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The ATLAS ITk detector system for the Phase-II LHC upgrade ☆

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ABSTRACT

The ATLAS experiment is planning a complete replacement of its inner detector with a new all-silicon inner tracker for the high luminosity phase of the LHC. The new detector is designed to cope with the increased pile-up, data rates and radiation levels of the HL-LHC, while maintaining or improving the current ATLAS tracking performance. The ITk design and technology R&D have been completed and pre-production of the detector modules is starting. This paper presents the ITk layout, performance and the ongoing transition into production phase.

1. Introduction

Scheduled to take place between 2026 and 2028, the Phase II upgrade of the Large Hadron Collider (LHC) will increase the machine luminosity by a factor of 5 to 7.5 above the nominal value ($1 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$). During 10 years of data-taking at the High Luminosity LHC (HL-LHC), the experiments will collect an integrated data set of $4000\,\mathrm{fb^{-1}}$ (a factor 10 higher than during the 14 years long LHC data-taking period).

The increase in instantaneous luminosity will translate into higher particle multiplicity leading to up to 200 pile-up interactions per bunch crossing, compared to a maximum of 55 during the LHC run. The detectors closest to the beam pipe will have to withstand radiation levels of up to $2 \times 10^{16}\,\mathrm{n_{eq}cm^{-2}}$ fluence and 10 MGy Total Ionising Dose (TID).

To cope with the experimental conditions at the HL-LHC, the ATLAS experiment [1] has developed a new all-silicon inner tracker (ITk). The ATLAS ITk detector has been designed with technologies providing higher granularity, radiation hardness, readout speed and low material budget to maintain, or even improve upon, the performance of the current tracking system, while meeting the challenges of operation in the harsh HL-LHC environment.

2. The ATLAS Inner Tracker Detector

The ATLAS ITk consists of pixel layers close to the interaction point, complemented by layers of strip detectors at larger radii. It will instrument an area of approximately $180\,\mathrm{m^2}$ with more than 5 billion channels. For comparison, the pixel and strip detectors currently installed in the ATLAS Inner Detector (ID) cover an area of approximately $63\,\mathrm{m^2}$ with almost 100 million channels. A schematic view of one quarter of the ITk layout is shown in Fig. 1.

Pixel and strip detector modules are mounted onto local support structures, in turn fixed into global mechanics supports, to form a system of cylindrical layers in the central detector region, called barrel, and a system of rings at the two sides, called end-cap regions. The pixel and strip systems feature respectively five and four barrel layers. The end-cap regions are made of several sets of pixel rings and six strip rings. In total more than 27 000 modules made of sensors and readout electronics will be used in the ITk, a factor almost 5 times higher than in the ATLAS ID.

Despite the significant increase in size and number of channels to service, the ITk will feature a lower material budget than the current ATLAS ID as shown in Fig. 2. This has been achieved through a number of innovations in cooling, power distribution, and readout configurations. Evaporative CO2 cooling with titanium pipes is used for both detector systems. Local supports are fabricated with lightweight carbon foam material. Novel powering schemes, based on DC-DC conversion and constant current power distribution (serial powering), have been developed for the strip and pixel detector respectively. The strip system employs optical links using the Low Power GigaBit Transceiver (lpGBT) [2] ASIC for off-detector data transmission.

The ITk detector provides highly granular, hermetic, lightweight coverage up to $|\eta| = 4$ (extended from $|\eta| = 2.5$ of the current ATLAS ID) with at least 9 points per track in the barrel region and 13 in the end-caps as shown in Fig. 3 to improve pattern recognition. Fig. 4 compares the simulated ATLAS ITk performance with 200 pile-up interactions with the performance of the ID with 38 pile-up interactions. Even in the much higher pile-up scenario, with a higher fake hit rate, the ITk tracking efficiency is comparable to that of the ID in the $|\eta| < 2.5$ region. The ITk tracking capability in the extended pseudorapidity region, $|\eta| > 2.5$, reaches an efficiency of 85%.

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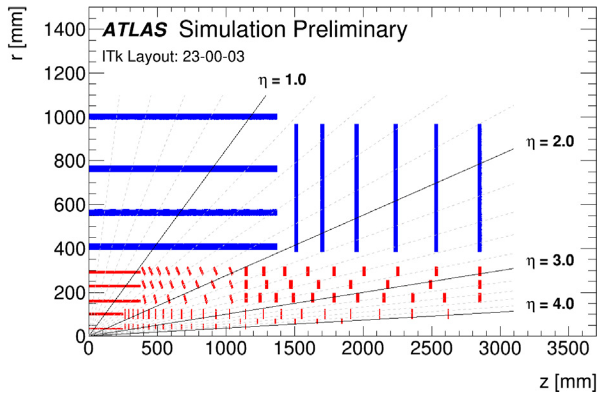

Fig. 1. Schematic view of the ITk layout. The figure shows only one quadrant. Only active detector elements are shown, in red for the pixel detector and in blue for the strip detector [3].

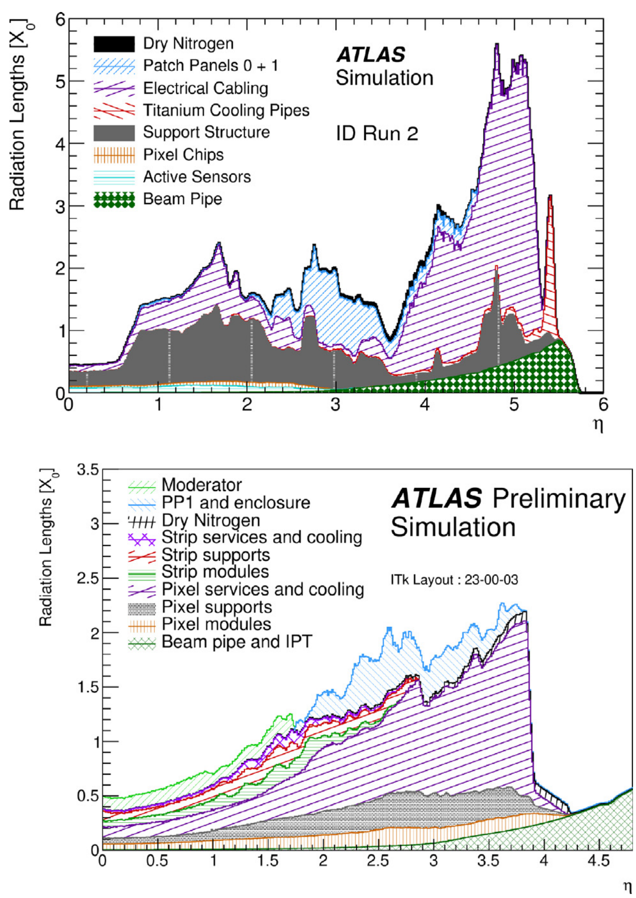

Fig. 2. Material thickness distribution in radiation lengths (X_0) versus pseudorapidity η of the ATLAS ID (top) [4] and of the ITk (bottom) [3].

3. ITk strip system

The ITk strip detector [4] is made of a barrel region and two identical end-cap regions. Modules are loaded on the two sides of local support structures with a small stereo angle to provide the second coordinate measurement. Local support structures consist of carbon-fibre composite with integrated electrical and cooling interfaces. Two different shapes are used for the barrel and end-cap local supports: rectangular staves and trapezoidal petals, respectively. These are assembled to form cylindrical layers and disks using larger mechanical structures.

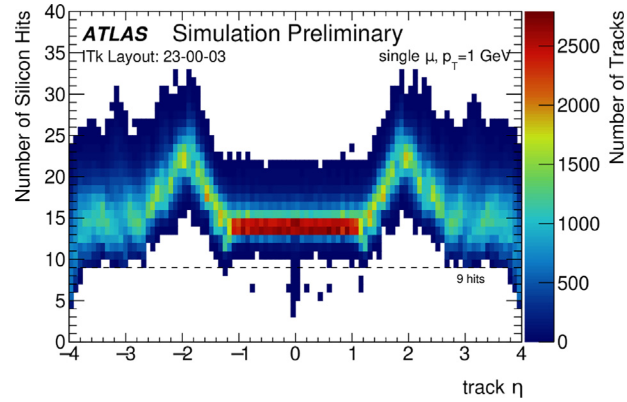

Fig. 3. Number of hits on a track as a function of η for single muon events with $p_T = 1\,\text{GeV}$ [3].

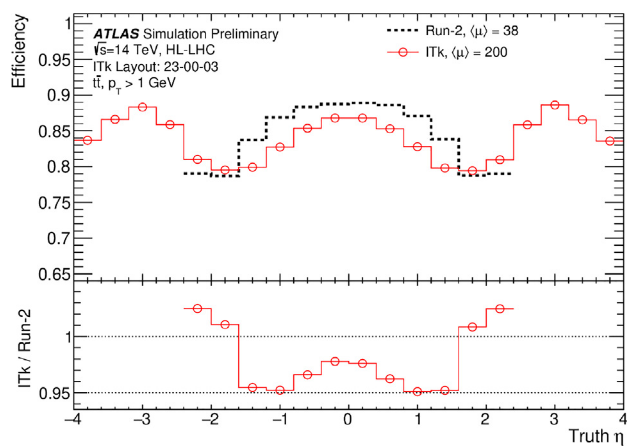

Fig. 4. Tracking efficiency for $t\bar{t}$ events with the ITk layout compared to that of the ATLAS ID (indicated as Run-2 in the legend). For the ITk an average pile-up value of $\langle\mu\rangle = 200$ is used. The efficiency of the ID is for $\langle\mu\rangle = 38$ [3]. The efficiency in reconstructing tracks from particles from the hard-scatter interaction in $\langle\mu\rangle = 200$ $t\bar{t}$ events is dominated by low-p_T pions.

The latter are known as global mechanics and are carbon cylinders for the barrel and carbon wheels for the end-caps.

The active elements of the detector, the modules [5], are made of a sensor, one or two hybrid circuits, and one power board. Eight different module flavours exist based on the shape of the sensor that is different in the inner and outer staves, as well as along a petal. An example is shown in Fig. 5 which depicts a barrel module. The hybrid circuit is a printed circuit board hosting up to 12 ABCStar readout ASICs, and up to 2 HCCStar controller ASICs. The power board provides circuitry for sensor bias, a DC-DC buck converter to power the ASICs and the AMAC ASIC for module control and monitoring functions. All three ASICs are custom developed in a 130 nm CMOS technology [6,7]. The hybrid and power board circuits are glued on the sensor and connections between sensor and readout ASICs is made via wire bonds.

ITk strip modules made with pre-production sensor and ABCStar ASICs have been tested with a 6 GeV electron beam after irradiation to accumulate a dose equivalent to 10 years of operation at the HL-LHC. Fig. 6 shows tracking efficiency and noise occupancy as a function of operational threshold for a barrel module. The plot indicates a clear window of operation where both constraints on 99% efficiency and less than 0.01% noise occupancy can be met. The signal to noise ratio measured at test beam is about 17, where the required value is 10. This result demonstrates the suitability of the developed strip module technologies for operation in the ATLAS ITk.

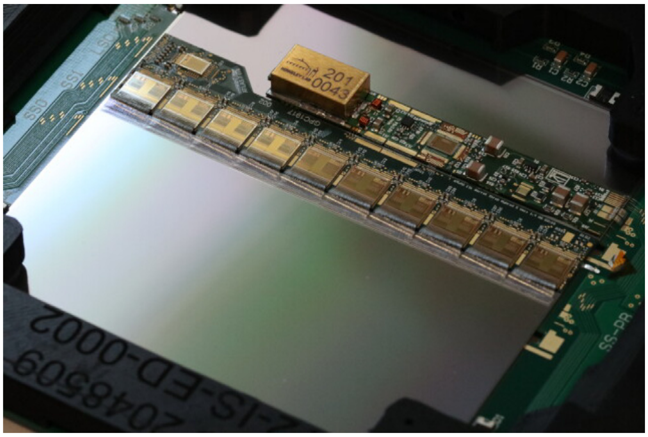

Fig. 5. Picture of a barrel Long Strip module of the ITk detector. The hybrid flex hosts 10 ABCStar chips and one HCCStar chip. The power board hosts the DC-DC converter and the AMAC chip.

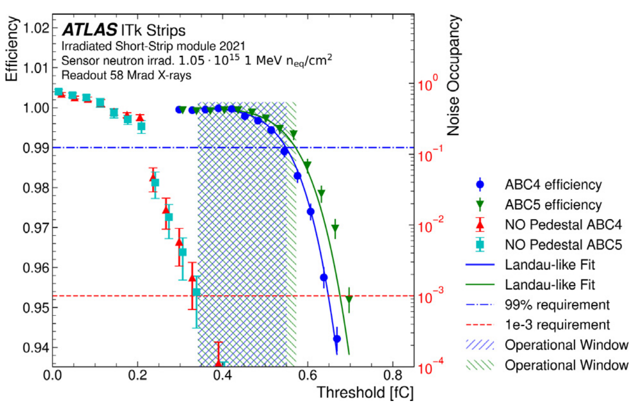

Fig. 6. Performance of an ATLAS ITk Short Strip module, irradiated to HL-LHC end of life dose, measured in a 6 GeV electron test beam [8]. Results are shown for the two tested ABCStar chips, labelled ABC4 and ABC5. Noise occupancy (red and turquoise markers) and efficiency (blue and green markers) are shown as a function of threshold. The requirements on noise occupancy and efficiency are marked with red and blue dashed lines respectively. The shaded areas show the range of thresholds for which these requirements are satisfied for each ASIC.

Production of the ITk strip detector is scheduled to start at the end of 2022, pending successful completion of the Production Readiness Review (PRR). More than 20 000 modules (including yield) will be built at 30 assembly sites in three years. Extensive quality control and quality assurance procedures are carried out on all module components and at each stage of assembly [4]. Readiness for production is achieved through two exercises ongoing at all assembly sites in the year ahead of production start: site qualification and pre-production. Sites demonstrate their ability to perform each assembly related procedure, including shipment, receipt and storage of components, as well as upload of information and test results to the database, with the site qualification process. During pre-production the module assembly sites build approximately 1000 modules, i.e. 5% of the total module production, to develop the full assembly procedure and exercise the complex logistic of parts distribution around multiple countries in view for production. The first phase of pre-production using pre-production sensor and ABCStar ASICs has been completed in early summer 2022. The second phase, using all pre-production components, is carried out in the remainder of the year leading to the start production.

4. ITk pixel system

The ITk pixel system [9] is divided in three separate mechanical areas. The Inner System (IS) is the closest to the beam pipe, with the innermost layer and rings placed at 34 mm from the beam pipe. The IS is designed to be replaced after 2000 fb^{-1} when the performance of the detector modules is anticipated to be deteriorated by radiation. The Outer Barrel (OB) system covers the central detector region at larger radii. It consists of three layers of modules mounted flat on staves and three sets rings. The latter are designed to mount the modules in an inclined position in order for the particles traversing the detector at these angles to go through less material. The third system, the Outer End-cap (OE), is made of three sets of double-sided rings installed on each side of the OB.

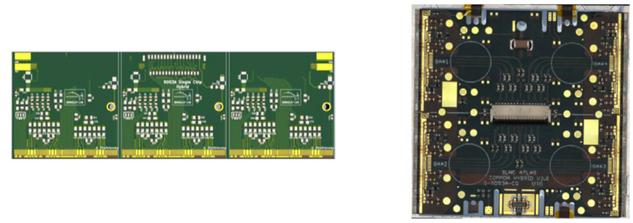

Fig. 7. Triplet module made of three single-chip assemblies (left). Quad module with one sensor tile flip-chip to four front-end readout chips (right).

Two different types of n-in-p sensors, 3D and planar, are used in the pixel detector. 3D sensors are used in the innermost layer and set of rings for their radiation hardness. With respect to the state-of-the-art 3D sensors installed in the ATLAS IBL [10], a number of modifications have been made to improve radiation hardness and yield. The sensors have a thin active substrate of 150 μm and a small pixel size (25 × 100 μm and 50 × 50 μm for the barrel and disks respectively) to reduce cluster size and data rates, keep occupancy low and improve impact parameter resolution. A single sided process is used to etch the electrodes into the substrates. Planar sensors are used in the remainder of the layers and rings, with a thickness of 100 μm in the IS and 150 μm in the OB and OE and a pixel size of 50 × 50 μm. Both sensor types are now in pre-production.

A new readout ASIC in 65 nm CMOS technology has been developed for the ITk pixel detector to satisfy the unprecedented requirements in terms of rate and radiation. The pixel readout chip has been designed to cope with 5 MGy TID corresponding to 1×10^{16} $n_{eq}cm^{-2}$ fluence. It accommodates a trigger rate of 1 MHz and can handle up to 3 $GHzcm^{-2}$. It features integrated data formatting including data compression, and dedicated regulators for serial powering. After a successful prototype submission, the RD53 A chip [11], the full size (20 × 20.7 mm^2) pixel readout ASIC, ITkPixV1, is now in pre-production.

Pixel modules will be built with 3D and planar sensors bump-bonded to the pixel readout ASIC. A flex circuit glued on top of the sensor is used for electrical connection to the detector services and parylene coating is deposited on the assembled module to reinforce bonds, avoid corrosion, prevent electrical discharge between the sensor and the readout ASIC. Pixel modules are of two flavours as depicted in Fig. 7. Triplets are built with three single-chip modules, where a 3D sensor is bump-bonded to a readout ASIC, connected to the same flex. Quad modules are made of one large planar sensor bump-bonded to four readout chips.

More than 200 pixel modules have been prototyped with the RD53 A ASIC. Single-chip module prototypes with 3D sensors have demonstrated 96% efficiency at a fluence of 1.6×10^{16} $n_{eq}cm^{-2}$ in test beams, with a bias voltage below 150 V and a power consumption below 40 $mWcm^{-2}$ [12]. Quad modules have also demonstrated the required hit efficiency. It has been measured in test beams to be above 98% at 5×10^{15} $n_{eq}cm^{-2}$ fluence at bias voltages of 600 V and 400 V for 150 μm and 100 μm thickness respectively [13]. Module pre-production is scheduled to start in the second half of 2022 followed by production a year later. Twenty assembly sites will deliver more than 9000 modules in two years. A large programme of pixel system demonstrator is underway in anticipation of pre-production where all pixel subsystems are building loaded local support prototypes.

5. Conclusion

A new all-silicon tracking system is being developed by the ATLAS experiment to cope with increased number of events per bunch crossing, particle multiplicity and radiation levels at the HL-LHC. The ITk detector installation will commence in 2026. The ITk design provides large acceptance for tracking with at least nine points per track, high granularity and radiation hardness, combined with a low material budget. Both strips and pixels technologies have demonstrated the required tracking efficiency up to end-of-life dose. The strip system is progressing through pre-production and production has started for several parts (sensors, ASICs, global mechanics). The pixel system is finalising an extensive prototyping phase and has recently started pre-production of some components (sensors, ASIC, local supports). ITk production will be a global effort with more than fifty institutes world wide delivering a total of almost 30 000 modules within a few years.

References

[1] ATLAS Collaboration, The ATLAS experiment at the CERN large hadron collider, JINST 3 (2008) S08003, http://dx.doi.org/10.1088/1748-0221/3/08/S08003.
[2] N. Guettouche, et al., The lpGBT production testing system, JINST 17 (2022) C03040, http://dx.doi.org/10.1088/1748-0221/17/03/c03040.
[3] ATLAS Collaboration, Expected tracking and related performance with the updated ATLAS inner tracker layout at the high-luminosity LHC, 2021, ATL-PHYS-PUB-2021-024. URL https://cds.cern.ch/record/2776651.
[4] ATLAS Collaboration, ATLAS inner tracker strip detector: Technical design report, 2017, ATLAS-TDR-025; CERN-LHCC-2017-005. URL https://cds.cern.ch/record/2257755.
[5] L. Poley, et al., The ABC130 barrel module prototyping programme for the ATLAS strip tracker, JINST 15 (2020) P09004, http://dx.doi.org/10.1088/1748-0221/15/09/P09004.
[6] W. Lu, et al., Development of the ABCStar front-end chip for the ATLAS silicon strip upgrade, JINST 12 (2017) C04017, http://dx.doi.org/10.1088/1748-0221/12/04/C04017.
[7] M.J. Basso, et al., A starry byte — proton beam measurements of single event upsets and other radiation effects in ABCStar ASIC versions 0 and 1 for the ITk strip tracker, JINST 17 (2022) P03017, http://dx.doi.org/10.1088/1748-0221/17/03/P03017.
[8] J.S. Keller, J. Kroll, A. Rodriguez, et al., Test beam performance of ITk-strip ABCStar module, 2021, ATLAS appoved plot. URL https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2021-003/.
[9] ATLAS Collaboration, ATLAS inner tracker pixel detector: Technical design report, 2017, ATLAS-TDR-030; CERN-LHCC-2017-021. URL https://cds.cern.ch/record/2285585.
[10] B. Abbott, et al., Production and integration of the ATLAS insertable B-layer, JINST 13 (2018) T05008, http://dx.doi.org/10.1088/1748-0221/13/05/T05008.
[11] M. Garcia-Sciveres, The RD53A integrated circuit, 2017, CERN-RD53-PUB-17-001. URL https://cds.cern.ch/record/2287593.
[12] S. Terzo, et al., A new generation of radiation hard 3D pixel sensors for the ATLAS upgrade, Nucl. Instrum. Methods A 982 (2020) 164587, http://dx.doi.org/10.1016/j.nima.2020.164587.
[13] S. Möbius, Module development for the ATLAS ITk pixel detector, JINST 17 (2022) C03042, http://dx.doi.org/10.1088/1748-0221/17/03/c03042.