PROCEEDINGS OF SCIENCE

ITk Strip Module Design and Performance

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The all-silicon ATLAS ITk Detector, vertexing and tracking device for the High-Luminosity LHC project, should operate at an ultimate peak instantaneous luminosity up to 7.5×10^{34} cm^{-2} s^{-1} corresponding to approximately 200 inelastic proton-proton interactions per beam crossing. The ITk Strip Detector will consist of four barrel layers and six disks in a forward region on each side of the barrel. They will be composed of individual structures called staves and petals, whose production will require almost 18,000 single-sided strip modules of 8 different designs with the hybrid circuits carrying the front-end microelectronics ASICs glued to the sensor surface. The sensing elements are high resistivity n-in-p silicon strips capable of withstanding fluences up to 1.2×10^{15} n$_{eq}$/cm^2. Both irradiated and non-irradiated prototypes of strip modules undergo testing procedures including test beam campaigns supplemented by laser and beta source tests to check if they meet the design requirements of the detector.

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1. Introduction

The Inner Tracker (ITk), all-silicon vertexing and tracking device, is being developed in the framework of the Phase-II ATLAS Upgrade project as a successor to the Inner Detector (ID) currently used in the complex ATLAS detector system [1] at the LHC at CERN. The ITk consists of the Pixel Detector placed close to the beam line and the large area Strip Detector at its outer radii.

After the 30-month shutdown scheduled between years 2024 and 2026 the High-Luminosity LHC (HL-LHC) will be put into operation at the peak luminosity of $5.0-7.5\times10^{34}$ cm^{-2} s^{-1} corresponding to approximately 200 inelastic proton-proton interactions per beam crossing. This places high demands on future detection modules, which will be exposed in the strip region to fluences equivalent to 1.2×10^{15} n$_{eq}$/cm^2, ten times higher than in case of current Semi-Conductor Tracker (SCT). The innermost and most radiation-resistant pixel Insertable B-Layer (IBL) of the current ATLAS tracker should be able to withstand up to 850 fb^{-1}, which is still far below the expected integrated luminosity of HL-LHC of 4000 fb^{-1} [2].

The strip detection system covers $\pm$ 2.7 units of pseudorapidity and occupies an area of 165 m^2. Both barrel and end-cap strip layers will be populated with identical substructures called staves and petals respectively, bringing together groups of modules. They will provide local support for the modules, mechanical rigidity and common electrical, optical and cooling services. Nearly 18,000 strip modules will be loaded on both sides of staves and petals with a stereo geometry to determine the z-position of the strip clusters.

2. Design of the ITk Strip Modules

The ITk strip module as a basic component of the detector consists of 300 μm thick n$^+$-in-p silicon sensor, on which one or two kapton PCBs, called hybrids, are glued. Each hybrid is hosting various numbers of ABCStar readout chips and at least one Hybrid Control Chip (HCCStar) developed on the basis of previous ABC130 prototypes [2]. The module powering is ensured by a power-board providing low voltage (LV) power to the front-end electronics of the hybrids through the DC-DC converter, sensor high voltage (HV) biasing and module level environmental measurements and control.

The two innermost / outermost barrel layers will be assembled from 14 short- / long-strip (strip length of 24 mm / 48 mm) modules per stave side. Each of 12 end-cap disks will consist of 32 petals, which will be occupied by 9 radial strip modules from each side. The schematic layout of the ITk is shown in Figure 1. In order to get complete tracking information the stereo angle between the opposite pair of strip clusters in the barrel region is set to 52 mrad, while the angle of 40 mrad in end-cap disks is directly implemented to the sensor design. The sensor pitch determining its resolution varies between 69 and 84 μm. Sensor bulk will be depleted by a nominal voltage of around 300 V including possibility to increase the value up to 500 V or even 700 V to improve its performance after radiation damage at the end of life. The lowest required limit of signal-to-noise ratio for the ITk strip modules at the end of life of HL-LHC is 10:1 to reach detection efficiency greater than 99% and keep channel noise occupancy below 10^{-3}, but estimations show performance to be almost twice as high as these specifications.

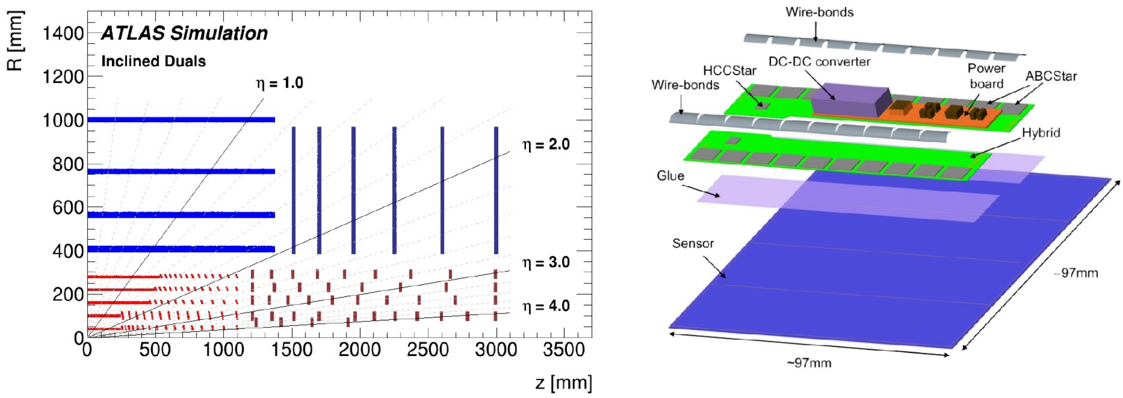

Figure 1: Left: The Schematic layout of the ATLAS ITk detection layers shows their placement in the cylindrical coordinate system [3]. Right: Assembly schema of a short strip barrel module [2].

3. Data Acquisition

The strip section of the ITk detector requires reading out from nearly 60 million channels. An enormous amount of data is being processed by the front-end (FE) electronics based on the ABC-Star ATLAS Binary chips, in which signal generated from sensor is amplified, shaped and finally discriminated to get binary output.

Binary data from hybrids are transmitted through the HCC at the speed of 640 Mbit/s to the End-of-Substructure (EoS) card of the stave/petal via copper/kapton bus tape. The tape provides transmission of Timing, Trigger and Control (TTC) input data to ASICs, output data coming from their channels and power distribution of LV and HV to the power boards.

The final EoS data processing and optical conversion is performed by universal components of Phase-II electronics such as low power Gigabit Transceiver (lpGBTx) chips and Versatile Tranceiver (VTRx+) providing multimode optical I/O fibres. Moreover, the global and local interlock and common monitoring systems, as parts of the Detector Control System (DCS), generates additional data information.

The EoS serves as an interface between the on- and off-detector electronics that is represented by the FELIX board [2]. This board is able to convert specific optical signals from the detector to standard communication protocols.

4. Testing Methods and Results

In order to check that the ITk strip modules meet the design requirements, they are being tested by both external and internal charges, which are injected in the individual channels of the ABCStar ASICs. The internal charge is generated by the calibration circuit that is integrated in the read-out electronics of the module and controlled by a complex software called ITSDAQ [2]. The external charge is induced on the sensor strips by ionizing particles produced at test beam facilities or by using the beta or laser sources in the laboratories of several collaborating institutes. Typical results of these methods for a non-irradiated module are shown in Figure 2.

Test beam campaigns at the DESY II test beam facility use electrons with energies typically

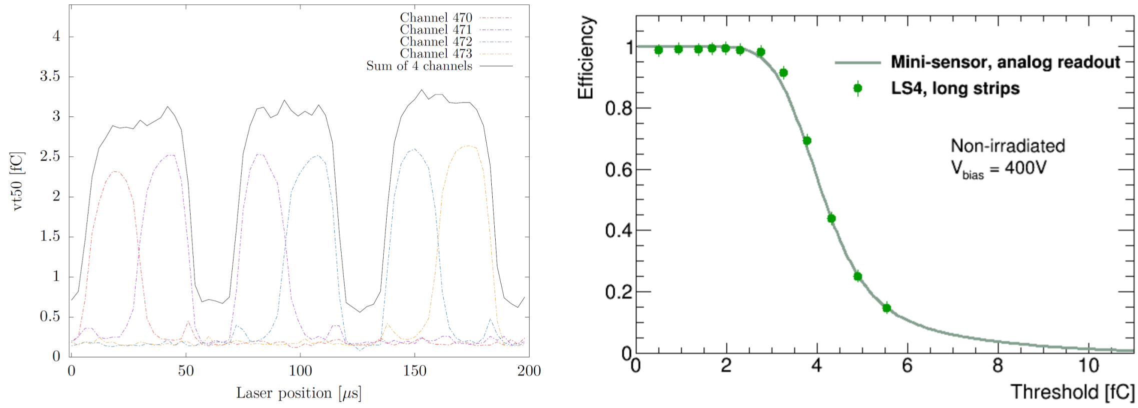

Figure 2: Left: A laser interstrip scan of an ITk strip miniature sensor [4]. Right: Comparison of CERN test beam results reconstructed in the low-cluster-size region (dots) and sensor charge collection studies done with the ^{90}Sr source and analogue readout (line) [2].

between 4.0 - 5.0 GeV, while those at CERN SPS test beam facility are done with 120 GeV pions. For particle tracking and subsequent residual analysis the DATURA/DURANTA and ACONITE EUDET telescopes [5] are used at DESY and CERN, respectively. The basic components of these telescopes are 6 Mimosa26 detectors with well-known pixel sensor parameters (pitch 18.4 μm, resolution 2 μm). In order to refine the timing and track tagging an additional FE-I4 pixel layer is included as well as scintillator detectors providing the external trigger signal.

Scintillator as an external triggering tool is also being used during tests with a radioactive beta source. In the absence of tracking information, the most widely used isotope, ^{90}Sr, allows cluster and depletion studies using the external injection of beta electrons. Red or infra-red laser studies on the other hand offer very good spatial resolution and adjustable beam intensity, which allow additional sensor testing without any dependency on the internal calibration circuit of chip electronics.

All these testing methods require electrical readout based on specialized ITSDAQ software [6] that scans over the threshold which is set at the FE discriminators, since the modules use binary readout. The most critical measured properties are the Equivalent Noise Charge (ENC), the gain, the collected charge, the hit efficiency and the noise occupancy.

The ITk strip project uses several different irradiation facilities providing neutrons, protons, pions or electrons at different energies. Studies of irradiated sensors and modules show the impact of radiation damage on the collected charge, especially at the end of their expected lifetime. While its value for the non-irradiated modules is around 4 fC and the sensor is fully depleted at 350 V, the signal from the irradiated ones is in the range of 2.2 - 3.1 fC for the region of highest irradiations and different module types at a depletion voltage of 700 V. The hybrids, ASICs and sensor surface suffer during the irradiation procedure from ionizing radiation, while the sensor bulk is mainly affected by point and cluster defects caused by non-ionizing energy loss. The impact of silicon sensor irradiation is evident from Figure 3. It was shown that the largest changes under irradiation affect the sensor inter-strip resistance, but it still stays significantly above the 15 MΩ specification [2].

For testing purposes three irradiation campaigns were organized in 2018 at the CERN IRRAD proton facility, during which 88 miniature sensors, one full-sized ATLAS17LS sensor as well as one R0 module were irradiated to different total fluences. The R0 module, that received the total fluence of 1.6×10^{15} 1 MeV n_{eq}/cm^2 corresponding to the total maximal fluence to be delivered to strip modules during the HL-LHC operation, including the safety factor 1.5, was later tested at the CERN SPS test beam facility using the ACONITE EUDET telescope. Complete results will be presented at regular ATLAS ITk meetings.

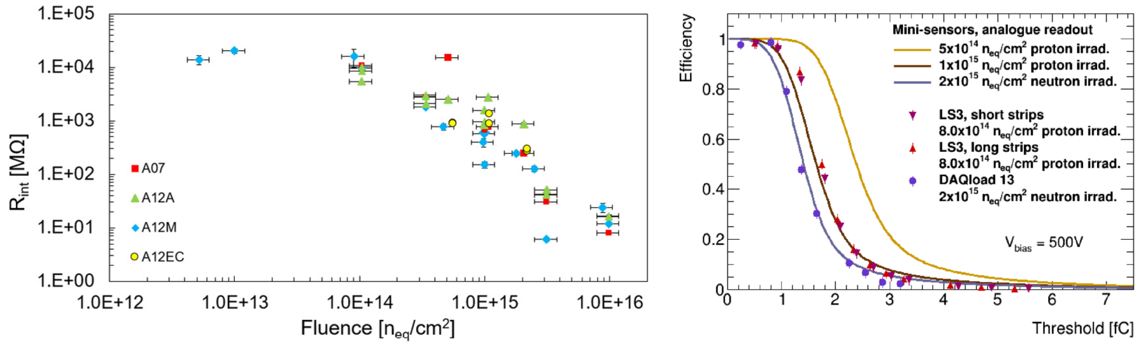

Figure 3: Left: Interstrip resistance evolution with irradiation with protons on different sensor prototypes at a depletion voltage of 400 V [7]. Right: Comparison of threshold scans of differently irradiated module prototypes [2].

5. Database

During the pre-production and production phases of the ATLAS ITk project, monitoring of all individual components will be carried out by the ITk Production Database (PD) common for ITk strips, pixels and mechanics/electronics. The PD will be able to record assemblies, shipments and Quality Assurance (QA) / Quality Control (QC) test results of almost 10^7 numbered items and provide detailed information leading to better understanding of future defects.

At the end of 2019 the one-year pre-production phase of module building will start. This includes the necessary process of uploading module subcomponents, basic properties and QA/QC electrical test results into the PD. The scripts uploading the test results to the PD will be incorporated into the ITSDAQ software, that operates the individual module analysis tools.

6. Conclusions

The ATLAS ITk project brings many technical and logistical challenges arising from the outlined requirements and distributed production model. The strip detection system is designed to reasonably fill the whole volume of the current Inner Detector. From the end of 2019, the pre-production phase will start followed by the production phase at the beginning of 2021. All procedures and gradual steps aim to insert the assembled ITk detection complex in 2025 instead of the current Inner Detector, which will be decommissioned.

The ITk strip modules encompass eight different designs mounted on complex support structures (barrel staves and end-cap petals) that also play an important role interfacing between the on-and off-detector electronics. The active strip detection system will be supplemented by the global mechanical support. The intensive Long-Strip (LS), Short-Strip (SS), Ring 0 (R0) and miniature module testing of both the non-irradiated and irradiated samples is ongoing at the institutions involved. Production will require specific QA/QC testing procedures such as visual inspection, metrology and multiple electrical and mechanical characterization of all detector components. One of the key points is the Production Database, which will serve as a production data store for these components and their QA/QC test results.

In the next few months, modules with their hybrids hosting the final production ABCStar chips will be available for irradiation and beam testing. The production of the remaining end-cap sensor types will start and new test beam and irradiation facilities will be chosen in view of the CERN Long Shutdown 2 (LS2).

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