Extremely radiation-hard technologies: 3D silicon sensors

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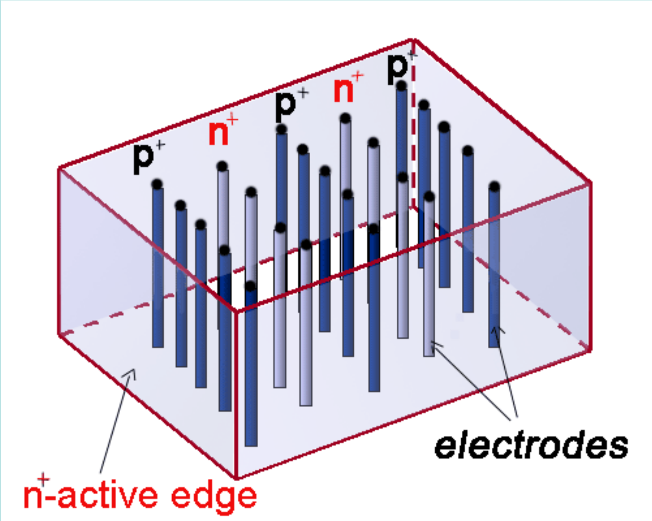
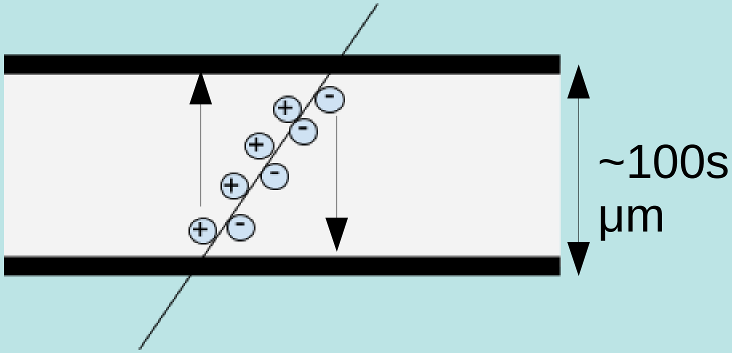
Outline

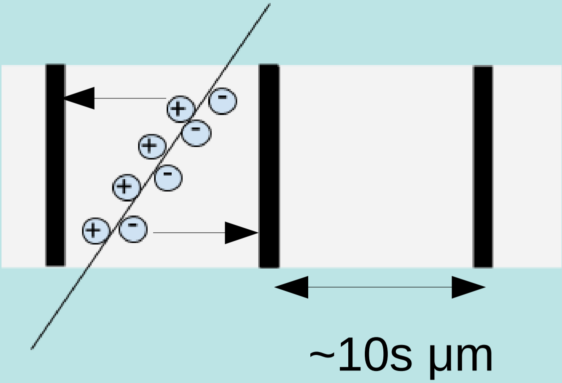
- Introduction to 3D sensors
- Fabrication process
- Small pitch 3D sensors
  - Design and results
- 3D trench sensors
  - Design and simulation
- Outlook

3D Sensors



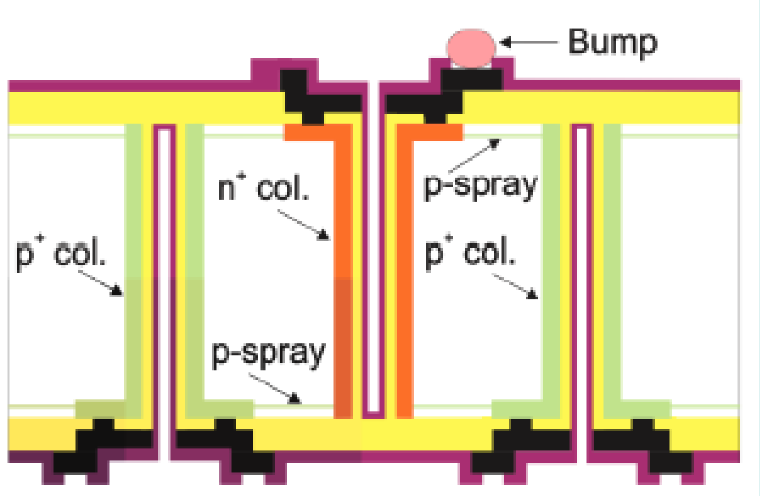
- Advantages:
  - Low Depletion Voltage
  - Lateral Drift
    - Fast Response
    - Low Sensitivity to mag. fields
  - Short inter-electrode distance
    - Fast Response
    - Reduced trapping probability => more rad hard
- Disadvantages
  - Non-Uniform Electric Field
  - High Capacitance
  - Complicated + expensive manufacturing process



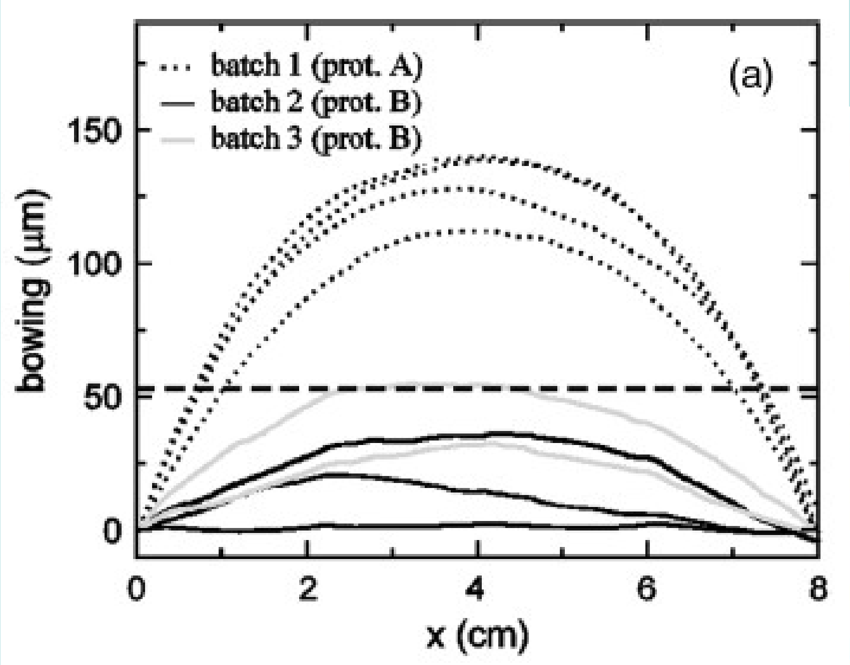


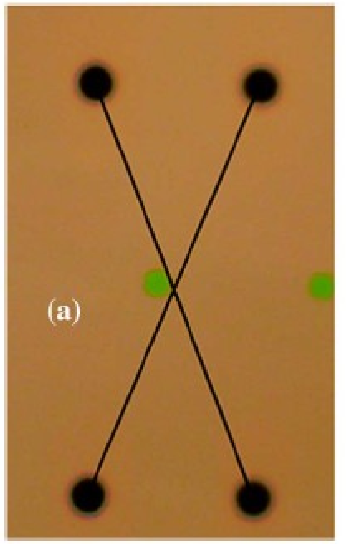
ATLAS IBL Sensors

- Used double sided 3D sensors
- Advantages:
  - Reduced process complexity
  - Backside accessible for bias
  - Allows slim edge
- Downsides:
  - Active edge not possible
  - Mechanically more fragile
  - Wafer bowing



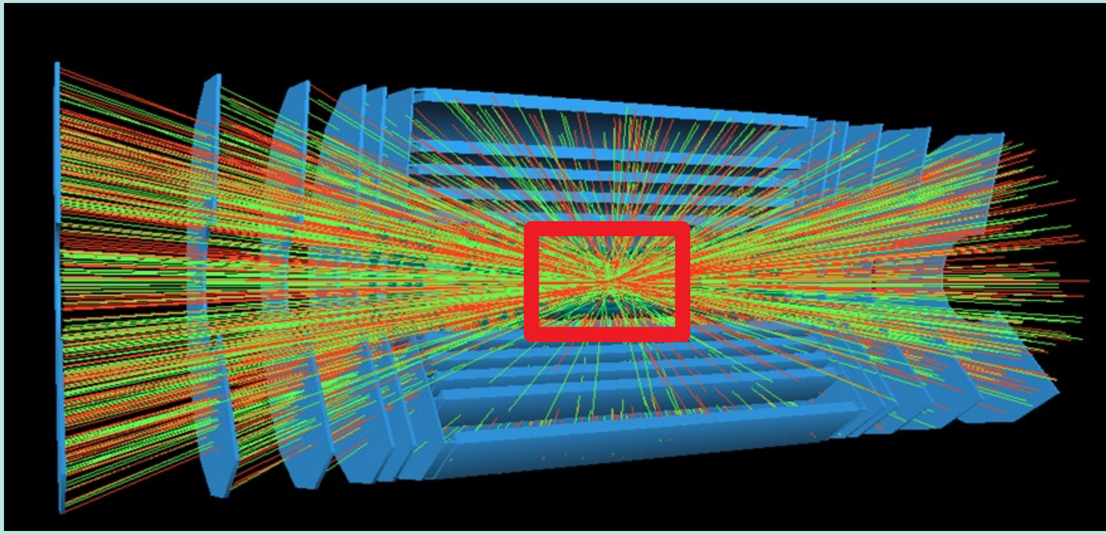
ATLAS IBL, JINST 7 (2012) P11010





G. Giacomini, et al., IEEE TNS 60(3) (2013) 2357

3D sensors at HL-LHC

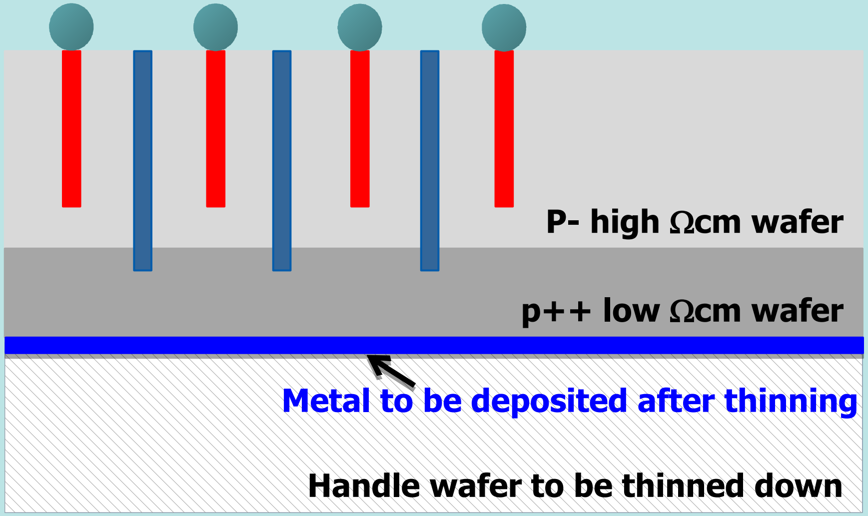


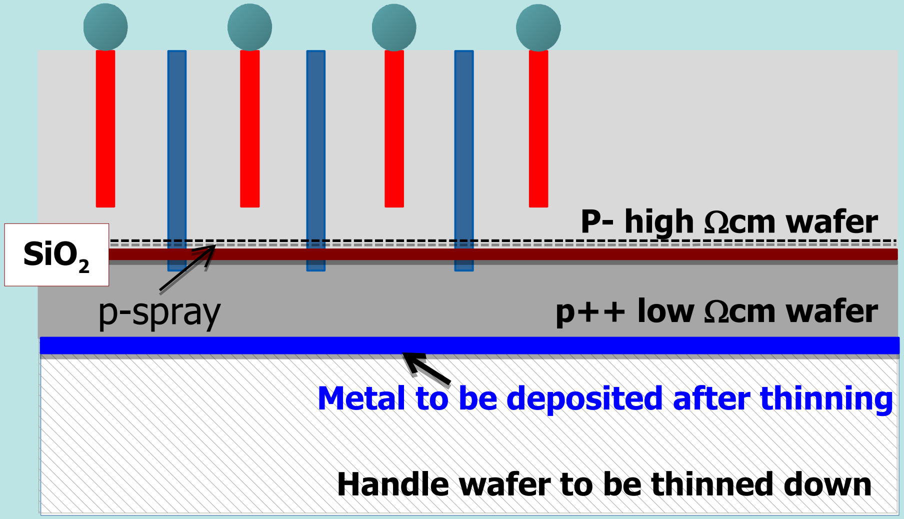
- Requirements:
  - higher hit-rate
  - increased granularity
  - higher radiation tolerance
  - lighter detectors
- To meet Requirements:
  - Produce thinner sensors (~100μm)
  - Reduce electrode spacing (~30μm)
  - Narrower electrodes (5μm)
  - Small/Active edges (<100μm)

=> need to change fabrication method

Single sided production method

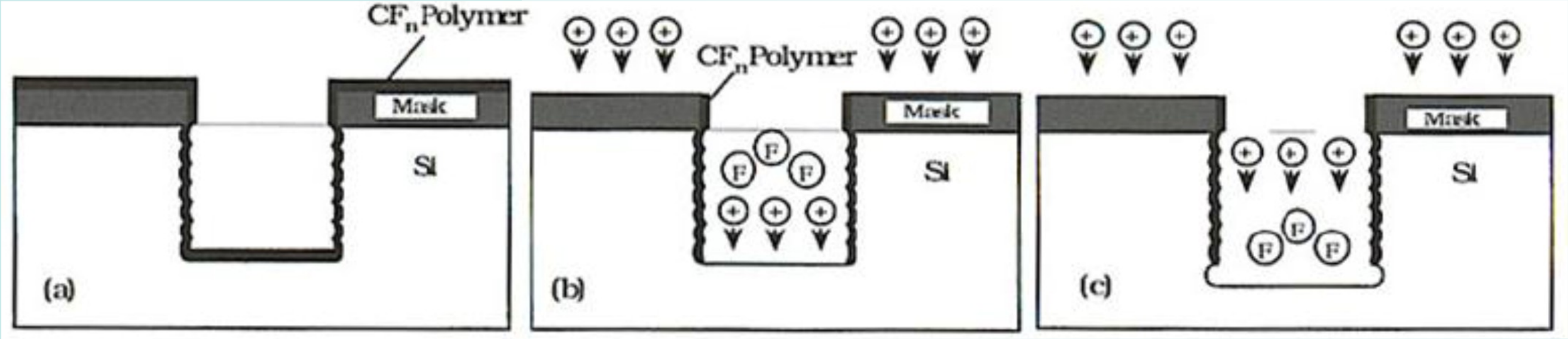
- Use single sided process with support wafer
  - Can reduce active thickness without compromising mechanical properties
  - Active edges
  - Post processing required to thin support layer and deposit metal
  - Front side layout => processing can be complicated

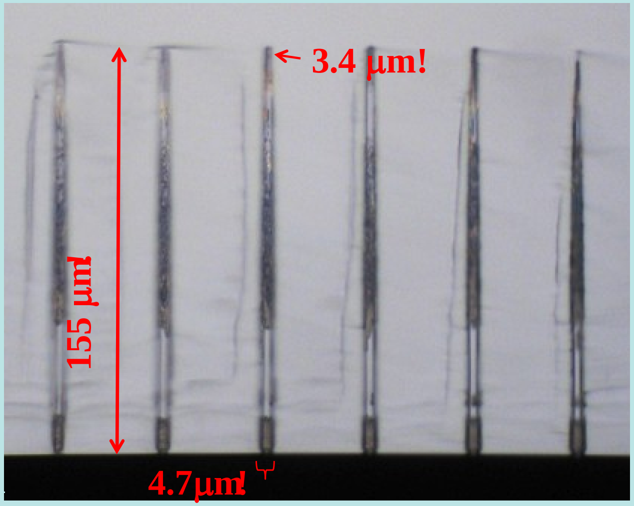


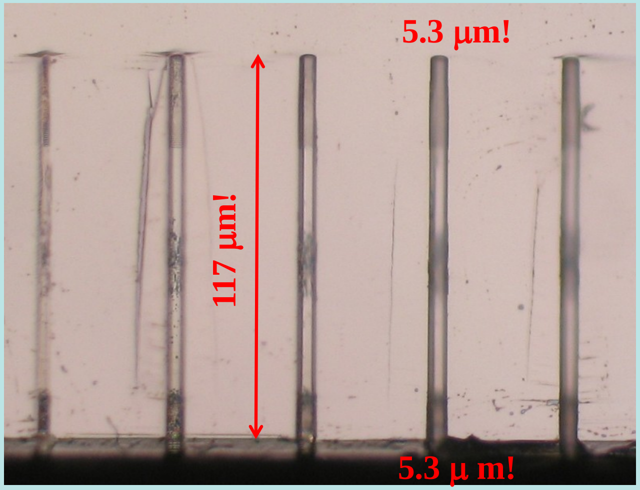


Fabrication Process

- Columns produced using Deep Reactive Ion Etching (DRIE) by the Bosch process
- Alternating etch cycles (SF_6) and passivation cycles (C_4F_8)
- Can achieve high aspect ration (~30:1 or better) and good uniformity



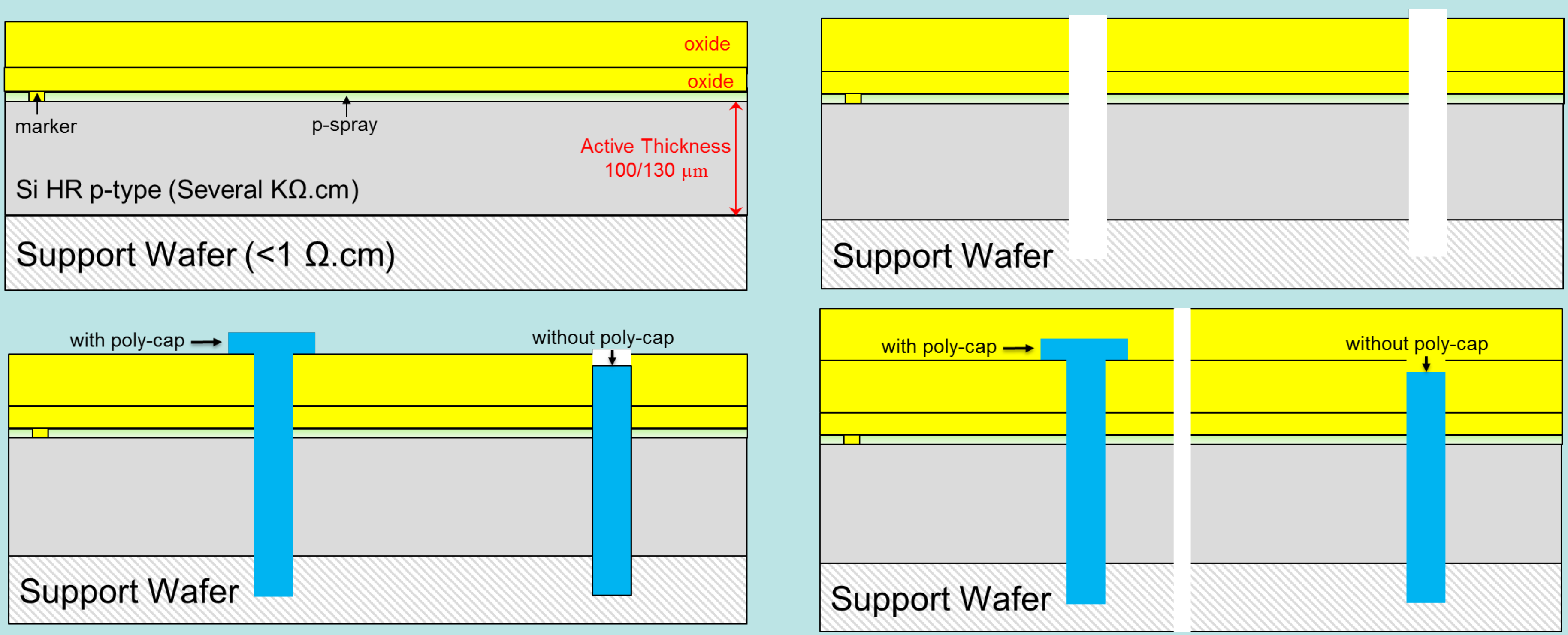




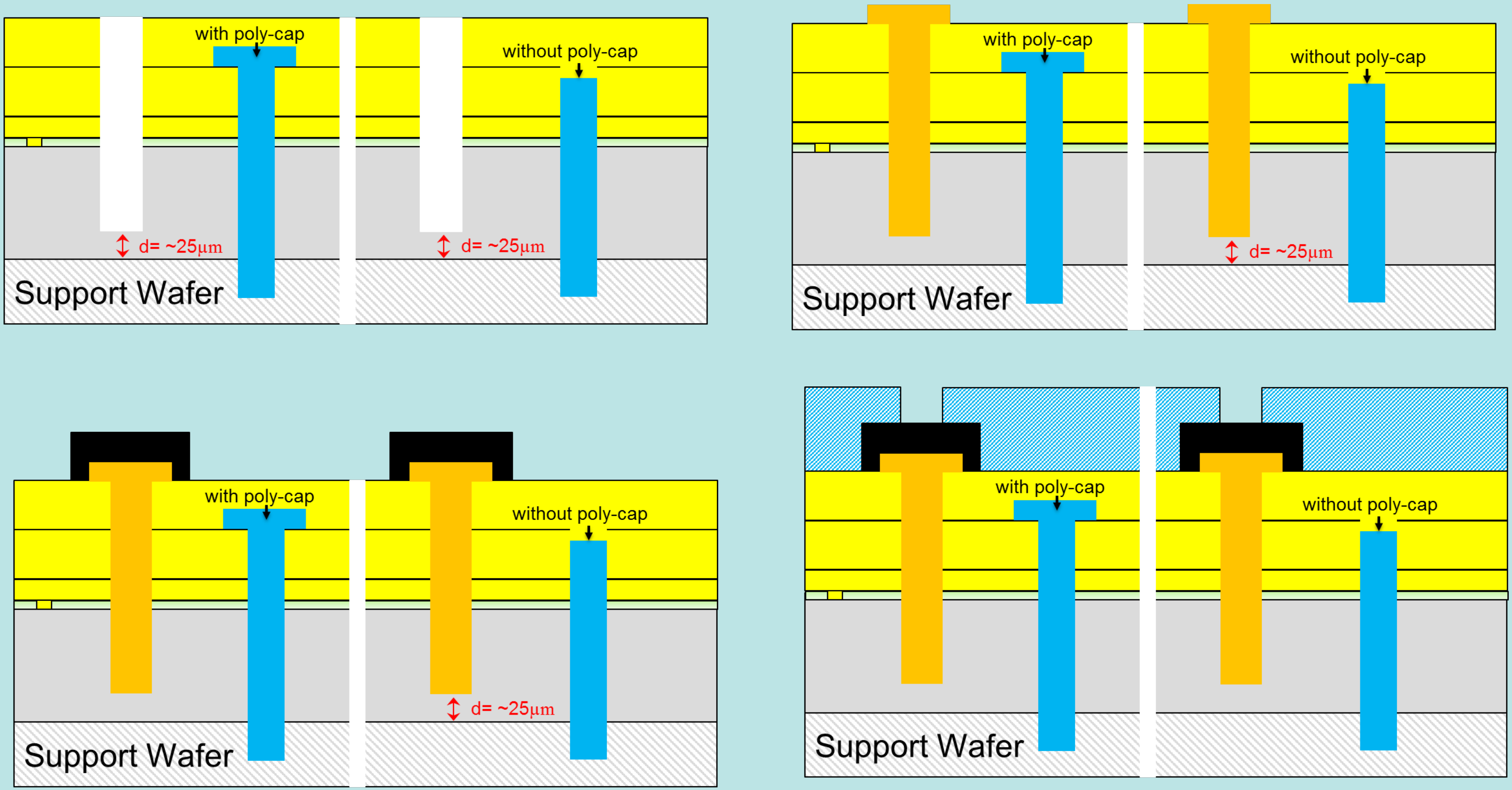
G.-F. Dalla Betta et al., NIMA 824 (2016) 386 and 388

FBK Fabrication Process

- Production steps:
  - Etch ohmic columns > active thickness
  - Fill with Poly-Si (at least partially)
  - Etch junction columns < active thickness

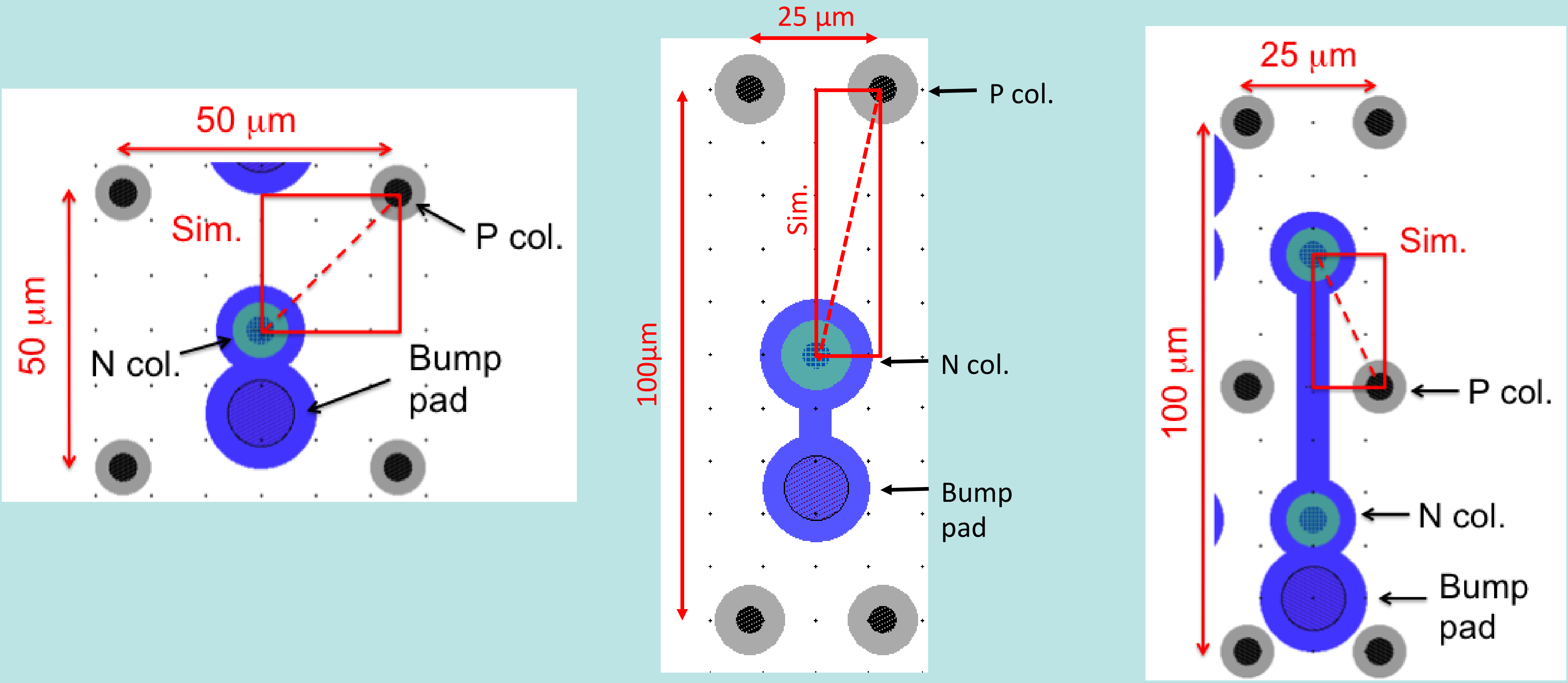


FBK Fabrication Process

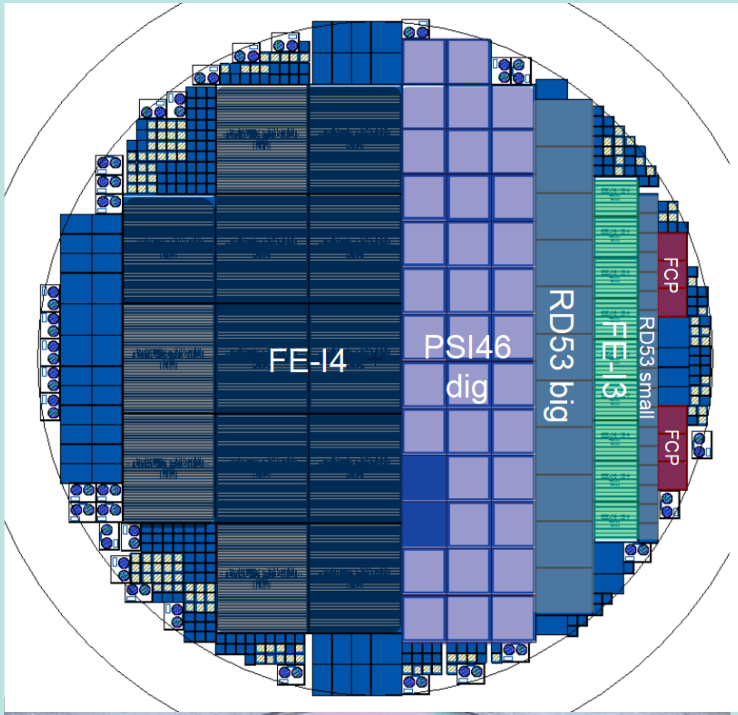


3D Sensors at FBK

- Small pitch 3D layouts being investigated
- 50x50μm^2, 25x100μm^2 1E, 25x100μm^2 2E
- 25x100μm^2 2E difficult to manufacure due to constraints on position of bump

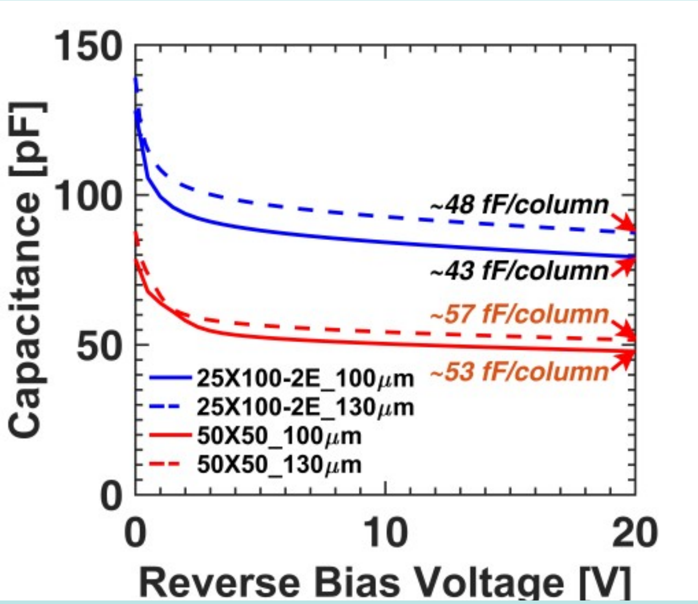


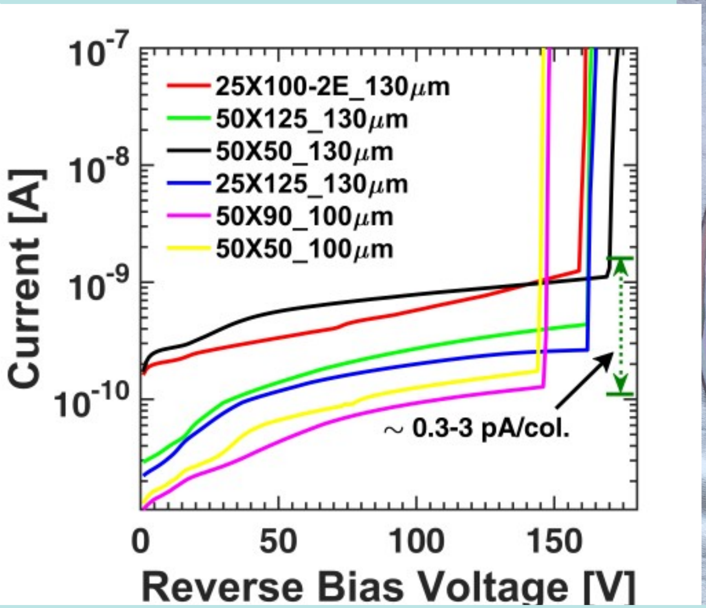
3D Sensors at FBK

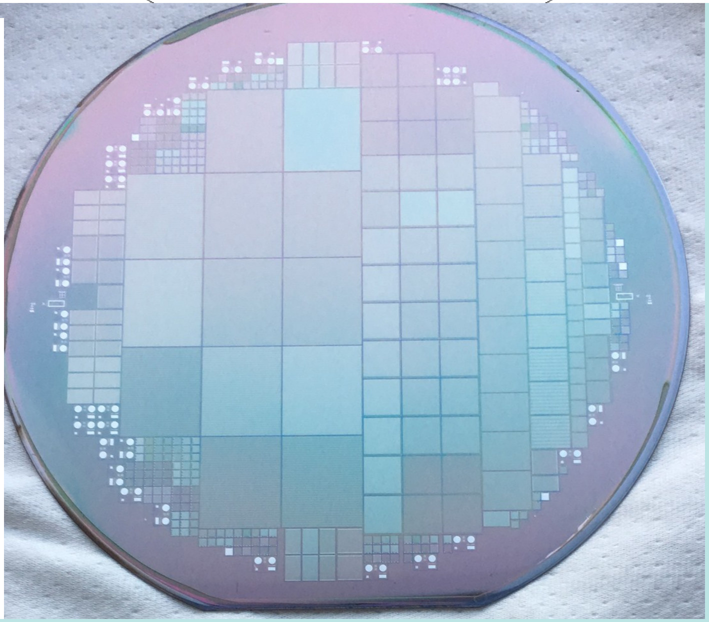


- First batch successully manufactured
- Good Electrical properties
- Measurements made pre and post irrad

DMS Sultan et al., JINST 12 (2017) C01022

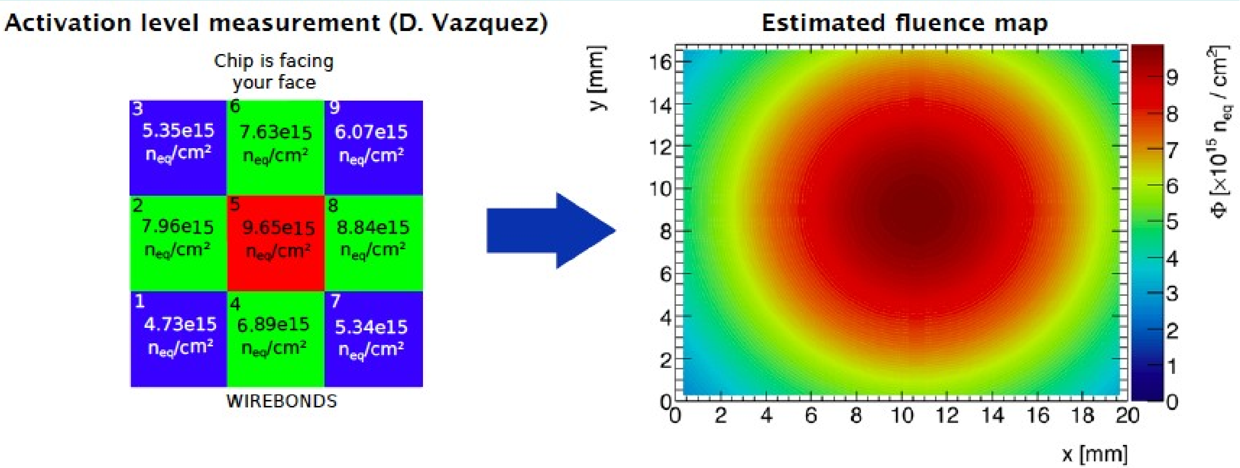




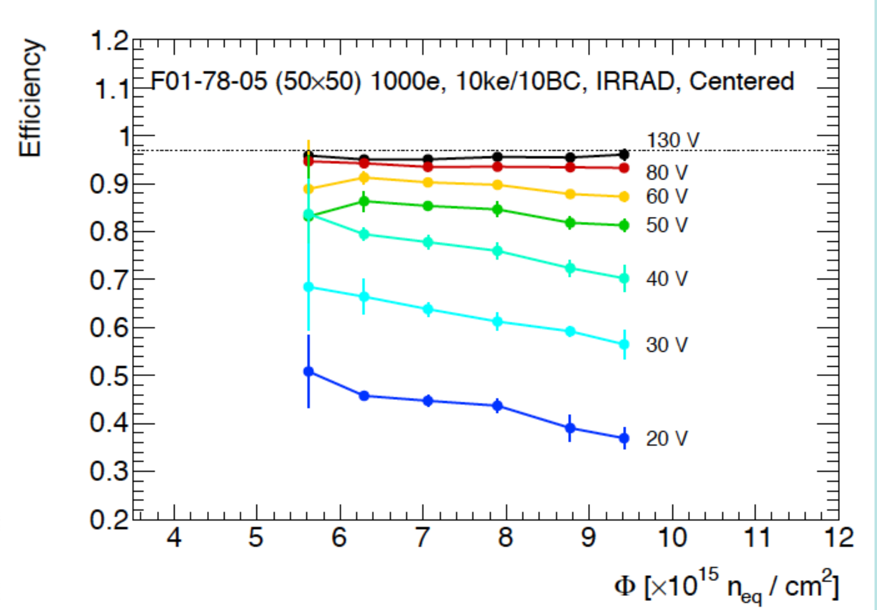


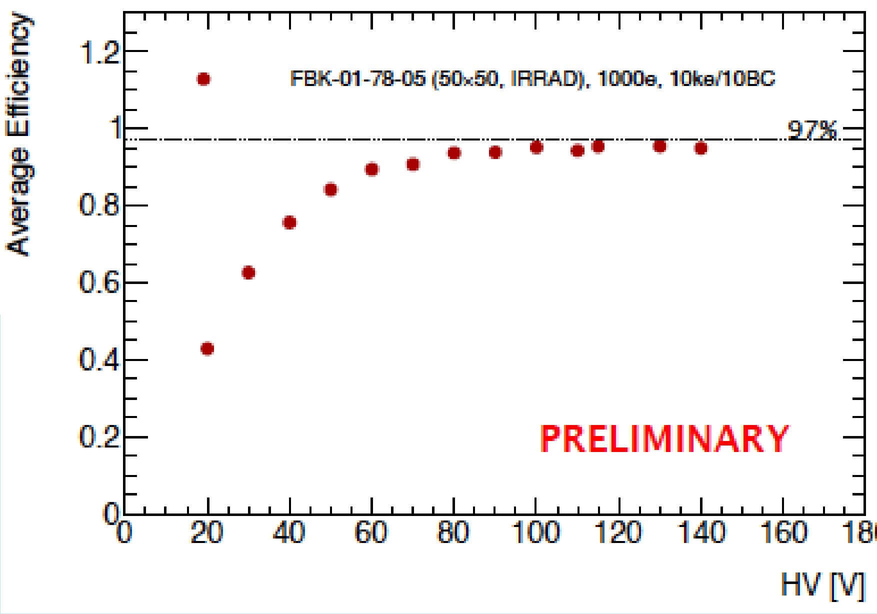
3D Sensors at FBK

- CERN Non uniform 24GeV proton irradiation, peak $9.6 \times 10^{15}\ n_{eq}/cm^2$
- Neutron Irradiation at JSI, Ljubljana



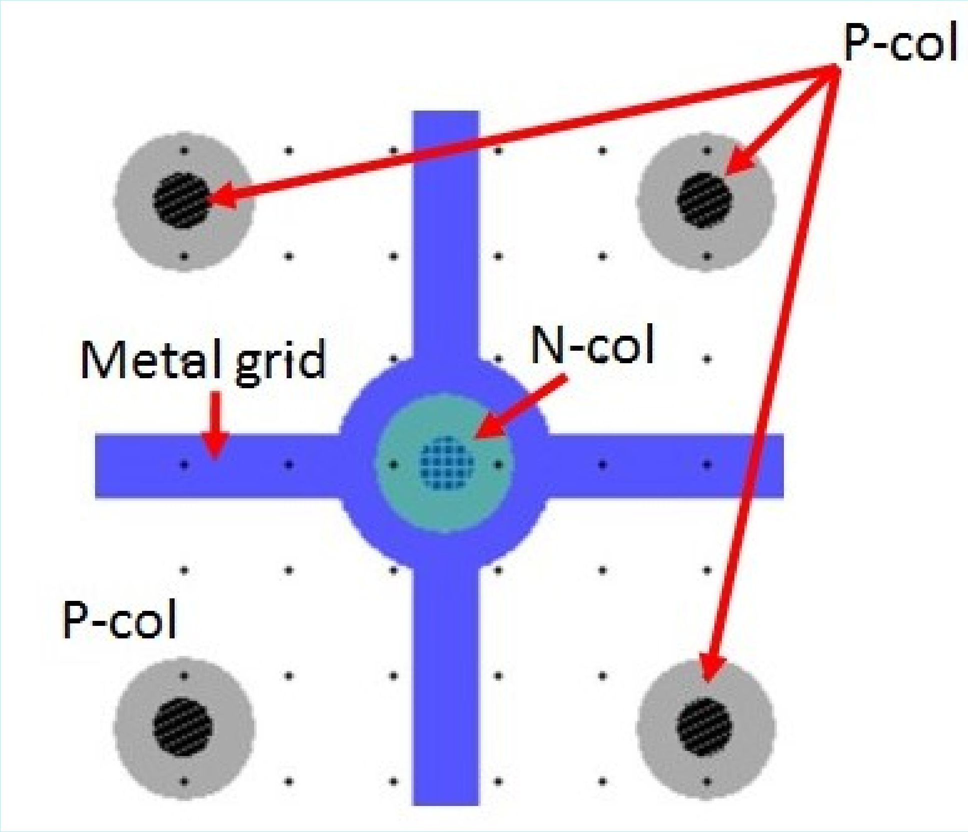
H. Oide et al., HSTD11, 2017





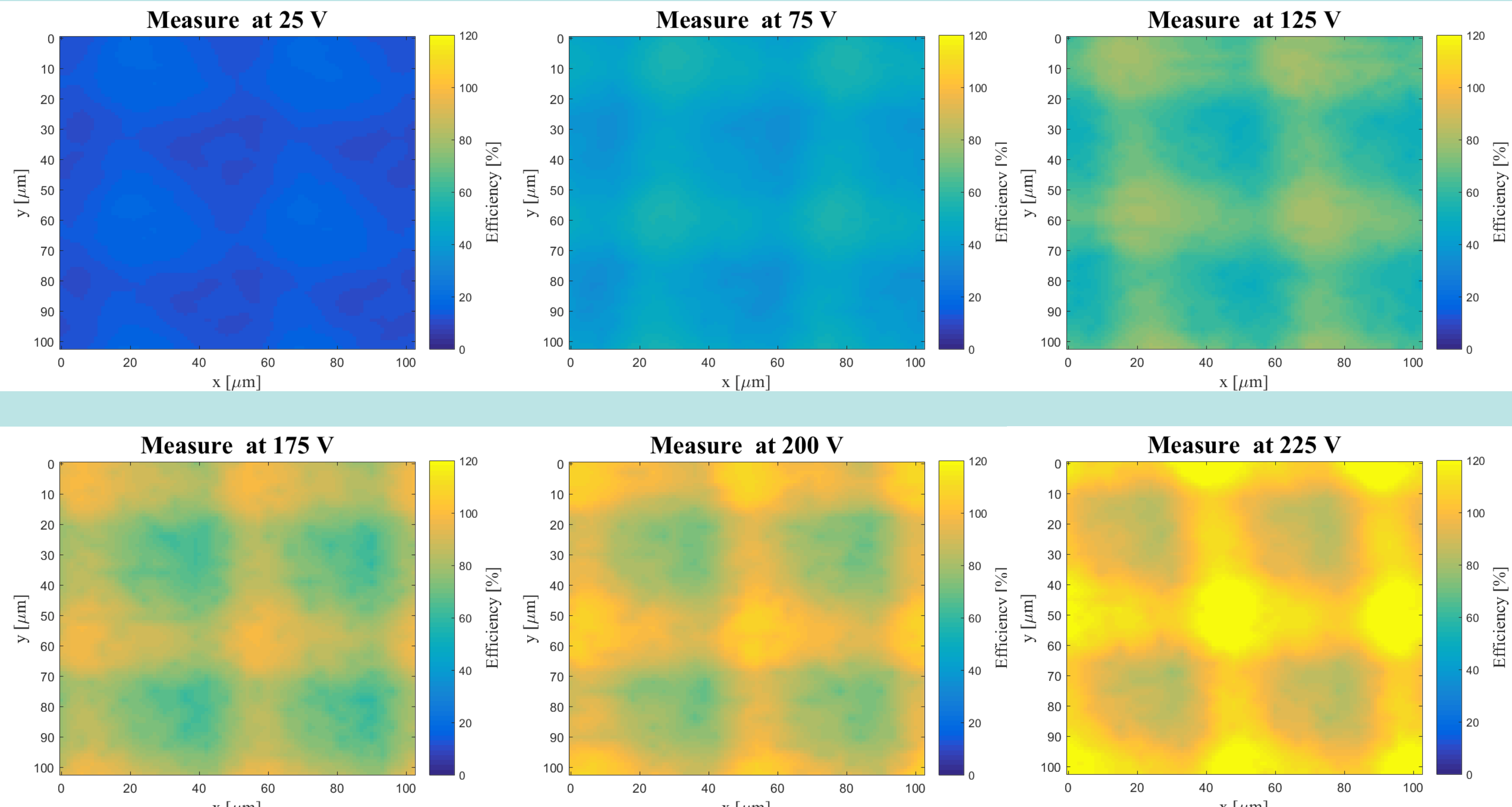
3D Sensors at FBK

- Measurements made using position resolved IR laser setup (λ=1064 nm, pulse width 40 ps (Alphalas))
- Measure relative signal efficiency vs pre-irradiation
- 80x80μm^2 region on interest



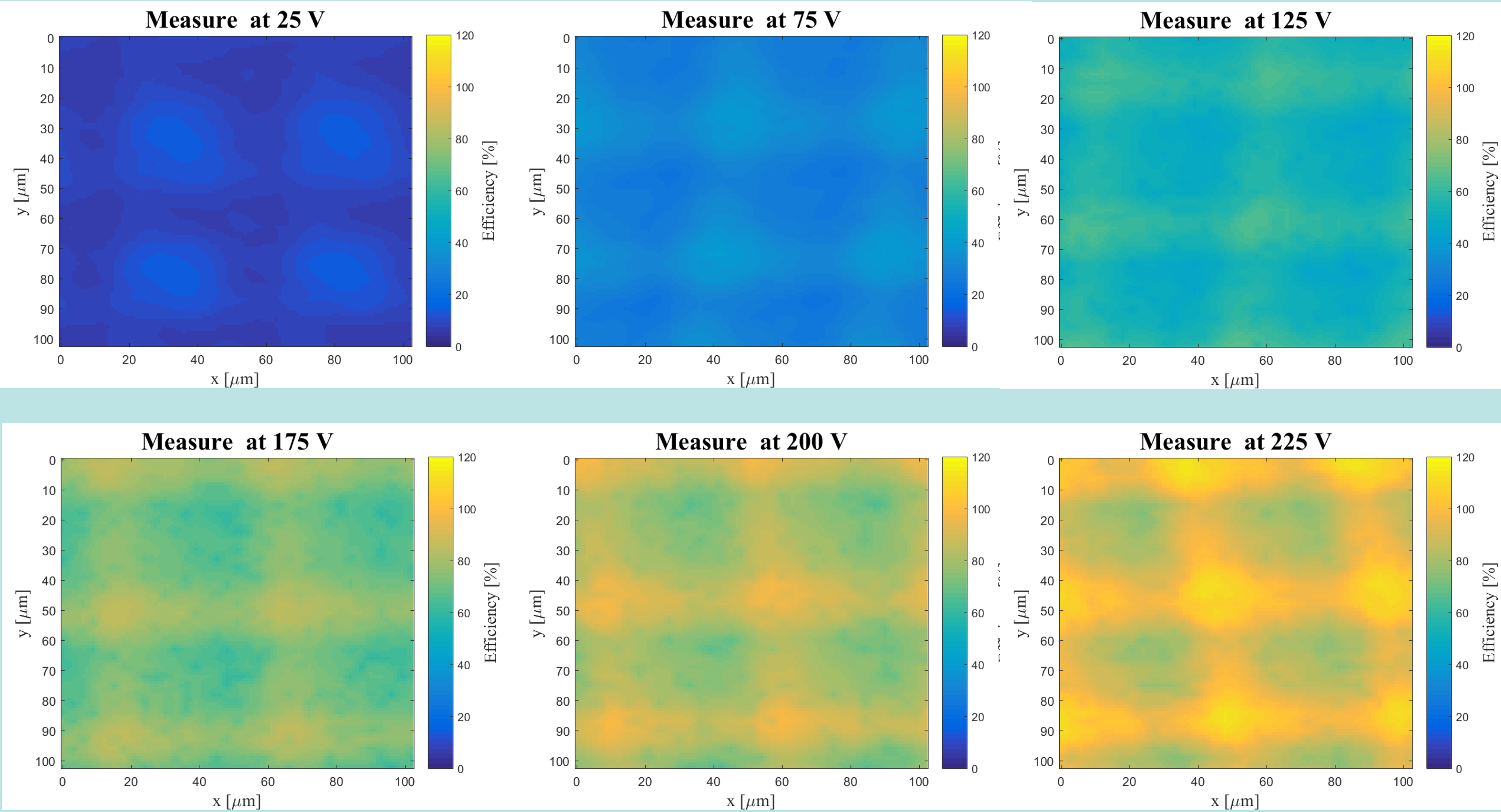
3D Sensors at FBK

- 50x50μm, $1x10^{16}$ n_{eq}/cm^2



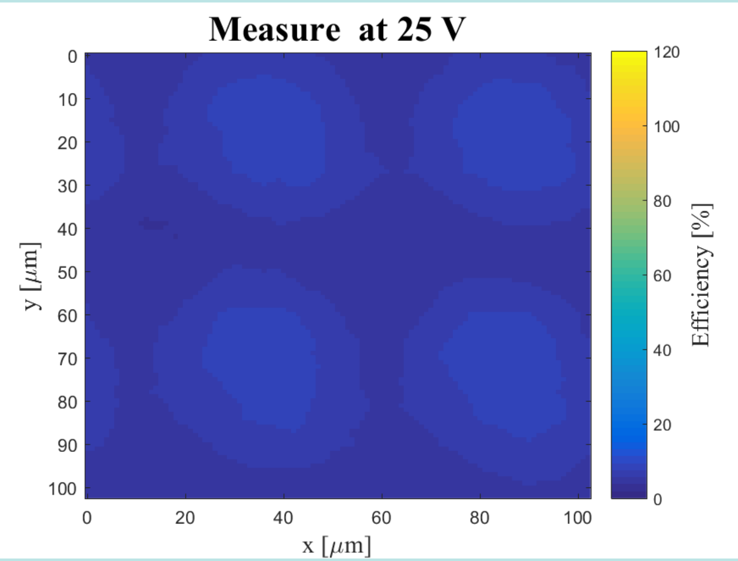
3D Sensors at FBK

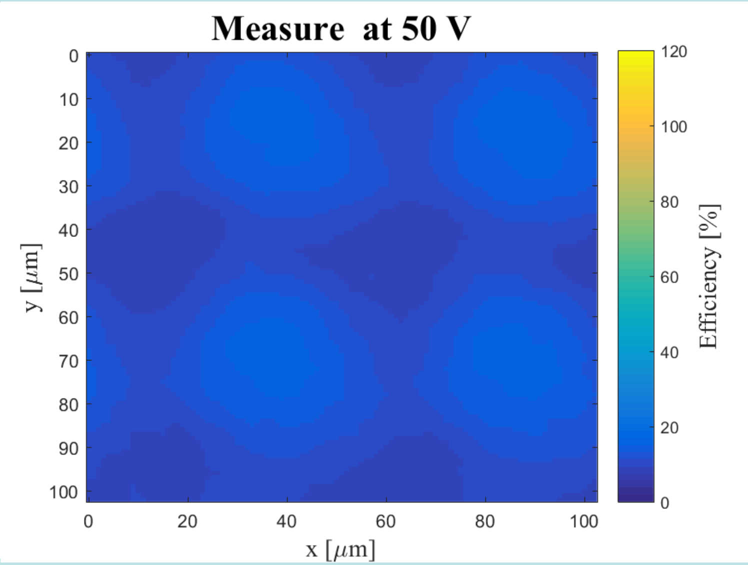
- 50x50µm, 2×10^{16} n_{eq}/cm^2

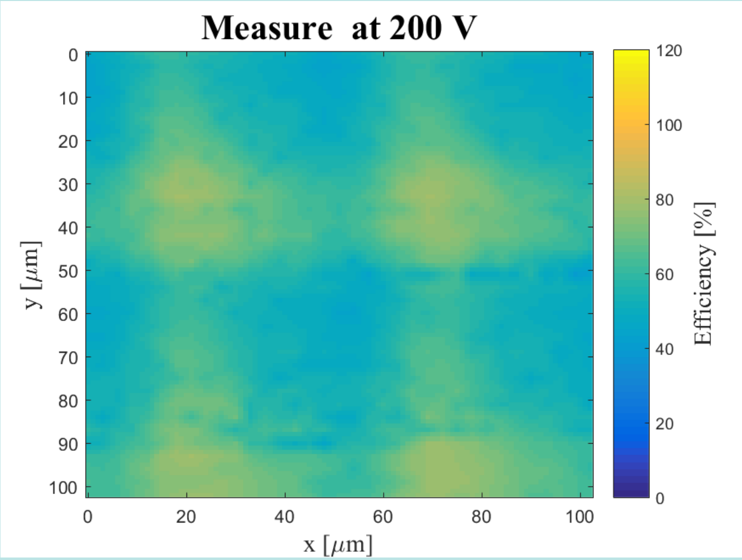


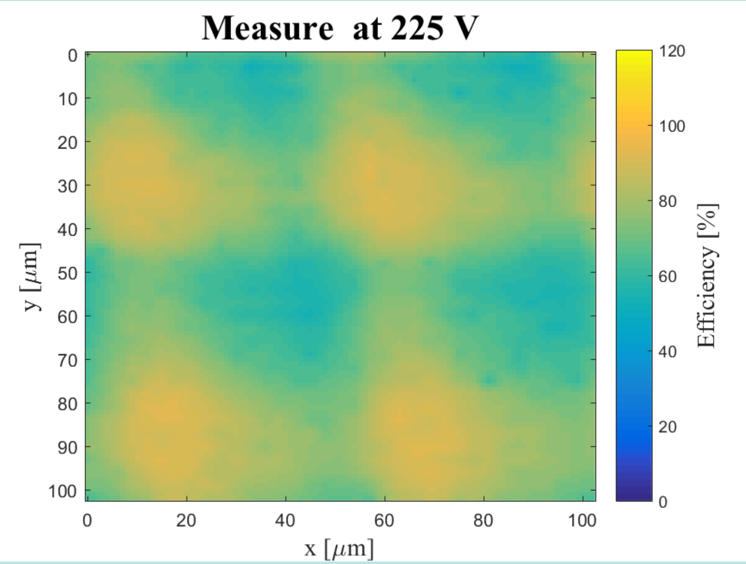
3D Sensors at FBK

- 50x50µm, 3.5x10^{16} n_{eq}/cm^2



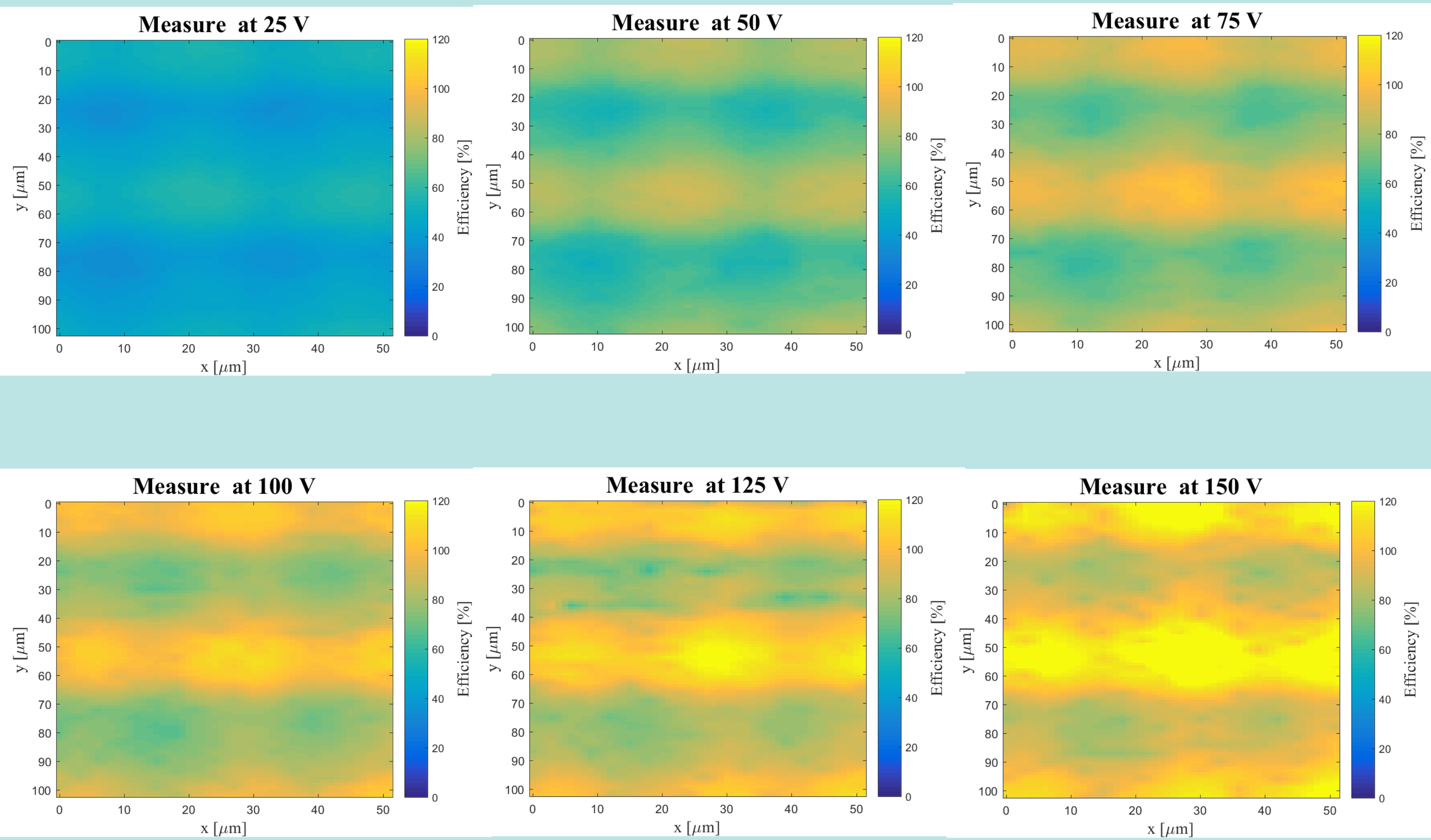






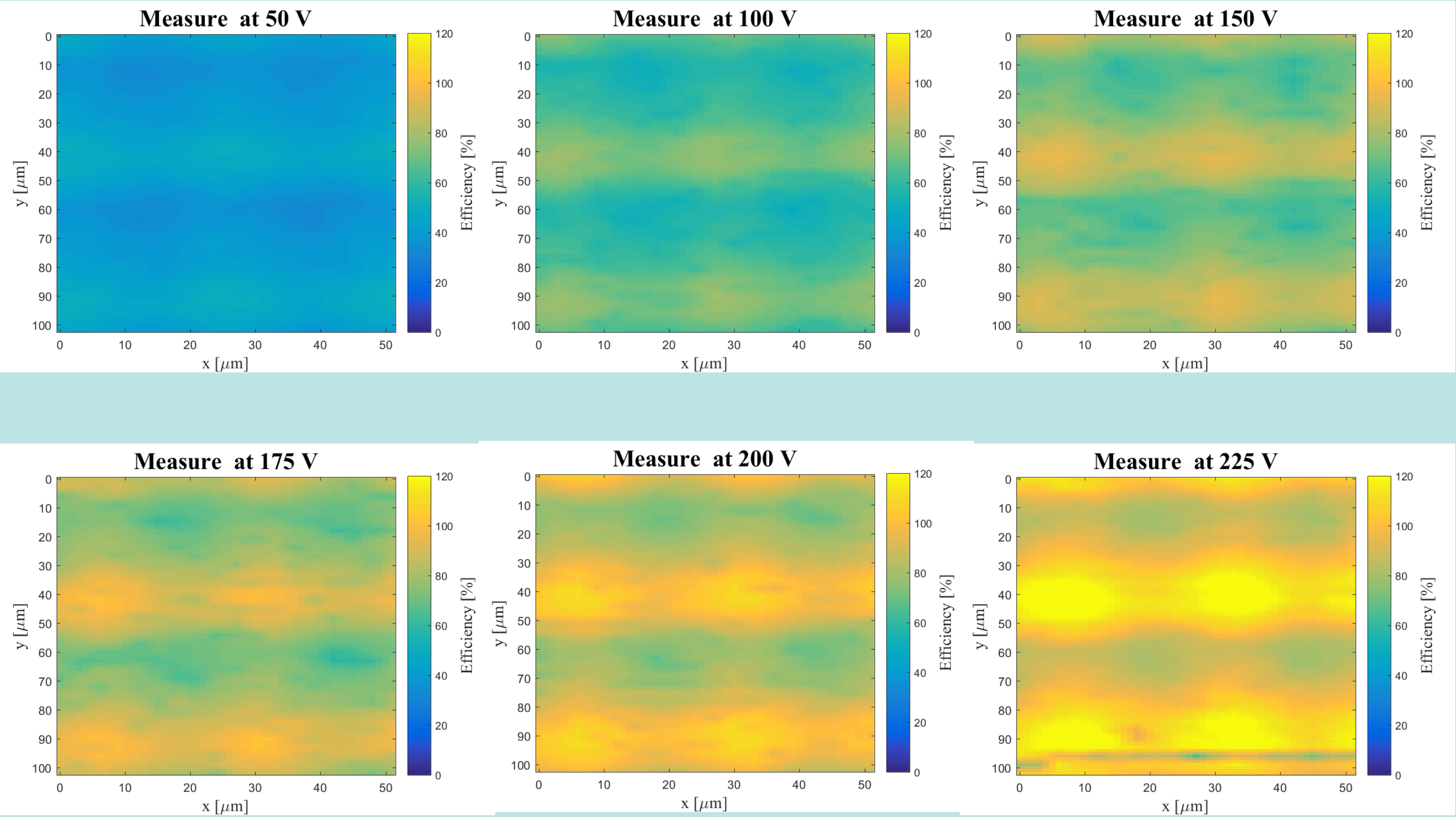
3D Sensors at FBK

- 25x100μm 2E, $1x10^{16}$ n_{eq}/cm^2



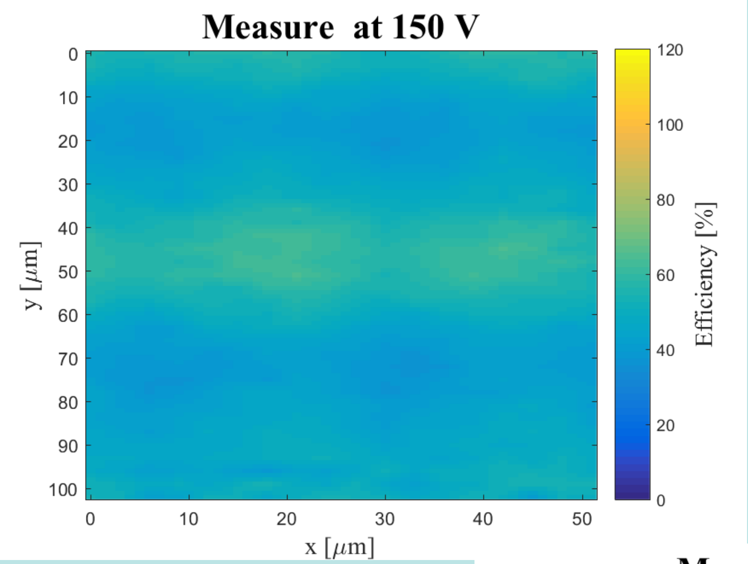
3D Sensors at FBK

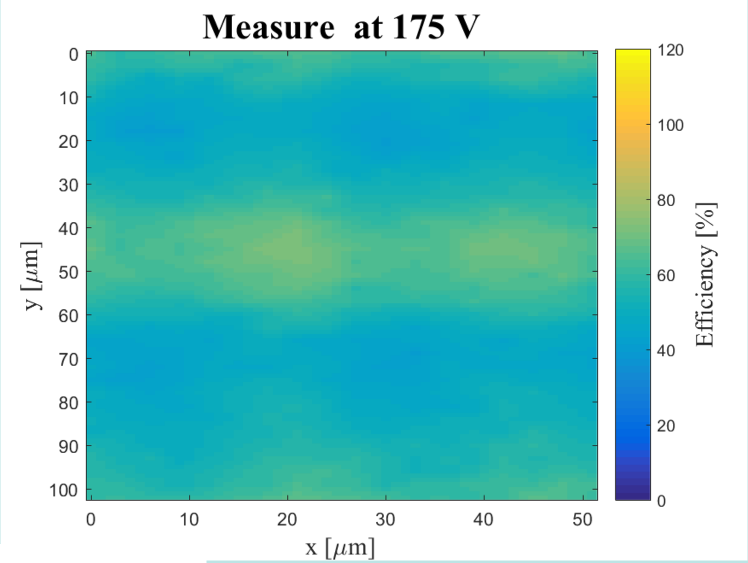
- 25x100µm 2E, $2\times10^{16}\ n_{eq}/cm^2$

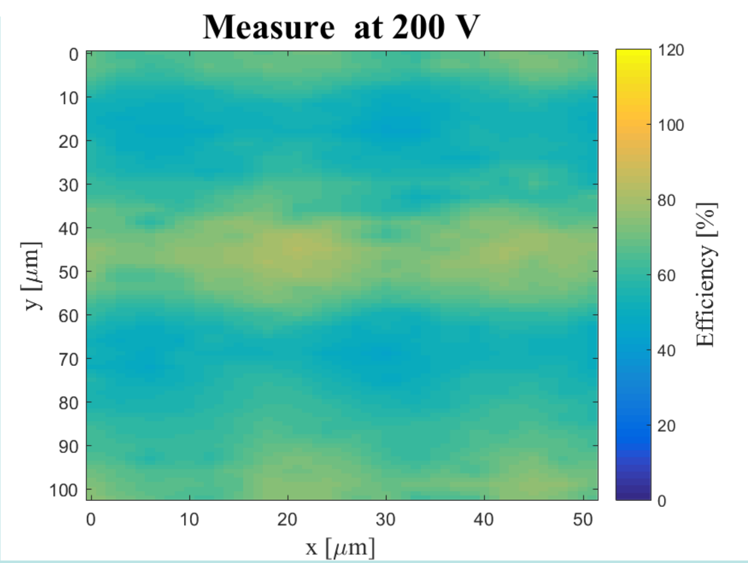


3D Sensors at FBK

- 25x100µm 2E, $3.5\times10^{16}\ n_{eq}/cm^2$

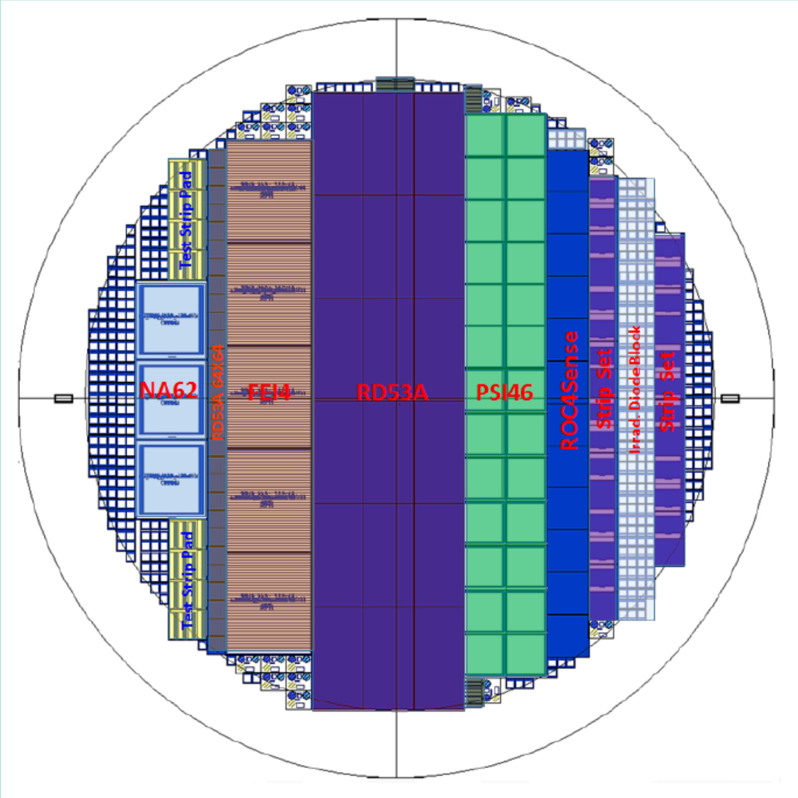


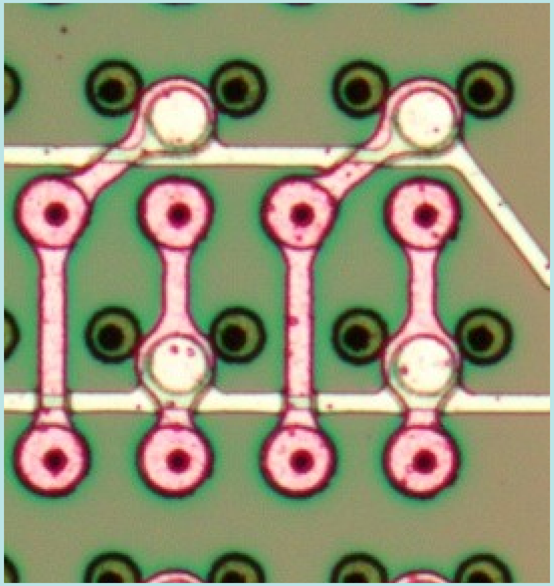


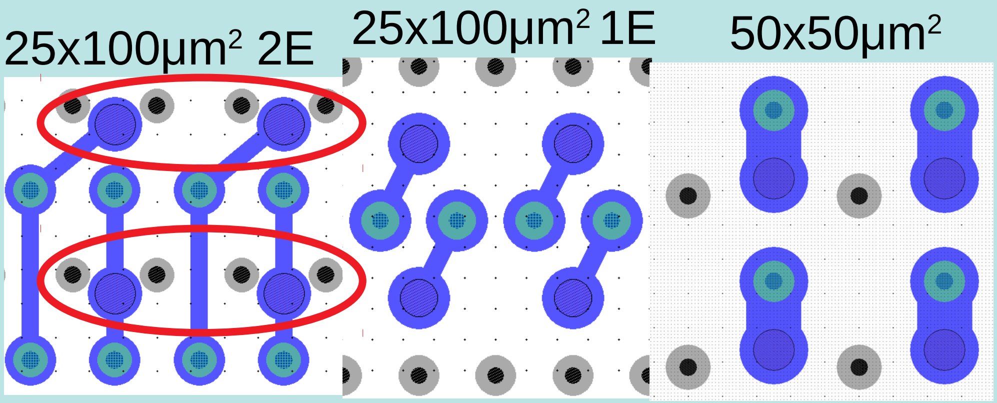


3D Sensors at FBK

- Second batch of sensors produced
- 25x100μm^2 2E problematic to manufacture, low yield
- Try to overcome using stepper
- Measurements ongoing

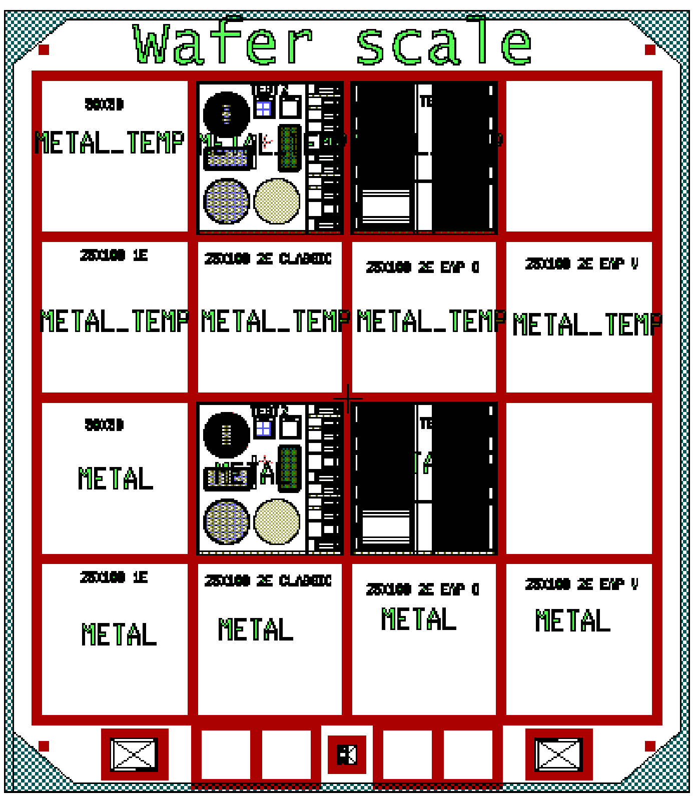


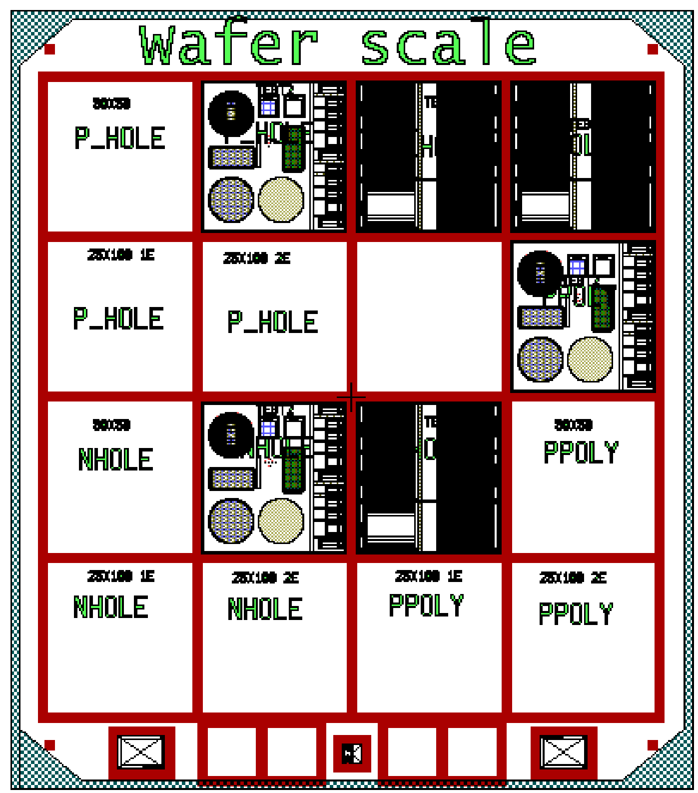




3D Sensors at FBK

- Try to use stepper
  - Minimum feature size 350nm
  - Alignment accuracy 80nm
  - Projection => low defect level
  - Max exposure area ~2x2cm^2
  - Can produce larger devices using photo-composition

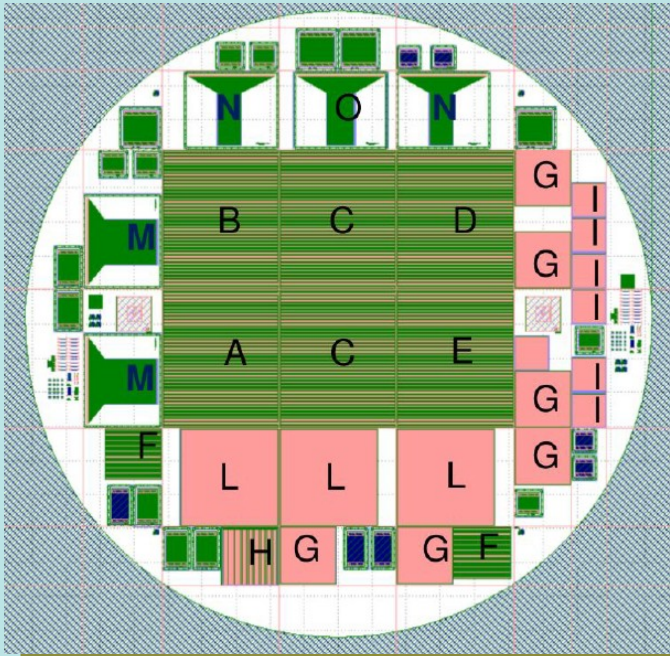


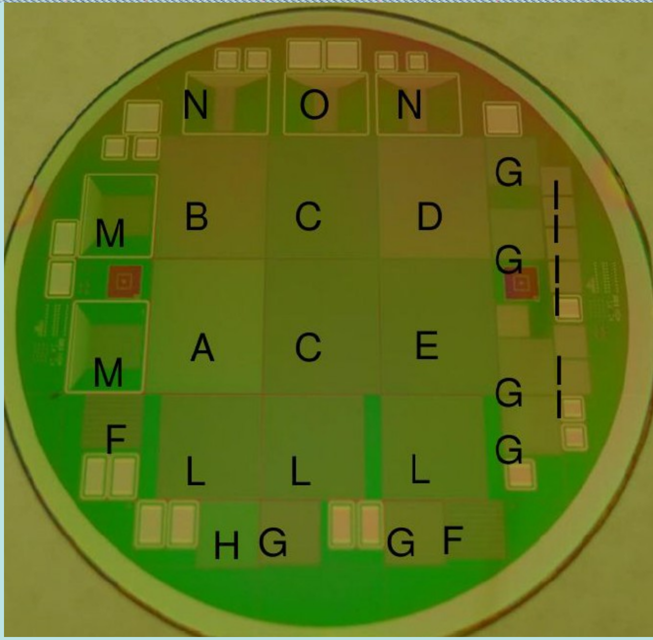


- First Layout complete
- Use photo-composition
- Contains:
  - Test Structures
  - 50x50μm^2
  - 25x100μm^2 1E
  - 25x100μm^2 2E

3D Sensors at CNM

- Produced first batch of sensors using double sided process on 230μm wafer 8um column diameter
- Produced different types of sensors
  - 50x50μm^2 and 25x100μm^2 strips
  - 50x50μm^2 and 25x50μm^2 pads for electrical tests
- Later produced sensors using single sided process
- Measured capacitance of pads: 50x50μm^2: 40fF/pixel; 25x50μm^2 60fF/pixel
- Tests Ongoing

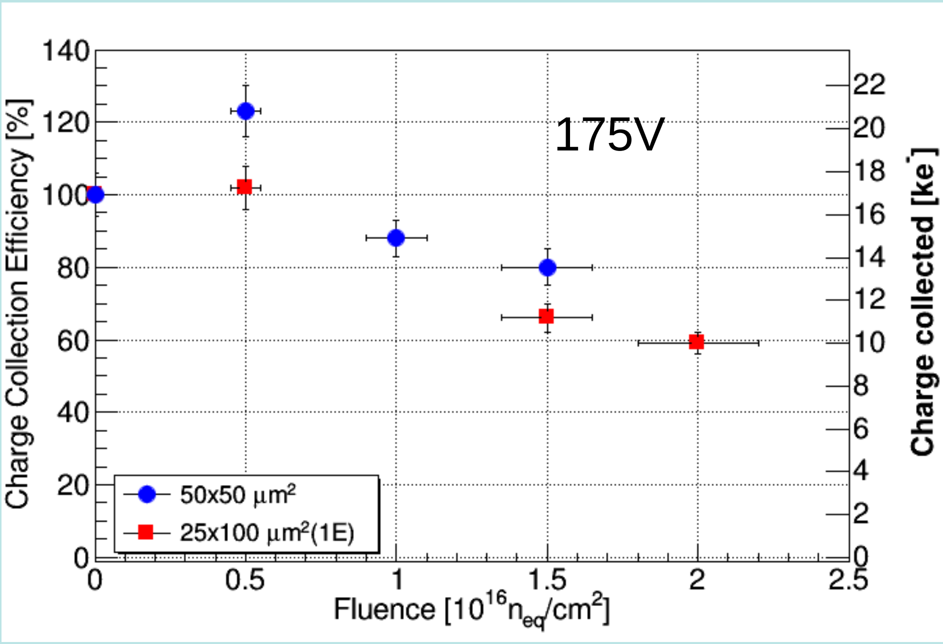




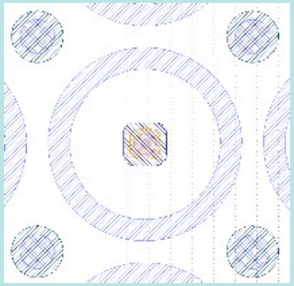
E. Curras et al., RD50, June 2017

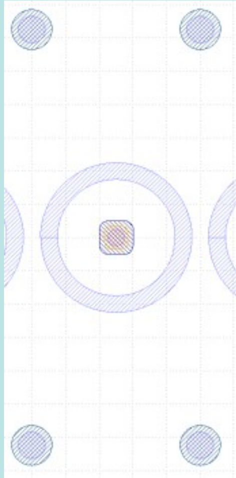
3D Sensors at CNM

- Performed number of irradiations on DS strip devices
- Acheived 100% efficiency at 5V before irradiation
  - 80% efficiency at $1.5 \times 10^{16}\ n_{eq}/cm^2$ for $50 \times 50 \mu m^2$ sensors
  - 65% efficiency at $1.5 \times 10^{16}\ n_{eq}/cm^2$ for $25 \times 100 \mu m^2$ sensor
- So far indication that 50x50µm more radiation hard than 1E



M. Manna et al., RD50, June 2018

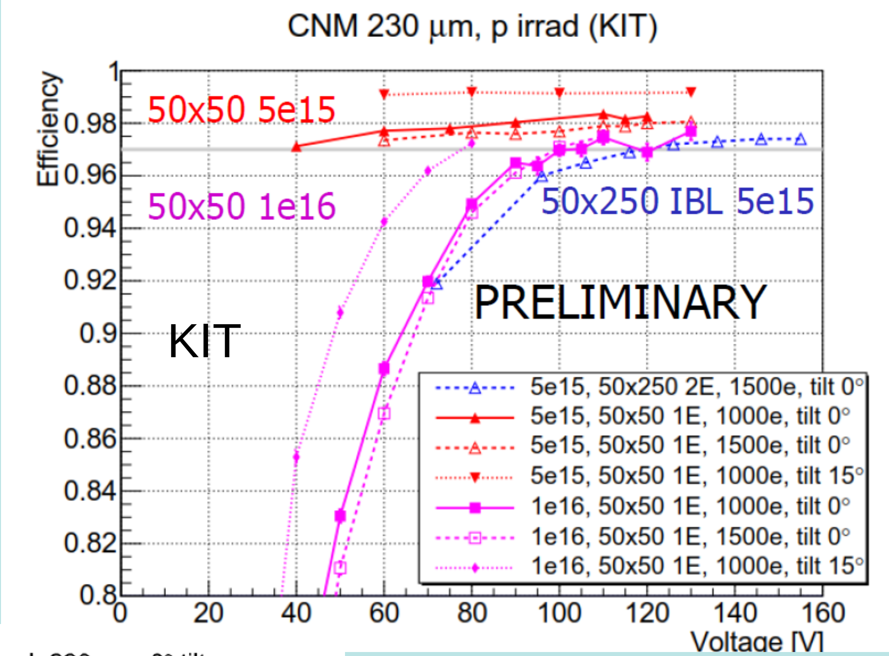


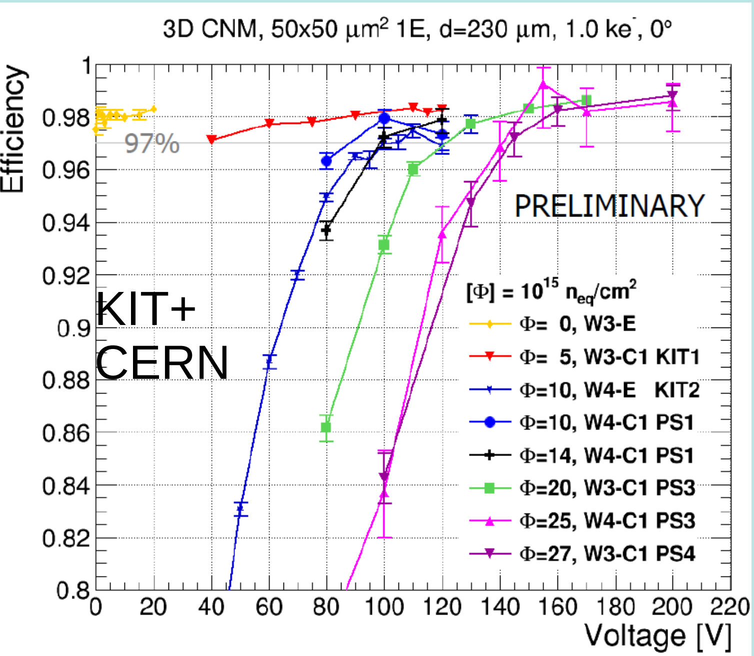


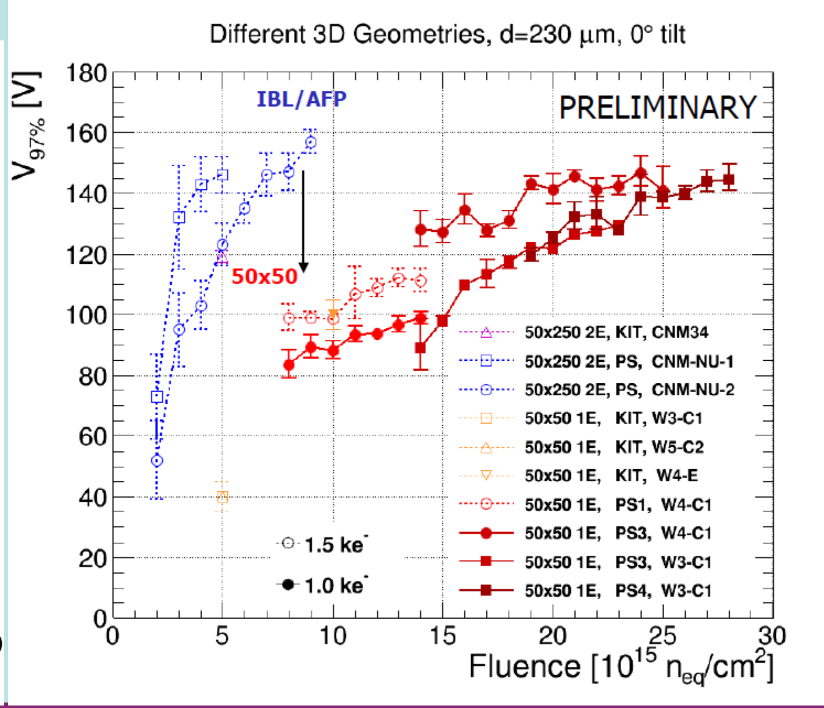
3D Sensors at CNM

- Uniform Irradiation at KIT
- Non Uniform irradiation at CERN
- Reach 98% efficiency plateau after 2.7×10^{16} n_{eq}/cm^2
- Significant improvement on IBL sensors

J. Lange et al., HSTD11, 2017

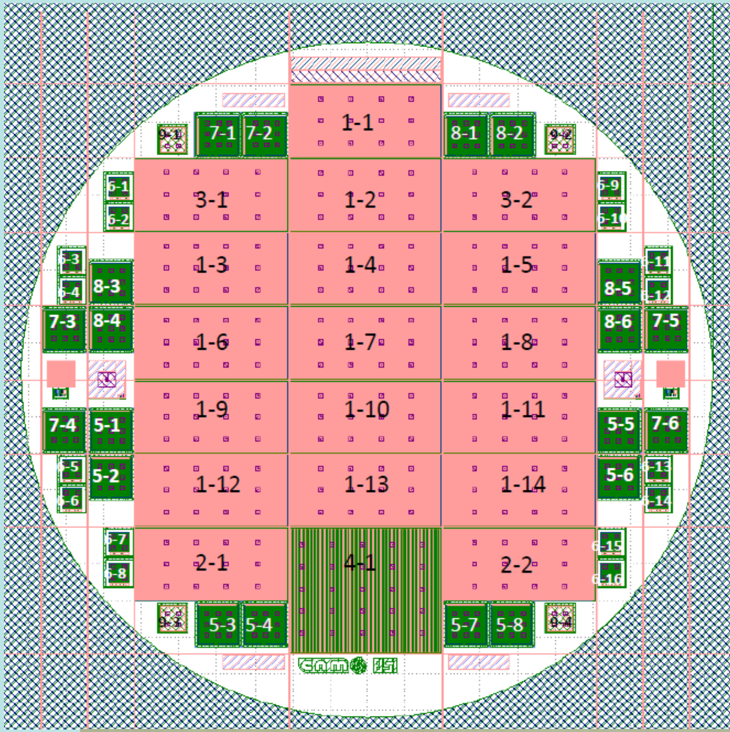


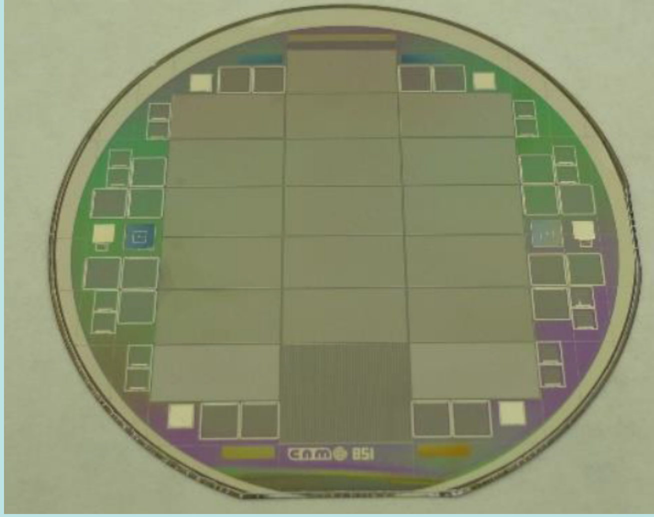




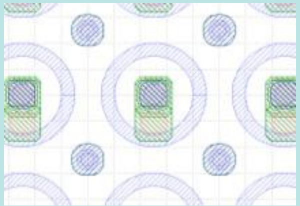
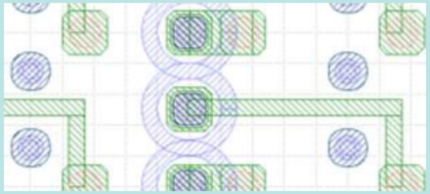
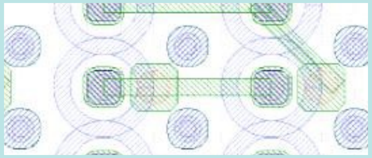
3D Sensors at CNM

- New batch of Single Sided devices produced; 100μm & 150μm active thickness on 300μm support layer
  - 50x50μm^2 cells
  - 25x100μm^2 1E cells
  - 25x100μm^2 2E cells
- Measurements ongoing (irradiated device testbeam)





M. Manna et al., RD50, June 2018

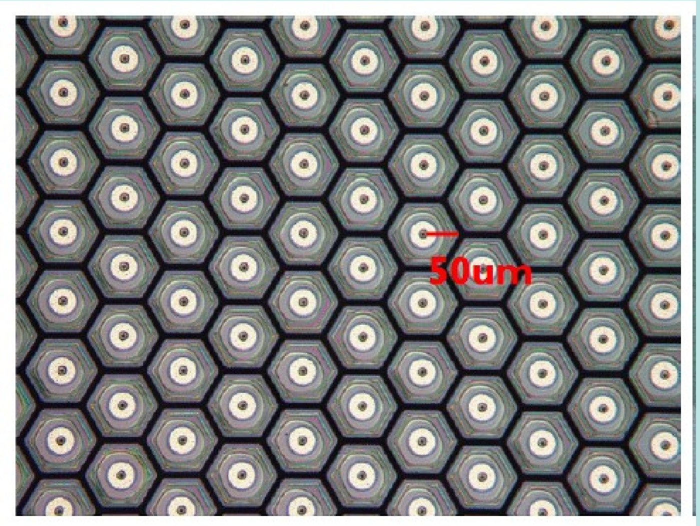




Timing in 3D Sensors

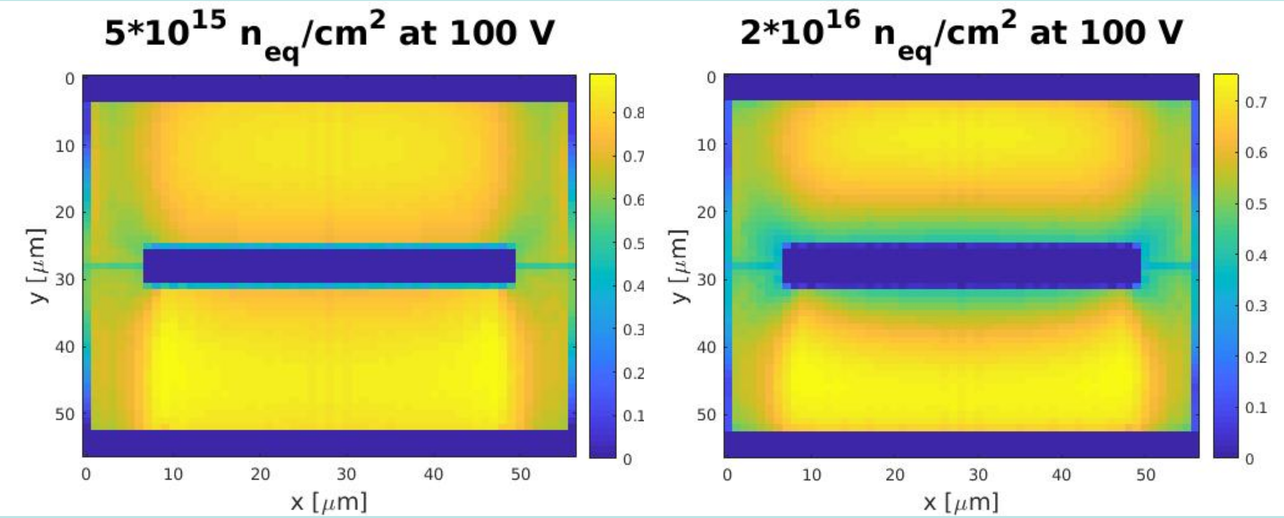
- 3D trench sensors being investigated for timing applications
- Some sensors produced at CNM in 2013, sensors worked but with high leakage current

Advantages:
- High average field
- Uniform weighting field
- Initial pulse (largely) independent of position
- Very Radiation Hard

Drawbacks:
- Possible fabrication problems
- High electrode capacitance

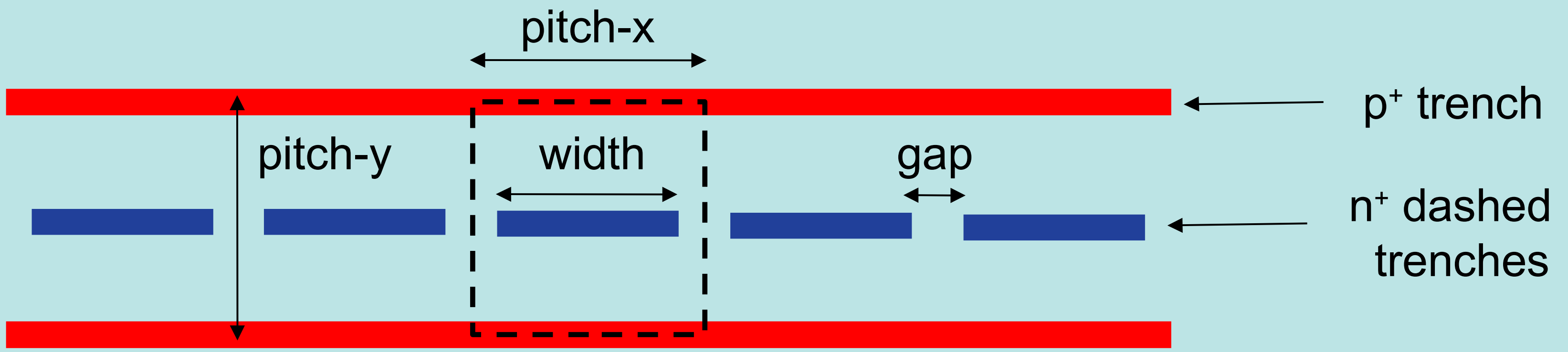


A. Montalbano et. al.
NIMA 765 (2014), 23



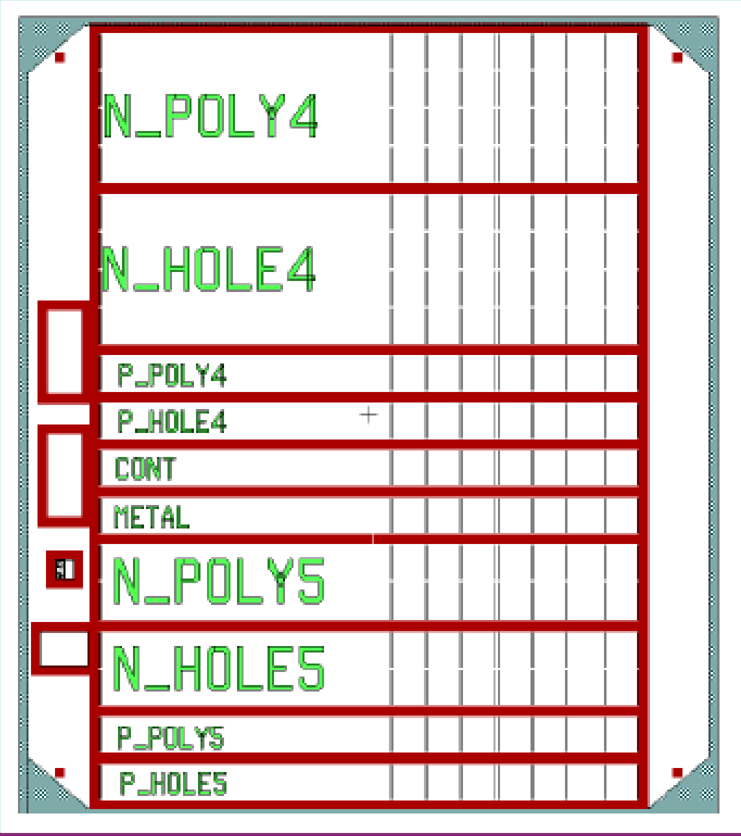
Trenched Sensors at FBK

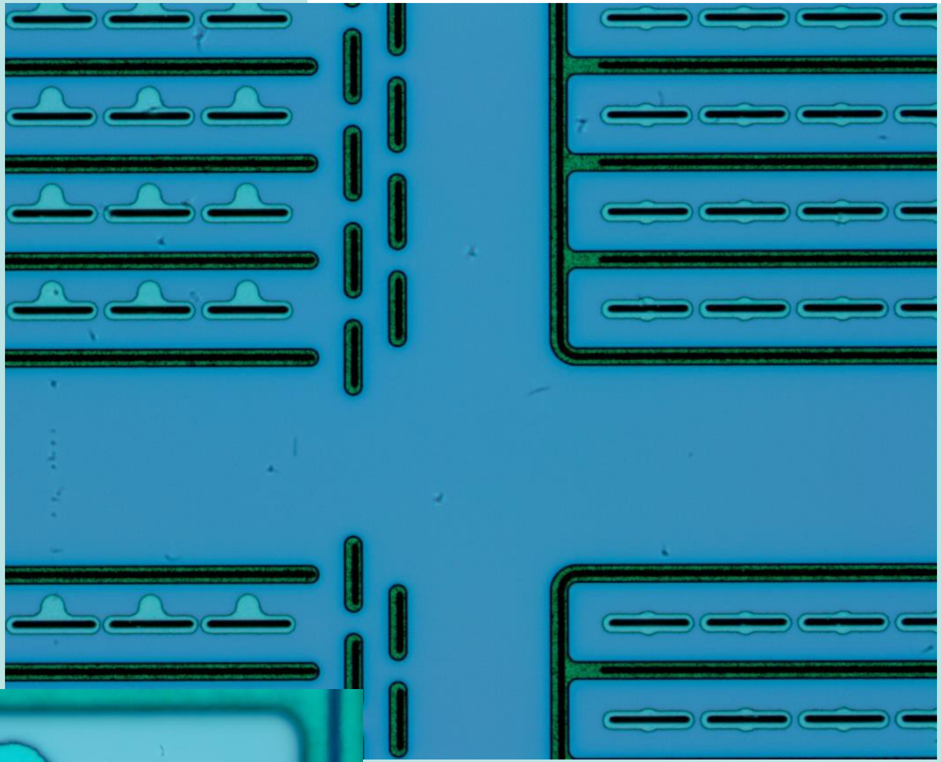
- Investigating TIMEPIX compatible trench sensors
- Trenches are dead area, so minimize thickness (~4μm)
- Tests of fabrication procedure underway to optimize fabrication parameters
- Test mask produced with wide range of possible geometries and spacings for tests
- Design being optimized with TCAD simulations
- New mask being designed for first lot of sensors



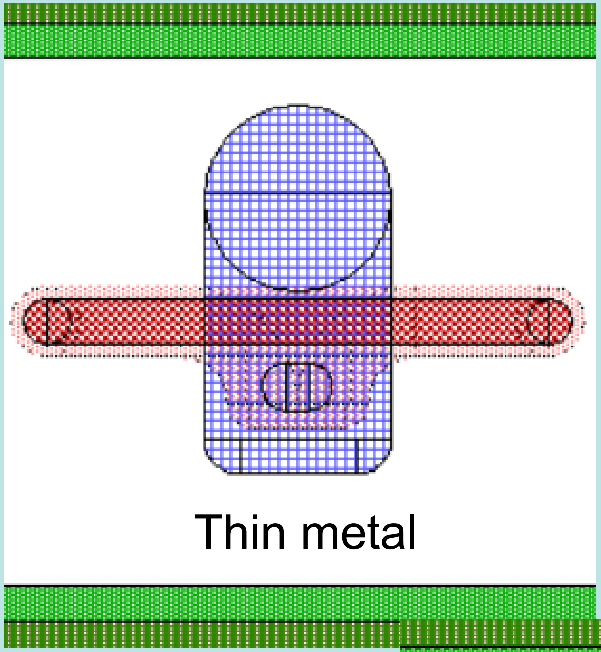
Trenched Sensors at FBK

- Tests of the procedure are ongoing
- Results look promising
- Still some issues to fully resolve



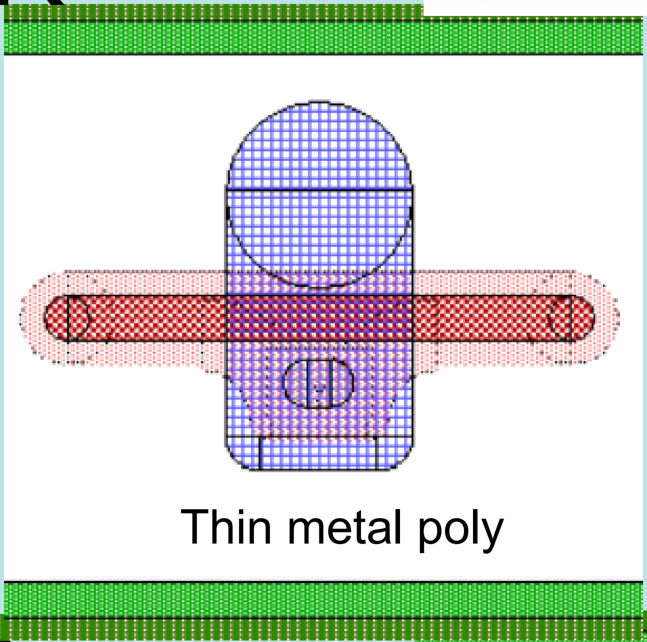


Trenched Sensors at FBK



Thin metal

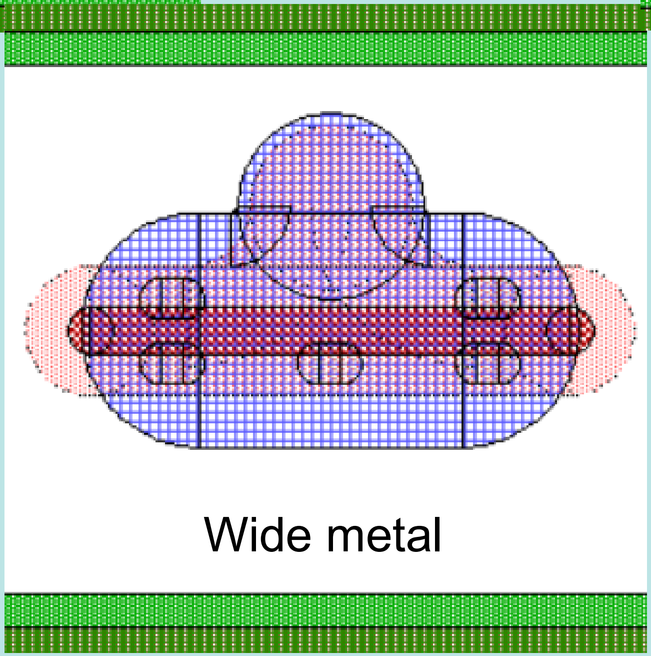
Trench Length:
41 μm
43 μm
45 μm
47 μm
49 μm



Thin metal poly

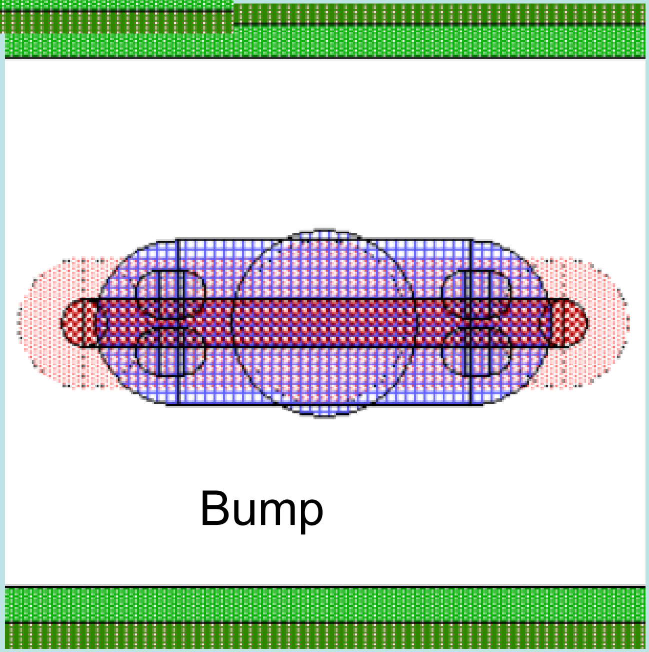
Trench Length:
41 μm
43 μm
45 μm
47 μm
49 μm

Trench Length:
41 μm
43 μm
45 μm
47 μm



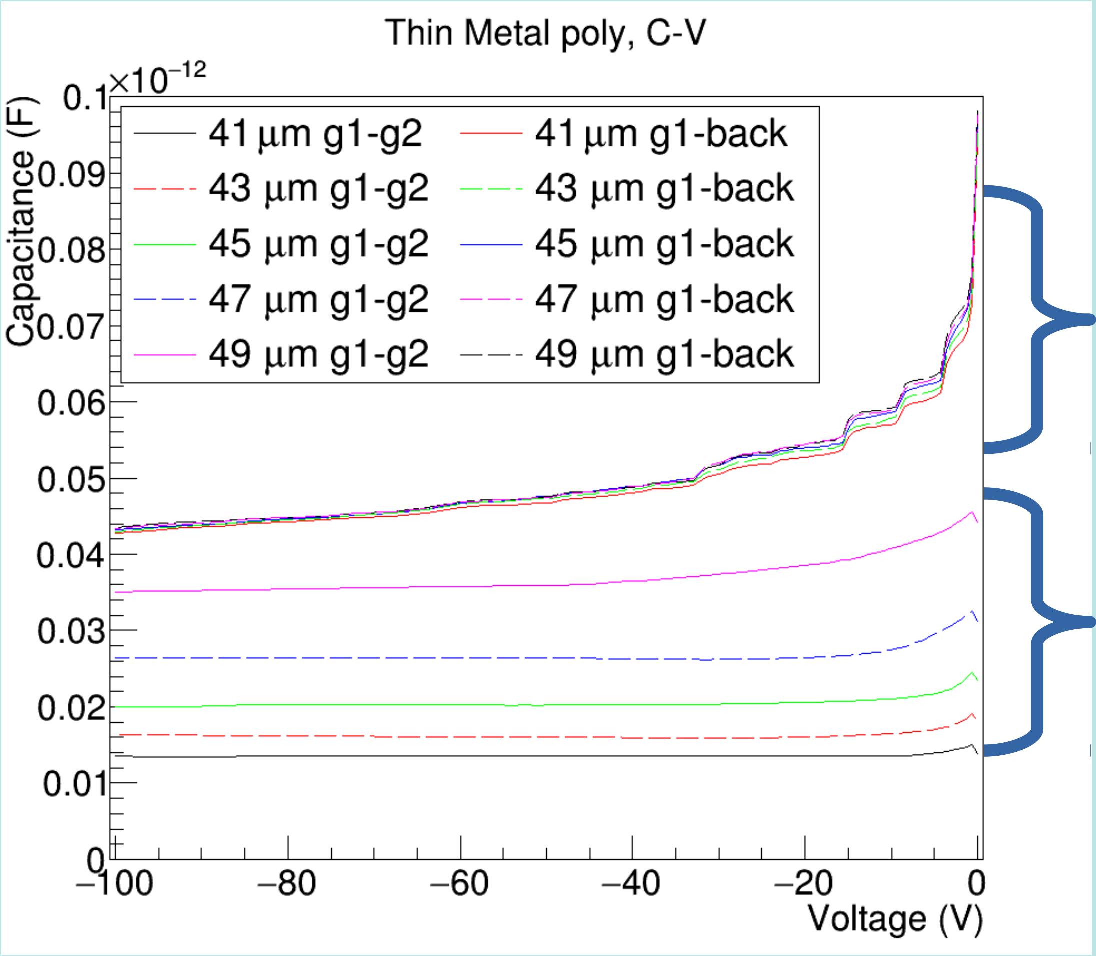
Wide metal

Trench Length:
45 μm



Bump

Trenched Sensors at FBK

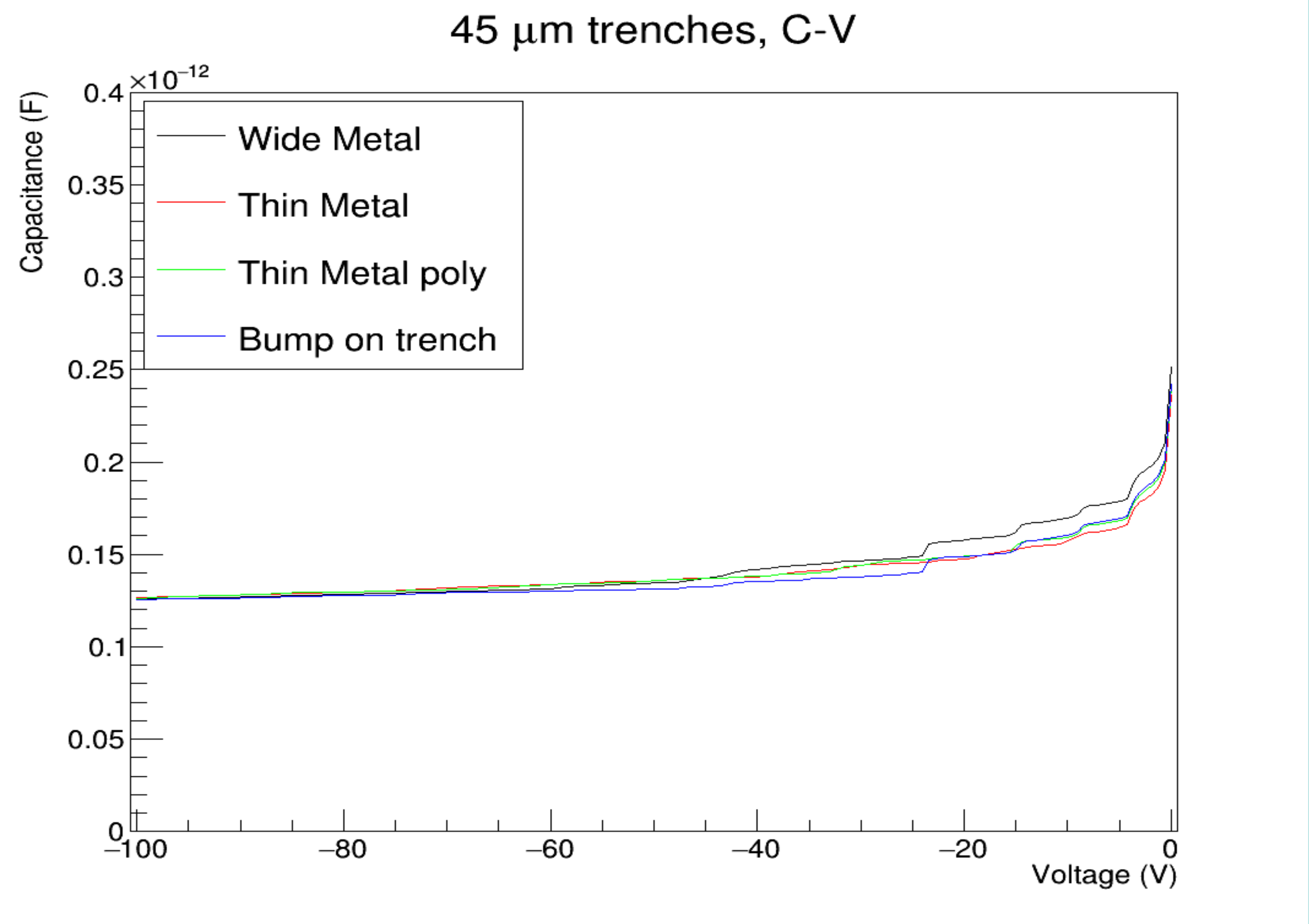


Opposite electrode capacitance (half-pixel)

Inter-pixel capacitance (1 neighbour)

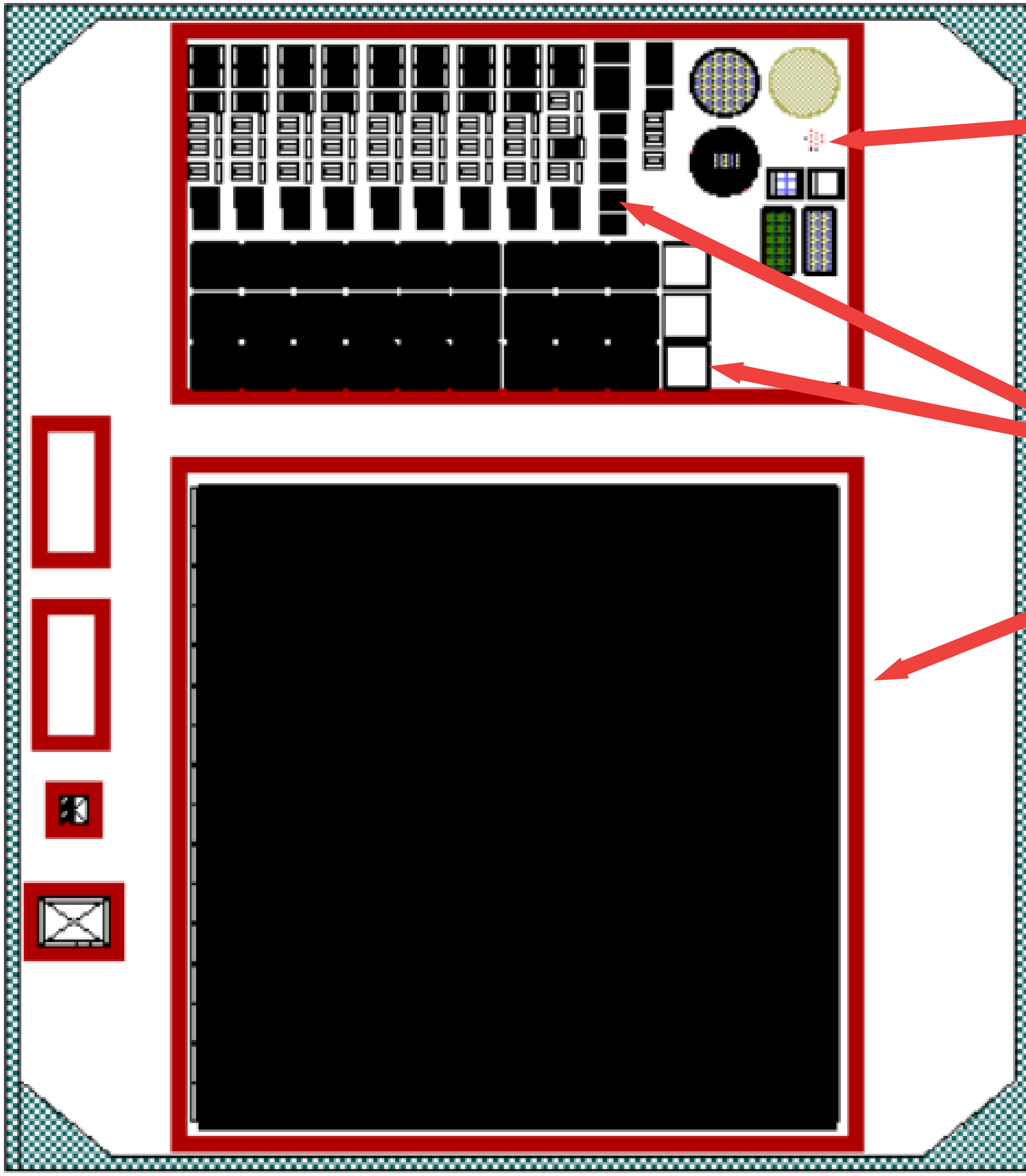
- Strong dependance of trench dimension on inter-pixel capacitance
- Small change in capacitance between opposite electrodes due to trench dimensions

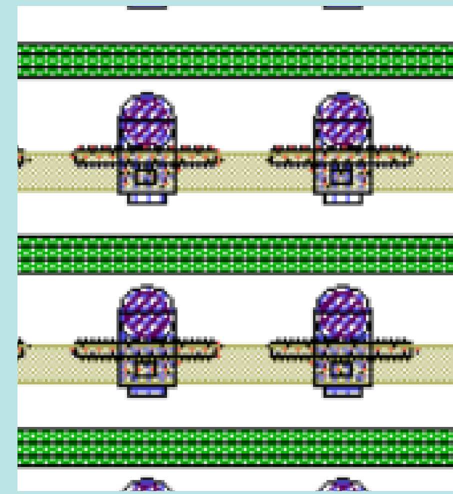
Trenched Sensors at FBK



- At full depletion, negligible difference in capacitance between different geometries

Trenched Sensors at FBK



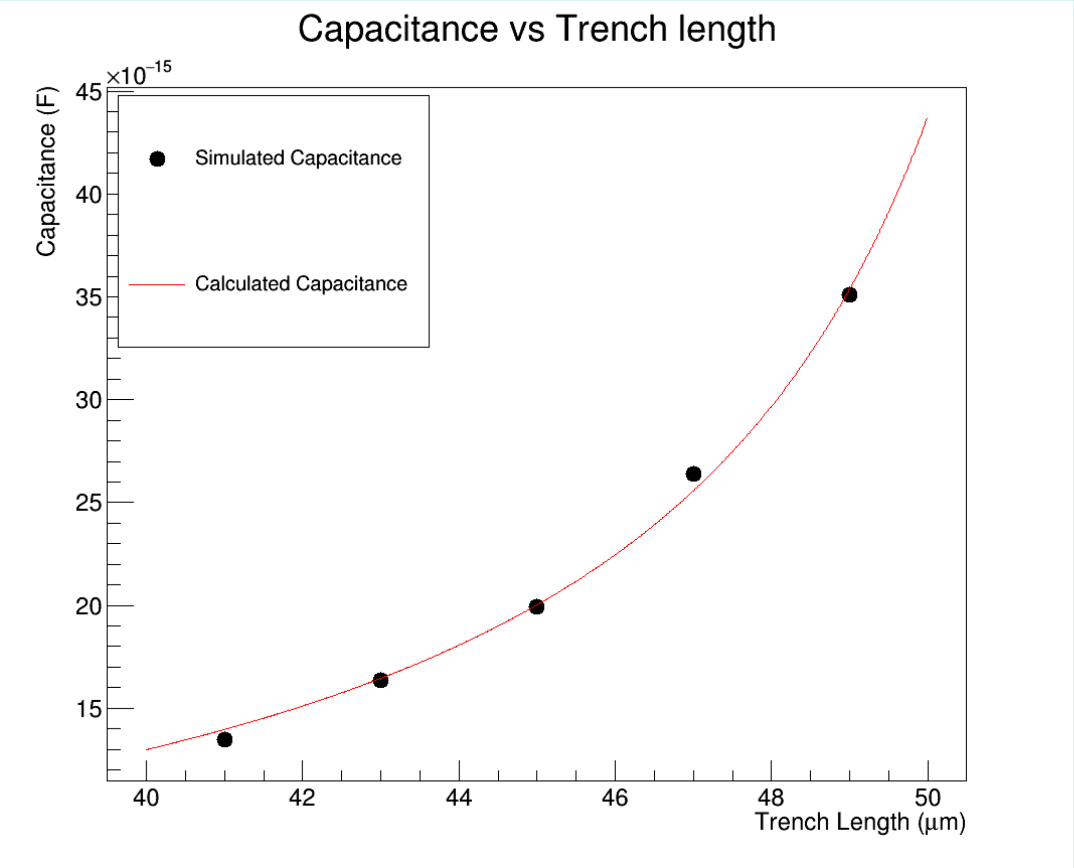


Outlook + Conclusions

- New approach desired after production of IBL
- A number of small pitch 3D devices have been successfully fabricated using this method
- Good performance even after irradiation
- Single Sided CNM sensor testbeam
- Lot using stepper about to get underway at FBK
- 3D trench sensors are being investigated the for the HL-LHC

Backup Slides

Capacitance Results

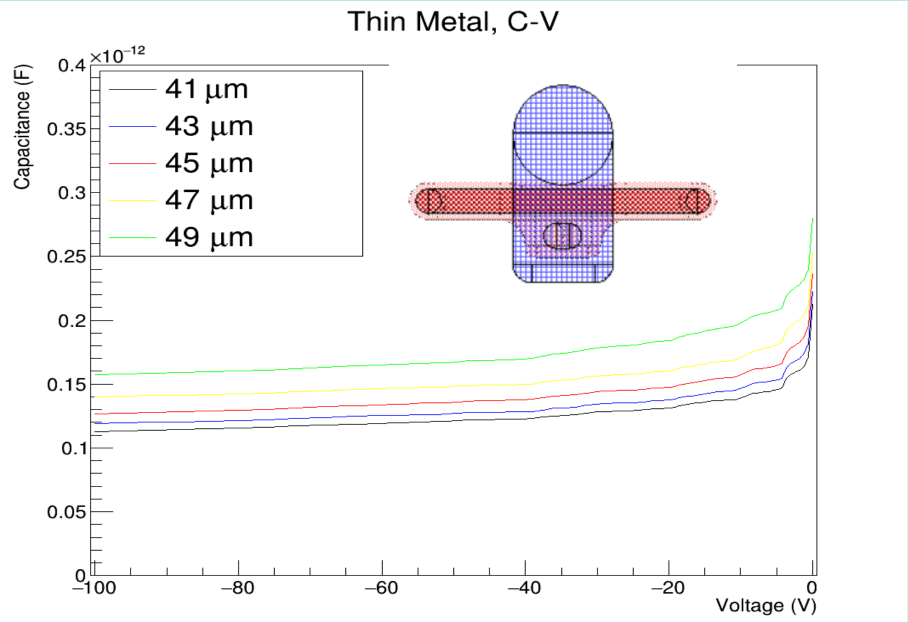


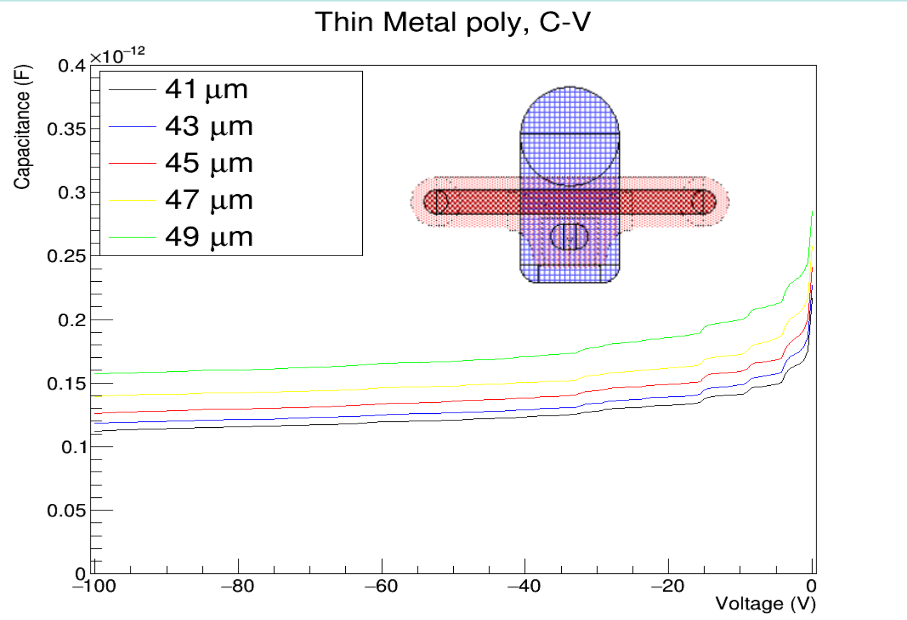
- Find relationship between interpixel capacitance and trench length
- Approximate inter-pixel capacitance using parallell plate capacitor equation

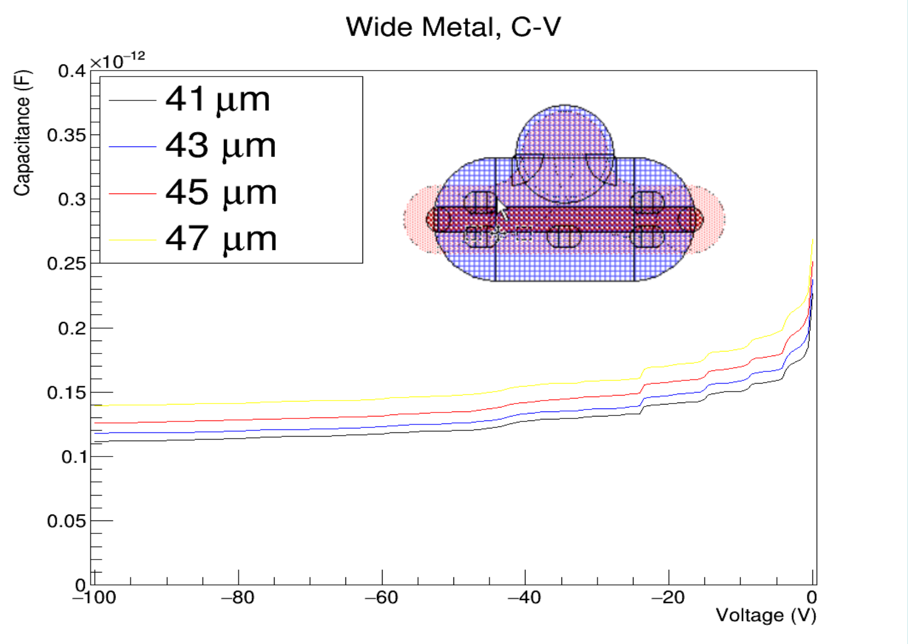
$$C=\frac{\varepsilon\,\varepsilon_0\,A}{d}$$

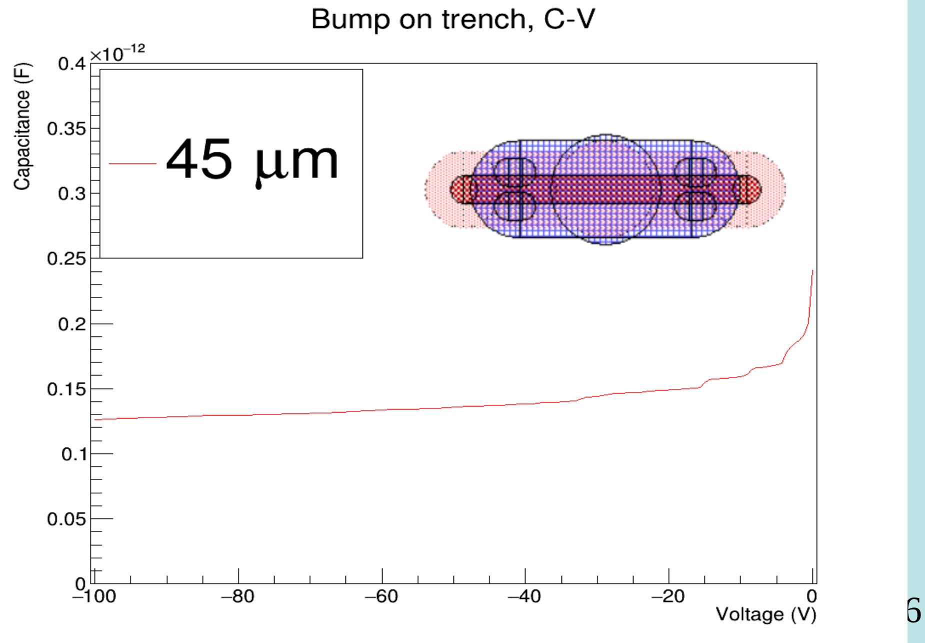
- Find effective area ~1790µm^2

Capacitance Results



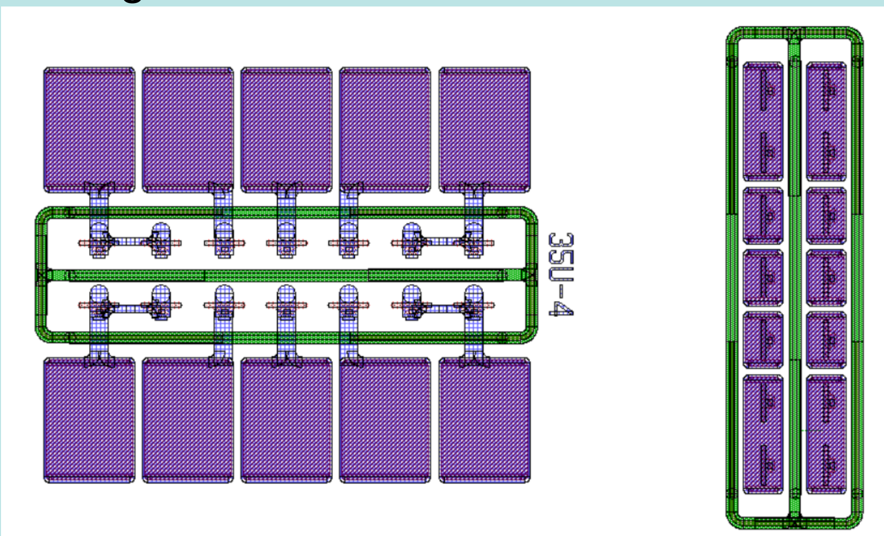


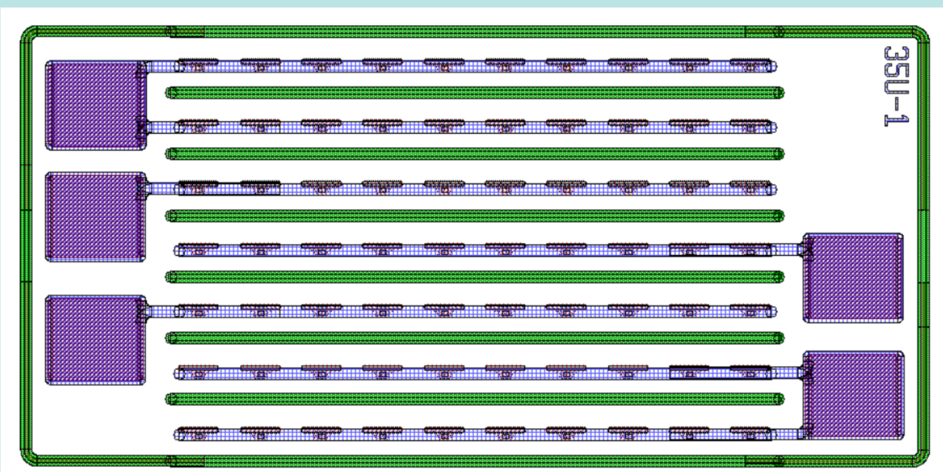




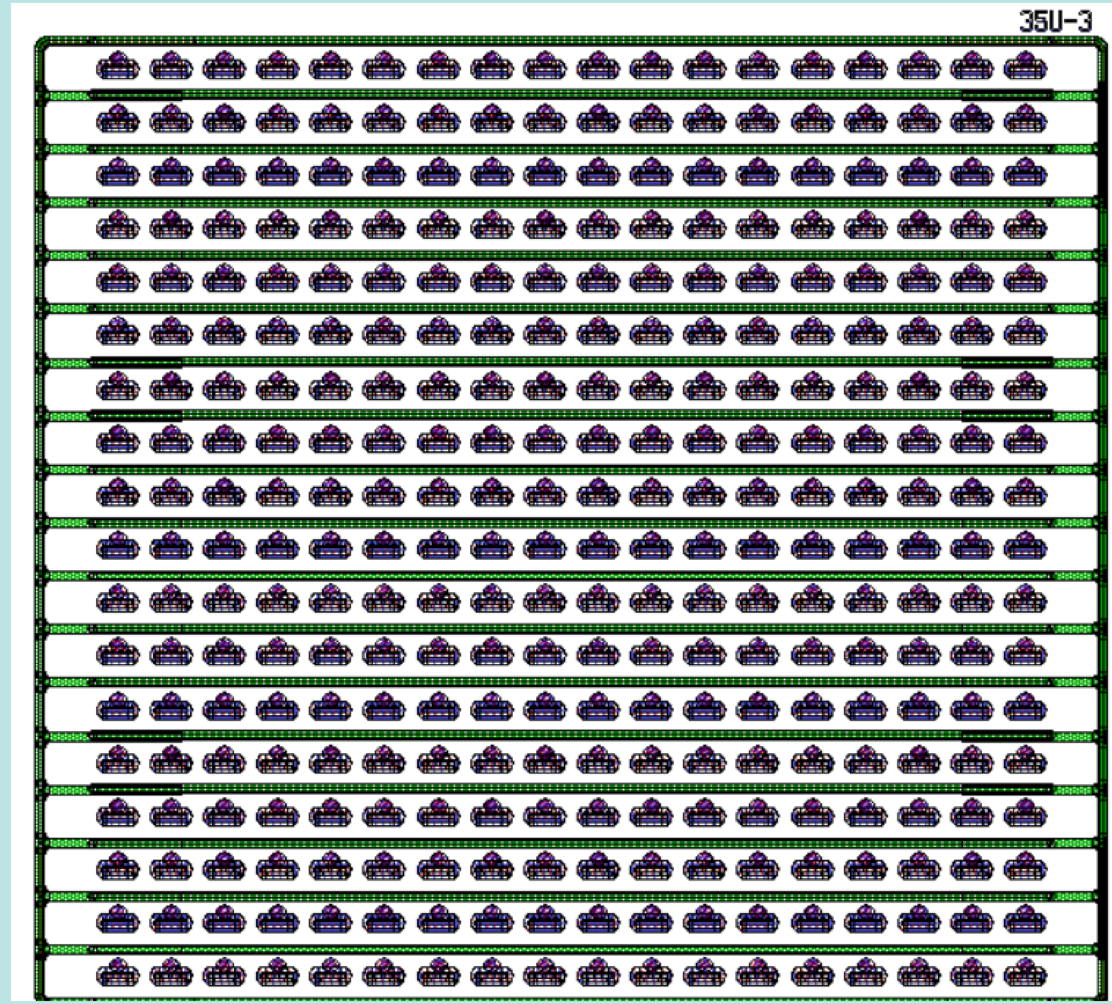
3D Test Structures

Single Pixel





Multi-Pixel Strips



Test Pixel Devices