Review of 3D pixel technology

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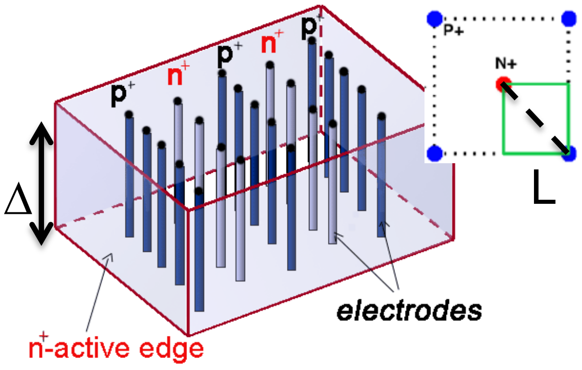
Outline

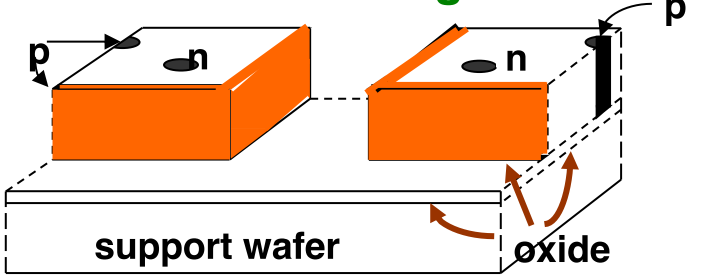
- Introduction & Background
- 3D pixels for HL-LHC
- 3D-trenched pixels for tracking + timing
- Conclusions

Introduction: 3D Sensors



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

Active edge



C. Kenney et. al. IEEE TNS 48(6) (2001) 2405

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

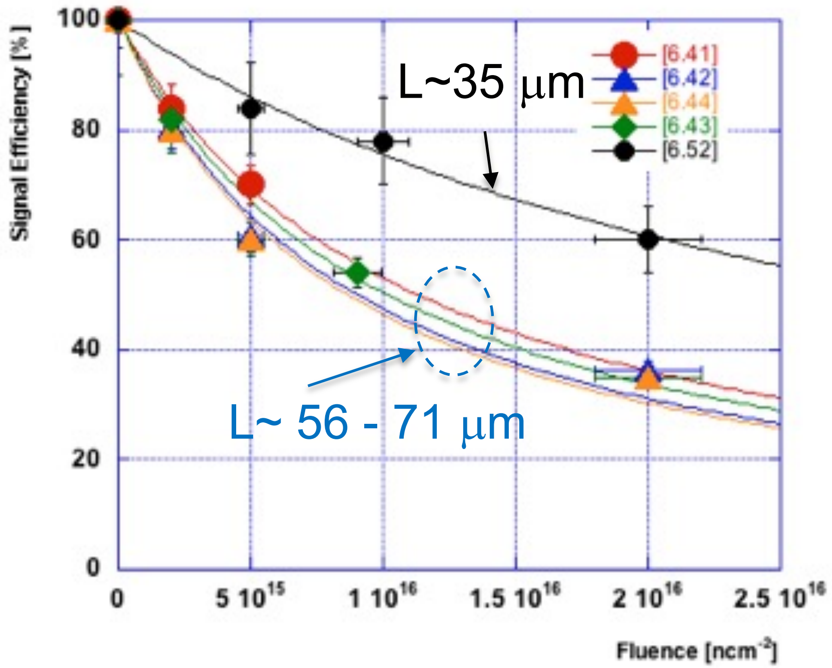
High radiation hardness at relatively low voltage (power)

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)

Signal Efficiency

C. Da Via, G.-F. Dalla Betta, S. Parker, “Radiation Sensors with 3D electrodes”, CRC PRESS, 2019



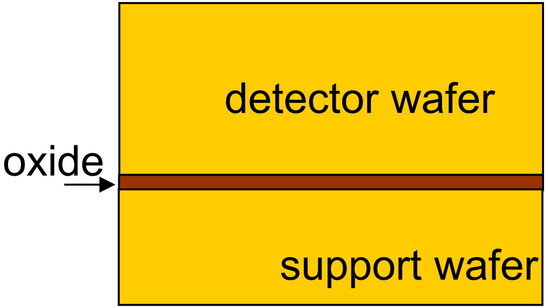
Signal Efficiency = Ratio of max. signal after irradiation and before irradiation

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

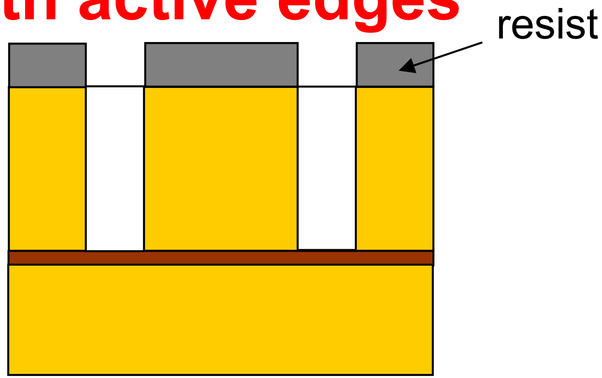
C. Da Via, S. Watts, NIMA 603 (2009) 319

[6.41] ATLAS IBL Collaboration, JINST 7 (2012) P11010
[6.42] G.-F. Dalla Betta, et al., NIMA 765 (2014) 155
[6.44] M. Fernandez et al. NIMA 732 (2013) 137
[6.43] I. Haughton et al., NIMA 806 (2016) 425
[6.52] G.-F. Dalla Betta, et al., IEEE NSS (2015) N3C3-5

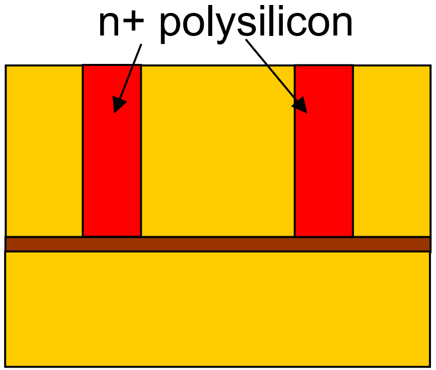
Tech 1: Full-3D with active edges



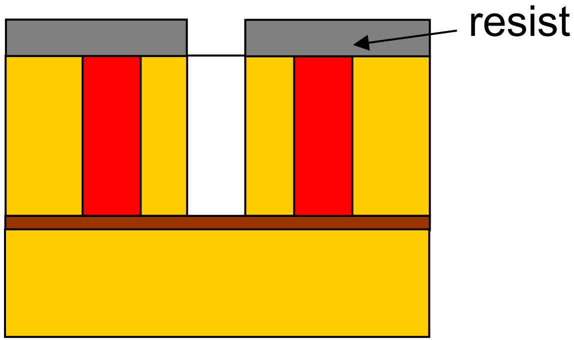
1) wafer bonding



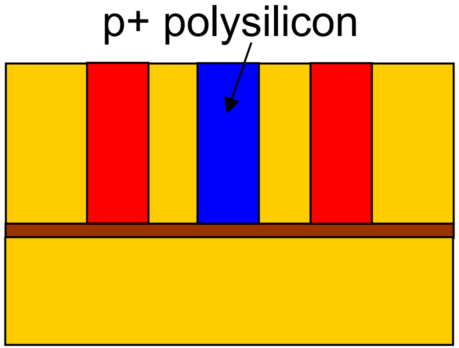
2) n+ hole definition & etching



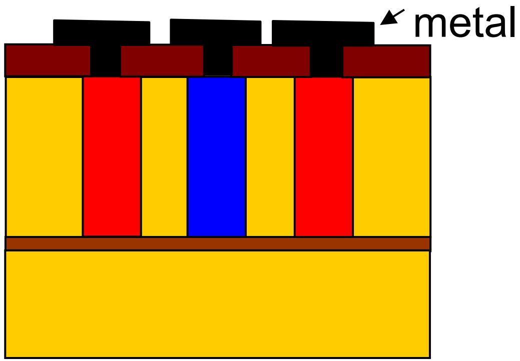
3) n+hole doping & filling



4) p+ hole definition & etching



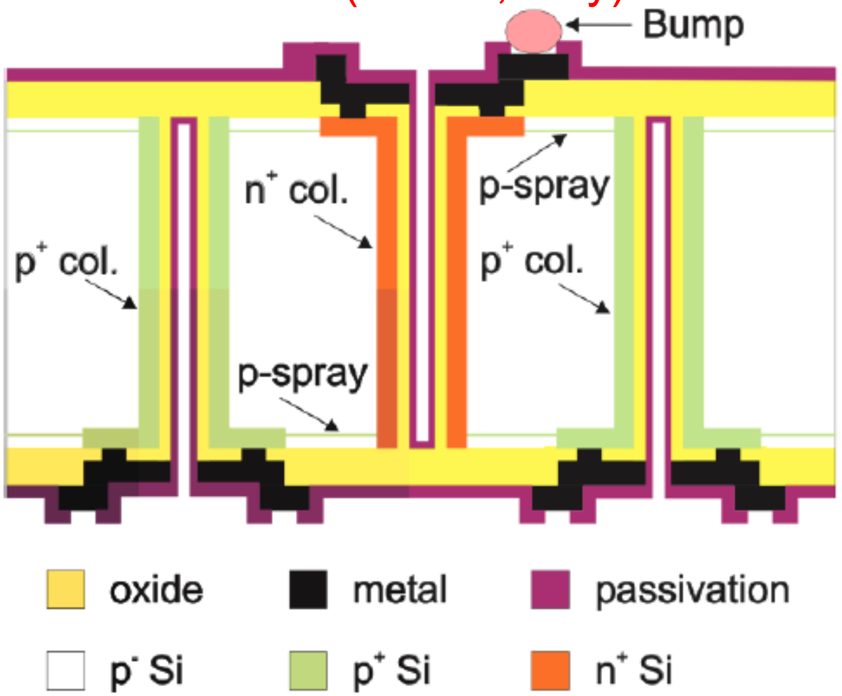
5) p+ hole doping & filling



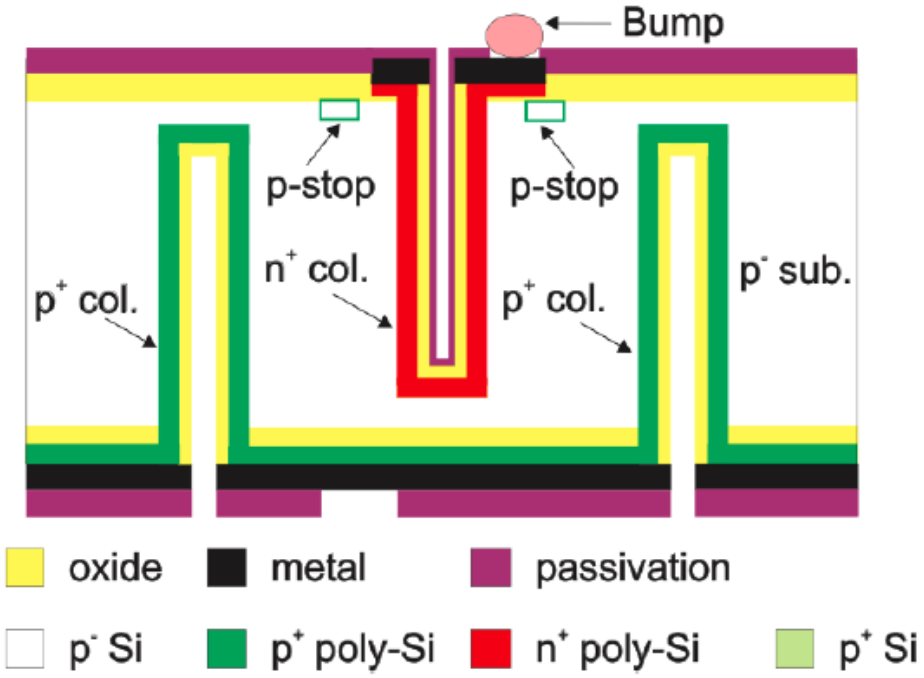
6) Metal deposition & definition

Tech 2: Double-sided 3D sensors

FBK (Trento, Italy)



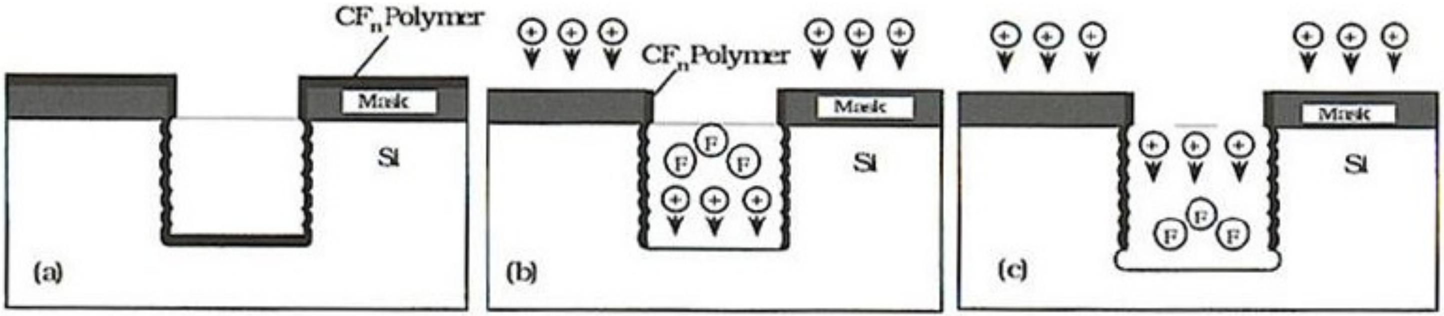
CNM (Barcelona, Spain)



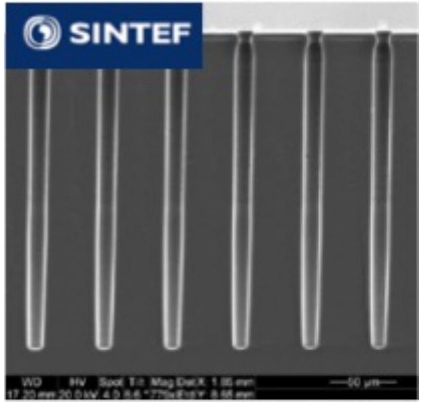
A. Zoboli et. al., IEEE TNS 55(5) (2008), 2775
G. Giacomini, et al., IEEE TNS 60(3) (2013) 2357

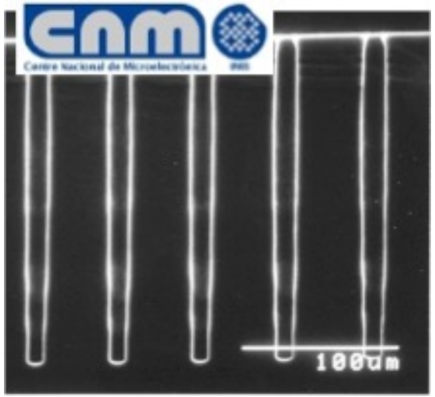
G. Pellegrini et. al. NIMA 592(2008), 38
G. Pellegrini et. al. NIMA 699(2013), 27

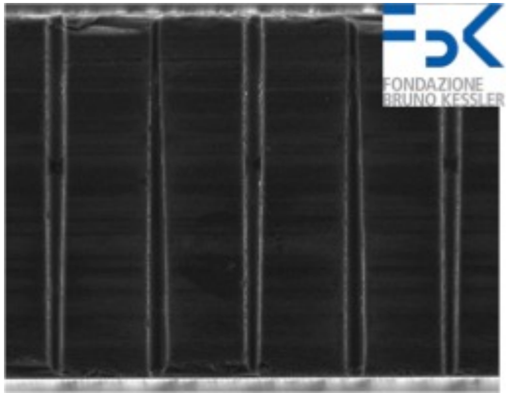
Key technology: DRIE by the Bosch process



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



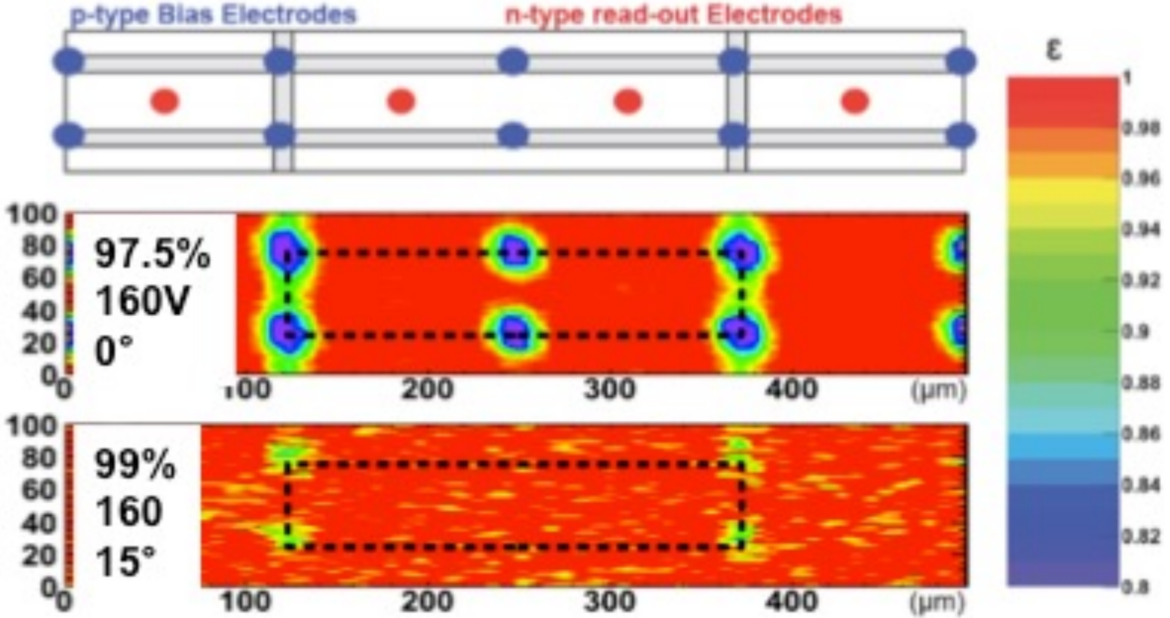




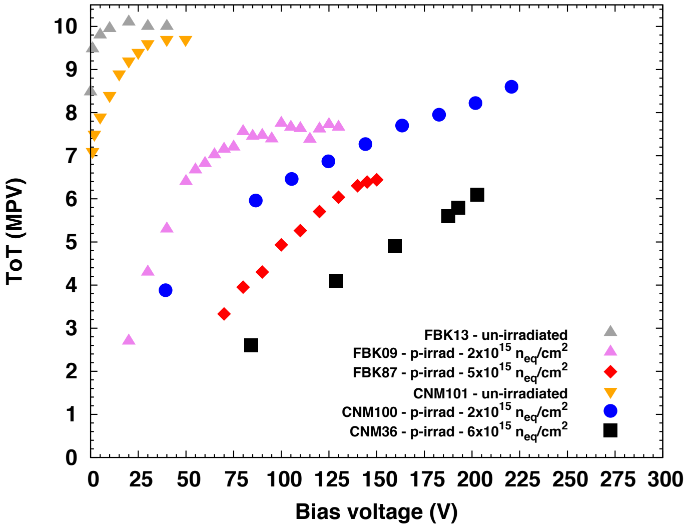
Main milestone: ATLAS IBL 3D pixels

- Double-sided 3D's by CNM and FBK
- First demonstration of small volume production
- Excellent performance up to > $5\times10^{15}\ n_{eq}\ cm^{-2}$

S. Grinstein, Sh. Tsiskaridze, A. Micelli, C. Gemme

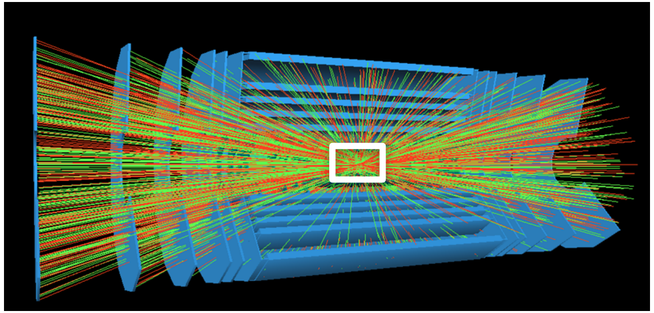


ATLAS IBL, JINST 7 (2012) P11010



- Also used in ATLAS AFP and CT-PPS

Pixel Roadmap: LHC → HL-LHC



- To maintain occupancy at ~% level and increase the spatial resolution → Reduce pixel size
- 50x50 or 25x100 μm², compatible with next ROC generation (CMOS 65 nm) from CERN RD53 Collaboration

Challenges at HL-LHC

- Luminosity of 5×10^{34} $cm^{-2}s^{-1}$
- Higher hit-rate capability (up to 200 events per bunch-crossing)
- Radiation fluence up to $\sim 2 \times 10^{16}$ n_{eq}/cm^2 for the innermost pixel layers

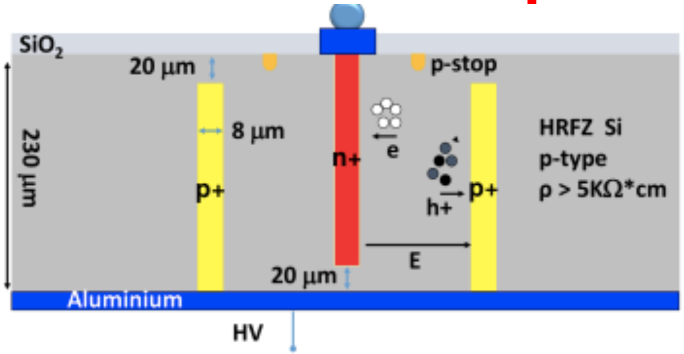
Implications for small-pitch 3D's

Modified technology/design for:

- smaller pixels with reduced inter-electrode spacing (~30 um)
- narrower electrodes (~5 um)
- thinner active region (~150 um)

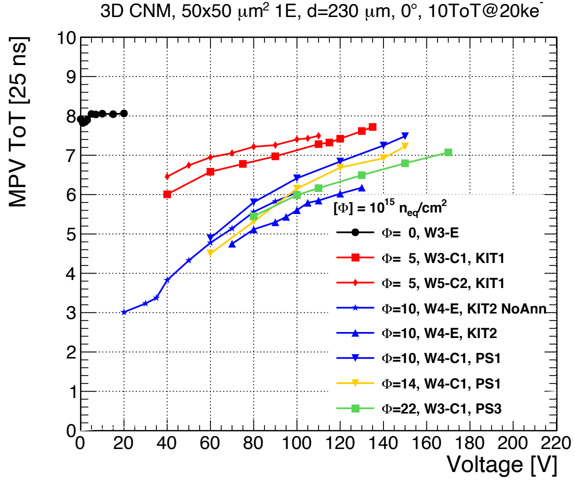
Intense R&D programs with 3 processing facilities since 2014

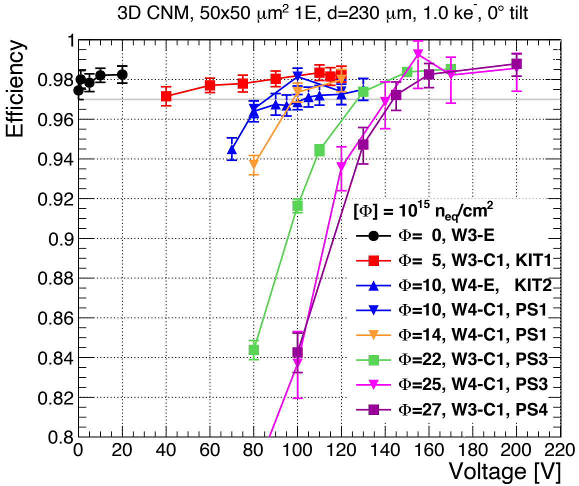
CNM small-pitch 3D pixels with double-sided process

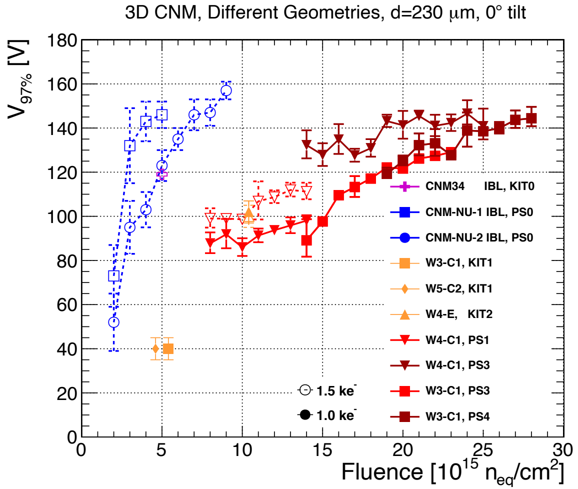


- CNM 3D pixel detector, 50x50 μm^2 cells
- (Partial) readout with FEI4 ROC
- Proton irradiation up to ~$3x10^{16}$ n_{eq}/cm^2
- Beam tests at CERN SPS

J. Lange et al., JINST 13 (2018) P09009

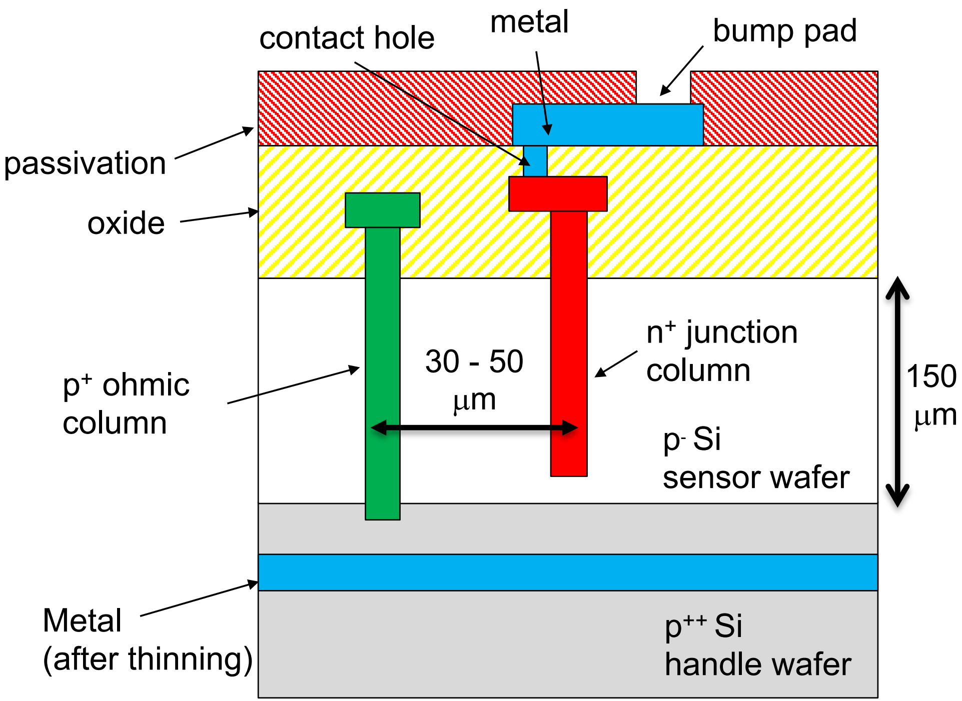






New single-side approach to 3D pixels

Double-sided process not favoured for thin sensors, especially on 6” wafers



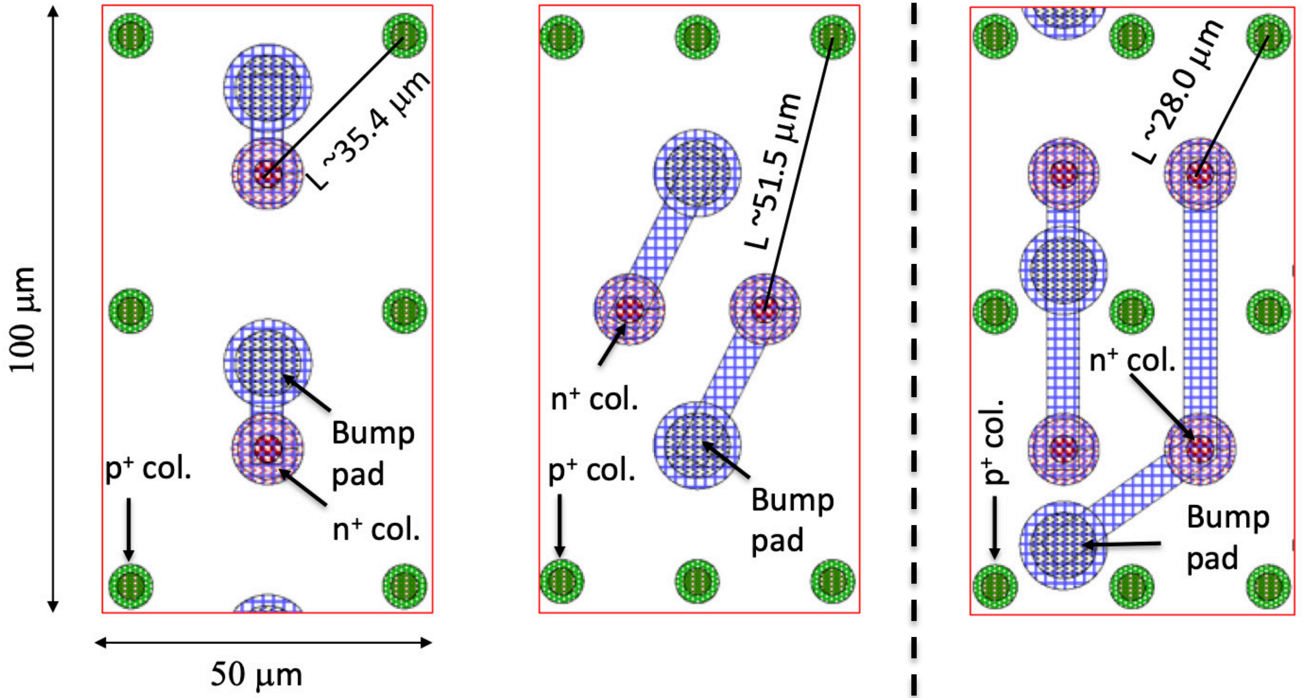
G.-F. Dalla Betta et al., NIMA 824 (2016) 386 and 388

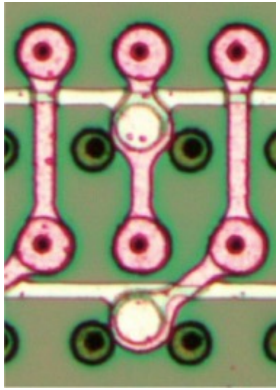
- Thin sensors on handle wafer: SiSi DBW
- Ohmic column depth > active layer depth (for backside bias)
- Junction columns depth < active layer depth (for high V_{bd})
- Reduction of hole diameters to ~5 um
- Holes (at least partially) filled with poly-Si
- Post-processing: handle wafer thinning and metal deposition

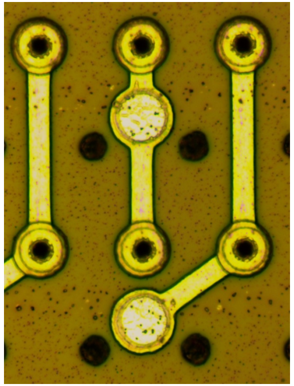
Small-pitch 3D pixels layouts

FONDAZIONE BRUNO KESSLER

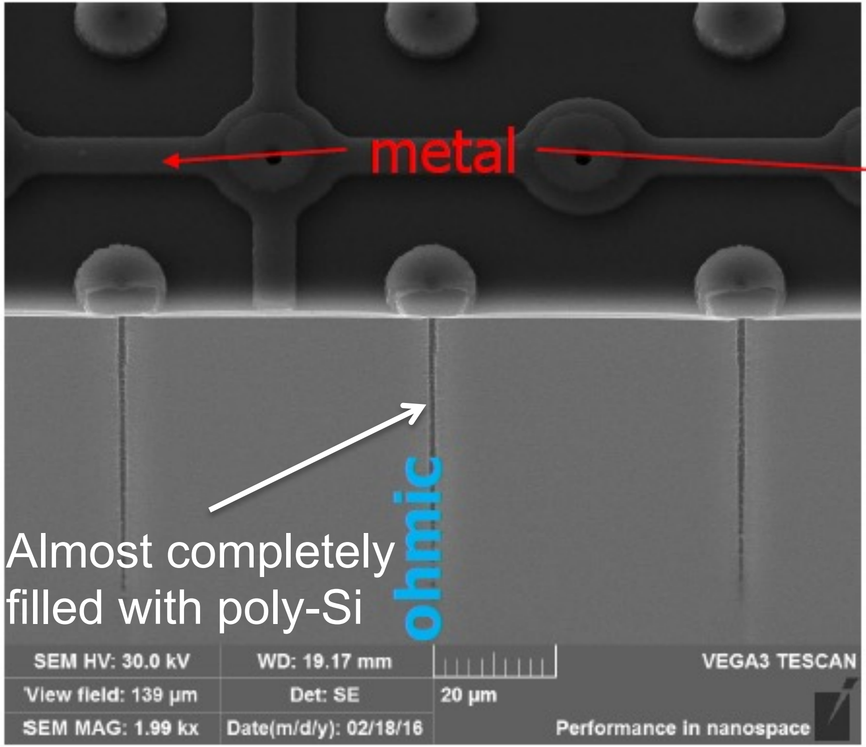
G.-F. Dalla Betta et al., Frontiers in Physics 8:625275

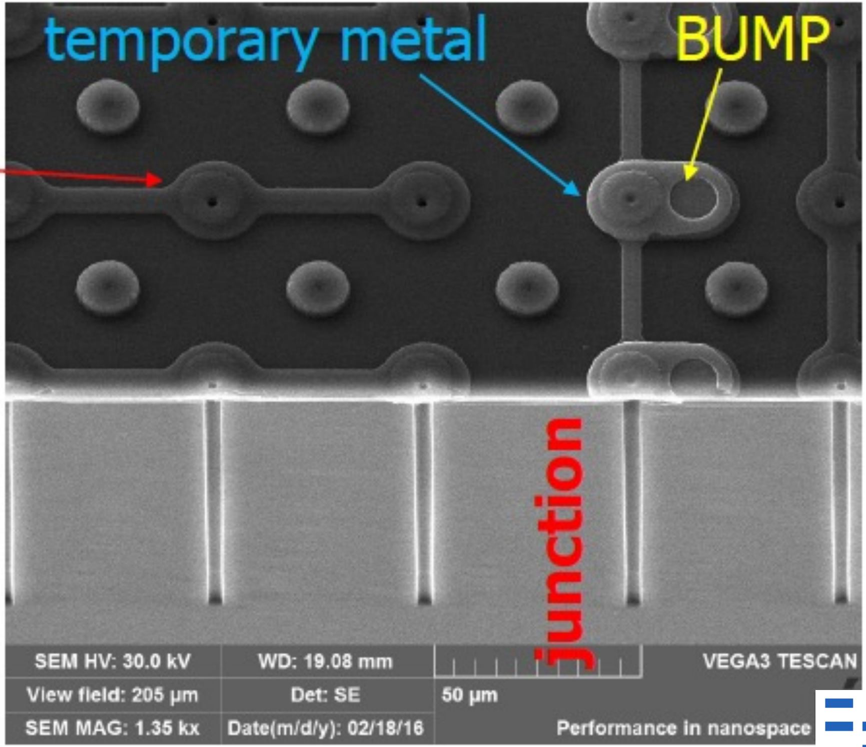



Mask Aligner


Stepper

Fabrication details @ FBK

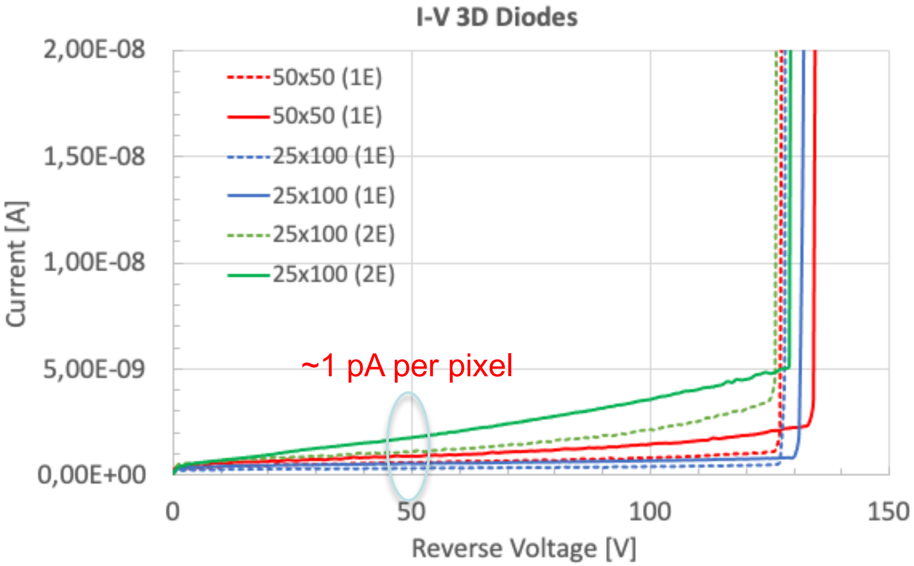


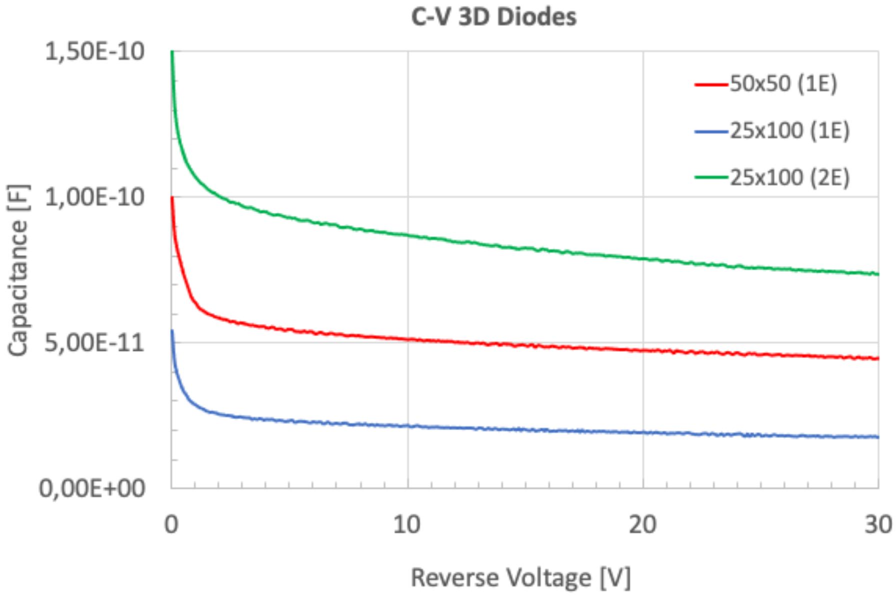


FONDAZIONE BRUNO KESSLER

3D diodes: leakage current and capacitance

- Very low leakage current and high breakdown voltage
- Capacitance: ~ 20, 50, 85 fF per pixel, depending on geometry





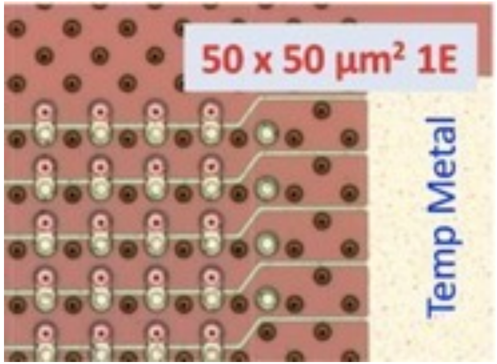
S. Terzo et al., Frontiers in Physics 9:624668

Electrical tests on pixels by temporary metal

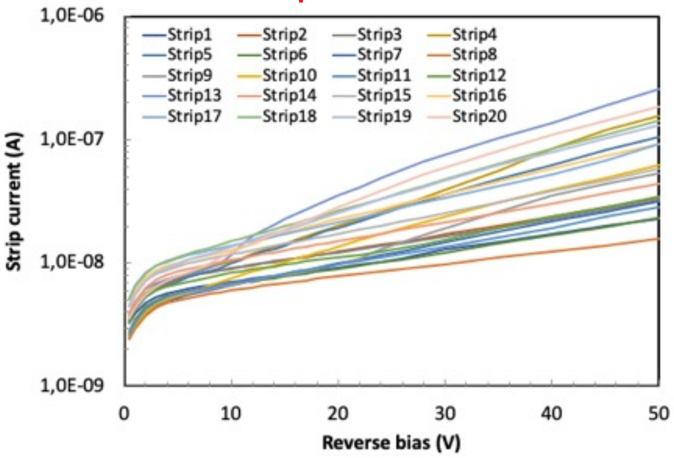
- It's important to check the device quality at wafer level before bump bonding
- Multiple rows of pixels (strips) are shorted by temporary metal for electrical tests
- Detailed monitoring of process defects
- Sum of I-V's provides total currents
- Temporary metal removed after testing

G.-F. Dalla Betta et al., Frontiers in Physics 8:625275

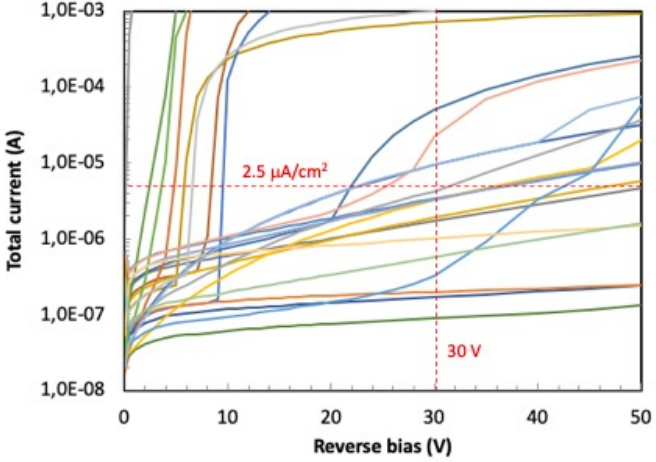
Micrograph



All strips in one sensor



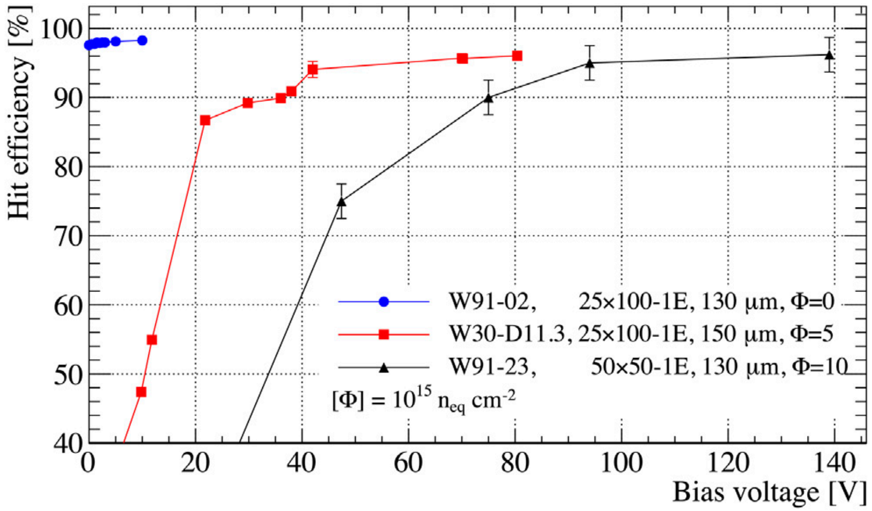
Total currents



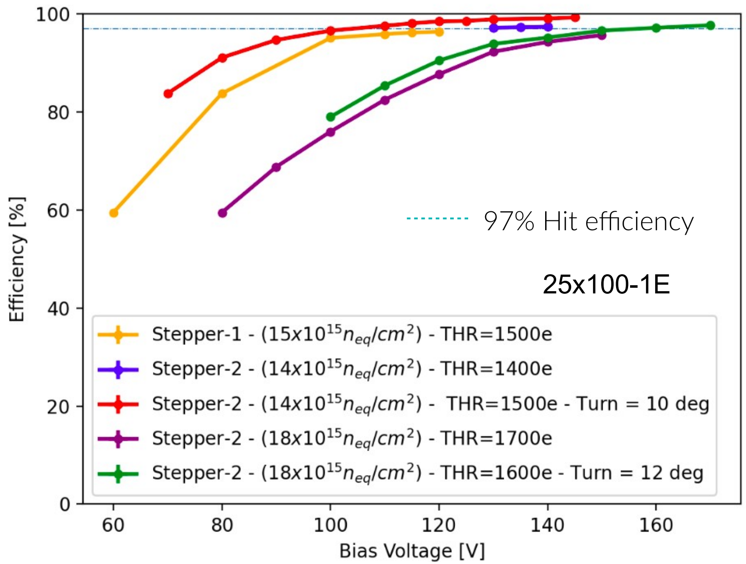
Efficiency of irradiated modules at beam test

- RD53A assemblies with different 3D sensor geometries
- At 10^{16} n_{eq}/cm^2 a hit efficiency of 96% at normal beam incidence reached below 100 V
- Larger voltages (~150 V) required at 1.8×10^{16} n_{eq}/cm^2

S. Terzo et al., Frontiers in Physics 9:624668



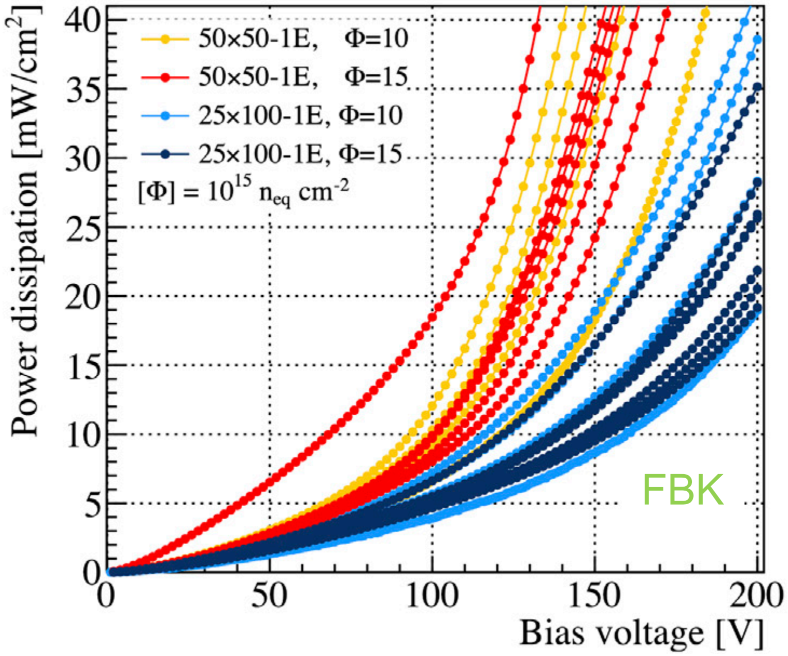
G. Bardelli et al., IWORID 2022

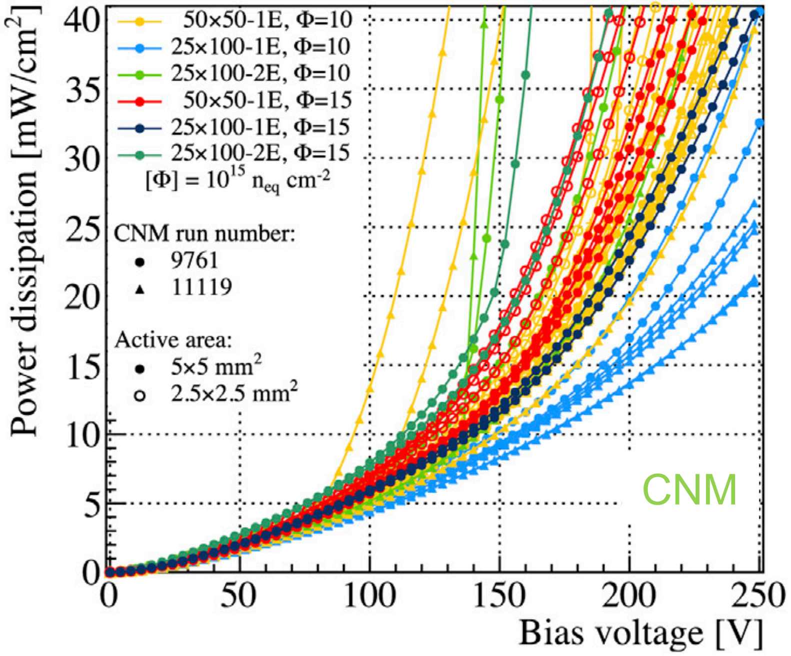


Power dissipation

- At the voltages of interest for a high hit efficiency, the power dissipation is still low

S. Terzo et al., Frontiers in Physics 9:624668

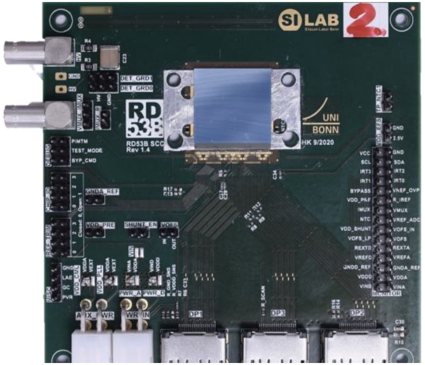




Pre-production phase for ATLAS ITk

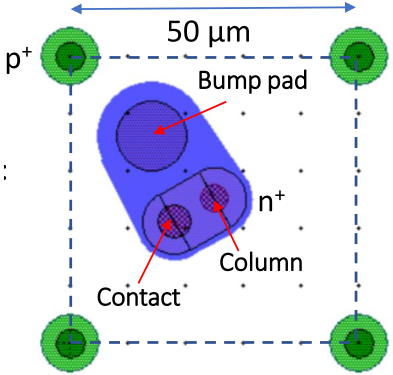
- Layer 0 of ATLAS ITk will use 3D sensors:
- Barrel (25 x 100 μm^2 - 1E)
  - CNM, 4-inch wafers (~500 sensors)
- Endcap (50 x 50 μm^2):
  - FBK and SINTEF, 6-inch wafers (800 sensors each)
- FBK delivered pre-production in 2021
- CMS also opted for using 3D sensors in the innermost layer, and is finalizing the R&D

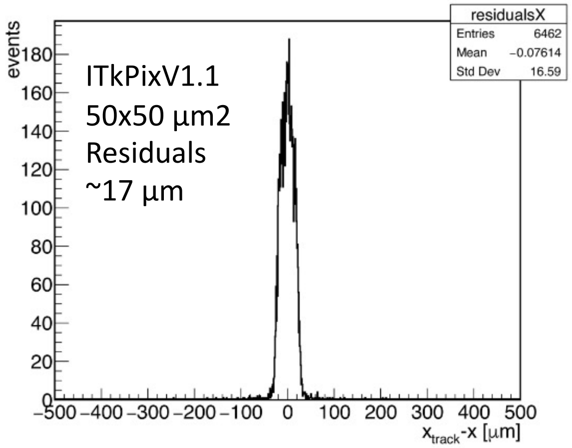
First beam test results of ITkPixV1 modules

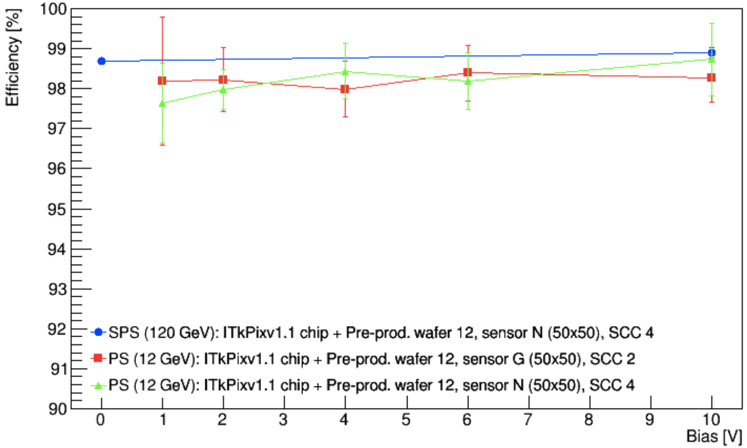


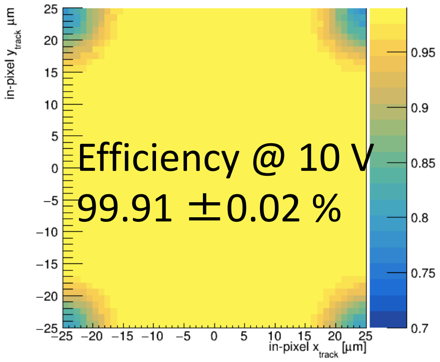
A. Lapertosa et al., IWORID 2022

- Sensors from FBK pre-production
- Bump bonded to ROC at IZM
- Assembled on Bonn single chip cards at INFN Genova
- Tested at CERN PS/SPS in spring 2022

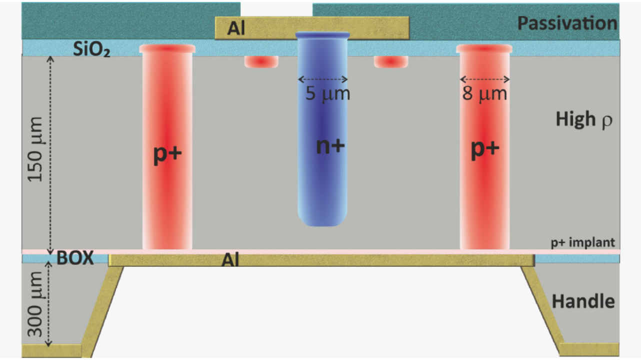


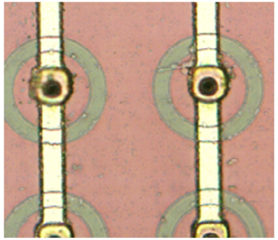






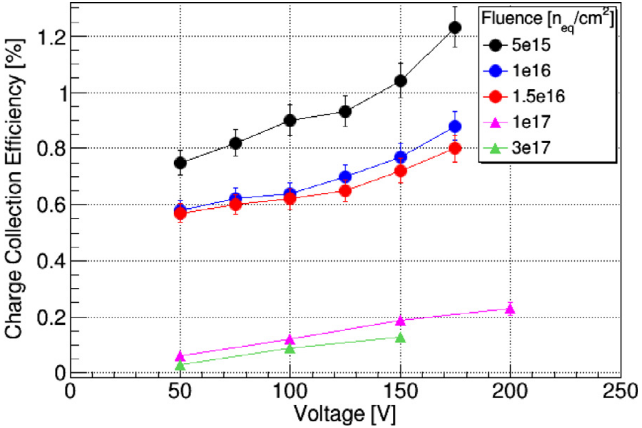
Looking at post-LHC applications

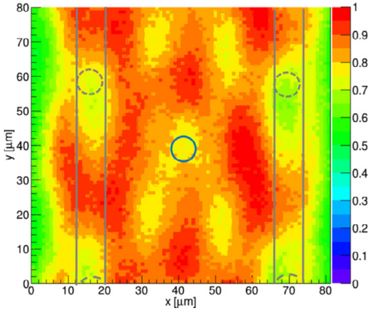


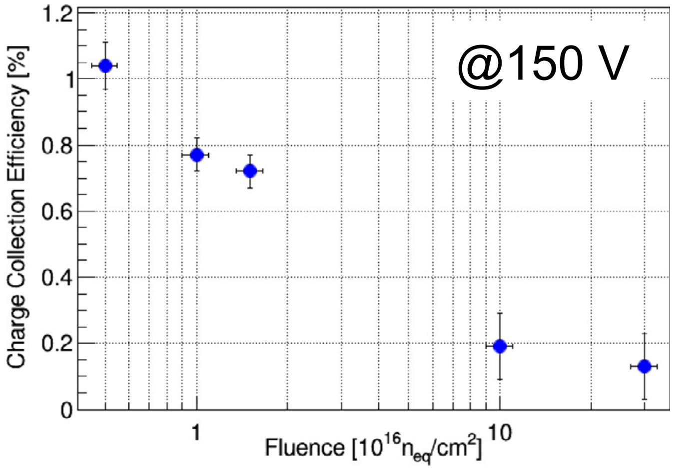


- CNM 3D diode and strip detectors
- 50x50 μm^2 cells
- Neutron irradiation up to $3x10^{17}$ n_{eq}/cm^2
- IR laser TCT tests

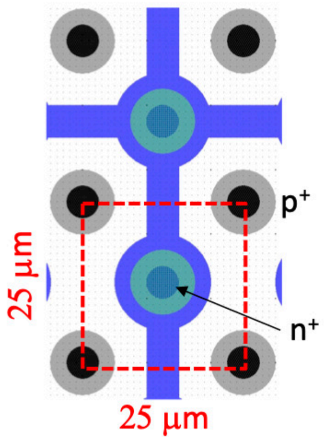
M. Manna et al., NIMA 979(2020) 164458

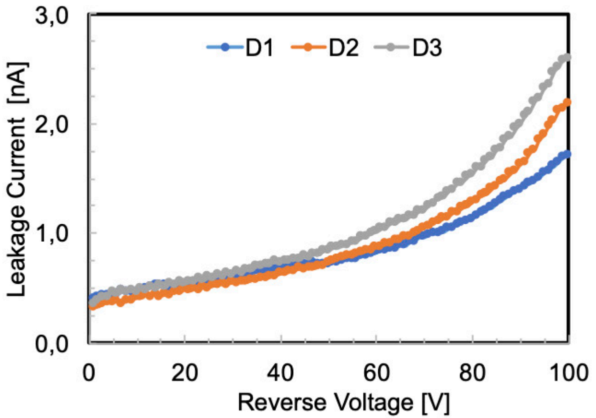


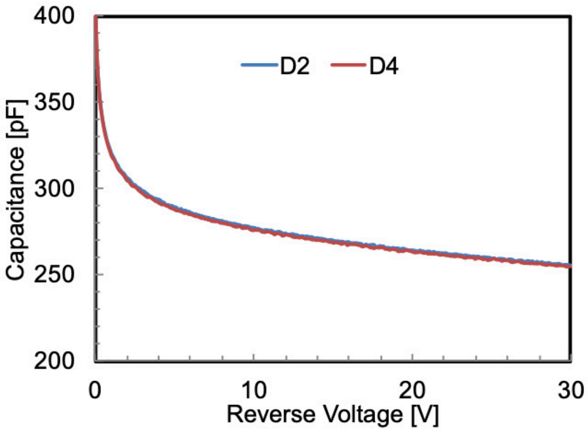




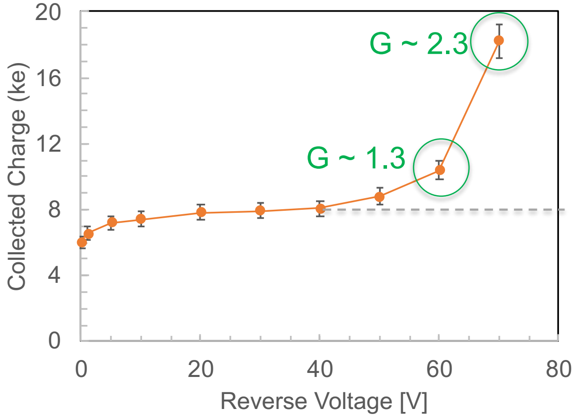
Very small-pitch 3D sensors





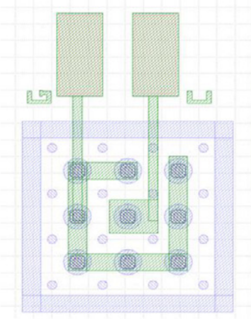


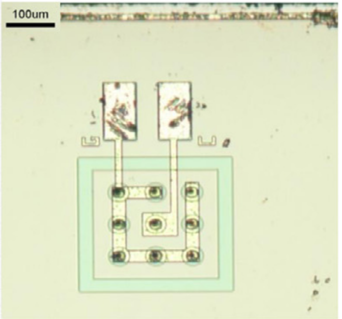
- Feasibility proved on 3D diodes with standard process
- Good electrical characteristics
- Beta source test at UNM (room temperature)
- Moderate gain is observed above 40 V, up to ~2.3 at 70 V
- Requires dedicated effort for technology optimization



G.-F. Dalla Betta et al., IEEE NSS 2019 N30-02

3D pixels for timing





- 3D sensors are also expected to be fast …

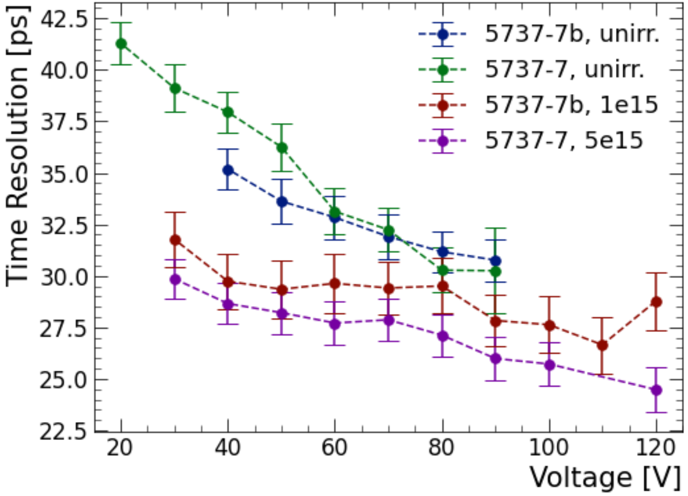
  S. Parker et al., IEEE TNS 58 (2011) 404

- Increasing interest in the past few years
- CNM 50x50 μm^2 single cells DS-3D (230 and 285 μm thick) tested by several groups

  G. Kramberger et al., NIMA 934(2019) 26
  C. Betancourt et al., MDPI Instruments 6 (2022)
  P. Fernandez Martinez et al. Pisa Meeting 2022

- Beta source setups, LGADs as reference
- Best result ~25 ps timing resolution

L.-Diehl. et al., Pisa Meeting 2022

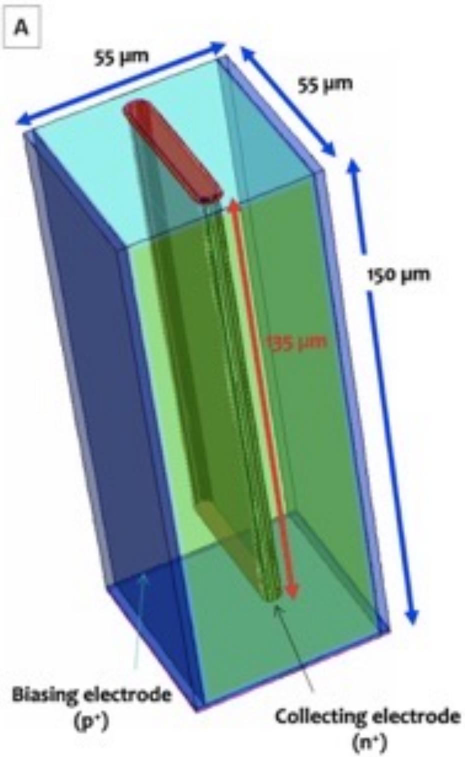


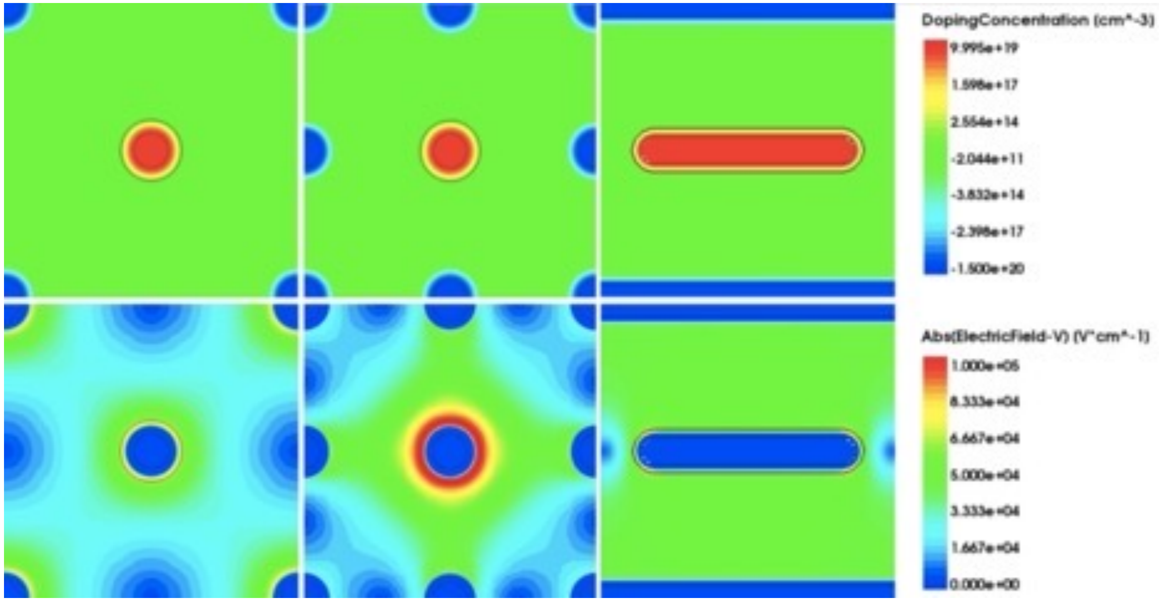
TimeSPOT

3D-trenched pixel sensors

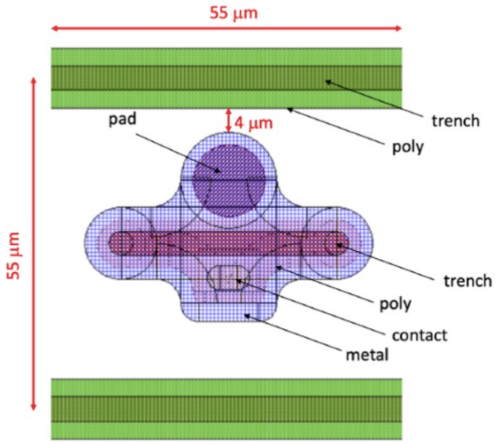
- Layouts with columnar electrodes have non uniform electric and weighting field distributions → go for trenches

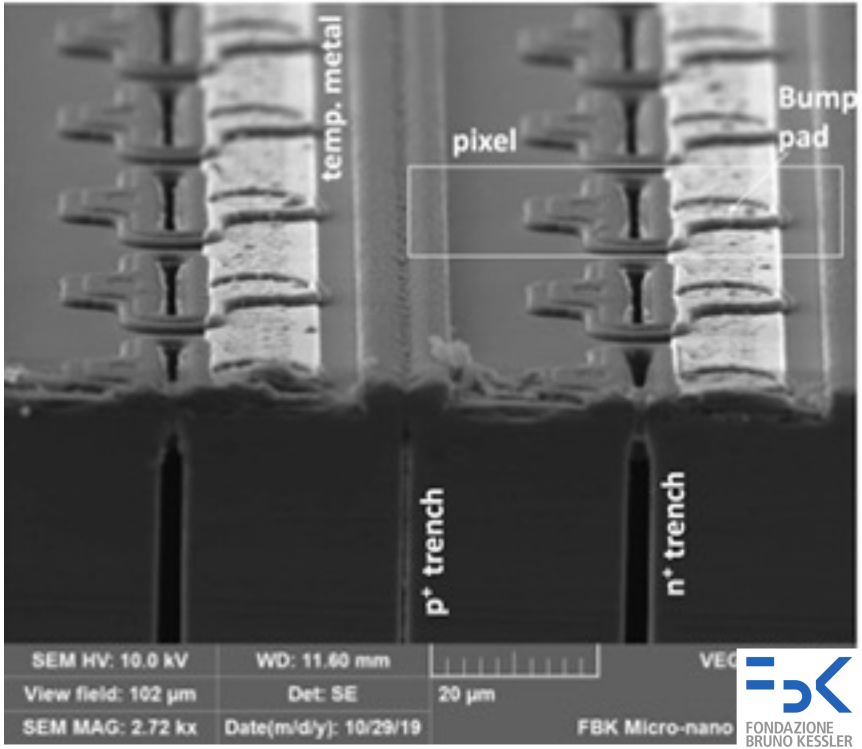
L. Anderlini et al., JINST 17 (2020)

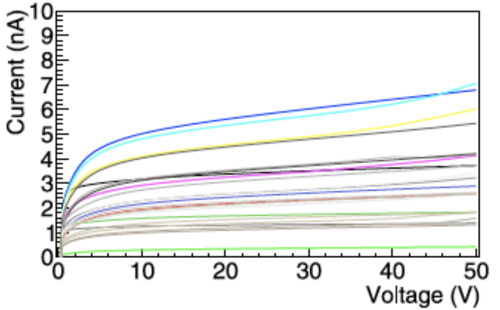


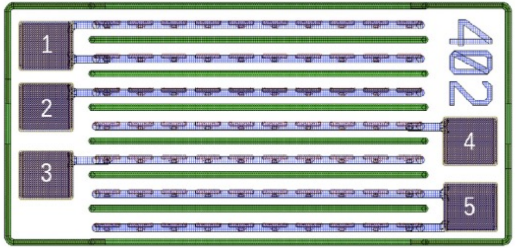


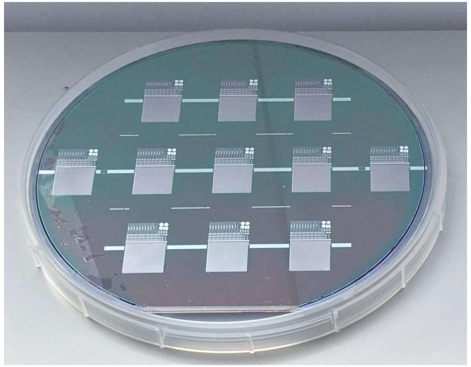
TIMESPOT: first batch

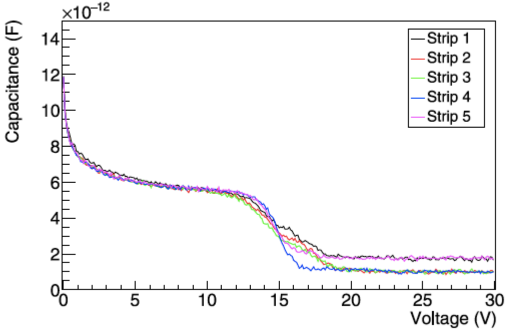










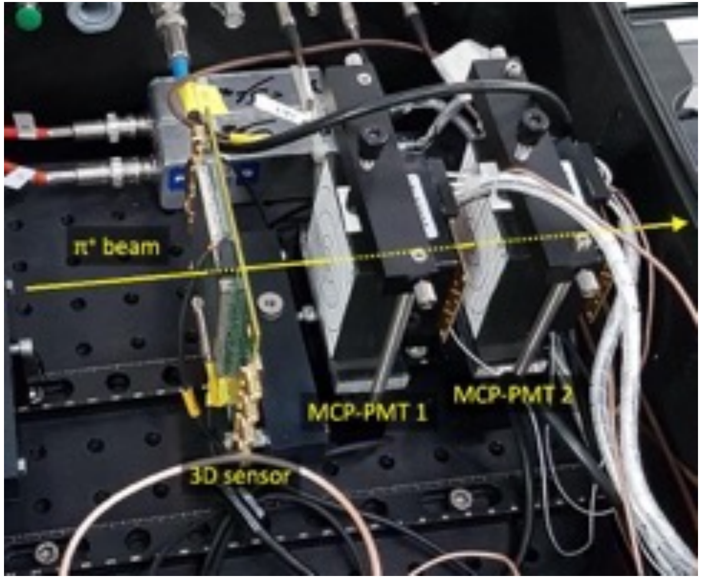


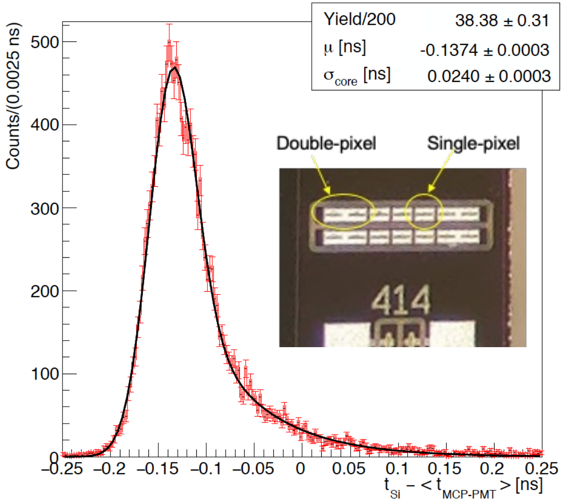
G. Forcolin et al., NIMA 981 (2020) 164437

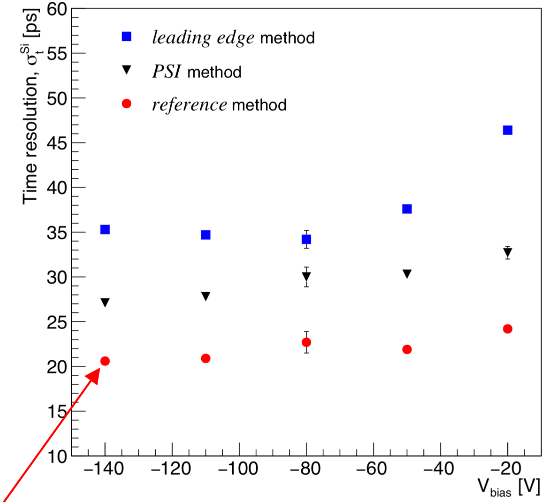
Beam test @ PSI (10/2019)

Time resolution of 3D-trench silicon pixels with MIPs (test-beam & lab) at room temperature

(*Intrinsic time resolution of 3D-trench silicon pixels for charged particle detection*, 2020 JINST 15 P09029)





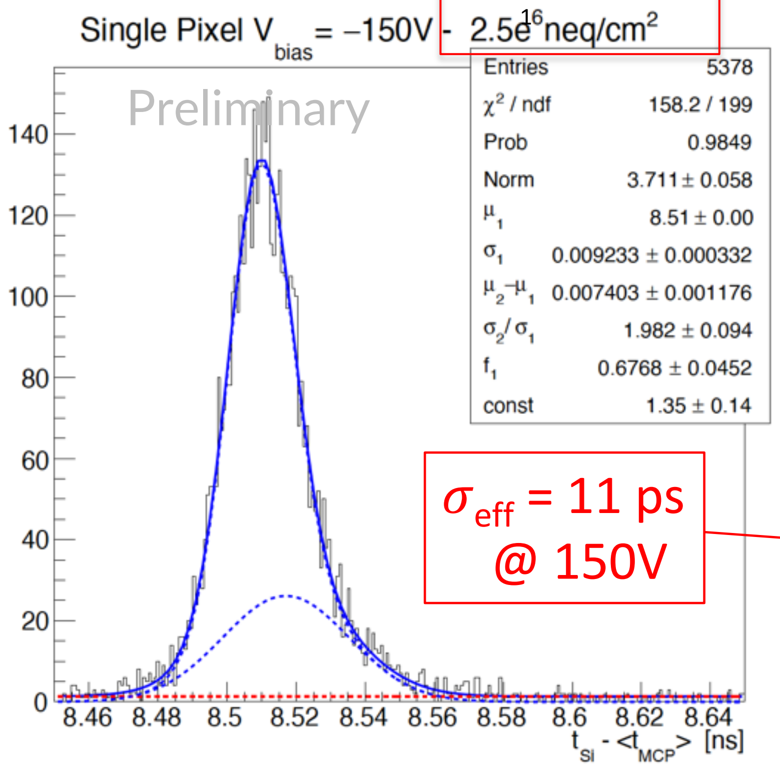


PSI πM1, π^+ beam, 270 MeV/c

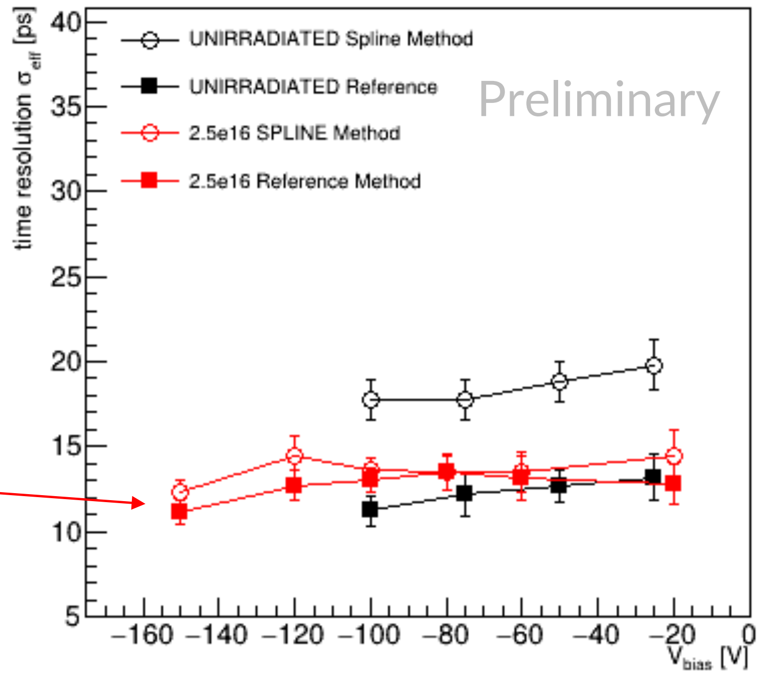
$\sigma_t \approx 20$ ps

(after correction for MCP contribution) confirmed in corresponding laboratory measurements (with ^{90}Sr source)

Beam test @ CERN SPS (10/2021)



σ_{eff} = 11 ps @ 150V



π^+ beam, 180 GeV/c

A. Lampis et al., IWORID 2022

Conclusions

- 3D pixel sensors have gone through an impressive progress in the past few years, aimed at the ATLAS and CMS tracker upgrades at HL-LHC

- Small-pitch 3D pixel modules with RD53A ROC have demonstrated to be radiation hard up to a fluence of ~2×10^{16} n_{eq}/cm^2

- High signal efficiency was proved to much larger fluences on test structures of similar geometries

- 3D sensors also appealing for tracking + timing, ~25 ps timing resolution demonstrated on single cell test structure

- 3D-Trenched Electrode pixel sensors are also being developed, showing excellent timing performance (~10 ps) on test structures, now to be tested on the first pixel assemblies (32x32) with TIMESPOT1 ROC