Vertex 2022 - The 31st International Workshop on Vertex Detectors

Characterisation of 3D pixel sensors for the CMS upgrade at the High Luminosity LHC

- The CMS Inner Tracker upgrade
- 3D sensor fabrication
- Readout chip and testbeam setup
- Results
- Summary

Mauro Dinardo

Università degli Studi di Milano Bicocca and INFN, Italy

on behalf of the CMS-Tracker working group

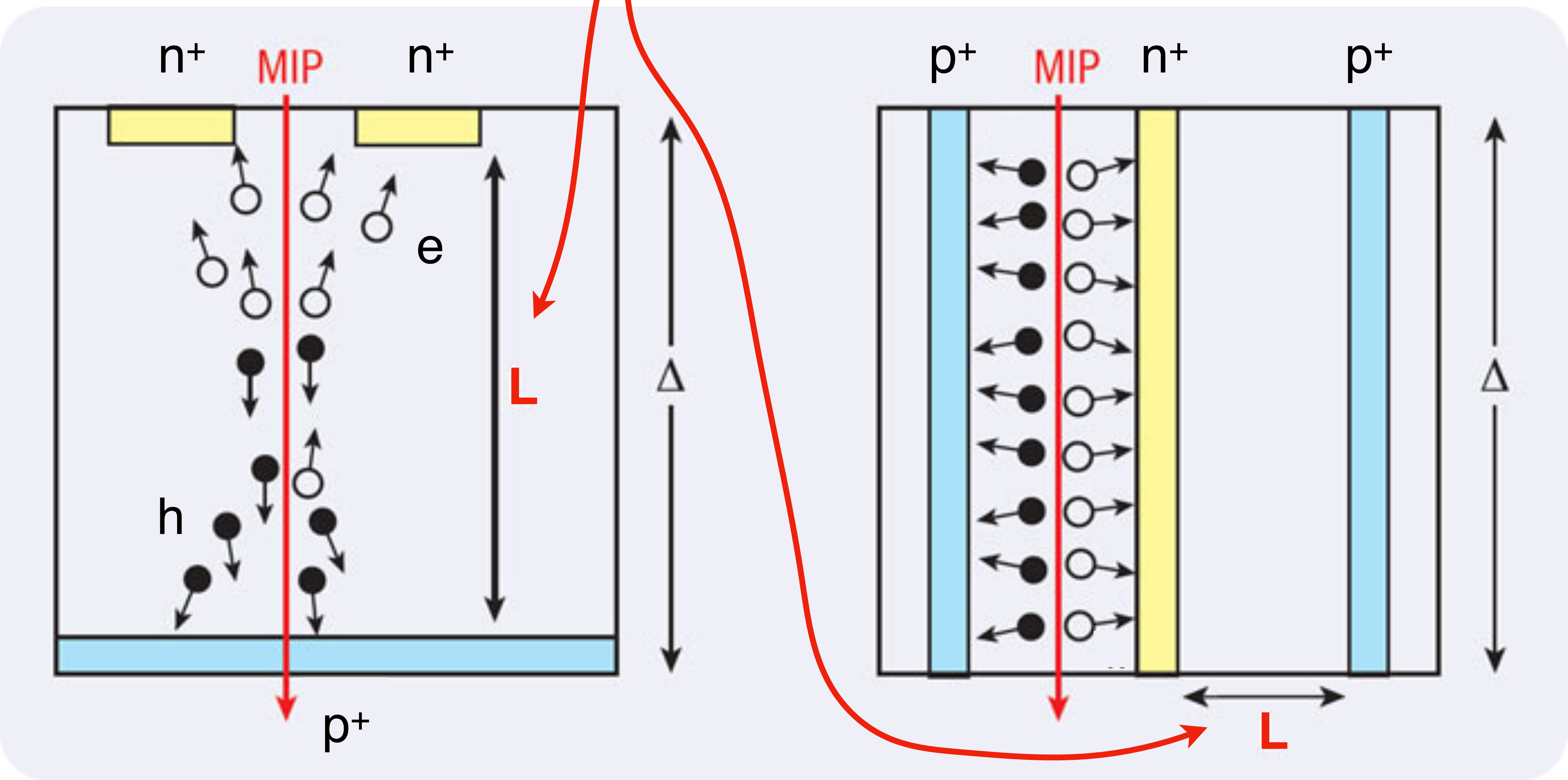
24/10/2022

Tateyama

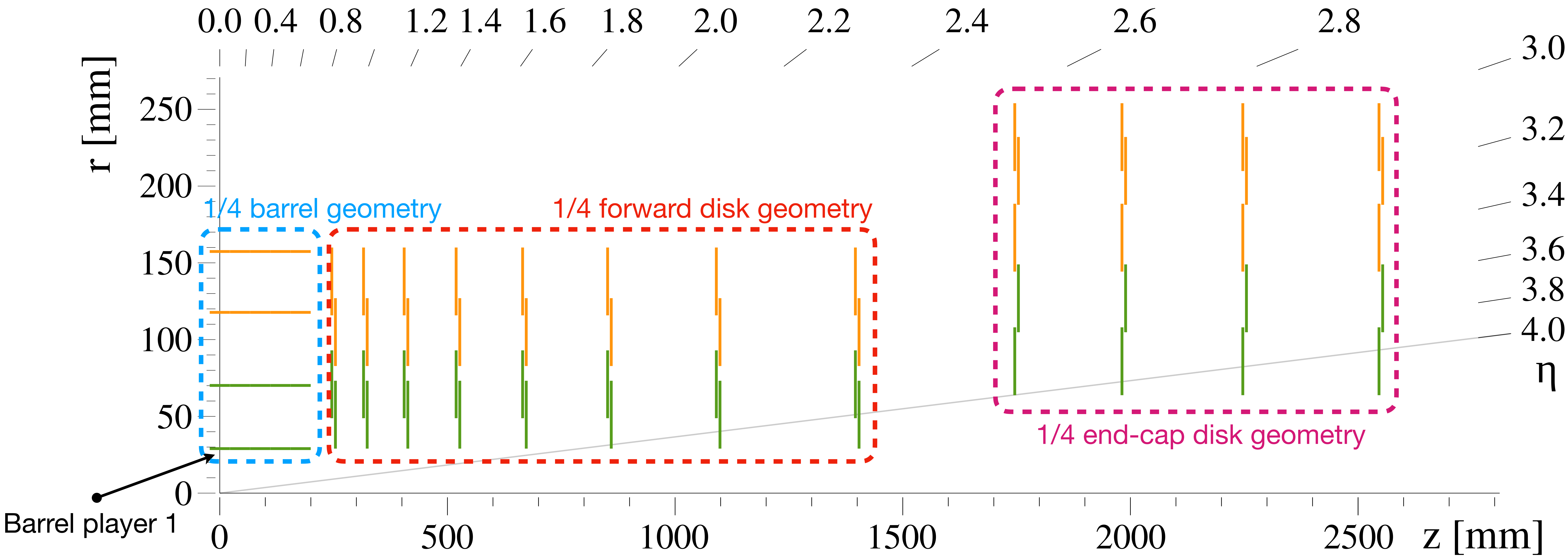
HL-LHC operation conditions	Sensor design constraints
Luminosity 7.5x10^{34}/(cm^2•s) ➜ up to **200 events/25 ns** bunch crossing	Maintain occupancy at ‰ level and increase spatial resolution ➜ pixel size x6 smaller than present pixels ➜ 25x100 μm^2 (current detector in CMS 100x150 μm^2)
CMS baseline choice: replace pixel layer closer to beamline at integrated fluence **~1.9x10^{16} n$_{eq}$/cm^2** (end of *"Run 5"*, i.e. after ~6 years of operation) ➜ electron **mean free path** greatly **reduced** (also damaged readout ASIC at ~1 Grad)	Reduce electrodes distance (L) to increase electric field and thus the signal ➜ thin planar or 3D columnar technologies

3D silicon sensors made by

- Fondazione Bruno Kessler-***FBK*** (Trento, Italy), **n-in-p** sensors on **150 mm FZ wafers** in collaboration with ***INFN***
- Centro Nacional Microtecnologia-***CNM*** (Barcelona, Spain), **n-in-p** sensors on **100 mm FZ wafers**



C. Da Vià et al., NIMA (2012)



Sensor main features

- **~2 billion pixels ➜** active surface ~4.9 m² (**4 barrel** layers and **12+12 forward / end-cap** disks)
- **Planar 25x100 µm² x 150 µm active length** sensors baseline choice for whole Inner Tracker but barrel layer 1
- **3D** sensors, **same size** of planar, baseline choice for **barrel layer 1** (better thermal performance than planar)
- 50 x 50 µm² x 150 µm active length discarded since marginal gain doesn't justify additional design

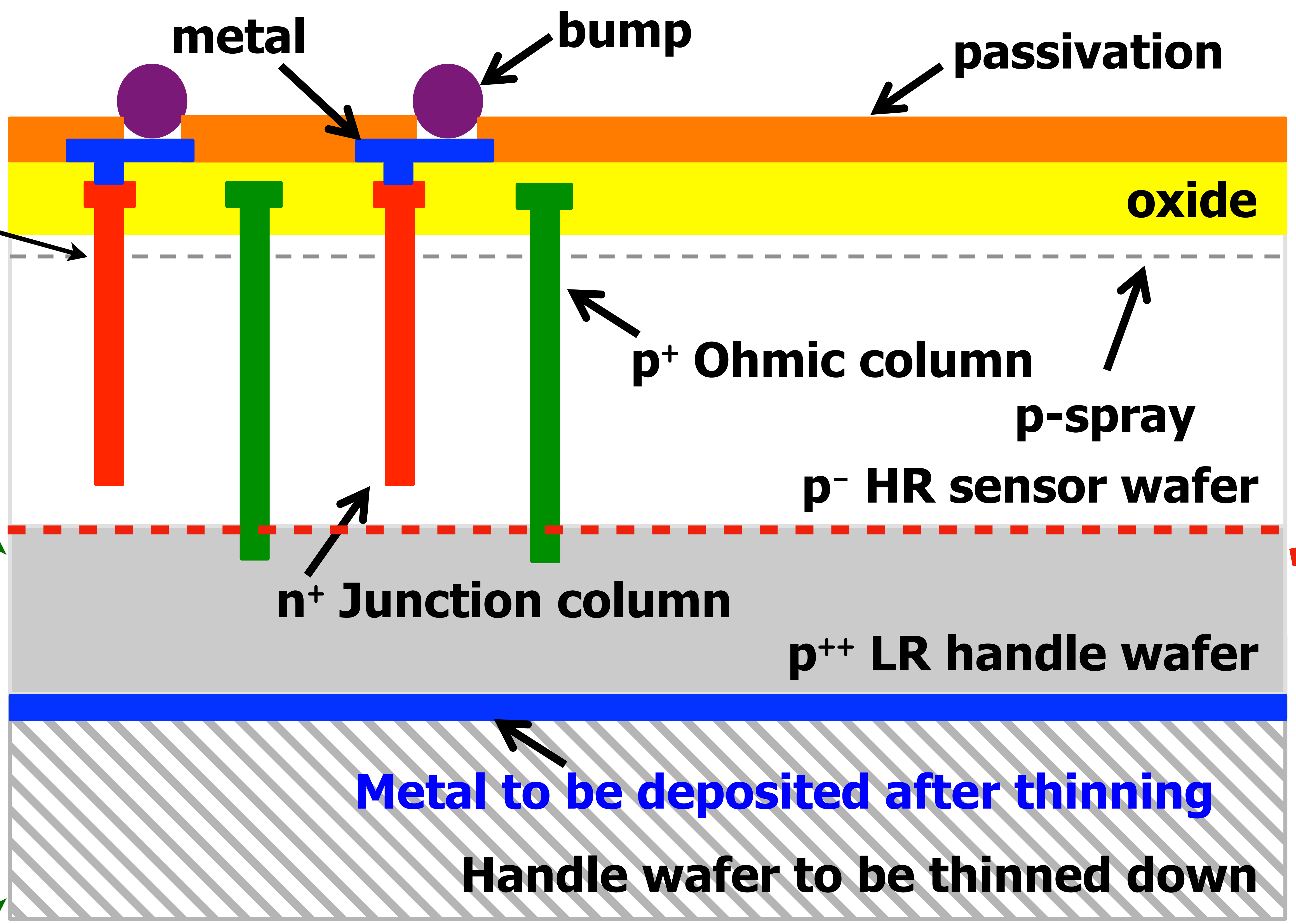
Column diameter **~5 µm**

High Resistivity layer

- Active layer thickness **~150 µm**
- Resistivity > 3 kOhm•cm

Low Resistivity layer

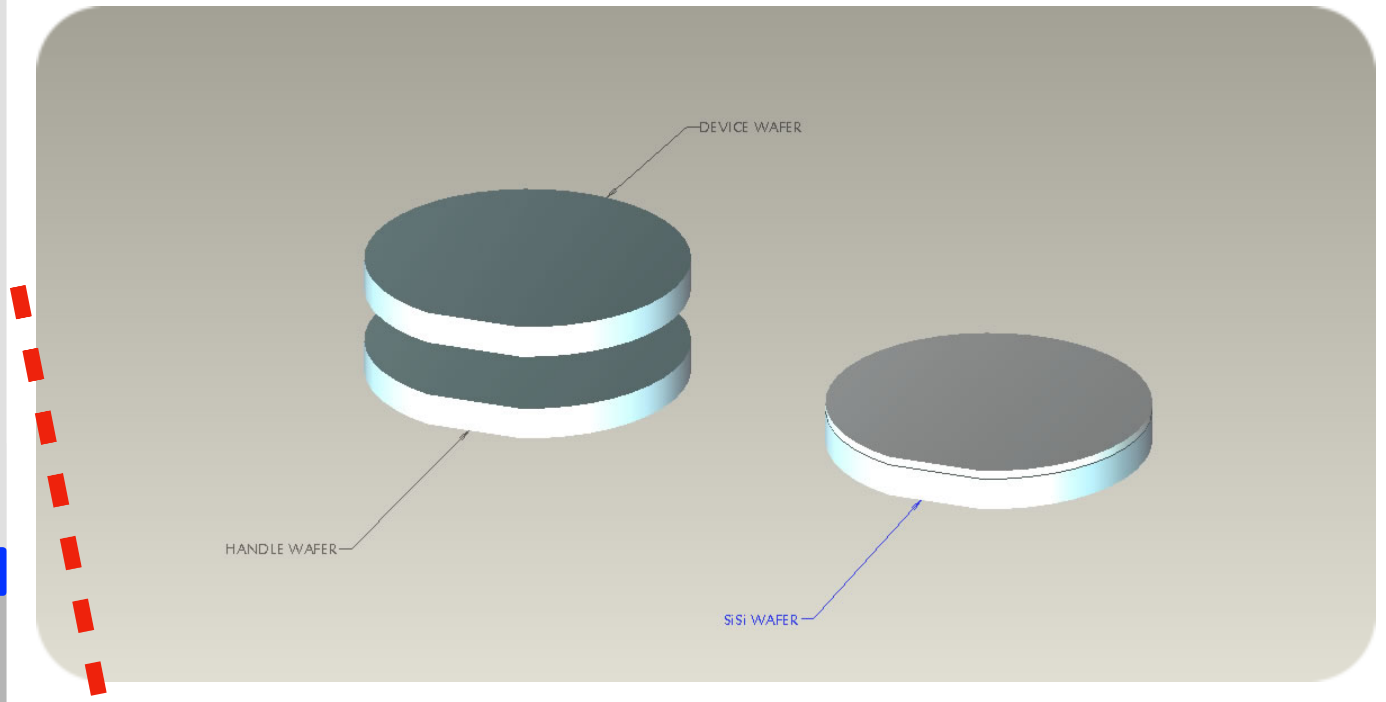
- Resistivity 0.1-1 Ohm•cm
- Initial wafer thickness **~500 µm**
- Residual wafer thickness after thinning **50-100 µm**

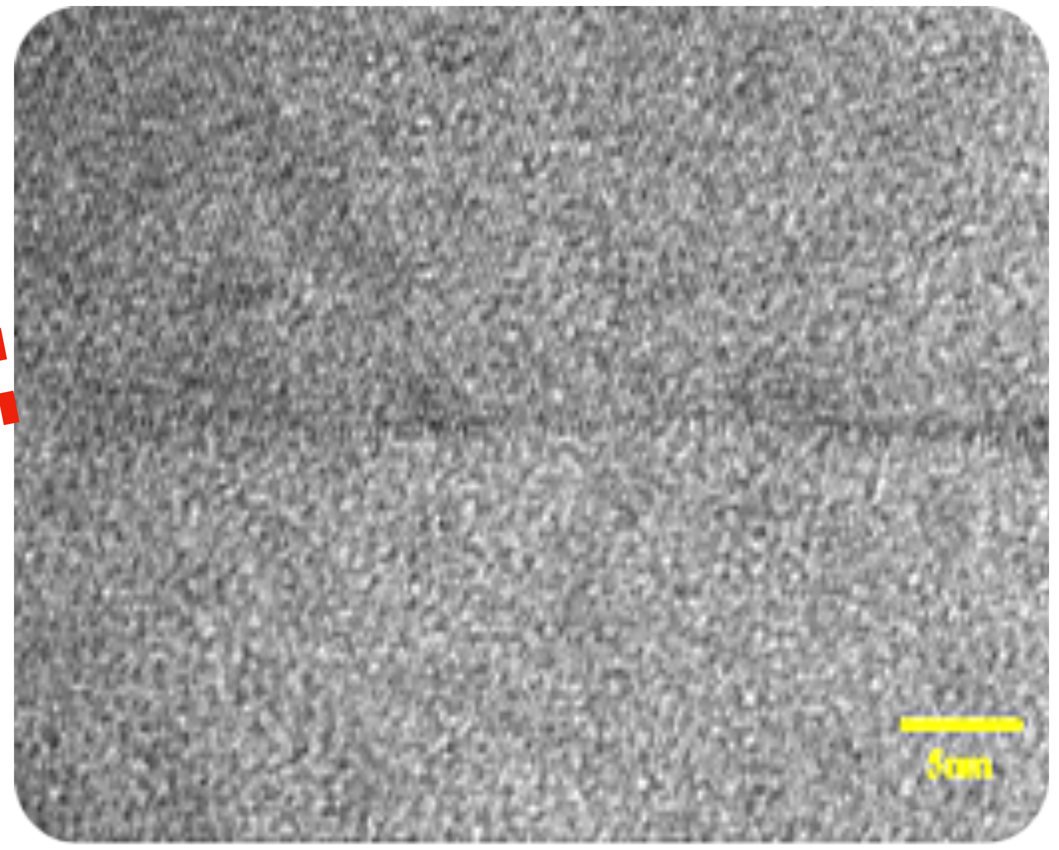


G.F. Dalla Betta et al., NIMA 824 (2016) 386

Two wafers:

High-**R**esistivity and **L**ow-**R**esistivity, bonded with **D**irect **W**afer **B**ond - **DWB** technique by IceMos Technology, Belfast



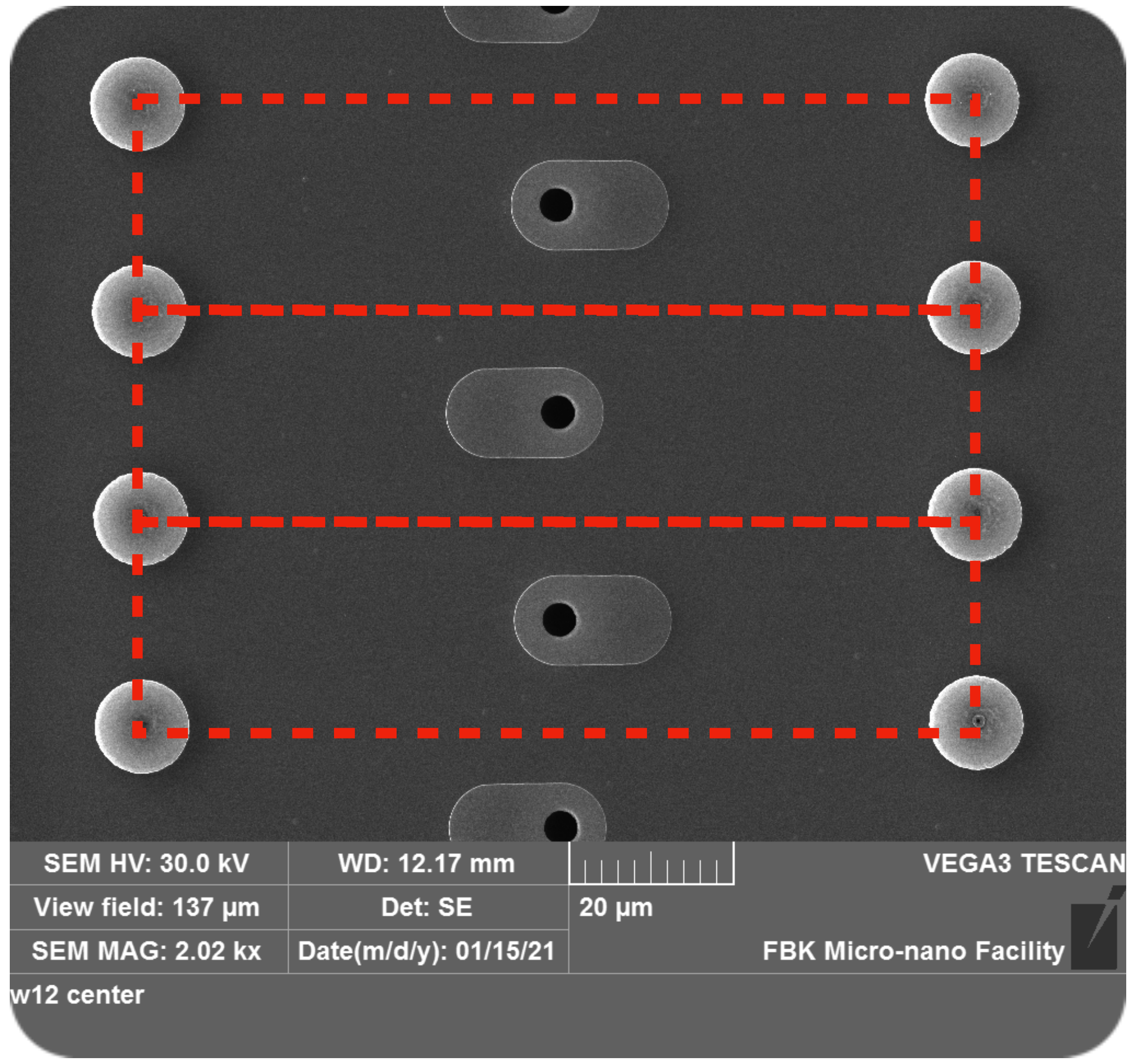


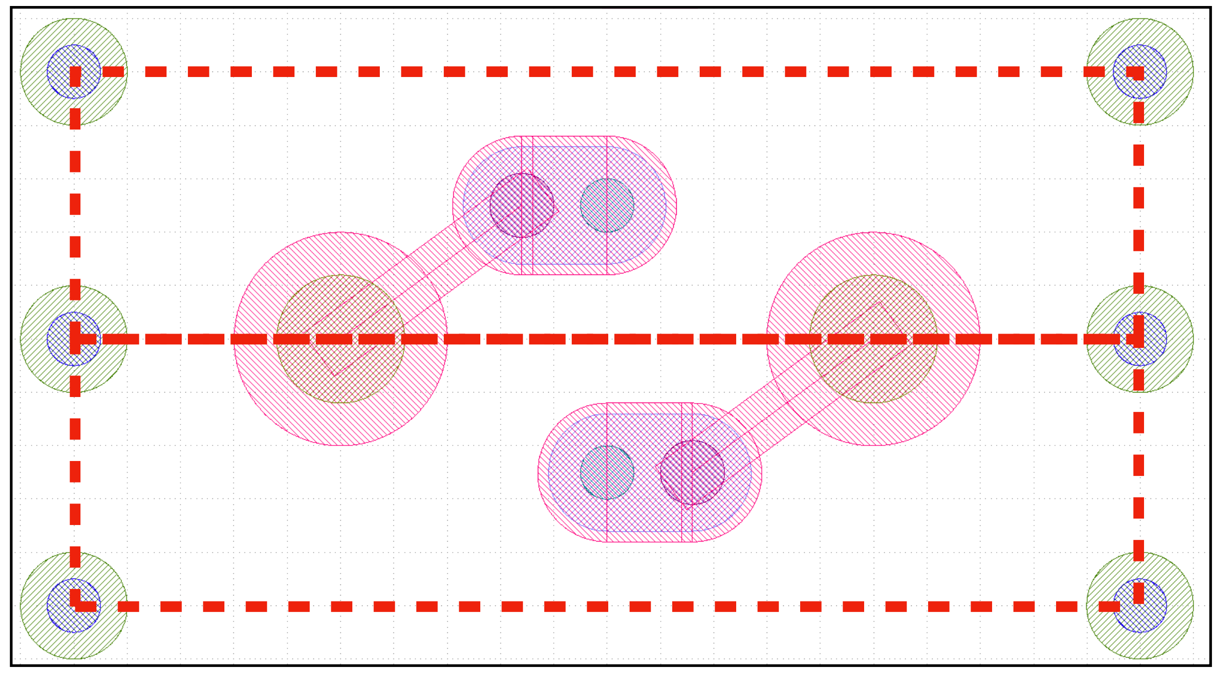
High resolution TEM image of two bonded wafers cross section

Columns produced by:

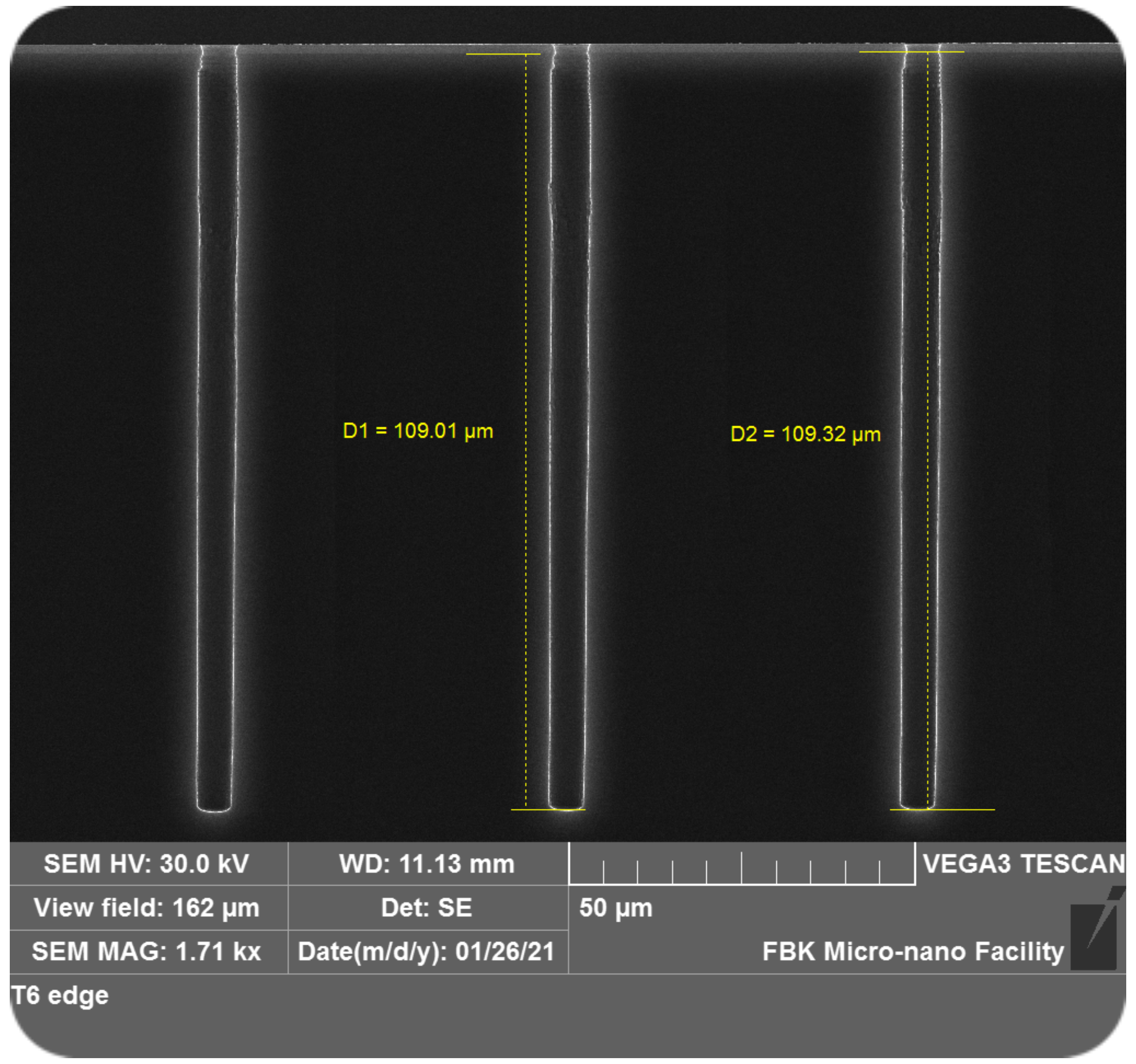
single-side **D**eep **R**eactive **I**on **E**tching - **DRIE** process optimised by *FBK* (less expensive than double-side process)

Silicon pixels: 3D *FBK* — single-side





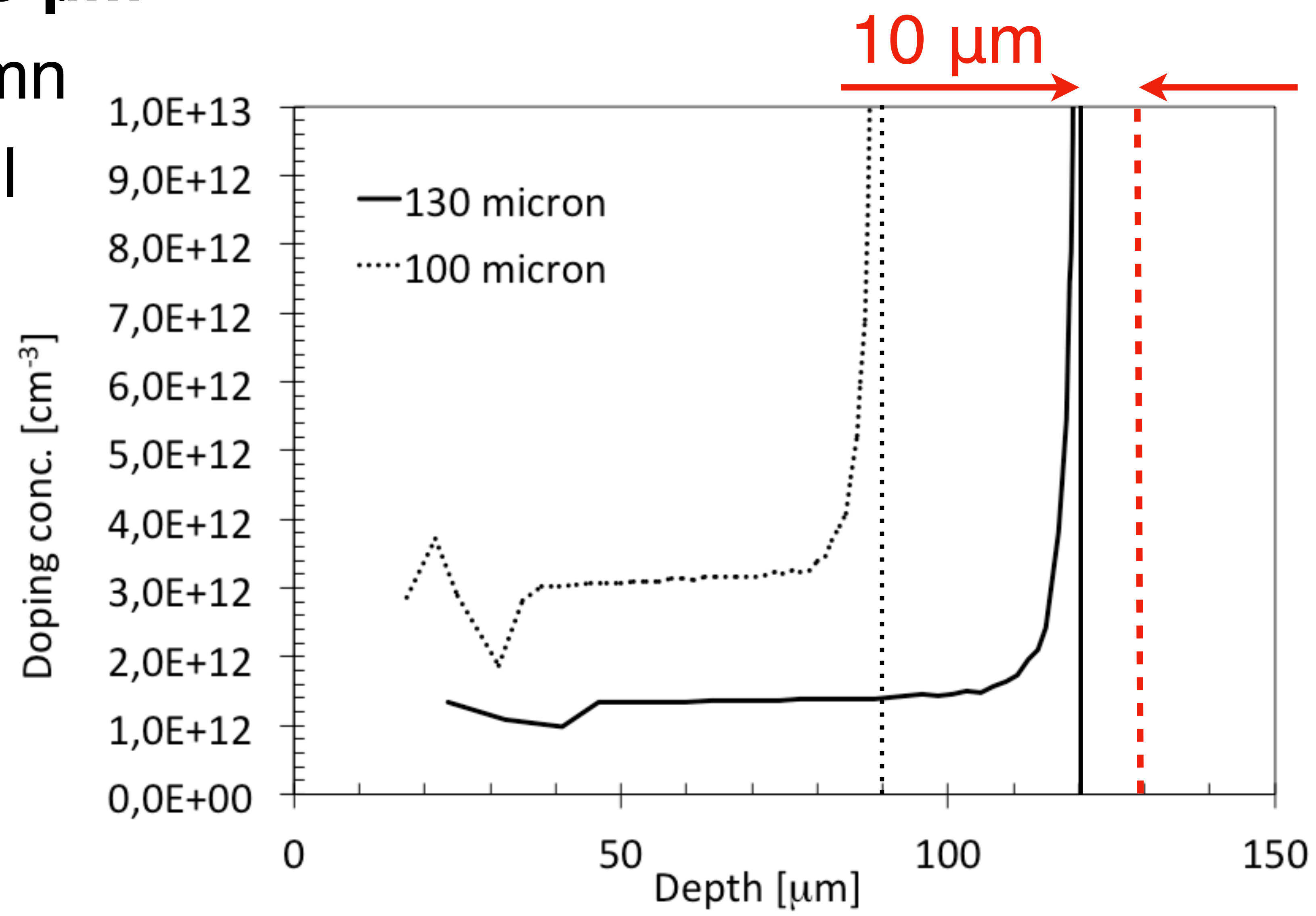
- **25x100 µm² pitch**
- Junction columns still to be filled with polysilicon



- **Column length 110±5 µm**
- 1E, one junction column electrode per pixel cell

Effective active layer **thickness reduced** by *Boron* diffusion from wafer carrier: **~10 µm**

Expected **M**ost **P**robable **V**alue - **MIP**: **~10190 e⁻** for **150 µm** active layer



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

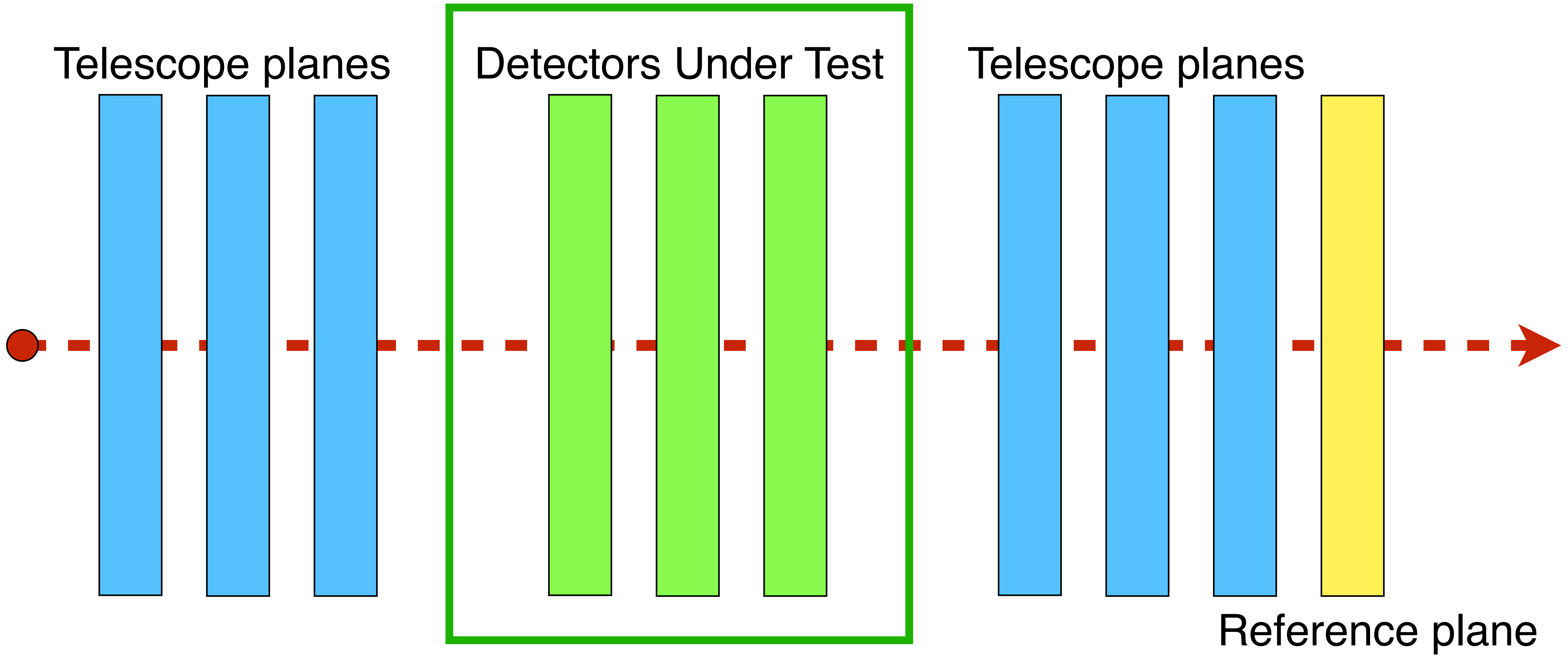
Material kindly granted by FBK

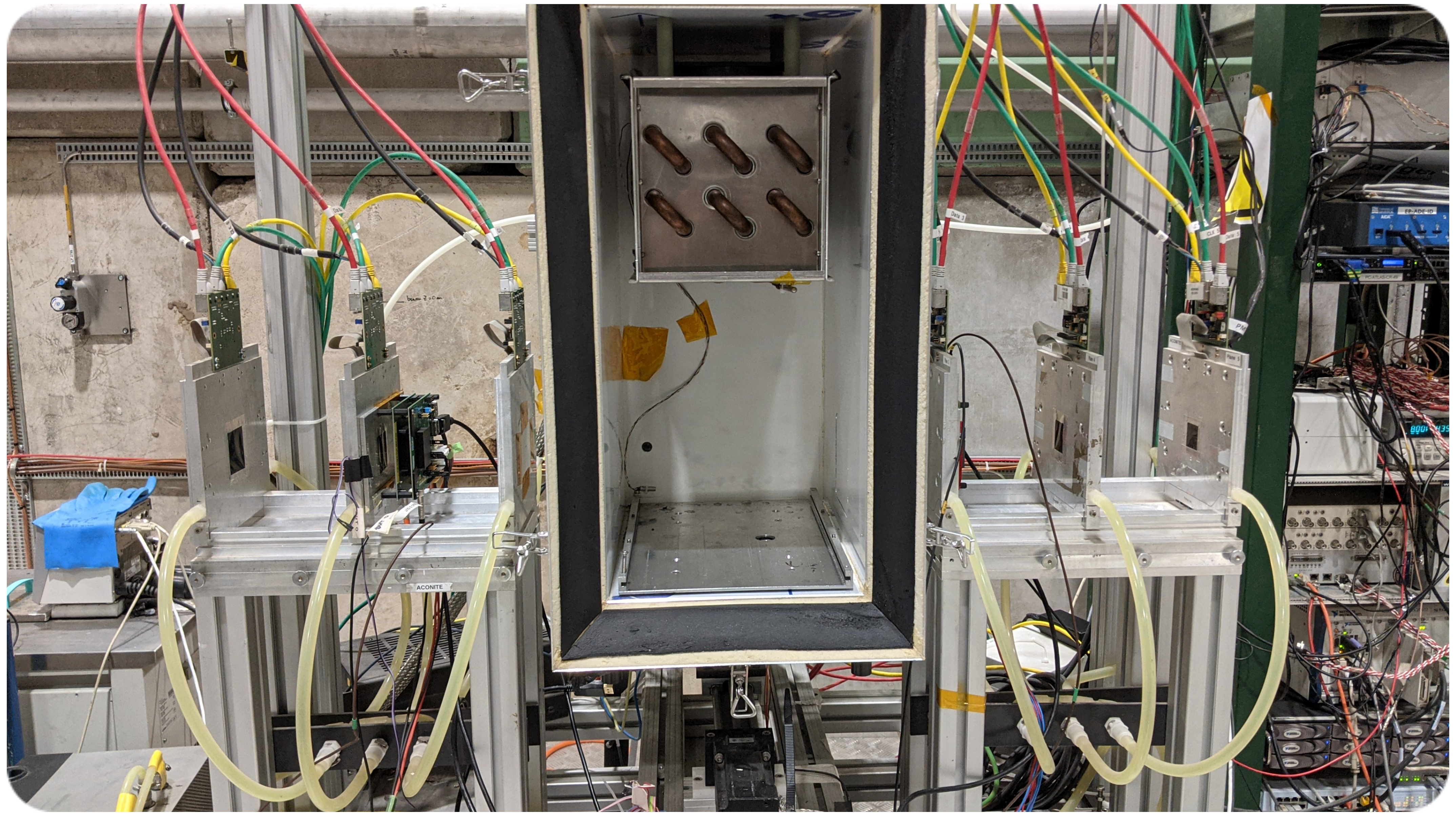
- *Sabina Ronchin*
- *Maurizio Boscardin*
- *Francesco Ficorella*

FBK JUNIOR RICERCA SCUOLA INNOVAZIONE

CNM sensors very similar to *FBK* but with **8 µm** column diameter (see backup slides)

Readout chip and testbeam setup





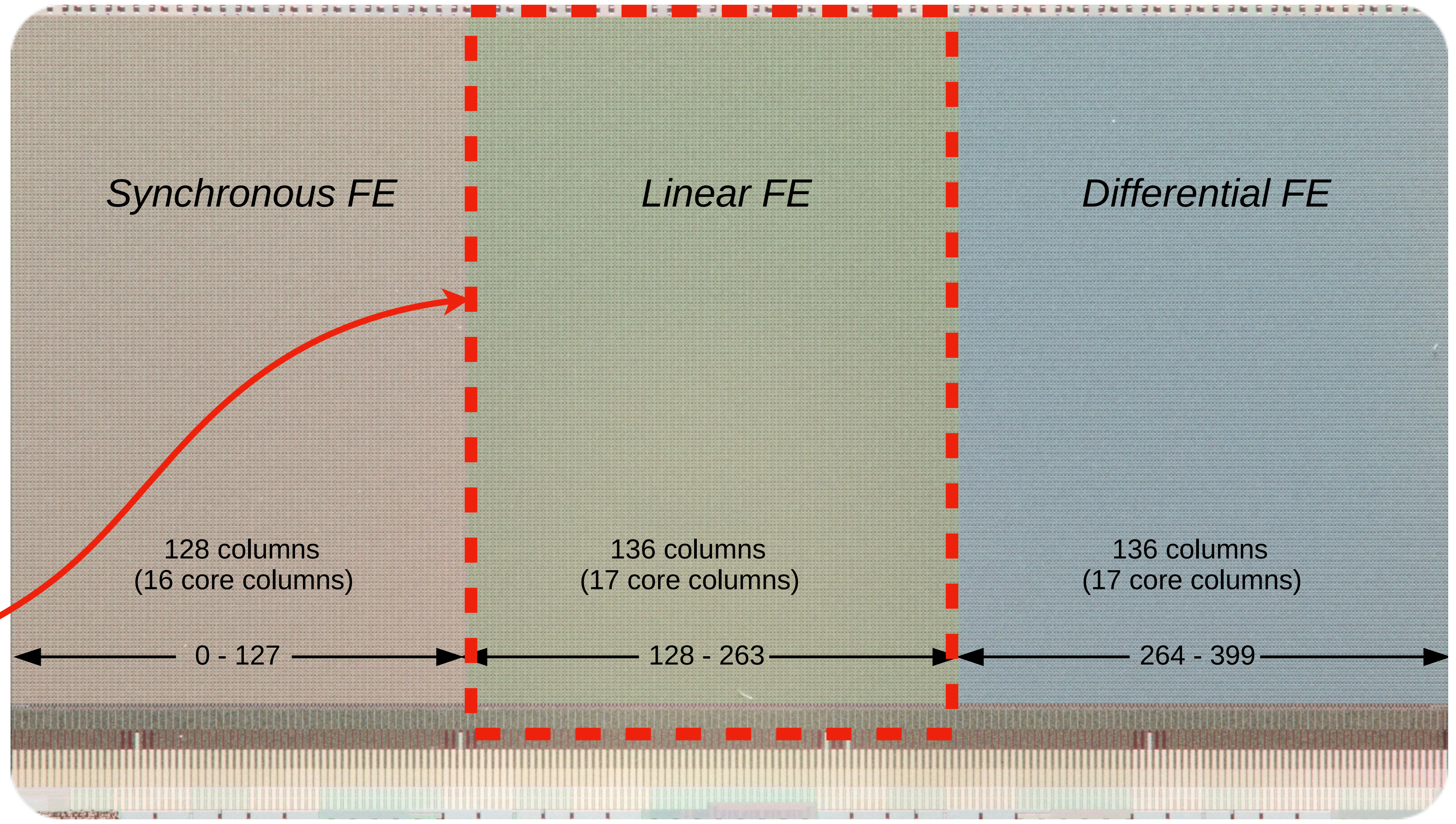
Jansen, H. et al., EPJ Techn Instrum 3, 7 (2016)

EUDET telescope on CERN SPS / DESY beam lines

- 120 GeV pions (CERN) / 5.2 GeV electrons (DESY)
- 5 or 6 pixel planes (depending on beam-area)
- Based on Mimosa26 chip, 18.4 µm pitch, square pixels, 576 rows x 1152 columns
- **~2 µm** resolution on each coordinate

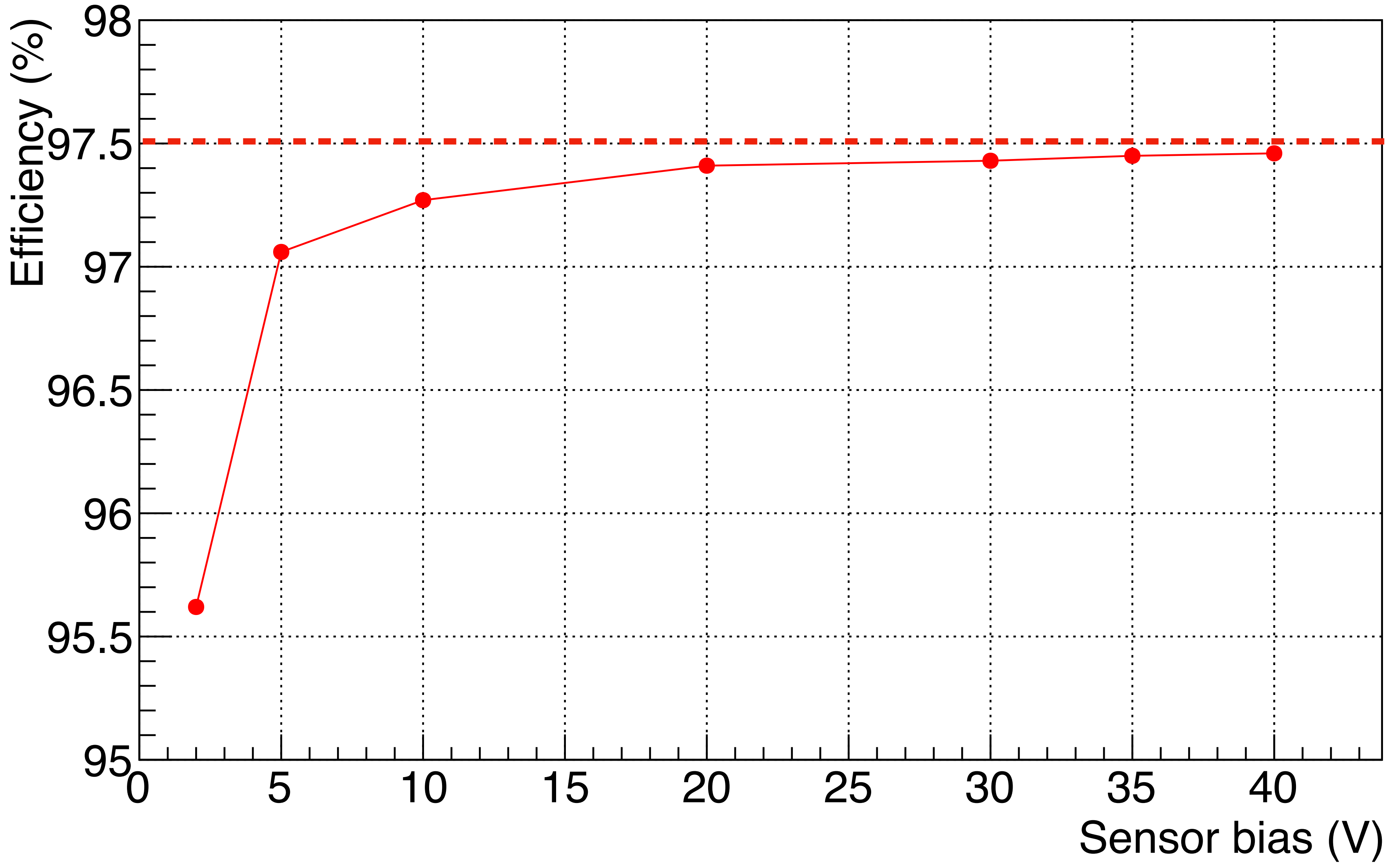
ReadOut Chip (ROC)

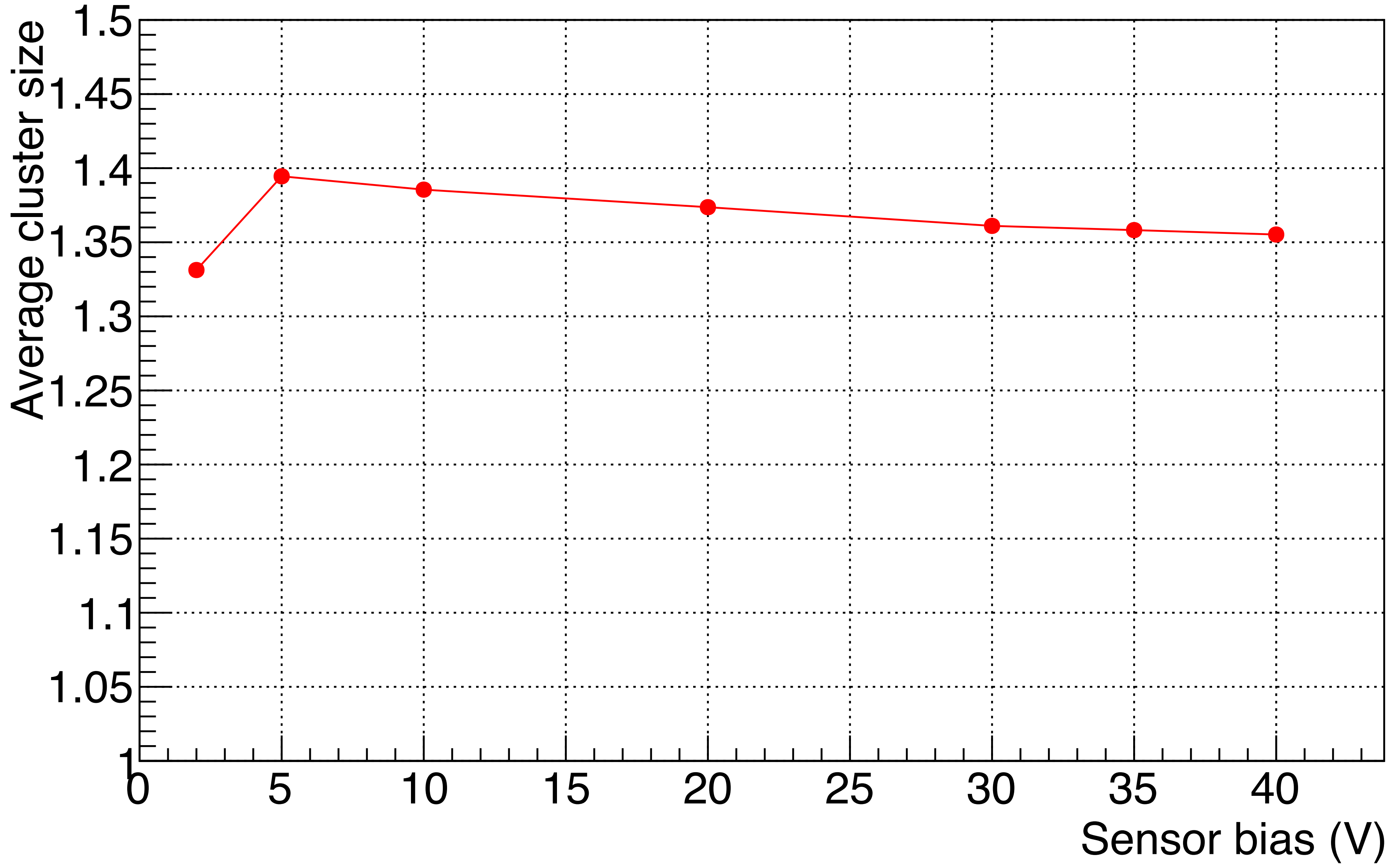
- Common CMS-ATLAS R&D (**RD53A**): 65 nm CMOS technology
- 3 frontends, CMS chose linear-frontend: **192** rows x **136** columns
- Readout multiple bunch crossings
- Global threshold with **per pixel 4 bit threshold trimming**
- **Time-over-Threshold** hit charge measurement with **4 bits ADC**



Readout chip prototype **RD53A**

Results: 3D *CNM* non-irradiated

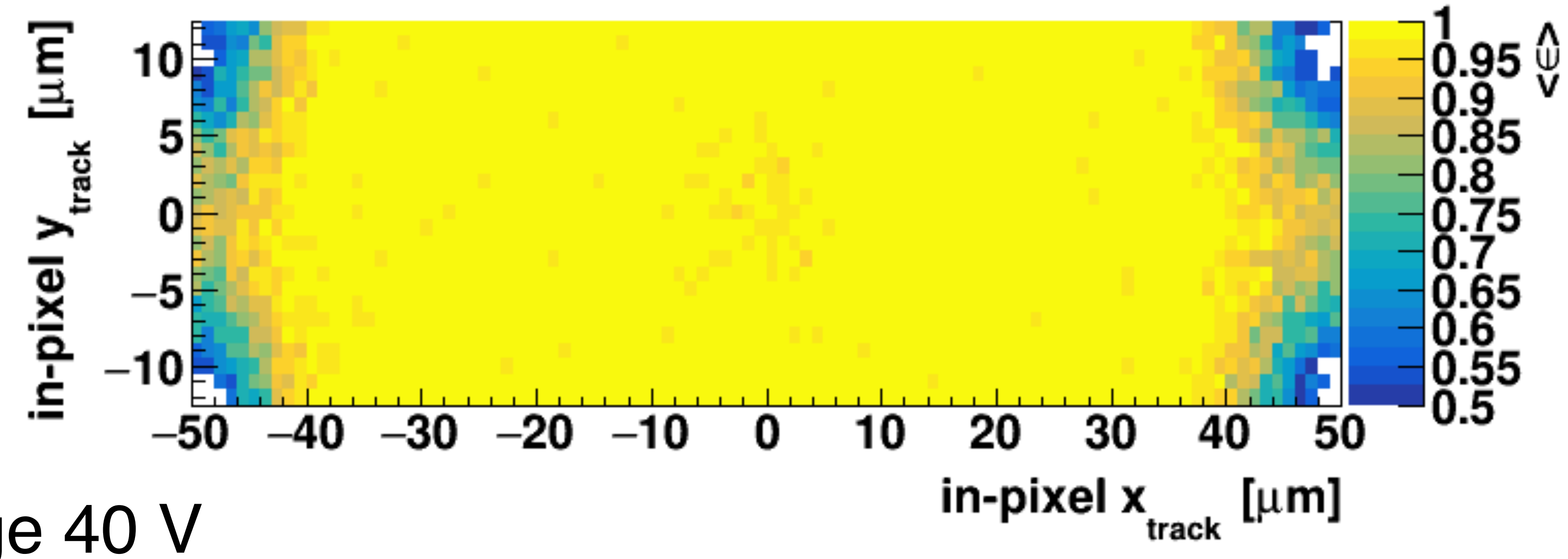




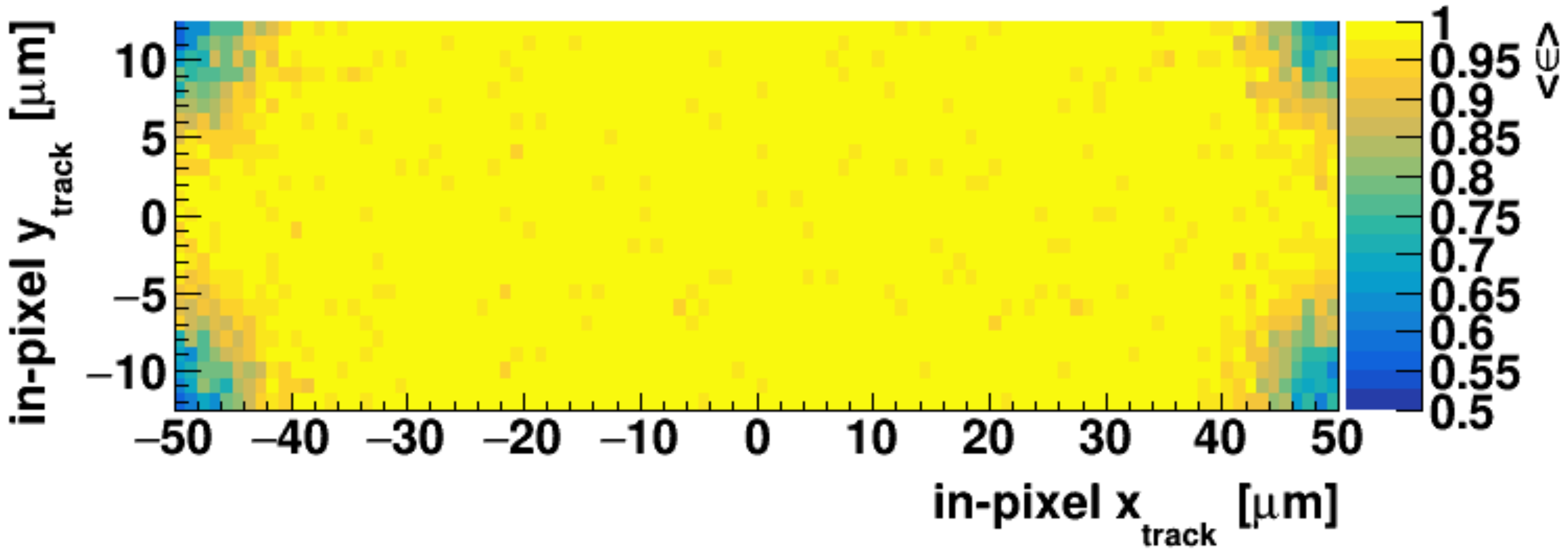
Efficiency stops at 97.5%:

- Ohmic column inefficiency
- 4-pixel sharing and relatively high threshold

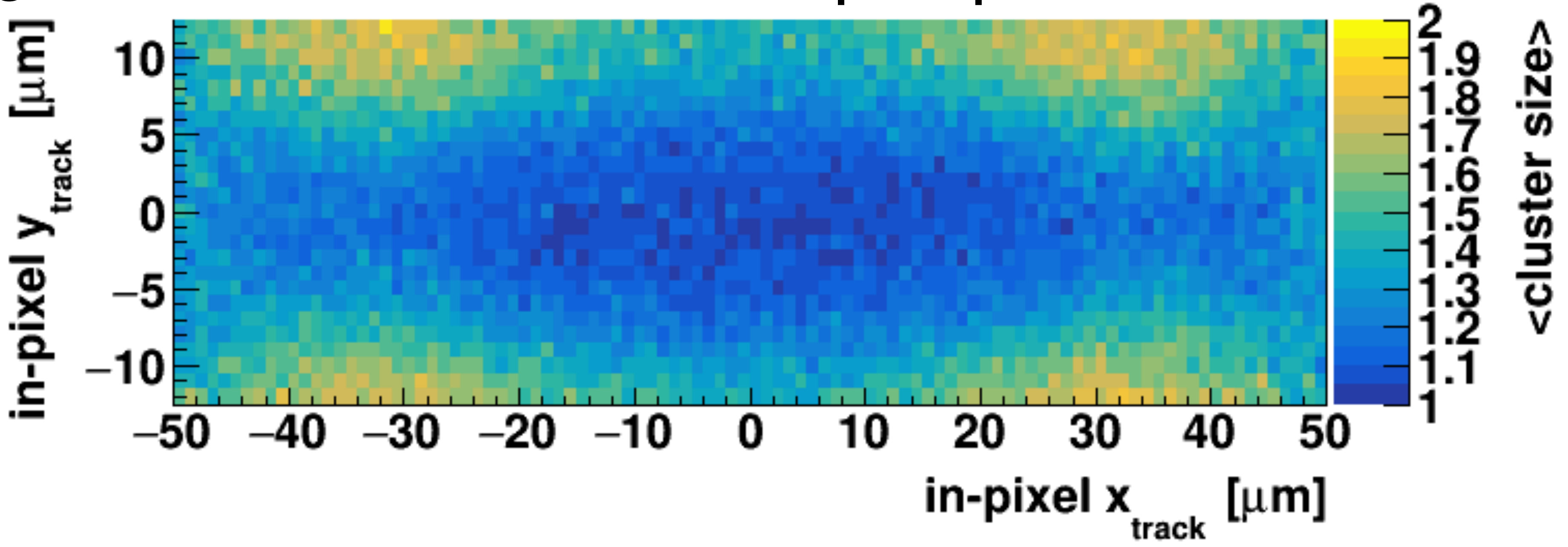
Bias voltage 2 V — Efficiency maps in pixel cell



Bias voltage 40 V



Bias voltage 40 V — Cluster size map in pixel cell



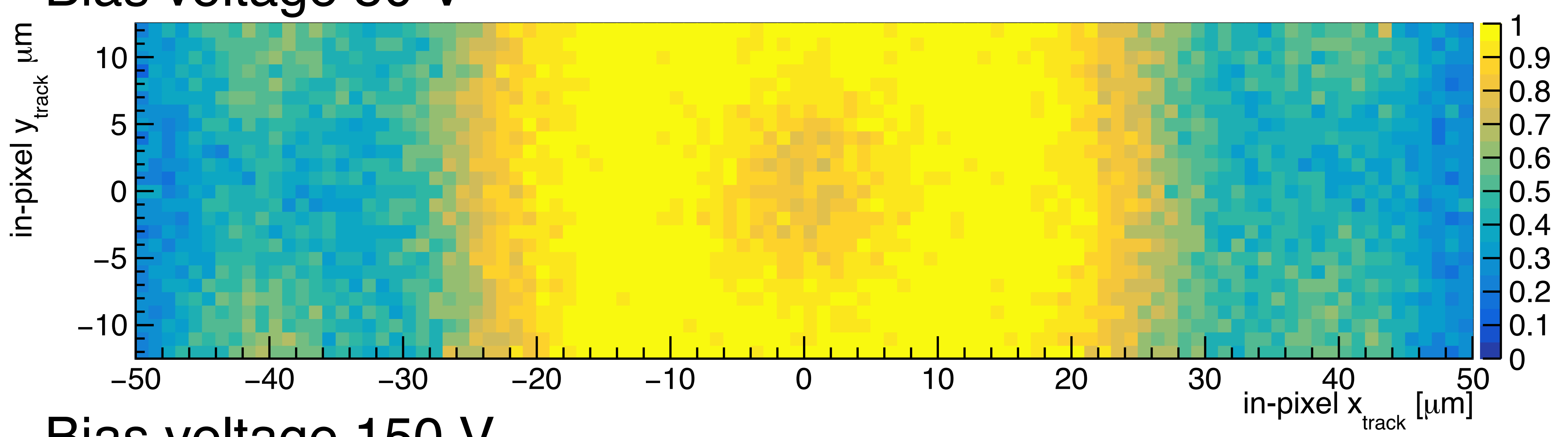
All data shown refers to:

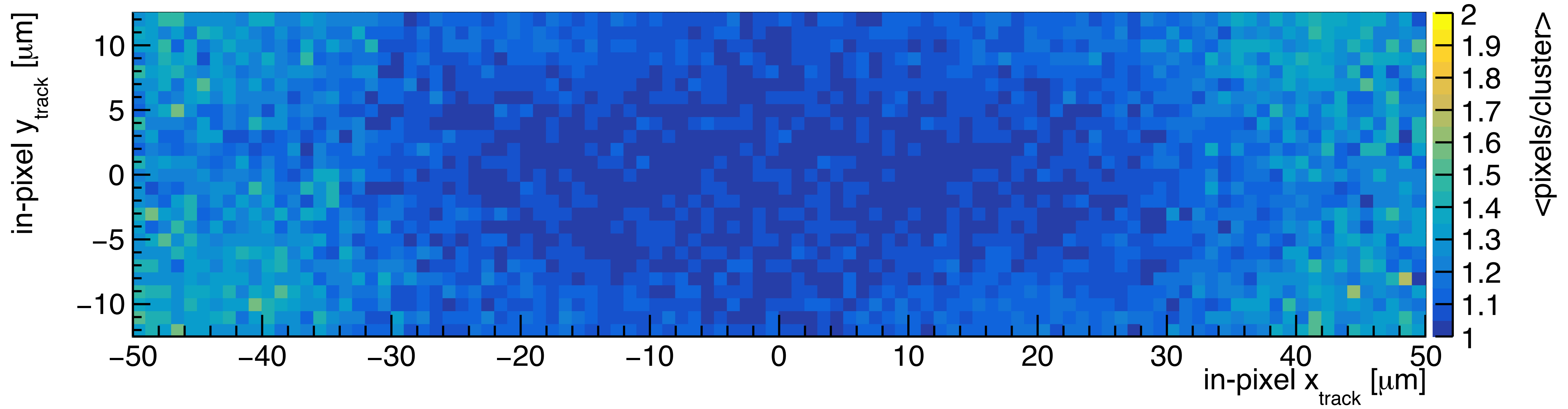
- Normal incidence
- Threshold **2500 e^-**

*Results from irradiated 3D **CNM** will be available very soon*

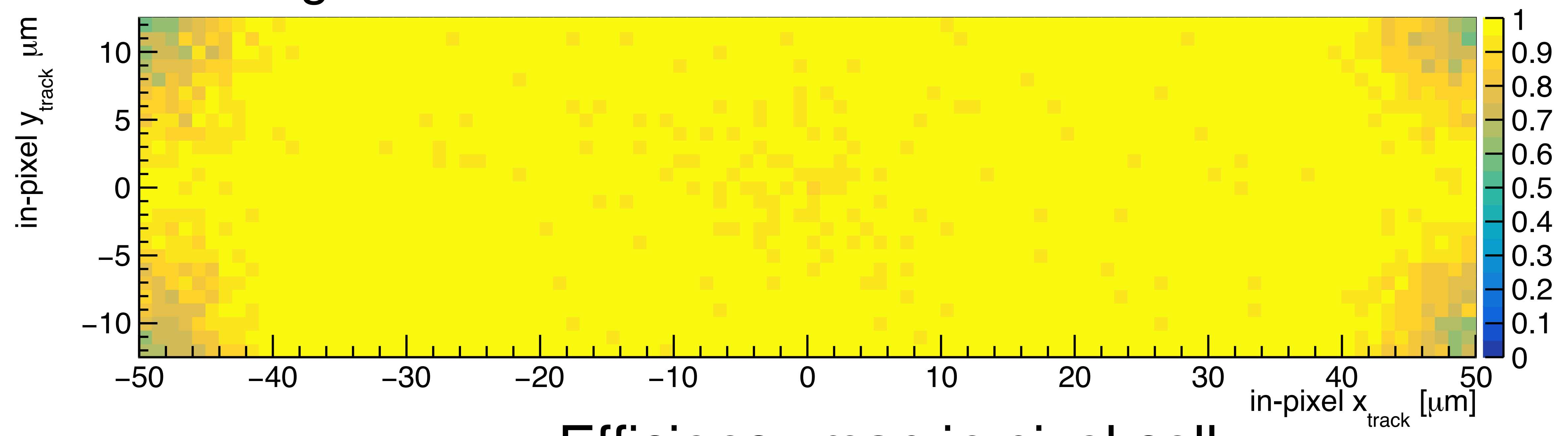
Results: 3D *FBK* irradiated at $1.5 \times 10^{16}\ n_{eq}/cm^2$

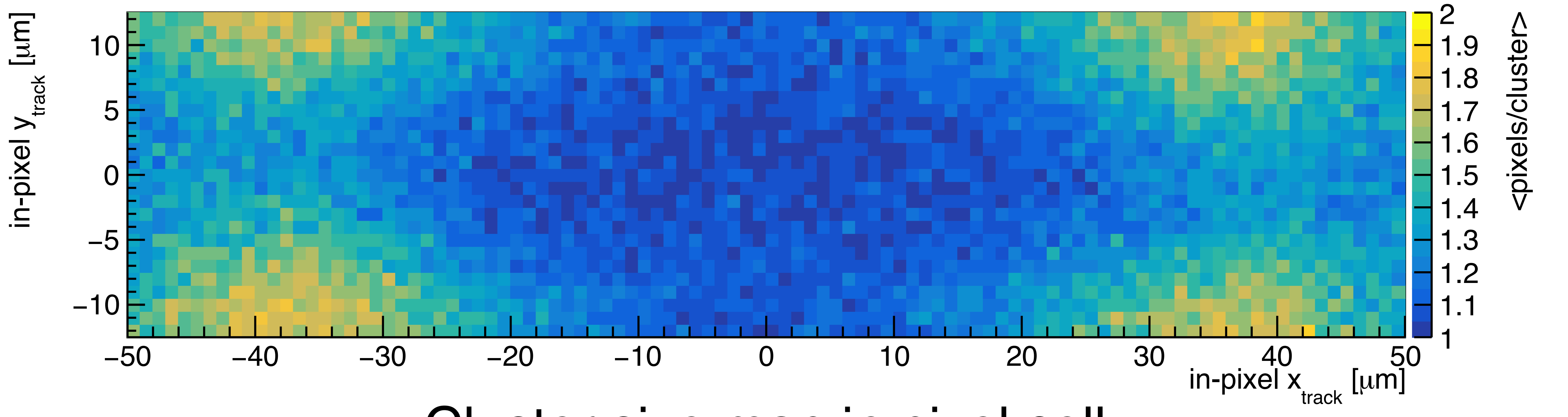
Bias voltage 50 V





Bias voltage 150 V

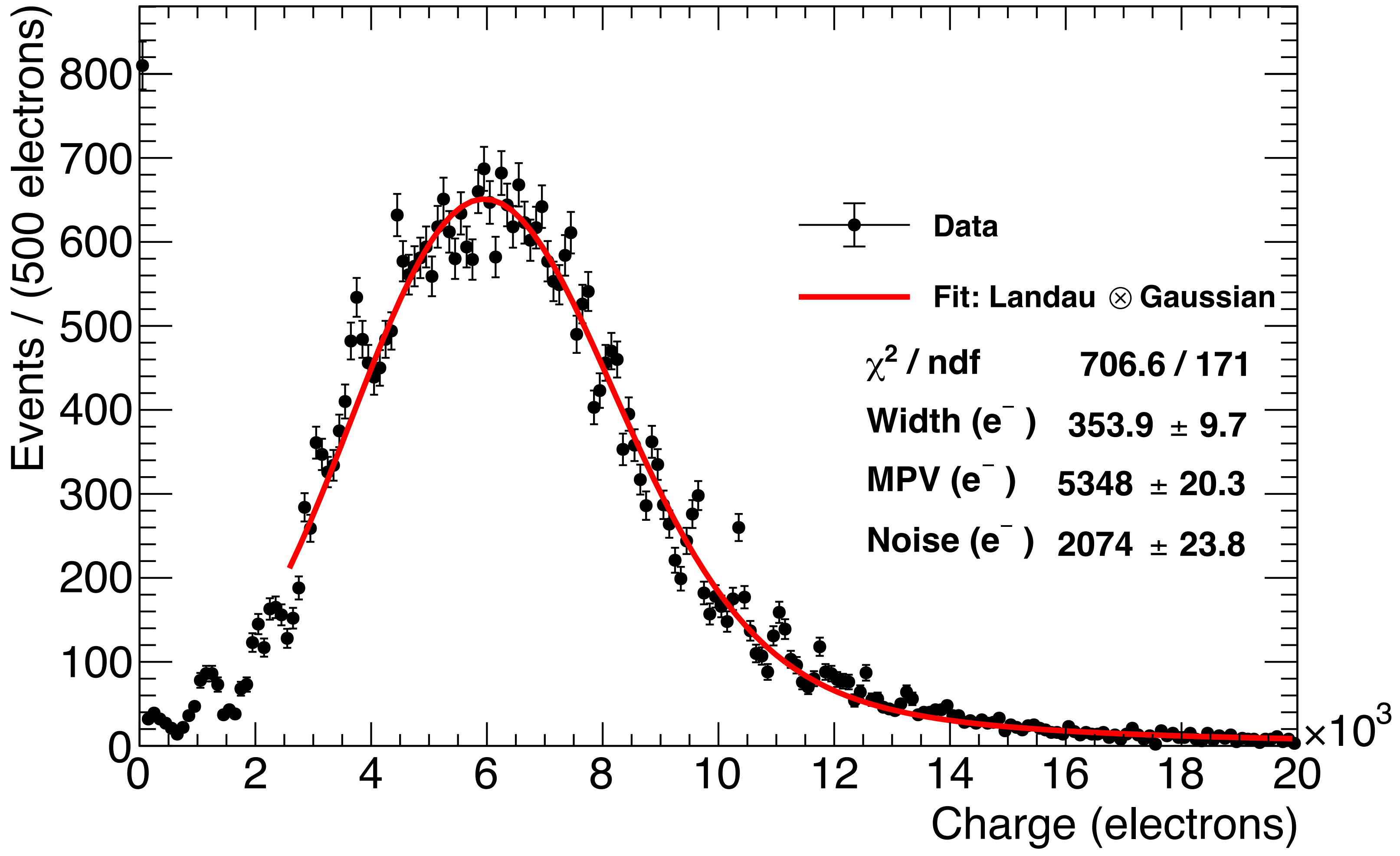




Efficiency map in pixel cell

Cluster size map in pixel cell

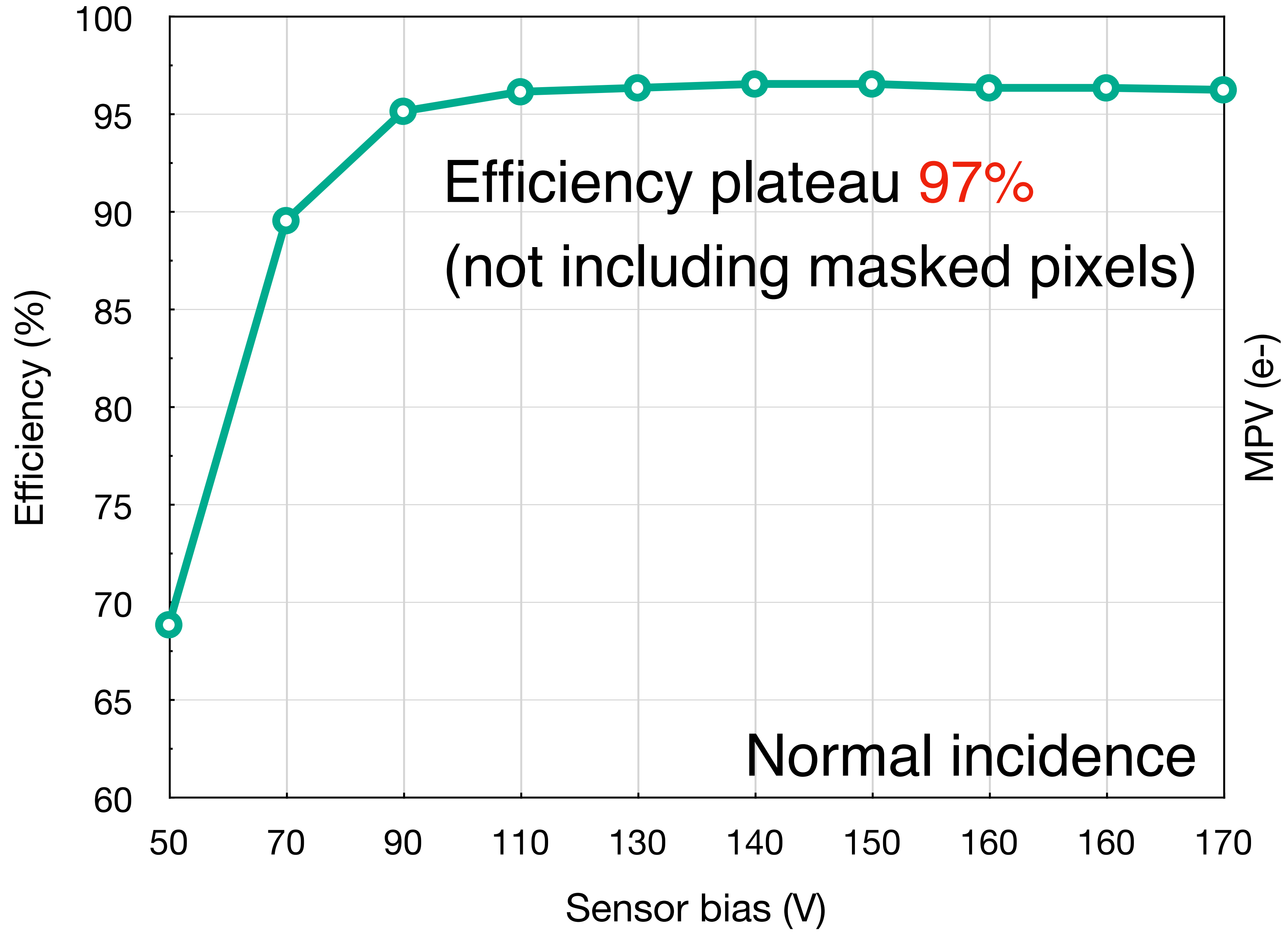
Landau distribution measured at bias voltage 120 V

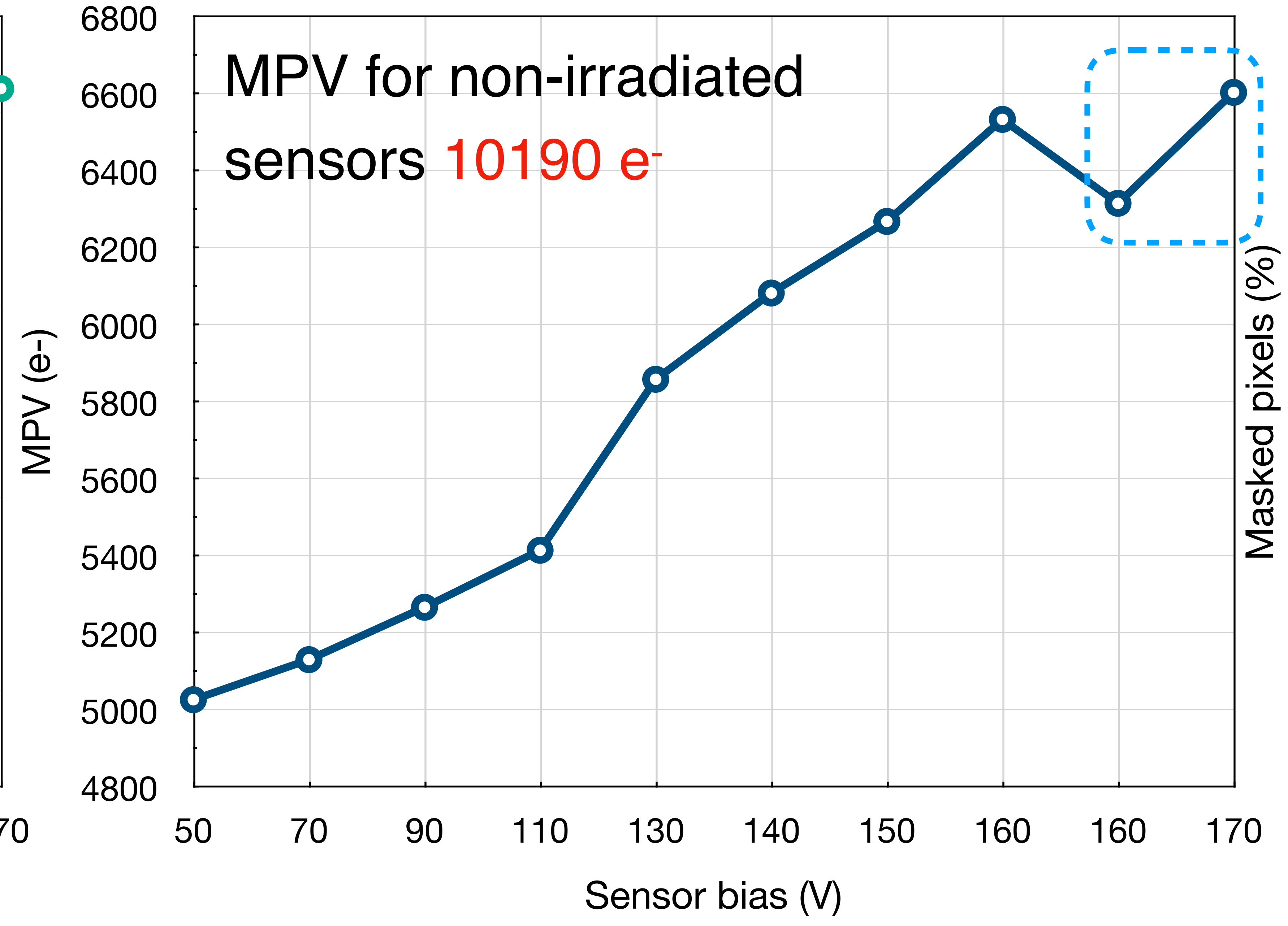


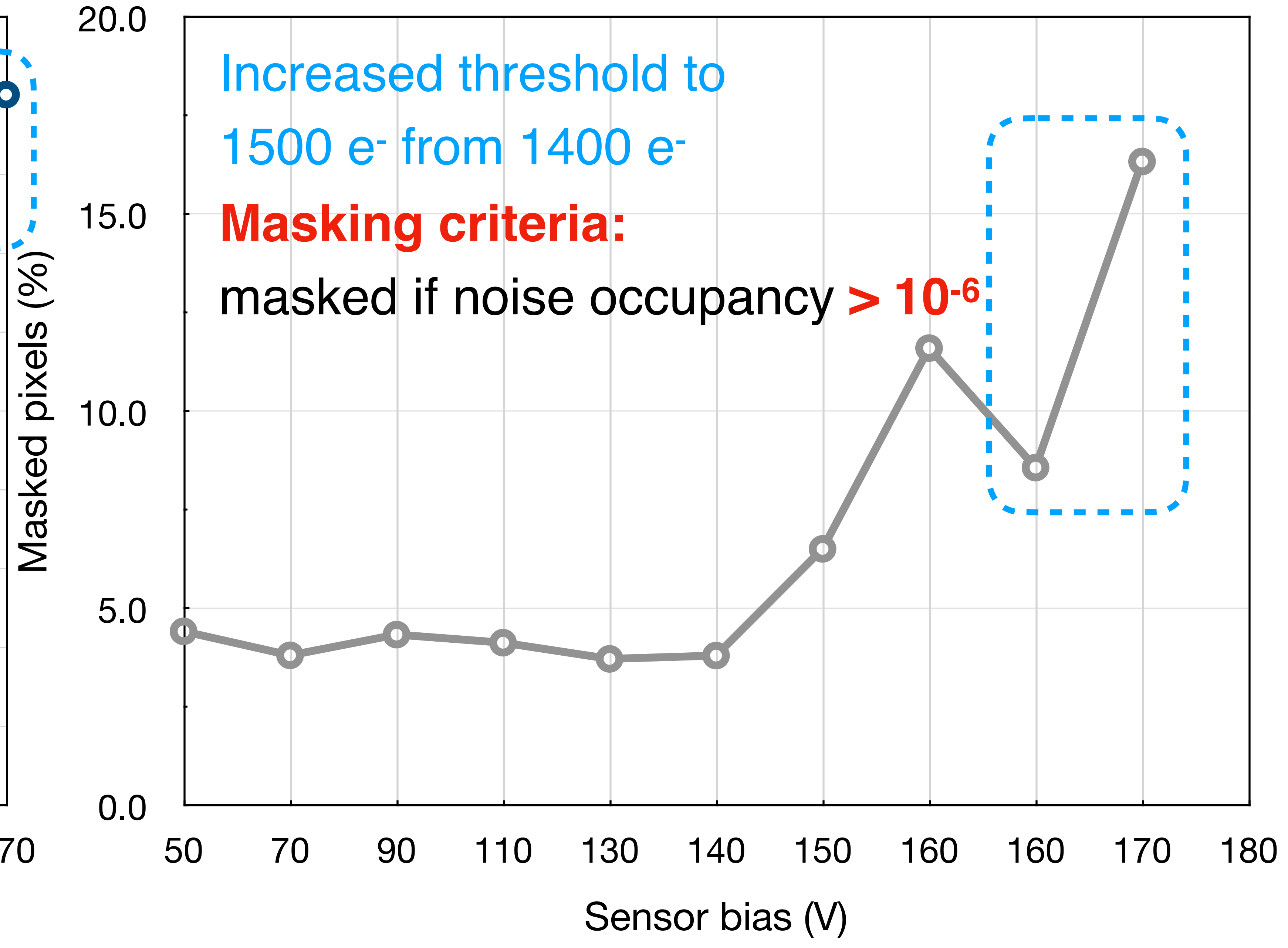
All data shown refers to:

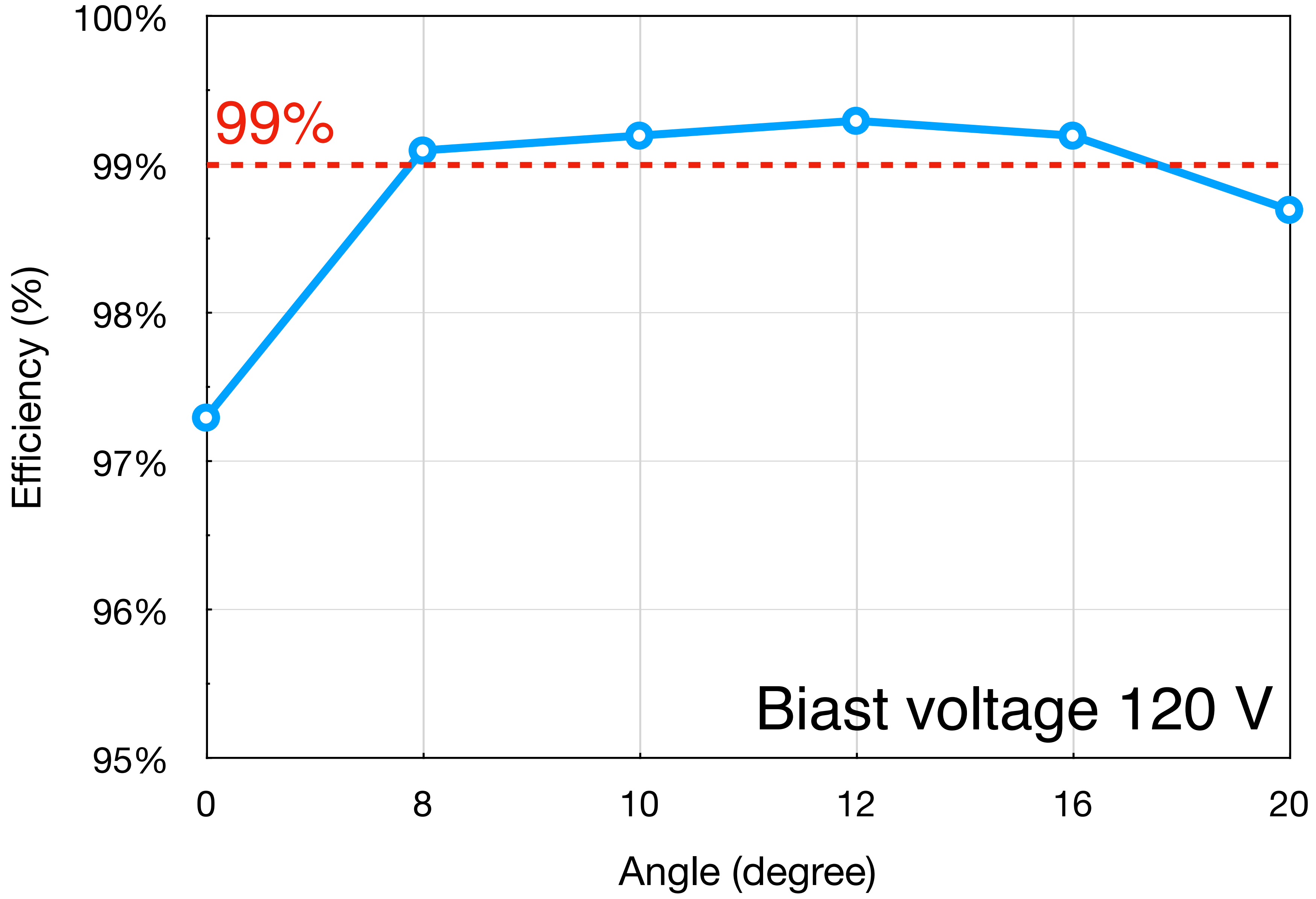
- Normal incidence
- Threshold **1400 e^-**
- Irradiated at **1.5**$\times 10^{16}\ n_{eq}/cm^2$ at **KIT** (25 MeV protons, **uniform irradiation**)
- Temperature -30/-20°C (near sensor)

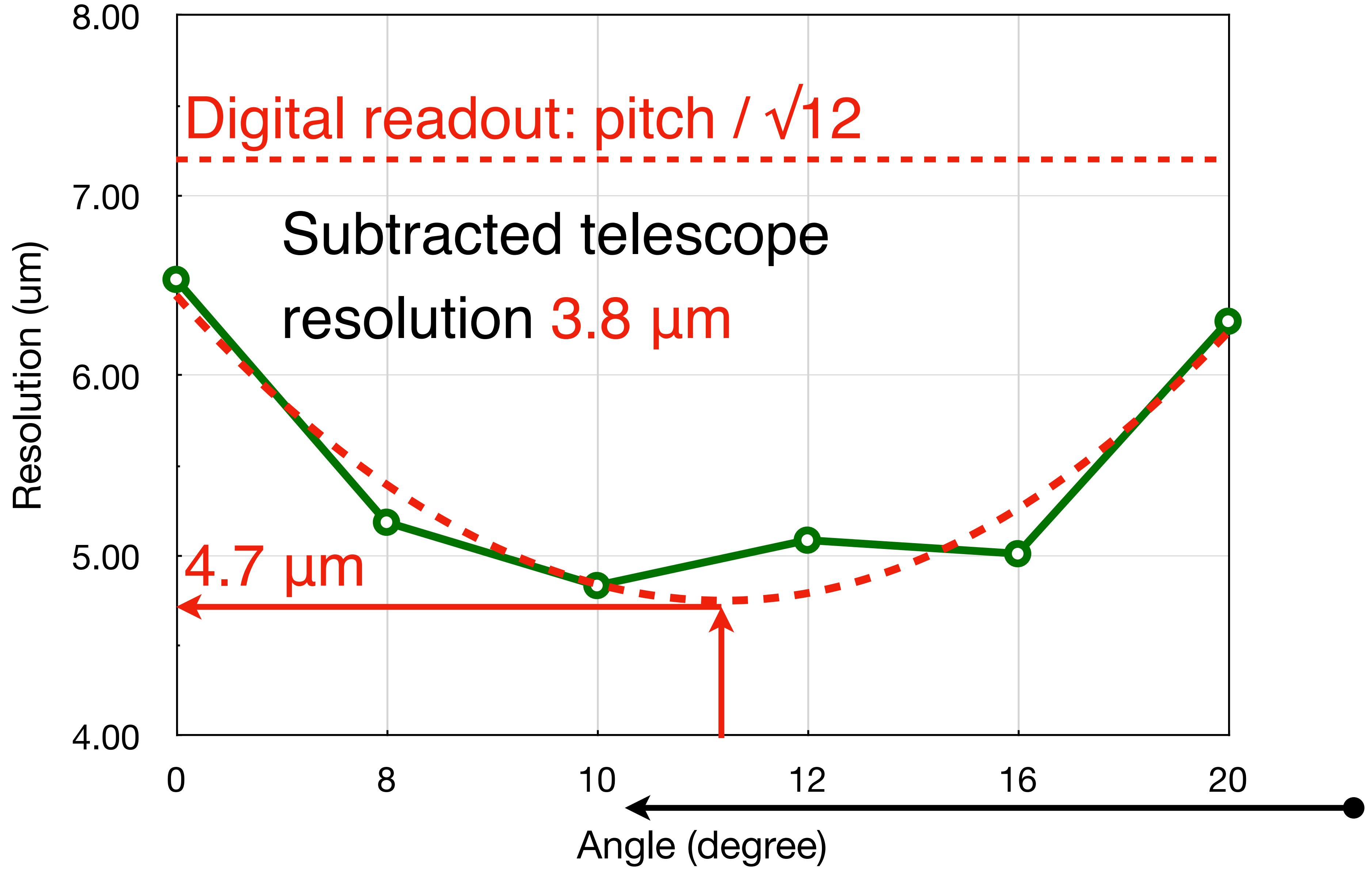
Results: 3D FBK irradiated at 1.5×10^{16} n_{eq}/cm^2







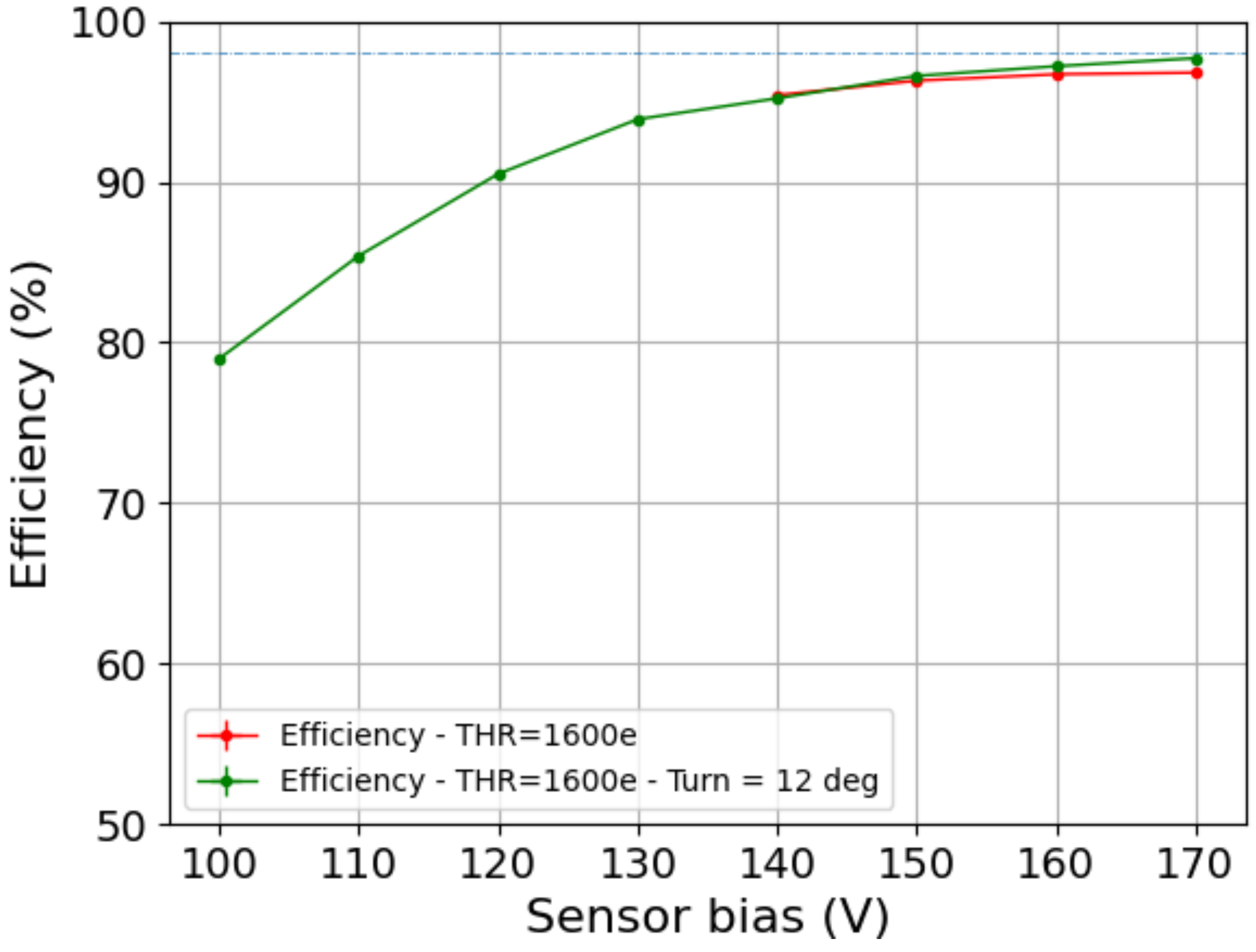




Relatively high number of masked pixels ➜ under investigation

Can be mitigated by increasing the threshold, as backup plan a replacement of barrel layer 1 can be foreseen when needed, maybe earlier than anticipated

Best resolution expected at `atan(25/140)` ≃ `10` degrees



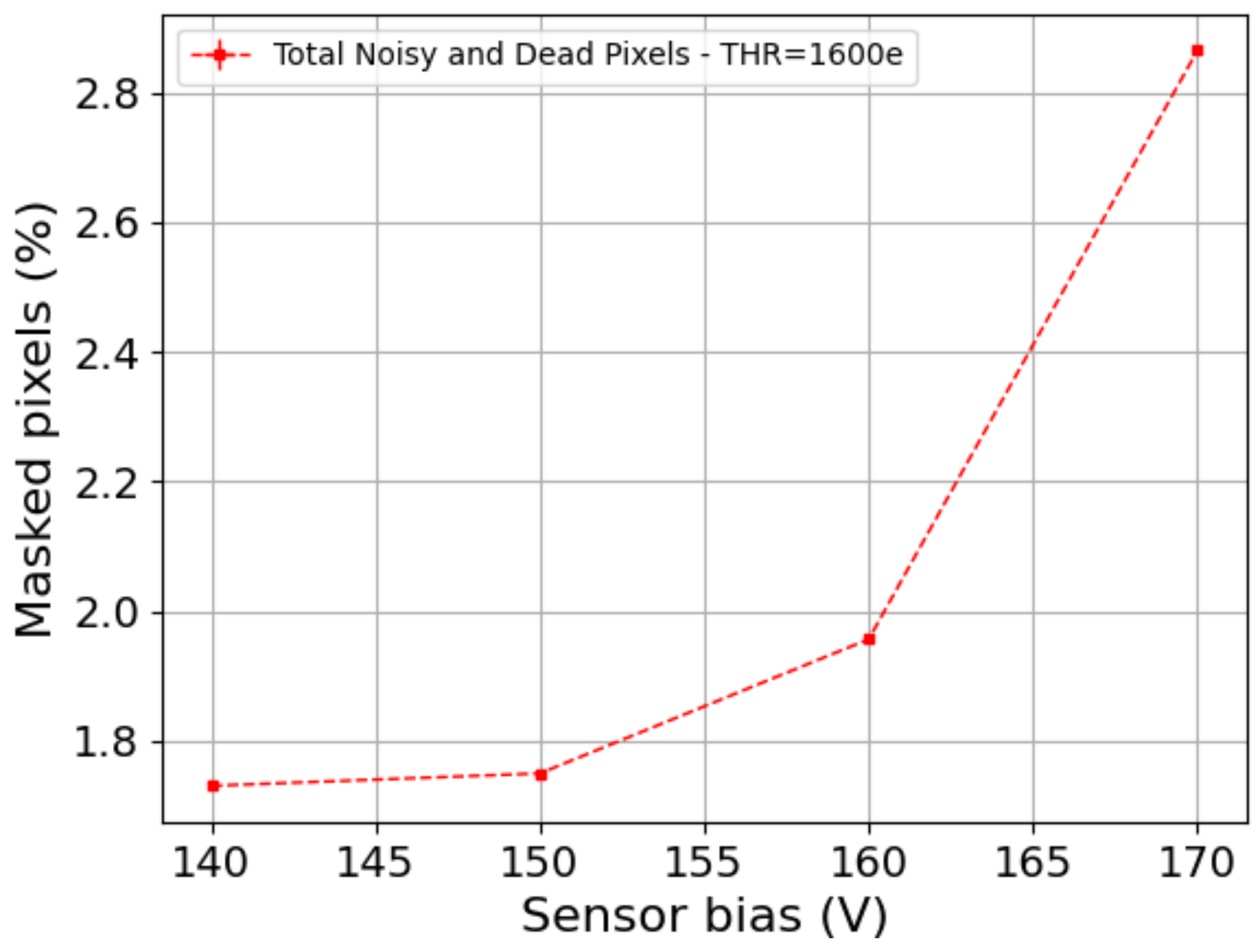
⬅ **98%** efficiency

Efficiency vs sensor bias

(not including masked pixels)

— normal incidence

— 12^o incidence angle



Masked pixels vs sensor bias

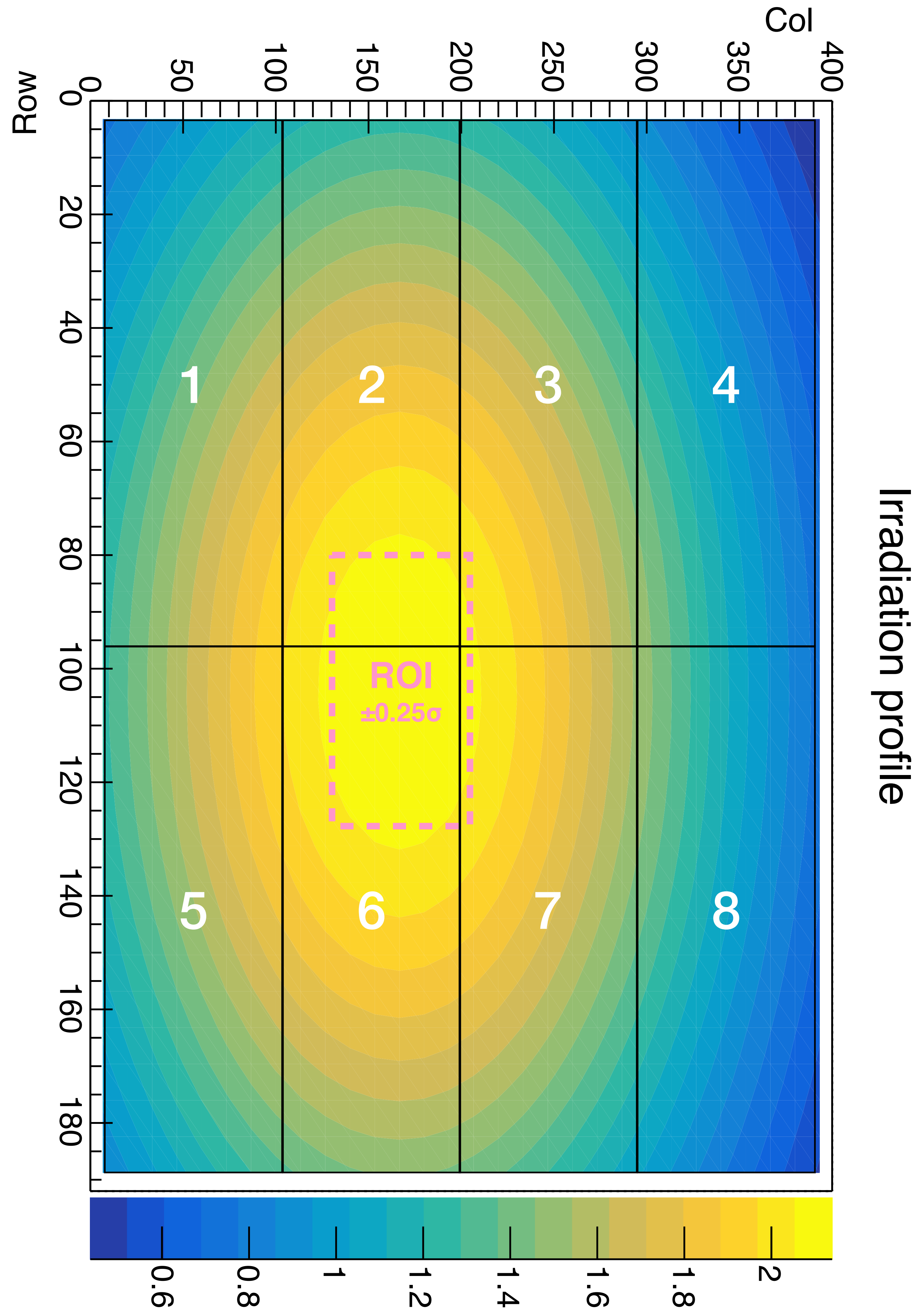
Masking criteria:

masked if noise occupancy **> 2x10^{-5}**

All data shown refers to:

- Threshold **1600 e^-**
- Irradiated at 1.8x10^{16} n_{eq}/cm^2 at **KIT** (25 MeV protons, **uniform irradiation**)
- Temperature -20^oC (near sensor)

Results: 3D *FBK* irradiated at 2.1-2.6 $\times 10^{16}$ n_{eq}/cm^2



Irradiation profile on sensor surface

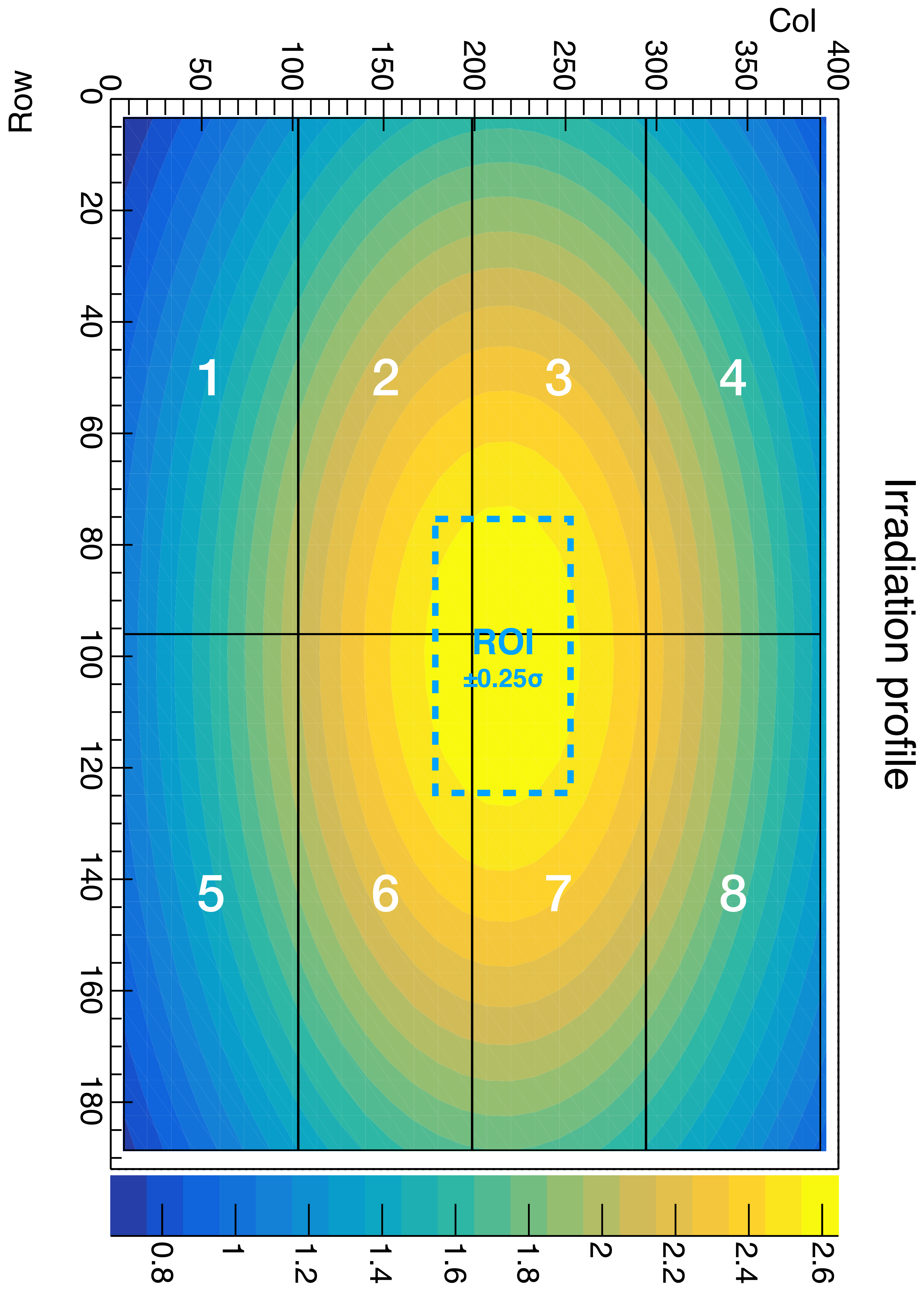
ROI (±0.25σ): (2.10±0.08) $\times 10^{16}$ n_{eq}/cm^2, variability **0.03**

Irradiated at **CERN PS** (24 GeV protons, beam narrower than sensor size)

Dosimetry evaluation

1. Aluminum foil placed on sensor surface during irradiation campaign
2. Cut into **8** pieces and measured activity
3. Fit with bivariate Normal distribution
   - no correlation
   - constraints on widths
   - constraint on position along rows
4. Define a **R**egion **O**f **I**nterest - **ROI** of ~uniform irradiation

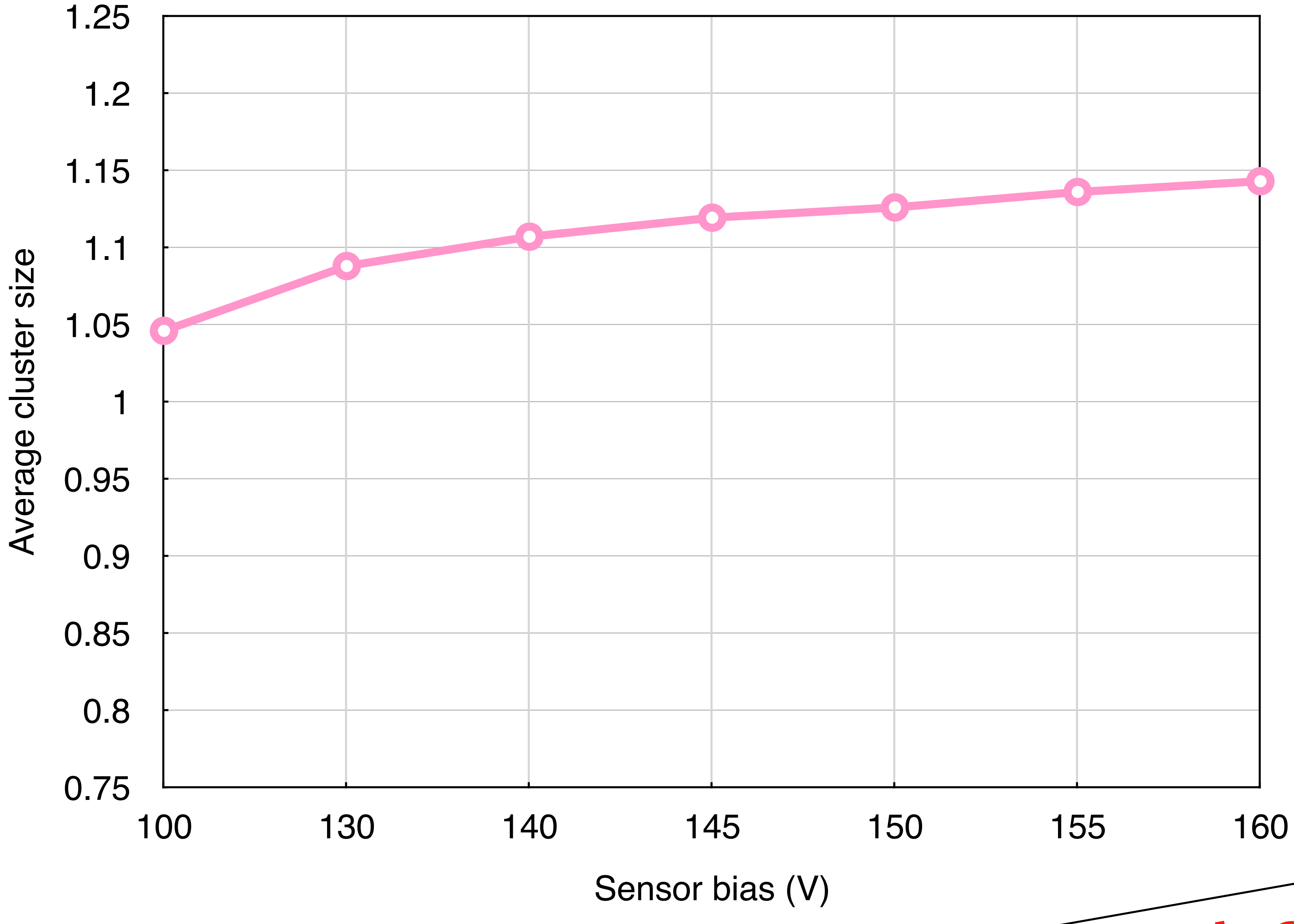
Standard deviation of fluence in ROI

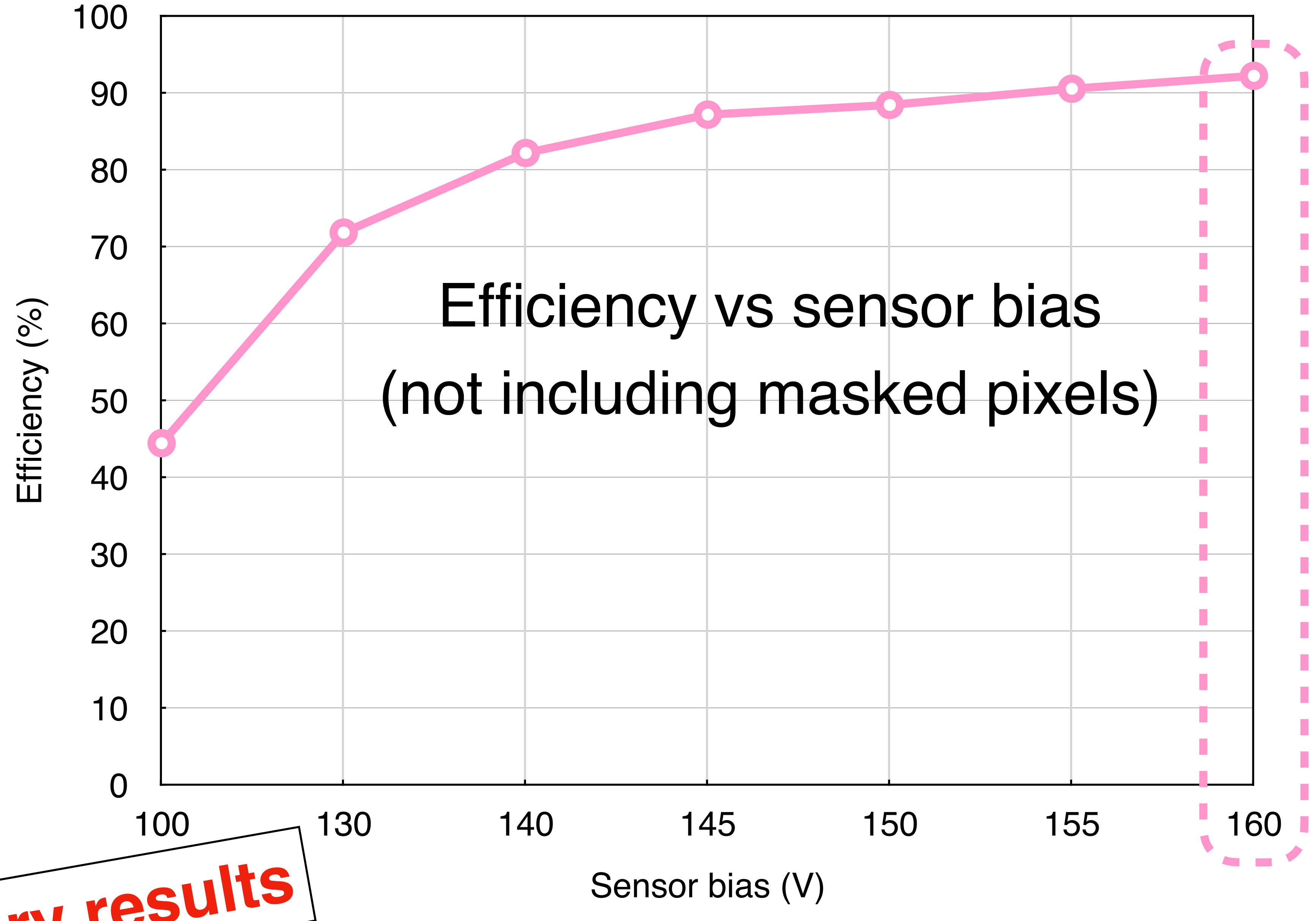


Irradiation profile on sensor surface

ROI (±0.25σ): (2.60±0.09) $\times 10^{16}$ n_{eq}/cm^2, variability **0.03**

Results: 3D *FBK* irradiated at 2.1-2.6 $\times 10^{16}$ n_{eq}/cm^2

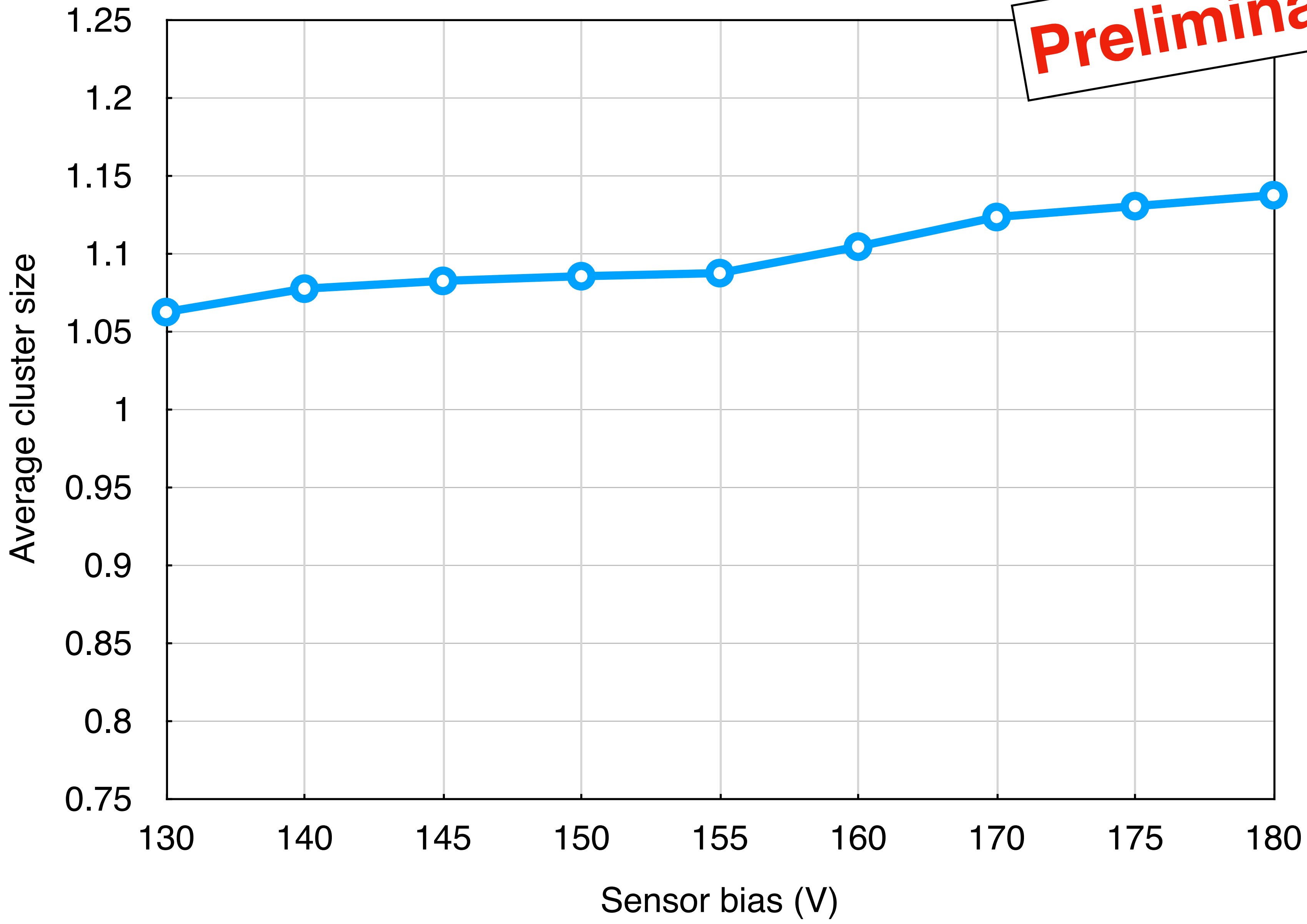


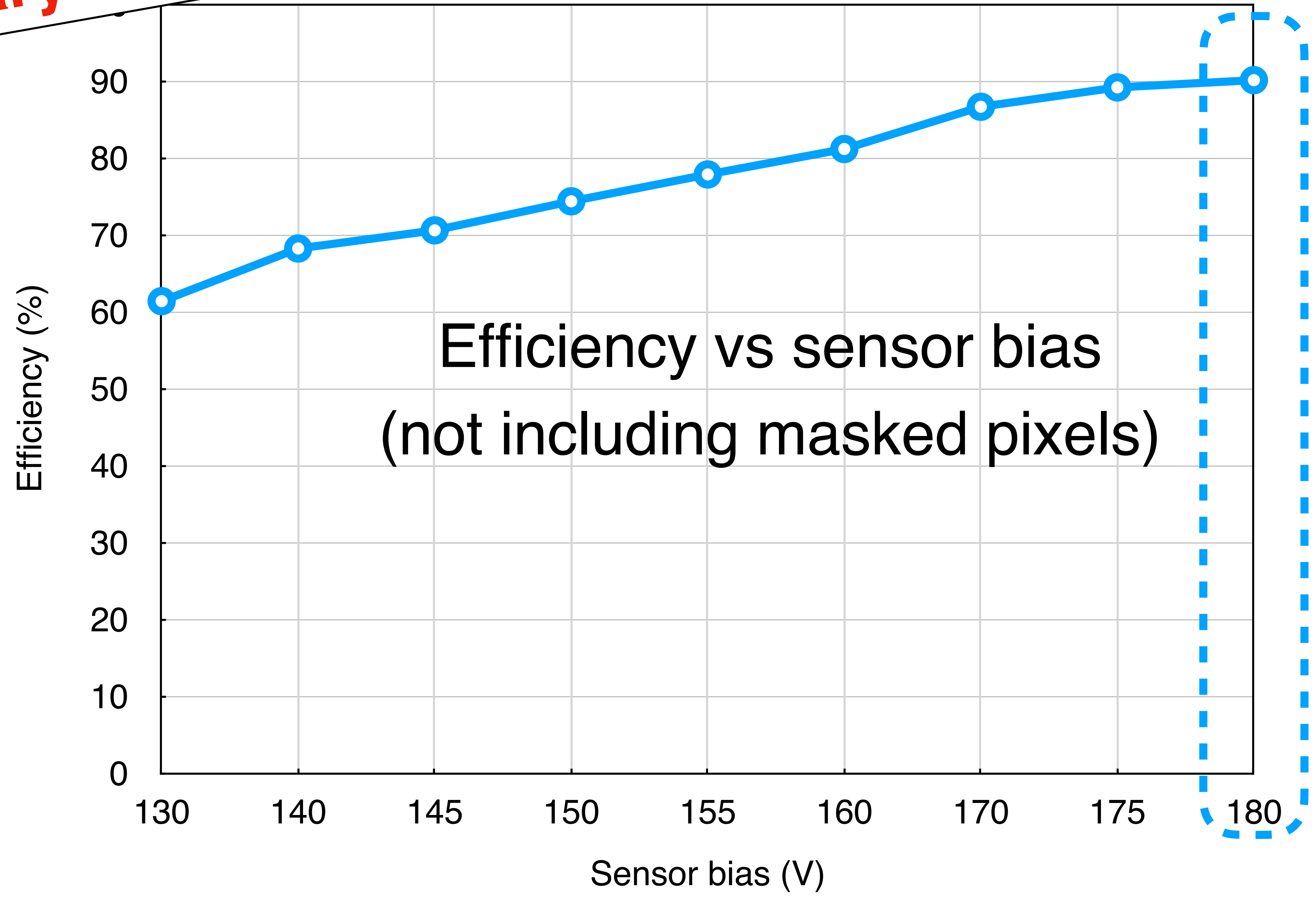


- Normal incidence
- Fluence in ROI (**2.10**±0.08) $\times 10^{16}$ n_{eq}/cm^2, variability 0.03
- Threshold **2000 e^-**

- Efficiency 92%
- Masked pixels ~7%

Preliminary results





- Normal incidence
- Fluence in ROI (**2.60**±0.09) $\times 10^{16}$ n_{eq}/cm^2, variability 0.03
- Threshold **1900 e^-**

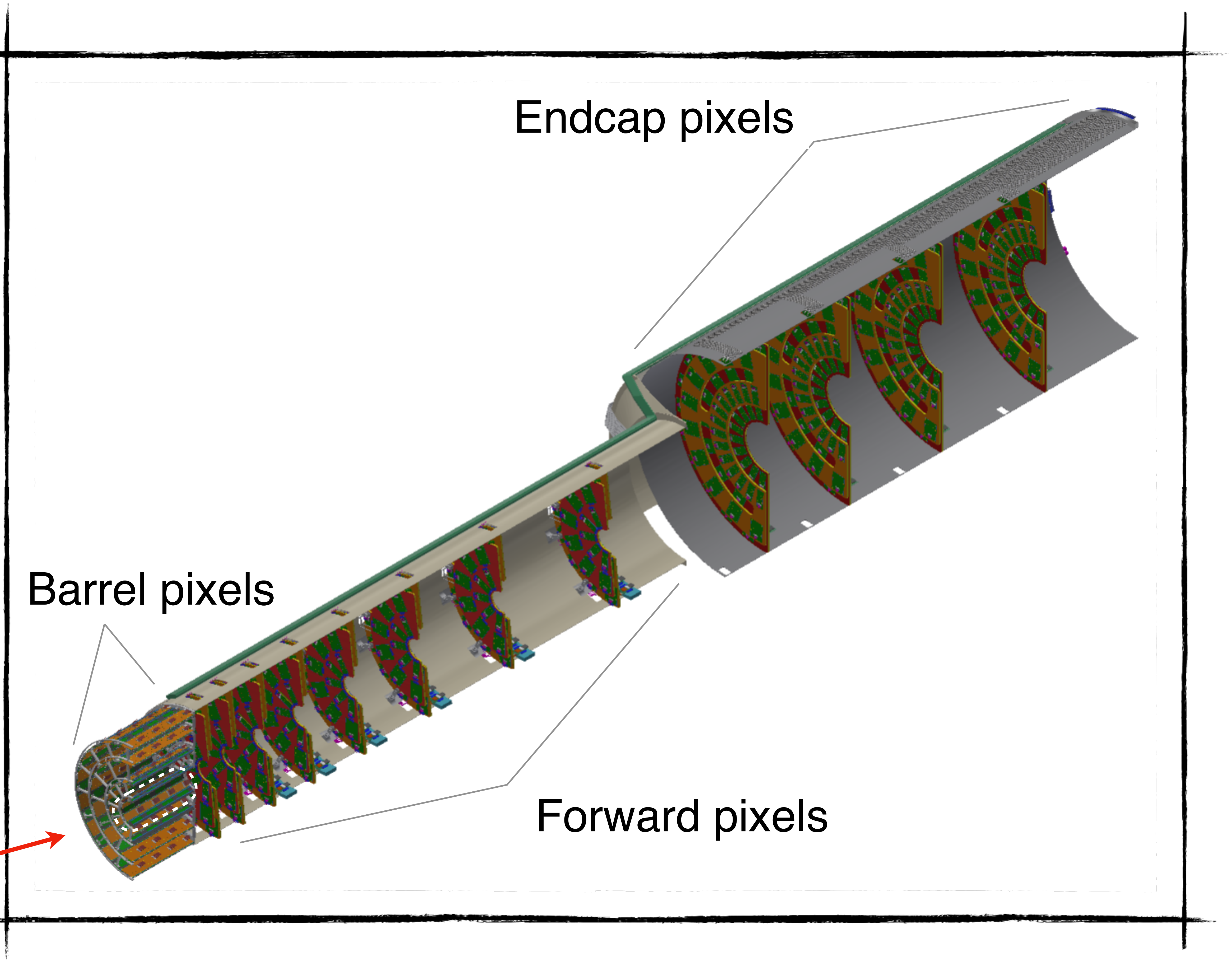
- Efficiency 90%
- Masked pixels ~4%

Masking criteria:
masked if noise occupancy **> 2×10^{-5}**

We presented the status of the CMS **3D sensor R&D**

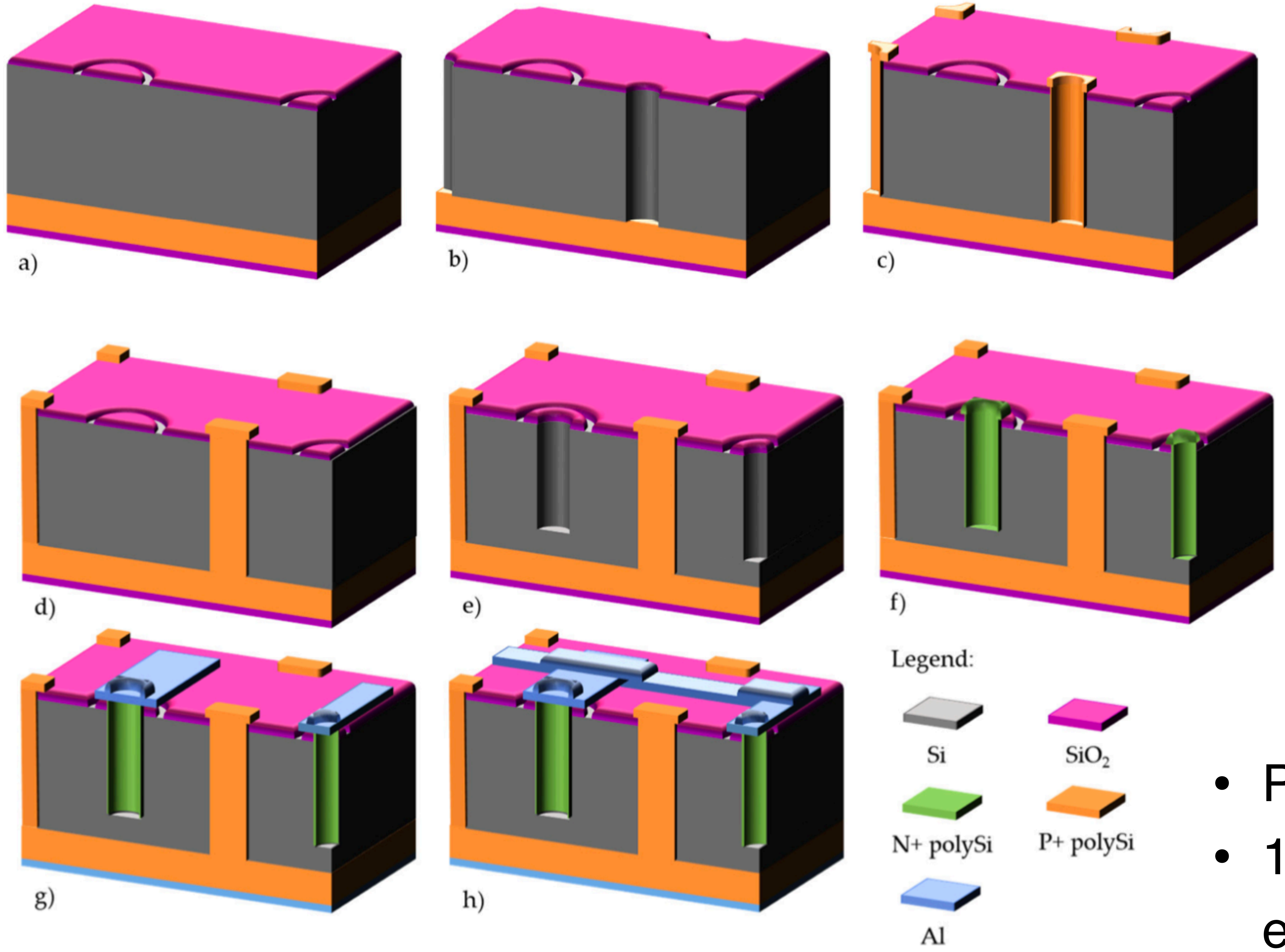
- **3D pixels** are baseline choice for **barrel layer 1**
- Tested at different fluencies up to **2.6×10^{16} n_{eq}/cm^2**
- Overall performances are extremely encouraging
  - Large increase of noisy pixels vs bias at fluences **$>1.5 \times 10^{16}$ n_{eq}/cm^2** under investigation
- Need to test with the final version of the readout chip

Next year we will choose the strategy for changing barrel layer 1 during HL-LHC era



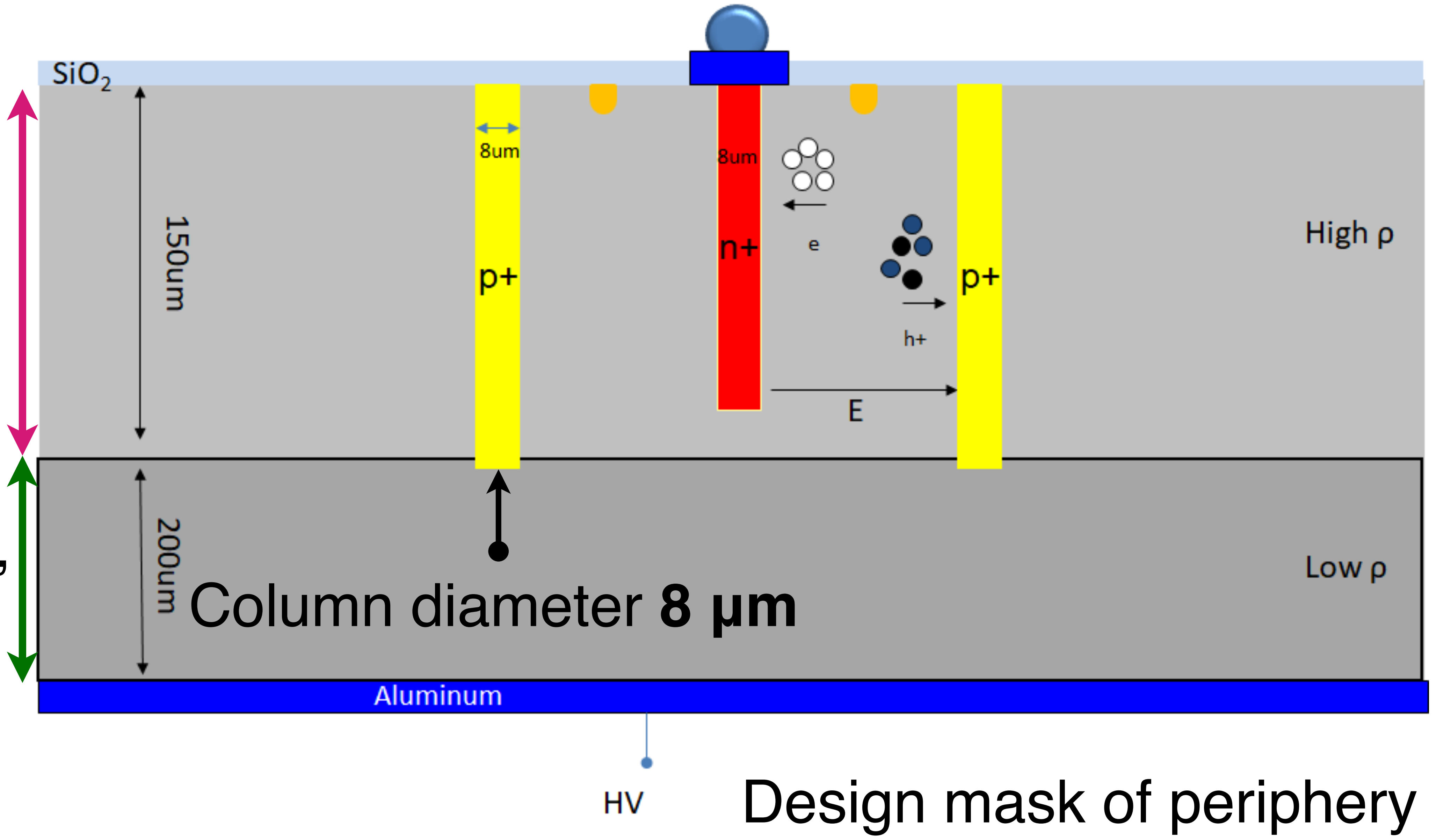
Backup

Silicon pixels: 3D ***CNM*** — single-side



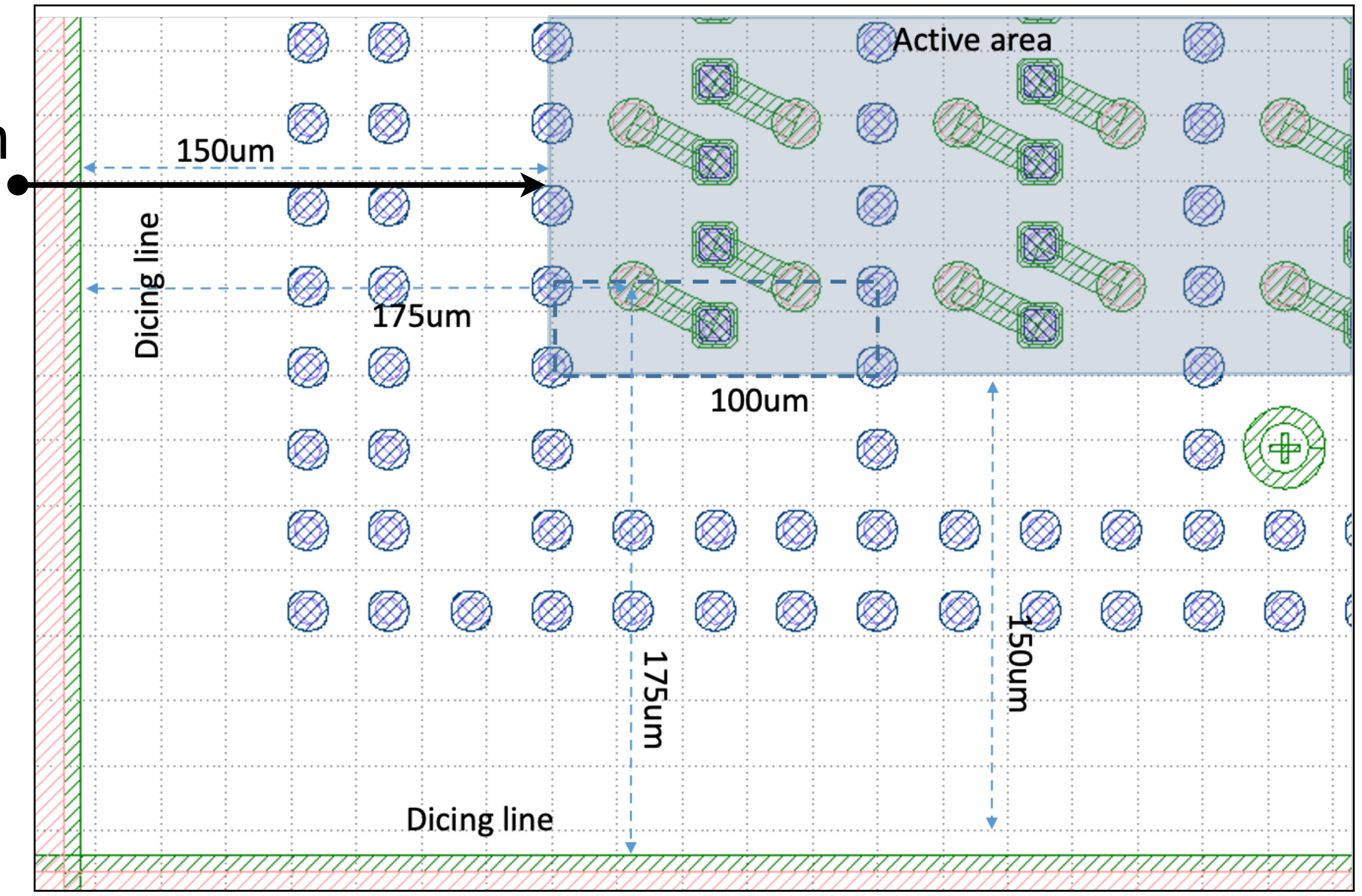
Active layer thickness **150 µm**

Support wafer thickness **200 µm**, after thinning **50-100 µm**



- Pitch 25 x 100 µm^2
- 1E, one junction column electrode per pixel cell

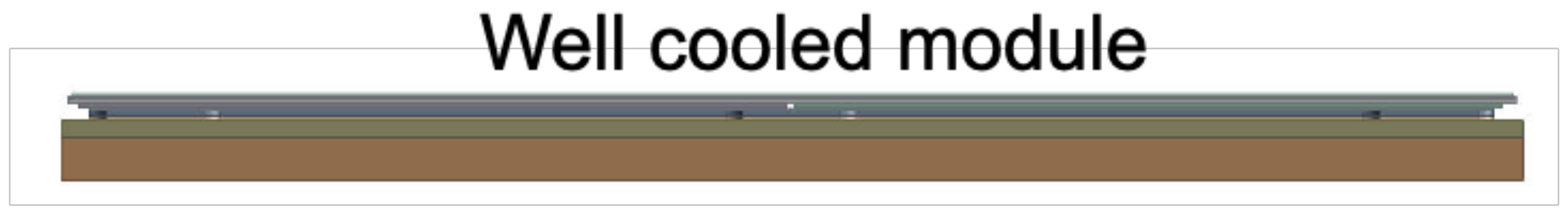
Design mask of periphery

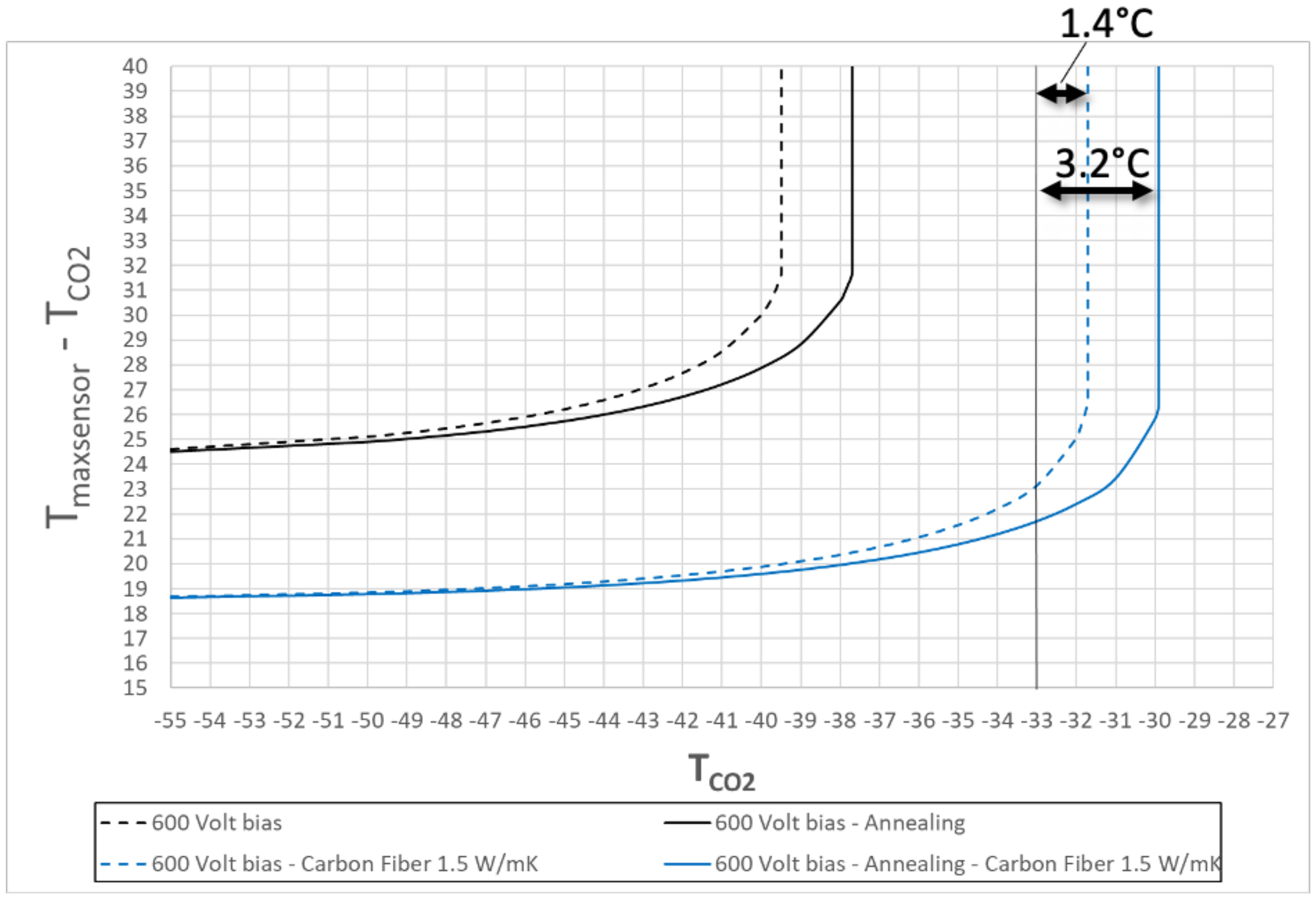


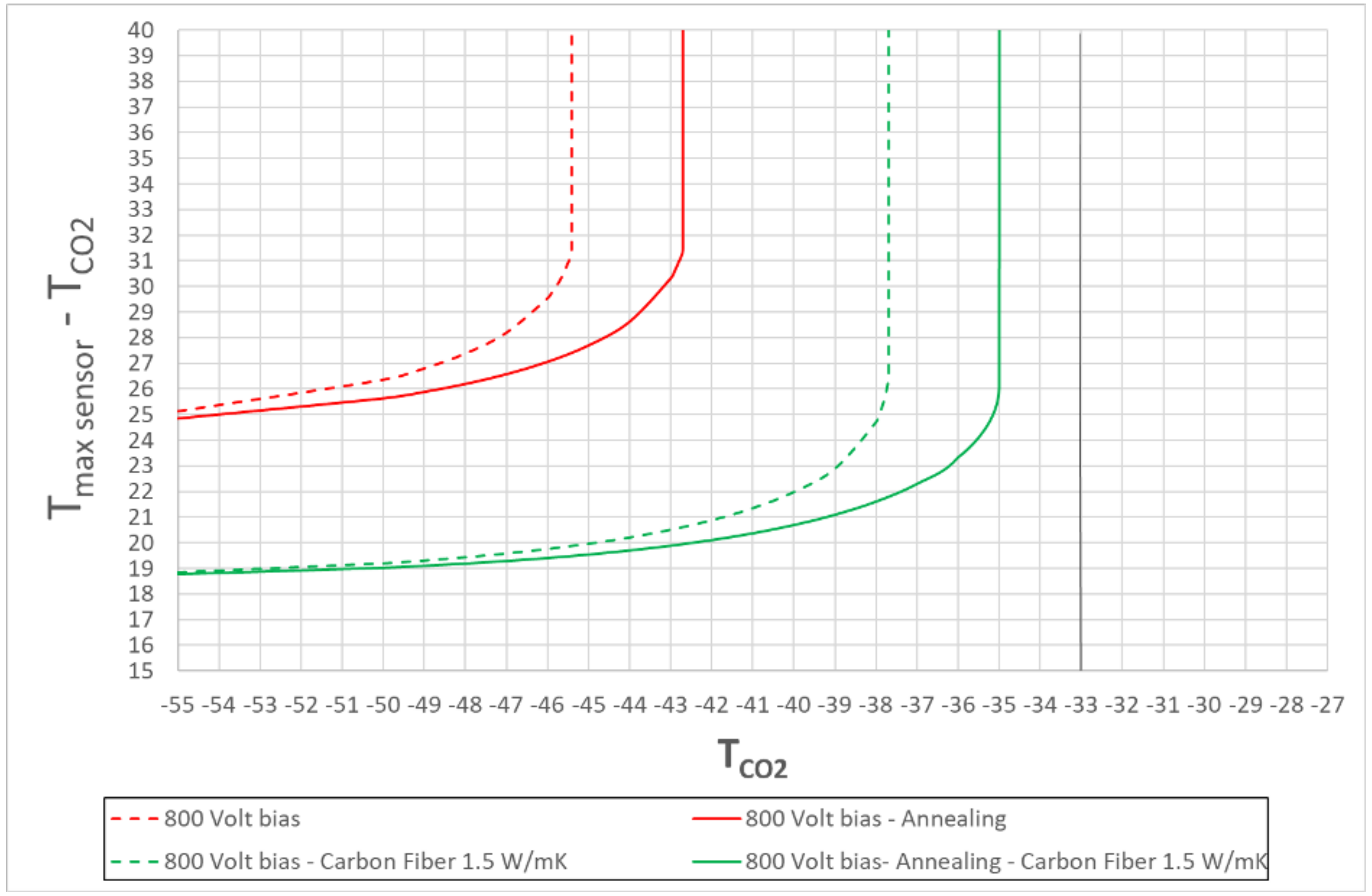
a) Two wafers bonded with **DWB** technique as ***FBK***
b) **DRIE** to make holes on frontside for ohmic columns
c) & d) deposit and filling with polysilicon
e) & f) **DRIE** to make holes on frontside for junction columns and then polysilicon deposition
g) & h) **metallisation**

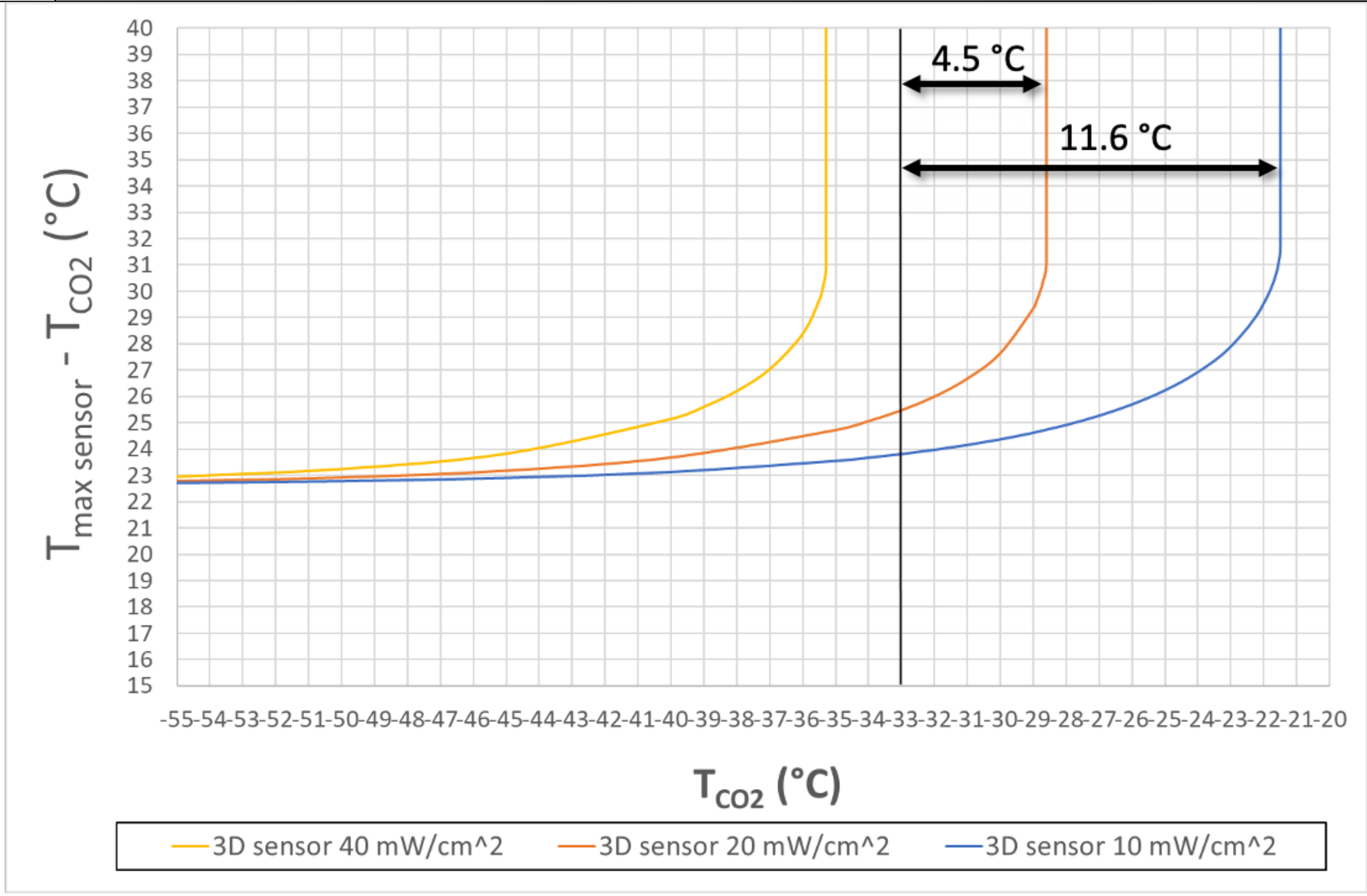
Planar sensor - barrel layer 1

Thermal conductivity (through plane) carbon fiber effect









3D sensor - barrel layer 1

Thermal conductivity (through plane)
carbon fiber effect

Main driving reason for choosing 3Ds for barrel layer 1

- Planar sensors at 1E16: 3°C margin at 600 V but thermal runaway at 800 V
- 3D sensors at 2E16: > 4.5°C margin at 150 V ➜ large margin for 3D at 1E16

References

- **Corrywreckan framework for alignment and analysis:**
  https://project-corryvreckan.web.cern.ch/project-corryvreckan/
- **Telescope EUDAQ-DAQ:** https://eudaq.github.io
- **RD53 Ph2_ACF-DAQ:** https://gitlab.cern.ch/cms_tk_ph2/Ph2_ACF