Published by IOP Publishing for Sissa Medialab

Received: September 30, 2025
Revised: November 29, 2025
Accepted: December 11, 2025
Published: January 9, 2026

26th International Workshop on Radiation Imaging Detectors
Bratislava, Slovakia
6–10 July 2025

Up-to-date test beam results of ATLAS ITk pixel sensors and modules

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Abstract: The ATLAS Inner Detector will be replaced by a new all-silicon Inner Tracker (ITk) in 2029 to meet the challenges of the High Luminosity LHC (HL-LHC). The ITk pixel system combines 3D sensors at the innermost layer, operating after exposure to fluences of up to $2 \times 10^{16}\,\mathrm{n_{eq}/cm^2}$, with thin n-in-p planar modules in the outer layers. Beam tests are essential for qualifying these sensors and modules before and after irradiation. Recent test beam campaigns in 2024 evaluated new fabrication techniques, thick planar sensors, and modules with the latest ITkPixV2 readout chip, while the 2025 program introduces novel 3D triplet and planar quad configurations. Recent test beam results will be presented here, highlighting sensor performance and readiness of the ITk pixel detectors for HL-LHC operation.

Keywords: Beam-line instrumentation (beam position and profile monitors, beam-intensity monitors, bunch length monitors); Hybrid detectors; Radiation-hard detectors

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https://doi.org/10.1088/1748-0221/21/01/C01008

2026 JINST 21 C01008

Contents

1 Introduction 1

2 Test beam setup 1

3 3D sensor results 1

4 Planar sensor results 5

5 Conclusions 5

1 Introduction

The High Luminosity upgrade of the Large Hadron Collider (HL-LHC) requires significant modifications to the ATLAS detector to withstand the increased event rate and radiation environment. As part of this transformation, the current Inner Detector will be fully replaced by an all-silicon Inner Tracker (ITk), scheduled for installation during 2026–2028. This upgrade is essential for maintaining tracking precision and operational efficiency in the high-radiation, high-occupancy conditions expected during HL-LHC operation. The innermost layer (L0) of the ITk will be equipped with 3D sensor technology capable of withstanding fluences up to $2 \times 10^{16}\,n_{eq}/cm^2$ [1], while the outer layers (L1–L4) will employ n-in-p planar hybrid modules with 100 µm and 150 µm thick silicon sensors. All fluences quoted in this paper correspond to the 1 MeV neutron-equivalent fluence as defined by NIEL scaling. To validate the performance of these sensors under HL-LHC conditions, beam tests are carried out both before and after irradiation.

2 Test beam setup

The test beam campaign was carried out at the CERN SPS H6 beam line using 120 GeV pion beams. An overview of the setup is shown in figure 1. The beam telescope consists of six Mimosa26 tracking planes and a planar FBK FE-I4 plane used for timing. The devices under test (DUTs) are placed inside a cooling box with controlled environmental conditions [2]. The separate DAQ systems for the beam telescope components and the DUTs are controlled by EUDAQ V2 [3]. The telescope provides precise triggering and track reconstruction for the performance evaluation of the tested sensors. Track reconstruction was performed with the Corryvreckan framework [4]. Reconstructed tracks were extrapolated to the DUTs to check for hits at the intersection point. Particle tracks reconstructed through disabled or masked DUT pixels, or through adjacent pixels, were excluded from the efficiency calculation. Further details on ITk test beam data analysis are available here [5].

3 3D sensor results

The 3D sensors under test were fabricated by SINTEF using deep reactive ion etching (DRIE) to form p^+ and n^+ columns in 150 µm thick silicon. Previous prototypes suffered from wafer bowing,

2026 JINST 21 C01008

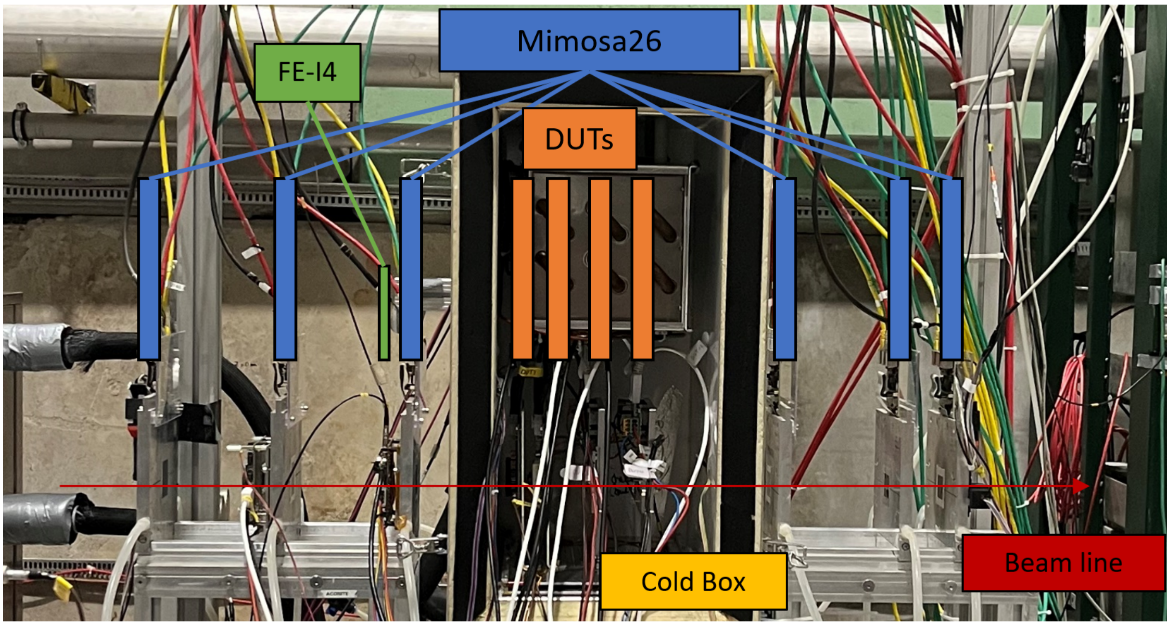

Figure 1. Test beam setup used for sensor testing. The configuration includes six Mimosa26 tracking planes, a planar FBK FE-I4 timing plane, and a temperature-controlled cooling box housing the DUTs. The 120 GeV pion beam is incident from the left. The telescope provides a track-pointing resolution of approximately 2 µm at the DUT position.

resulting in warping and disconnected pixels, particularly in the corners. To address this, the design was modified during the pre-production phase. A new Si_3N_4 final passivation layer was implemented using plasma enhanced chemical vapour deposition (PECVD), resulting in significantly reduced bowing and improved mechanical stability [6]. The sensors were bump-bonded to RD53B readout chips, with a pixel pitch of 50×50 µm and a matrix of 384×400 pixels.

The new sensors were irradiated with 25 MeV protons at the Karlsruhe Institute of Technology (KIT) irradiation facility to a fluence of 1.7×10^{16} n_{eq}/cm^2, a level exceeding the expected total lifetime dose for the L0 region in the ITk. During testing, the threshold was tuned to 1000 electrons. The sensors were operated at bias voltages between −20 V and −100 V, with the cooling box maintained at an average temperature of −35 °C, with the beam incident perpendicularly to the sensor surface.

The majority of detected clusters were single-pixel clusters, with an average cluster size of 1.192, as shown in figure 2. The increase in cluster size with applied bias voltage is shown in the same figure. Additionally, an increase in cluster size was observed in individual pixel corners, where two-pixel clusters were more frequently observed, as illustrated in figure 3. This effect is attributed to pixels being above the threshold and increased charge sharing at higher electric fields, which is expected for this sensor geometry.

The in-pixel efficiency is defined as the ratio of particle tracks whose associated hits are detected within a given pixel, to the total number of tracks predicted to traverse that pixel. The prediction is provided by the reference telescope. The in-pixel efficiency maps, shown in figure 4, were obtained by binning the pixel area into 50×50 sub-pixel bins to provide sub-pixel resolution and showcased that efficiency increased with bias voltage. At 51 V, the inefficiency in the central pixel region disappeared, while inefficiencies in the corners persisted. These were caused by the presence of the p^+ etched columns

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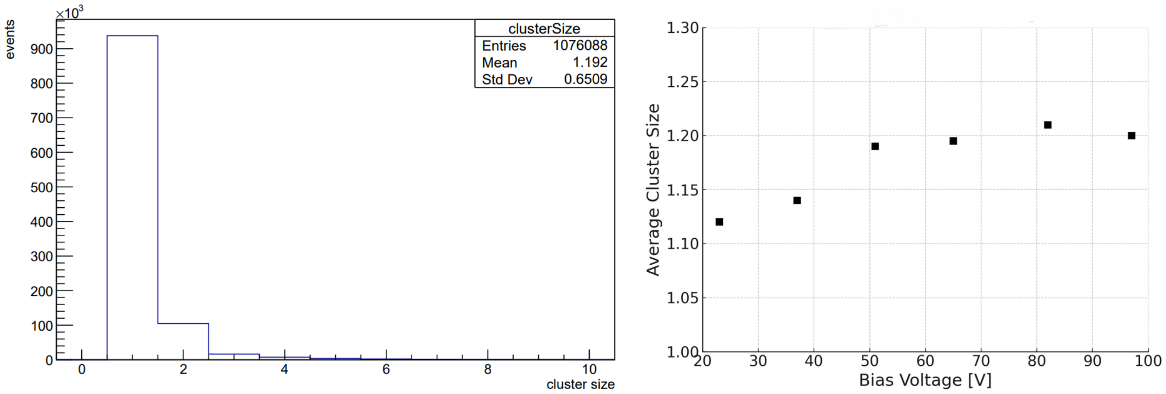

Figure 2. Cluster sizes for a bias voltage of 65 V (left) and the average cluster size as a function of the bias voltage (right) of the new SINTEF 3D sensors. For all measured bias voltages, the average cluster size is between 1.1 and 1.2 pixels. As expected for pixel sensors, an increase in bias voltage resulted in larger cluster sizes. Reproduced with permission from [7].

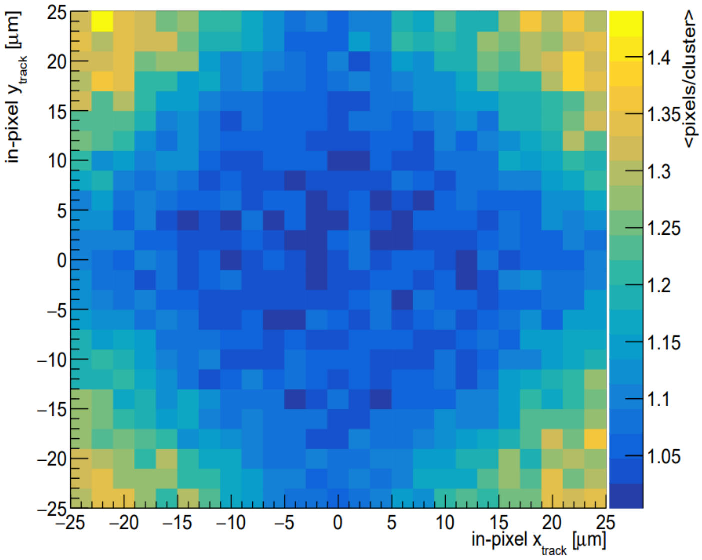

Figure 3. In-pixel mean cluster size for tested 3D sensors. The increased cluster size in the corner regions reflects enhanced charge sharing near the p^+ column structures, particularly at higher bias voltage. Reproduced with permission from [7].

and are consistent with the expected behavior of 3D sensors under perpendicular beam incidence. In the ITk, where tracks will arrive at a 15° angle, such effects are expected to be less prominent.

The ITk requires a minimum efficiency of 96 % for irradiated 3D sensors under perpendicular incidence. This threshold was achieved at a bias voltage of 67 V. The maximum measured efficiency was 98.2 %. The measured efficiencies for different bias voltages are depicted in figure 5. Compared to the original sensor design, the new version with modified passivation performed equivalently, reaching the same efficiency at higher voltages, although larger data samples are required to draw firm conclusions in the low-voltage region. Therefore, the radiation hardness of the new design is preserved.

2026 JINST 21 C01008

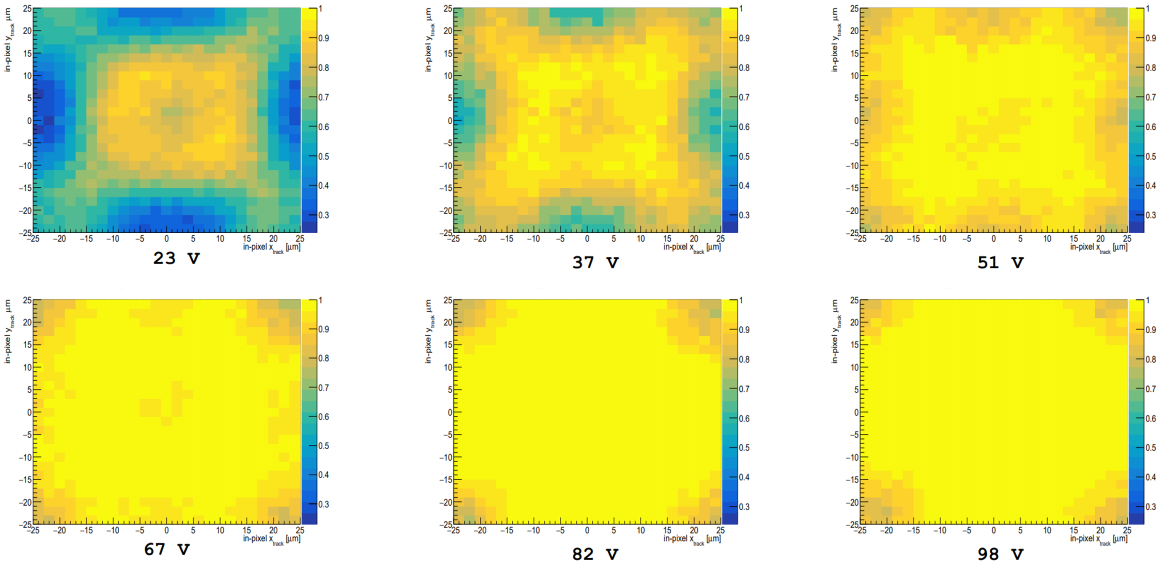

Figure 4. New 3D sensor in-pixel efficiency map for different voltages. Increased efficiency can be seen primarily in areas with increased electric field near the etched p^+ and n^+ columns with a 3 µm diameter. Simultaneously, pixel corners (p^+) do not achieve the same efficiency as the pixel center (n^+), as the p^+ columns are etched through the detector to the support wafer [6], which reduces the necessary active area for particle detection, decreasing the efficiency in pixel corners. Reproduced with permission from [7].

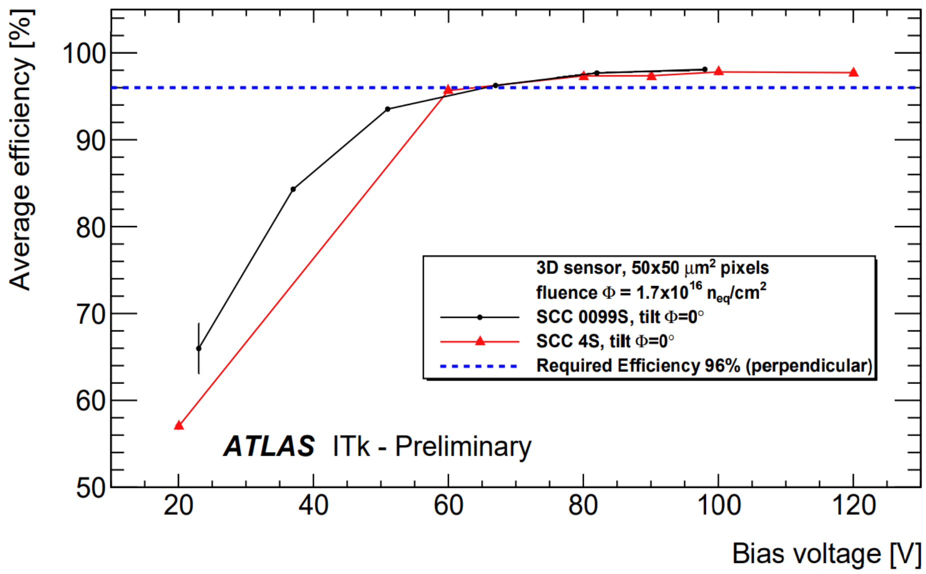

Figure 5. Average efficiencies for the new 3D sensor (SCC 0099S) as a function of bias voltage compared to the original design (SCC 4S). Both sensors were oriented perpendicularly to the incident beam and were irradiated to a fluence of $1.7 \times 10^{16}\ n_{eq}/cm^2$ before testing. The ITk-required efficiency for irradiated 3D sensors of 96 % is shown as a blue dotted line. Reproduced with permission from [7].

2026 JINST 21 C01008

4 Planar sensor results

The planar sensors were tested in a quad-chip configuration of four RD53B readout chips bump-bonded to a single sensor [8]. These quad modules feature an inter-chip region with differently shaped pixels to bridge the gap between chips. The tested sensors were produced by multiple manufacturers. Unirradiated modules were supplied by Advafab (QV2), HPK (QV2, KEKQ9), and Micron (Q18, Q19). Irradiated modules included HPK (KEKQ16) at a fluence of $4.31 \times 10^{15}\ n_{eq}/cm^2$ and Micron (PPPQ8, PPPQ12) at $2 \times 10^{15}\ n_{eq}/cm^2$.

Irradiation reduced the frequency of multi-pixel clusters due to increased charge trapping. Tilting the sensors restored larger clusters by enhancing charge-sharing paths. These trends are consistent with the reduced carrier mean free path after irradiation and the geometric increase in path length under tilt. Cluster-size distributions for all tested modules are shown in figure 6.

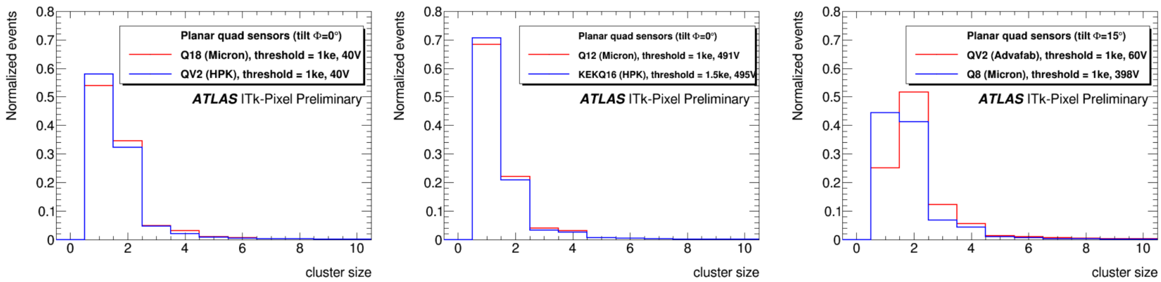

Figure 6. Planar sensors measured cluster size. The left-most two plots correspond to measurements performed with the sensors oriented perpendicularly to the incident beam. The left plot compares the cluster sizes of non-irradiated Q18 and QV2 sensors, while the middle plot compares irradiated Q12 and KEKQ16 sensors. The third plot shows results from a separate measurement campaign in which the sensors were tilted by 15° with respect to the incoming beam. It contrasts a non-irradiated QV2 sensor with an irradiated Q8 sensor. While the irradiated sensors exhibit similar cluster-size distributions across both measurement sets, and likewise for the non-irradiated sensors, the comparison illustrates the expected increase in cluster size distribution after irradiation. Reproduced with permission from [9].

According to ITk requirements, unirradiated sensors must achieve a hit efficiency greater than 98.5 %, while irradiated ones must exceed 97 %. These requirements were met during the beam tests at bias voltages of 20 V for non-irradiated and 250 V for irradiated sensors, as shown in figure 7. However, stable and simultaneous operation of all four chips on irradiated modules proved challenging, which might be due to a lack of experience with irradiated modules, inhomogeneous irradiation, or bugs in DAQ.

5 Conclusions

Recent beam test results of ATLAS ITk pixel sensors and modules were presented. The newly designed SINTEF 3D sensors, using optimized passivation layers, satisfy all ATLAS ITk specifications. They achieved the required 96 % efficiency at 67 V and reached 98.2 % at higher voltages, with performance matching or exceeding that of the original design. The observed inefficiencies in the sensor corners are expected due to the p^+ column geometry and are less critical under non-perpendicular angles.

2026 JINST 21 C01008

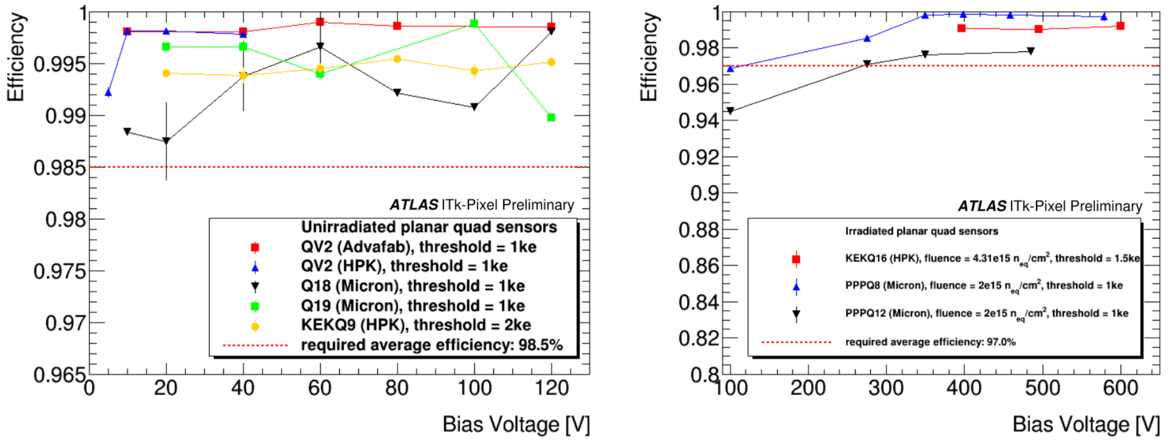

Figure 7. Efficiencies of tested non-irradiated (left) and irradiated (right) planar sensors as functions of bias voltage, with ITk required average efficiency noted as a red dotted line (98.5 % for non-irradiated sensors and 97.0 % for irradiated). Reproduced with permission from [9].

Irradiated and non-irradiated planar quad-chip modules from multiple vendors were tested. The modules satisfied the ITk hit efficiency requirements. However, stable operation of all four readout chips on irradiated modules remains technically challenging. Cluster sizes decreased after irradiation due to charge trapping, while tilting increased them as expected.

Data analysis and further testing of the new triplet-configured 3D sensors and quad-configured planar sensors from the 2025 test beams are in progress.

Acknowledgments

Supported via the LM2023040 CERN-CZ project.

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2026 JINST 21 C01008