Characterisation with test beams of ITk pixel detectors for the upgrade of the ATLAS Inner Detector

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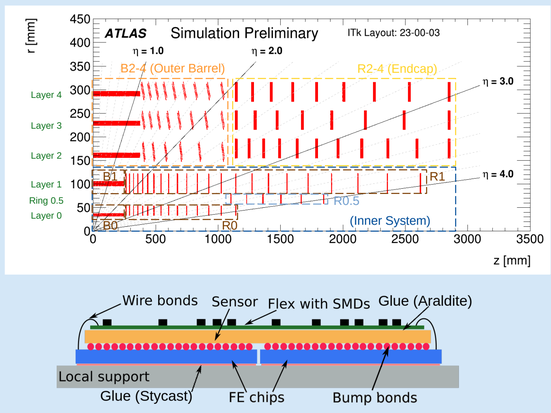
ATLAS Pixel Detector and Modules

ATLAS detector upgrade for the High-Luminosity LHC (HL-LHC):

- Replace Inner Detector by all-silicon **I**nner **T**rac**k**er (ITk)
- Under higher occupancy - instantaneous luminosity 7.5×10^{34} cm^{-2}s^{-1} $\Rightarrow$ average 200 inelastic p-p collisions per bunch crossing in 25 ns
- More radiation hard - 2×10^{16} n_{eq}/cm^2 fluence
- Increased acceptance $|\eta|$ from $<$2.5 to 4.0
- Better granularity
- Planned data taking: 2029 to 2039

Pixel detector: innermost part of ITk $\rightarrow$ 5 layers, contains hybrid modules

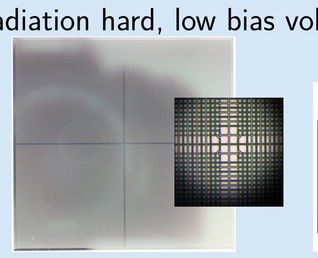
- Module = sensors bump bonded with front-end readout electronics , glued with PCB
- Sensor performance tested on fully-assembled module level in beam



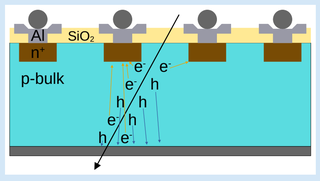
The Sensors - different geometry, technology, position

	Pixel pitch	Active Thickness	Position	Vendor	Bias structure
Planar (n^+-in-p)	50×50 µm^2	150 µm	B2-4, R2-4	HPK	Poly-Si
				Micron	Punch-through
		100 µm	B1, R1	FBK	None
3D (n^+ & p^+ col.-in-p^-)	50×50 µm^2 25×100 µm^2	150 µm	R0, 0.5 B0	FBK, SINTEF FBK	None

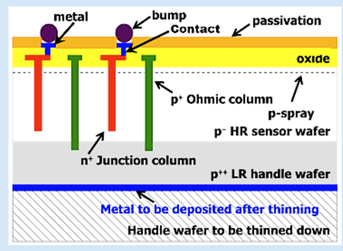
3D: radiation hard, low bias voltage - innermost layer



Quad sensor and inter-chip region

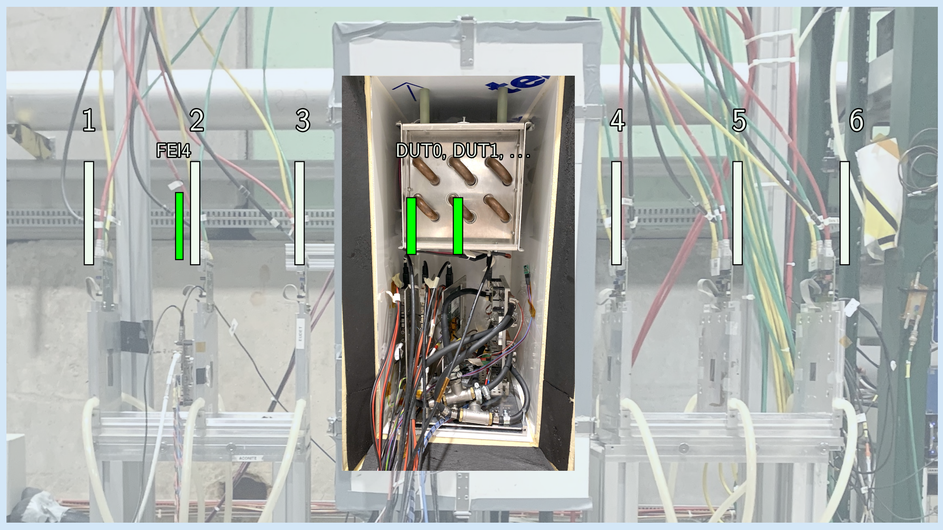


Cross-section of planar sensor



Cross-section of 3D sensor

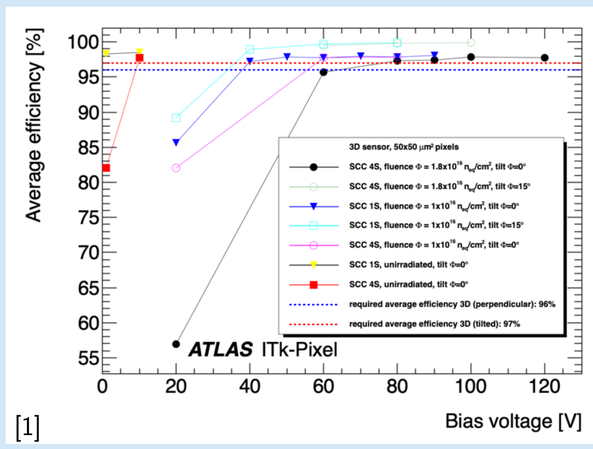
Setup



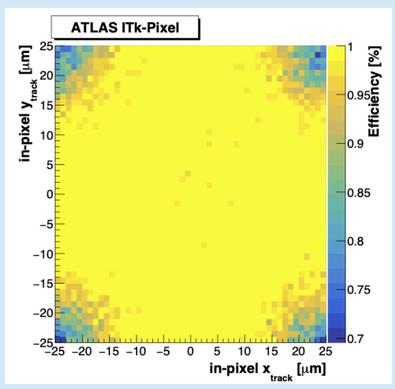
- CERN SPS, with 120 GeV pion beam, PS with 12 GeV p beam
  - Beam telescope: ACONITE, 6 planes with MIMOSA26 sensors, tracking
  - Multiple devices under test (DUT)
  - 1 FEI4 (known&stable) as reference
- Results shown are for pre-production sensors bump-bonded with ITkPixV1.1 readout chip (RD53B, 65 nm CMOS)
- Reconstruction&analysis software: Corryvreckan
  - Procedure: mask noisy/dead pixels $\rightarrow$ align all planes $\rightarrow$ analysis

Results - SINTEF 3D, 50×50 µm^2

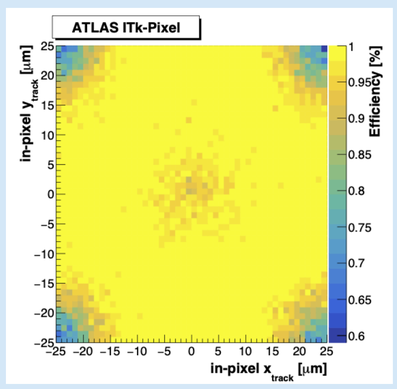
- Modules tuned to 1000 e threshold
- ϵ measured for 2 modules at different angle and fluence



[1]



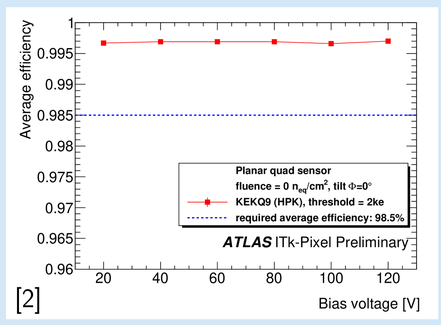
Un-irradiated, SCC1S, 10 V [1]



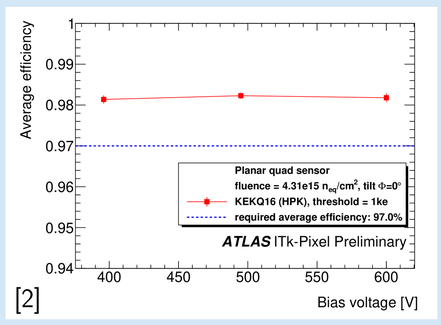
1 Φ, SCC1S, 60 V [1]

- In-pixel efficiency: perpendicular to beam direction, before irradiation low at p^+ columns, after irradiation also at n^+ columns

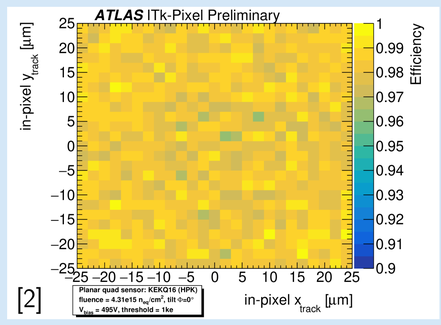
Results - HPK Planar



[2]



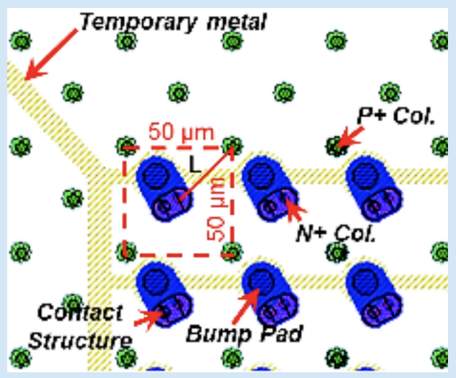
[2]

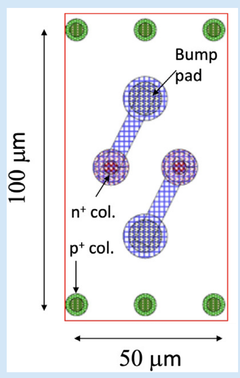


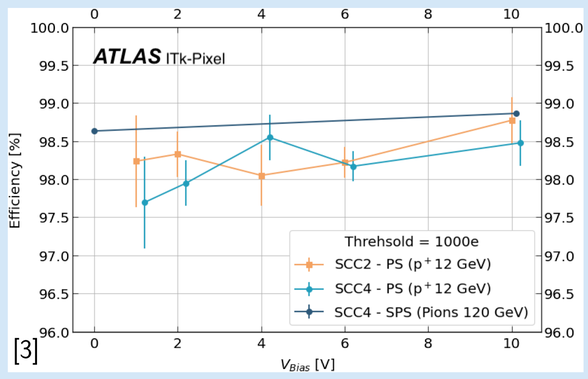
[2]

- Q9 tuned to 2000 electron threshold (conservative measurement), Q16 to 1500 e threshold
- Hit detection efficiency ϵ specification: 98.5 % at V_{dep} +50 V for un-irradiated sensors, 97 % at 600 V for sensors irradiated with 5×10^{15} n_{eq}/cm^2
- In-pixel efficiency (figure showing irradiated) shows no low efficiency spots from bias structure

Results - FBK 3D, 50×50 µm^2 or 25×100 µm^2

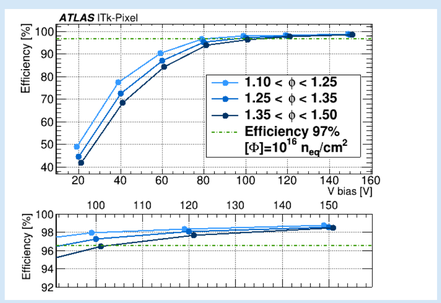




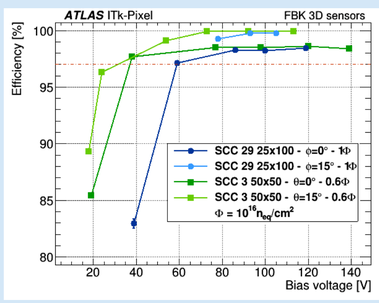


[3]

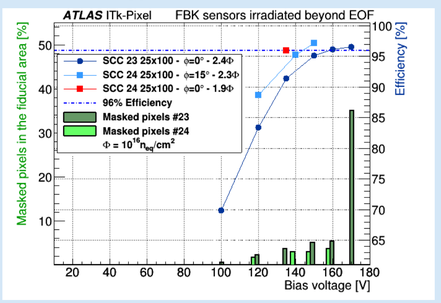
- Modules tuned to 1000 e threshold
- Un-irradiated 50×50 µm^2 sensors measured in different beam type and energy, perpendicular



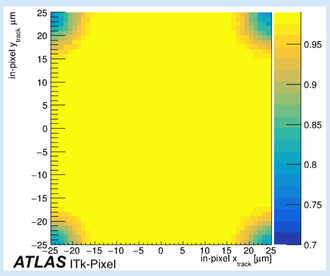
50×50 µm^2, 1.5 to 1.9 Φ, SCC3, perpendicular to beam [4]



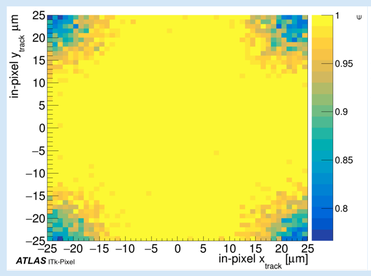
Both pitches, 0.6 or 1 Φ [5]



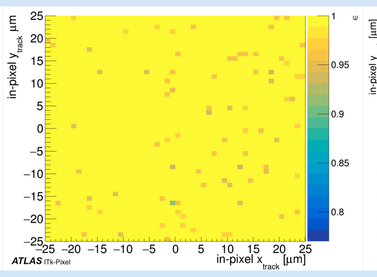
25×100 µm^2, up to 2.4 Φ (beyond requirement) [5]



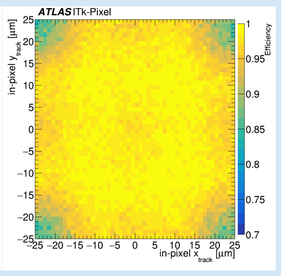
Un-irradiated, SCC4, 10 V, perpendicular [3]



1 Φ, SCC5, 100 V, perpendicular [3]



1 Φ, SCC5, 90 V, 15 ° [3]



Up to 1.5 Φ, SCC3, 100 V, perpendicular [4]

- $\Phi = 10^{16}$ n_{eq}/cm^2, spec in ϵ after irradiation at 1.7 Φ: perpendicular - 96 %, 13 ° to 16 ° - 97 %
- Maximum operation voltage 250 V

Conclusions & Outlook

- Sensors tested in beam for various vendors
- Hit detection efficiency meet specification at required bias voltage before & after irradiation
- In-pixel efficiency: no drop for HPK planar & 3D tilted, decrease for 3D perpendicular at etched columns

Outlook:

- Moving to production phase
- Measure production version ITkPixV2 modules
- More tests on sensors from other vendors, look closely at inter-chip region of planar quad sensors
- Move to Eudaq2, corryvreckan development

[1] ATLAS ITk Collaboration, *Test Beam Results of SINTEF 3D Pixel Silicon Sensors*, 2023, URL: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2023-004/

[2] ATLAS ITk Collaboration, *Test Beam Results of Planar HPK Pixel Silicon Sensors*, 2023, URL: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2023-005/

[3] ATLAS ITk Collaboration, *3D FBK irradiated Pixel modules*, 2022, URL: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2022-004/

[4] ATLAS ITk Collaboration, *3D FBK irradiated at ultimate fluence*, 2022, URL: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2022-005/

[5] S. Ravera et al., *Qualification of irradiated 3D pixel sensors produced by FBK for the pre-production of the ATLAS ITk detector*, *Proceedings of The 32nd International Workshop on Vertex Detectors — PoS(VERTEX2023)*, **448**, 2024, 072

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