PROCEEDINGS OF SCIENCE

ATLAS ITk Strip Detector for the Phase-II LHC Upgrade

Andrea García Alonso^{a,*} **on behalf of the ATLAS ITk collaboration**

[a] *Nikhef, Amsterdam, The Netherlands*

E-mail: agarciaa@cern.ch

The inner detector of the present ATLAS experiment has been designed and developed to function in the environment of the current Large Hadron Collider (LHC). At the ATLAS Phase-II upgrade, the particle densities and radiation levels will exceed current levels by a factor of ten. The instantaneous luminosity is expected to reach unprecedented values, resulting in up to 200 proton-proton interactions in a typical bunch crossing. The new detectors must be faster, more highly segmented, and they require much greater power delivery to the front-end systems ($\sim$10 mW/cm^2). The sensors closest to the beam pipe will face radiation levels over 10^{16} n_{eq}/cm^2 fluence and around 10 MGy total ionising dose, reason why they also need to be far more resistant to radiation. At the same time, they cannot introduce excess material which could undermine tracking performance. To meet these requirements a new all-silicon design, the ATLAS Inner Tracker (ITk), is being constructed, and it will replace the Inner Detector (ID) in 2027.

The ITk detector is contained in a cylinder of 6 m long with a diameter of 2 m. 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 ITk. The central part of the strip tracker (Barrel) is composed of rectangular short ($\sim$2.5 cm) and long ($\sim$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 completed. This paper provides an overview of the Strip System, highlighting final design choices for sensors, module designs, and ASICs. It summarises results achieved during prototyping and the current status of pre-production and production on various detector components, with an emphasis on QA and QC procedures. An update is also provided on the progress since the conference till the writing of this paper.

Corfu 2023 Workshop on Future Accelerators
23-29 April 2023
Faliraki, Corfu, Greece

PoS(CORFU2023)027

---

[*] Speaker

Contents

---

1. LHC and the ATLAS detector

The largest particle accelerator in the world, the LHC, accelerates protons to 13 TeV and brings them to collision at four points. One of those points is surrounded by the ATLAS detector, registering the outcome of those collisions. This massive multi-purpose detector whose name is the acronym of A Toroidal ApparatuS, is 25 m tall, 46 m long, weighs as much as the metallic structure of the Eiffel tower (7000 tons) and it is composed of different sub-detectors.

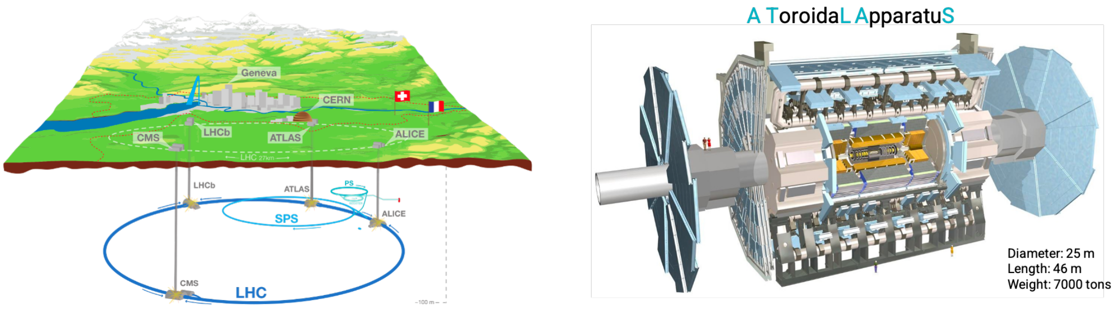

Figure 1: Underground LHC acceleration system at the border between Switzerland and France. The four big detecting experiments of the LHC are found along this tunnel: ATLAS, ALICE, CMS and LHCb. The ATLAS detector is zoomed-in on the right.

2. Tracker, high luminosity upgrade and needs

The innermost layer of ATLAS is the tracker. The current one is called Inner Detector (ID). The inner tracking system (6 m × 2 m), records the trajectories of charged particles in a magnetic field of 2 T provided by a solenoid. Figure 2 shows a representation of a 7 TeV proton-proton collision in the ID.

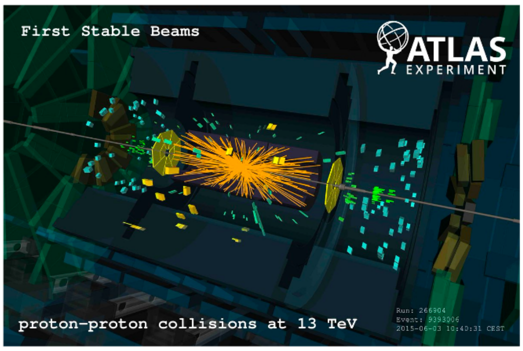

Figure 2: Proton-proton collision in ATLAS. The Inner Detector (ID) surrounds the interaction point measuring tracks (in orange) of charged particles.

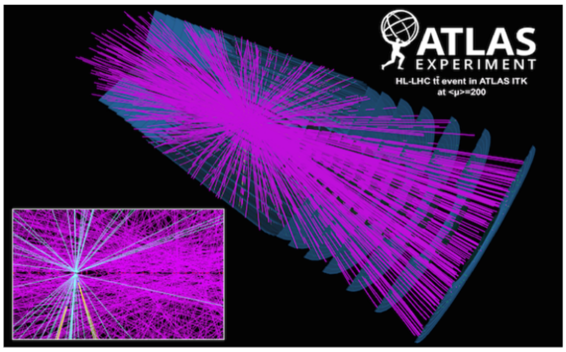

Figure 3: Proton-proton collision in the next ATLAS Inner Tracker (ITk), during HL-LHC. The number of measured trajectories (in purple) is ∼20 times higher.

With the LHC upgrade to high luminosity (HL), instantaneous luminosity will reach unprecedented values: $7{\times}10^{34}$ s^{-1} cm^{-2}, up to 200 p-p interactions per bunch crossing. The ATLAS detector will operate after exposure to large particle fluences, as shown in Fig. 4. Particle densities and radiation levels will exceed current levels by a factor of ten during this higher luminosity scenario, the track density (Fig. 3) will be so high that the ID will not be able to distinguish it. Upgrading is required to guarantee a working detector. A new tracker is in construction: the ATLAS Inner Tracker, ITk.

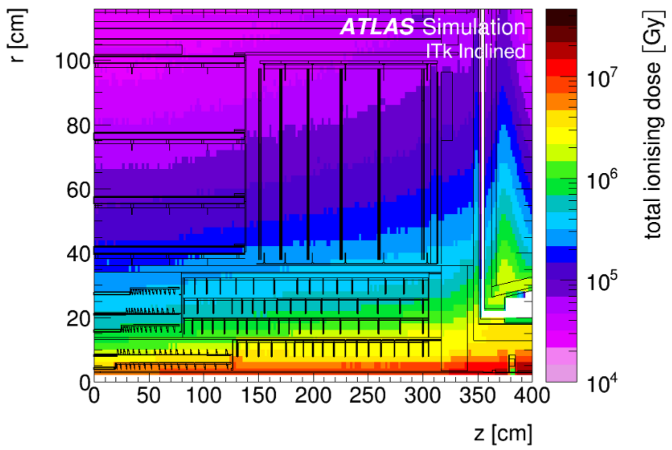

Figure 4: Expected total ionising dose in the r-z plane of the ITk detector. This simulation shows the high levels of radiation expected in the tracker, particularly in its innermost layers. Taken from Technical Design Report for the ATLAS Inner Tracker Strip Detector ATLAS-TDR-025.

The current ATLAS tracker, the ID, was designed and developed to operate within the existing LHC environment. However, for HL the requirements for the new ITk detector are:

- Higher radiation tolerance to deal with higher ionisation from 300 kGy (ID) to 10 MGy.
- Higher granularity to keep the occupancy below 1%.
- Faster response due to increased pile-up from 20 to 200 p-p collisions per bunch crossing.
- Novel powering solutions that provide a greater power delivery to the front-end systems, in order to power 10 times more strip channels and 60 times more for pixels.
- Limited amount of inactive material that can undermine the tracking performance.
- Smaller pixel sizes than the current $50 \times 400\,\mu\text{m}^2$ and $50 \times 250\,\mu\text{m}^2$ to improve high transversal momentum performance.
- Reduced sensor cost to cover a detecting surface larger than the current $63\,\text{m}^2$.
- Increased trigger rate than the current 100 kHz due to the larger expected event size [1].

3. The ATLAS ITk

The ITk detector, displayed in Fig. 5, will be a full-silicon detector with pixel (inner radii) and strip (outer radii) sensors. The Pixel detector extends from 33 mm from the beam to a radius of ~40 cm, while the Strips extend up to a maximum radius of 1 m. The layout of ITk in the r-z plane is depicted on the right side of Fig. 5.

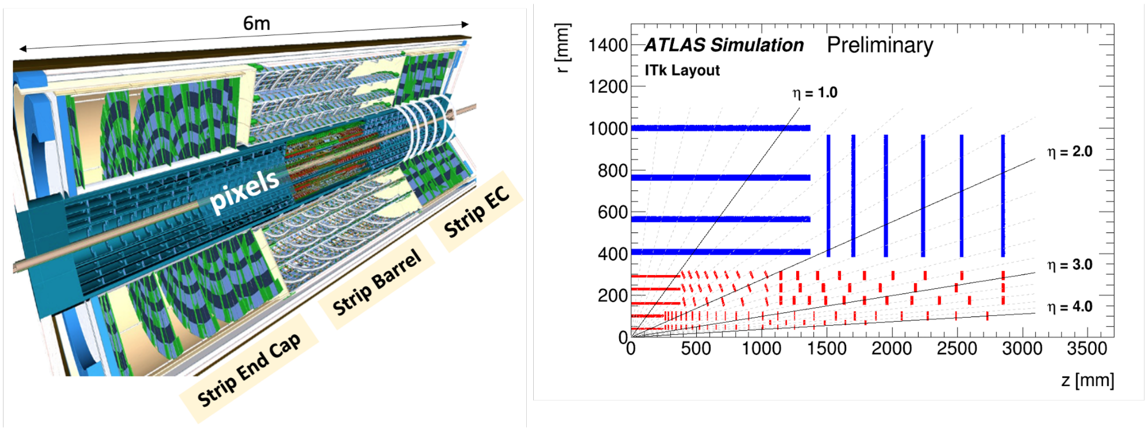

Figure 5: Left: A 3D view of the ITk detector. Right: a 2D projection of the ITk layout, with pixels in red and strips in blue. The Strip Barrel is composed of the four horizontal layers with the lowest z, and the Strip End-Caps are the six outermost vertical layers.

The ATLAS ITk will cover the pseudorapidity (η) range of $|\eta| < 4$, which is significantly larger than the current ID that covers $|\eta| < 2.5$. The ITk detector will have an increased surface of $178\,\text{m}^2$, and the number of modules will be raised to 28000 from the 6000 installed in ID.

The ITk detector will have more than 5×10^9 channels, while the ID has 100×10^6 channels. Furthermore, the trigger rate will be 1 MHz [2] [3].

3.1 The Strip detector

The ITk-Strip detector surrounds the pixels, covering the range of $|\eta| < 2.7$. About 18000 modules and 60 million strip channels distributed [4], as shown by Fig. 5, in a central region known as the Barrel, and two lateral cylinders called End-Caps (EC).

3.2 The Strip Barrel

The Barrel covers the central region and features a four-layer cylindrical geometry. It is assembled at CERN, and the global mechanical structures are previously produced in UK Institutes and LBL (US). The sensor modules are combined on staves, that will be inserted in the global structure.

3.2.1 Staves

The ITk-Strip Barrel is composed of staves, which are rectangular structures with silicon sensors along with high and low-voltage power controls and application-specific integrated circuits (ASICs). Each stave hosts 14 identical rectangular modules on each side, as shown in Fig. 6 (left).

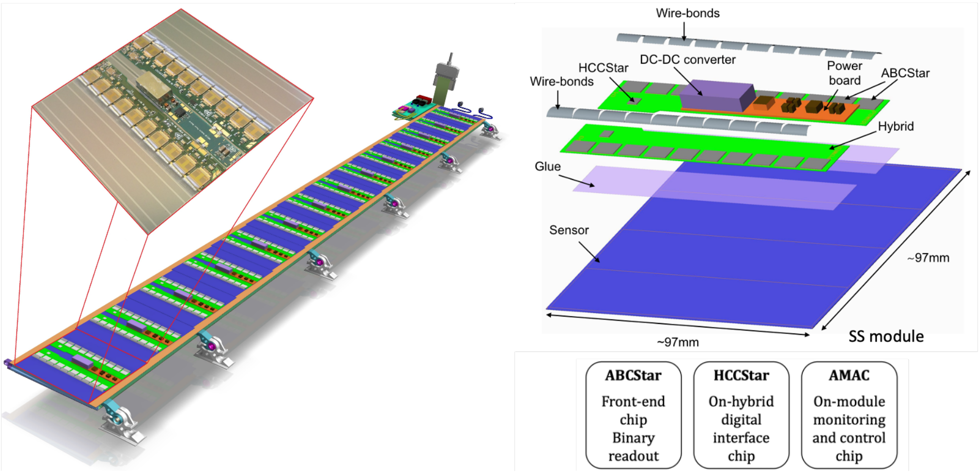

Figure 6: Stave with 14 Short Strip modules. Two hybrids and one powerboard are glued on the sensor.

The module has a size of around 97 mm × 97 mm, as shown on the right side of Fig. 6, and it has four rows (or two rows for long-strip sensor) of 1280 strips.

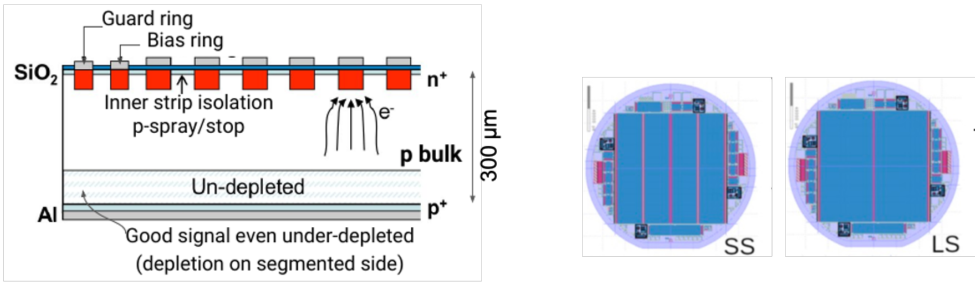

Figure 7: Transversal cut of a stave sensor (left). Short and long strip wafers (right).

Barrel sensors have a square geometry, with single-sided microstrips, where n^+-strips are implanted on a p-type silicon bulk (n^+-in-p), as shown in Fig. 7. They are manufactured in 6-inch silicon wafer technology, with a sensor pitch of 75.5 µm. Short strips (SS) are 24.1 mm long and they will be installed in the two inner layers of the Barrel, while long strips (LS) are 48.3 mm long and will be in the two outer layers of the Barrel [5].

The hybrids are readout PCBs which contain the front-end chips to read the signals from the strips and they are glued to the sensors. The ASICs are: the ATLAS Binary Readout Chips (ABC) wire-bonded to the sensor and the Hybrid Controller Chips (HCC) glued to the hybrids. The HCC forwards clock and control signals to ten ABCs and reads out data. The STAR architecture is used for coping with 1 MHz trigger rates and delivering 640 Mbit/s downlinks from each HCC.

The powerboard or power PCB, which is glued on the sensor next to/in between the hybrids, is responsible for providing and monitoring the HV (up to 500 V with a few mA current) for the sensor bias, and the LV (1.5 V with up to 4 A current) for the front-end chips on the hybrids. Its ASIC is the Autonomous Monitor And Control or AMAC chip. There is a DC-DC converter for LV powering since the ITk Strip baseline powering scheme uses parallel powering with DC-DC converters.

At the end of the stave, the End-of-Substructure (EoS) card links the modules with off-detector systems and transforms the digital signal into an optical one. Each stave side contains one 11 V LV line and four HV lines, which are shared by the 14 modules. The 11 V is converted into 1.5 V with the module DC-DC converter. Each HV line on the stave is shared by groups of modules, and the AMAC chip controls the HV ON/OFF on an individual module [4].

3.2.2 Integration and installation

The manufacturing and preparation of the global structures of the ITk-Strip Barrel has already started. Some of those efforts are shown in Fig. 8. The bare cylinders of the Barrel 2 and 3 have been produced and transported to CERN. The stave insertion tooling, that was commissioned at RAL (UK) in the mock-up shown on the left of Fig. 8, is now at CERN. A setup to cool down and test staves has been commissioned. Stave testing with YARR and ITSDAQ has already started with one stave. Several Service Module mock-ups have been installed and connected to dummy staves (power, cooling, opto, readout). Furthermore, among other activities, preparations at CERN for the cooling and environmental monitoring have begun.

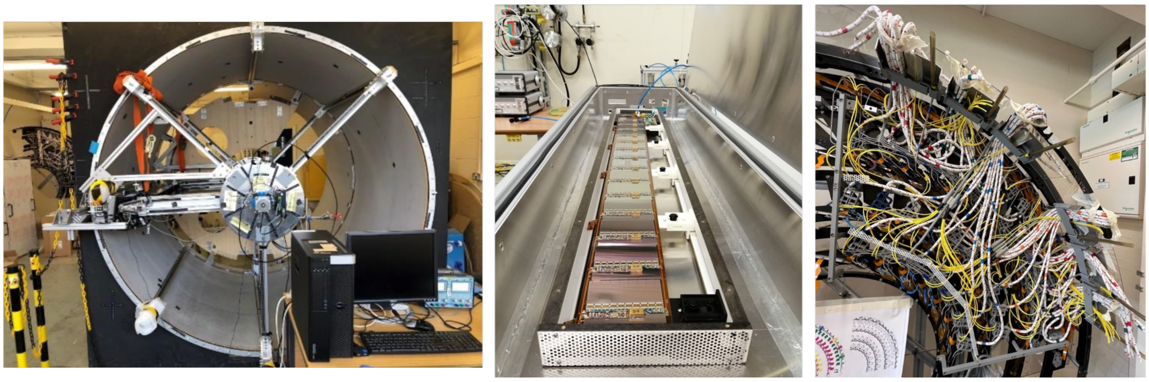

Figure 8: Stave insertion tooling (left), stave in reception test box (center), service module mock-up (right).

3.3 The Strip End-Caps

The End-Caps are two cylinders with six disks each, which extend the range of the strip detector. Nikhef is producing the structures of both ECs, one of which will remain at Nikhef for further integration, while the other one will be finished at DESY. The EC building blocks are the petals.

3.3.1 Petals

An EC petal is a low-mass, high precision, double-sided, high thermal conductivity structure, shown in Fig. 9. It is fully integrated with sensors, readout and control electronics, power components and cooling. Petals are designed for precision mounting of microstrips, minimizing material, powering and providing services for the modules, and for end-insertion in EC disks. There will be 32 petals per disk covering the radial range, which means 384 petals in total, 6912 modules, and a total of 8 times more channels than the SCT end-caps of the current ID detector.

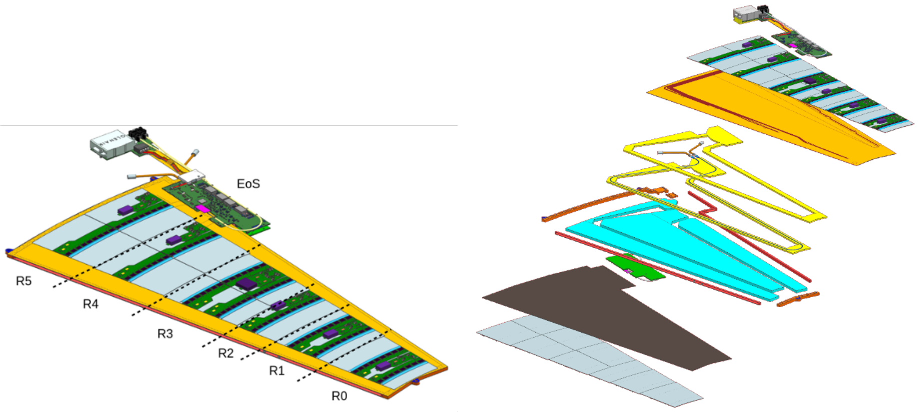

Figure 9: End-cap petal and its structure exploded view. Six silicon modules and a EoS card are placed on each side. In the core, the mechanical support for the modules is carbon-fiber with an embedded titanium cooling pipe; electrical connections are provided by a multi-layered copper polyimide bus tape on each side.

Petals have a trapezoidal shape and six different module geometries (Fig. 10) cover the sensitive area on each side. In Fig. 9, it is shown how the modules on R3, R4 and R5 are split in two to cover the full area. Modules are manufactured in 6-inch silicon wafer technology, and, as in the Barrel, they are single-sided microstrips with n^{+}-type readout implants on a p-type float-zone silicon substrate. The strips are 15-60 mm long, and the sensor pitch is between 70-80 µm with a spatial resolution of about 20 µm and a time resolution around 3 ns [6]. The sensor thickness is around 325 µm, as shown by the measurement of pre-production wafers, in Fig. 11 (left).

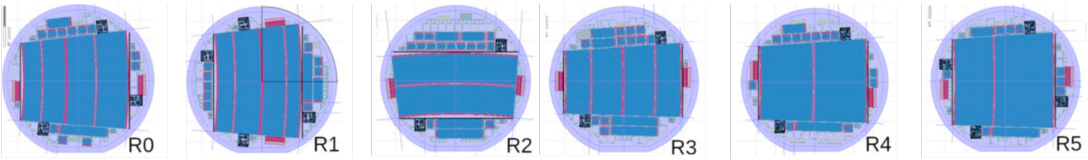

Figure 10: Silicon wafers of the module geometries on an Strip EC petal. The numbering corresponds to their radial position on the petal, addressed in Fig. 9.

Approximately one thousand ATLAS18 wafers, the 5% of the production volume of the ITk pre-production phase, were manufactured by Hamamatsu Photonics (HPK) [7] and subjected to testing at various institutes. The quality control tests [8] showed that, for the majority of sensors, the maximum bow was below 50 µm, well within the limit defined by the specifications, and only two sensor failed the thickness measurement, with 302 µm and 304 µm, as shown in Fig. 11.

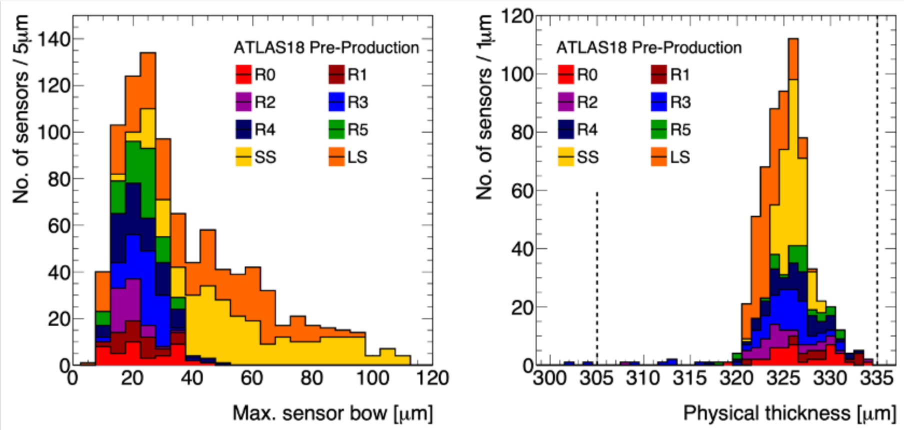

Figure 11: Mechanical test results of the quality control of ATLAS18 wafers produced by HPK. The maximum sensor bow (left) and physical thickness (right) are shown for the the six types of petal modules (R) but also the two types of stave modules (SS and LS). The limits of the specifications range are shown as dashed lines in both figures (for the sensor bow they fall out of range) [8].

Regarding the radiation tolerance, crucial aspect of ITk, a summary of neutron, proton, and pion irradiation measurements at 500 V bias voltage is shown in Fig. 12, for minimum ionising particles. The maximum expected fluence within the ITk Strip Detector, including the safety factor, is around 10^{14} n_{eq}/cm^2, at which the collected charge is reduced for neutron-irradiated samples, while the rest behaves in a similar manner.

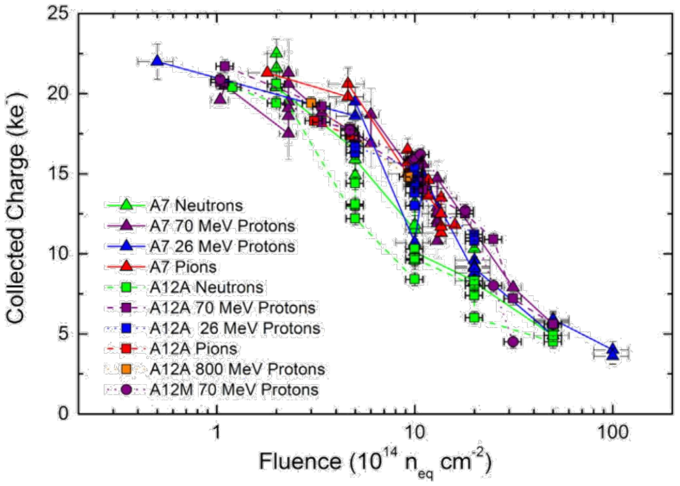

Figure 12: Collected charge at 500 V bias voltage for minimum ionising particles as function of 1 MeVn_{eq}/cm^2 fluence, for different particles [9].

3.3.2 Integration and installation

The integration and installation of the ITk-Strip End-Caps at the time of this talk had already hit major milestones. At Nikhef, the first naked structure of one of the ECs had been already completed (Fig. 13). At DESY, the superframe for EC handling had been produced and the first petal insertion tower had been assembled and tested (Fig. 14). The second tower was in preparation.

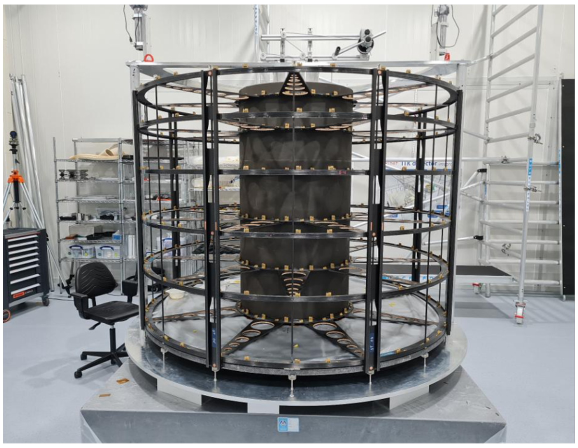

Figure 13: Finished naked structure of the first ITk-Strip EC, in the Nikhef clean room.

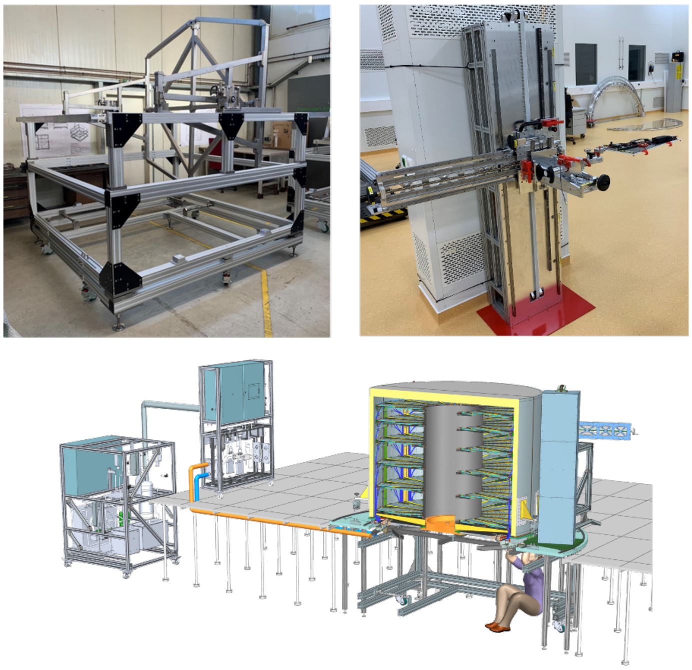

Figure 14: Integration tooling of the Strip EC: superframe and first petal tower insertion (pictures on top, at DESY) and their representation (bottom) in the clean room setup with the cooling system and one EC inside the thermal enclosure.

For sensor operation with high radiation doses, cooling is a crucial aspect. The CO_2 cooling LUCASZ plants were produced at DESY, and they will provide cooling for both finished ECs, one at Nikhef and the other one at DESY. Nikhef has produced the 24 cooling service modules to each cool down 16 installed petals with 2-phase CO_2 at $-40\,^\circ$C.

To validate the characteristics of the CO_2 flow and pressure drop, a full-size cooling service module mock-up, servicing sixteen petals, was built. Its basic elements were fake petals mimicking the power consumption of genuine petals, expected to generate 68 W (nominal) and 84 W (maximum). As shown in Fig. 15 left, the power board is the hottest part on modules, due to the high thermal load.

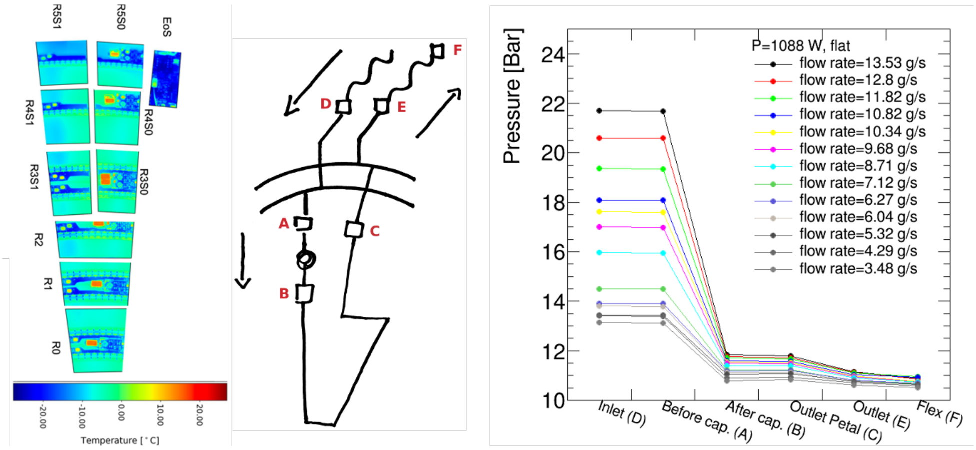

Figure 15: On the left, IR thermography on electrical petal to identify power consumption peaks for ASICs [10]. On the right, sketch of the petal cooling circuit and the pressure drop along the system. Sensors at D, E and F are located outside the EC, B is right before entering the petal inner cooling circuit.

The cooling service setup was tested in the Baby-Demo at CERN. The observed pressure drop at 10.88 g/s (68 W) was ~6 bar over the capillaries, represented as a circle between A and B in the sketch of Fig. 15. The pressure drop at 13.44 g/s (84 W) was ~9 bar. The figure shows that the saturation temperature is -35 to $-38\,^\circ$C for a wide range of flow rates. The pressure drop of the cooling circuit is 90% determined by the capillary. Higher temperatures were also checked for a wide range of massflows, as high as $0\,^\circ$C, expected temperature during stand-by. No dry-out problems were observed and the manifolds were also successfully compared in a different phi orientation to exclude stratification problems.

4. ITk-Strip EC Integration and installation: an update

At the moment, the two EC global mechanical structures have been finished at Nikhef, see Fig. 16. Quality control tests have been conducted to ensure their proper alignment and stiffness. A load of a hundred kilograms was placed inside the EC inner cylinder to mimic the operational conditions, see EC on the right side of Fig. 16. Several 3D laser measurements indicated that the EC structures have a high stiffness leading to only 20 to 60 µm effects when loaded.

By now, at Nikhef all cooling manifolds have been produced and tested. The majority of them have been installed in the ECs. Regarding the data acquisition systems, critical for future petal reception and testing at the EC production sites (Nikhef and DESY), large progress has been

Figure 16: Finished mechanical structures of the two ITk-Strip ECs, currently at Nikhef. One superframe arrived from DESY and it is holding the EC on the right. At that moment, a few cooling manifolds were already installed on the EC on the left. Photograph taken by the author.

achieved with both FELIX (YARR) and Genesys (ITSDAQ), by testing modules and both partially and fully loaded petals (see Fig. 17).

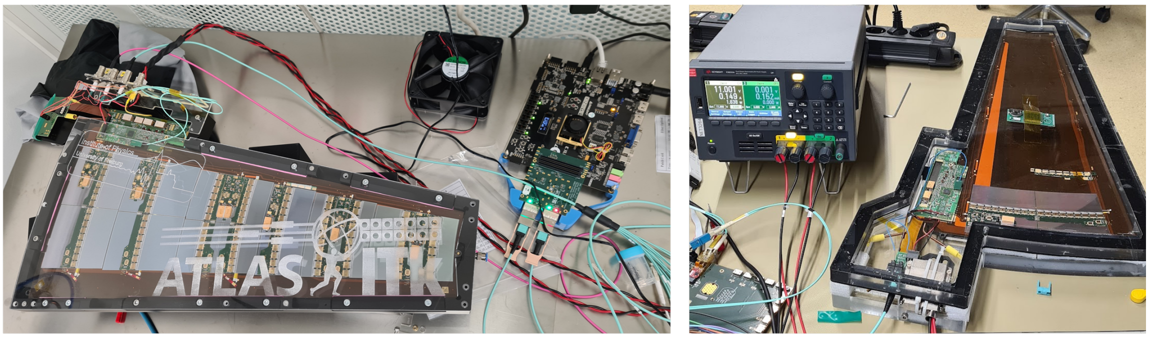

Figure 17: One DAQ setup with a pre-production petal and the Genesys board in Freiburg (left) and another one with a PPB R5 petal read by FELIX in Nikhef (right). Photographs taken by the author.

5. ITk-Strips production status and schedule

The Strip Barrel loading at CERN is expected during the period 2024-2026. At DESY, petal insertion in one Strip EC is expected to finish in 2026 as well, while at Nikhef, a similar schedule to DESY is adopted, but with a shift of three months later.

Once both ECs have been finished at DESY and Nikhef, they will be transported to CERN to be installed in the large outer cylinder that also accommodates the Barrel. Eventually, the ITk-Pixel detector will be inserted into the Strip one.

In 2027, ITk is scheduled to be ready for installation inside ATLAS, and services and connections will get ready for full system cold testing.

6. Conclusions

The new tracking system of the ATLAS experiment for the era of high luminosity, will be the Inner Tracker ITk. This detector will cope with increased particle multiplicity and radiation levels, providing large acceptance, large number of hits per track, high granularity and radiation hardness with a minimised material budget.

This detector is divided in two main subsystems: the pixels and the strips. This paper has focused on the strip system and describes the progress that has already taken place through production and integration at the level of sensors, ASICs, modules, staves and petals, services and global mechanics. The whole project is moving forward and aiming for installation inside of ATLAS to start operation in LHC Run 4.

References

[1] The ATLAS Inner Detector. URL `https://atlas.cern/Discover/Detector/Inner-Detector`. [Accessed: 2024.01].

[2] L. Gonella. The ATLAS ITk detector system for the Phase-II LHC upgrade. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 1045:167597, 2023. ISSN 0168-9002. doi: https://doi.org/10.1016/j.nima.2022.167597. URL `https://www.sciencedirect.com/science/article/pii/S0168900222008890`.

[3] M. Wu. FELIX: Readout upgrade for the ATLAS Trigger DAQ system in HL-LHC. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 1048:167994, 2023. ISSN 0168-9002. doi: https://doi.org/10.1016/j.nima.2022.167994. URL `https://www.sciencedirect.com/science/article/pii/S0168900222012864`.

[4] C. Haber et al. Production and testing of the powerboard for ATLAS ITk Strip barrel modules. *Journal of Instrumentation*, 18(01):C01043, jan 2023. doi: 10.1088/1748-0221/18/01/C01043. URL `https://dx.doi.org/10.1088/1748-0221/18/01/C01043`.

[5] Y. Unno et al. Specifications and pre-production of n^+-in-p large-format strip sensors fabricated in 6-inch silicon wafers, ATLAS18, for the Inner Tracker of the ATLAS Detector for High-Luminosity Large Hadron Collider. *Journal of Instrumentation*, 18(03):T03008, mar 2023. doi: 10.1088/1748-0221/18/03/T03008. URL `https://dx.doi.org/10.1088/1748-0221/18/03/T03008`.

[6] M. Mikestikova et al. ATLAS ITk strip sensor quality control procedures and testing site qualification. Technical report, CERN, Geneva, 2022. URL `https://cds.cern.ch/record/2835012`.

[7] Hamamatsu Photonics K.K., 2017. URL `https://www.hamamatsu.com`.

[8] C.T. Klein et al. ATLAS ITk Strip Sensor Quality Control and Review of ATLAS18 Pre-Production Sensor Results. Technical report, CERN, Geneva, 2023. URL `https://cds.cern.ch/record/2846511`.

[9] K. Hara et al. Charge collection and field profile studies of heavily irradiated strip sensors for the atlas inner tracker upgrade. *NIM-A*, 831:181–188, 2016. URL `https://www.sciencedirect.com/science/article/pii/S0168900216302078`.

[10] J.H. Arling. Thermal performance tests of petals for the ATLAS ITk strip end-cap detector. Forum on Tracking Detector Mechanics 2021, May 2021. URL `https://indico.cern.ch/event/1017981/contributions/4348694/`.