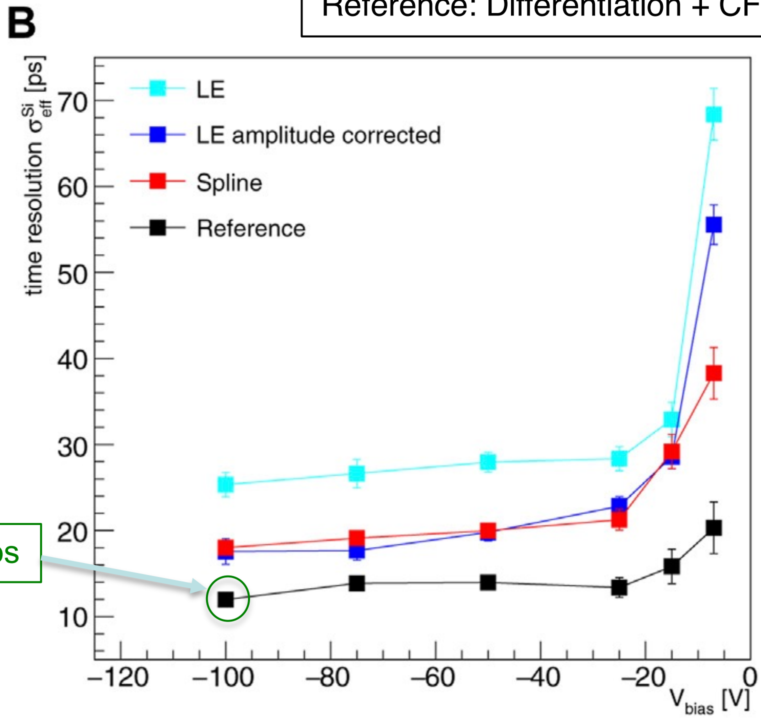
- 2 MCP-PMTs on the beam line to time-stamp the arriving particle (σ_{avg} = 5 ps)
- Piezoelectric stages to precisely align the two 3D structures with beam, all mounted in a RF-shielded box
- Possibility of operating the fixed sensor down to -40° C using dry ice to test irradiated sensors
- New faster front-end circuit (jitter < 7ps @ 2fC)
- Readout with an 8 GHz bandwidth 20 GSa/s scope: trigger on the AND of one 3D sensor and one MCP-PMT

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

LE: Leading edge, NO ToT correction
LE: Leading edge, ToT correction
Spline: Classic CFD
Reference: Differentiation + CFD



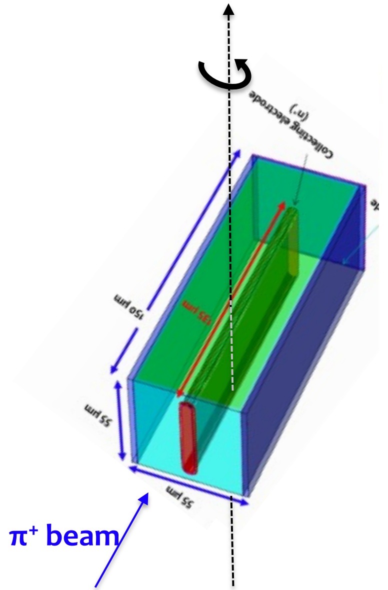


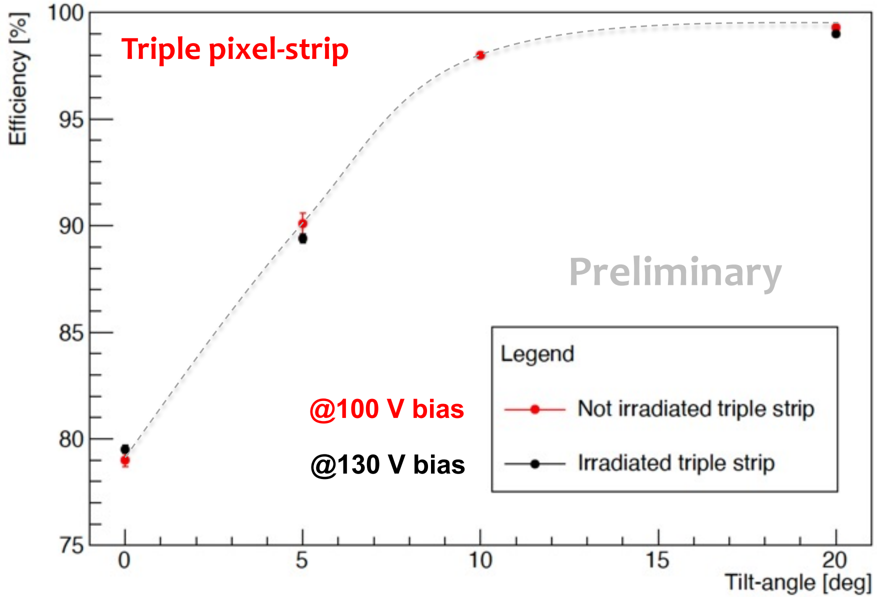


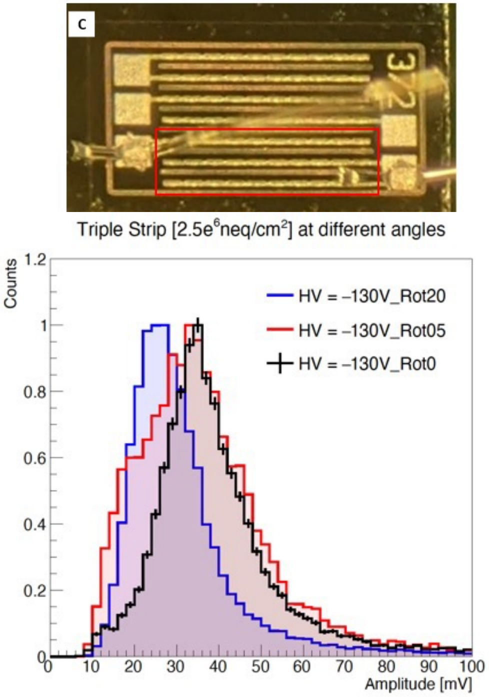
σ_{eff} accounts for the two-gaussian behaviour

F. Borgato et al. Frontiers in Physics 11 (2023) 1117575

Efficiency measurements (triple pixel-strip @ different α_{tilt})



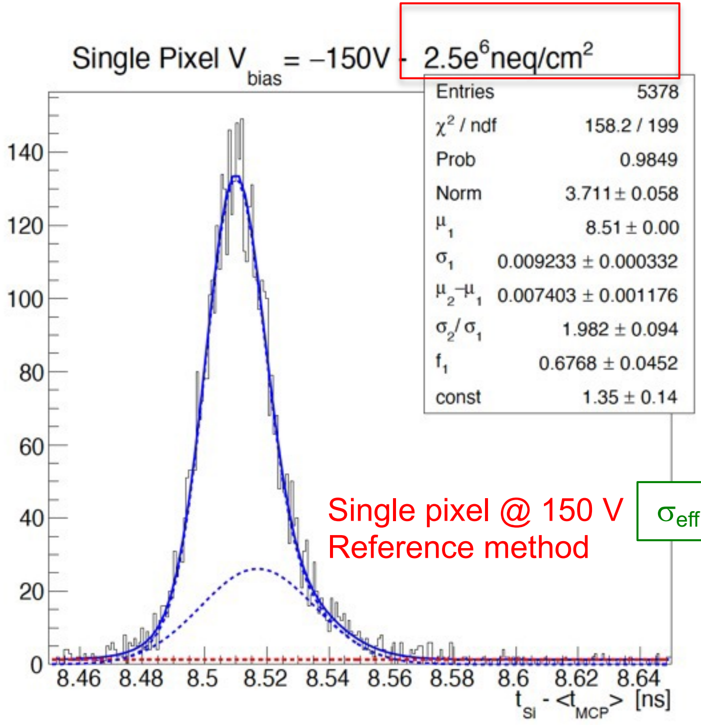




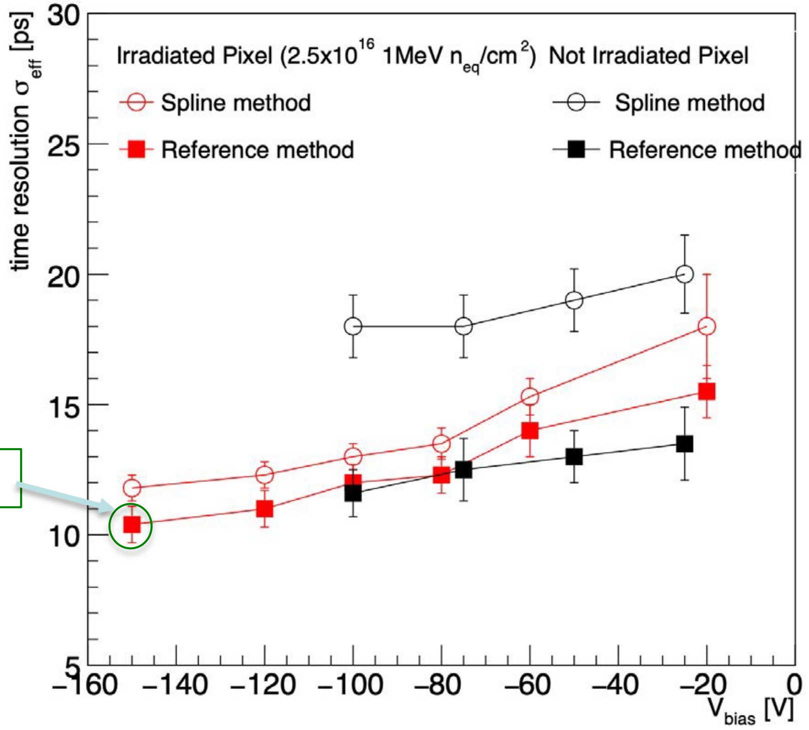
A. Lampis et al. JINST 18 (2023) C01051

The inefficiency (at normal incidence) due to the dead-area of the trenches is fully recovered by tilting the sensors around the trench axis also for sensors irradiated at $2.5 \cdot 10^{16}$ n_{eq} cm^{-2}

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



σ_{eff}≃10.3±0.5 ps

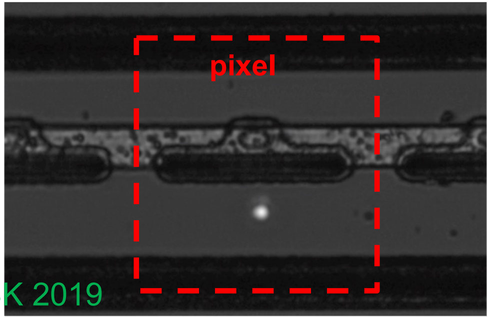


To be compared with ~ 11 ps @ 100 V of the not-irradiated case

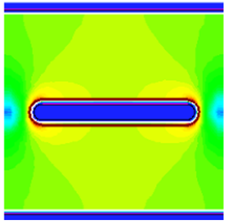
A. Lampis et al. JINST 18 (2023) C01051

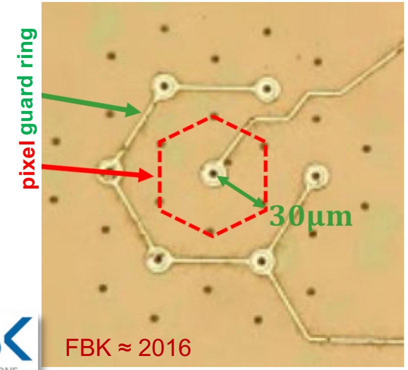
Column vs trench: a direct comparison

IR laser setup (1 mip eq.) , RT, 50 V bias, not irrad.

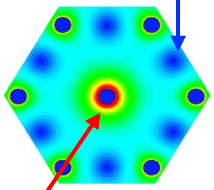


Uniform field

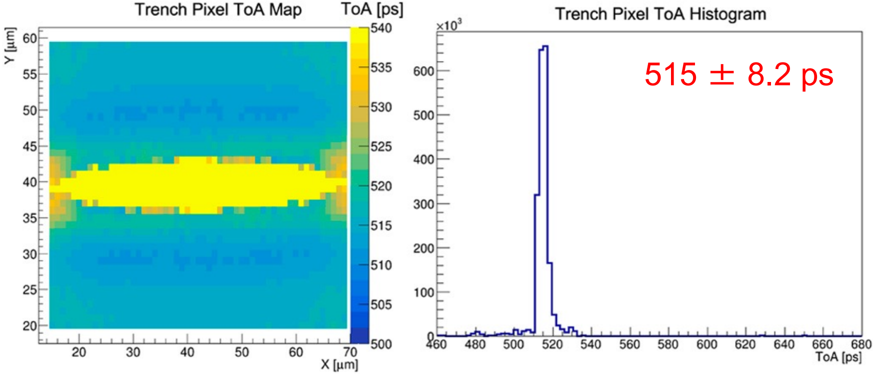




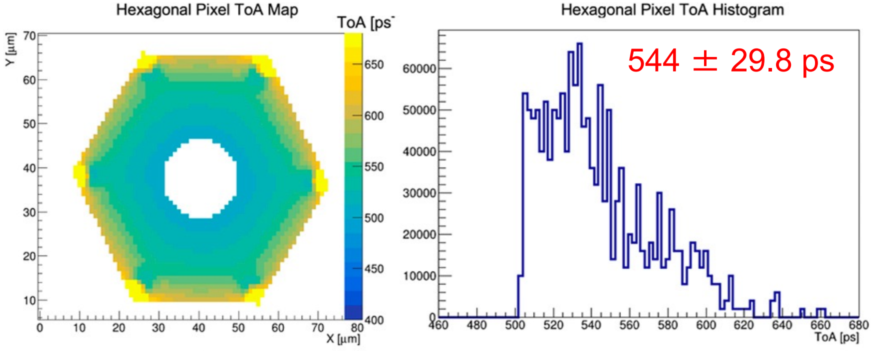
Very slow/inefficient spots
Intrinsically long tails



Super-fast spot not included (covered by metal)



(a) (b)



(a) (b)

M. Addison et al. NIMA 1054 (2023) 168392

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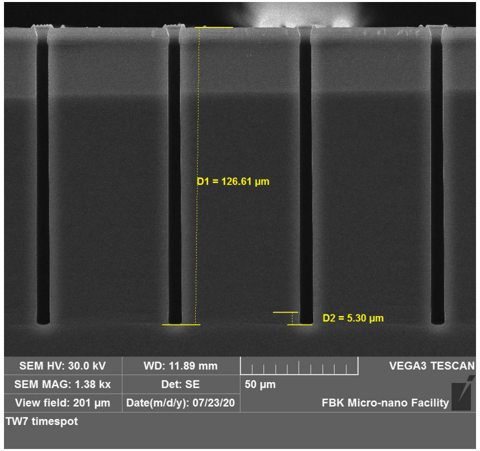
3D-Trench: technological challenges

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

DRIE etching of junction trench



SENSORS AND DEVICES
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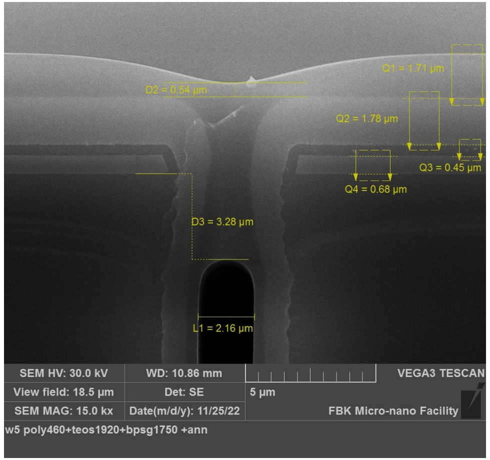
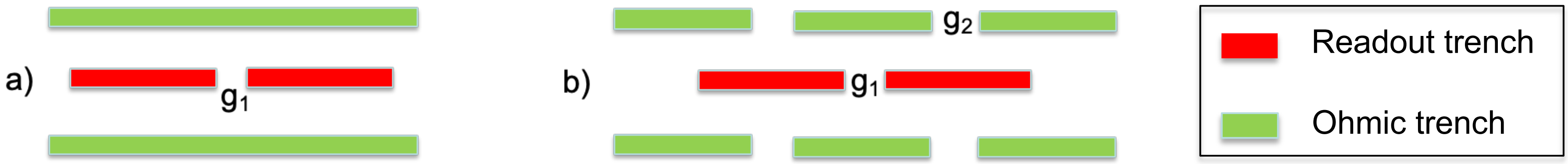
Ohmic trench filling with BPSG (Borophosphosilicate glass)



Alternative layout

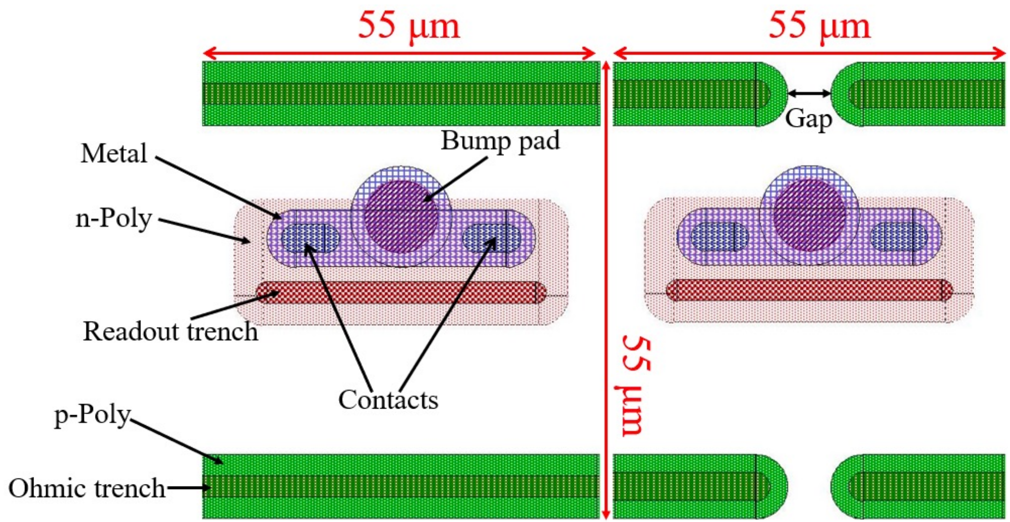
- Continuous ohmic trench (a) vs dashed ohmic trench (b)



New batch funded by

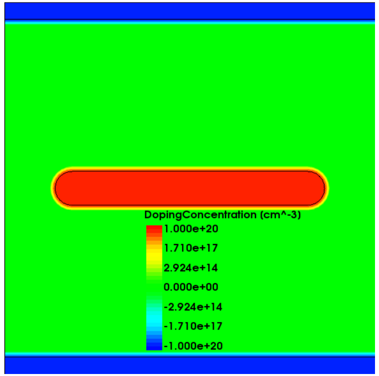
AIDA innova

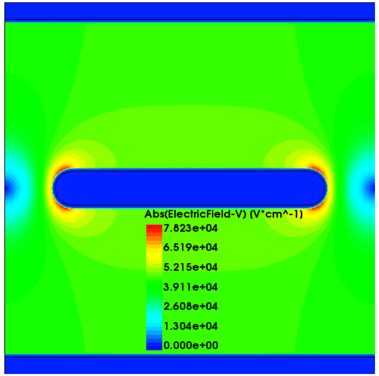
WP6: Hybrid Pixel Sensors for 4D Tracking and Interconnection Technologies

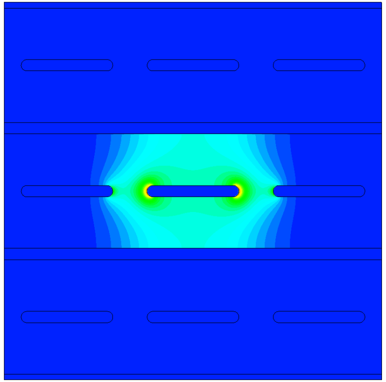


TCAD static simulations

Continuous trench





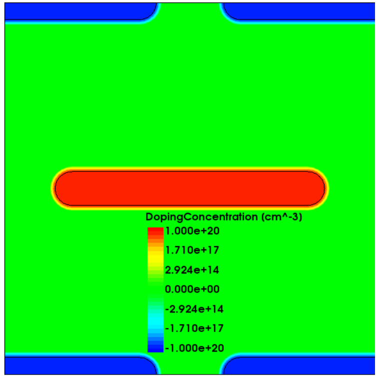


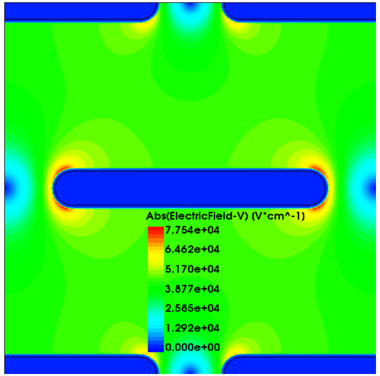
Doping

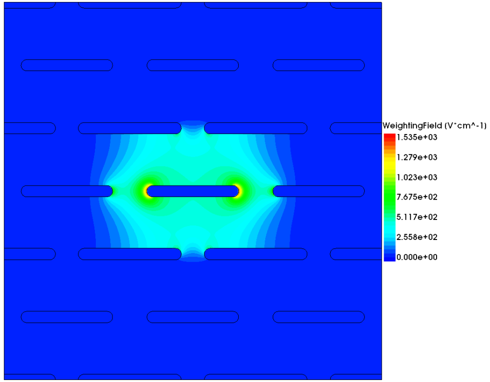
Electric field@100 V

Weighting field

Dashed trench

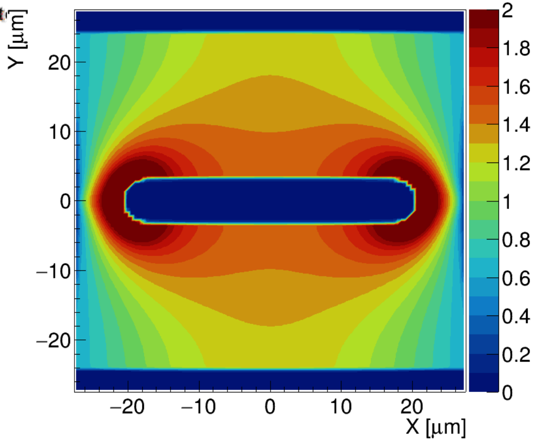






Signal simulations

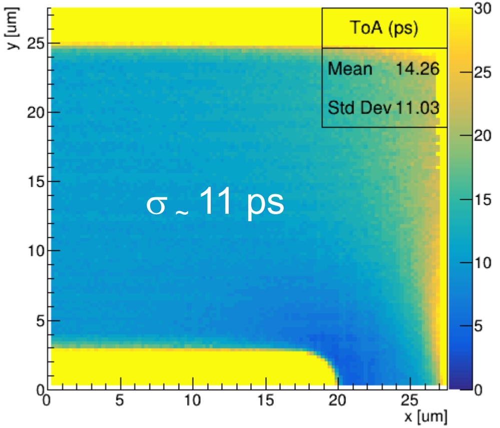
Continuous trench



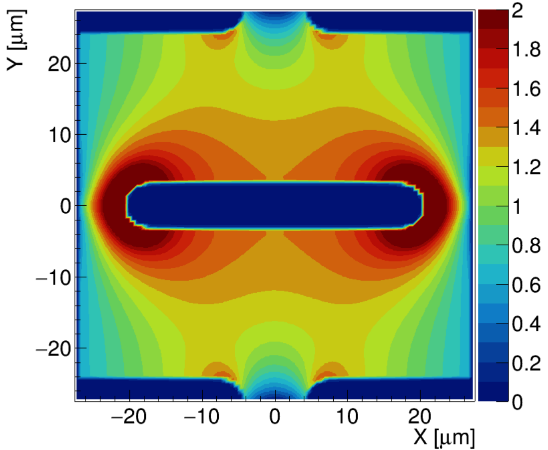
1) TCAD + Ramo's theorem

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

Ramo maps @ 100 V (induced currents [nA])



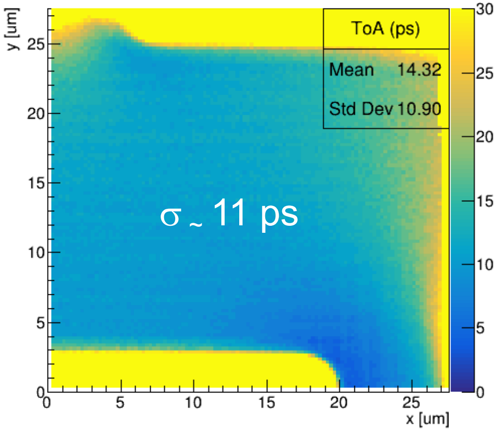
Dashed trench



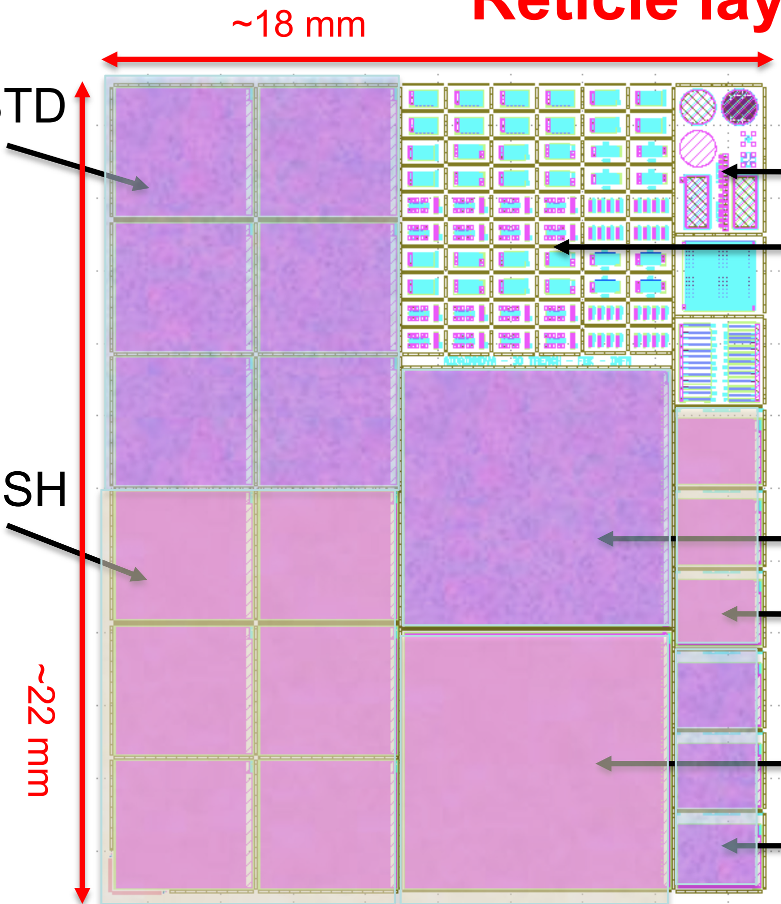
2) AllPix² MC simulations

Geant4 (mips) + TCAD input, Jacoboni-Canali charge transport Model + default digitizer

ToA [ps] maps @ 100 V (threshold = 1000 e)



Reticle layout



6x Pixels STD (64x64)

6x Pixels DSH (64x64)

Technological Test Structures

Device test structures (55 μm pitch and 42 μm pitch, std and dashed)

- Groups of individual pixels
- Strips
- Diodes

1x Pixels STD (128x128)

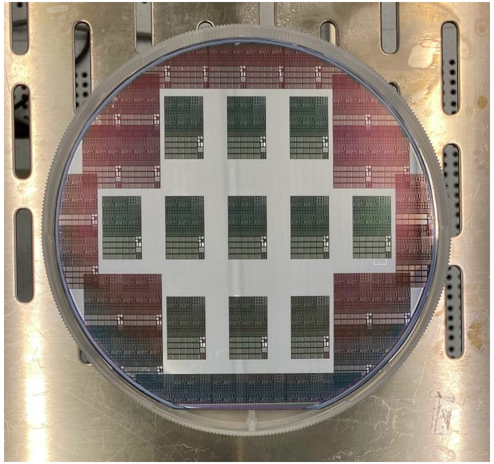
3x Pixels DSH (32x32)

1x Pixels DSH (128x128)

3x Pixels STD (32x32)

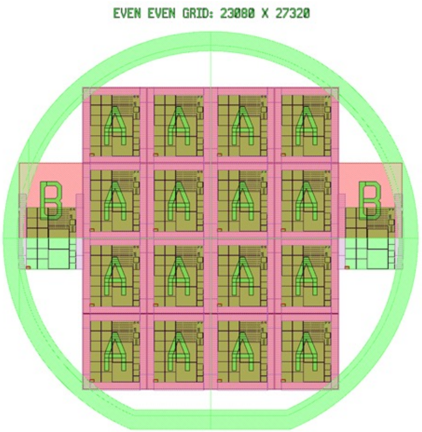
Fabrication at FBK

TIMESPOT batch #2

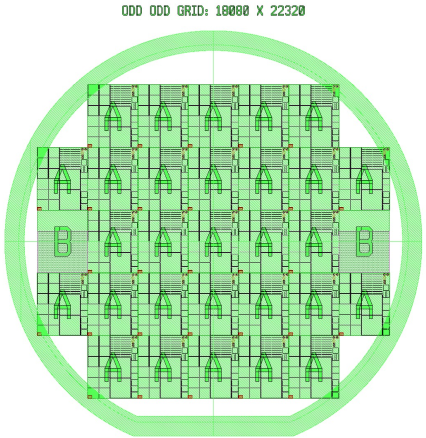


11 shot exposure

AIDAInnova batch



18 shot exposure



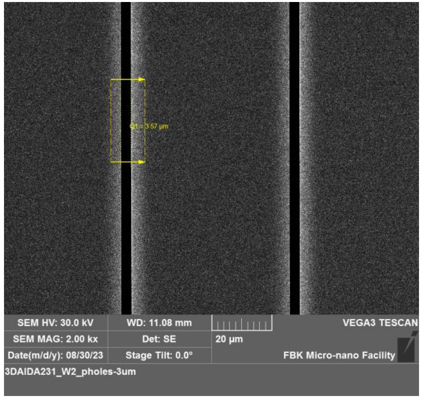
29 shot exposure

- Fabrication under way at FBK, to be completed by Dec. 2023
- Largely increased device density on wafer wrt TIMESPOT batches
- Bow under control (~max 20 μm)

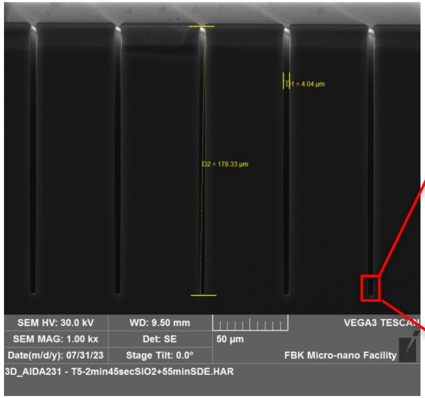
DRIE etching of ohmic trenches

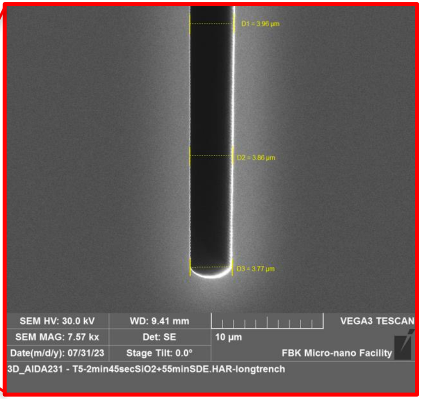
1) Long continuous ohmic trenches: 3 μm x mm's

Width 3.5 μm



Depth 178 μm





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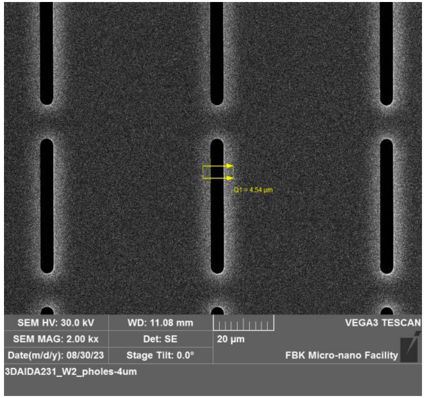
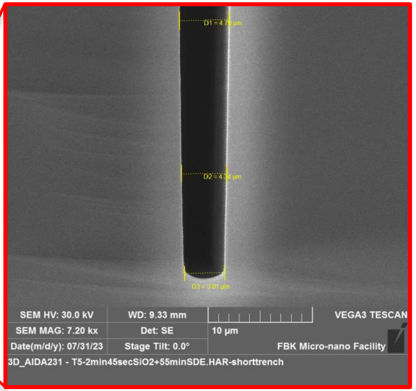
SENSORS AND DEVICES

2) Short dashed ohmic trenches: 4 μm x 40 μm

Width 4.5 μm

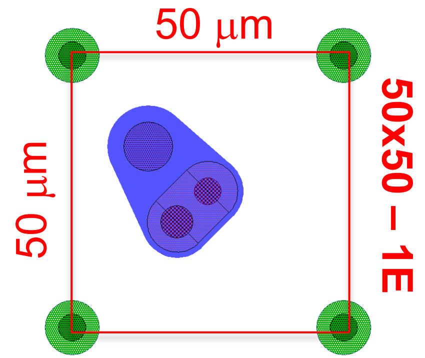


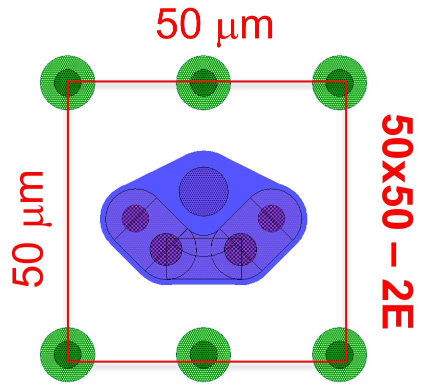
Depth 174 μm



Exploring different 3D-column solutions

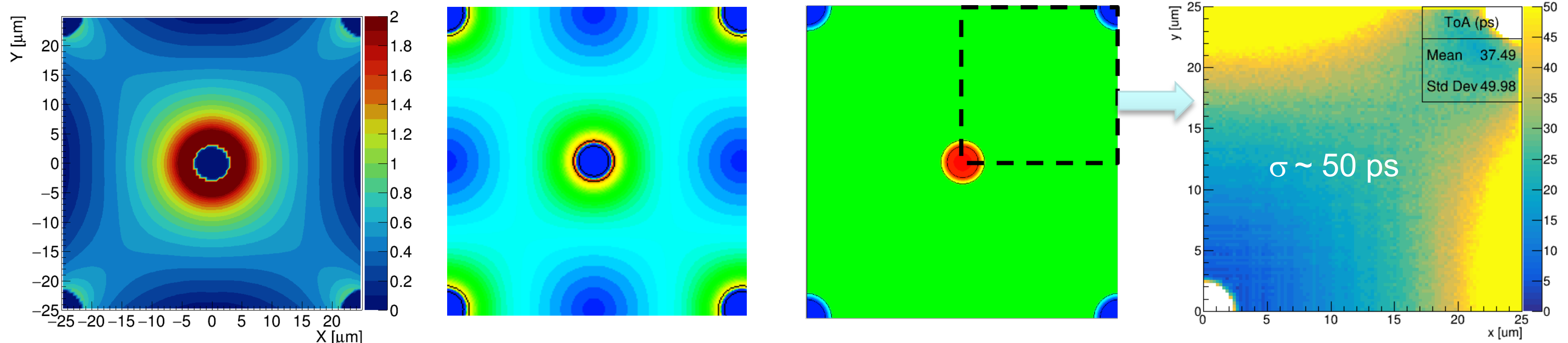
- The intrinsic timing resolution of 3D-trench sensors cannot be maintained in pixel implementations, due to the power constraints in the ROC
- 3D-column sensor performance might be good enough for some applications, easing the fabrication
- We are also studying 3D-column designs with different cell size and column arrangement
- These designs will be implemented in a new batch funded by INFN CSN1 (LHCb), to be launched at FBK in January 2024





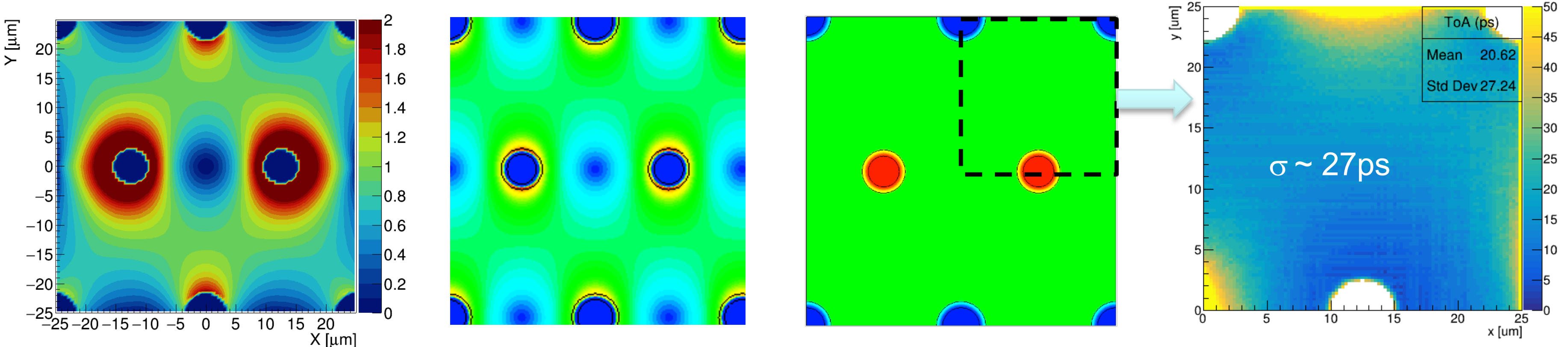
Preliminary comparison of 3D-column designs

50x50 – 1E



Ramo maps @ 100 V | Electric field@100 V | Doping | AllPix^2 simulations

50x50 – 2E



Conclusions

- 3D pixels are a promising candidate for future “tracking+timing” applications
- Excellent timing resolution so far demonstrated on test structures with discrete, high-speed electronics:
    - ~25 ps for 3D-columnar electrodes
    - ~10 ps for 3D-trenched electrodes

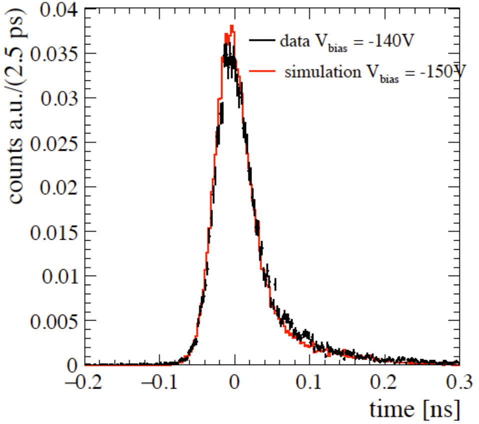
  } Also confirmed after large radiation fluences
- Fabrication technology for 3D-trenched sensors to be optimized for large areas and yield (modified 3D-trench designs might ease fabrication with minimum penalty on the performance)
- Different 3D-column designs are also worth investigation (trade-off between intrinsic speed and capacitance/noise)

Acknowledgements

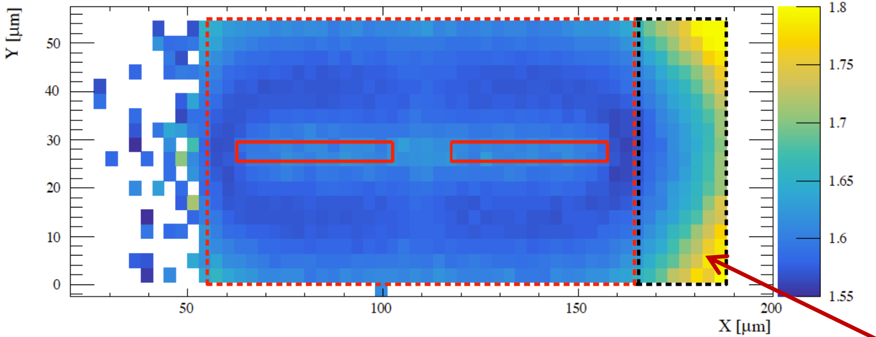
- This work has received funding from:
  - the Italian National Institute for Nuclear Physics (INFN) through the Projects TIMESPOT (CSN5) and LHCb (CSN1)
  - INFN and FBK through the Framework Agreement MEMS4
  - the EC under Grant Agreement 777222, ATTRACT-INSTANT project.
  - the European Union’s Horizon 2020 Research and Innovation programme under GA no. 101004761 (AIDAInnova)
- Special thanks to:
  - the TIMESPOT Collaboration, especially Adriano Lai and Angelo Loi (INFN Cagliari)
  - Maurizio Boscardin, Sabina Ronchin and Laura Parellada Monreal (FBK)
  - Sherwood Parker for inspiring this work, and Cinzia Da Via (Univ. Manchester, UK) for fruitful discussions

Back Up Slides

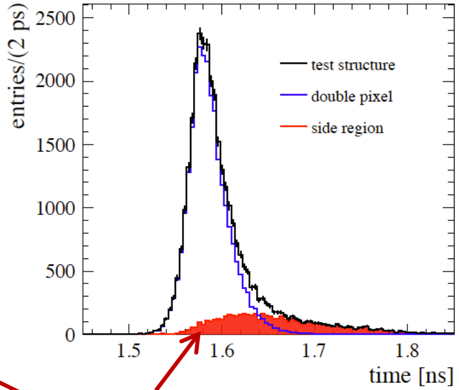
Origin of (non-intrinsic) tails



PSI test beam data



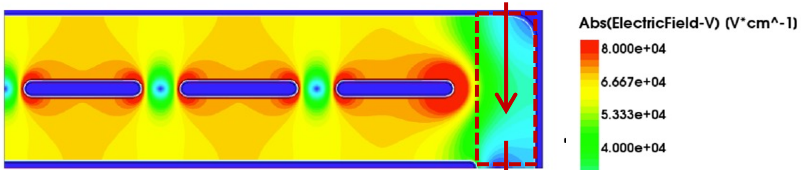
ToA from front-end



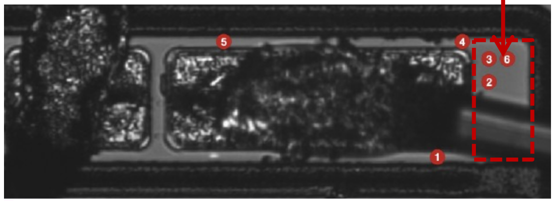
side region

Tails have been studied with very accurate pixel modeling, from the ionization process to the front-end output (TCode).

A clear assignation of the tail contribution was done to the (out)side region of the pixel (outside the nominal pixel area in this particular case).



Electric field at V_{bias} = – 150 V



Double pixel picture

Details of this analysis on:
D. Brundu et al., *Accurate modelling of 3D-trench silicon sensor with enhanced timing performance and comparison with test beam measurements*. arXiv:2106.08191v2 [physics.ins-det], JINST 16 (2021) 09, P09028.

Laser test

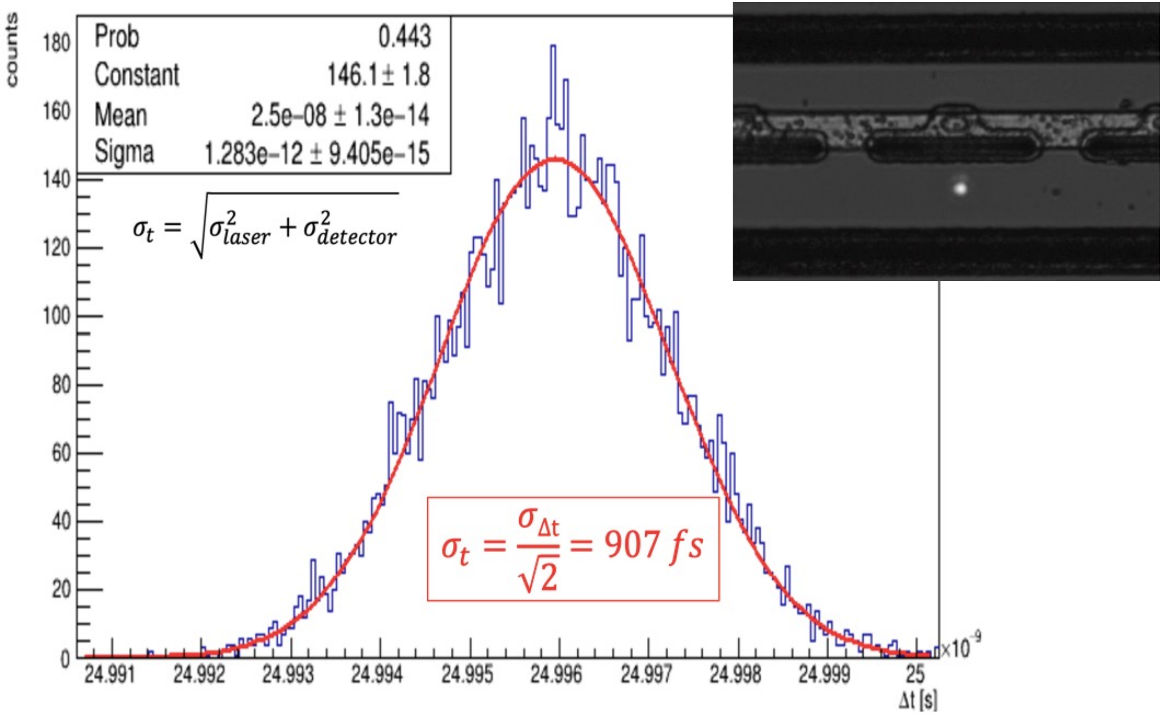
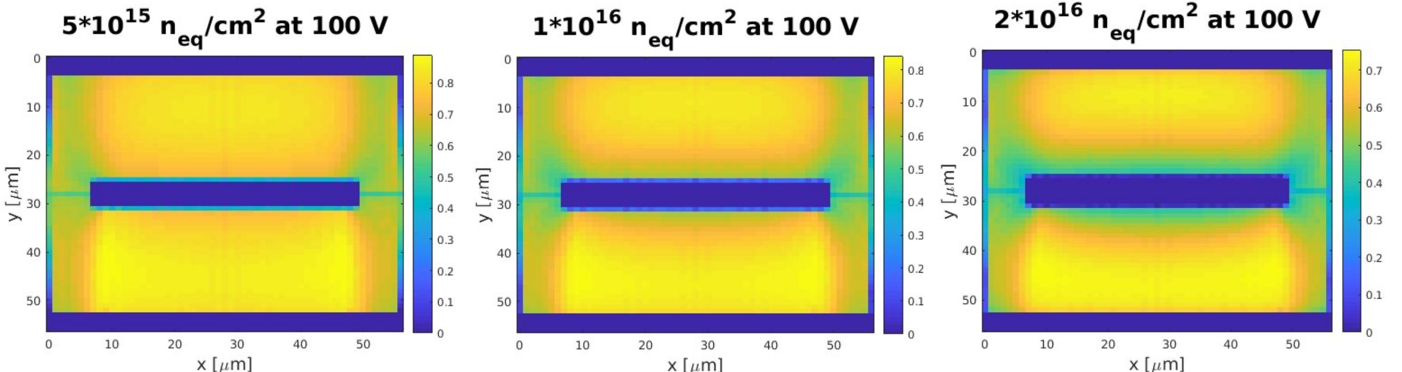


Fig. 3. Time delay measurement between two laser pulses on 3D-trench sensors, used both as time reference and time measuring device. Laser intensity is calibrated to have a 10 MIP equivalent deposit.

3D-trench: radiation hardness

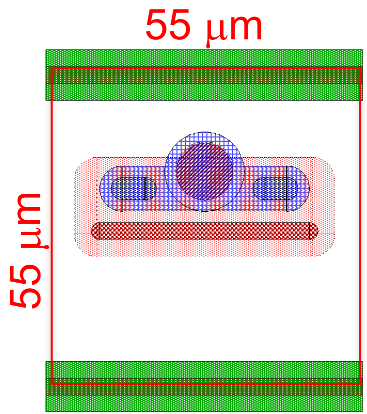
R. Mendicino et al., NIMA 927 (2019) 24

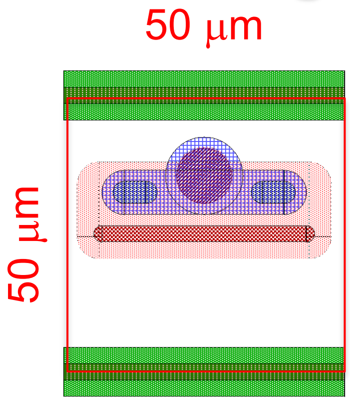
- Ramo's Theorem with input from TCAD: $i_k = -q\vec{v} \cdot \overrightarrow{E_Q}$
  - ✓ $\vec{v}$ is the drift velocity of charge carriers
  - ✓ (Electric field → charge trajectory and velocity)
  - ✓ $\overrightarrow{E_Q}$ is the "weighting Field" → charge motion coupling to a specific electrode
  - ✓ Charge trapping included: $Q(t) = Q_0 e^{-t/\tau}$
- New Perugia model (bulk damage) F. Moscatelli et al., IEEE TNS 64 (2017) 2259
- Very high signal efficiency expected

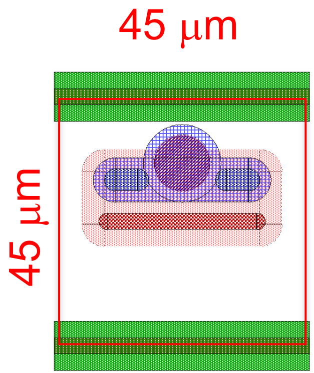


3D-Trench cell scaling

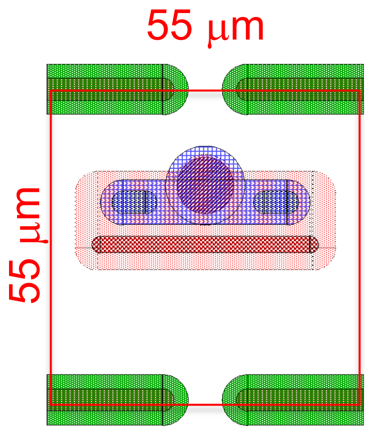
Continuous Ohmic trench

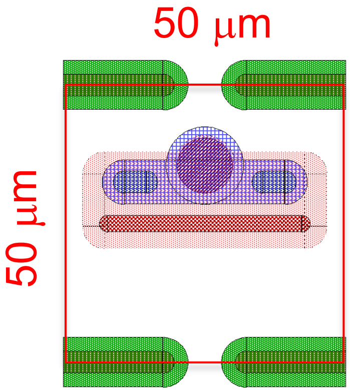


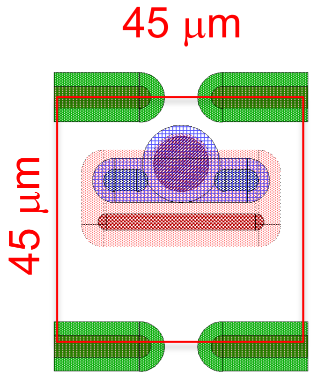




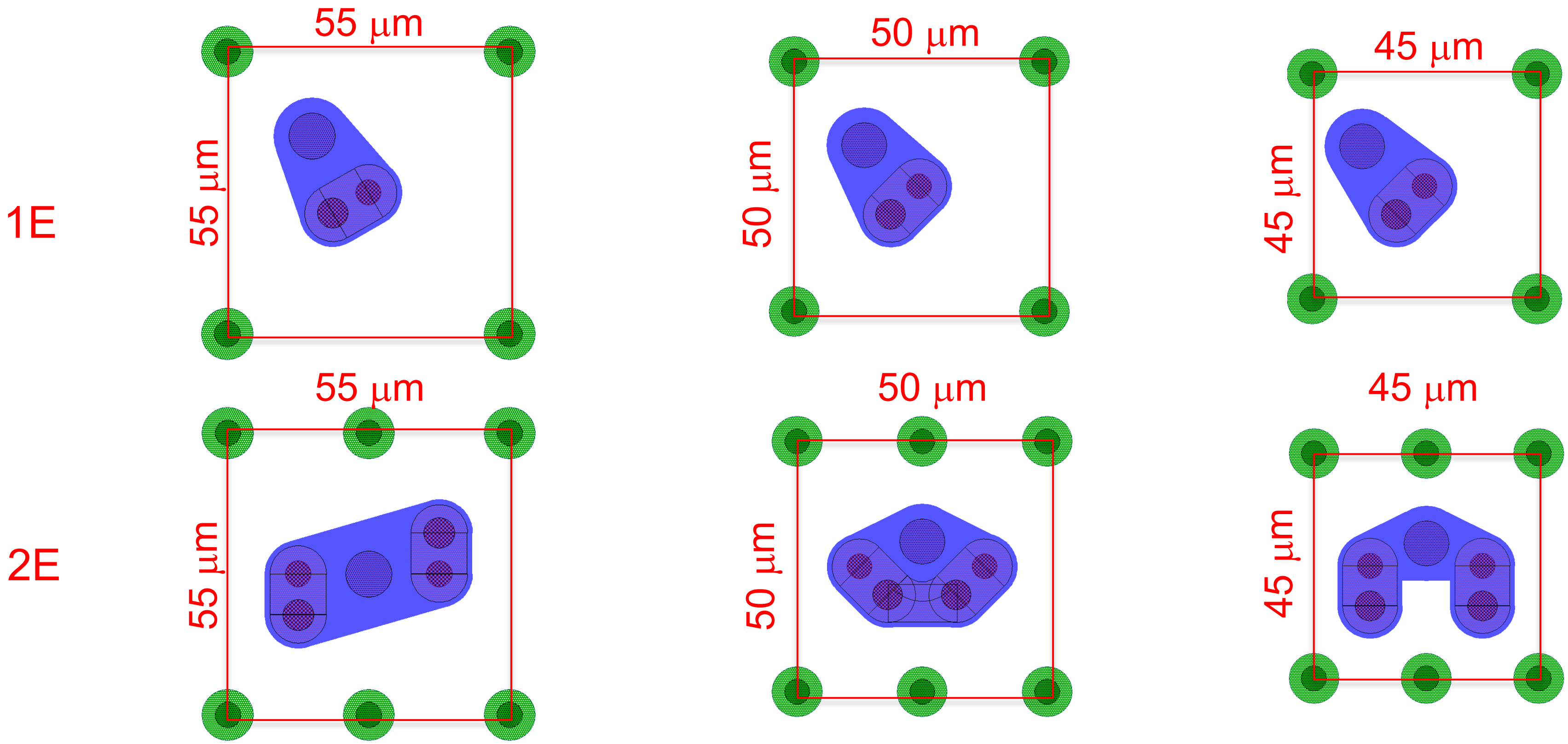
Dashed ohmic trench



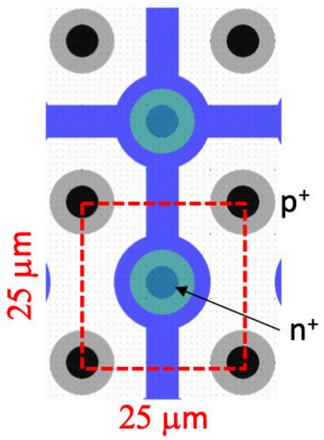


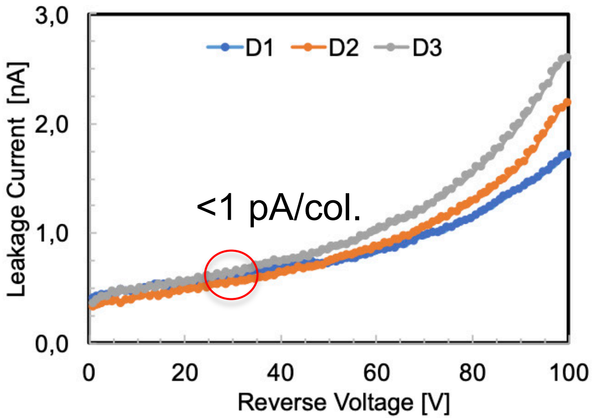


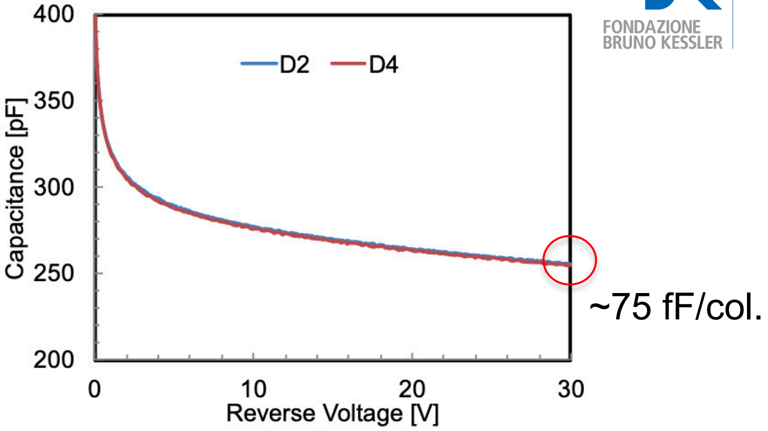
3D-Column cell scaling



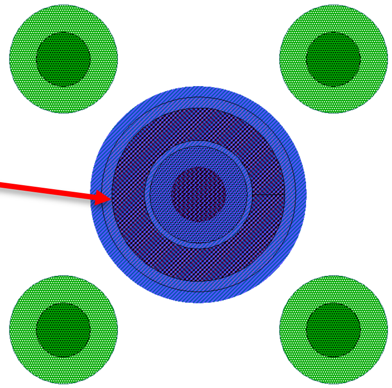
Very small-pitch 3D sensors







- Feasibility proved at FBK on 3D diodes with standard process
- Good electrical characteristics
- Additional challenge for pixels would come due to bump pad
- Dedicated effort for technology optimization required



G.-F. Dalla Betta, M. Povoli, Front. Phys. (2022) 10:927690