Recent test beam results of the ATLAS ITk Pixel detector

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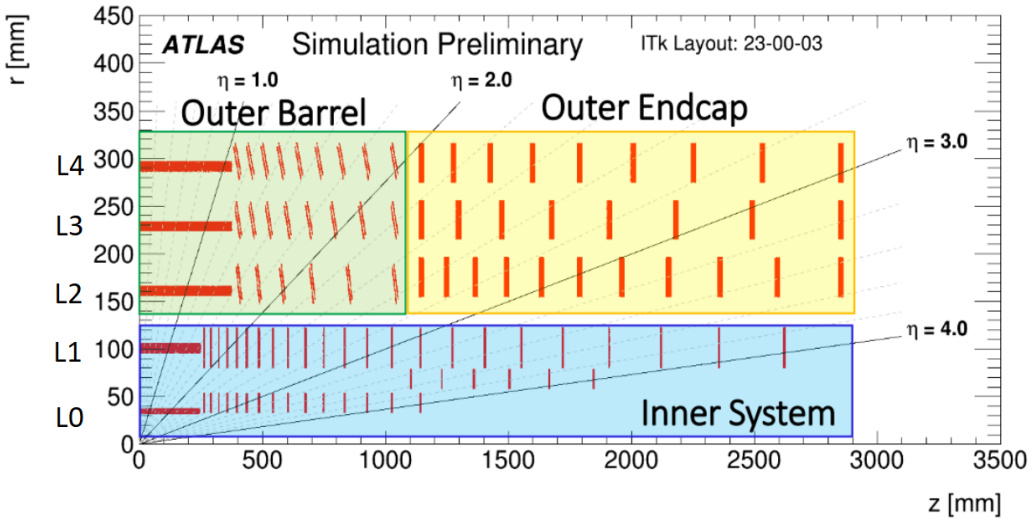
11th BTTB Workshop

ATLAS ITk Upgrade

- High-Luminosity LHC in 2029:
  - Instantaneous Luminosity increases (≈5x)
  - Pile-up events increases (≈4x)
  - Radiation damage increases
    (up to $2 \cdot 10^{16}\ n_{eq}/cm^2$, 1.5 safety factor)



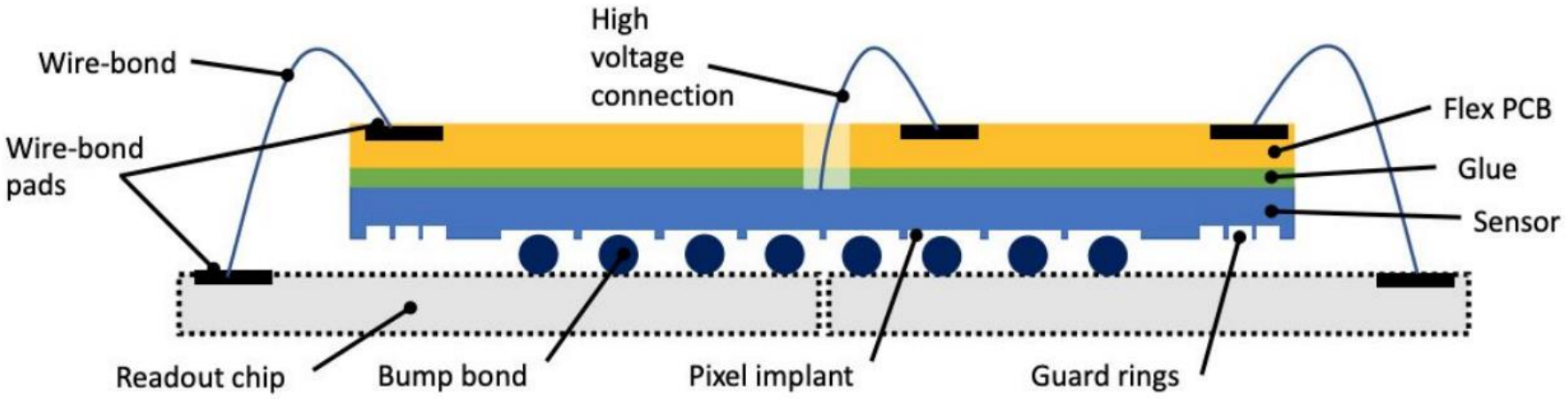
[ATL-PHYS-PUB-2021-024]

- Inner Detector will be replaced with ITk
  - All-silicon detector consisting of pixels and strips
  - Single-chip 3D sensors ($2x2cm^2$) in L0
  - Quad planar sensors ($4x4cm^2$) in L1-L4
  - Inner-system (L0 and L1) will be replaced after half HL-LHC program ($\approx 2000fb^{-1}$)

ITk Pixel Modules

- ITk hybrid pixel module assembly steps
  - ➢ Readout chip bump bonded to bare sensor (Quad: 4 chips bonded to sensor)
  - ➢ Flex PCB is glued to the bare module

- Performance of assembled modules investigated in laboratories and testbeams afterwards



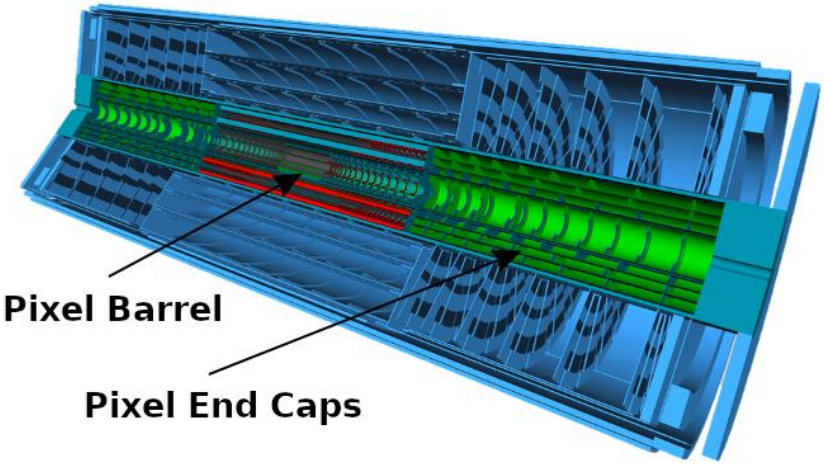
[Optimisation of Pixel Modules for the ATLAS Inner Tracker at the High-Luminosity LHC]

Pixel Sensor Vendors

- 3D Sensors in L0 (triplet)
  - ➢ 25x100µm^2 sensors in barrel, produced by **CNM** (Backup: **FBK**)
  - ➢ 50x50µm^2 sensors in endcaps, produced by **FBK** and **SINTEF**

- Planar sensors in L1 (100µm thickness, quad):
  - ➢ 50x50µm^2 sensors, produced by **FBK** and **Micron**

- Planar sensors in L2-L4 (150µm thickness, quad):
  - ➢ 50x50µm^2 sensors, produced by **HPK** and **Micron**



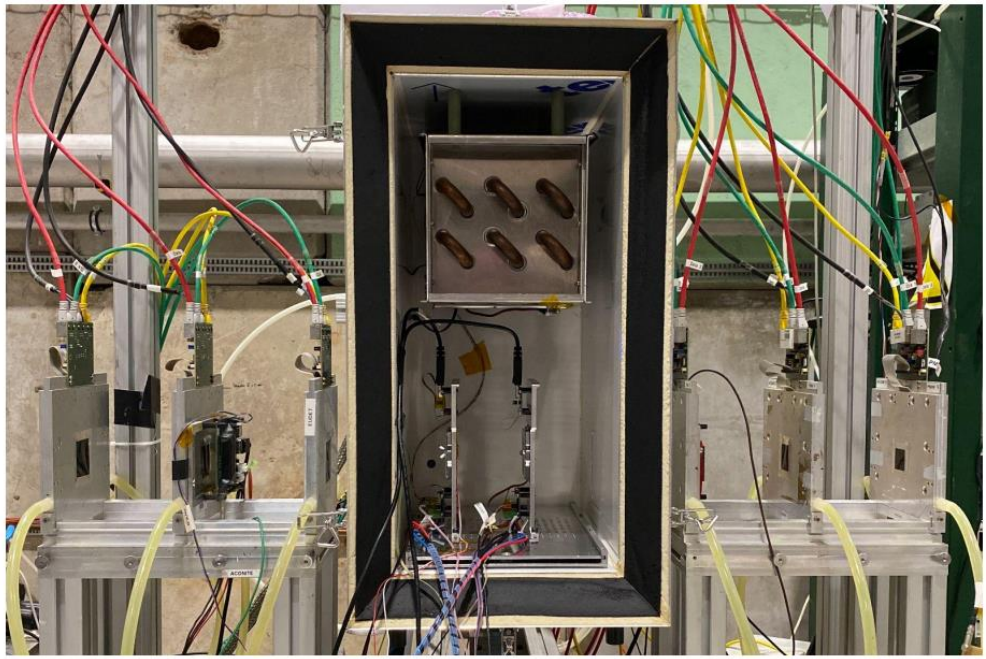
[hep.physik.uni-siegen.de/research/atlas/atlas-itk]

Investigated Sensors

Name	Vendor	Module	Front-End	Pixel Size	Thickness	Irradiation
Q2	Micron	Planar, Quad	RD53a	50x50µm^2	150µm	0
Q4	HPK	Planar, Quad	RD53a	50x50µm^2	150µm	$5 \cdot 10^{15} n_{eq}/cm^2$
Q8	HPK	Planar, Quad	RD53a	50x50µm^2	150µm	0
SCC2	FBK	3D, Single	ITkPixV1.1	50x50µm^2	250µm	0
SCC3	FBK	3D, Single	ITkPixV1.1	50x50µm^2	250µm	Up to $1.9 \cdot 10^{16} n_{eq}/cm^2$
SCC4	FBK	3D, Single	ITkPixV1.1	50x50µm^2	250µm	0
SCC5	FBK	3D, Single	ITkPixV1.1	50x50µm^2	250µm	Up to $1.9 \cdot 10^{16} n_{eq}/cm^2$

Testbeam Setup

- Testbeam measurements performed at CERN SPS North Area and PS East Area (Aconite telescope)
  - 120 GeV pions/12 GeV protons
  - Scintillators in coincidence used for triggering
  - FEI4/FBK 3D sensor for time reference
- EUDAQ1 framework used for data acquisition
  - EUDAQ2 migration in progress

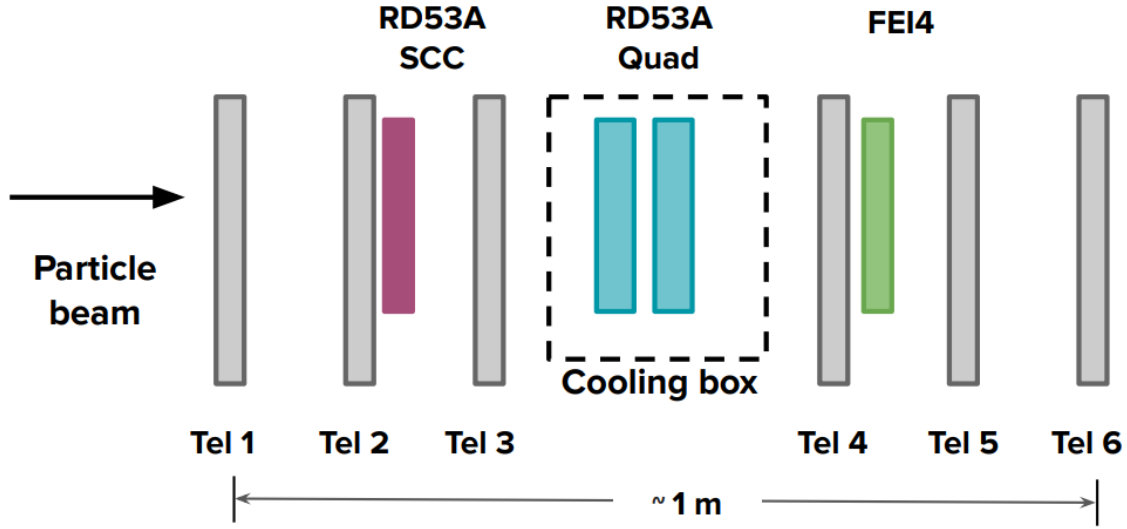


[ATLAS ITk Pixel quad module test beam measurements]

Data Analysis

- Track reconstruction performed with Corryvreckan framework
  - 6-plane telescope
  - Alignment with χ^2 minimisation, GBL
  - Quad: Matching radius = 2 pixel pitches
  - 3D sensors: Matching radius = 30µm

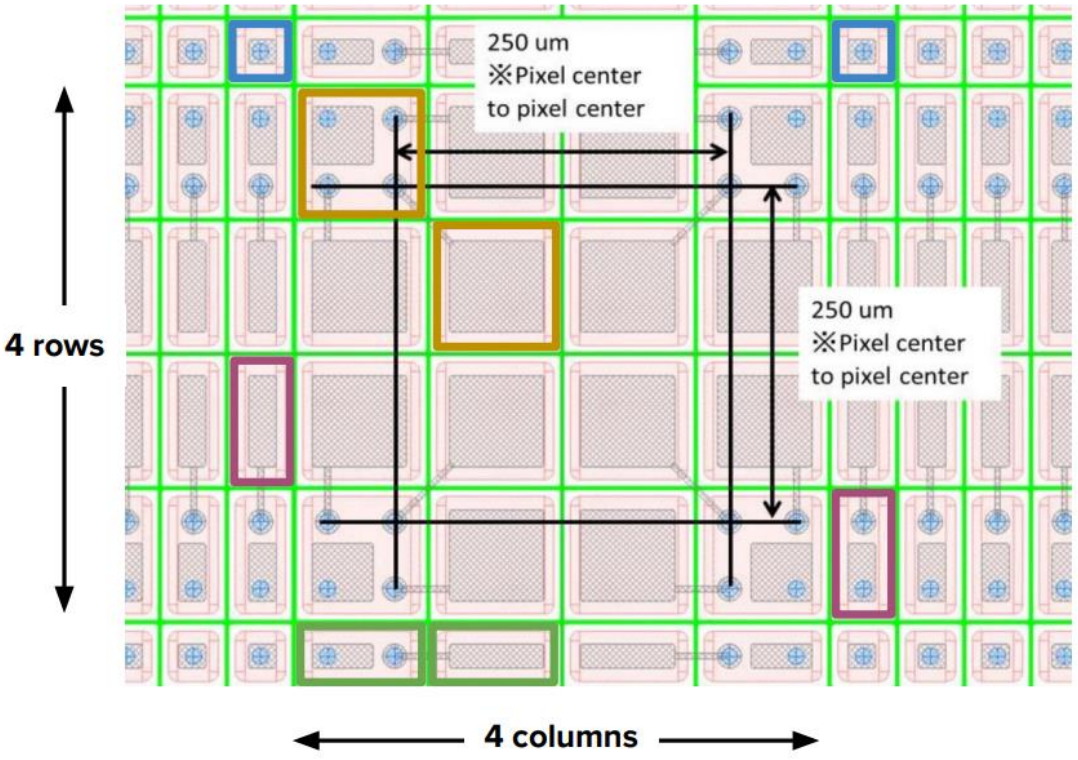
- Efficiency analysis
  - Only tracks within spatial/time cut
  - Masked and disabled pixels not taken into account



[ATLAS ITk Pixel quad module test beam measurements]

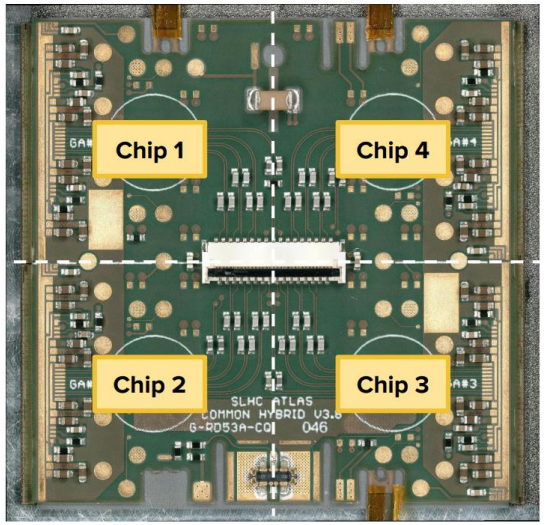
$$\varepsilon = \frac{\text{Number of tracks with associated cluster on DUT}}{\text{Total Number of tracks intersecting DUT}}$$

RD53a Quad Modules



Pixel size (column × row; column=X, row=Y)

- 50×50 μm²
- 100×100 μm²
- 50×100 μm²
- 100×50 μm²

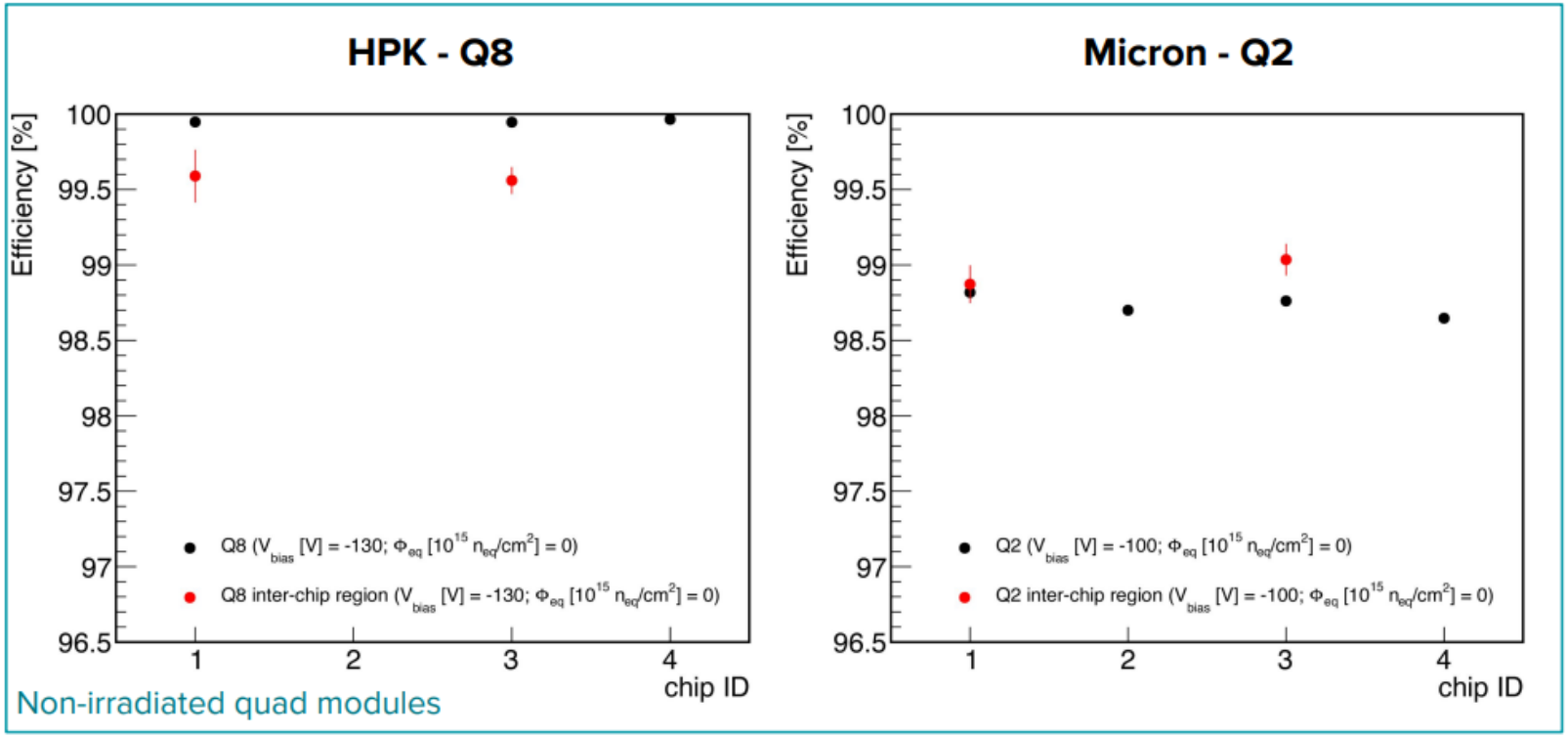


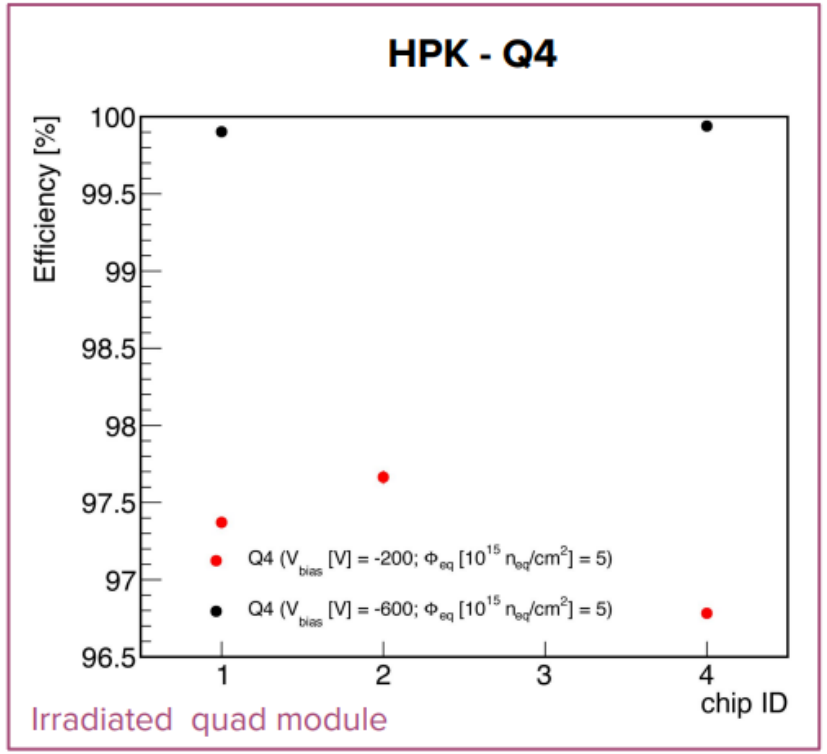
[ATLAS ITk Pixel quad module test beam measurements]

- Inter-chip region of quad sensor has different pixel sizes
- ITk requirements: Non irradiated: ε > 97%, irradiated: ε > 96%

Quad Chip Efficiency

[ATLAS ITk Pixel quad module test beam measurements]





Q8: 2nd chip disabled

ε > 99.9% (All chips)

ε > 99.9% (Inter-chip)

Q2: All chips enabled

ε > 98.5% (All chips)

ε ≈ 99.9% (Inter-chip)

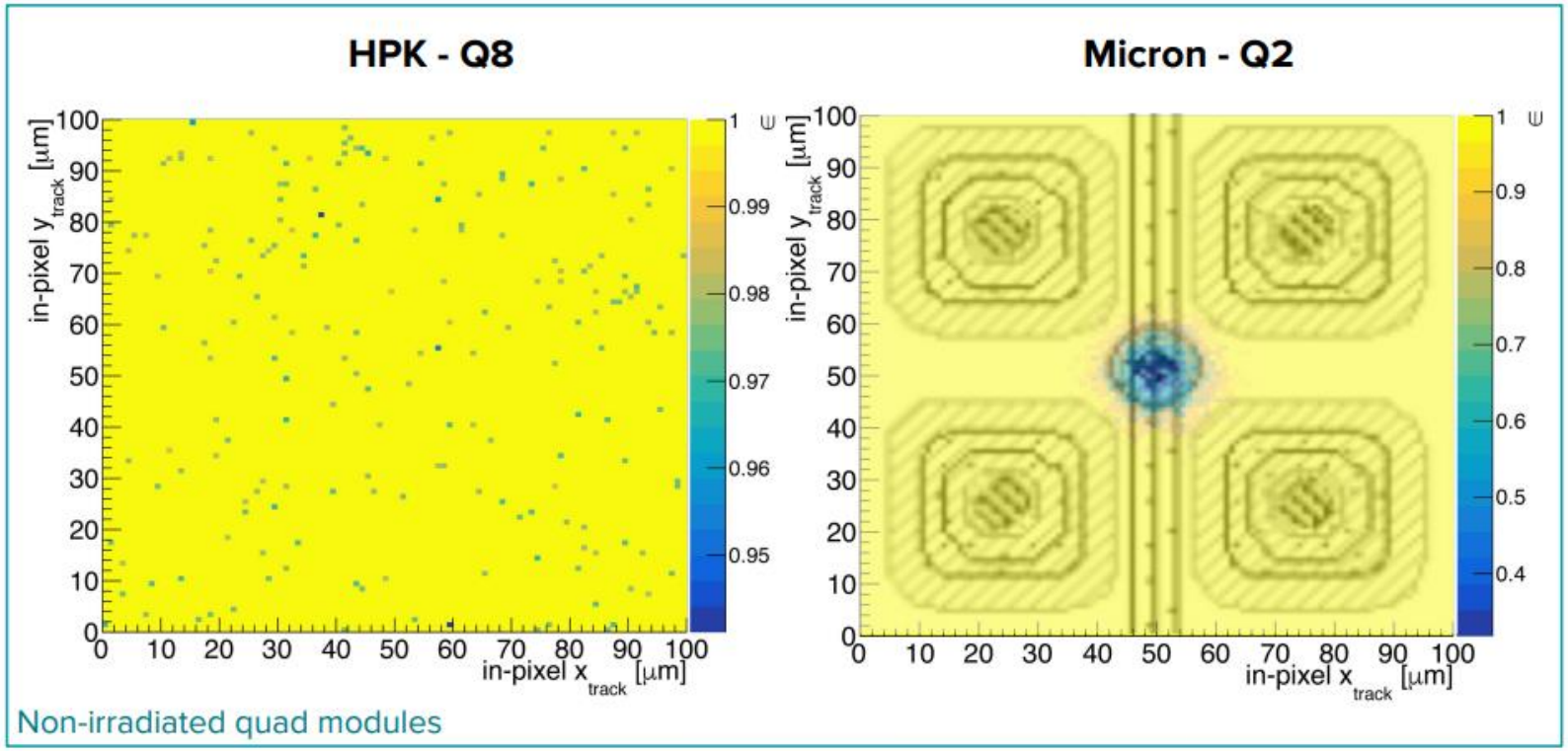
Q4: 3rd chip disabled

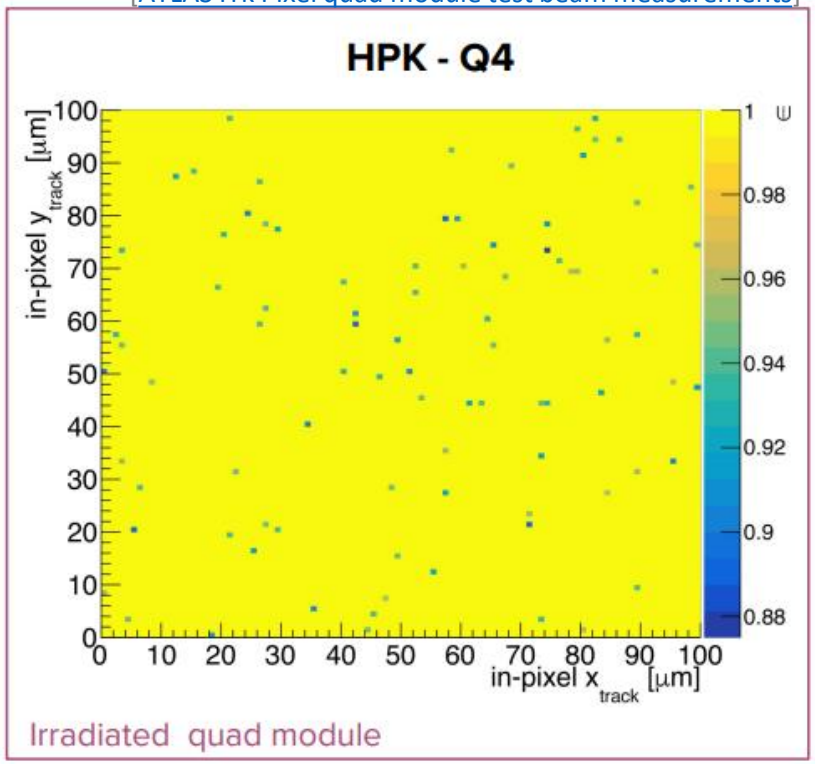
ε ≈ 97% (-200V)

ε ≈ 99.9% (-600V)

Quad In-pixel Efficiency

[ATLAS ITk Pixel quad module test beam measurements]



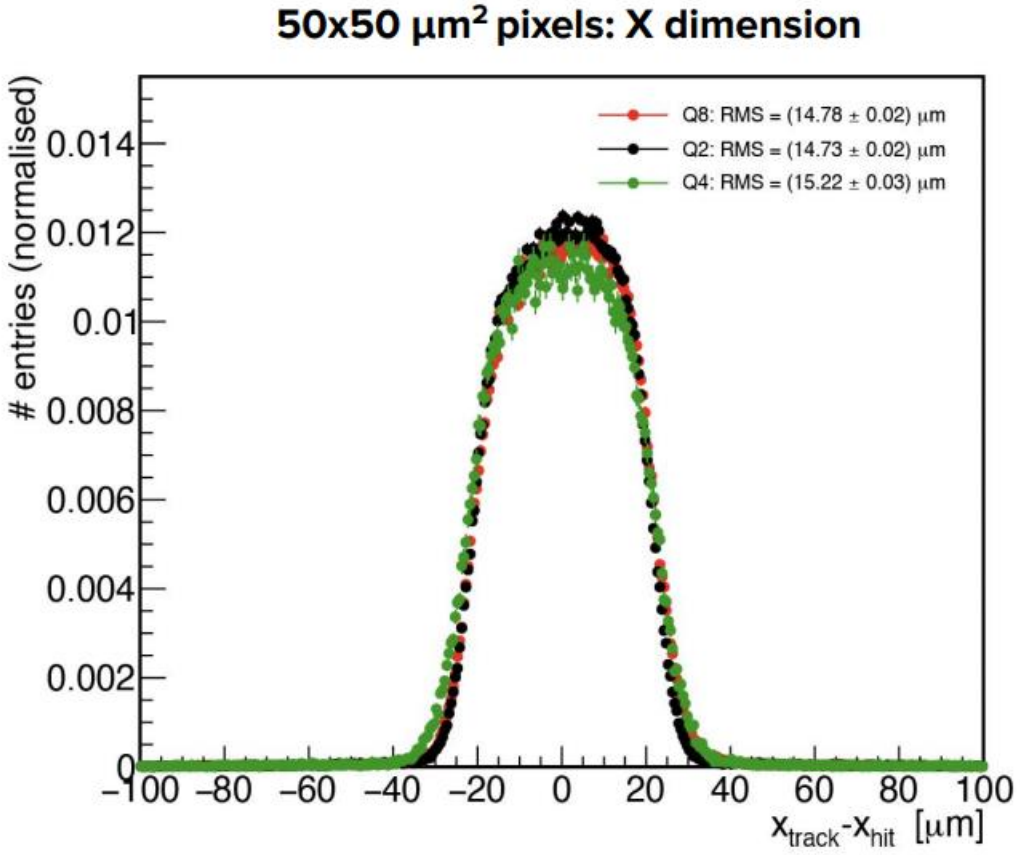


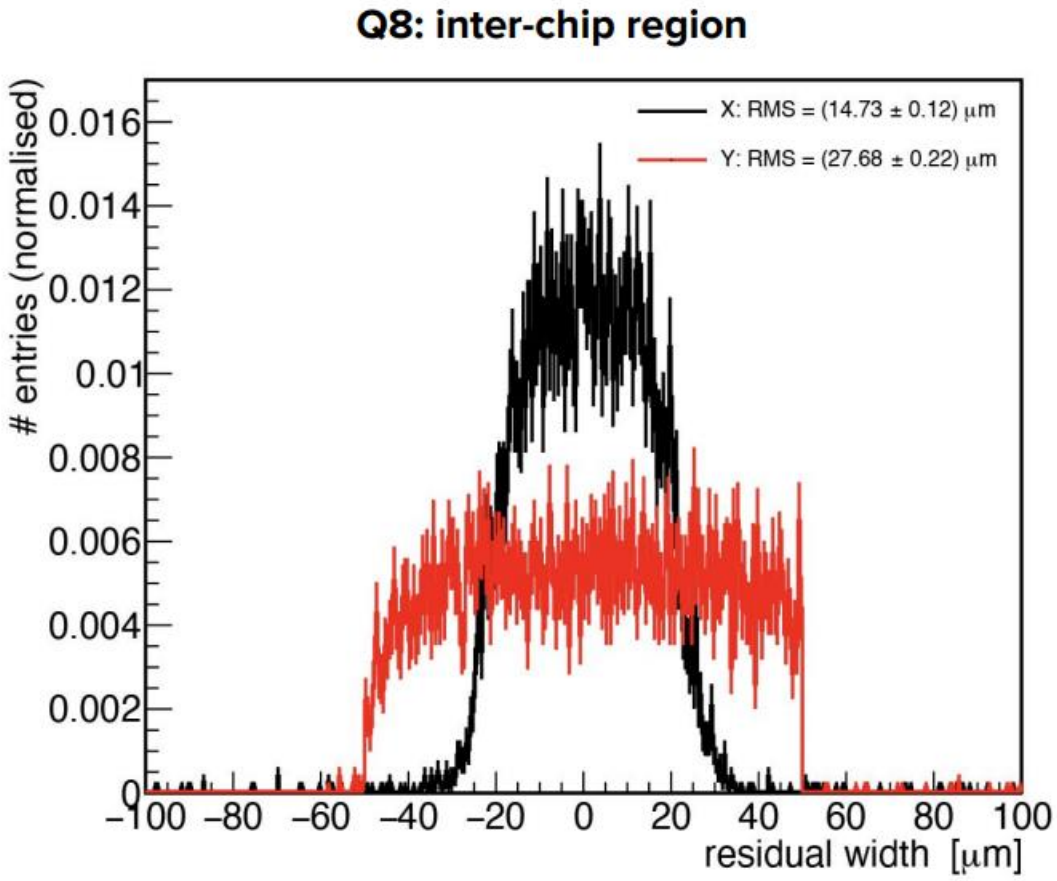
V_{bias} = -130V
Threshold: 1500e
T ≈ 20°C

V_{bias} = -100V
Threshold: 1500e
T ≈ 25°C
punch-through bias

V_{bias} = -600V
Threshold: 1500e
T ≈ -30°C

Residuals





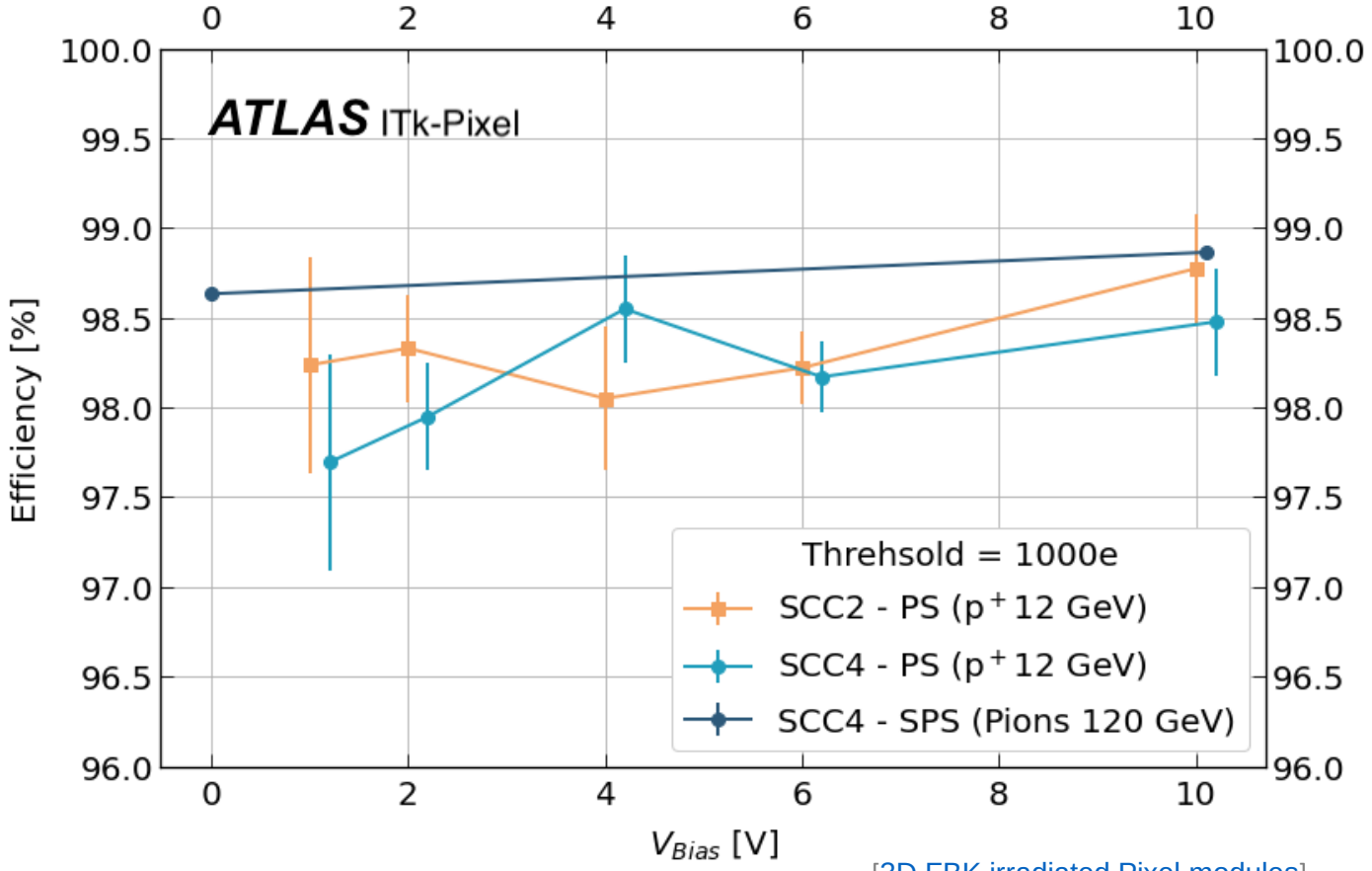
[ATLAS ITk Pixel quad module test beam measurements]

- Unbiased residuals $r^2 = \sigma_{int}^2 + \sigma_{tel}^2$, $\sigma_{tel} \approx 4$ µm
- Inter-chip: r(50µm, 100µm) ≈ (14.97µm, 29.14µm)

Unirradiated FBK 3D Modules

- Unirradiated modules tested at PS (1-10V) and SPS (0V, 10V)
- Efficiency already > 98% at 0V
- Average efficiency:
  - 0V: 98.7 ± 0.1%
  - 10V: 98.9 ± 0.1%
- Compatible with 50x50µm prototype tested at DESY

[Test of ITk 3D sensor pre-production modules with ITkPixv1.1 chip]

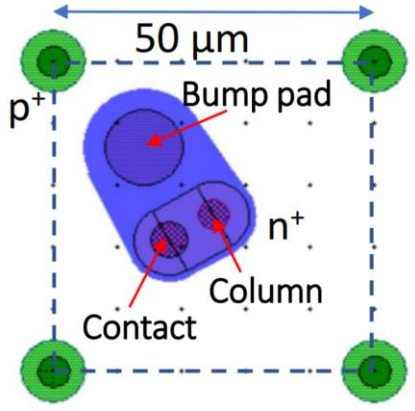


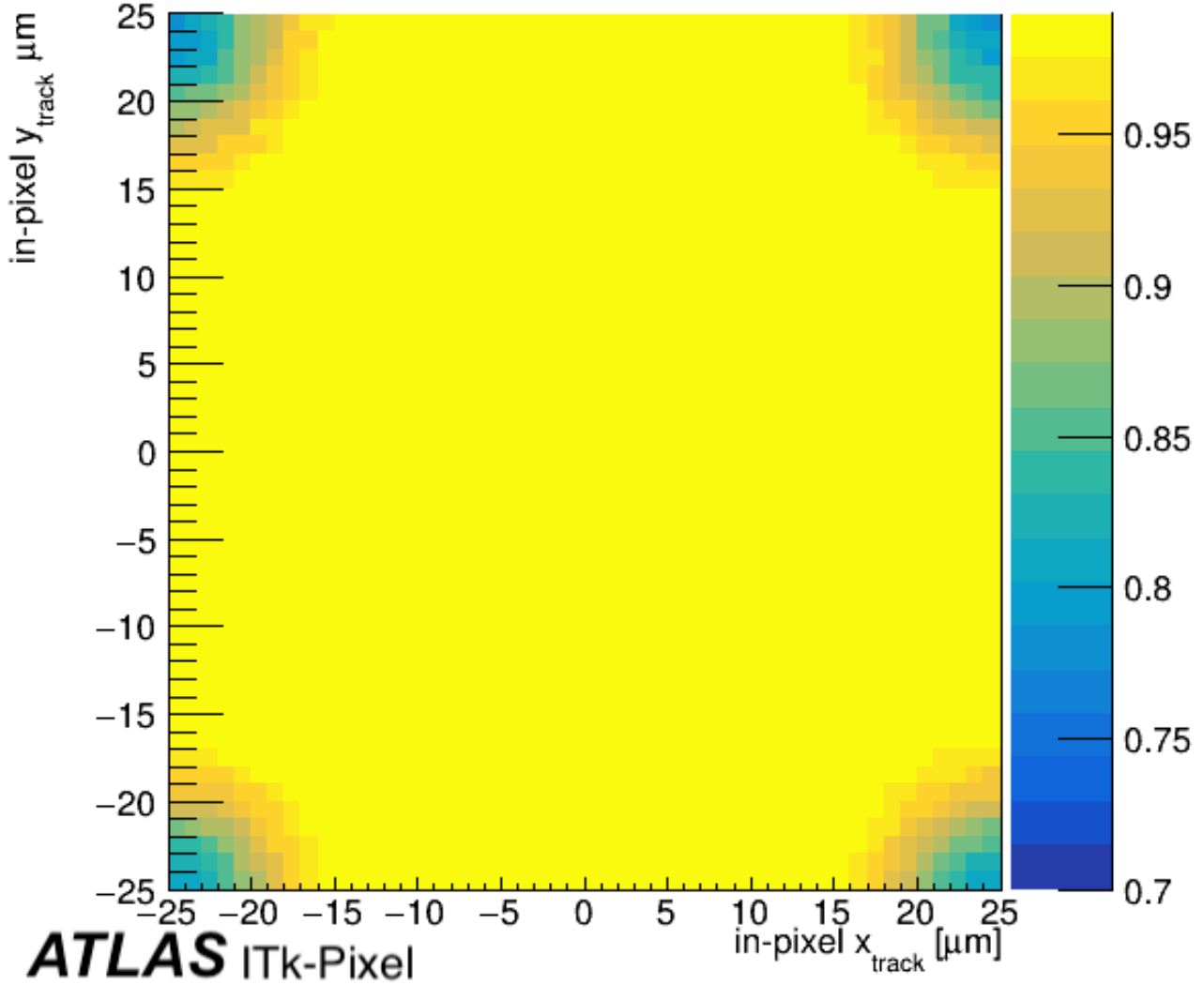
[3D FBK irradiated Pixel modules]

In-Pixel Efficiency

- Unirradiated SCC4 at 10V
  - Sensor perpendicular to beam
  - Fully depleted

- In-pixel Efficiency
  - ε = 98.87 ± 0.06% (mean)
  - At n^+ column: ≈99%
  - Lower ε in corners (75-99%)



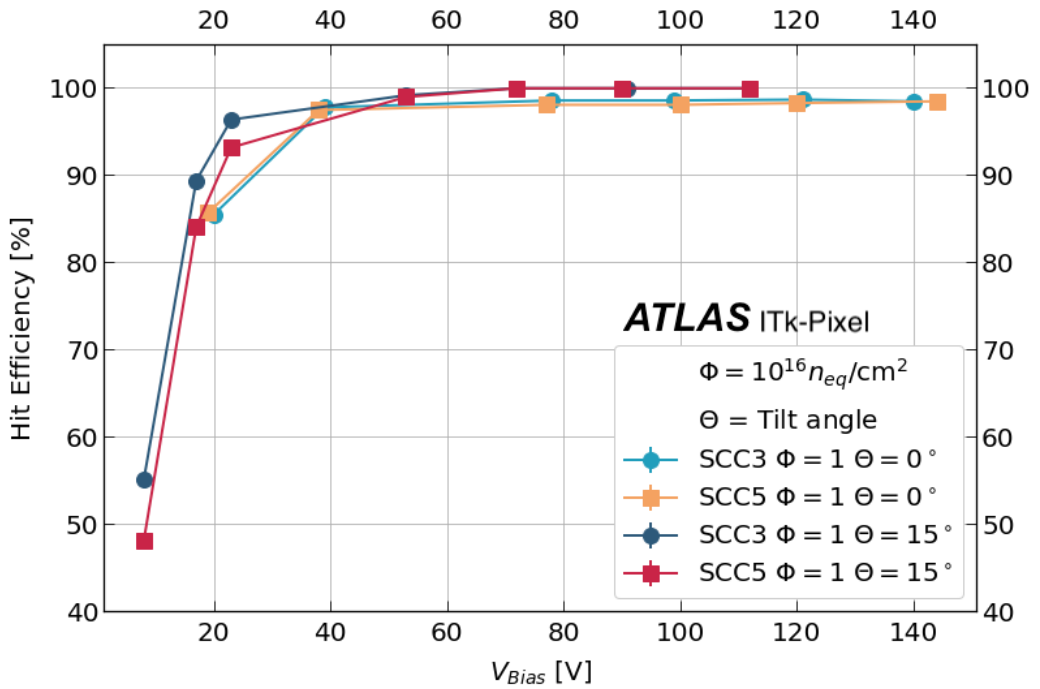


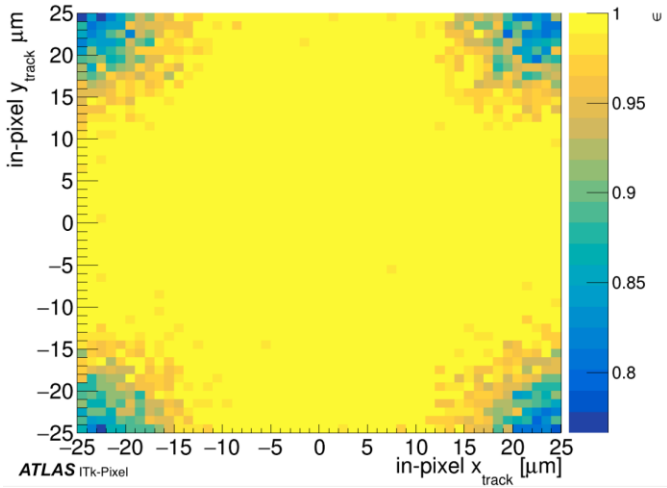
[3D FBK irradiated Pixel modules]

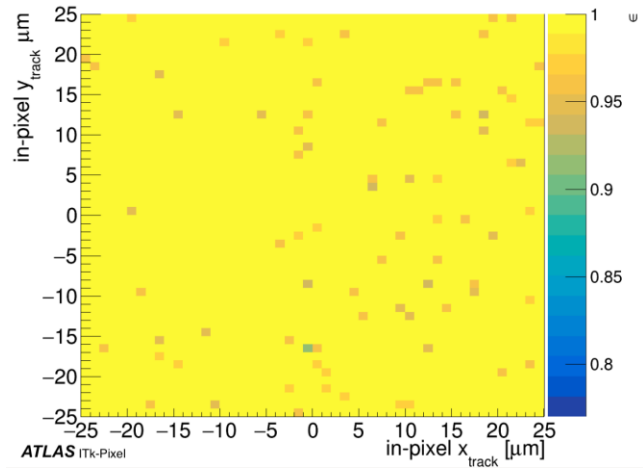
[Test of ITk 3D sensor pre-production modules with ITkPixv1.1 chip]

Irradiated FBK modules

- SCC3 and SCC5 first irradiated at Bonn
  - ➢ Uniform fluence of 10^{16} n_{eq}/cm^2
- Average efficiency > 97% at 40V bias
  - ➢ Tested perpendicular and tilted
- Front end tuned to 1000e threshold
- Similar in-pixel efficiency pattern for perpendicular sensor (100V)
- Higher mean in-pixel efficiency for tilted sensor (90V) as expected



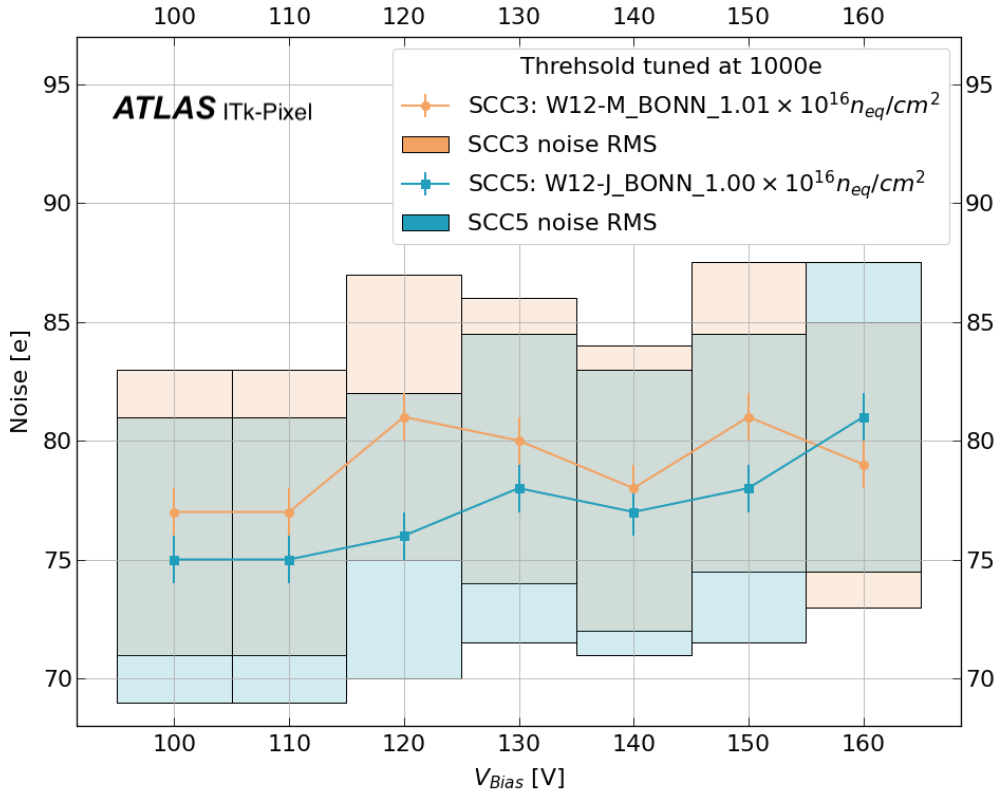


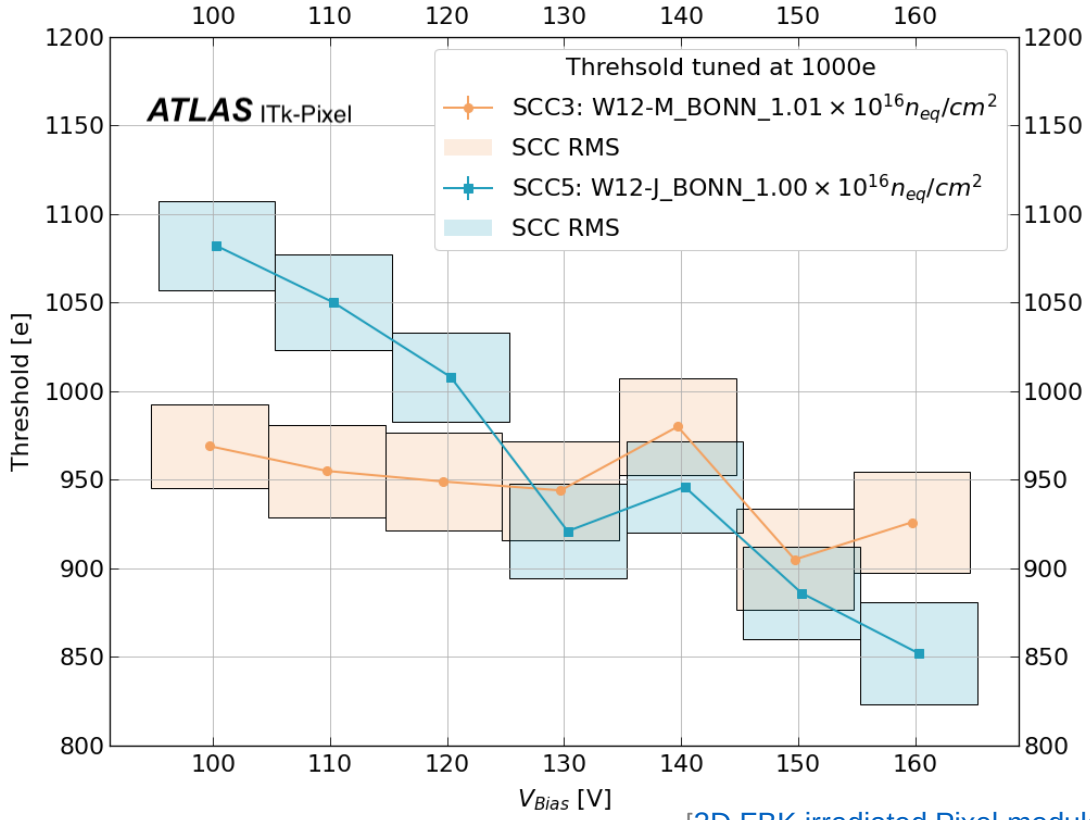


[3D FBK irradiated Pixel modules]

Tuning after irradiation

- 1000e tuning at 100V bias after irradiation



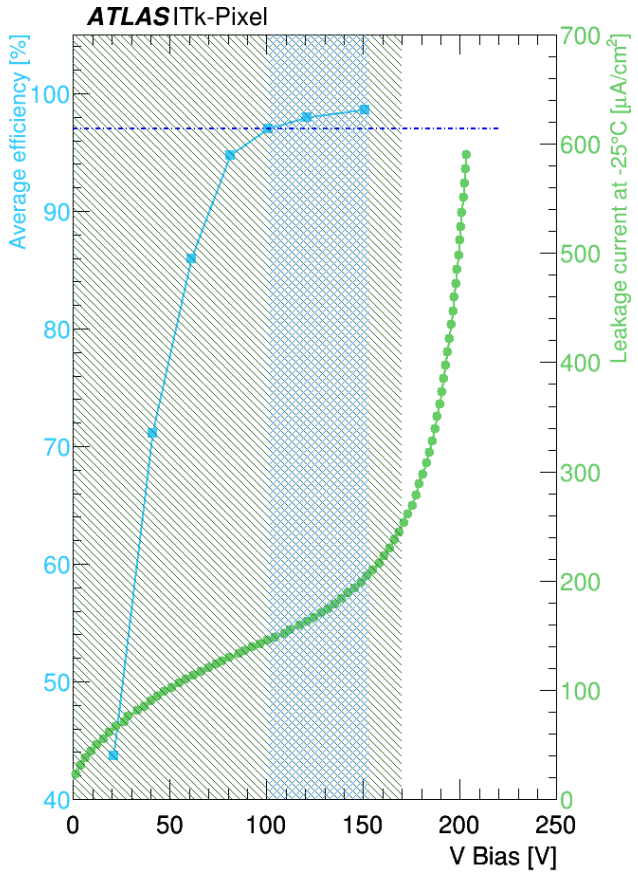


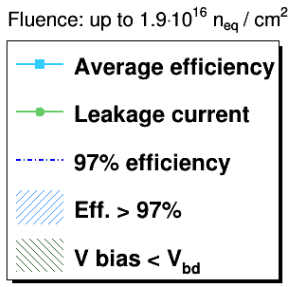
[3D FBK irradiated Pixel modules]

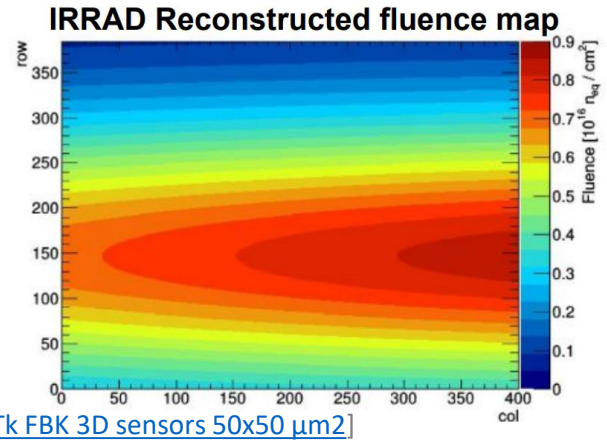
- No significant change in noise and threshold for a large bias voltage range

Further Irradiation

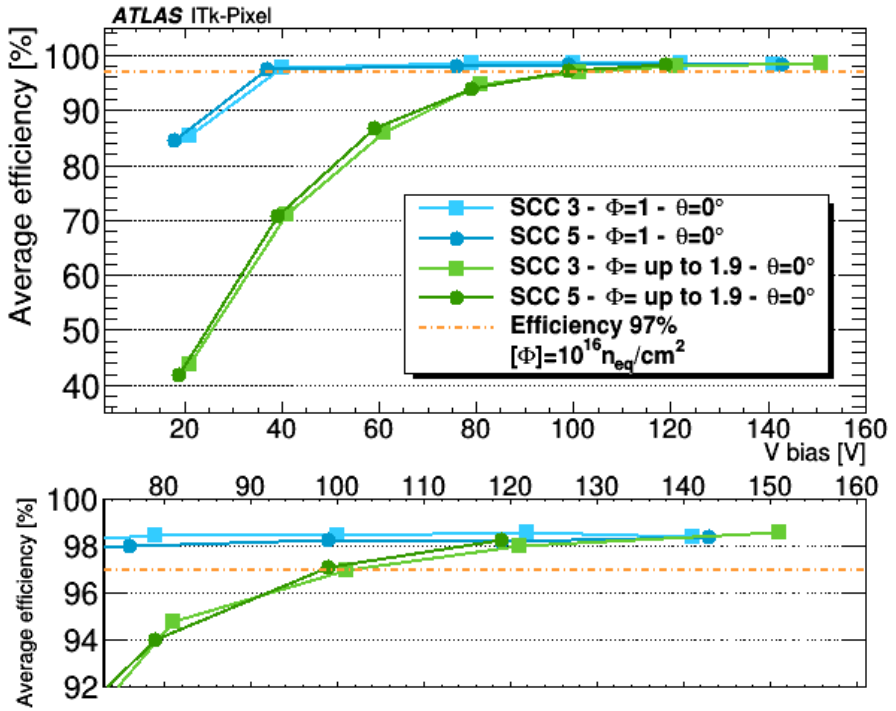
- 2nd irradiation at the CERN IRRAD facility
  - ➢ Total fluence not uniform, up to $1.9 \cdot 10^{16}$ n_{eq}/cm^2







[ATLAS ITk FBK 3D sensors 50x50 µm2]



[3D FBK irradiated at ultimate fluence]

- Average efficiency decreases significantly for V_{bias} < 80V (1000e threshold)
- Breakdown voltage (170V) larger than necessary bias voltage for ε > 97%

Summary

- Data of 3 RD53a quad modules taken in beam tests
  - 2 unirradiated (HPK: $\varepsilon > 99.9\%$, Micron: $\varepsilon > 98.5\%$)
  - 1 irradiated with $5 \cdot 10^{15}\ n_{eq}/cm^2$ (HPK: $\varepsilon > 97.0\%$)
  - Hit efficiencies fullfill ITk requirements (including inter-chip region)
  - Residual distributions compatible with expected result
  - RD53b quad module data taken and will be analysed

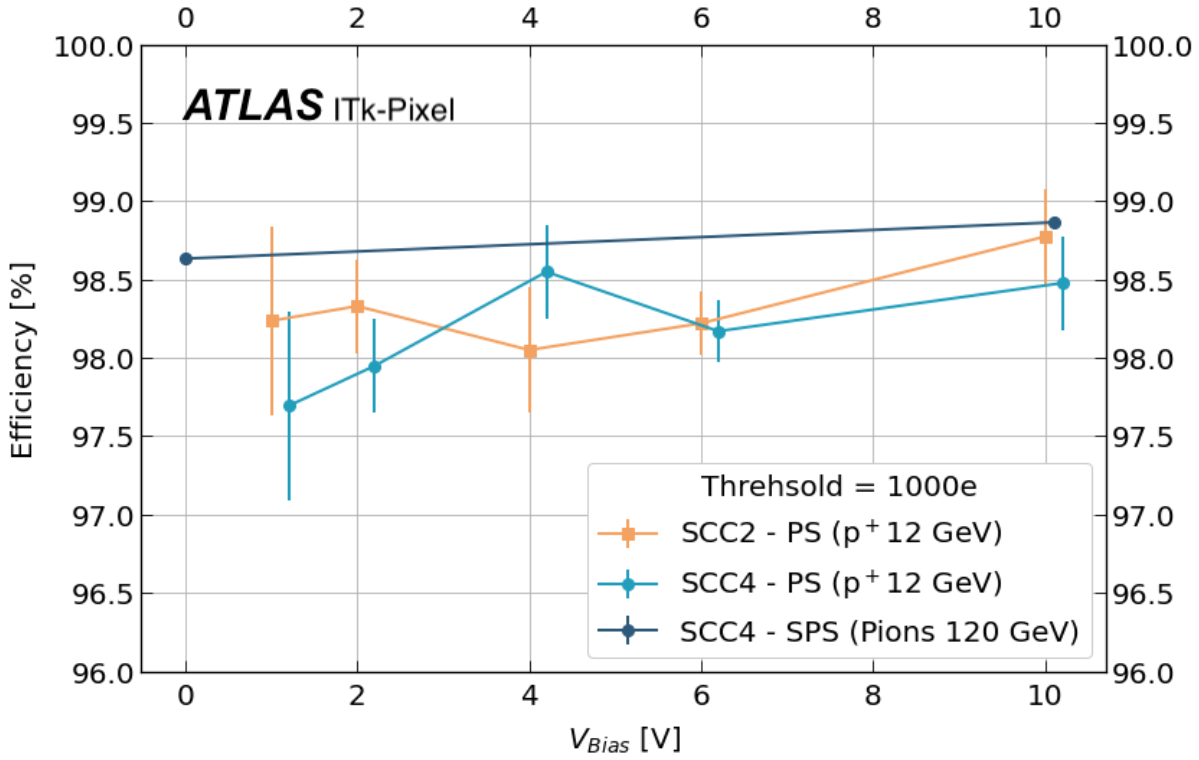
- 3D FBK sensors tested before and after irradiation
  - Fluence up to $1.9 \cdot 10^{16}\ n_{eq}/cm^2$ (not uniform)
  - p^+-columns : Lower in-pixel efficiencies in corner as expected (not for 15° tilt)
  - Efficiency > 97% reached at ≈0V (non-irradiated), ≈110V (irradiated with $1.9 \cdot 10^{16}\ n_{eq}/cm^2$)

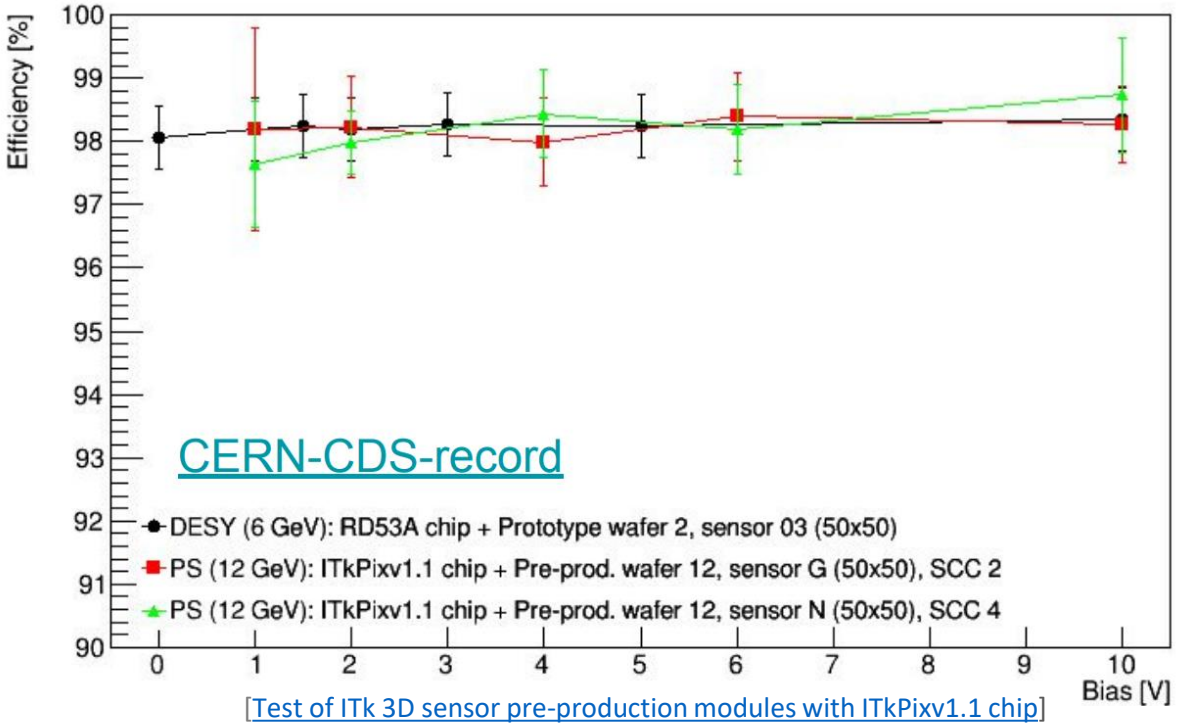
Outlook: Further beam tests in 2023 for planar and 3D sensors

Backup

FBK 3D DESY Measurements

- Unirradiated 3D FBK efficiencies measured at DESY in agreement with CERN





[Test of ITk 3D sensor pre-production modules with ITkPixv1.1 chip]