PROCEEDINGS OF SCIENCE

Design and construction of the ATLAS ITk Strip Detector

Igor Mandić on behalf of the ATLAS ITk Strip Community [a,*]

[a] *Jožef Stefan Institute,*
Jamova 39, Ljubljana, Slovenia

E-mail: igor.mandic@ijs.si

For the ATLAS Phase-II Upgrade the inner tracker of the ATLAS detector will be replaced by the new full silicon tracker ITk designed for operation in the HL-LHC environment. ITk consists of several layers of silicon particle detectors. The innermost layers will be composed of silicon pixel sensors, and the outer layers will consist of silicon microstrip sensors. This contribution focuses on the strip region of the ITk. The central part of the strip tracker (barrel) will be composed of rectangular short ($\simeq$ 2.5 cm) and long ($\simeq$ 5 cm) strip sensors. The forward regions of the strip tracker (end-caps) consist of six disks per side, with trapezoidal shaped sensors of various lengths and strip pitches. After the completion of final design reviews in key areas, such as Sensors, Modules, Front-End electronics, and ASICs, a large scale prototyping program has been successfully completed in all areas. In this contribution, 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 pre-production and production of various detector components, with an emphasis on QA and QC procedures.

The 32nd International Workshop on Vertex Detectors (VERTEX2023)
16-20 October 2023
Sestri Levante, Genova, Italy

[*]Speaker

https://pos.sissa.it/

PoS(VERTEX2023)020

1. Introduction

After the upgrade of the Large Hadron Collider (LHC) to the High-Luminosity LHC (HL-LHC) the instantaneous luminosities will reach values of up to 7.5×10^{34} cm^{-2}s^{-1} at a centre of mass energy of 14 TeV. ATLAS collaboration aims to record up to 4000 fb^{-1} of proton-proton collisions by the end of the HL-LHC era.

At such high luminosity, there will be 140 to 200 inelastic proton-proton collisions per bunch crossing. This will result in high track density and therefore high radiation background. The pixel detectors closest to the beam pipe will have to withstand radiation levels of 1 MeV equivalent neutron fluences (including safety factors) of up to 2×10^{16} n$_{eq}$cm^{-2} and Total Ionising Dose (TID) of 10 MGy. At the radii of the strip detector maximum design fluence (including safety factors) is 1.6×10^{15} n$_{eq}$cm^{-2} and TID = 660 kGy. Current ATLAS Inner Detector (ID) [1] would not be able to cope with the expected data rates and radiation levels so a new Inner Tracker (ITk) [2], designed to operate at the HL-LHC will replace the current ATLAS ID.

ITk will be an all-silicon detector system comprising of a pixel detector and a strip tracker. The pixel detector will consist of five central layers and an array of 30 rings with varying radii in the forward regions. The strip system, surrounding the pixel detector, is made of a barrel with four layers and two end-caps containing 6 discs each. There will be 60 million channels (strips) in the strip detector, the area covered with silicon sensors will be ≃165 m^2. The whole ITk will be approximately 6 m long and around 2 m in diameter and will cover the pseudo-rapidity region up to $|\eta| = 4$. Figure 1 shows the schematic layout of the ITk.

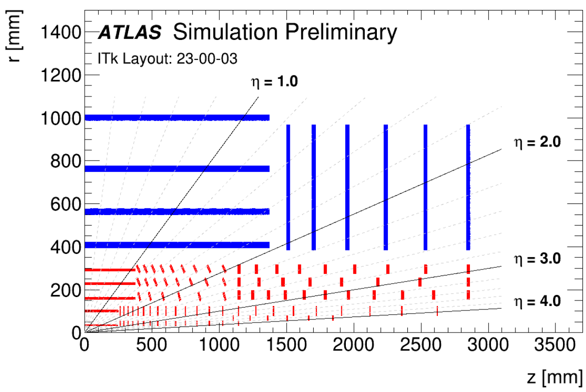


Figure 1: Schematic layout of the ITk [3]. Strip detector is shown in blue and the Pixel Detector in red. The horizontal axis runs along the beam line with zero being the interaction point. The vertical axis is the radius measured from the beam line.

2. The ITk Strip Detector

Drawing of the ITk detector can be seen in Figure 2. The strip detector is surrounding the pixel detector and it consists of a barrel and two end-caps. The barrel consists of four concentric layers, each of the two end-caps has 6 discs. In the two inner barrel layers silicon sensors with short strip segments (SS) are used while long strip (LS) sensors are used in the outer two layers. Sensors are rectangular and the strips are oriented in the proton beam direction. In the end-caps, sensors are mounted on discs with strips running perpendicular to the beam line. Six different trapezoidal sensor geometries with varying strip lengths and gradually widening strip pitch are used to cover the discs.

The basic unit of the system is a module which consists of silicon sensor, readout ASICs and power control. In the ITk strip system there will be about 18000 modules.

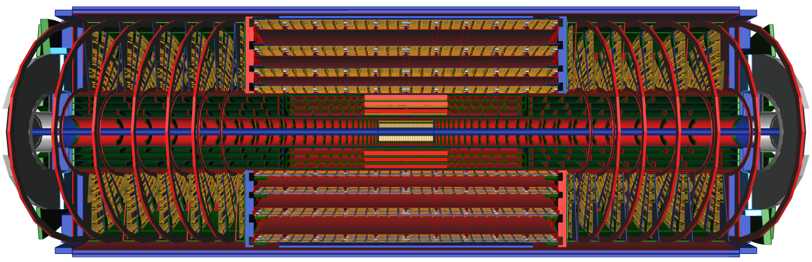


Figure 2: Drawing of the ITk detector system. Inner layers are pixel detectors. The outer four layers in the barrel region and 6 end-cap discs on each side are the strip detector system [3].

2.1 Sensors

Sensors for the ITk strip detector [4] are being produced by Hamamatsu Photonics on 6-inch p-type float zone wafers. The physical sensor thickness is 320 μm, the active thickness is 300 μm and the full depletion voltage is around 300 V. The dimension of both barrel sensor types (SS and LS) are 97.95×97.62 mm^2 with a strip pitch of 75.5 μm; strips are parallel to the sensor edge. Strips on SS sensor are divided into four segments, each 24.2 mm long, while LS sensors have two segments with strip length of 48.4 mm. In the end-caps six different trapezoidal sensor layouts are used with strip pitches ranging between 70 μm to 80 μm and strip lengths from 15.1 mm to 60.2 mm. The petals, the structural units of the end-caps (see Fig 3b and 5b), are divided into rings and first three rings, counting from the beam line, can be covered with a single sensor. At larger radii the petal is too wide for a single sensor from a 6-inch wafer so two separate sensors are needed for the last three rings.

Strips are AC coupled with the covering metal, therefore each n$^+$ strip implant in the sensor is connected to the bias ring over a 1 MΩ bias resistor. Bias ring is connected to the ground potential with wire bonds and the back plane of the sensor is connected to the high voltage pad on the bus tape by a TAB bond.

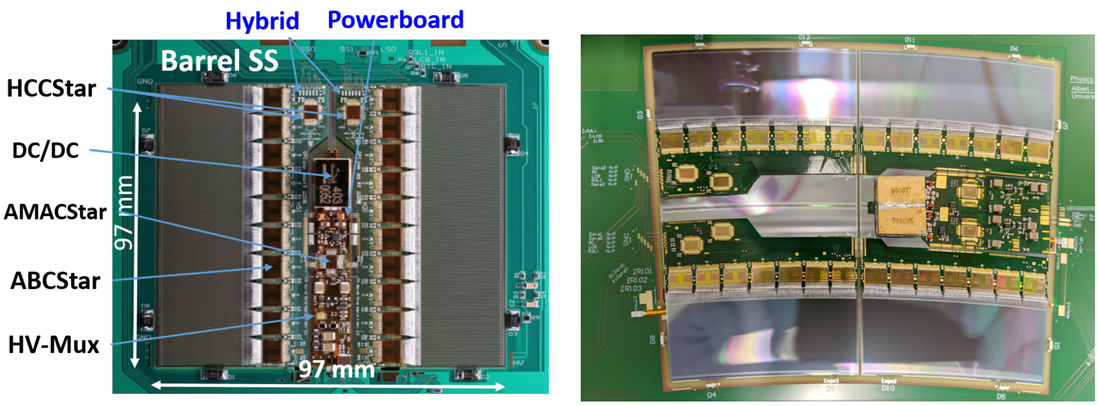
2.2 Modules

A module consists of one (or two) silicon sensors, up to four hybrids and one power-board. Figure 3a) shows a barrel short-strip module consisting of two hybrids, each with 10 read-out chips (ABCStar [5]), powerboard and a short-strip sensor. Figure 3b) shows the end-cap R3 module made of two sensors and 4 hybrids.

Hybrids are flexible electronic circuits, made of polyimide, hosting ABCStar and Hybrid Controller Chips (HCCStar [6]). Readout is designed in a star topology in which the data from each front-end chip is directly routed to the HCCStar. HCCStar chip merges the data and transmits it at 640 Mbit/s to the End of Substructure (EoS) card. Hybrids are glued on top of the sensor and strips are wirebonded to the ABCStar input channels.

Hybrids are powered from the powerboard - a flexible circuit also glued on top of the sensor. To minimize power losses in cables, power is supplied to the powerboard via bus tapes at 11 V. On the powerboard a DC-DC buck converter bPOL12V [7] converts 11 V to 1.5 V required by the front-end chips. The Autonomous Monitor and Control chip (AMACStar [8]) on the powerboard is powered by a separate voltage converter LinPOL12V. This chip measures temperatures, voltages and currents and controls power states of the module. High voltage lines on bus tapes are shared by several modules on each bus tape. AMACStar measures the high voltage current and controls the high voltage switch - HVmux. The maximal bias voltage for the ITk strip sensors is 500 V.

ABCStar, HCCStar and AMACStar chips are ASICs produced in 130-nm CMOS technology by GlobalFoundries (GF). All these ASICs suffer from the so called Total Ionising Dose (TID) bump, an increase of the power consumption with irradiation [9, 10]: digital current in these chips increases with TID and reaches the maximum of several times the pre-irradiation value at about 1 Mrad. With further increase of dose the current falls back to near the pre-irradiation level and stays there up to the highest doses. To avoid this large increase of current, all ASICs for ITk strips produced in 130 nm GF technology will be pre-irradiated to 5 Mrad with gamma rays from ^{60}Co source at RBI, Zagreb [11] before being assembled on ITk strip modules.



a) b)

Figure 3: Photos of modules mounted on test boards. a) Short Strip (SS) barrel module. Two hybrids and a power-board are glued on top of the strip sensor. The sensor is divided into four strip segments, each strip segment is bonded to a readout channel on the ABCStar chip. b) R3 end-cap module built with two trapezoidal sensors divided into 4 strip segments each. There is one power-board and four hybrids on this module (two on each sensor). Hybrids on the left and the right sensor are interconnected with wire bonds.

2.3 Local support

Modules are glued to carbon fibre structures called cores. The mechanical stiffness of the core is ensured by the thermally conductive carbon fibre honeycomb with titanium cooling pipes embedded in thermally conductive foam - see Figure 4. The cores can be cooled down to -35° with evaporative CO_2 cooling system. On each side of the core there is a polyimide bus tape containing power and data transmission lines for modules. An End-of-Substructure card (EoS) on each local support side is used for the electrical and data connection of the core with off detector electronics and power supplies. EoS hosts the Low Power GigaBit Transceiver (lpGBT) chip [12] which communicates with HCCstar chips on modules via transmission lines on bus tapes and with the off-detector electronics via the VTRx+ fibre optic driver/receiver [13].

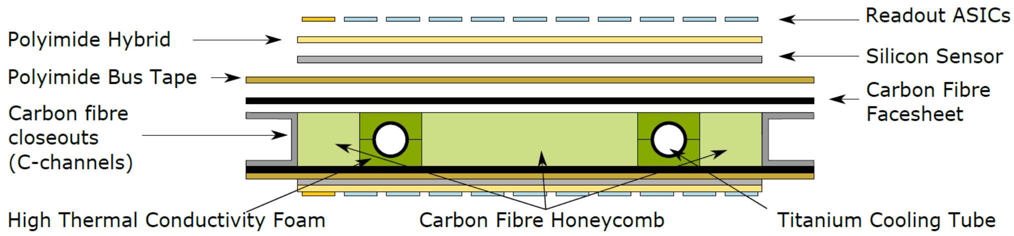
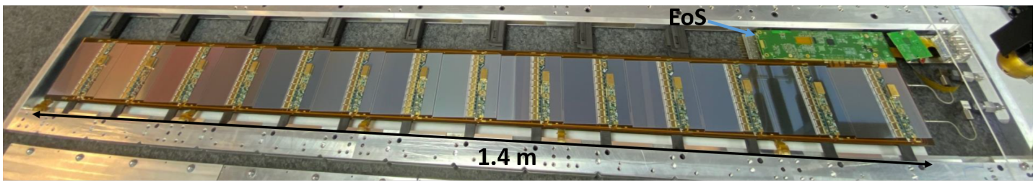
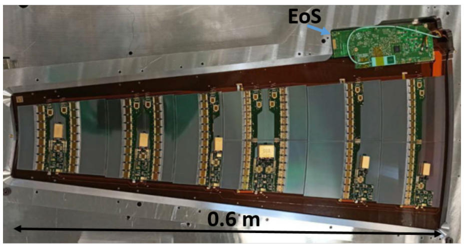


Figure 4: Structure of the core. [2].



a)



b)

Figure 5: Photos of a) a stave loaded with 14 barrel Long Strip modules and b) petal loaded with 6 end-cap module flavours. End of Substructure (EoS) boards are marked on the photos.

The basic support structure (core) unit of the barrel is a stave shown in Figure 5a and of the end-cap a petal (see fig 5b). Modules are glued on both sides of the cores. On the staves, modules are positioned at an angle so that the direction of strips is rotated by 26 mrad with respect to the stave axis (beam line), resulting in a total stereo angle between strips on both sides of the stave of 52 mrad which enables two dimensional space point reconstruction. In the end-caps, the stereo angle is built into the sensor design by displacing the focal point of the strips from the focal point of the petal on the beam line (see [4]). Each stave holds 14 modules on each side and there are 392 staves in the barrel. Modules, assembled at module building sites, will be mounted on staves at Brookhaven National Laboratory and at Rutherford Appleton Laboratory, half at each site. Petals host six modules on each side, half of which are the split modules made with two sensors. There are 32 petals in each disc and there are 6 discs per end-cap. Modules will be mounted on petal cores at TRIUMF, DESY, Freiburg, and IFIC.

Staves and petals will be fixed on carbon fibre enforced plastic structures called global structures. Staves will be mounted at CERN on 4 concentric cylindrical layers. The length of the cylinder spans the length of two staves i.e. 2.8 m. Staves will be fixed on cylinders at 10° angle to allow for the overlap of sensors on neighbouring staves. Petals will be mounted on 6 discs in each end-cap. One end-cap will be built at Nikhef and the other at DESY. Finalized end-caps will be transported to CERN and integrated with the barrel into the ITk strip detector.

3. Summary

Installation of complete ITk (pixels and strips) into ATLAS detector is planned for the year 2028. To reach this goal production of most of component of the strip system has started or is about to start.

Production of sensors started at HPK in 2021 and will finish in 2025. In this period about 22000 sensors will be produced. Thorough quality control [14] and quality assurance procedures including tests after irradiation [15] are being performed by the ITk strip sensor community to select good quality sensors for the harsh HL-LHC environment. Production is progressing according to the plan, more than 50 % of sensors have already been produced at low rejection rate of 2 to 3 %.

The production of all three flavours of ASICs (ABCStar, HCCStar, AMACstar) in 130 nm technology at GF is progressing well. Over 90% of chips have been manufactured. Probing and dicing is going on with good yield as well as pre-irradiation to 5 Mrad with ^{60}Co.

Production of modules is starting. During testing of pre-production barrel modules, increased noise in certain channels was observed, especially when operated at low temperature (the so called cold noise [10],[16]). It was found that the source of noise is in the DC-DC converters on powerboards. Recently a way to mitigate this problem has been found and production of modules can start.

Production of end-cap bus tapes is going on, pre-production cores were finished with good results. Production of barrel bus tapes is expected to start soon. Global support structures are being produced and will soon be ready to accept staves and petals.

The ITk strip project is on track to deliver the full ITk silicon based tracking system in time for the start of HL-LHC operation near the end of this decade.

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