Test Beam results of FBK 3D pixel sensors interconnected to RD53A readout chip after high irradiation

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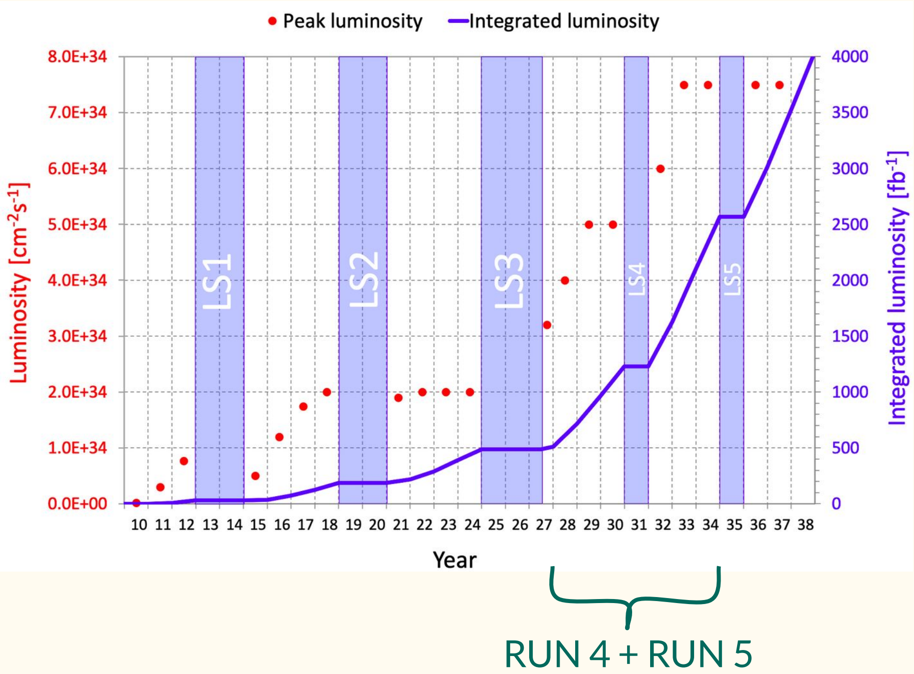
High Luminosity Phase of LHC

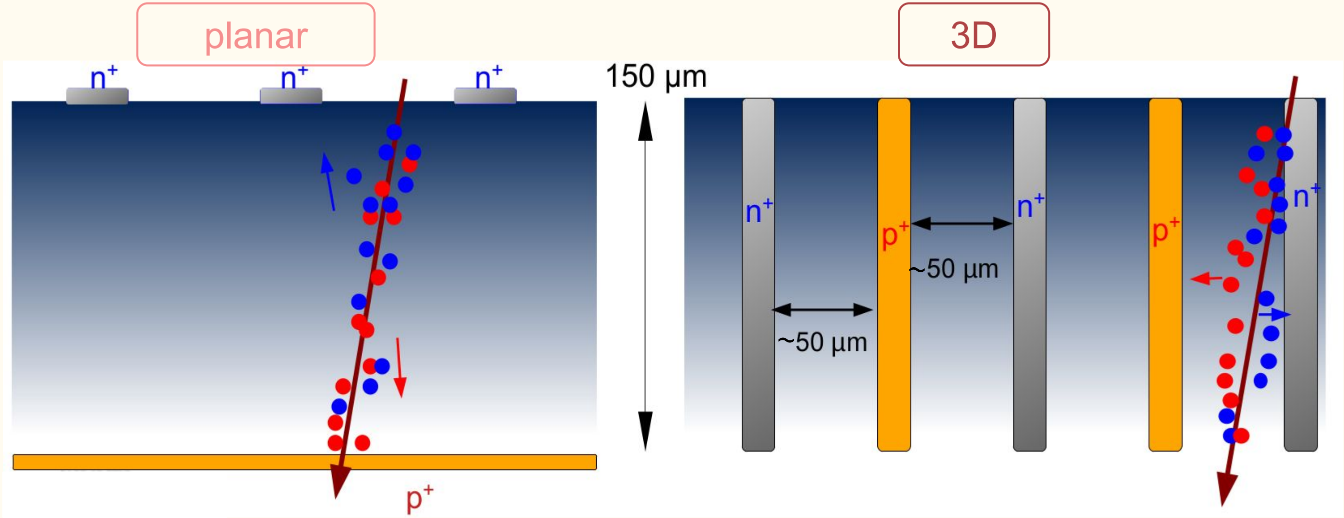
- Instantaneous Luminosity reaches 7.5 $\times 10^{34}$ cm^2/s.
- Collect data up to 4100 fb^{-1} over 10 years.
- CMS needs to be upgraded to cope with higher luminosity.
  - Up to 200 events per Bunch Crossing.
  - Fluence for innermost pixel layer ~ 1.9×10^{16} n_{eq}/cm^2 for Run 4-5.
- The tracker will be completely replaced.
  - Two technologies under study for inner tracker sensors: traditional planar and 3D pixel.



Further details for planar sensor in M. Antonello's talk. "New test beam results of HPK planar pixel sensors for the CMS Ph2 upgrade". @14:30

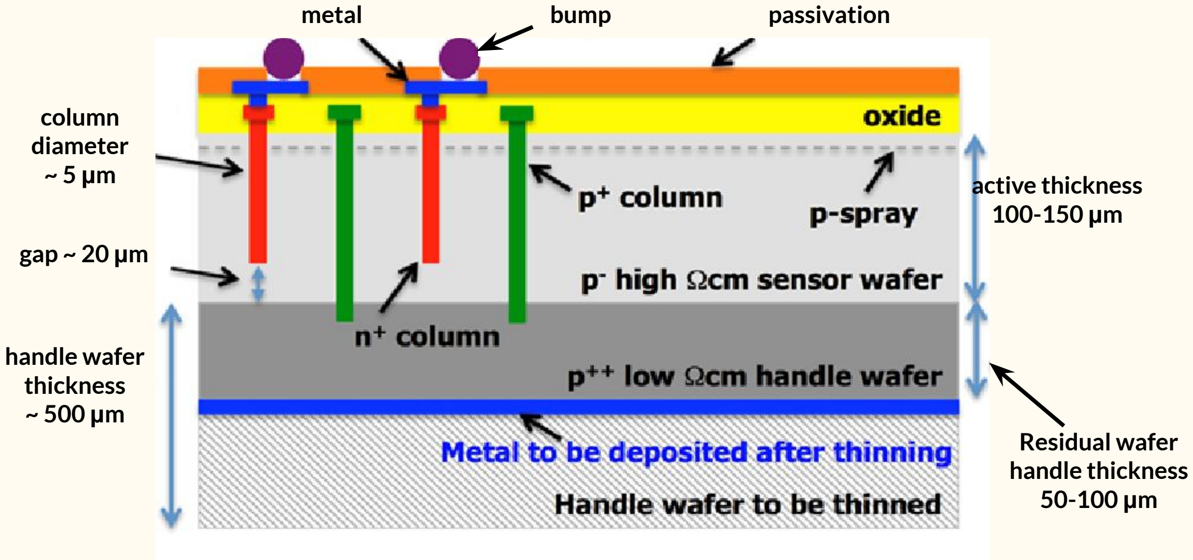
3D pixel sensors

- 3D pixels: new technology with columnar electrodes etched inside the bulk.
- 3D advantages with respect to planar:
  - Smaller depletion voltage.
  - Same active thickness.
  - Shorter drift distance for carriers:
    - reduced trapping probability when irradiated.



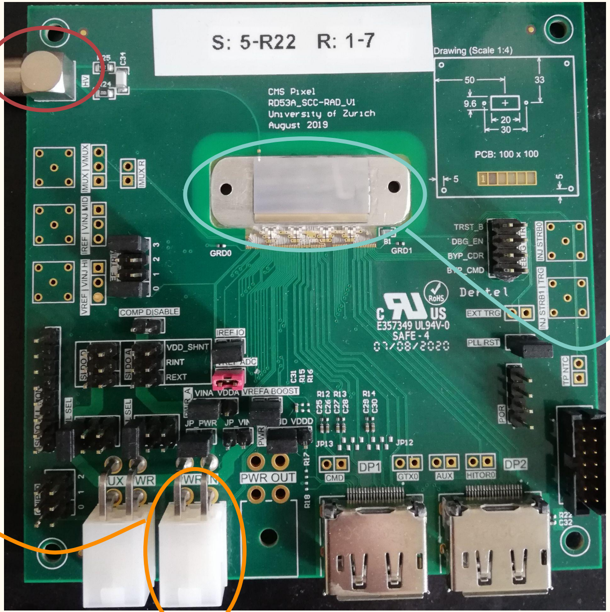
3D pixel sensors - technology

- Single side process in which columns are etched only from the front side.
  - P^+ columns in contact with back side of the sensor.
  - N^+ columns connected to the bump bonding pads for the readout.
    - The gap between n^+ columns and back side electrode is a critical parameter with respect to production yield vs. sensor performance.



FBK 3D sensors under test

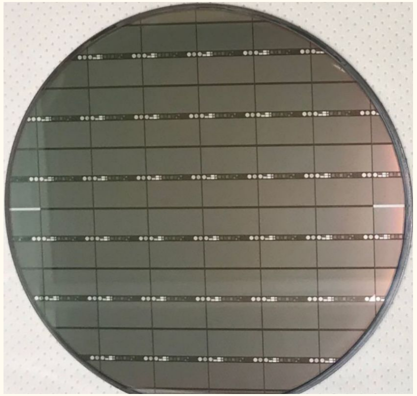
- Two “Step and Repeat” batches: Stepper-1 and Stepper-2.
  - Stepper-2: increased gap between n^+ columns and backside.
- Bump bonded at IZM with RD53A readout chip.
- Mounted on a single chip card developed at UZH.



Bias voltage

Sensors interconnected with RD53A ROC

LV



CNM 3D sensors discussed in S. Dittmer’s talk. “Study of irradiated CNM 3D sensors” . @17:45

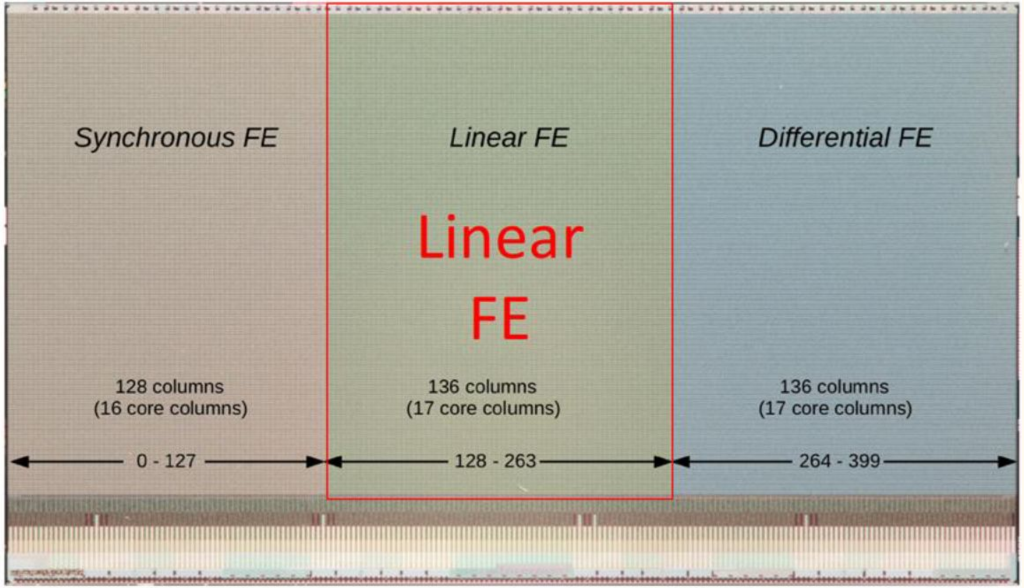
Irradiated sensor samples

- Modules irradiated with low energy protons, 23 MeV, at Karlsruher Institut für Technologie (KIT).
- Modules irradiated in a wide range of fluences.

module@fluence [n_{eq}/cm^2]	Bias Voltage @ Leakage Current	Status
25×100 μm^2 Stepper-1 @1.5×10^{16}	50 V @ 80 μA - 150 V @ 150 μA	✅
25×100 μm^2 Stepper-1 @2.3×10^{16}	50 V @ 150 μA - 150 V @ 440 μA	❌
25×100 μm^2 Stepper-2 @1.4×10^{16}	50 V @ 110 μA - 150 V @ 220 μA	✅
25×100 μm^2 Stepper-2 @1.8×10^{16}	50 V @ 170 μA - 150 V @ 400 μA	✅

→ Hard to analyze, high number of noisy channels

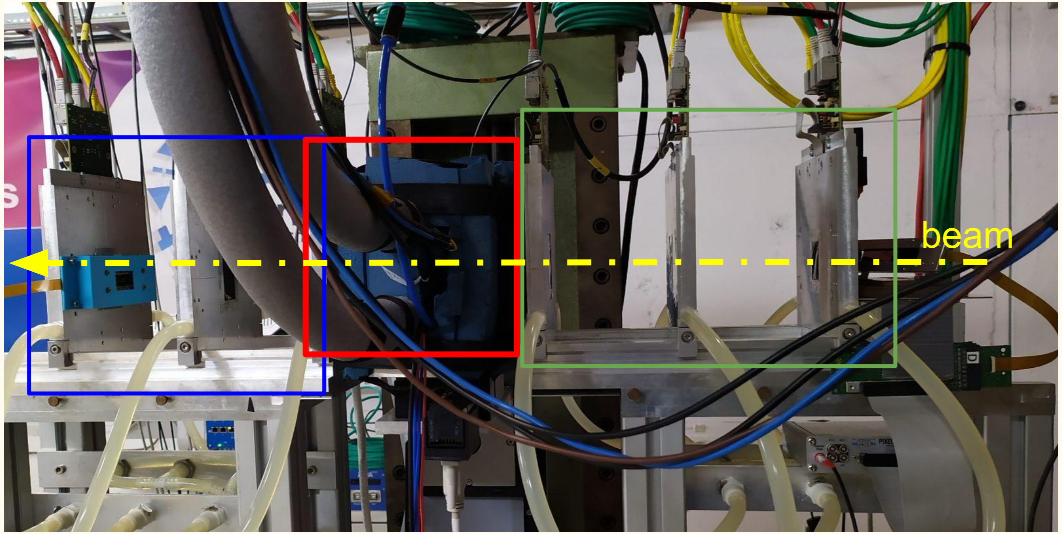
The Readout chip RD53A

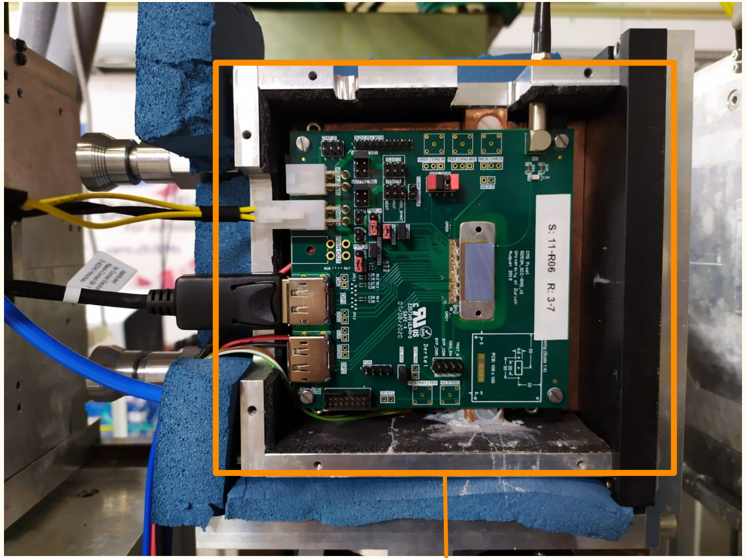


- 65nm CMOS technology; 50x50 μm^2 cell.
- Low threshold (1000 - 1500 e-) and low noise (< 100 e-).
- Radiation resistant: tested up to fluences of 2.4×10^{16} n_{eq}/cm^2.
- Three analog front ends for development purpose.
  - CMS choice: linear FE. All the results obtained with linear FE.

Test Beam set-up at DESY

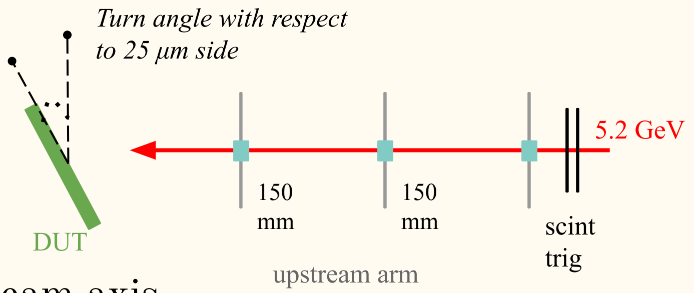
- Beam: 5.2 GeV electrons
- Mimosa telescope:
  - 3 pixel planes before the Device Under Test (DUT) - upstream.
  - Cooling Box (Irradiated DUT must be cooled to mitigate radiation damage effects).
  - 3 pixel planes after the DUT - downstream.





DUT inside cooling box

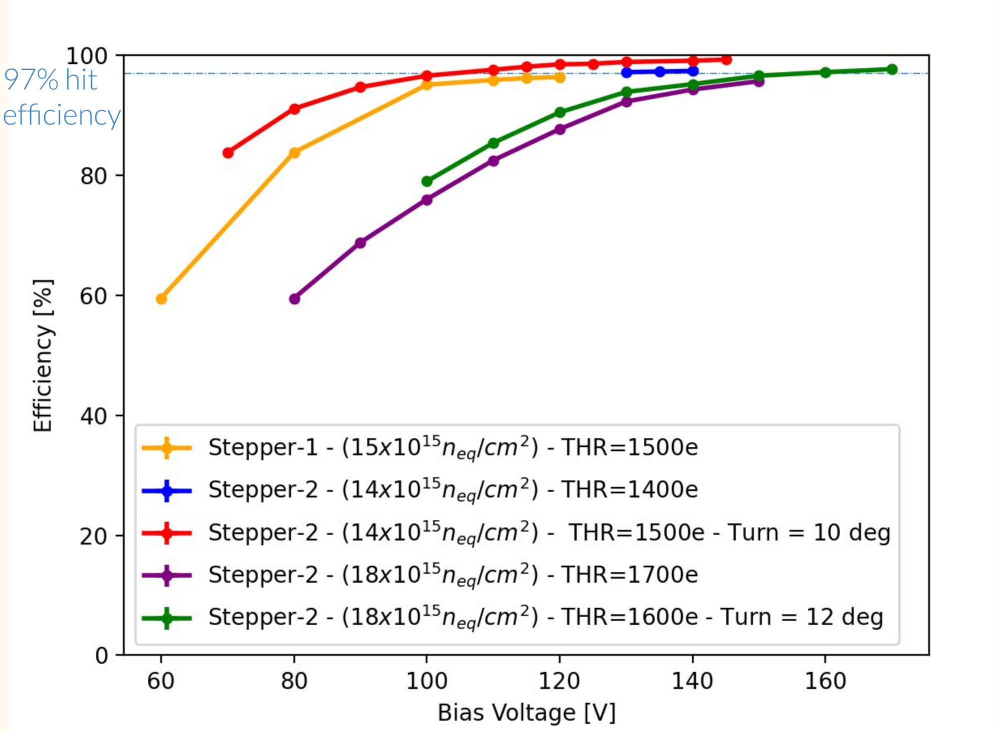
Data taking



- Data collected in October and in December 2021
- Operating conditions.
  - Sensor Temperature around -20 °C.
  - The DUT can be rotated with respect to the beam axis.
- DUT tuning.
  - Channel thresholds trimmed to average values ranging from 1400 e- to 1600 e-.
  - Noisy and dead channels are masked during analysis.
    - Channel with high occupancy (typ 2×10^{-5} per sampling cycle) tagged as noisy
- Test procedure
  - Hit efficiency as a function of bias voltage:
    - Perpendicular track incidence
    - Incidence around 10° with DUT rotated.
  - Spatial Resolution (and Cluster Size) as a function of the turn angle.

3D sensors - Hit efficiency

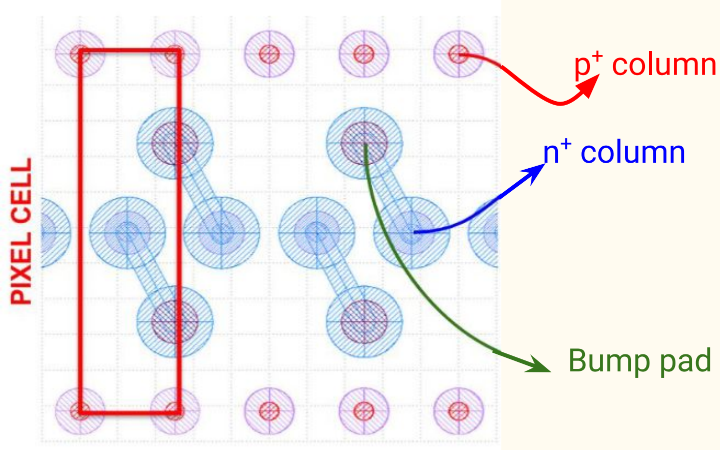
- Orthogonal beam incidence.
  - 97% hit efficiency for all sensors.
  - Hit efficiency plateau with V_{bias} from 110 V up to 140 V for all sensors.
  - Reduced hit efficiency due to passive material (columns).
- DUT turned of 10° :
  - 99% hit efficiency for less irradiated sensors.
  - 98% for Stepper-2 @ 1.8 $\times 10^{16}$ n_{eq}/cm^2.

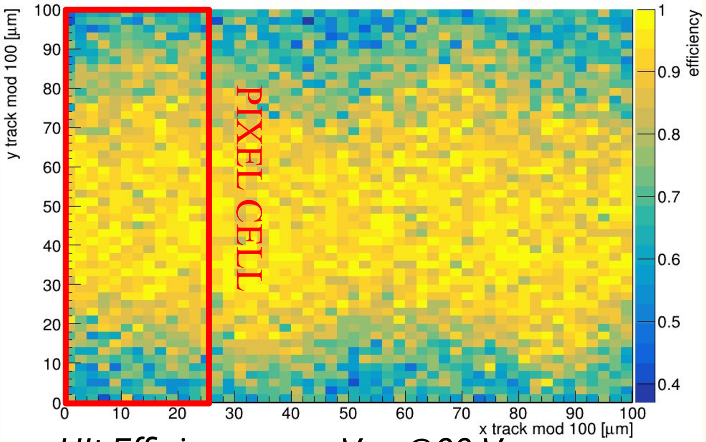


Hit efficiency map

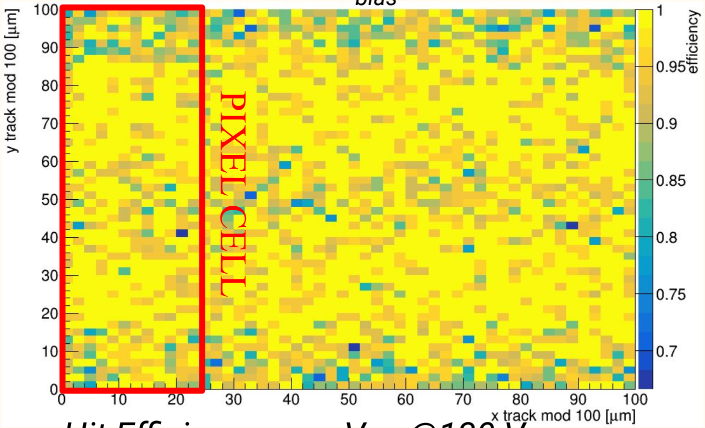
Stepper-1 @ 1.5×10^{16} n_{eq}/cm^2

- Orthogonal beam incidence.
- Superposition of all 4×1 pixel regions
- Hit Efficiency increases with effective bias voltage.
- Hit Efficiency around 97% at V_{bias} = 130 Volt.





HIt Efficiency map V_{bias}@80 V

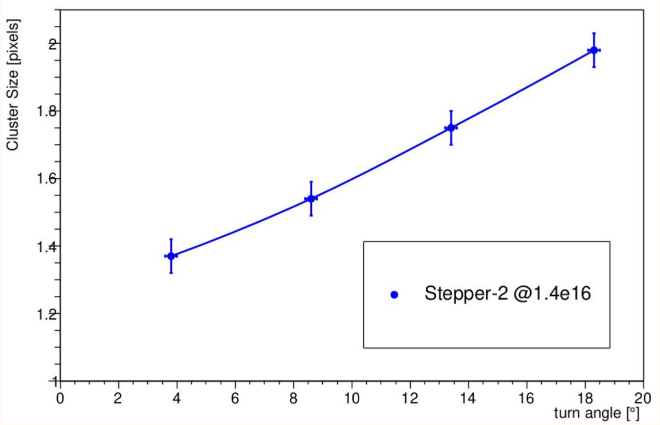


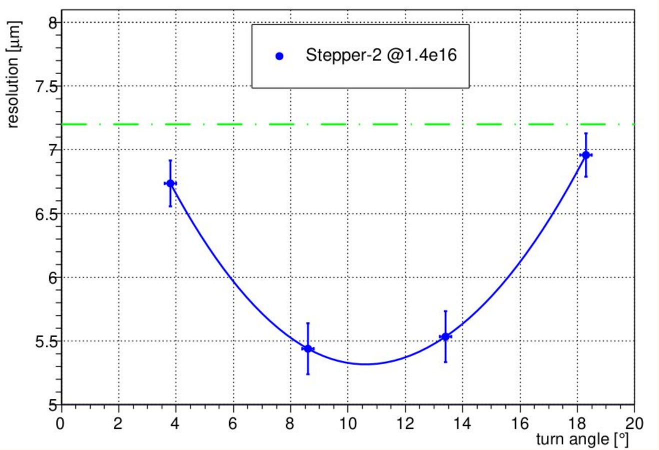
Hit Efficiency map V_{bias}@130 V

Procedure for Spatial Resolution

Stepper-2 @ 1.4×10^{16} n_{eq}/cm^2

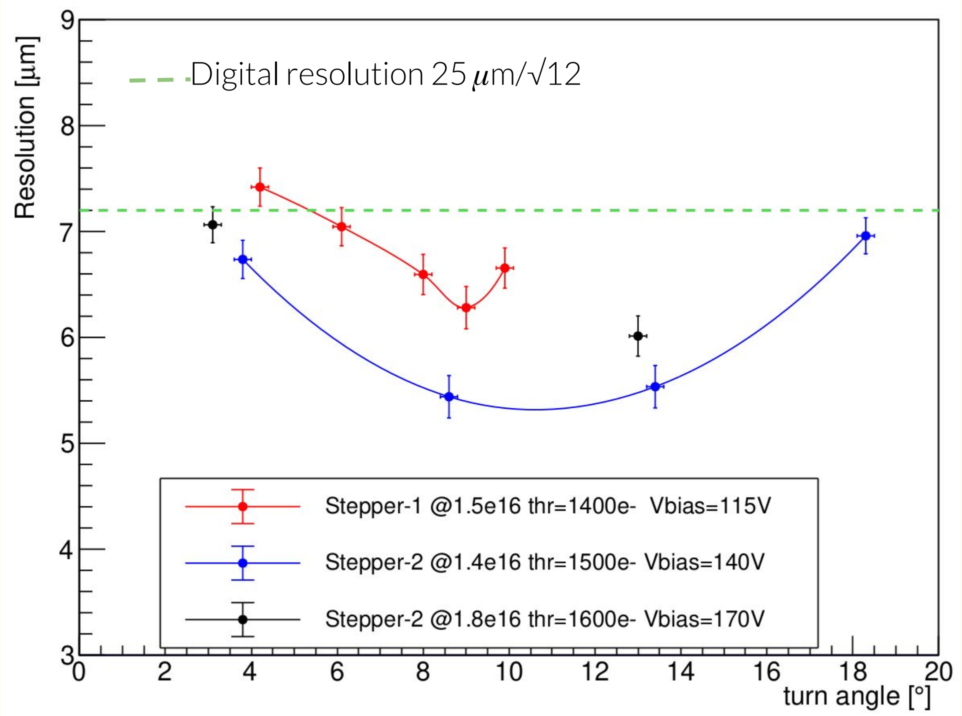
- Angle scan with respect to pixel short side at the hit efficiency plateau (140 V for Stepper-2@1.4×10^{16}).
- Intrinsic DUT resolution
  - telescope resolution (around 7μm - estimated from MC simulations) subtracted from DUT total spatial resolution [$\sigma^2_{DUT} = \sigma^2_{tot} - \sigma^2_{tele}$]
- Only the upstream telescope is used.
- Minimum spatial resolution 5.4 μm at around 9°for Stepper-2@1.4×10^{16}.
- Average Cluster Size for Stepper-2@1.4×10^{16} is 1.5 at around 9°.





3D sensors - Spatial Resolution

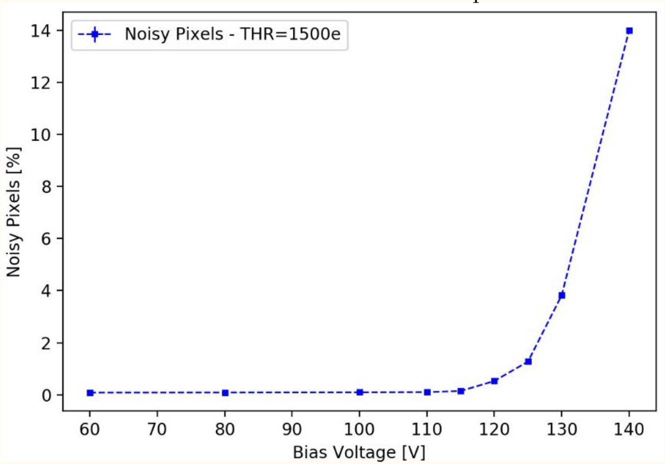
- Angle scan for less irradiated sensors.
  - Minimum of spatial resolution at 9° turn angle.
    - Stepper-1 6.3 µm.
    - Stepper-2 5.4 µm.
- Two points for Stepper-2 @ 1.8×10^{16} n_{eq}/cm^2 at plateau efficiency.
  - At 13° turn angle 6 µm spatial resolution.
- Spatial resolution comparable with the one measured for FBK planar sensors measured in DESY.



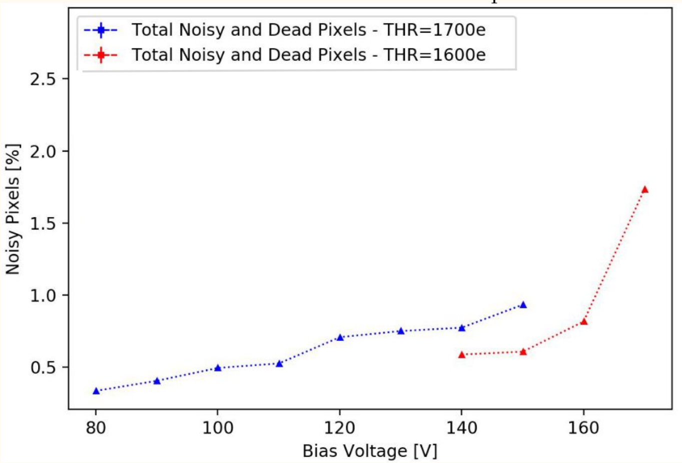
Noisy channels

- Observed quick increase in the number of noisy and dead channels at high bias voltage for Stepper-1 modules.
- Under investigation:
  - sensor: possible correlation with breakdown voltage?
  - ROC: TID for irradiations with low energy protons (1.5 GRad in $1\times10^{16}\ n_{eq}/cm^2$) is higher than RD53A design tolerance (0.5 GRad)?
- Lower and more stable number of noisy channels in Stepper-2 sensors.

Stepper-1@$1.5\times10^{16}\ n_{eq}/cm^2$



Stepper-2@$1.8\times10^{16}\ n_{eq}/cm^2$



Summary and Conclusion

- 3D sensors irradiated up to 1.8×10^{16} n_{eq}/cm^2 show performances suitable with HL-LHC requirement with lower bias voltage and lower power consumption with respect to planar pixel sensors.
- Minimum spatial resolution around 5.5 μm at 9° turn angle. Comparable with irradiated planar sensors.
- 3D pixels are good candidates for innermost pixel layer of CMS Tracker during HL-LHC.

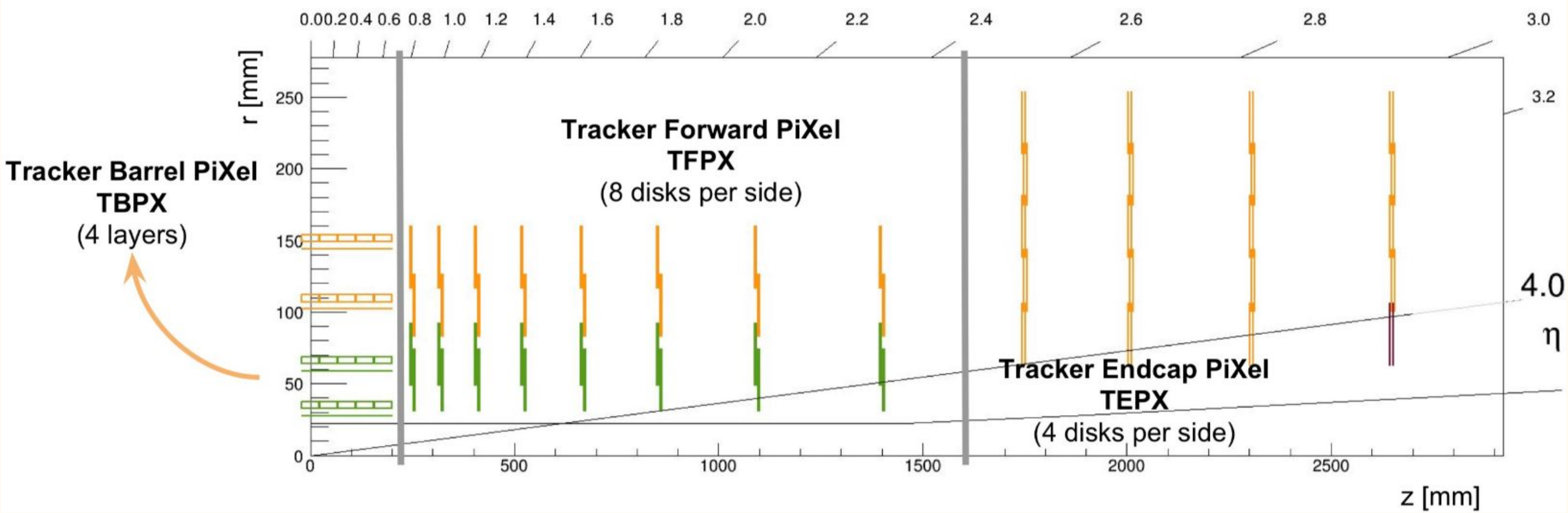
Additional Material

The Inner Tracker of CMS during HL-LHC

- Single sensor cell size of 2500 μm^2 to keep occupancy below 0.1%. Two cell under study: **25x100** and 50x50 μm^2.
- Planar sensors baseline choice, but 3D sensors considered for first layer (3 cm from beam).

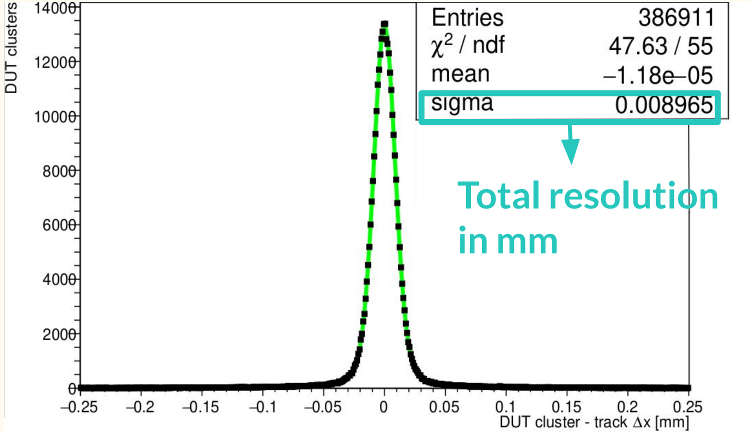
2736
2x2 pixel modules

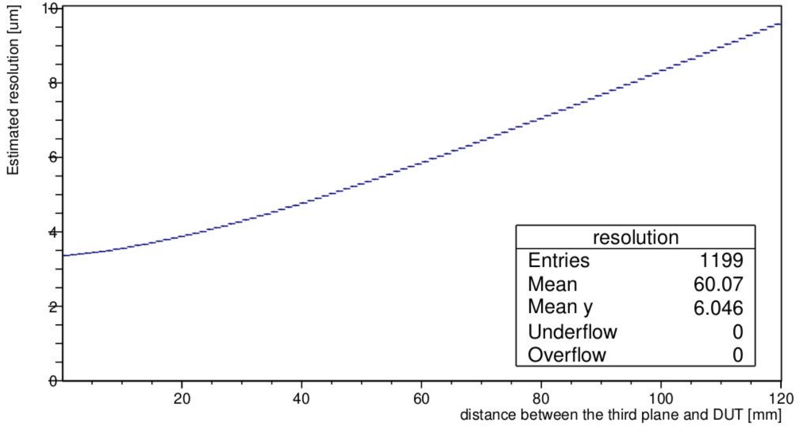
1156
1x2 pixel modules



Resolution at DESY

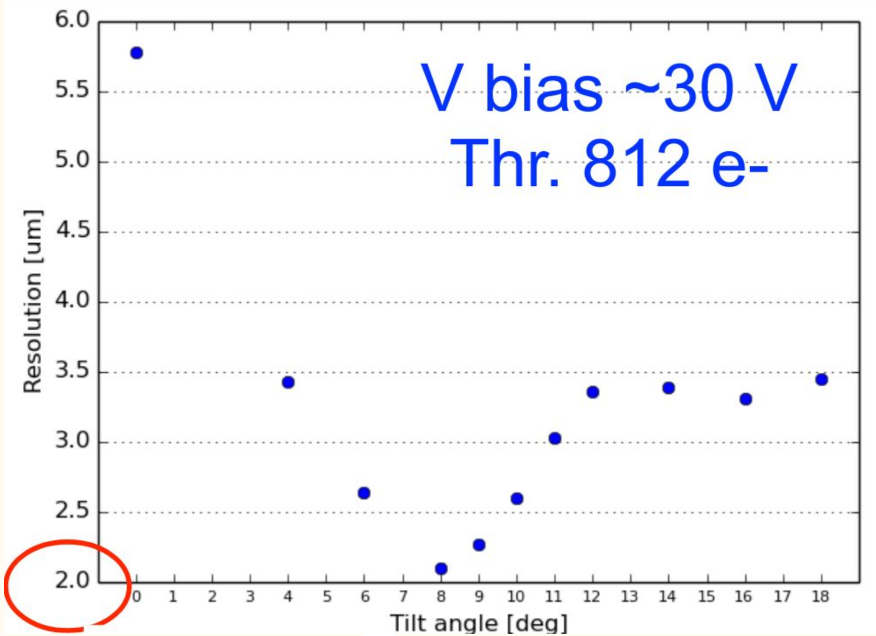
- Residuals are the difference between DUT measured tracks and reconstructed tracks.
- Fit with student-t distribution from -30 μm to 30 μm.
- Range chosen to reach $\chi^2 \cong 1$.
- An error of 0.1 μm is associated to total resolution.
- Simulation dependent on the distance between DUT and third plane.
- Simulation computed with 5.2 GeV beam energy.





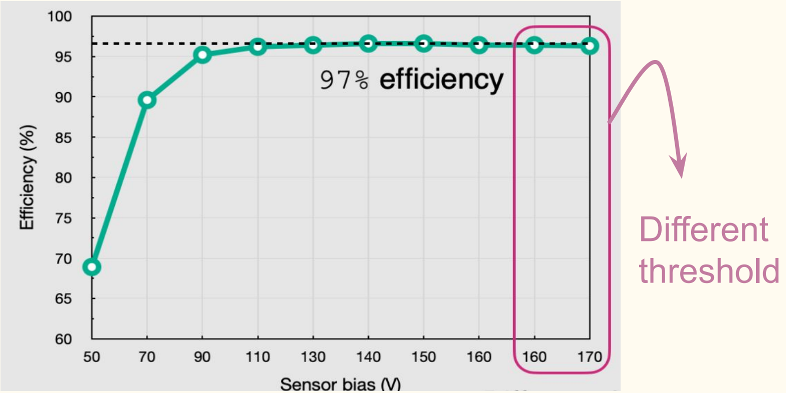
Resolution of a fresh 3D sensor

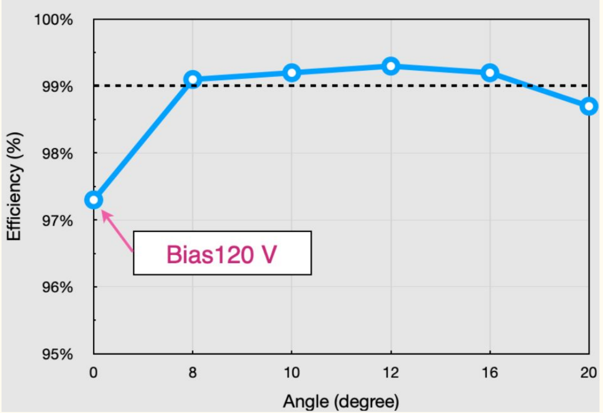
- Fresh 3D sensor measured a DESY in 2020.
- Threshold suffer from a past conversion (10% higher).
- Best $\sigma_{DUT} \sim 2\ \mu m$ at 8°.
- In the most angular range σ_{DUT} is 3.5 μm or better.
- No cooling box needed: track reconstructed with the entire telescope.
    - Decrease of systematic uncertainties.

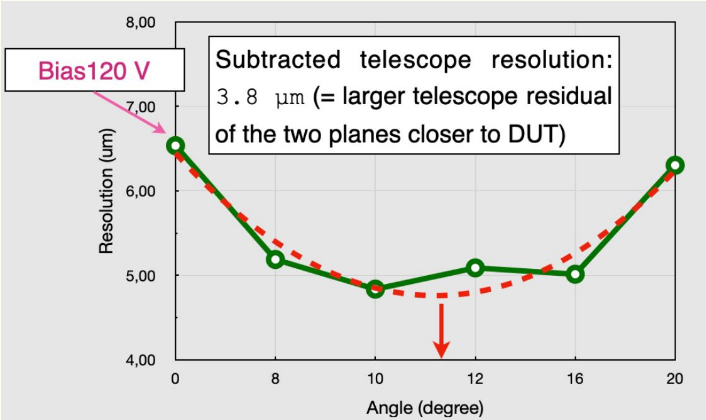


CERN Test Beam

- FBK Stepper-1@ 1.5e16 n_{eq}/cm^2 tested at CERN-SPS with 400 GeV proton beam.
- Hit Efficiency 97% @130 V with orthogonal incidence.
    - 99% with 8° turn angle.
- Threshold 1400 e-.
- Entire telescope used in CERN
- Spatial resolution minimum 5 µm.



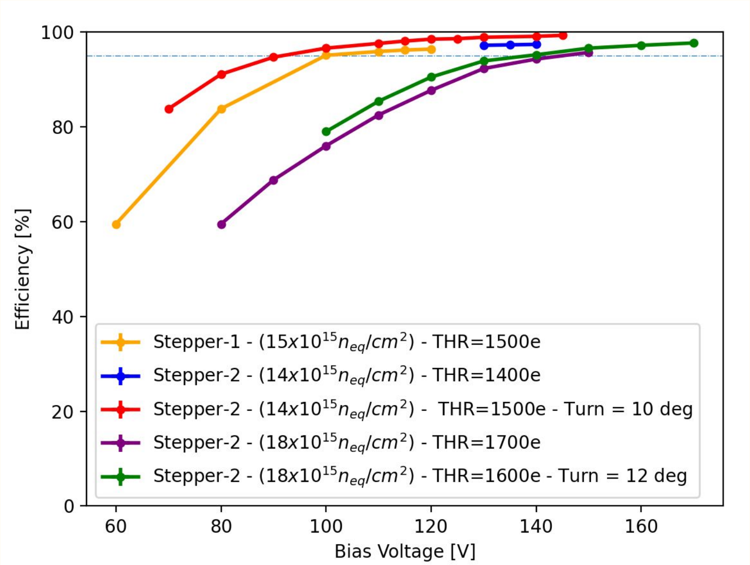




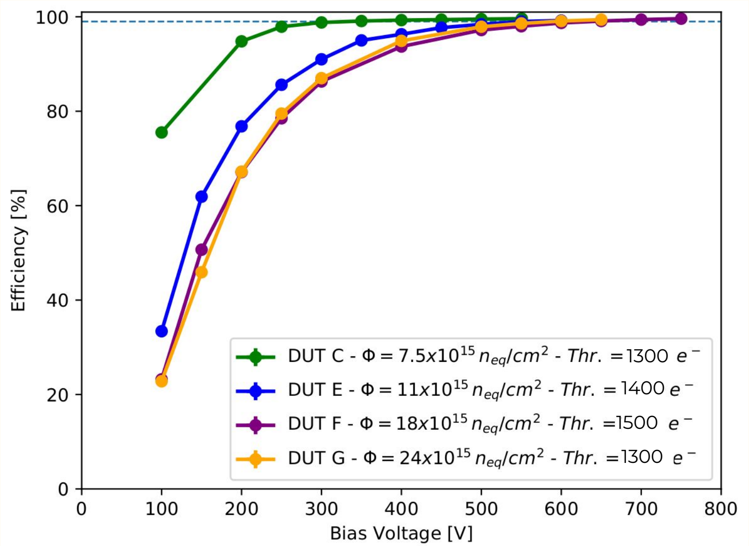
Comparison with planar modules - Hit efficiency

- 25x100 μm^2 planar irradiated FBK sensors tested in past test beams (2020-early 2021).
- For planar 99% detection hit efficiency above 500 V for fluences $> 10^{16} n_{eq}/cm^2$.
- For 3D same hit efficiency reached at lower bias voltage.

3D

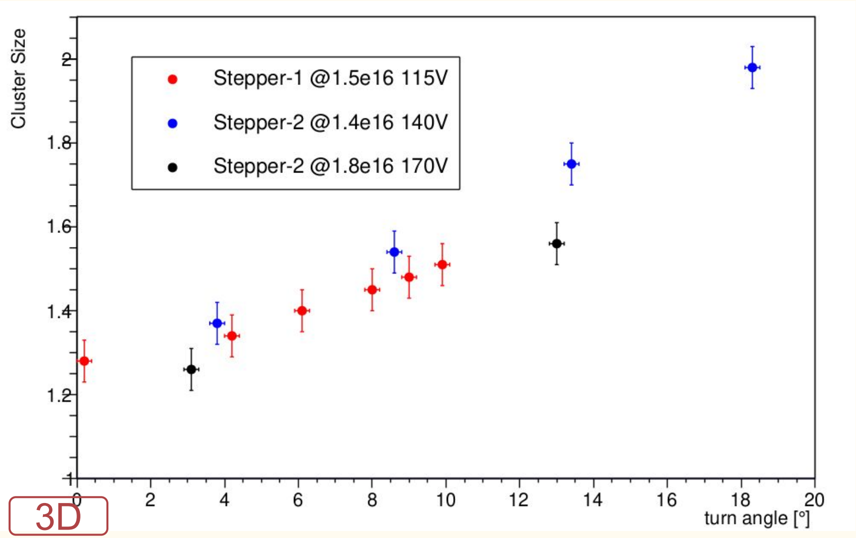


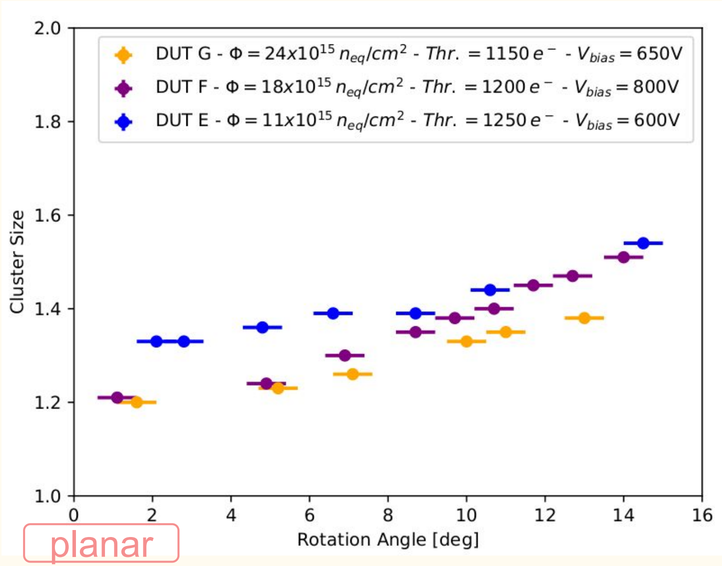
planar



Comparison with planar modules - cluster size

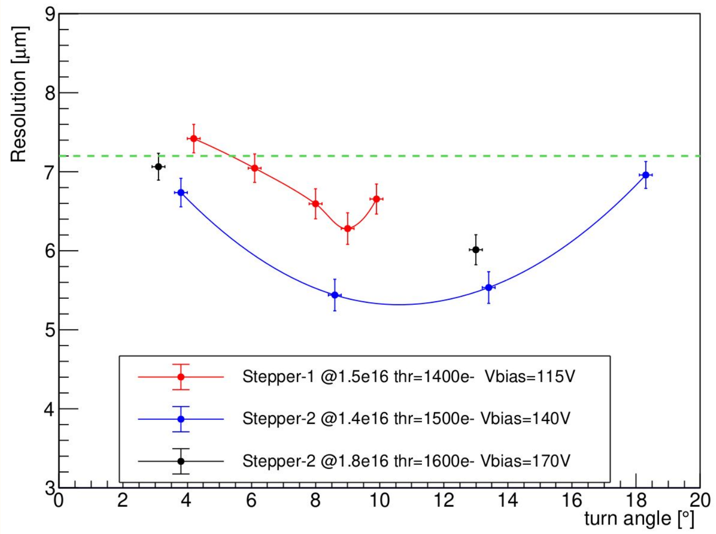
- 25x100 μm^2 planar irradiated FBK sensors tested in past test beams (2020-early 2021).
  - Threshold of planar suffers from a past electron conversion(real one 10-15 % higher).
- Compatible cluster size between the two layout compared.
- Planar 1.8e16 n_{eq}/cm^2 1.5 cluster size at 13° while 3D 1.8e16 n_{eq}/cm^2 1.56 cluster size at 13°.



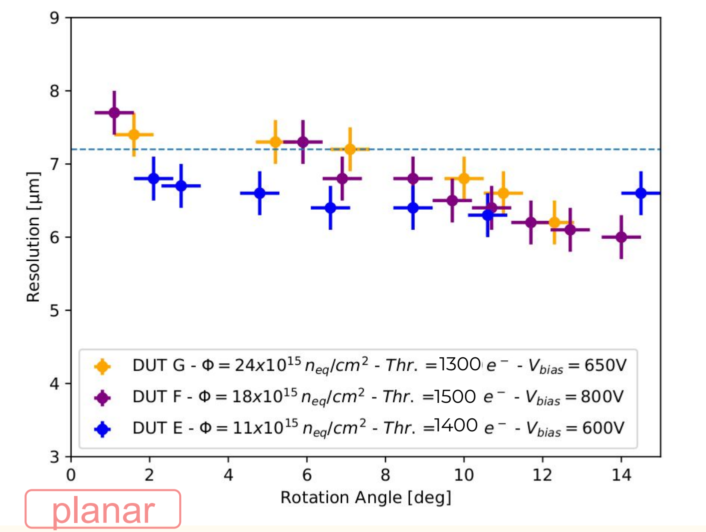


Comparison with planar modules - spatial resolution

- 25x100 μm^2 planar irradiated FBK sensors tested in past test beams (2020-early 2021).
- Planar @1.8×10^{16} n_{eq}/cm^2 spatial resolution around 6 μm at 13°.
- 3D @1..8×10^{16} n_{eq}/cm^2 spatial resolution around 6 μm at 13°.
- Minimum resolution for 3D@1.4×10^{16} n_{eq}/cm^2 5.4 μm at 9°.



3D



planar