PROCEEDINGS OF SCIENCE

ATL-ITK-PROC-2024-029
25/09/2024

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

Y. Tian,[a,b,*] **G. Calderini,**[c] **T. I. Carcone,**[c] **J. I. Carlotto,**[d] **P. Chabrillat,**[c] **C. Gemme,**[e] **A. Grigorev,**[b] **J. Große-Knetter,**[a] **T. Heim,**[f] **S. Hellesund,**[g] **S. K. Huiberts,**[g] **C. Krause,**[h] **L. Meng,**[i] **M. Mironova,**[f] **A. Quadt,**[a] **S. Ravera,**[e,j] **M. Ressegotti,**[e,j] **A. Rummler**[k] **and A. Skaf**[a]

[a] *II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
[b] *now at Département de Physique Nucléaire et Corpusculaire, University of Geneva, Geneva, Switzerland*
[c] *LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France*
[d] *IFAE, Barcelona Institute of Science and Technology, Barcelona, Spain*
[e] *INFN, Sezione di Genova, Italy*
[f] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA, United States of America*
[g] *Department for Physics and Technology, University of Bergen, Bergen, Norway*
[h] *Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[i] *Physics Department, Lancaster University, Lancaster, United Kingdom*
[j] *Dipartimento di Fisica, Università di Genova, Genova, Italy*
[k] *CERN, Geneva; Switzerland*

E-mail: yusong.tian@cern.ch

The ATLAS Inner Detector will be replaced with an all-silicon tracking detector (ITk) to cope with the new challenging conditions arising with the High-Luminosity Large Hadron Collider (HL-LHC), where the instantaneous luminosity will increase by three times compared to that of the LHC, and bring higher radiation damage. The pixel detector will be the innermost part of the ITk, consisting of five radial layers. The sensors in different positions are designed with different geometries and technologies, and are procured from different vendors. n^+-in-p planar hybrid modules with 150 µm and 100 µm thickness will instrument the outer layers, and 3D sensor technology was chosen to instrument the innermost layers due to its radiation hardness. Additionally, the production of the sensors is distributed among four different vendors: HPK, Micron, FBK and SINTEF, with HPK producing the majority of the sensors. As soon as pre-production modules and sensors of different types and produced by different vendors become available, they are being tested with test beams before and after irradiation to assess their performance at the fluence expected at the end of their life during HL-LHC. An overview of the current test beam results is given. The results shown are for pre-production modules equipped with ITkPixV1.1 (RD53B) readout chips. The reconstruction and analysis was done with the Corryvreckan software.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

*Speaker

1. Introduction

The layout of the ATLAS ITk pixel detector is shown in fig. 1, and table 1 summarises the main features of different types of sensors in the detector.

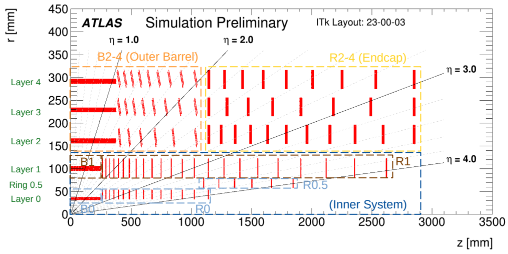


Figure 1: Different regions of the ATLAS ITk Pixel detector [1].

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

Table 1: Technology, geometry, planned positions, vendor, and bias structure of ITk pixel detector sensors.

2. Setup and Data Analysis

Test beam campaigns were conducted in CERN SPS with 120 GeV pion beam and PS with 12 GeV proton beam. Fig. 2 shows the setup, which includes the EUDET-type beam telescope [2] ACONITE, and an FEI4 module as reference. Specifications on the hit detection efficiency ϵ are shown in table 2.

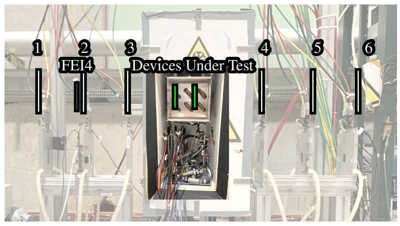


Figure 2: Test beam setup.

Planar			3D			
Irradiation	ϵ [%]	Bias voltage [V]	Irradiation	Orientation	ϵ [%]	Bias voltage [V]
Unirradiated (0 Φ)	98.5	V_{dep} +50	1.7 Φ	Perpendicular (0°)	96	Max 250
0.5Φ	97	Max 600	1.7 Φ	Tilted (13 to 16°)	97	Max 250

Table 2: Specifications on hit detection efficiency ϵ. V_{dep} is the depletion voltage, $\Phi = 10^{16}\,n_{eq}/cm^2$.

3. Results

HPK Planar: fig. 3 shows results for an unirradiated and an irradiated module (note the different threshold). Specifications on hit detection efficiency ϵ are met before and after irradiation, no low efficiency region from bias structures.

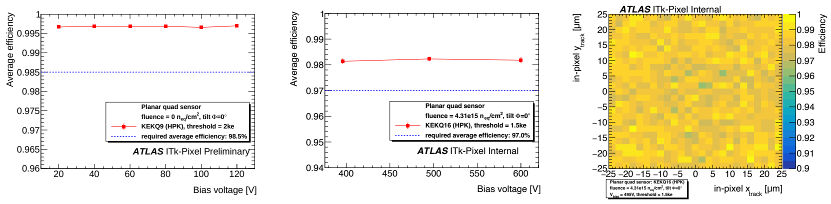
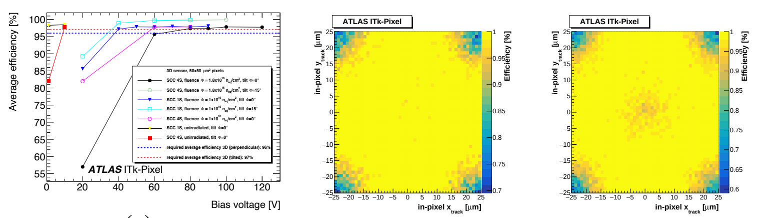


Figure 3: Average efficiency before (left) and after (middle) irradiation and in-pixel efficiency (right) for HPK sensors [3] measured perpendicular to beam.

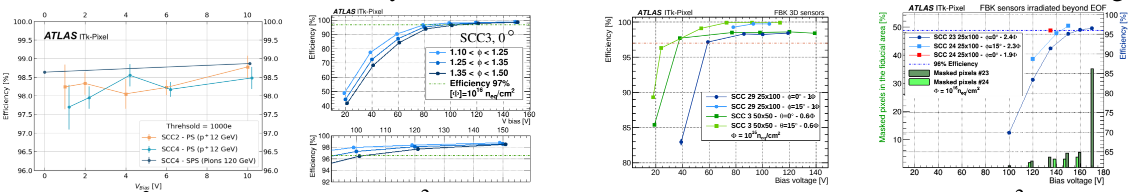
SINTEF 3D $50{\times}50\,\mu m^2$ pixel pitch: tested before and after irradiation and with different angles of incidence are shown in fig. 4. ϵ is within specification. When measured perpendicular to beam direction, the in-pixel efficiency decreased at p^+ columns before irradiation. After irradiation, the efficiency also decreased at n^+ columns, but this can be due to the relatively low bias voltage.



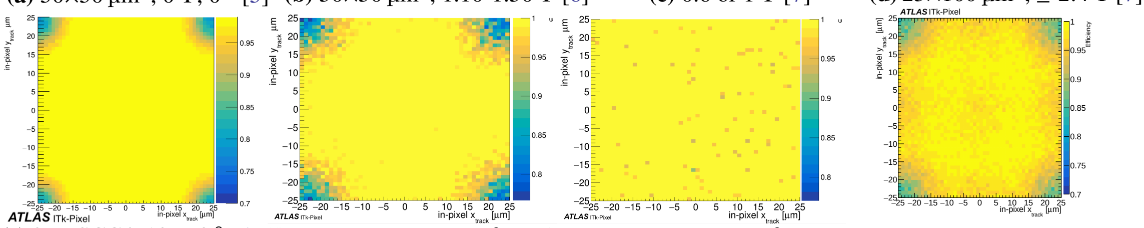
(a) ϵ **(b)** 0 Φ, SCC1S, 10 V **(c)** 1 Φ, SCC1S, 60 V

Figure 4: ϵ at different angle and fluence (left), and in-pixel efficiency (middle and right) for normal beam incidence for SINTEF 3D sensors [4].

FBK 3D $50\times50\ \mu m^2$ or $25\times100\ \mu m^2$ pixel pitch: as shown in fig. 5, unirradiated $50\times50\ \mu m^2$ sensors were measured in different beam type and energy at 0° beam incidence. After irradiation, ϵ for both sensor pitches meet specification. A fluence beyond requirement (fig. 5d) led to a high number of masked pixels. The in-pixel efficiency decreased at p^+ columns at 0° beam incidence both before and after irradiation, but this effect disappears with tilted beam incidence as expected. Higher irradiation resulted in an efficiency decrease also at n^+ columns, attributed to too low a bias voltage.



(a) $50\times50\ \mu m^2$, $0\ \Phi$, 0° [5] **(b)** $50\times50\ \mu m^2$, 1.10-1.50 Φ [6] **(c)** 0.6 or 1 Φ [7] **(d)** $25\times100\ \mu m^2$, $\leq 2.4\ \Phi$ [7]



(e) $0\ \Phi$, SCC4, 10 V, 0° [5] **(f)** $1\ \Phi$, SCC5, 100 V, 0° [5] **(g)** $1\ \Phi$, SCC5, 90 V, 15° [5] **(h)** $\leq 1.5\ \Phi$, SCC3, 100 V, 0° [6]

Figure 5: ϵ and in-pixel efficiency for FBK 3D sensors measured at different fluence and angle. $\Phi = 10^{16}\ n_{eq}/cm^2$. The highest irradiation fluence in fig. 5d is beyond requirement.

4. Conclusions & Outlook

The hit detection efficiency of HPK, FBK and SINTEF sensors meet specification at required bias voltage both before irradiation and after irradiated to around the expected fluence. In-pixel efficiency for HPK planar sensors and at tilted position for 3D sensors showed no decrease due to bias structures, and decreased for 3D sensors at etched columns when measured perpendicular to beam. Measurements of production modules with the final read-out chip version ITkPixV2 [8] using EUDAQ2 [9] as well as Corryvreckan [10] versions that include new developments are ongoing.

References

[1] ATLAS Collaboration, *Expected tracking and related performance with the updated ATLAS Inner Tracker layout at the High-Luminosity LHC*, ATL-PHYS-PUB-2021-024

[2] EUDET Consortium, *Infrastructure for Detector Research and Development towards the International Linear Collider*, arXiv:1201.4657, 2012

[3] ATLAS ITk Collaboration, *Test Beam Results of Planar HPK Pixel Silicon Sensors*, ITK-2023-005

[4] S. Hellesund et al., *Test Beam Results of SINTEF 3D Pixel Silicon Sensors*, *Proceedings of The 32nd International Workshop on Vertex Detectors — PoS*, **448**, 2024, 076

[5] ATLAS ITk Collaboration, *3D FBK irradiated Pixel modules*, ITK-2022-004

[6] ATLAS ITk Collaboration, *3D FBK irradiated at ultimate fluence*, ITK-2022-005

[7] 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*, **448**, 2024, 072

[8] RD53 Collaboration, *RD53C Chip Manual*, CERN-RD53-PUB-24-001, 2024

[9] *EUDAQ2 – A Flexible Data Acquisition Software Framework for Common Test Beams*, JINST 14 (2019) P10033

[10] D. Dannheim et al., *Corryvreckan: a modular 4D track reconstruction and analysis software for test beam data*, JINST 16 (2021) P03008

Acknowledgments

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511 (EURO-LABS). Part of this work was supported by the Federal Ministry of Education and Research (BMBF), FIS under contract number 05H21MGCA9.