CHARACTERIZATION OF PLANAR AND 3D SILICON PIXEL SENSORS FOR THE HIGH LUMINOSITY UPGRADE OF THE CMS EXPERIMENT AT LHC

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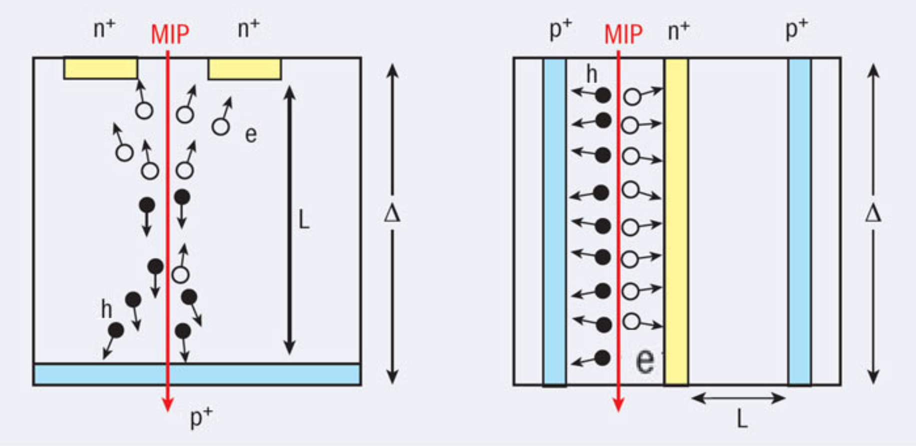
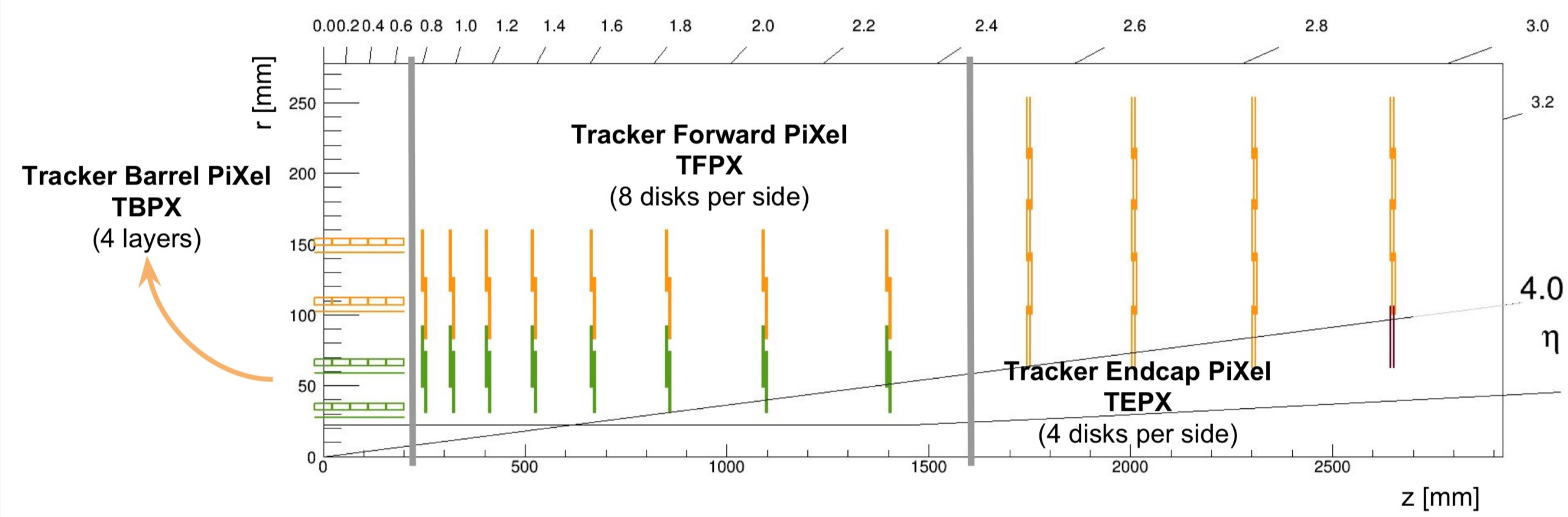
High Luminosity upgrade of the CERN-LHC

Operation conditions	Sensor design constraints
Luminosity 7.5 x 10^{34} cm^{-2} s^{-1}, up to 200 collisions per 25 ns bunch crossing	Maintain occupancy at per mille level and increase the spatial resolution → pixel cell size reduced from 100 x 150 μm^2 to 25 x 100 μm^2 or 50 x 50 μm^2
Radiation level for first pixel layer after Run4+5 (2200 fb^{-1}): 1.9 x 10^{16} n_{eq}/cm^2 → carrier lifetimes ~ 0.3 ns, mean free path ~ 30 µm for electrons at saturation velocity	Reduce distance between electrodes to increase the signal → thin planar or 3D columnar technologies 

The CMS Inner Tracker (IT) for HL-LHC



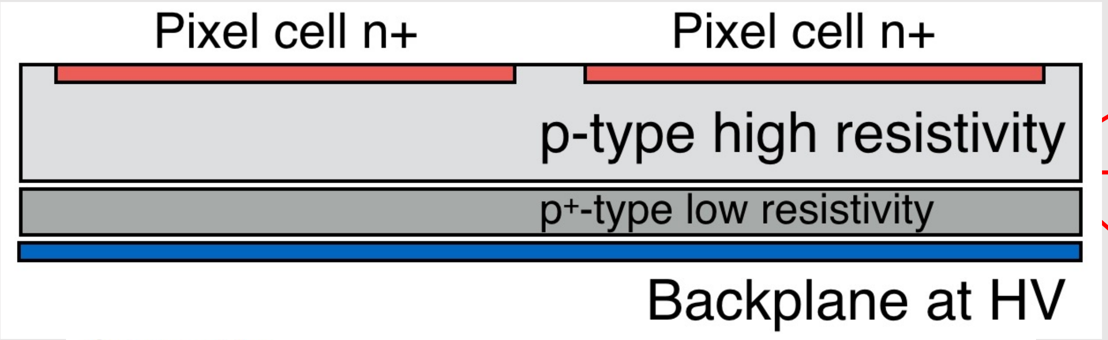
- Upgrade of the CMS Tracker documented in this Technical Design Report
- 25 x 100 x 150 μm^3 planar sensors baseline choice for the CMS IT
  - *3D sensors are investigated as an option for the first layer*
  - *50 x 50 x 150 μm^3 option discarded since marginal gain does not justify introduction of additional design*

2736
2 ✕ 2 pixel modules

1156
1 ✕ 2 pixel modules

Planar sensors - generalities

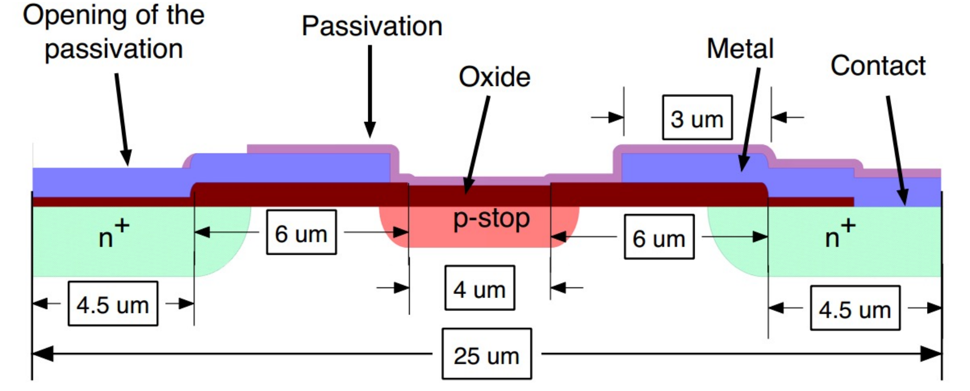
- Floating zone n+ on p type
  - *collect electrons, the faster carriers*
  - *avoid type inversion after irradiation*
  - *single sided process → much less expensive than double sided*
- Fondazione Bruno Kessler (FBK) foundry employs Direct Wafer Bonding technology



Active layer (100 or 150 µm)

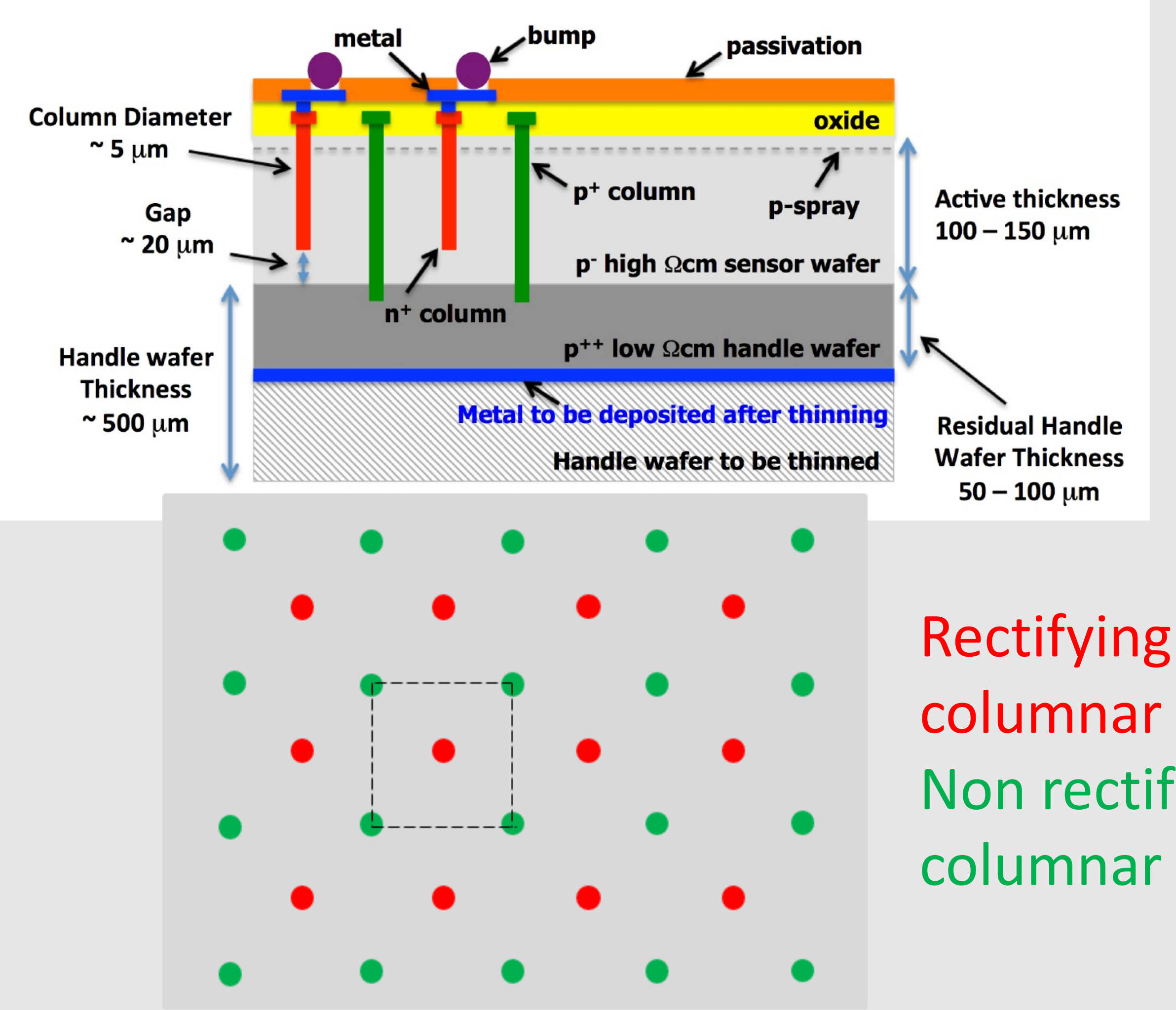
Bonding using superficial short range forces

Mechanical support and ohmic contact



Hamamatsu Photonics (HPK) design

3D sensors - generalities



Single-sided DRIE process optimized by FBK → much less expensive than double-sided

Rectifying n+ columnar implant

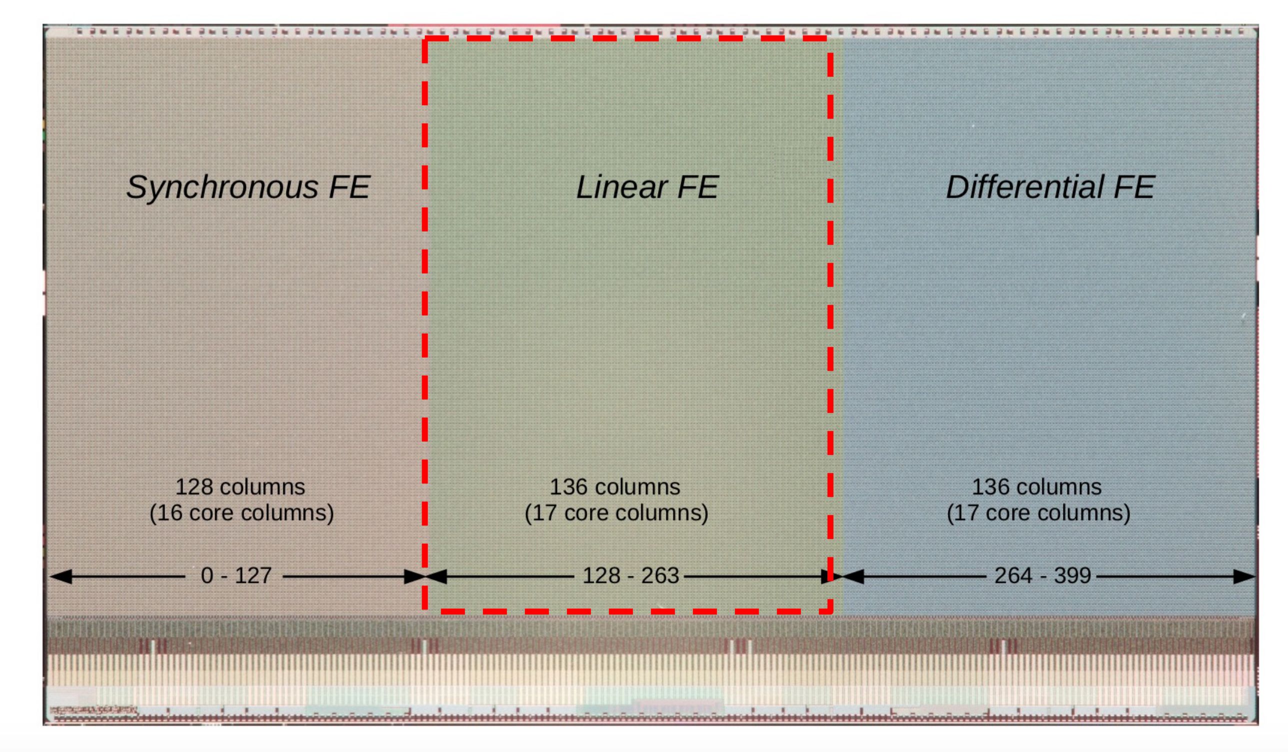
Non rectifying p+ columnar implant

The RD53A ROC

The RD53A ROC has a pitch of 50 x 50 μm^2 and **can be operated at thresholds lower than 1000 electrons before irradiation and 1500 electrons after irradiation, depending on the fluence.**

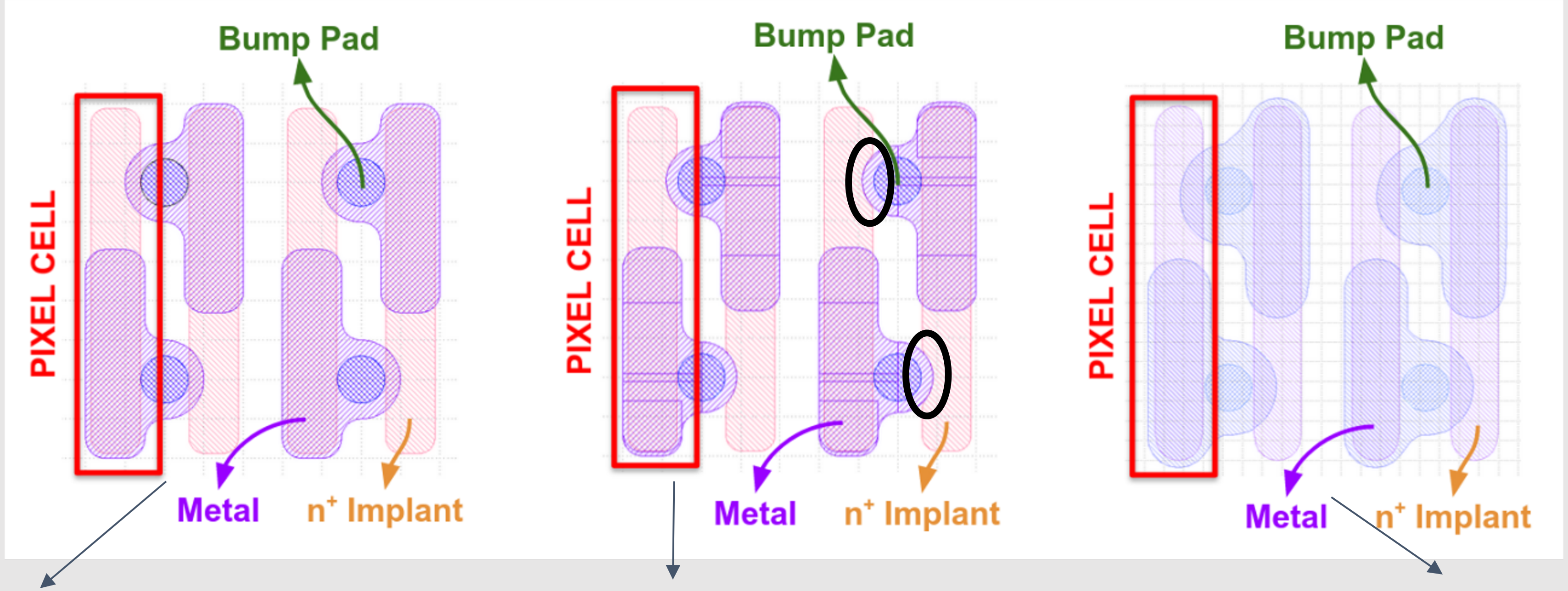
Sensors bonded to this ROC have been irradiated to fluences up to 24 x 10^{15} n_{eq}/cm^2.

Only measurements on the Linear Front End will be shown



FBK planar sensors - design

- DUT C → 25 x 100 Standard (100 μm thickness) → 7.5 x 10^{15} n_{eq}/cm^2
- DUT E → 25 x 100 Bitten (150 μm thickness) → 11 x 10^{15} n_{eq}/cm^2
- DUT F → 25 x 100 Standard (150 μm thickness) → 18 x 10^{15} n_{eq}/cm^2
- DUT G → 25 x 100 Bitten (150 μm thickness) → 24 x 10^{15} n_{eq}/cm^2
- Bitten design introduced to reduce cross talk observed in previous measurements

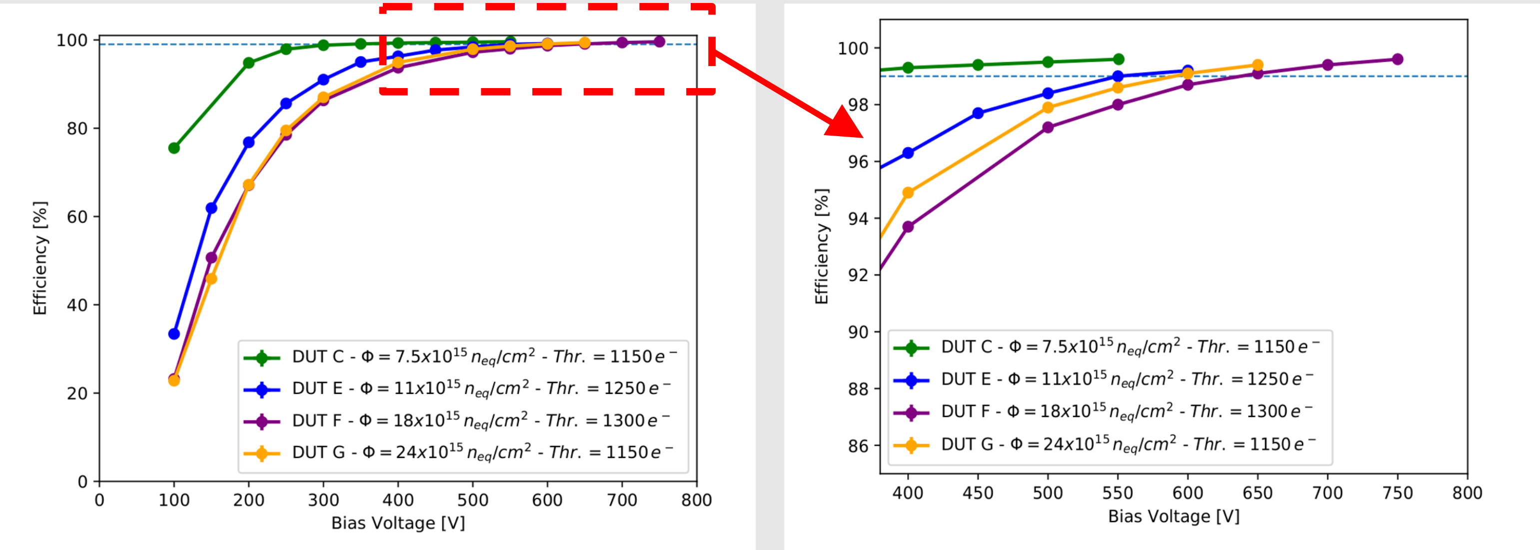


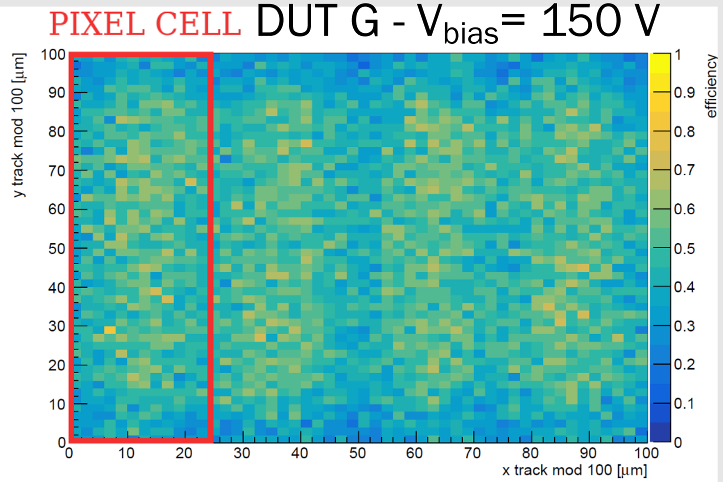
DUT F

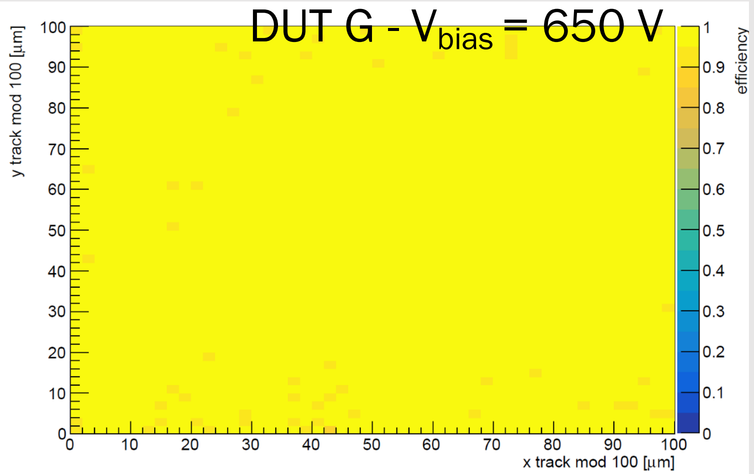
DUTs E & G (**bitten implants**)

DUT C

FBK planar sensors - efficiency



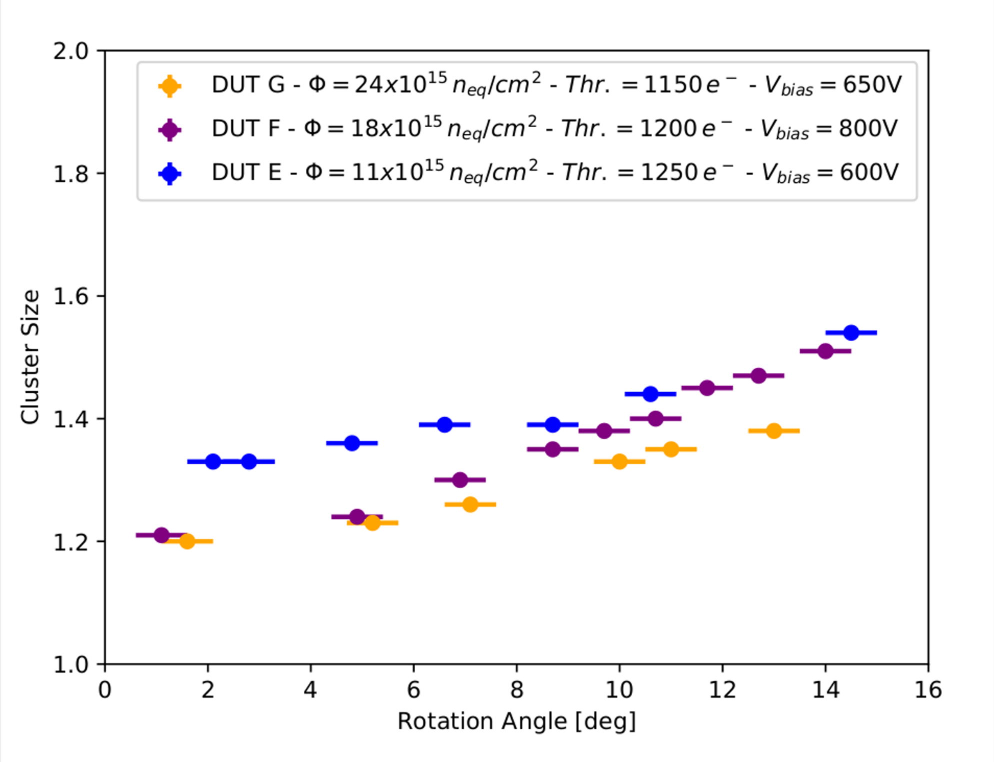

DUT G - V_{bias}= 150 V


DUT G - V_{bias} = 650 V

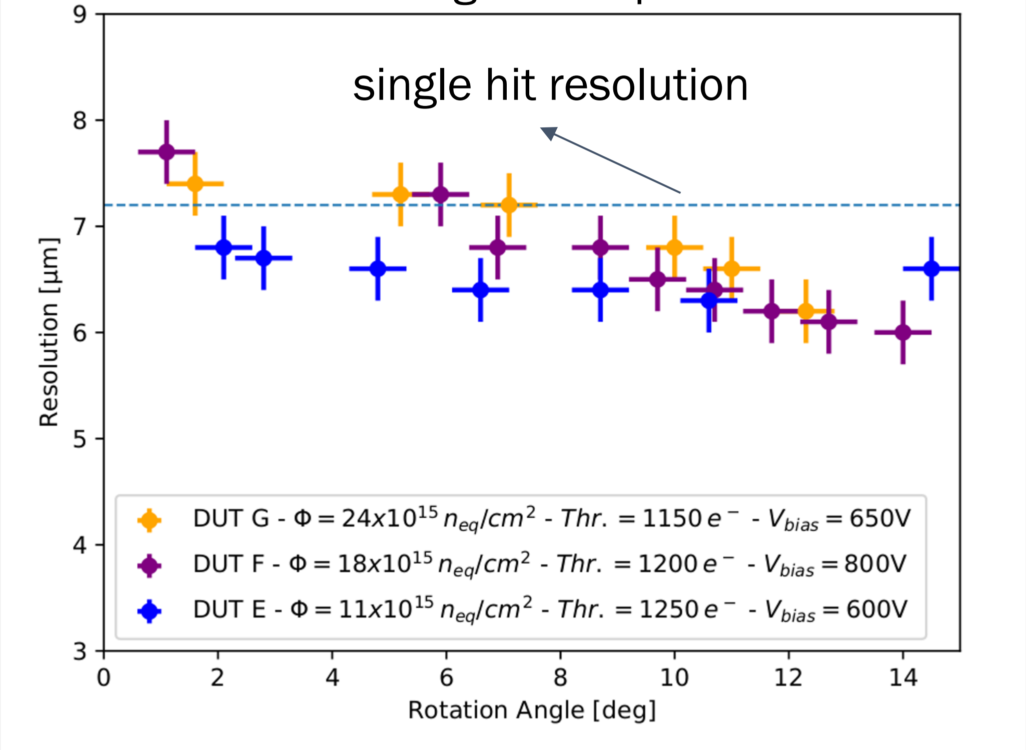
Vbias for 99% detection efficiency:
350 V @ 7.5 x 10^{15} n_{eq}/cm^2
550-650 V @ higher fluences

Uniform in-pixel detection efficiency observed at these bias voltages

FBK planar sensors - resolution



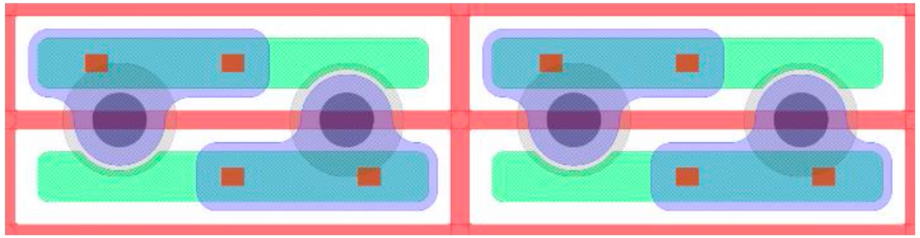
Resolution along the 25 µm direction



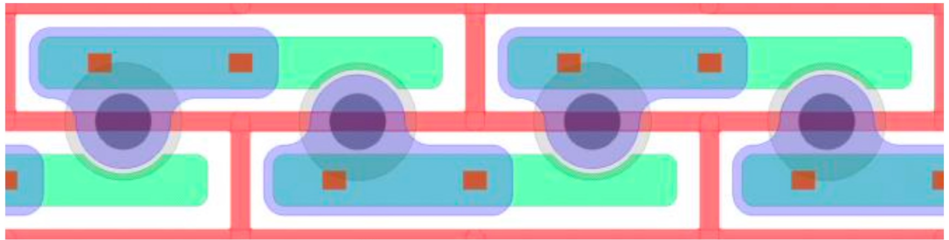
Cluster size reaches ~ 1.5 at around 15 deg→ measured resolution around 6 µm

Resolution for fresh sensors is measured to be around 2 µm (at the optimal angle), compatible with simulation expectation

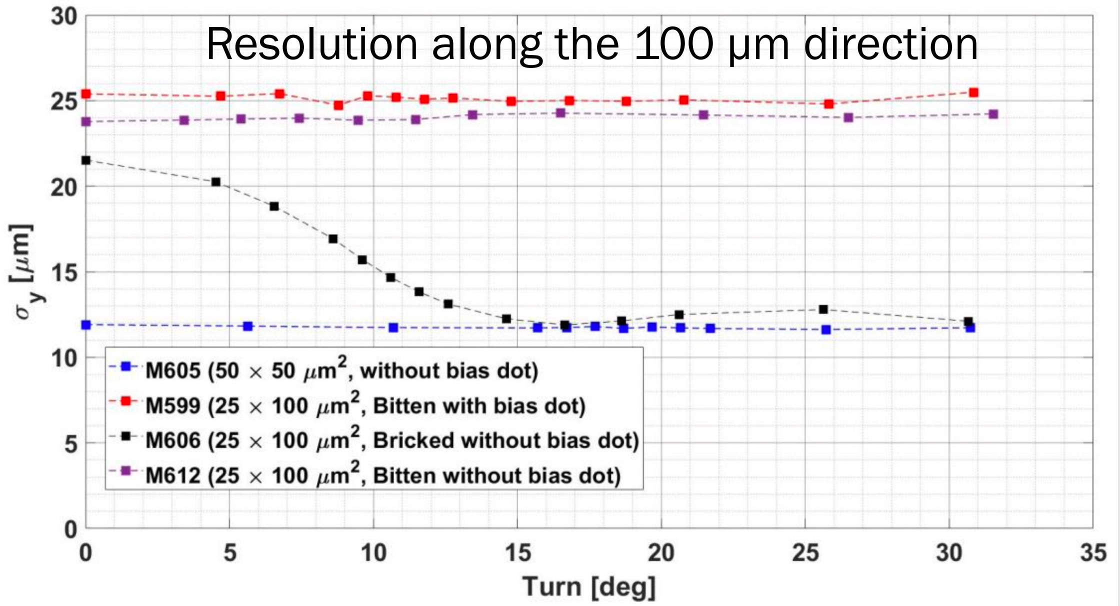
HPK planar sensor - design



$25 \times 100\ \mu m^2$, bitten without bias dot



$25 \times 100\ \mu m^2$, bricked without bias dot



Bricked design introduced to increase resolution in the long pitch direction

Possible application in central part of the barrel detector

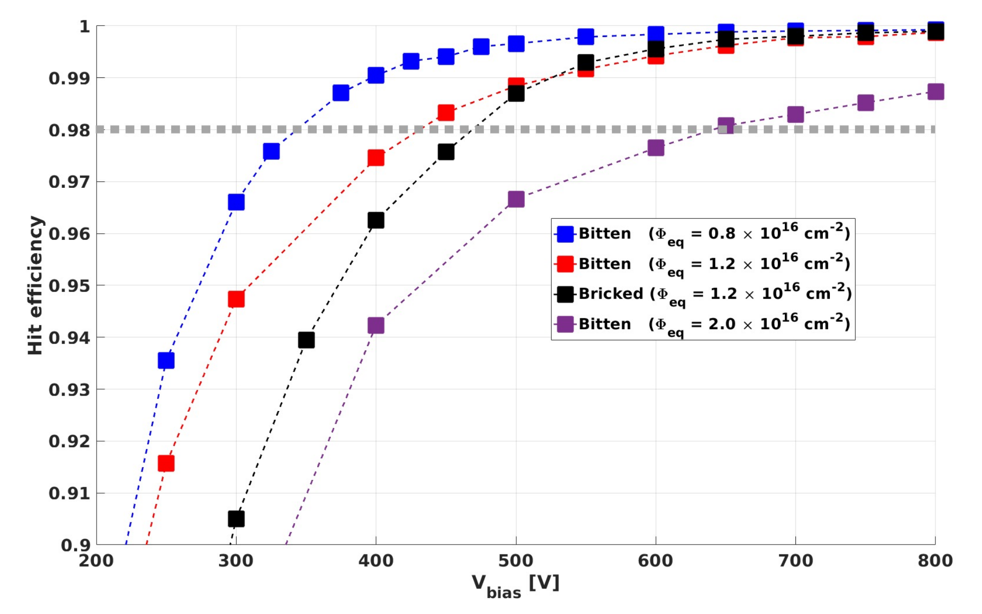
Fresh sensors

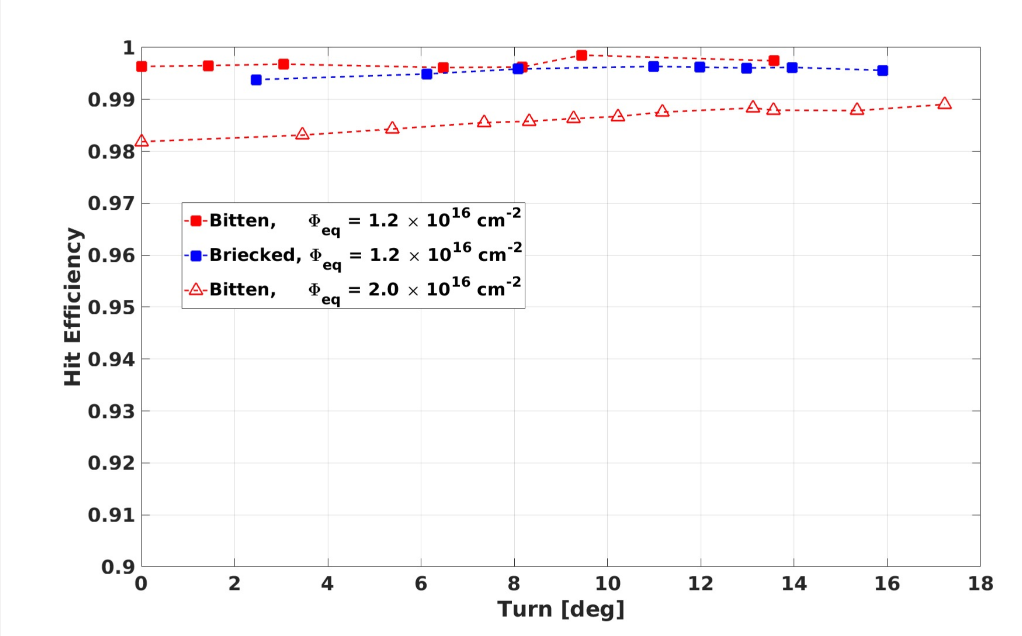
Vbias = 120 V

Online threshold 750-1100 electrons

Bricked 25 x 100 same resolution of 50 x 50 for turn angles > 15 deg

HPK planar sensor - efficiency





Online threshold 1100-1300 electrons

Vbias for 99% detection efficiency:

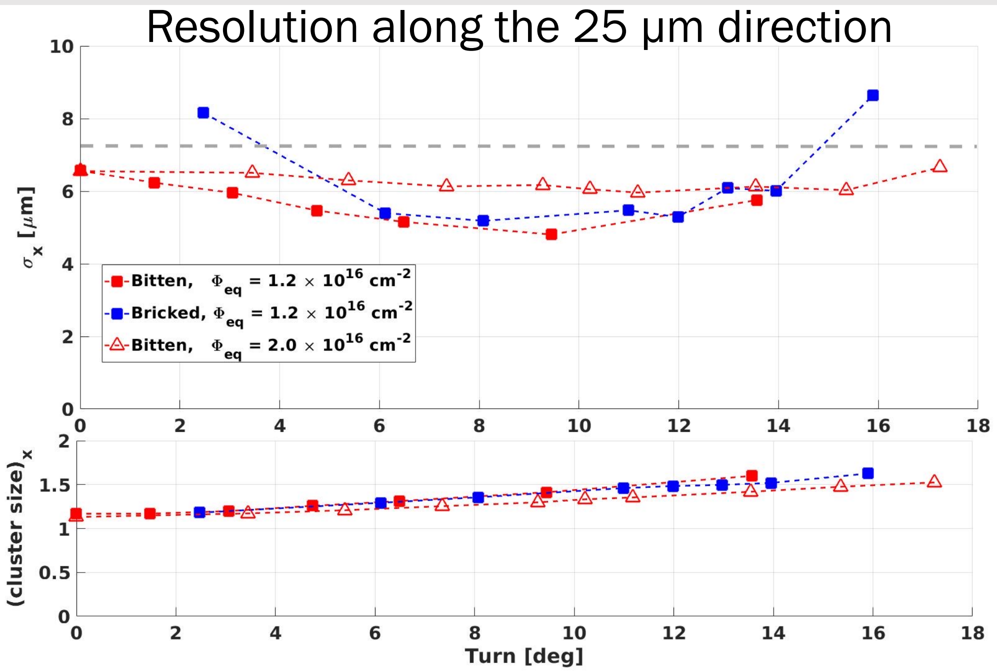
400 V @ 8 x 10^{15} n_{eq}/cm^2

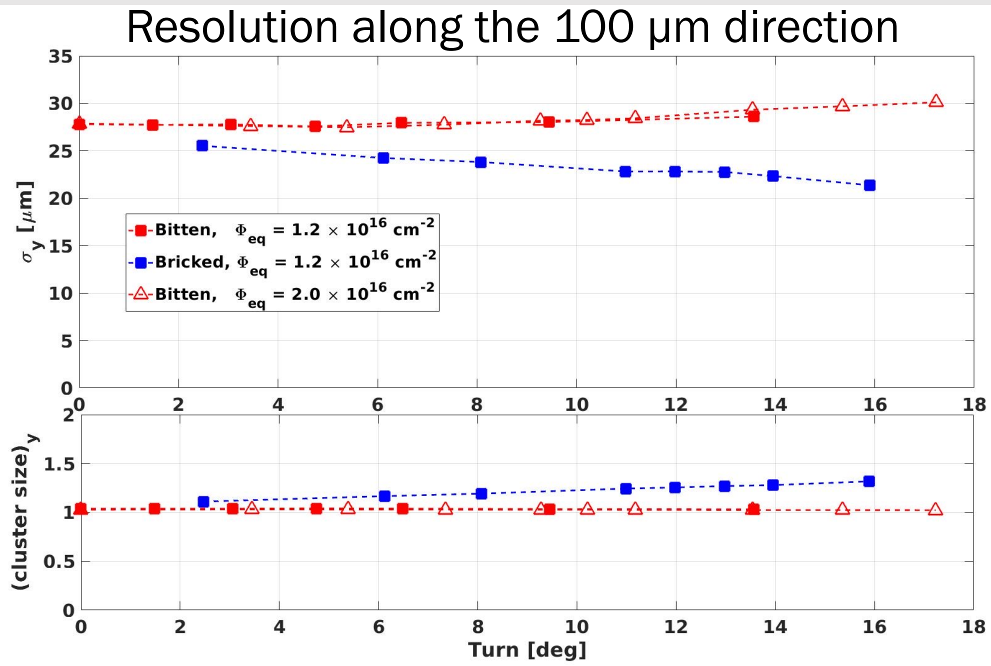
550 V @ 12 x 10^{15} n_{eq}/cm^2

Highest irradiated sensor reaches 98% efficiency at 650 V → reaches 99% when tilted

Compatible with FBK sensors

HPK planar sensor - resolution


Resolution along the 25 µm direction

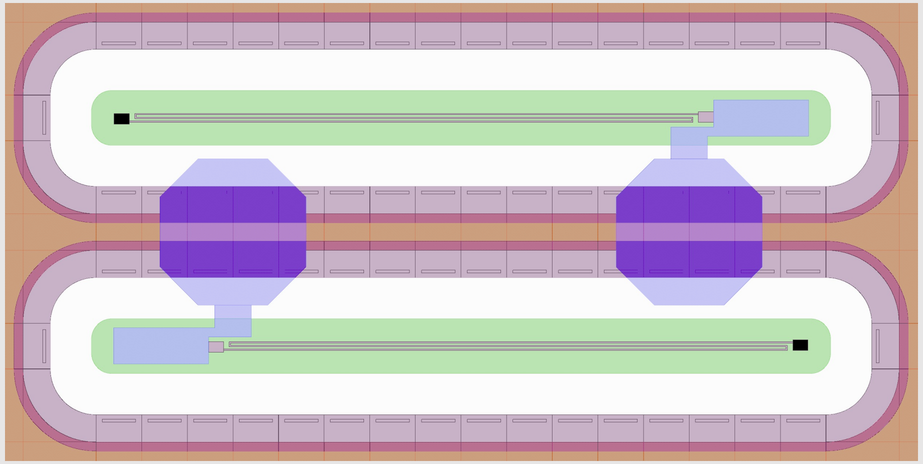

Resolution along the 100 µm direction

Sensors irradiated at 12 x 10^{15} n_{eq}/cm^2 show a resolution of 5 µm at the expected angle (~9 deg)

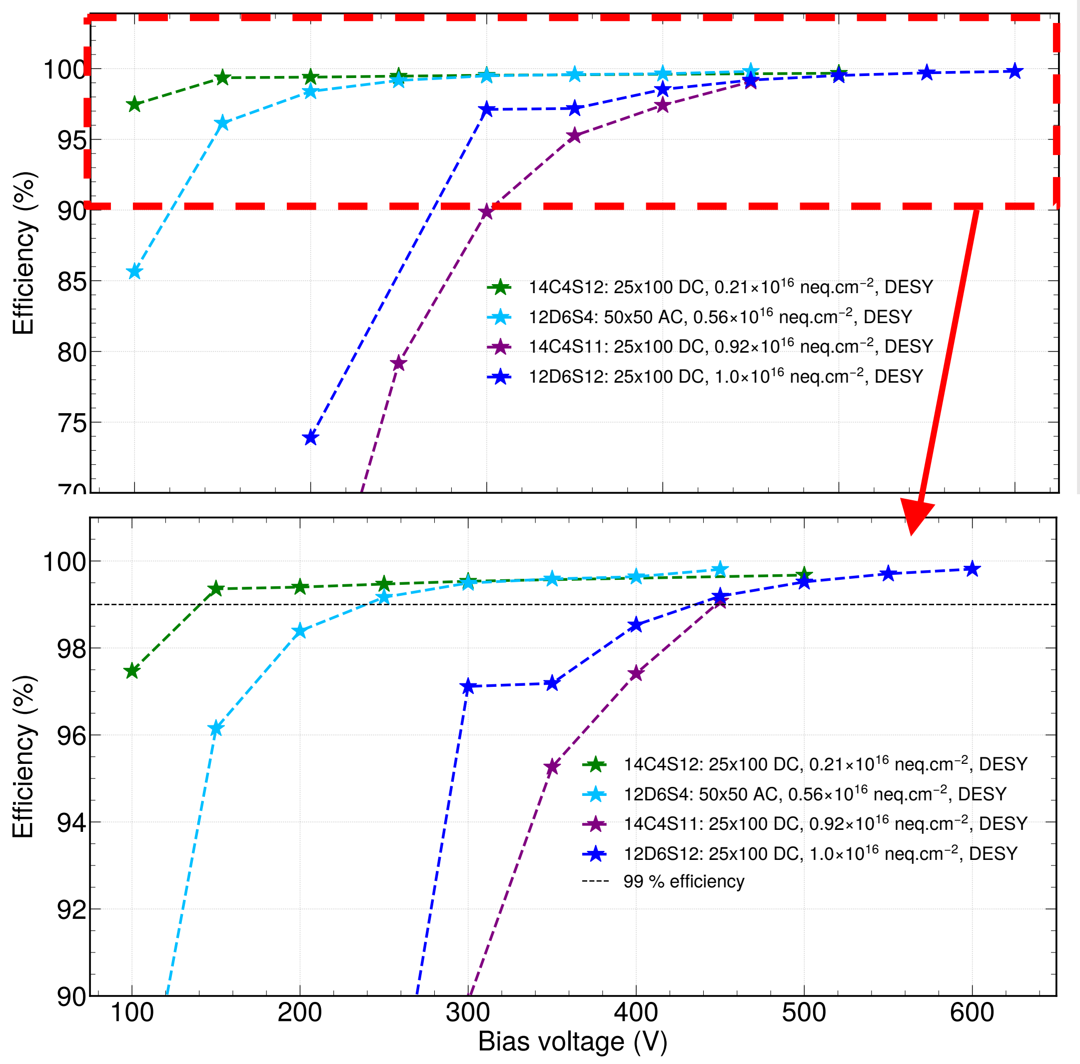
- Bricked sensor features higher cluster size and hence better resolution than bitten sensors
- Improvement in resolution diluted after radiation

LFoundry planar sensors - design

- Passive CMOS sensor in 150 nm technology, 150 µm thickness
- Cost-effective and high-throughput commercial process
- Possible implementation of small on-pixel structures
  - *multiple metal layers for signals routing → more freedom to optimize sensor design*
  - *high resistive poly-silicon used as bias resistors → better hit efficiency than with punch through structures*
  - *MIM-capacitors → AC-coupled sensors possible → leakage current not flowing in the chip → CMS will adopt DC-coupling since sensors' leakage current can be tolerated by the ROC*

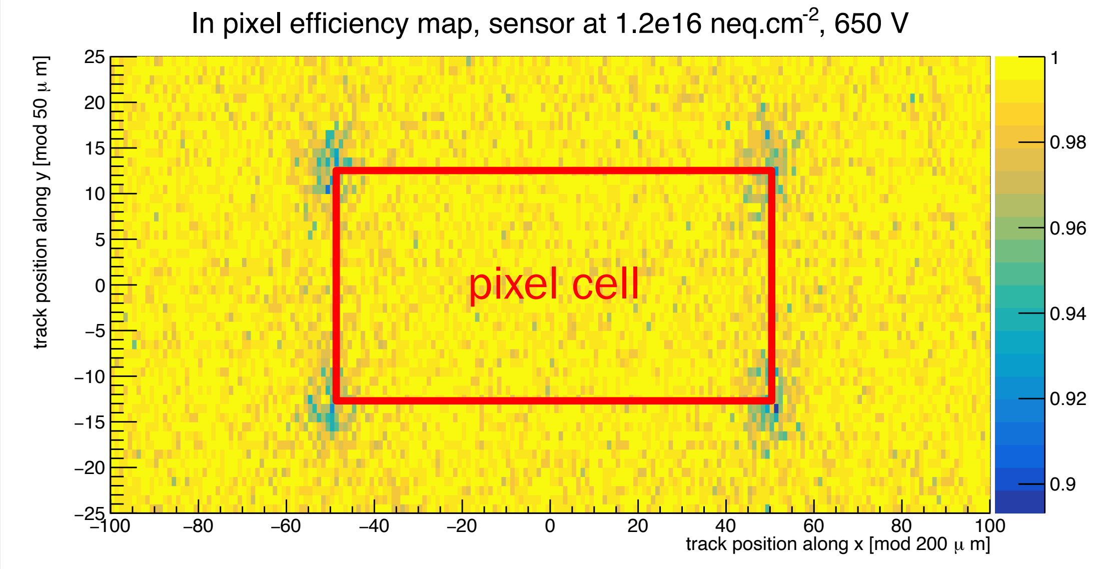


LFoundry planar sensors - efficiency



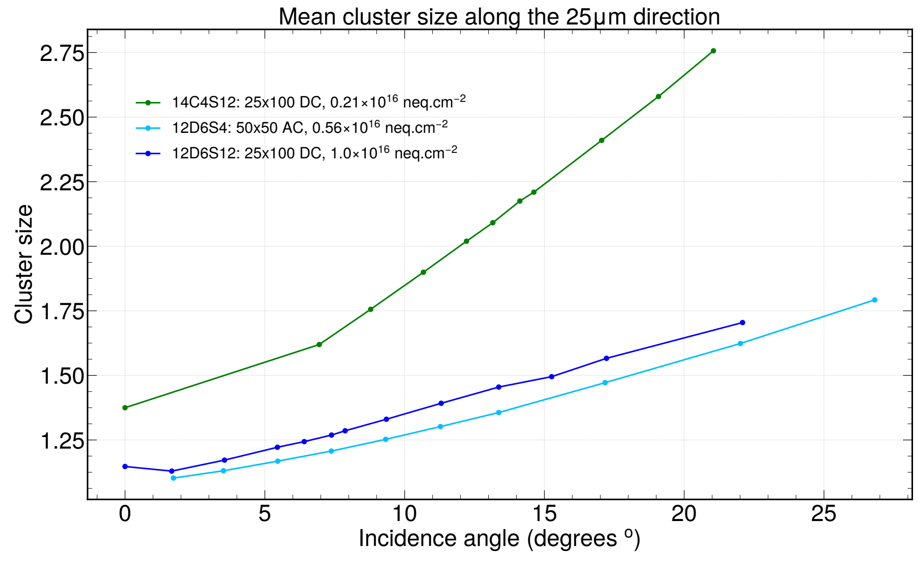
Online threshold 1200-1300 electrons

Vbias for 99% detection efficiency:
450 V @ 10 x 10^{15} n$_{eq}$/cm^{2}
compatible with HPK and FBK sensors

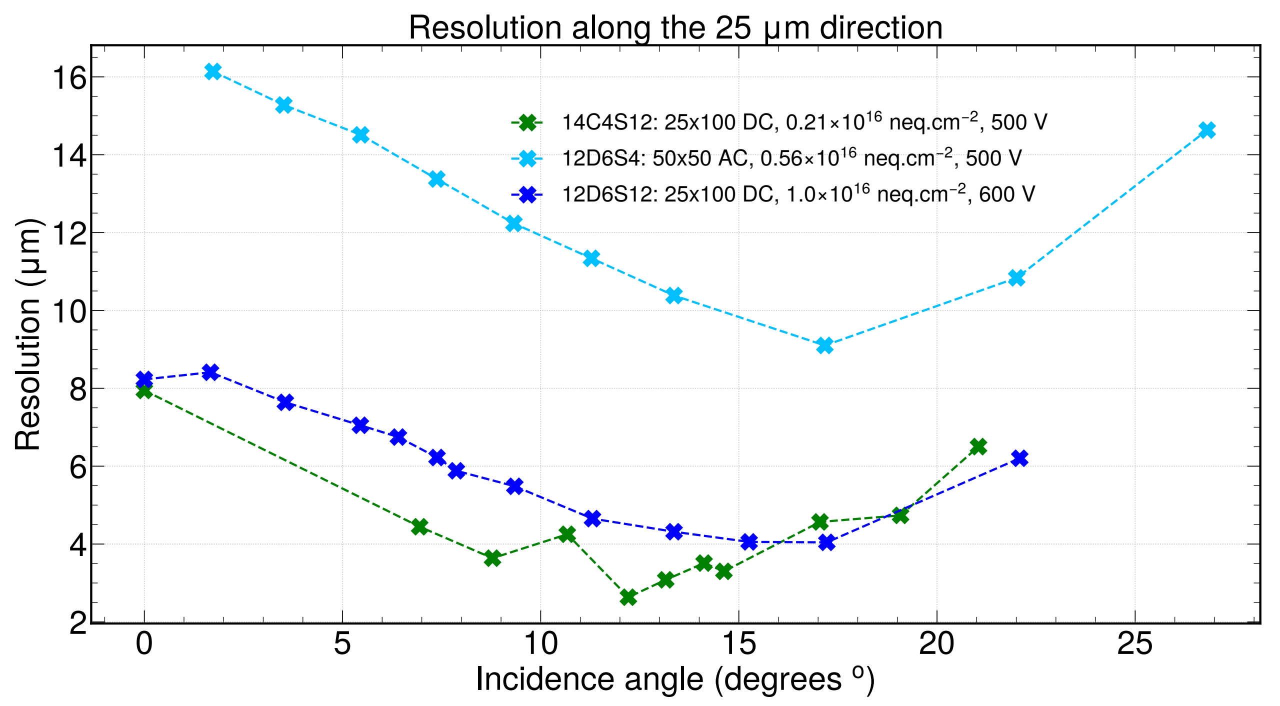

In pixel efficiency map, sensor at 1.2e16 neq.cm^{-2}, 650 V

In-pixel efficiency is uniform at the highest bias voltage → reduced charge sharing leads to reduced efficiency in the corners

LFoundry planar sensors - resolution



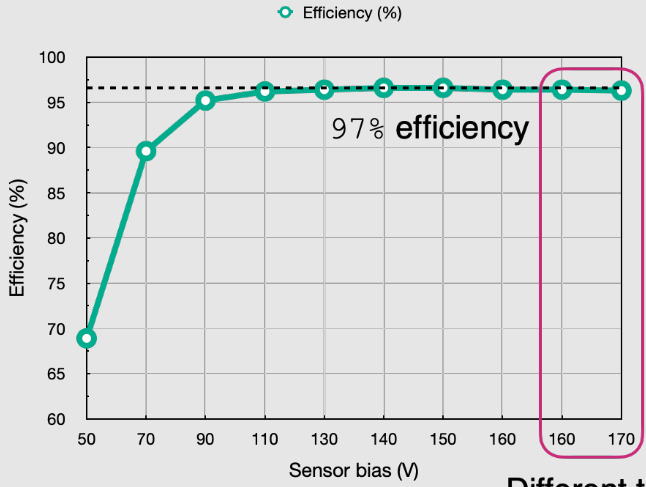
Also in this case cluster size is < 2 at the highest irradiation fluences



- Rectangular sensor irradiated at 2 x 10^{15} n_{eq}/cm^2 reaches 2 μm resolution at around 12 deg
- Rectangular sensor irradiated at 10 x 10^{15} n_{eq}/cm^2 reaches 4 μm resolution at around 17 deg
- Reduced charge sharing → higher angle for optimal resolution

FBK 3D sensors - CERN TB

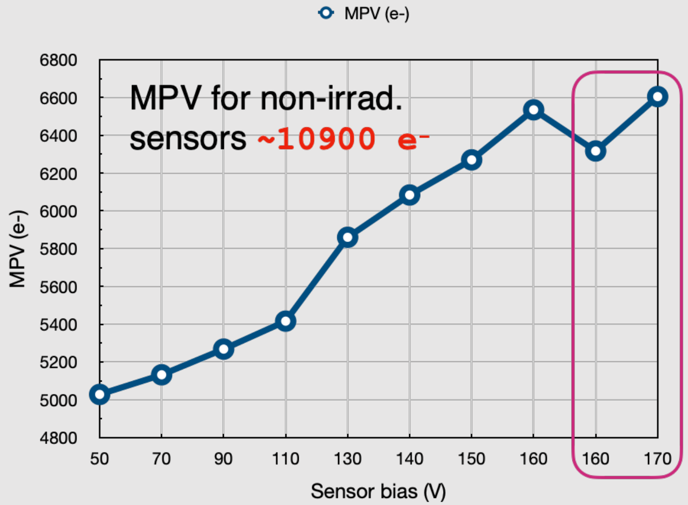
Efficiency vs bias



97% efficiency

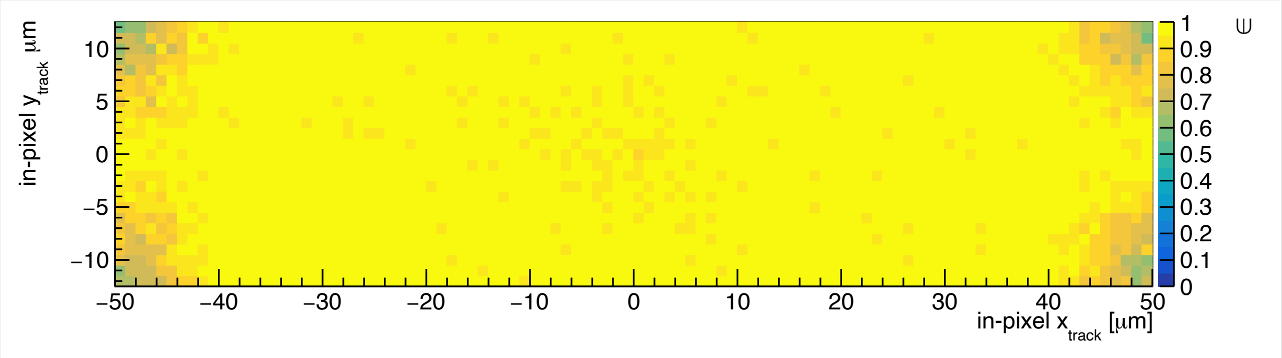
Different threshold

MPV vs bias

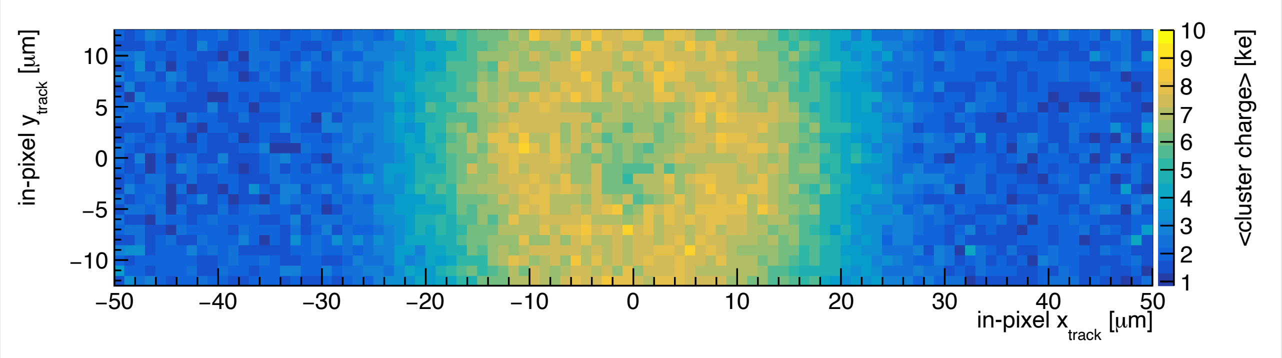


MPV for non-irrad. sensors ~10900 e-

Irradiation fluence: 15 x 10^{15} n_{eq}/cm^2 - normal incidence



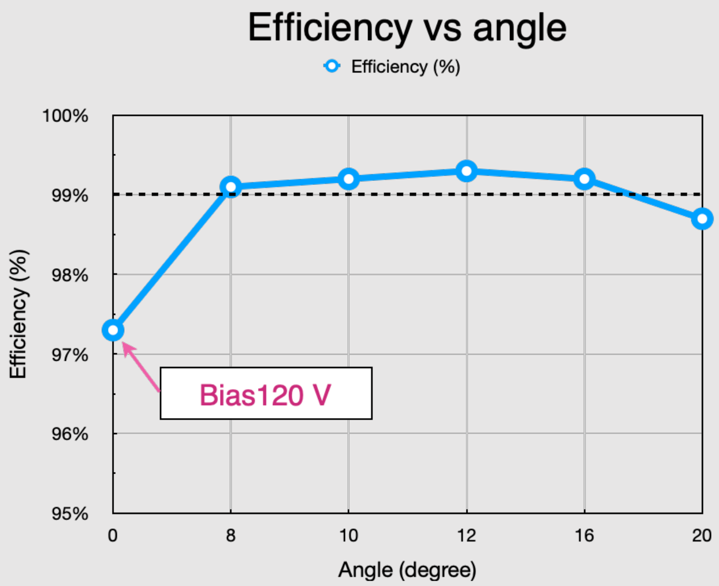
In-pixel efficiency map @ 150 V - 1400 electrons threshold

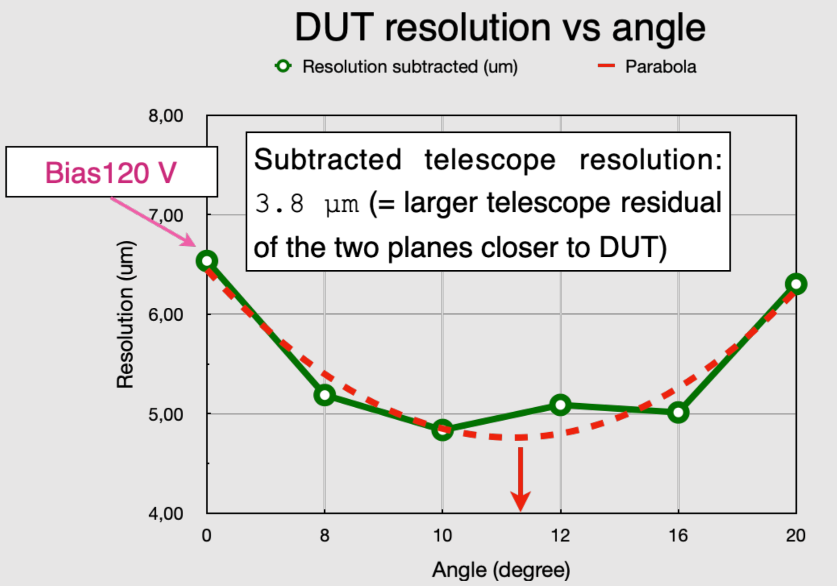


In-pixel charge map @ 150 V - 1400 electrons threshold

FBK 3D sensors - CERN TB

Irradiation fluence: $15 \times 10^{15}\ n_{eq}/cm^2$



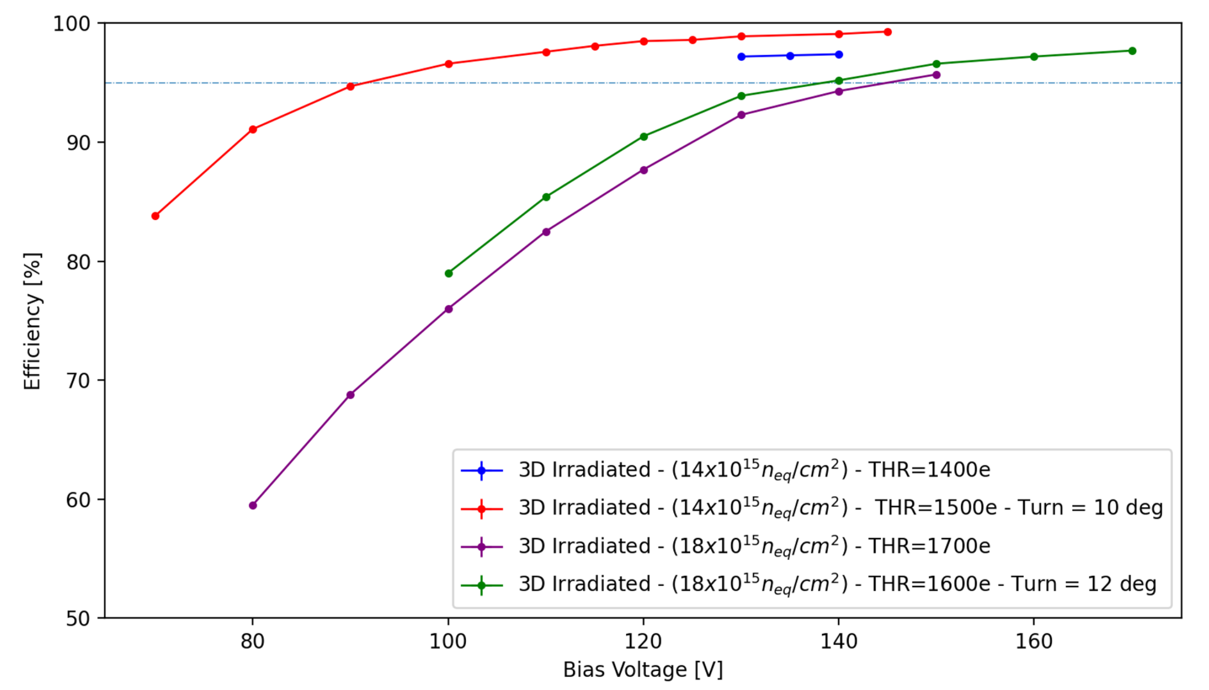


Subtracted telescope resolution: 3.8 µm (= larger telescope residual of the two planes closer to DUT)

99% detection efficiency reached a 8 deg tilt (no data acquired at smaller angles)

Measured resolution is ~5 µm, compatible with planar sensor

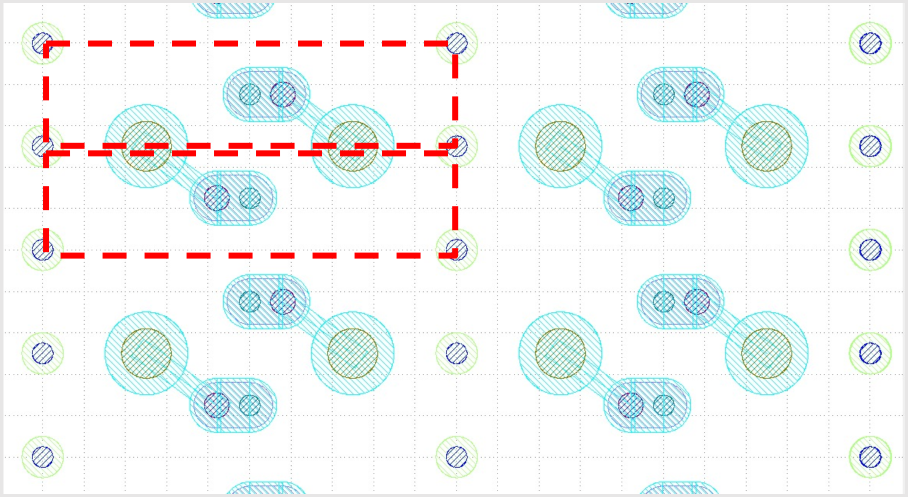
FBK 3D sensors - DESY TB



Sensors coming from newest FBK production → increased distance between n+ type column and low resistivity wafer

14×10^{15} n_{eq}/cm^2 : 99% efficiency at Vbias 130 V

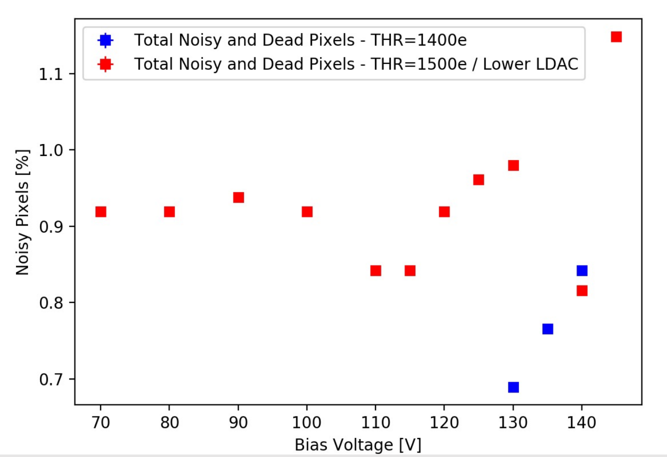
18×10^{15} n_{eq}/cm^2: 98% efficiency at Vbias 170 V



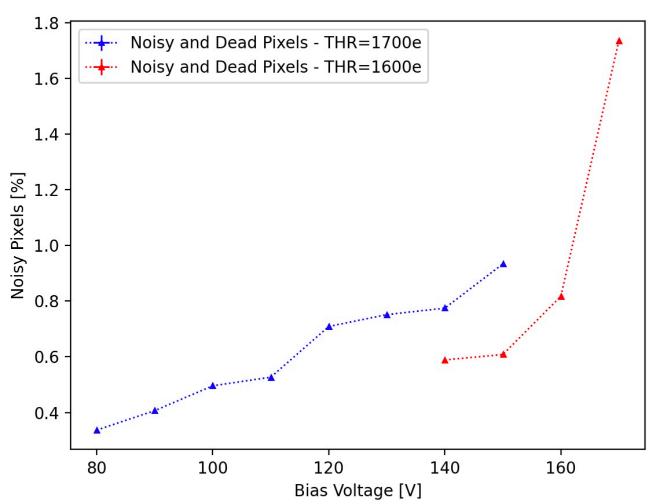
First measurements on irradiated sensors coming from this production → more sensors ready for irradiation and beam test in the next month(s)

Noise in 3D sensors

FBK - Stepper 2 - 14 x 10^{15} n_{eq}/cm^2

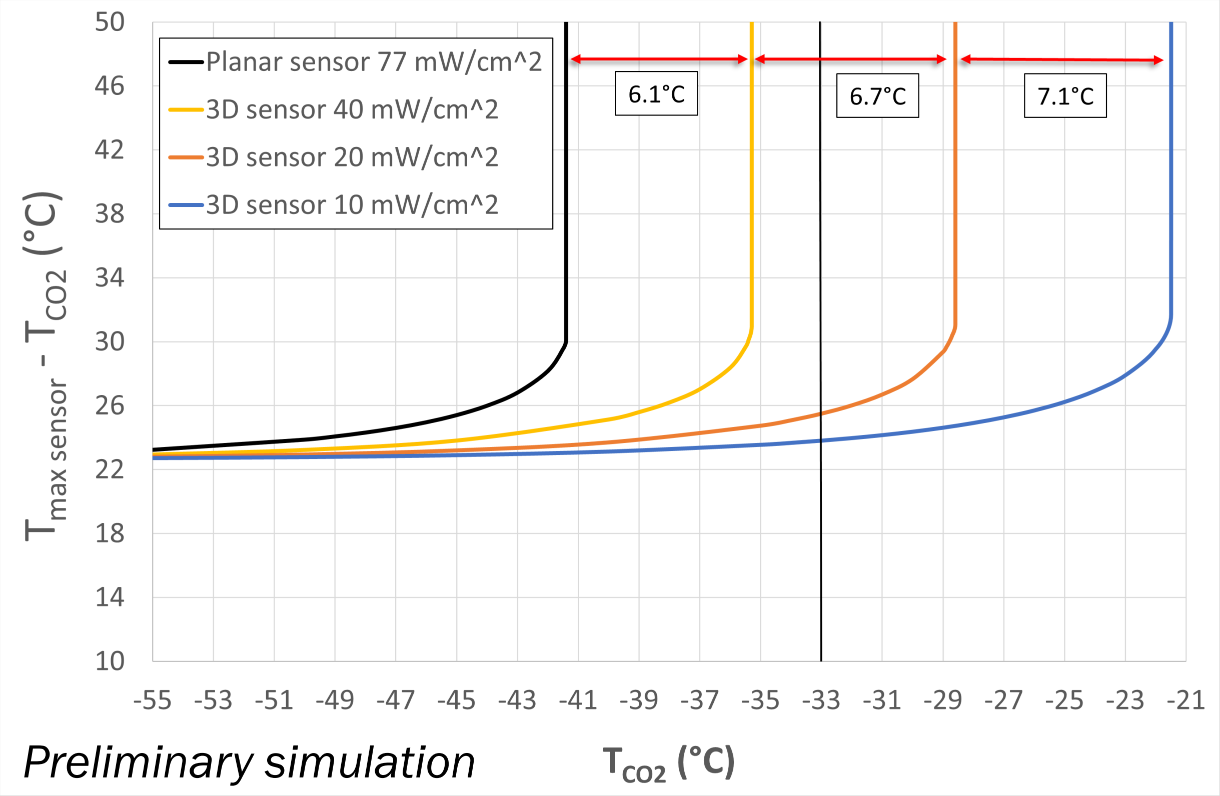


FBK - Stepper 2 - 18 x 10^{15} n_{eq}/cm^2



- During test beam characterizations of 3D sensors at CERN and DESY in Autumn 2021 a sudden increase in the number of noisy pixel at high bias voltages was observed
- TID for irradiations with low energy protons (KIT, 23 MeV) 1.5 GRad per 10 x 10^{15} n_{eq}/cm^2 → higher than RD53A tolerance (1 Grad)
- Action items in progress
    - irradiate samples with higher energy protons (Fermilab ITA, 400 MeV)
    - measure noise in planar sensors to eventually rule-out ROC irradiation effects
    - measure IV curves to investigate possible correlation with breakdown

Power dissipation simulation



Preliminary simulation

- Barrel Layer 1
- planar sensors: T_{CO2} required to prevent thermal runaway is much lower than -33 °C achievable
- 3D sensors: at least 4 °C margin if the power dissipated in the active volume of the sensor is less than 20 mW/cm^2 after 2 x 10^{16} n_{eq}/cm^2
- power dissipation <20 mW/cm^2 confirmed by lab measurements

Conclusions

- Planar sensors
  - *Irradiation up to 24 x 10^{15} n_{eq}/cm^2 → detection efficiency in line with specification*
    - 99% for Vbias > 350 (550) V @ 8 x 10^{15} n_{eq}/cm^2 (12 x 10^{15} n_{eq}/cm^2)
    - 98% for Vbias > 650 V for fluence > 20 x 10^{15} n_{eq}/cm^2
  - *resolution of irradiated sensor in the range 4 -- 6 µm depending on the fluence*
- 3D sensors
  - *irradiation up to 15 x 10^{15} n_{eq}/cm^2 → 99% detection efficiency for Vbias > 130 V*
  - *performance at higher fluence to be verified in next test beams (only one sample at the moment)*
  - *resolution compatible with planar sensor*
- Choice to be made in the coming months
  - *3D sensors in barrel layer 1*
  - *bricked pixels only in the central η region of TBPX L2-L3-L4*
  - *inputs from more test beam campaigns and simulation (tracking, vertexing, object reconstruction)*

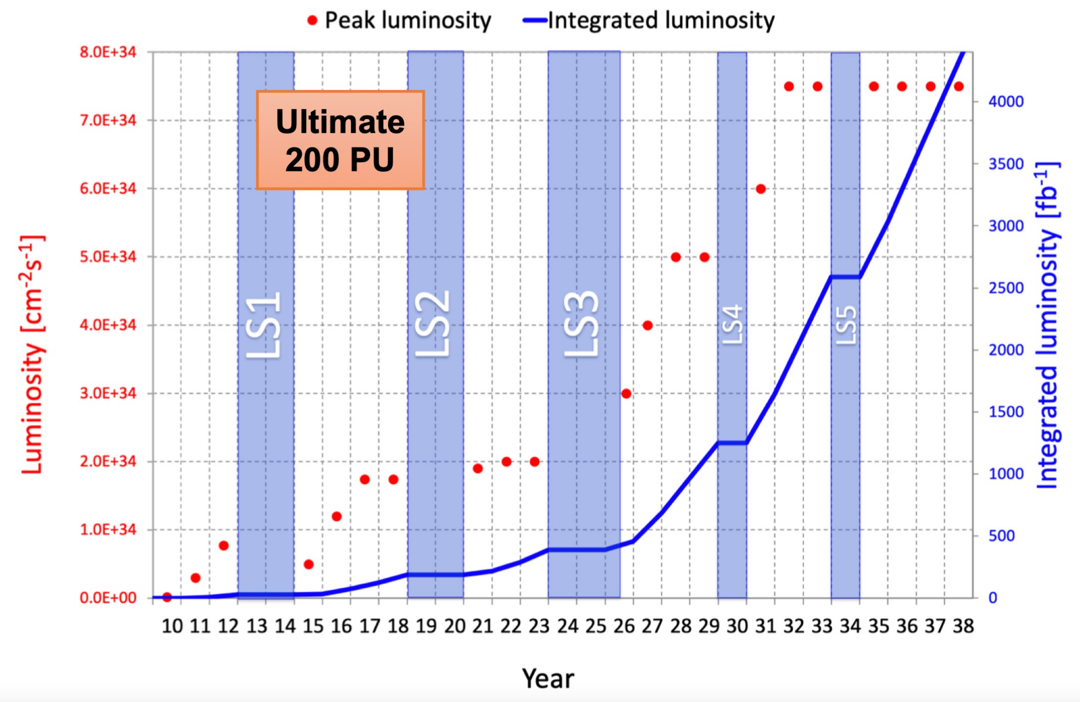
Acknowledgements and Blibliography

- Lfoundry: https://arxiv.org/abs/2111.07797, https://cds.cern.ch/record/2799582/files/CR2021_260.pdf
- FBK: 10.1016/j.nima.2019.163222
- HPK: https://doi.org/10.1016/j.nima.2020.164438

- FBK Team: Maurizio Boscardin, Matteo Centis Vignali, Francesco Ficorella, Sabina Ronchin

Additional material

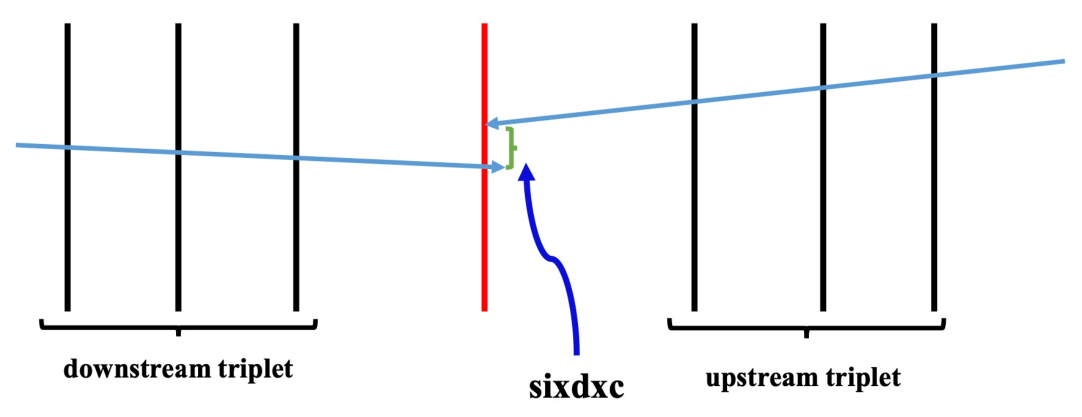
HL-LHC at a glance

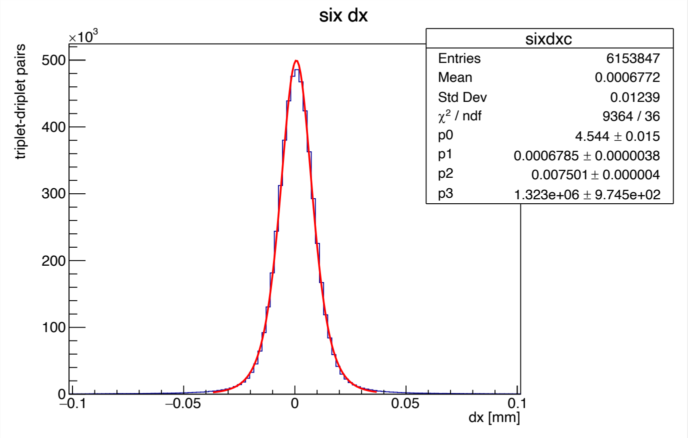


	Ultimate		
	RUN 4	RUN 5	RUN 6
Per run (fb^{-1})	850	1350	1900
Accumulated (fb^{-1})	850	2200	4100

	1E16 1 MeV n_eq	**Grad**
BPIX L1 Run 5	1.16	0.63
FPIX R1 Run 4+5	1.25	0.81
BPIX L1 Run 4+5	1.88	1.03
FPIX R1 Run 4+5+6	2.34	1.50
BPIX L1 Run 4+5+6	3.51	1.91

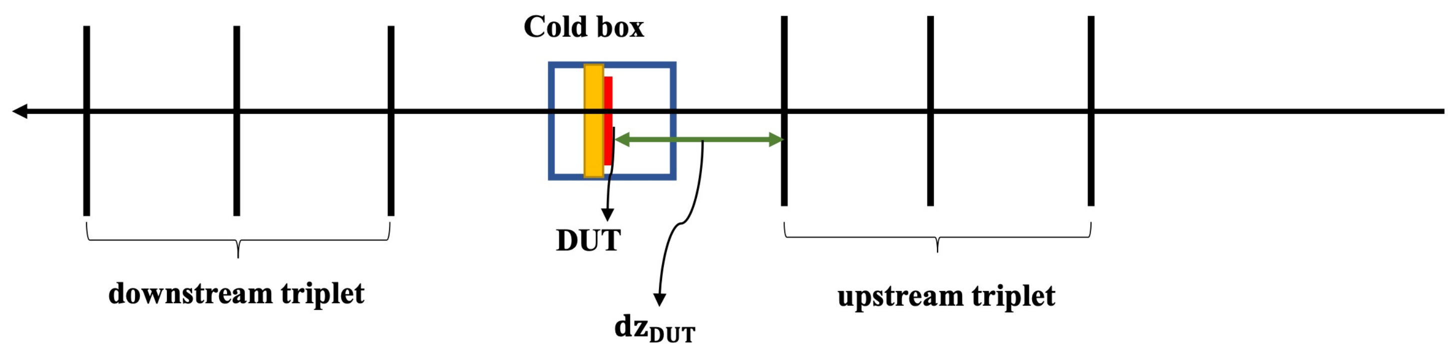
Resolution measurement@DESY - 1

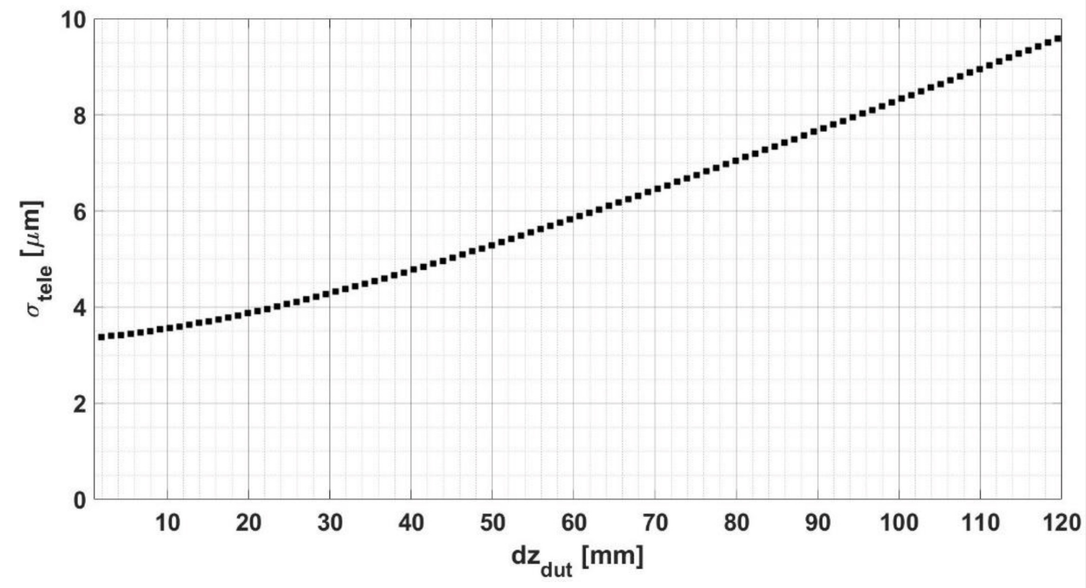




- Fit two tracks using upstream and downstream triplets
- Compute distance between the two impact points at the DUT (“sixdxc”)
- The DUT residual is computed as the difference between the measured coordinate and the mean values of the track impact points coordinate predicted by the upstream and downstream triplets
- The tracking error at the DUT is hence half the RMS of the distribution of sixdxc
- A student-t function is used for the fit

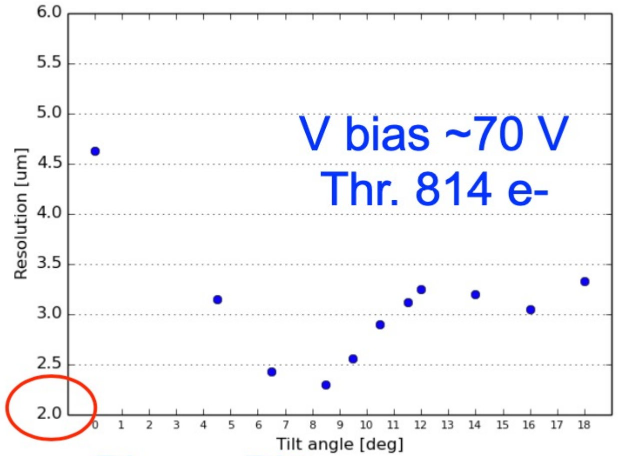
Resolution measurement@DESY - 2



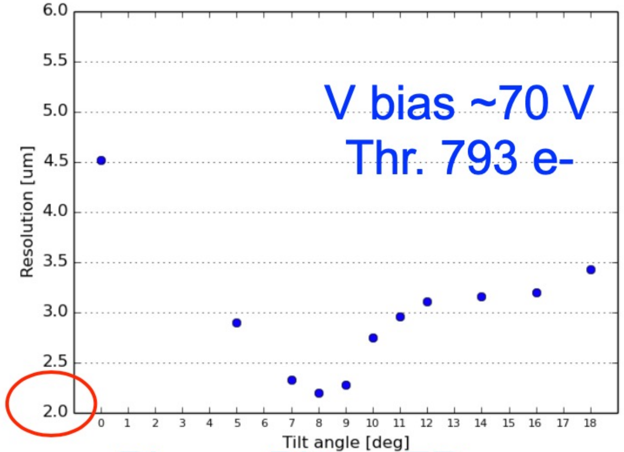


- Telescope resolution computed using General Broken Lines (GBL) algorithm as function of dz_{DUT} (distance between DUT and closest telescope plane)
- Verified measuring resolution of the same DUT inside and outside the cooling box

FBK fresh sensors - resolution

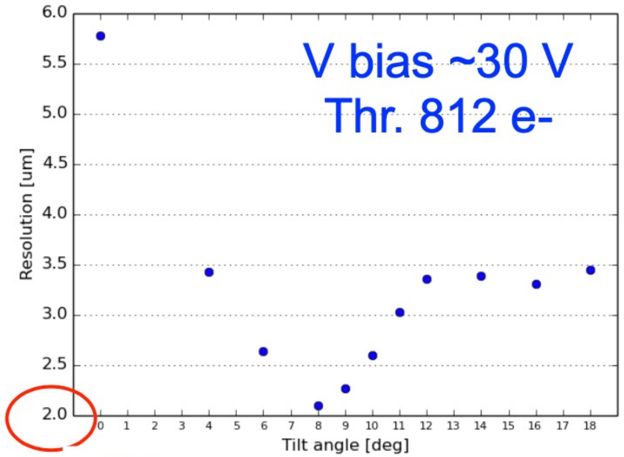


Planar Bitten



Planar Bitten FP

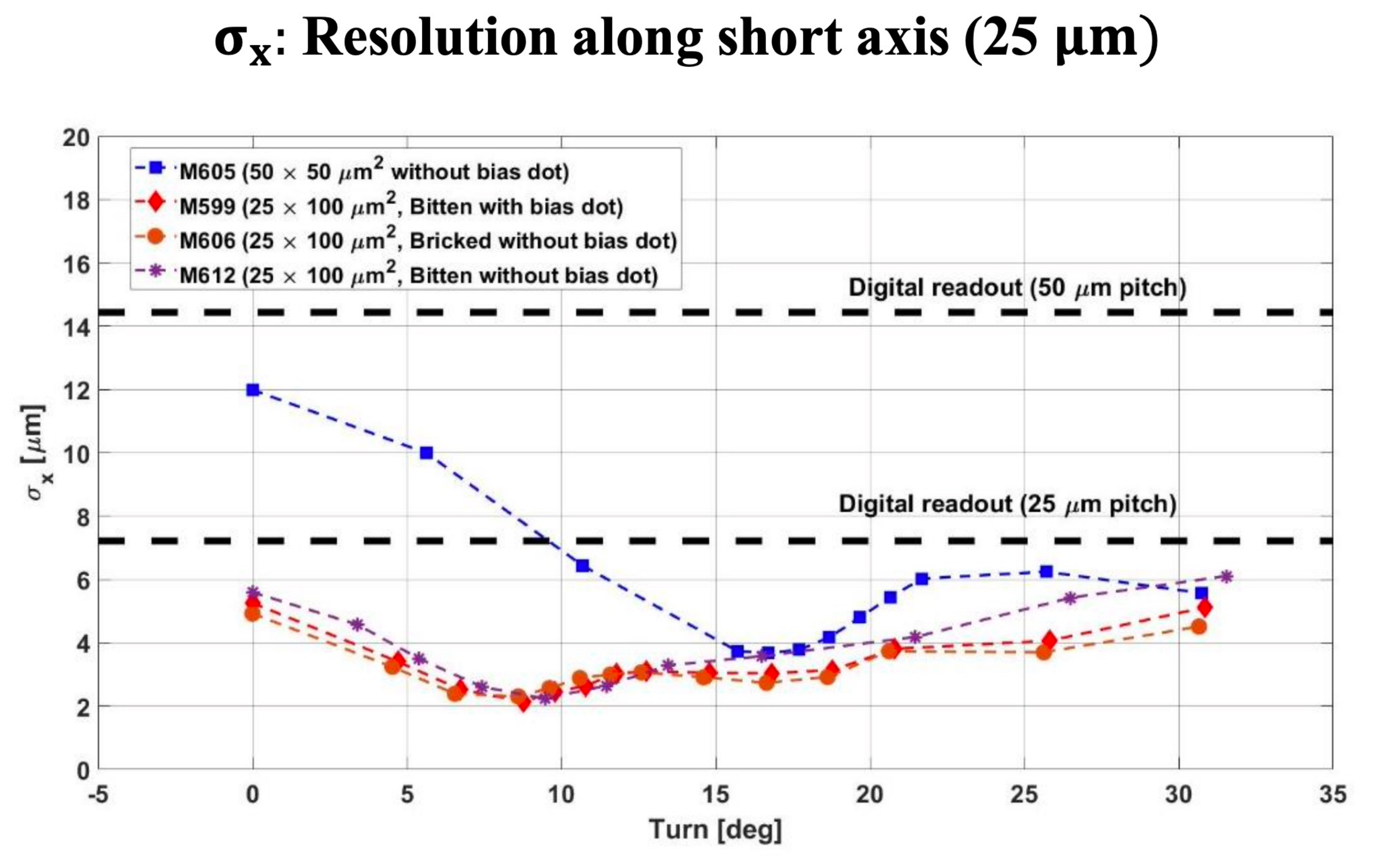
Position resolution well below the digital value



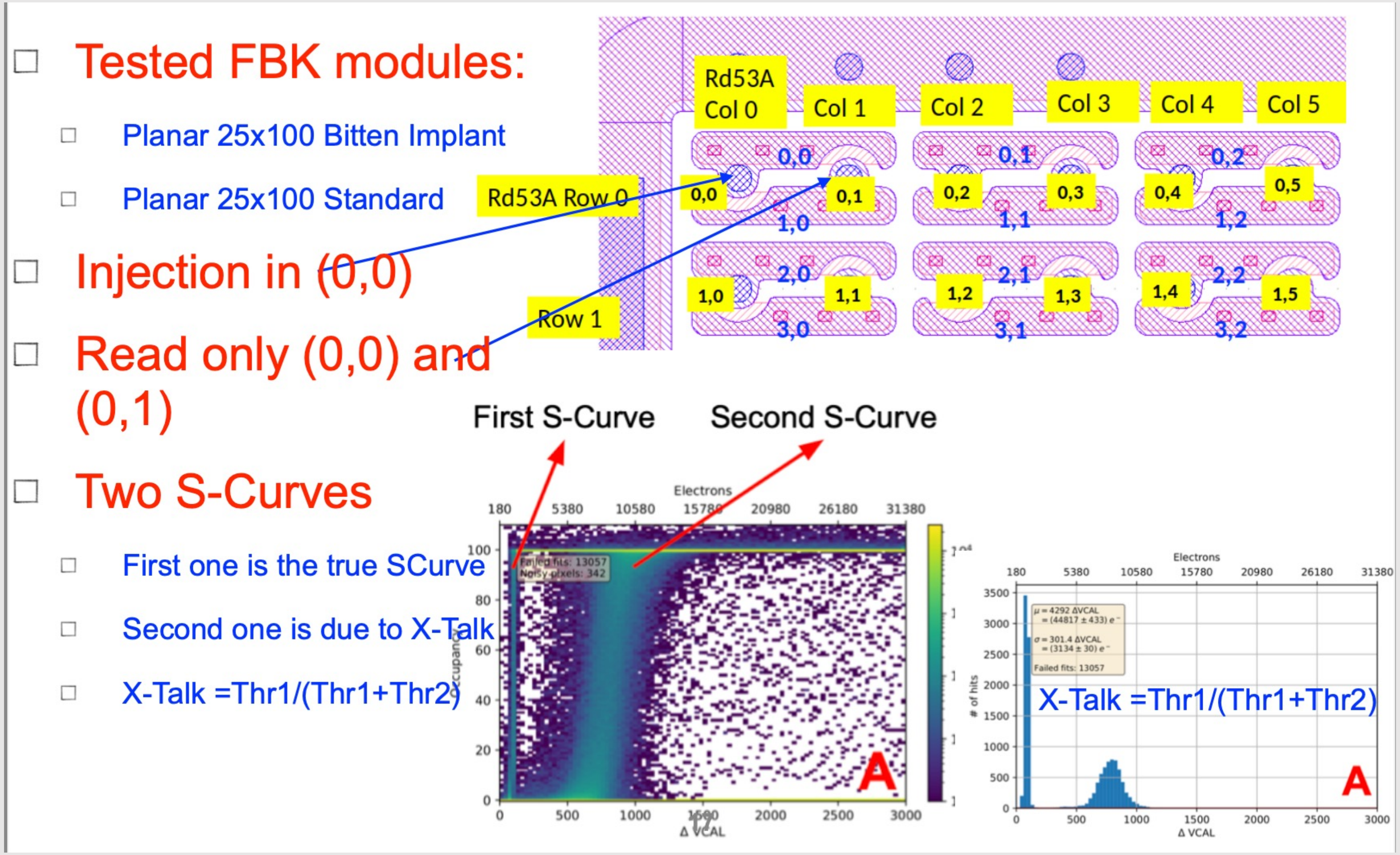
3D

Sensor thickness = 150 um

HPK fresh sensors - resolution



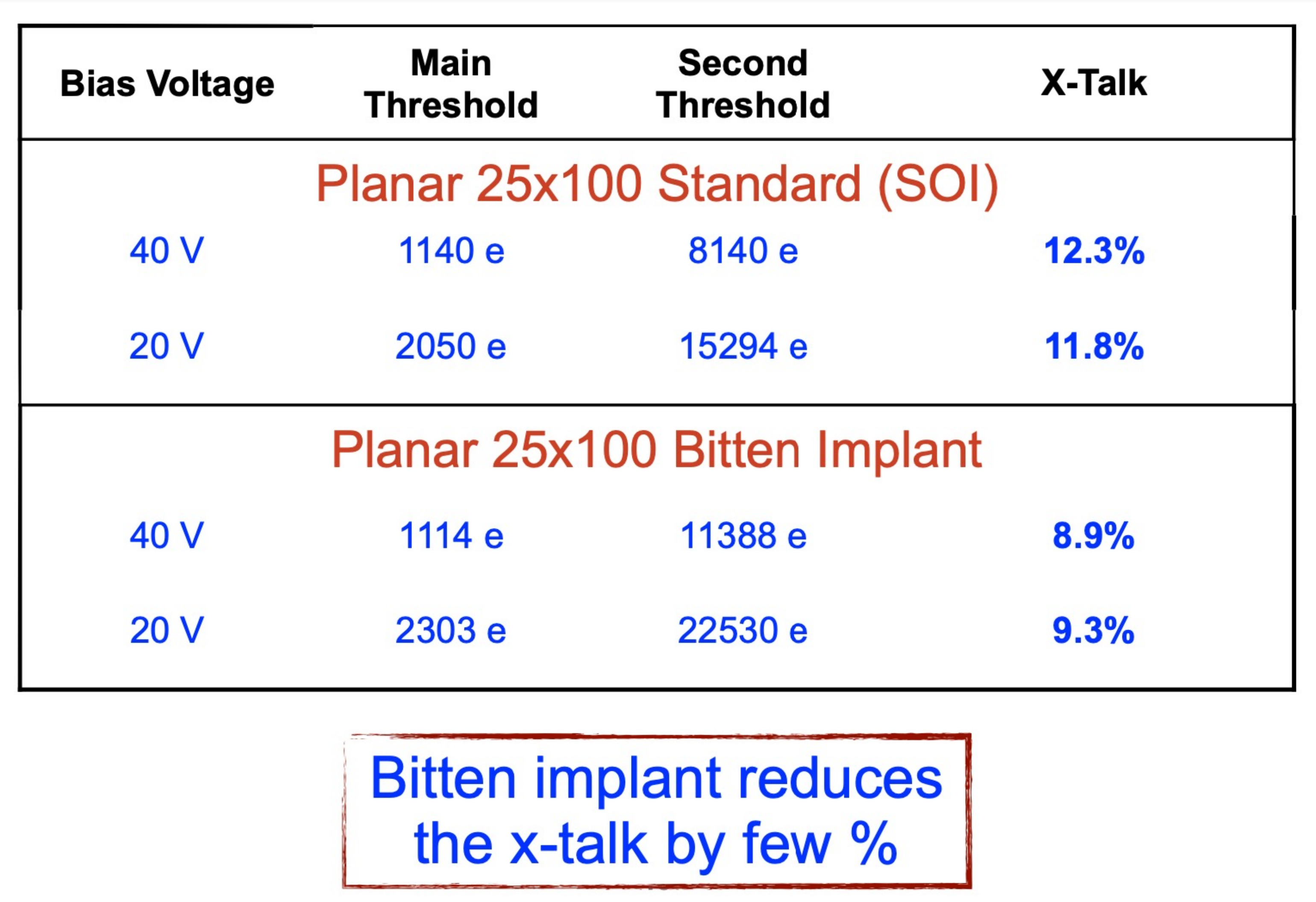
Cross talk - test bench measurements



- ☐ Tested FBK modules:
  - ☐ Planar 25x100 Bitten Implant
  - ☐ Planar 25x100 Standard
- ☐ Injection in (0,0)
- ☐ Read only (0,0) and (0,1)
- ☐ Two S-Curves
  - ☐ First one is the true SCurve
  - ☐ Second one is due to X-Talk
  - ☐ X-Talk =Thr1/(Thr1+Thr2)

X-Talk =Thr1/(Thr1+Thr2)

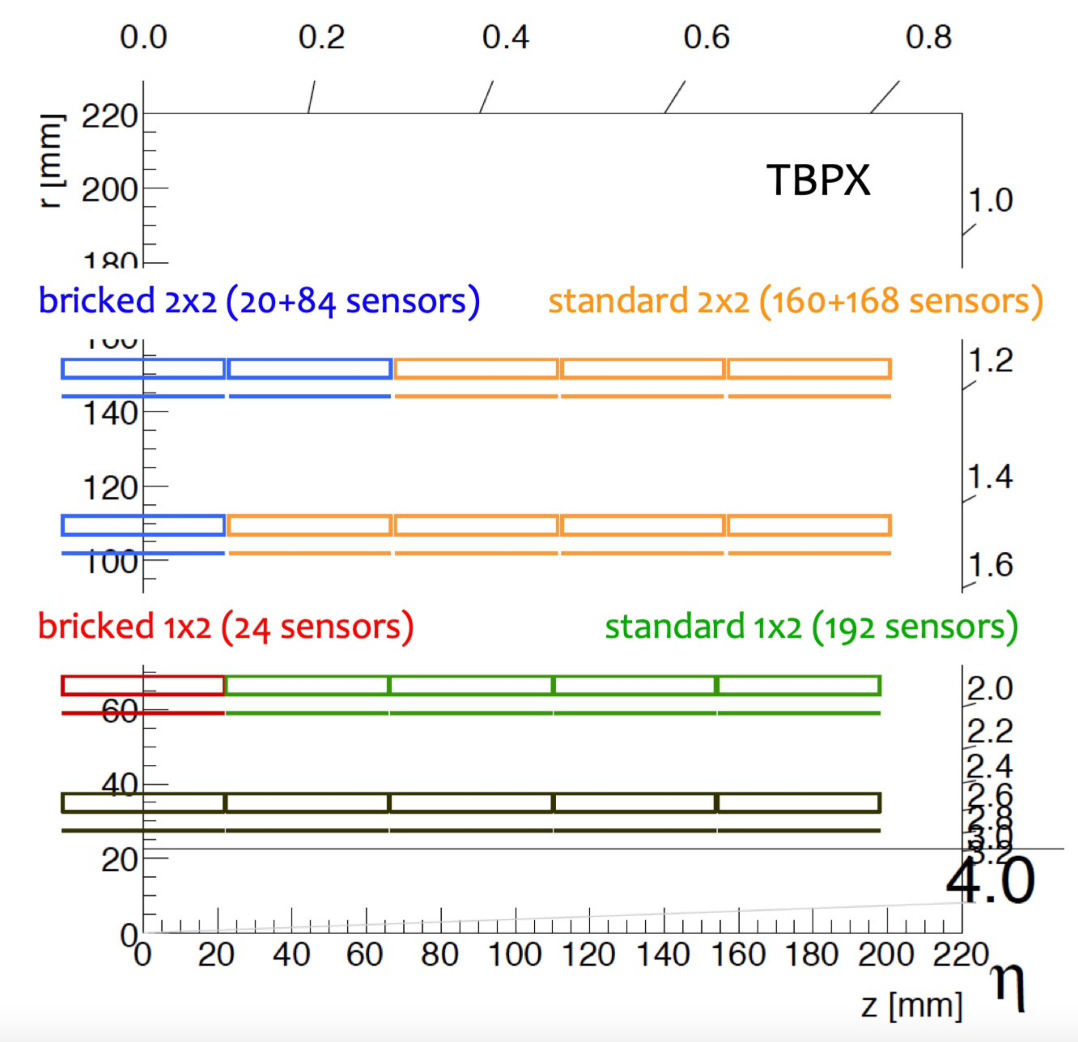
Cross talk - test bench measurements

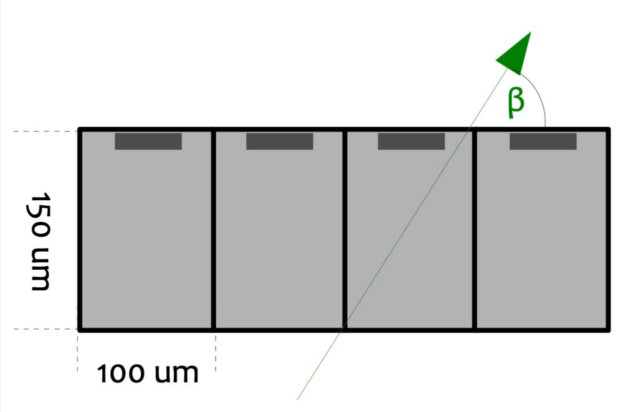


Bias Voltage	Main Threshold	Second Threshold	X-Talk
	Planar 25x100 Standard (SOI)		
40 V	1140 e	8140 e	**12.3%**
20 V	2050 e	15294 e	**11.8%**
	Planar 25x100 Bitten Implant		
40 V	1114 e	11388 e	**8.9%**
20 V	2303 e	22530 e	**9.3%**

Bitten implant reduces the x-talk by few %

Bricked sensors





- barrel: no advantage in using bricked for η≥0.62 (cotg β=100um/150um)
- endcaps: small/no charge sharing → no advantage in using bricked for η≤1.8
- Positioning of the modules with bricked pixels, especially in the endcaps, requires a lot of care → barrel only studies
- bricked pixels option brings challenges in the offline reconstruction as it couples the two coordinates and therefore they are more difficult to model after irradiation