The ITk Strip Tracker for the phase-II upgrade of the ATLAS detector of the HL-LHC

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ABSTRACT: The current Inner Detector in the ATLAS experiment does not meet the requirements of the High Luminosity-LHC upgrade. A new detector, known as the Inner Tracker, will be built in place of the current Inner Detector and will consist exclusively of silicon based sensors, pixels and strips. This contribution summarizes the on-going R&D activities within the different institutes involved in the phase II upgrade of the Strip Tracker. An update on the current status of testing and prototyping is given as well as the next steps before the submission of the ITk Strips Technical Design Report by the end of 2016.

KEYWORDS: Detector design and construction technologies and materials; Particle tracking detectors (Solid-state detectors)
1 Introduction

The High Luminosity LHC (HL-LHC) upgrade is designed to deliver instantaneous luminosities of up to $7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ giving up to 200 interactions per bunch crossing. Figure 1 shows the expected roadmap towards the HL-LHC. Two long shutdowns (LS) are planned to progressively upgrade the accelerator and the detectors, named LS2 and LS3. The HL-LHC upgrade phase II is scheduled for 2024.

For the ATLAS experiment [2], the phase II upgrade will result in an integrated luminosity of $3000 \text{ fb}^{-1}$ over a period of about ten years. At this luminosity level, the number of particles produced will increase considerably. The current Inner Detector (ID) is located around the collision point and extends to a radius up to $R = 1.0 \text{ m}$ and covers $|z| = \pm 1.4 \text{ m}$. The expected radiation damage in the current ID will be ten times higher than the damage suffered since the beginning of LHC. Therefore, ATLAS will replace the entire current ID with a new all-silicon based detector, the Inner Tracker (ITk).

The ITk has higher granularity with respect to the current ID. This is achieved with silicon pixel sensors at inner radii close to the beam-line and with silicon strip sensors surrounding the...
pixel sensors. These sensors are known as Pixel Tracker and Strip Tracker respectively and are arranged in Barrels and Endcaps.

The layout of the ITk needs to cover a pseudorapidity range up to $|\eta| = 4.0$. The final design of the layout is still under discussion. At the moment, four options are considered that are mainly focused on the layout optimization of the Pixel Tracker. Quarter segments of two of the four options are shown in figure 2.

![Figure 2](image)

**Figure 2.** Two out of the four layout options currently under discussion showing hit positions on the $r$-$z$ plane [3]. They cover a pseudorapidity range up to $|\eta| = 4$ with at least 13 hits. In both options, the Strip Tracker, shown on each figure as the outer sections, has four Barrel layers (horizontal lines) and six Endcap disks (vertical lines) at each side, each of which has two layers of sensors with a stereo angle between them.

All four options propose the same layout for the Strip Tracker. The Strip Tracker includes a Barrel section in the center and an Endcap section at each side. The Barrel consists of four layers where the innermost have short strips (24.1 mm) and the outer two have long strips (48.2 mm). The Endcaps have six disks each. The momentum resolution and tracking efficiency requirements dictate the choice of the radii for the Barrel and the $z$ positions for the Endcaps. The Barrel covers a radius range of $R = 405–1000$ mm and covers up to $|z| = 1.4$ m. The Endcaps cover a pseudorapidity range up to $|\eta| = 2.5$ and up to $|z| = 3$ m.

## 2 ATLAS ITk Strip Tracker upgrade

The requirements for the Strip Tracker include low occupancy levels (below 1%) and radiation hard components able to withstand a maximum dose of $2 \times 10^{15} \text{n}_{eq}/\text{cm}^2$. In addition, the material budget must be kept low in the active and passive detector components and in all the services around the detector to minimize multiple scattering, photon conversions, electron bremsstrahlung and hadronic interactions, as it is needed to achieve a good resolution on the trajectories of the reconstructed tracks.

A description of the Strip Tracker components follows. The basic detector unit is the module. A module consists of the sensor, the ASICs and power boards. Multiple modules are placed on a local support.

The proposed sensor is an AC-coupled 320 $\mu$m thick p-type silicon substrate with n$^+$ strips built on a 6 inch wafer. Figure 3 shows a n-in-p float zone technology sensor. This is a different technology compared to the current detector that features a p-in-n type sensor. Type inversion is avoided in a n-in-p sensor and the charge collection is faster since the segmented electrodes collect electrons. Moreover, higher signal is expected after irradiation compared to the current p-in-n type sensor [4].
Figure 3. Illustration of a sensor with \( n^+ \) strips in p-type substrate (n-in-p) where electrons are collected by the segmented electrodes [5].

The pitch per strip for the Barrel is approximately 74.5 \( \mu m \) while the pitch for the Endcap is in the range of 65–85 \( \mu m \). The sensors are single sided and are placed on both sides of the local support. The Barrel has rectangularly shaped sensors while the Endcap sensors are trapezoidally shaped. There is a 52 mrad stereo angle in the Barrel and a 40 mrad stereo angle in the Endcaps between the strips on opposite side sensors in order to provide a second coordinate measurement. The bias voltage for the sensor is expected to be within a range of 100 V up to 700 V. The depletion voltage in the silicon sensors increases as well as the noise level in the ASICs, after being exposed to prolonged radiation. Therefore, the voltage of the silicon sensors is increased to reduce charge trapping, maintain the signal-to-noise ratio above 10 and increase the lifetime of the experiment.

To cope with the higher interaction rates and expected radiation damage, the Strip Tracker features new front-end readout electronics. The ASICs are binary readout chips built in 130 nm CMOS technology, known as ABC130 [6]. Each ABC130 has 256 binary readout channels. The channels are directly wire-bonded to the sensor strips and are mounted on a low-mass flexible printed circuit board known as the hybrid. Each hybrid serves two rows of strips. The Hybrid Controller Chip (HCC), built in 130 nm CMOS technology, is the interface between the local support and the ABC130 chips. The HCC is also located on the hybrid. The ABC130 chips communicate with the HCC at a maximum rate of 320 Mbps. The HCC sends data received from the ABC130 chips to the End of Structure (EoS) at a maximum rate of 640 Mbps. The EoS is the interface between the modules and the off-detector electronics and uses an optical link known as Versatile Link [7]. Some of the DCS components are also included in the EoS. A single copper/polyimide bus tape serves all the high-speed data links and includes the Trigger, Timing and Control (TTC) signals, part of the Detector Control System (DCS) components as well as power and bias voltage lines. Figure 4 shows an example of the main electrical paths for thirteen Barrel modules with the EoS on the side of the local support. The modules are glued directly on the bus tape.

The current powering scheme, where each module has its own independent Low Voltage (LV) and High Voltage (HV) supply, needs to be replaced due to the increased number of channels and modules. In the proposed scheme, the modules are grouped and share the same LV and HV supply lines. In this way, the inactive material in the tracking volume is kept low. A Direct Current to Direct Current (DC/DC) powering scheme has been selected reducing the amount of copper needed. The DC/DC powering conversion scheme includes a radiation hard DC/DC converter that receives 11 V and supplies the hybrids with 1.5 V [9]. A HV multiplexing scheme is chosen for the HV lines [10].
Figure 4. Overview of main electrical components of thirteen Barrel modules on bus tape and with the EoS at the side of the local support [8].

Each line has a HV switch to disconnect non-operating modules. Finally, an Autonomous Monitor and Control Chip (AMAC) is responsible for monitoring the temperature and voltage, controlling the HV switch and powering of the hybrids.

The local support is a double sided structure that hosts the modules and the electrical services. The local support for the Barrel is the Stave and the equivalent structure for the Endcaps is the Petal. Each Stave has fourteen modules and each Petal has nine modules on each face.

Petals and Staves are lightweight carbon-fiber support structures with embedded cooling tubes routed along the structures. Figure 5 depicts the cross section of a Stave. A layup of three high modulus, unidirectional, pre-impregnated carbon fiber facesheets per side is used to provide stiffness and in-plane heat spreading. Bus tape and facesheets are co-cured. Low-density core material is placed between the facesheets to ensure extra stiffness and flatness. Thermally conductive carbon foam surrounds the titanium tube and improves the heat transfer between the heat sources and the tube while keeping the material budget low. Evaporative CO$_2$ cooling is used for both the Stave and Petal. This cooling method satisfies the cooling requirement of uniform temperature profile along the tube while keeping the material budget low [11].

Figure 5. Cross section of a Stave.
3 Status of prototyping and testing

Studies of small-scale prototype versions of the Stave and Petal (known as Stavelet and Petalet [12, 13]) were conducted in the previous years. These prototypes were usually of shorter length and equipped with fewer modules than the Stave and Petal. These studies contributed significantly to gaining experience with the module behavior. Following this successful effort, studies are focused this year on full-size modules, hybrids and thermo-mechanical structures in view of the submission of the ITk Strips Technical Design Report (TDR).

The prototyping and assembly procedure of the modules includes the gluing of the ASICs to the hybrid, the gluing of the hybrid on the sensors, the wire-bondings and finally the mounting of the modules on the local support. Quality control and quality assurance procedures, during the prototyping and assembly phase, aim to ease the construction and handling of the modules while satisfying operation requirements. An overview of the current status of the prototyping, testing and optimization studies is given.

Full-size modules have been assembled for testing. Studies were conducted in advance to improve the assembly process during the prototyping of the modules. For example, optimization studies were focused on the replacement of silver epoxy glue between ASICs and hybrid. The silver epoxy glue needs 6 to 12 hours curing time, slowing down the production. As an alternative, various ultra-violet (UV) cure glues were selected for testing that are expected to have low or zero activation effects after irradiation and no corrosive effects on other components. A similar performance during construction and operation of the modules such as ease of handling, flexibility and rigidity is also expected. Tests conducted on UV cure glue include irradiation, thermal cycling and shear tests. Figure 6 depicts the temperature profile of the different UV cure glues compared to the silver epoxy glue. Most of the UV cure glues showed similar thermal performance for un-irradiated and irradiated hybrids. One of the glues met all the requirements and will be used in further prototyping.

The loading of the modules on the local support, referred as module-on-core assembly, is progressing towards a fully-established quality control process. The module-on-core assembly

![Figure 6. Comparison of the temperature profiles measured on a hybrid for different glues, for un-irradiated and irradiated hybrid areas [14].](image)
requires the positioning of the modules on the local support with precision of 100 µm, electrical
counters to the bus tape via wire-bonds and good thermal connection to the local support for
effective cooling. For these reasons, module-on-core assembly machines are built that include an
optical table equipped with a microscope for locating the coordinates and pick-up bridges where
the modules are guided to the desired position. The assembly machine for the Barrel modules
is in place and operational. Regarding the Endcap, most of the assembly frames and tools are
in the development phase. Figure 7 shows the pick up station with the bridge system designed, manufactured and assembled in Freiburg this year.

Figure 7. Module pick-up station with bridge system for the Endcap assembled in Freiburg.

Full-size thermo-mechanical structures were made with dummy modules with the purpose
of testing the mechanical and thermal performance of the structure. Figure 8(a) depicts a full-
size thermo-mechanical Petal that has been assembled manually at DESY and consists of dummy
modules. It includes silicon sensors, FR4 printed circuits boards, glass ASICs with heater patterns
and bonding pads, step-down DC/DC converters and bus tape. The Petal will further be tested
mechanically and thermally while optical metrology measurements will provide the positions of
the different components. In the U.K., eleven full-size thermo-mechanical Staves were built using
the assembly machine for the Barrel mentioned earlier. The thermo-mechanical Staves were tested
mechanically and thermally. The tests showed that the structures fulfill the design requirements.
Figure 8(b) shows a full-size thermo-mechanical Stave with the bus tape and 26 modules mounted on.

The fully-functional modules that have been assembled, were tested both at test beams and in
the lab. The EUDET telescope, consisting of FE-I4 pixel detectors, was used as an external track
reference [16]. Test beam studies include measurements on signal-to-noise ratio, charge sharing,
sensor biasing and tracking efficiency. These tests were conducted on the modules before and after
irradiations. The irradiation of the ASICs was conducted at different dose rates and temperatures
to study the increase in the digital current consumption experienced in the irradiated ASICs, that is
dose rate and temperature dependent [17, 18].

For example, a full-size Endcap hybrid with ASICs wired-bonded to mini-sensors (sensors of
smaller size compared to the final design) has been tested. Figure 9 shows the tested Endcap module,
which is a full-size hybrid of the final design with ABC130 and HCC chips connected to two mini-
sensors. The mini-sensors have been neutron irradiated at a total NIEL dose of $2 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
and annealed at 60°C for 80 minutes [19]. Only one of the ABC130 chip was irradiated with X-rays
at 0.85 Mrad/hr and kept cooled at $-5^\circ\text{C}$ in order to combine studies on irradiated and un-irradiated
ASICs.
(a) Building of full-size thermo-mechanical Petal at DESY. (b) A full-size thermo-mechanical Stave built at RAL [15].

Figure 8. The thermo-mechanical program on full-size local supports is currently on going.

Figure 9. Hybrid with ABC130 chips and HCC connected to EC mini-sensors tested. The sensors are neutron irradiated at $2 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ and the ABC130 were X-ray irradiated at 0.85 Mrad/hr and cooled at $-5^\circ\text{C}$.

Also, a large number of full-size Barrel sensors has been produced and was tested with the EUDET telescope. For example, a full-size long strip Barrel assembled module was irradiated at the CERN Proton Synchrotron (PS) receiving a total NIEL dose of $7.8 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$ and a total ionizing dose of 37 Mrad. The module was kept cooled at $-20^\circ\text{C}$ while the ASICs were powered. Electrical tests performed after irradiation measured noise around 920 ENC and 1410 ENC for short and long strips respectively [19]. Regarding the ABC130 chips of the Barrel module, the tests showed a factor of 1.3 increase in the digital current at a total ionizing dose of 1.5 Mrad. This dose is approximately 4% of the total ionizing dose expected over the ten years of operation of the ITk.

Other studies focused on the HCC. The HCC was irradiated with X-rays at RAL showing again an increase in the digital current similar to the ABC130 chips. Regarding the studies on HV
multiplexing scheme, the focus was mainly on the design of a new silicon vertical JFET (V-JFET) switch. The irradiation tests of the first batch of HV switches are scheduled soon [20].

4 Summary

The R&D activities of the institutes involved in the ITk Strip Tracker upgrade phase II focus on prototyping and testing of sensors, ASICs and modules in view of the submission of the ITk Strips TDR. Full-size Endcap sensors will be produced soon. Reliable set-ups exist in many institutes and valuable experience is gained with prototype testing and tool manufacturing. Evaluation of the assembly processes and the adaption of the core design continues while quality assurance and quality control tests are being designed. The R&D effort for the ITk Strip Tracker upgrade phase II leads to optimized designs, detailed construction and assembly procedures with confidence that the requirements will be met.

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