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Test Beam Results of SINTEF 3D Pixel Silicon Sensors

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Abstract: This contribution presents test beam results of SINTEF 3D pixel sensors designed for the Inner Tracker (ITk) of the ATLAS detector at the High Luminosity LHC (HL-LHC). The sensors are required to withstand extreme radiation doses and to maintain efficiency above 96-97% after a lifetime of operation of the ITk at the HL-LHC. We present details on the production and design of these sensors, the setup for the experiment at CERN, and the analysis of the test beam data. Results are promising, showing excellent position resolution and high efficiency after irradiation. The sensors meet operational efficiency targets for both perpendicular and tilted configurations, validating their design and performance for future HL-LHC operations.

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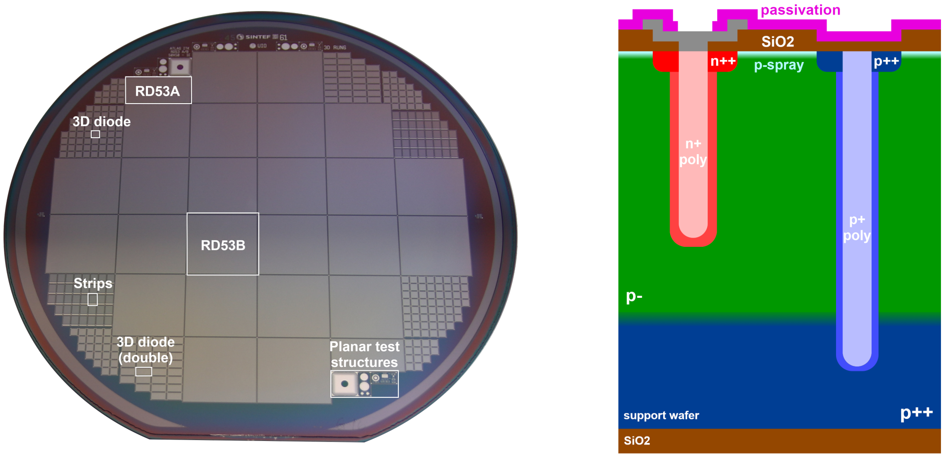
1. Introduction

The ITk sensors must be able to withstand extreme radiation at the HL-LHC. The tracking layer closest to the ATLAS interaction point is expected to receive a fluence greater than $1.6\times10^{16}\mathrm{n_{eq}/cm^2}$ during HL-LHC operation.

In 3D sensor technology, the electrodes are etched vertically into the silicon bulk, as opposed to planar sensors, where the electrodes are placed on the surface. The 3D sensor geometry gives shorter charge collection distances and consequently reduced probability of charge trapping. As a result, 3D pixel sensors have a higher radiation tolerance than conventional planar pixel detectors, and will therefore be used for the innermost layer of the ITk. Norwegian ATLAS groups have collaborated with SINTEF on the development of 3D sensors for many years. Here we present an ATLAS ITk-Pixel preliminary efficiency analysis of SINTEF 3D silicon sensors.

2. SINTEF 3D Pixel Sensors

The SINTEF 3D pixel sensors from the Run 6 pre-production campaign [1] are manufactured on 6″ silicon-on-silicon (Si-Si) p-type wafers in a single-sided process. The floor plan of the wafer, displayed in Figure 1a, shows the compatible sensors, as well as smaller test structures. During Run 6, the wafer layout included 24 sensors, and 24 wafers were manufactured in total. The good sensor yield ranges from 63% to 75%, depending on the wafer.



(a) **(b)**

Figure 1: (a) Wafer layout of Run 6 wafer. (b) Cross-section of a 50×50 µm^2 pixel showing the n$^+$-electrode and p$^+$-electrode in red and blue respectively.

The pixel detector have a pixel dimension of 50×50 µm^2 and an active thickness of 150 µm^2. A cross-section of the pixel layout is shown in Figure 1b. The electrodes are designed to have a radius of 3 µm. The Si-Si wafer type allows the p$^+$-electrode to be etched through the active layer, reaching the low resistivity backside. This removes the need for high-voltage metal on the front side, as electrical contact can be established from the backside of the sensor. The n$^+$-electrode is only etched 115 µm through the substrate. This results in a small gap of active material positioned between the tip of the electrode and the low resistivity backside layer. A slim-edge design is achieved with ohmic columns arranged in a grid-like pattern near the edge of the sensor.

3. Test Beam Setup

In the test setup, SINTEF 3D sensors are bump-bonded to readout chips, assembled on single-chip cards (SCCs), and mounted inside the EUDET Pixel Telescope. The EUDET Pixel Telescope [2], shown in Figure 2, is located in the CERN H6 test beam area in a 120 GeV pion beam line. The setup consists of 6 MIMOSA26 monolithic active pixel sensor (MAPS) planes for track reconstruction. Scintillators are placed at the front and back of the telescope for triggering. A planar pixel sensor from a Fondazione Bruno Kessler (FBK) pre-production, connected to an ASIC readout chip, is used as a reference sensor. The devices under test (DUTs) are housed in a temperature-controlled chamber in the middle of the beam telescope. Test beam runs are done with both perpendicular and tilted sensor configurations with respect to the beam.

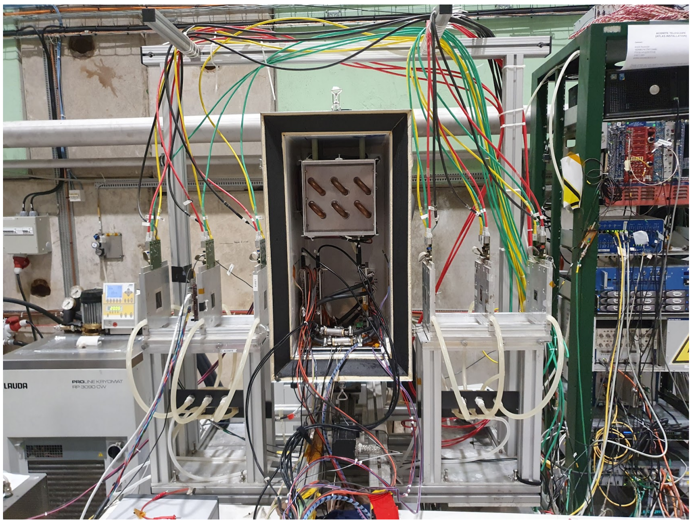
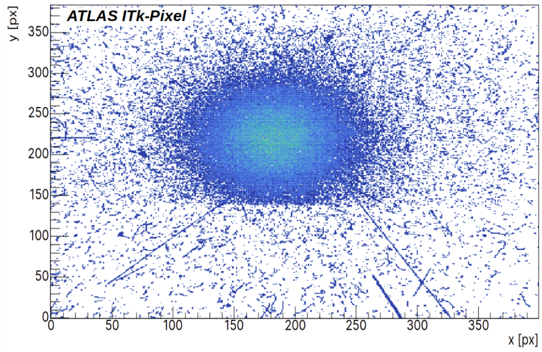
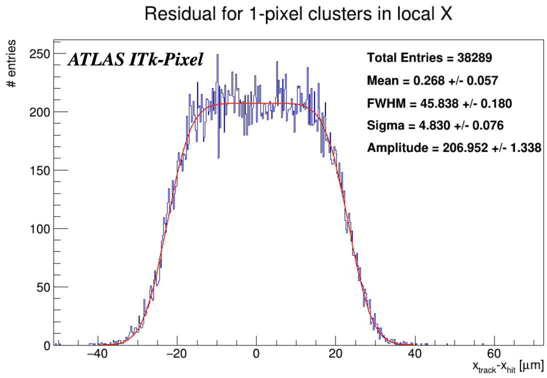


Figure 2: The EUDET Telescope. DUTs are mounted inside the cooling box shown in the centre of the setup.

The DUTs, labelled SCC 1S and SCC 4S, were tested before and after irradiation. The irradiation were performed at the Karlsruhe Institute of Technology (KIT) to a fluence of $1 \times 10^{16} n_{eq}/cm^2$. SCC 4S has been further irradiated at the CERN Proton Synchrotron (PS) to $1.8 \times 10^{16} n_{eq}/cm^2$.



(a)



(b)

Figure 3: A raw hit map on the sensor (a) and track residuals (b) for single pixel hit clusters [5]. Straight lines in (a) are tracks inside the sensor arising from knocked-out delta electrons. The fitted histogram in (b) shows a sigma of 4.8 µm and a FWHM of 46 µm.

4. Residual analysis

The Corryvreckan software framework [3] is used for the analysis of the test beam data. This framework has a modular architecture which involves the following steps: event building, hit clustering, pre-alignment and correlation, tracking, and analysis. In the event building stage, the Eventloader module decodes and processes the pixel information from the raw data from the DUTs. A raw hit map created from this step is shown as an example in Figure 3(a). The clustering module groups pixel hits into hit clusters. Using these clusters, the telescope and DUT planes are aligned in the pre-alignment and correlation step. Tracks are reconstructed in the tracking step. An analysis module is used to study both the in-pixel efficiency and the efficiency of the entire sensor.

To study the position resolution of the sensors, an analysis of track residuals is done on SCC 1S, before irradiation, biased at 10V. In this analysis, hits with single-pixel clusters are extracted from the data set and their residuals are plotted independently.

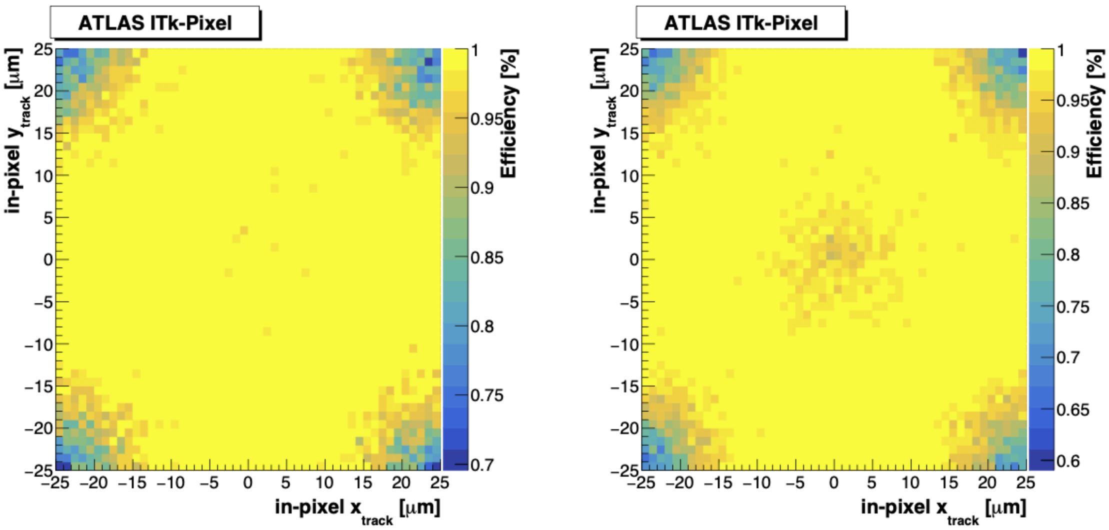
The track residual distribution for single-pixel clusters is shown in Figure 3(b) for the x-coordinate. The histogram is fitted with a two-step function convoluted with a smoothing function to represent a smeared-out box distribution. The width of this smoothing function, σ, has a value of 4.8 µm, which is due to the tracking resolution of the EUDET Telescope and the charge-sharing probability between pixels. The Full Width at Half Maximum (FWHM) of 46 µm of the rectangular box is smaller than the pixel size due to the selection of one-sized clusters, which removes hits close to the edge.

5. Pixel Efficiency Maps

Hit efficiency is defined as the fraction of events in which a particle traversing the active region of the sensors results in a registered hit. The reconstructed track positions on the sensor are projected onto a single pixel to study the efficiency regions within it. Here, in-pixel efficiency maps are presented for SCC 1S. Figure 4a show the efficiency map of the the unirradiated sensor when biased at 10V. Figure 4b show the efficiency map of the irradiated sensor when biased at 60V.

The unirradiated pixel efficiency map shows a high efficiency of about 100% in the central region. Inefficient regions are visible in the corners and show a decrease in efficiency down to about 85%. These inefficiencies are due to the presence of the p+ etched columns and are expected in perpendicularly mounted 3D pixel sensors.

For the irradiated sensor, measured at 60 V and at perpendicular beam incident, an additional area of slightly lower efficiency (90%) is seen in the centre due to the presence of the n+ etched columns. Here, the regions of inefficiency in the corners of the pixel reach a minimum of 55%. Except for these areas, the 3D sensor still shows a high efficiency of 99% or more after receiving a radiation dose of 1.0 $\times 10^{16}$ n_{eq}/cm^2.



(a) (b)

Figure 4: In-pixel efficiency maps for SCC 1S for the unirradiated (a) and irradiated (b) case[5]. Both cases are measured at perpendicular beam incidence. The sensor is held at a 10 V (60 V) bias in the unirradiated (irradiated) case.

6. Results

The ITk target efficiency for 3D sensors at perpendicular incidence is set at 96% for its entire operational lifetime, as lower values could lead to degradation in tracking and vertex reconstruction [4]. For sensors tilted by 15°, the specification is set at 97% since the inefficiencies due to the vertically etched electrodes are reduced.

The ITk target efficiency for unirradiated sensors at perpendicular incidence is set at 97%. Figure 5 displays the average efficiency for SCC 1S and SCC 4S, prior to irradiation, as a function of bias voltage. The modules are mounted perpendicularly with respect to the beam and tested at bias voltages of 1 V and 10 V. Both sensors reach 98% efficiency at both bias points, exceeding the 97% specification.

Efficiency after irradiation to a fluence of 1.0 $\times 10^{16}$ n_{eq}/cm^2 is shown in Figure 6(a). The bias voltage points range between 20 V and 90V. SCC 1S is evaluated in both tilted and perpendicular

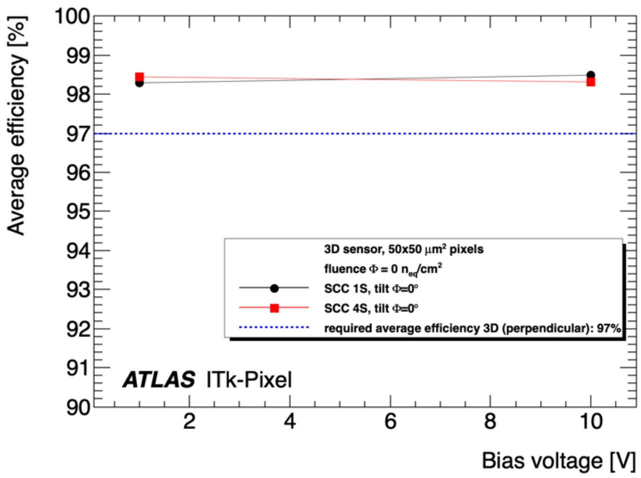
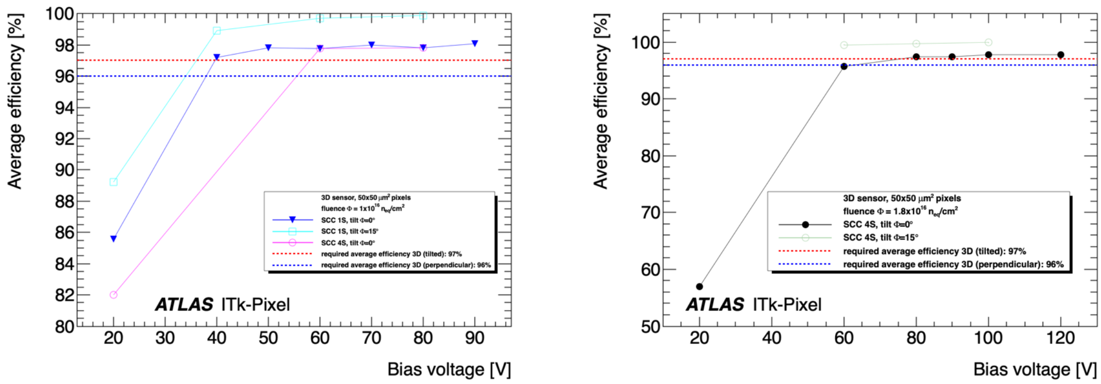


Figure 5: Efficiency as a function of voltage for the two unirradiated DUTs in perpendicular configuration[5]. The blue dotted line shows the ITk efficiency specification for perpendicularly mounted modules.

configurations and exceeds the target efficiencies at 40 V. SCC 4S exceeds its target efficiency at 60 V, which is the lowest bias voltage point tested after 20 V.



(a) **(b)**

Figure 6: Efficiency as a function of voltage for the two DUTs, irradiated to a fluence of 1.0×10^{16} n_{eq}/cm^2 (a) and for SCC 4S irradiated to 1.8×10^{16} n_{eq}/cm^2 (b)[5]. The sensors are tested in both tilted and perpendicular configurations.

In figure 6(b), SCC 4S is irradiated to an average fluence of 1.8×10^{16} n_{eq}/cm^2 and tested both mounted perpendicularly to the beam and with a 15° tilt. The target efficiency is achieved at 60 V for the tilted configuration and at 80 V for the perpendicular configuration.

7. Conclusion

We have presented an analysis of pixel efficiency and track residuals of 3D silicon pixel sensors from the Run 6 pre-production campaign at SINTEF. The sensors were tested with a pion beam inside the EUDET Pixel Telescope. The residuals for one-sized pixel clusters for an unirradiated

$50 \times 50\,\mu m^2$ sensor have a measured FWHM of 46 µm, pointing towards an excellent position resolution. A study of the in-pixel efficiency maps shows the inefficient regions that occur within the 3D pixel design, in particular the lower efficiency areas at the p+ etched columns. We show that the DUTs reach the target 96% and 97% efficiencies for perpendicular and titled configurations, respectively, at 60 V (80 V) after exposure to fluences of 1.0 (1.8) $\times 10^{16}\, n_{eq}/cm^2$.

8. Acknowledgements

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