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The ATLAS ITk Strip Detector System for the Phase-II LHC Upgrade

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Zhengcheng Tao[a,*], **on behalf of the ATLAS ITk Collaboration**

[a] *Department of Physics and Astronomy, University of British Columbia,*
6224 Agricultural Road, Vancouver BC, Canada

E-mail: `zhengcheng.tao@cern.ch`

The HL-LHC is expected to provide an integrated luminosity of 4000 fb^{-1}, that will allow to perform precise measurements in the Higgs sector and improve searches of new physics at the TeV scale. ATLAS is currently preparing for the HL-LHC upgrade, and an all-silicon Inner Tracker (ITk) will replace the current Inner Detector, with a pixel detector surrounded by a strip detector. The strip system consists of 4 barrel layers and 6 end-cap (EC) disks. After completion of final design reviews in key areas, such as Sensors, Modules, Front-End electronics and ASICs, a large scale prototyping program has been completed in all areas successfully. We present an overview of the Strip System, and highlight the final design choices of sensors, module designs and ASICs. We will summarise results achieved during prototyping and the current status of production on various detector components, with an emphasis on QA and QC procedures.

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[*] Speaker

1. Introduction

The Large Hadron Collider (LHC) will be updated to the High-Luminosity LHC (HL-LHC) [1] after the current run is completed. The HL-LHC, scheduled to be operational starting from 2029, will deliver an integrated luminosity of 4000 fb^{-1} instantaneous luminosity up to 7.5×10^{34} $\text{cm}^{-2}\text{s}^{-1}$ at a centre of mass energy of 14 TeV. The average number of overlapping proton-proton collisions, also known as "pileup", is expected to be up to 200. While the HL-LHC brings great physics potential for both precision measurements and searches of physics beyond the Standard Model, its harsh radiation condition makes it very challenging for particle detectors at the HL-LHC. In preparation for the high luminosity era, the ATLAS experiment will be upgraded during the long shutdown period after the current run, referred to as the Phase-II Upgrade. As a part of the Phase-II upgrade, the current ATLAS Inner Detector (ID) is going to be replaced by a new all-silicon Inner Tracker (ITk), consisting of a pixel system [2] and a strip system [3]. The ITk detector is approximately six meter long and two meters in diameter, covering a pseudo-rapidity region up to ±4. The ATLAS ITk is designed to be more radiation tolerant with less passive material and to deliver a similar or better tracking performance compared to the current ID in a more challenging environment at the HL-LHC.

2. The ITk Strip Detector

The ITk strip detector, surrounding the innermost pixel detector, is made of micro-strip silicon sensors covering a total active surface of about 165 m^2. It consists of 17,888 modules with about 60 million readout channels. The ITk strip detector is further segmented into the barrel region in the centre and two end-caps in the forward and backward regions. The barrel part of the ITk strip detector is made of four cylindrical layers of the so-called "staves". There are 14 modules on each side of a stave. The silicon strips are all parallel to the beam axis and have a pitch of 75.5 μm. The shorter strips with a length of 24.1 mm are used in the staves of inner two layers, while the longer ones of 48.2 mm are used in the outer two layers. For the purpose of improving the hit resolution along the beam axis, the modules on each side of the a stave are rotated by a small angle of 26 mrad with respect to the beam axis to form staggered hits. Each ITk strip end-cap is made of 6 identical disks, and each disk has 32 so-called "petals". An end-cap petal consists of six different types of ring modules on each side. The silicon strips in end-caps are along the radial direction with a strip pitch ranging from 69.9 to 80.7 μm. The strip lengths vary between 15.1 and 60.2 mm with shorter strips at smaller radii. The strips in end-cap modules are rotated by 20 mrad around the centre of the module for stereo hits in order to achieve a better measurement in the radial coordinates.

3. Production of the ITk strip detector

After an extensive prototyping phase, all components of the ITk strip detector have completed final design reviews and started pre-production. Rigorous quality control (QC) and quality assurance (QA) procedures have been established and refined for each component and production stage. The production as well as the QC and QA procedures take place in about 60 institutes in 14 countries all over the world. While some components are already very advanced into production or even almost at the end of the production, a few complex technical issues are identified for some components during the pre-production and are under active investigations.

3.1 Sensors

Sensors of the ITk strip detector are silicon strips with n-type implants in a p-type float-zone silicon bulk (n^+-in-p FZ). The silicon strips are AC coupled to the readout circuitry. The choice of the n^+-in-p type silicon over the p-in-n type used in the current ATLAS tracking detector is largely driven by the radiation tolerance requirement at the HL-LHC. The n^+-in-p type silicon sensors provide good signal after irradiation even under-depleted. They also respond faster because electrons instead of holes are collected by the electrodes.

The sensors are manufactured by Hamamatsu Photonics in 6-inch 320 μm thick wafers. The sensor design has been finalized after many years of prototyping and R&D. Two different sensor geometries are defined for the barrel layers and six geometries for the end-caps. The performance of the final sensor design has been reviewed and judged excellent using sensors from the pre-production corresponding to 5% of the total production volume [4]. The silicon sensors have been in full-production since July 2021. As of August 2024, over 75% of the total quantity have been received from the manufacturer.

3.2 ASIC

The readout and control chips used in the ITk strip detector are based on the 320 nm CMOS technology. The chipset that handles all types of modules consists of three types of ASICs. The ATLAS Binary Chip, or ABCStar, is in charge of reading the analogue signal from strips and providing a hit-or-no-hit binary decision per strip. It encodes the hit pattern into clusters before sending them out. The Hybrid Control Chip, or HCCStar, aggregates the data packets from multiple ABCStars and sends them off detector. The HCCStar is also responsible for forwarding the clock and control signals to the ABCStars. The "Star" in ABCStar and HCCStar refers to the point-to-point connection between the HCC and ABC chips. The ABCStar and HCCStar ASICs are hosted on low-mass flexible PCBs made of Kapton, referred to as the "hybrids". The Autonomous Monitoring And Control chip, or AMAC, is in charge of distributing high and low voltage power and providing monitoring of modules. The AMAC chip is hosted on a similar low-mass flexible PCB referred to as the "power board".

In order to mitigate the single event effects, clocks, resets, and logic blocks are triplicated in the readout ASICs with a voting logic. All chips are probed on wafers to verify both the analogue and digital functionalities. To mitigate the total ionizing dose effect, also known as the "TID bump" [5], all ASICs are also pre-irradiated before being distributed to the downstream production sites. The production of ITk strip ASICs is advancing well. All ABCStar, HCCStar, and AMAC chips have been manufactured. Almost all of them are probed. About half of the ASICs have been pre-irradiated and are ready to be distributed.

3.3 Module

The modules are the basic building blocks of the ITk strip detector. There are two different types of barrel modules and six different types of end-cap ring modules. A module is made of silicon sensors, one or two hybrids with readout ASICs, and a power board. Hybrids are directly glued to the silicon sensors. Each hybrid hosts one HCCStar and between six and eleven ABCStars, depending on the module type. ABCStars are wire-bonded to the sensors. The power board is also directly glued onto the silicon sensors. In addition to an AMAC chip, a power board contains a high-voltage switch for sensor biasing and a low-voltage DC-DC converter converting 11 V to 1.5 V for the ASICs.

All module assembly steps, such as component placement and glue dispensation, are required to be of high precision. This is achieved by using customized toolings designed specifically for different module types. Extensive QC and QA steps are defined in every production stage, including IV curve measurement, visual inspection, and metrology. As the final QC step, every module is thermal cycled 10 times between 20 °C and -35°C, while electrical tests are carried out to evaluate the gain and noise performance. Currently, the module is in the pre-production phase with almost all module sites ready for production. During the pre-production, however, two technical issues were identified that require further investigations before full production can be started. Section 3.6 and 3.7 discuss in more details about these two issues.

3.4 Local support and module loading

The modules are installed to local support structures referred to as the stave and petal "cores". The cores are made of carbon fibres with imbedded titanium cooling pipes. Kapton bus tapes are glued on each side of the carbon fibre structure for routing electrical connection. The bus tapes and petal cores have already been in production, while the stave cores are getting ready to start the production soon.

Custom loading stations are used to glue modules to both sides of a core. Hybrids are wire-bonded to bus tapes. The position as well as flatness of the modules are examined after modules are loaded. The assembled staves and petals are also thermal cycled. Electrical tests are performed, and the characteristics are compared to the ones obtained from the single module tests.

3.5 System test and integration

The goal of the system test is to demonstrate full system performance with the complete service chain including power, cooling, monitoring, and data readout chains. The system test setup for barrel staves is hosted at CERN, and the setup for the end-cap petals is hosted at DESY. The system test setups are also used as testbeds for DAQ and DCS development and validation.

Staves and petals that pass QC are transported to the integration sites to be installed onto the global structures, mostly made of carbon fibre-reinforced plastic (CFRP). Two of the four inner barrel cylinders, as well as the outer cylinder, have been delivered to CERN as of July 2024. Both end-cap structures have been built. The petal integration happens at NIKHEF and DESY, after which the fully-loaded end-caps will be delivered to CERN for the final installation.

3.6 Cold noise

During the module pre-production, a cluster of noisy strips were found on some modules when they were tested at the target operating temperature of -35°C. These strips usually locate around the regions under the power board. No excessive noise was found on these channels at the room temperature. After extensive investigations, this issue, referred to as the "cold noise", is understood to be caused by mechanical vibrations from the capacitors in the DC-DC converter on the power board [6]. Figure 1 shows the origin of the vibration and how it propagates through sensors based on a vibrometer scan. While the exact mechanism of how mechanical vibrations inducing electrical signals is under active investigation, it was observed that using a different type of glue for module assembly can effectively reduce the cold noise, especially for the end-cap and long-strip barrel modules. Low level of cold noise is still observable on the short-strip modules. Studies have been ongoing to evaluate the impact of the residual noise on short-strip modules to the overall tracking performance.

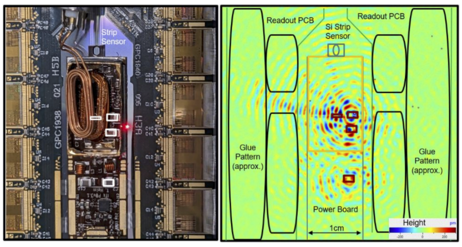
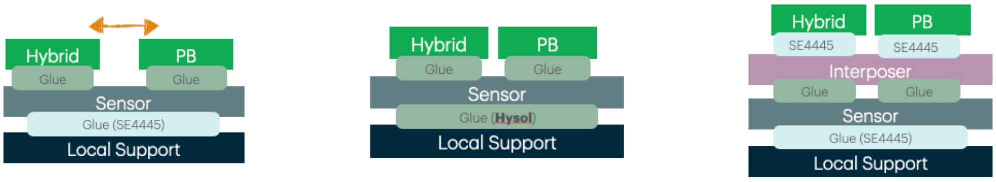


Figure 1: Left: photo of a barrel strip module. Right: a vibrometer scan showing the mechanical vibration propagating through the silicon sensors with other module components overlaid. Taken from [6].

3.7 Sensor cracking

Another issue that is holding back the module full production is the so-called "sensor cracking" [7]. During the pre-production, about 8% sensors were noticed to crack during the stave and petal cold tests with a bias voltage lower than the 500 V specification. Sensor cracking is observed only after modules are mounted to staves or petals at a temperature around -35°C for the barrel modules and below -35°C for the end-cap ones. It is also noticed that the cracks are usually located around the power board. Further investigation indicates that the sensor cracking is due to coefficient of thermal expansion (CTE) mismatch between the electronics and sensors. At low temperature, the hybrid and power board flexes curl up more than the silicon sensors below. Sensors can no longer follow the hybrids after glued to cores, causing localized stress built up especially in the gaps between the hybrid and the power board.

Three proposals to mitigate the sensor cracking issue are currently under evaluation. The "wide gap" approach, as illustrated in figure 2a, proposes to increase the gap between the hybrid and power board to spread out the stress. It is estimated in simulation doing so can reduce the peak stress by 10% to 20%. This is a minor modification of the module production precess, but is not applicable to all module types due to space constraints. The "Hysol" approach proposes to replace the soft glue (SE4445) underneath the sensors to a stiffer "Hysol" glue, as indicated in figure 2b. Almost half of the peak stress could be reduced based on simulation. This is also a relatively easier modification to the module production. The third "interposer" approach, as shown in figure 2c, adds an additional Kapton layer between the hybrids and sensors. Although this is a major design change that requires additional review and QC procedures, it can reduce the peak stress by about 95% base on simulation. It is also worth noting that among all short-strip modules built with the interposer for testing, no cold noise has been observed.



(a) **(b)** **(c)**

Figure 2: Three proposals to mitigate the sensor cracking are illustrated. (a): The "wide gap" approach. (b): The "Hysol" approach. (c): The "interposer" approach.

4. Conclusion

ATLAS is building an all-silicon Inner Tracker for the High-Luminosity LHC. The ITk strip team has been through years of prototyping and pre-production. Rigorous QC and QA procedures have been put in place. While many components have already been in production and advancing well, some technical issues have been identified during the pre-production. Mitigation strategies are being evaluated, and the preliminary results are promising. The full production will commence once these issues are resolved.

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