PROCEEDINGS OF SCIENCE

Testbeam studies of irradiated modules for the ATLAS ITk Strip upgrade

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To cope with the occupancy and radiation environment expected at the High-Luminosity LHC, the ATLAS experiment will replace its Inner Detector with an all-silicon Inner Tracker (ITk), containing pixel and strip subsystems. The strip subsystem will be built from modules, consisting of one or two n+-in-p silicon sensor(s), one or two PCB hybrid(s) containing the front-end (FE) read-out electronics, and one powerboard with high voltage, low voltage, and monitoring electronics. The sensors in the central barrel region of the detector will use a simple rectangular geometry, while those in the forward end-cap regions will use a radial geometry with a built-in stereo angle. To validate the expected performance of the ITk strip detector, a series of testbeam campaigns has been performed over several years at the DESY-II testbeam facility. Tracking was provided by EUDET telescopes, consisting of six Mimosa26 pixel planes. An additional FE-I4 pixel plane was used to provide sufficient timing resolution for the telescope. In the years 2021-2022, the focus of testbeam campaigns has been on assessing module performance post-irradiation, using the final production versions of the sensors, and most recent versions of front-end electronics. Three modules of differing geometry were built from irradiated components; a barrel Short Strip (SS), an end-cap R0, and an end-cap R5 type. With the R5 campaign also being the first time a "split" module design was tested at a testbeam (two sensors sharing FE electronics). Measurements of the collected charge, detection efficiency, and noise occupancy were performed on all tested modules, as well as of the tracking performance in various sensor regions. The results give confidence in the operability of the detector across its lifetime.

"The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)".

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[*] Speaker

1. Introduction

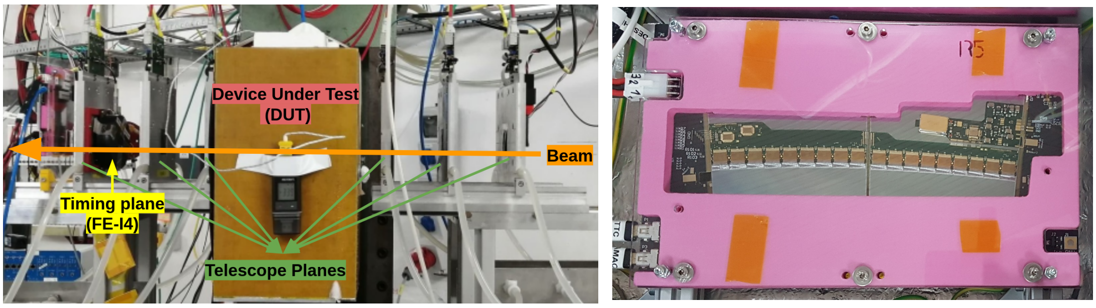


Figure 1: The Device Under Test (DUT) installed in the polystyrene cold box, which is positioned between the 3rd and 4th Mimosa26 plane of the DURANTA EUDET telescope at DESY II testbeam facility. The FE-I4 pixel detector used as the timing plane is mounted on the last telescope plane (left). The right hand photo shows the R5 end-cap module, built of two R5 sensors, installed in the cold box.

For the ATLAS HL-LHC upgrade, the entire inner tracking system will be replaced with an all silicon Inner Tracker (ITk) detector [1]. Showcasing sufficient performance of the ITk strip modules in close-to-real conditions, is an essential part of demonstrating final production readiness for the project. This is achieved through testbeam campaigns; ITk strip modules are placed in particle beams together with a reference detector system, see Figure 1, allowing us to evaluate the Device Under Test (DUT) performance. In 2021-2022, the focus has been on assessing the end-of-life performance for both barrel and end-cap type modules. This entails using the final production version of sensors and the most recent front-end electronics, pre-irradiated to the maximal expected HL-LHC fluence times 1.5 safety factor. We measured collected charge, detection efficiency, noise occupancy for all modules, as well as the tracking performance in various sensor regions.

2. Setup at DESY Testbeam facility

The DESY II synchrotron at DESY Hamburg delivers a tunable 1-6 GeV electron beam, and provides access to the EUDET-type beam telescopes used for reference tracking [2]. These beam telescopes, see Figure 1, consist of six Mimosa26 silicon pixel planes, each with a spatial resolution of ~5 µm and a 115 µs time resolution [3]. Since the ATLAS ITk strip modules operate at the LHC collisions clock of 25 ns, we also include the FE-I4 timing plane in the setup, operating at the same 25 ns clock rate - to facilitate proper hit efficiency studies.

3. The hunt for an operational window

The front-end readout of the strip modules utilises a binary hit/no-hit discriminator, with a tunable charge threshold to minimise bandwidth needs. This threshold setting is constrained by the design criteria implemented to ensure sufficient lifetime tracking performance of the ITk:

- Hit detection efficiency > 99 %.
- Noise occupancy < 0.1 %.

An increase in the charge threshold results in a lower noise occupancy, but also reduces the hit detection efficiency, since tracks are then more likely mischaracterised as noise due to e.g. a low charge deposition or significant charge sharing across multiple strips. This means that the two primary success criteria of our module design constrain the charge threshold setting from opposing directions. Demonstrating the existence of an operational window - a range of charge thresholds over which both criteria are satisfied, is therefore a primary goal of our testbeam campaigns.

4. Analysis procedure

The ITk strip testbeam group is moving towards Corryvreckan being our main data reconstruction and analysis framework [4]. Recently, significant effort was invested towards fully integrating the complex polar geometry of the ITk radial strip end-cap modules into Corryvreckan. The strips are arranged in a trapezoidal fan shape, with 2-4 segments of differing pitch & length - allowing for a common focal point; the beam pipe centre offset by 20 mrad wrt. the sensor centre (chp. 6.1 [1]). This effort is nearing completion, with the semi-automated reconstruction running significantly quicker, both in setup and computing time, compared to prior more manual methods.
Currently, reconstruction of the testbeam data is done in a four step process:

1. As the beam telescope and DUT run on different read-out systems, and at two very different clock rates (115 µs and 25 ns), this provides ample opportunities for desynchronisation of the two data streams - which results in artificially hindering the hit efficiency analysis. Therefore, pre-processing by a re-synchroniser algorithm is necessary.
2. Masking of noisy channels.
3. Alignment of the beam telescope and construction of tracks. The first telescope plane is set as the reference position, with the other telescope planes and the FE-I4 timing plane then spatially aligned through iterative track fitting and detector plane alignment.
4. When an acceptable telescope alignment has been achieved, the telescope positions are locked and a similar procedure is used to align the DUT. Then a search for DUT hits associable to the telescope track fit(s) in the relevant time frame is performed. This search is typically done using a simple distance-to-nearest-cluster cut.

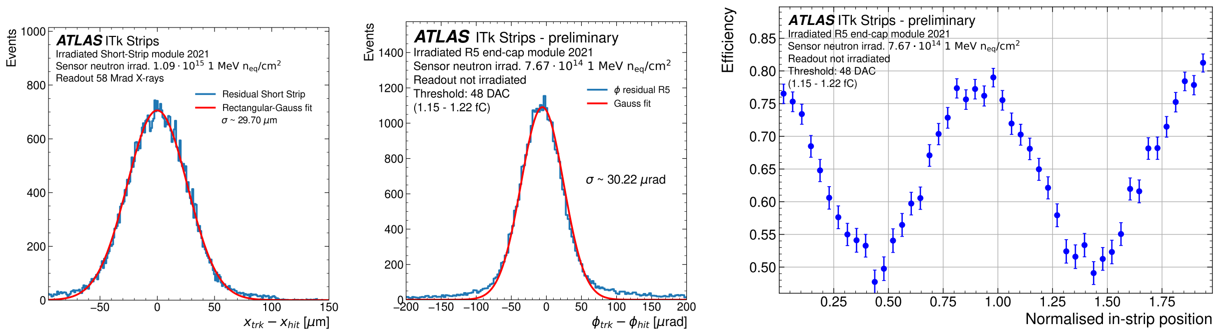
The final hit efficiency of the DUT is then calculated as

$$\epsilon = \frac{N_{tracks}^{DUT+FEI4}}{N_{tracks}^{FEI4}}, \tag{1}$$

where N_{tracks}^{FEI4} is the number of tracks with hits on both the DUT and FE-I4 timing plane, and N_{tracks}^{FEI4} the total number of tracks.

5. Results: Spatial resolution and operational window

Figures 2(a) and 2(b) show the good positional resolution achieved for the short-strip (SS) barrel and R5 end-cap modules, in both cases corresponding to ~ 0.4 fraction of the strip pitch. Figure 2(c) shows how, by normalising and overlaying all strips of the R5 module, we can demonstrate the impact of charge sharing on detection efficiency, as well as sub-pitch reconstruction accuracy. If the spatial alignment of the DUT and telescope is not successful, this plot would become featureless noise, so it serves as a good figure-of-merit for alignment. Figure 3(a) shows an operational window of 0.22 fC for the irradiated SS module. However for the end-cap modules, demonstrating sufficient end-of-life performance is still an ongoing effort. This is due to a combination of issues with the re-synchronisation of the DUT and telescope data, as well as unexpectedly high noise. Both observed issues are currently under intensive investigation by the ATLAS ITk strip collaboration.

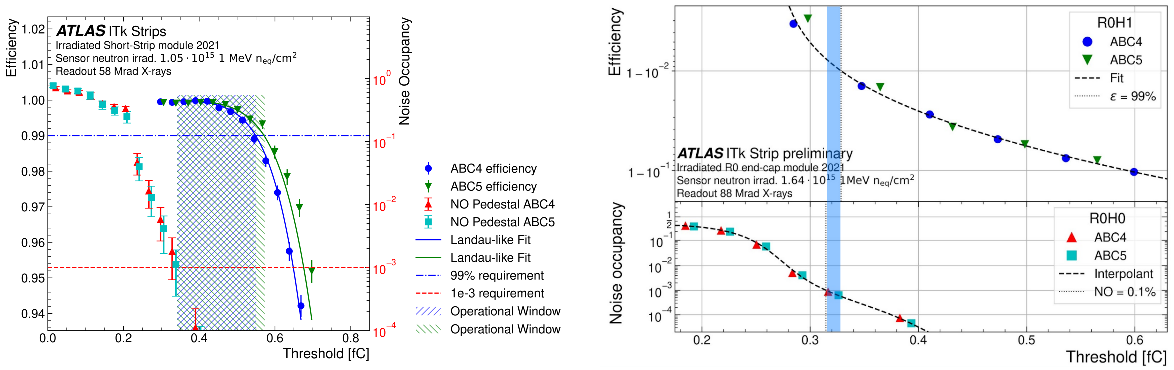


(a) Irradiated SS barrel module, measured in June and September 2021 [5].

(b) Irradiated R5 end-cap module measured in December 2021.

(c) Dependence of detection efficiency on the position of the track with respect to the strip. All strips are normalised to position 1, with nearest neighbours at 0 and 2.

Figure 2: Showcasing quality of the Corryvreckan spatial reconstruction. For the telescope-DUT residual distributions, the fitted standard deviation is interpreted as the achieved tracking resolution of the DUT.



(a) A good operational window for SS module is seen, 0.22 fC wide. Signal over noise (S/N) ratio was 16.9. Detection efficiency on left axis and noise occupancy to the right [5].

(b) An operational window of 0.09 fC was found for the R0 end-cap module, when combining detection efficiency of the R0H1 hybrid with the noise occupancy of the R0H0 hybrid.

Figure 3: Detection efficiency (blue and dark green) and noise occupancy (red and cyan) as a function of charge threshold. The blue engraved area highlights the identified operational window. Noise occupancy is determined by collecting data while the beam is turned off.

References

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[5] ATLAS public plots: `https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2021-003/`