Test Beam Studies of ATLAS ITk Strip Modules for the ATLAS Phase-II Upgrade

Abstract

The ATLAS experiment will replace its Inner Detector with an all-silicon Inner Tracker (ITk) to cope with the occupancy and radiation doses expected at the High-Luminosity LHC. The ITk is composed of pixel and strip subsystems. The strip subsystem is built from modules consisting of one n+-in-p silicon sensor, one or two PCB hybrids containing the front-end electronics, and one powerboard with high voltage, low voltage, and monitoring electronics. A series of test beam campaigns have been performed over several years to validate the expected performance of the ITk strip detector. EUDET telescopes consisting of six Mimosa26 pixel planes provide tracking, while a dedicated pixel or strip plane improves the timing resolution. Tracks are reconstructed using the General Broken Lines algorithm, resulting in a spatial resolution of several microns. The data allow for thorough tests of the module performance, including charge collection, noise occupancy, detection efficiency, and tracking performance. Studies before and after irradiation to the expected end-of-lifetime fluence of modules with preproduction-ready components are shown. Excellent tracking resolution and hit reconstruction efficiency are found. The results give confidence that the ITk strip detector will meet the requirements of the ATLAS experiment.

The ATLAS Inner Tracker (ITk) Strip Detector

At the **HL-LHC** the **ITk** detector will face:

Radiation Damage

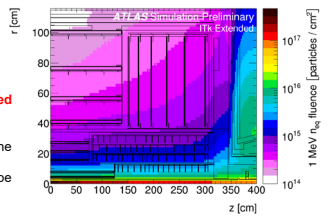
- **HL-LHC should deliver ~ 4000 fb^{-1}**

  Expected fluences
  - Pixels ~10^{16} 1 MeV n_{eq}/cm^2
  - Strips ~10^{15} 1 MeV n_{eq}/cm^2
  - New sensor design requires **increased radiation hardness**

Pileup from ~50 to ~200

- Requires increased granularity to mantain the current Inner detector perfomance

Transition Radiation Tracker would not be able to cope with track density

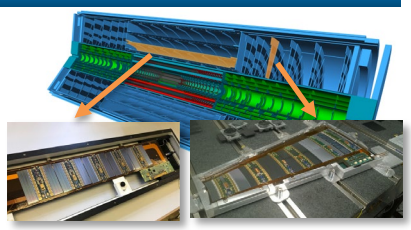


New all silicon design ensures:

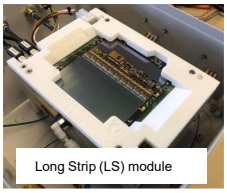
- Higher granularity
- Minimum material
- η coverage increased to 4 (currently ~2.5)
- CO_2 cooling

ITk Pixel Detector:

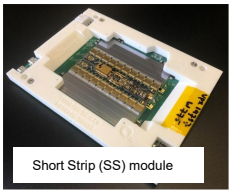
- 5-barrel layers: short barrel + inclined modules (|η| < 1.4)
- endcap rings (|η| < 4)



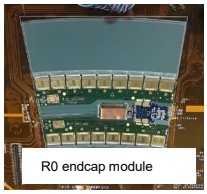
Barrel loaded support structure (stave) | Endcap loaded support structure (petal)



Long Strip (LS) module



Short Strip (SS) module



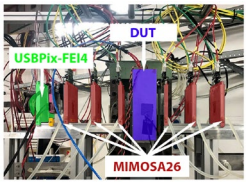
R0 endcap module

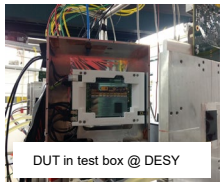
ITk Strip Detector:

Barrel
- 4-barrel layers with square sensors 96.640 x 96.669 mm^2
- 75.5 μm pitch, two strip lengths: 48.2 mm (Long Strip), 24.1 mm (Short Strip)
- Modules glued back-to-back onto the stave and rotated 26 mrad → total stereo angle 52 mrad

Endcap
- Six sensor designs with strip lengths from 1.5 to 6.0 cm
- Pitch varies from 70 to 81 μm
- Angular pitch from 85.7 to 193.1 μrad
- Six modules named R0-R5 → three modules use butted side-by-side sensors with a hybrid spanning over
- 20 mrad stereo angle implemented in sensor design
- Modules glued back-to-back onto the petal for a total of 40 mrad stereo angle

Test Beam Studies of ITk Strip Modules





DUT in test box @ DESY

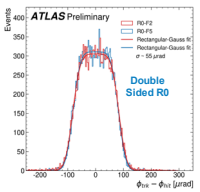
DESY Test Beam Facility uses e⁻/e⁺ beams obtained from double conversion from the main beam of the DESY II synchrotron in the DESY campus (Hamburg, DE). The beam momentum for test beams can be selected between 1-6 GeV/c^2. Calibrated tracking detectors (EUDET-type telescopes) are employed for track reconstruction with resolutions of a few micrometers. The experimental setup comprises:

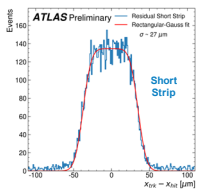
- EUDET-type telescope: sequence of 6 planes with Mimosa-26 pixel sensors, with 18.4 μm pitch with a total active area of 1x2 cm^2
- Reference timing plane (FEI4): to place a timing tag on the track due to the large integration time of the Mimosa planes (~ 115 μs) with respect to the DUT (~ 25 ns)
- Device Under Test (DUT): ITk Strip modules are placed in the center of the telescope planes → spatial resolution and efficiency measurements are performed

Data reconstruction and analysis is accomplished using either the EUTelescope or the Corryvreckan frameworks

Irradiated studies up to the end-of-lifetime fluence, including safety factors between 1.2-1.5

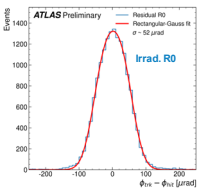
Tracking Resolution

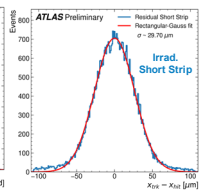




Irrad. sensor ~1.64x10^{15} 1 MeV n_{eq}/cm^2 by neutrons ABCStar front-end irrad. to 88 Mrad by X-rays

Irrad. sensor ~1.09x10^{15} 1 MeV n_{eq}/cm^2 by neutrons ABCStar front-end irrad. to 58 Mrad by X-rays





Resolution perpendicular to the strip is given by:

$$\sigma_{\perp} = \frac{pitch}{\sqrt{12}}$$

Non-Irradiated

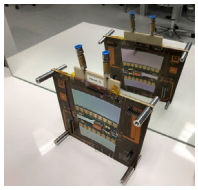
- Barrel $\sigma_{\perp} \simeq 22$ μm
- Endcap R0 $\sigma_{\perp} \simeq 50$ μrad
- Box-shaped dominated by cluster size one

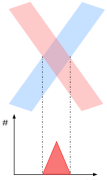
Irradiated

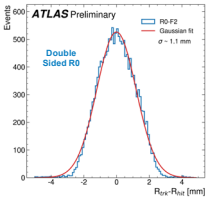
Irradiated
- Resolution within expectations
- Residual shapes affected by the increase of cluster size due to irradiation
- Active cooling produces constant movement of DUT, thus alignment not as precise as for non irradiated modules

Resolution along the strip needs the addition of another layer with strips crossing at a given angle. The radial resolution is the given as: $\sigma_R = \frac{pitch}{\sqrt{24}\cdot\sin\left(\Phi_S/_2\right)}$

- For 40 mrad stereo angle $\sigma_R \simeq 750$ μm
- Module built by hand → stereo angle of 31 mrad → $\sigma_R \simeq 1.1$ mm







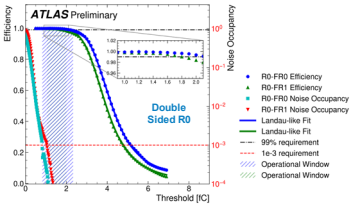
Detector Efficiency

The benchmark is to operate modules at thresholds providing a hit reconstruction efficiency higher than 99% and noise occupancies below 0.1% before and after irradiation or equivalently a signal-to-noise ratio higher than 10

- Because of the different integration time between the telescope and the DUTs, the efficiency is then calculated as:

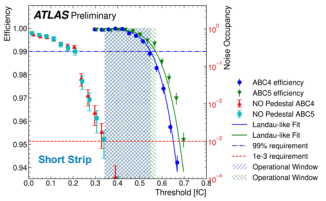
$$\xi_{DUT} = \frac{tracks_{hit\ on\ DUT+timing\ plane}}{tracks_{hit\ on\ timing\ plane}}$$

- Non irradiated Double-Sided R0 module
- ABC130 front-end



- Non-irradiated modules show clear range of thresholds (~1 fC, corresponding to ~60 DAC) where the operational requirements are satisfied

- Irrad. sensor ~1.09x10^{15} 1 MeV n_{eq}/cm^2 by neutrons
- ABCStar front-end irrad. to 58 Mrad by X-rays
- 80 min annealed at 60 °C



- Due to irradiation, module performance decreases. However, a clear range of thresholds (~0.2 fC, corresponding to ~10 DAC) is observed where the operational requirements are satisfied
- S/N ~ 16.9

Summary and Outlook

- Tracking resolution, hit efficiencies and noise of ATLAS ITk strip modules are within expectation and are well understood
- Irradiated modules built with production components prove that the operational requirements of efficiency and noise occupancy of the ATLAS ITk strip detector are satisfied
- More test beam campaigns with irradiated and non-irradiated modules with focus on different endcap sensor designs are planned
- Presented results give confidence in the tracking performance of the ATLAS ITk strip detector across its lifetime

References

- ATLAS Collaboration, Technical Design Report for the ATLAS Inner Tracker Strip Detector, CERN-LHCC-2017-005, ATLAS-TDR-025, https://cds.cern.ch/record/2257755.
- A. Rodriguez Rodriguez, The ATLAS strip detector system for the High-Luminosity LHC, JINST 15 (2020) 08, C08015

Arturo Rodriguez Rodriguez on behalf of the ATLAS Collaboration
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