PROCEEDINGS OF SCIENCE

ATLAS ITk Pixel Detector Overview

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To cope with the resulting increase in occupancy, bandwidth and radiation damage at the HL-LHC, the ATLAS Inner Detector will be replaced by an all-silicon system, the Inner Tracker (ITk). The innermost part will consist of a pixel detector with an active area of about 13 m^2. Several silicon sensor technologies will be employed. The pixel modules equipped with RD53B readout chips have been built and irradiation campaigns were done to evaluate their thermal and electrical performance before and after irradiation. This paper describes the most critical components of the detector and presents the status of the ITk-pixel project focusing on the lessons learned and the biggest challenges towards production, from mechanics structures to sensors, and it will forecast some of the challenges expected ahead.

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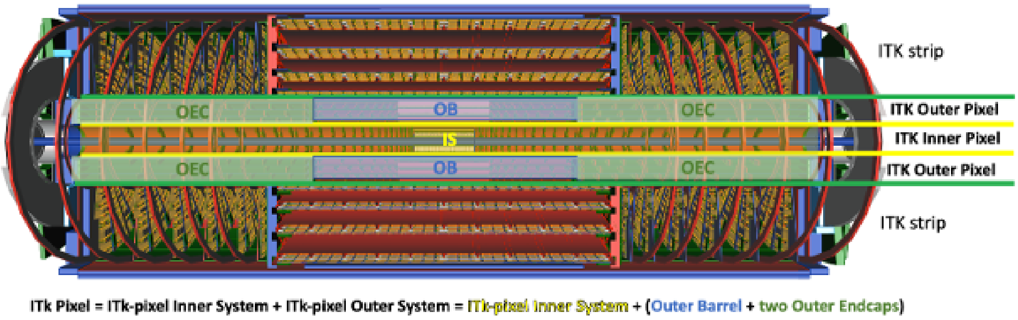


Figure 1: ITk layout [2] with the different subsystems highlighted. The pixel detector is closer to the collision point and is composed of three big sub-detectors: the Outer Barrel (OB), 2 × Outer Endcaps (OEC) and the Inner Pixel System (IS) detectors. The strip detector is composed by the outermost layers of the ITk.

1. Introduction

With the upgrade of the Large Hadron Collider (LHC) to the High Luminosity LHC (HL-LHC) [1], the ATLAS Inner Detector (ID) needs to be upgraded to a full silicon Inner Tracker (ITk). The peak luminosity will reach $7 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ while the integrated luminosity will add up to $\approx 3000\mathrm{fb}^{-1}$, event pile-up is expected to average around μ =200. The ITk will be exposed to 10 times higher radiation fluences than those at the LHC, reaching $\Phi_{\text{HL-LHC}} = 2 \times 10^{16}\mathrm{n}_{\mathrm{eq}}/\mathrm{cm}^2$ in the innermost layer. The ITk will cover $\approx 181\mathrm{m}^2$ and contain a strip [3] and a pixel [4] detector. In Figure 1, the ITk-layout [2] is presented where the different sub-detectors are highlighted: the Outer Barrel (OB), 2 × Outer Endcaps (OEC) and the Inner Pixel System (IS) detectors. In this document, only the Pixel Detector will be briefly discussed due to the complexity of the project and the lack of space.

2. ATLAS ITk: The Pixel detector

To cope with the challenging operating conditions of the HL-LHC, all materials and components to be used in the ATLAS-ITk Pixel Detector must have high radiation resistance to cope with the high fluences while the silicon modules must provide high granularity and data rate capabilities to cope with the high luminosity. Simultaneously, material has to be kept as low as possible to reduce the multiple scattering that reduces the position resolution of the signals. Serialising the powering of the pixel modules and applying data merging are some novel schemes adopted to keep the material low. The coolant in the detector will be operated at -35 C to mitigate the radiation damage on the silicon components. In Figure 2, a quadrant of the pixel detector layout is shown, where the silicon modules positions with respect to the interaction point (0,0) are visible. The OB consist of a flat section with staves at the center and several inclined support rings at the ends, the IS has also a flat central section and rings of different flavours and the OEC is composed of three different sizes of flat rings.

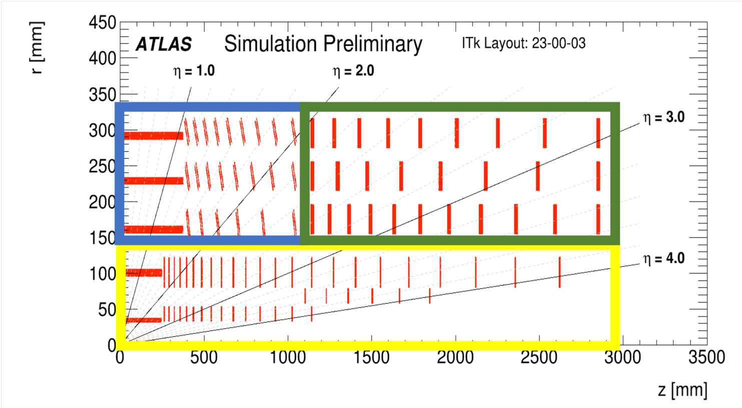


Figure 2: Quarter of the Pixel detector layout where the different sub-detectors are marked: Yellow:Inner System, Green: Outer Endcap, Blue: Outer Barrel. Modified image from [2].

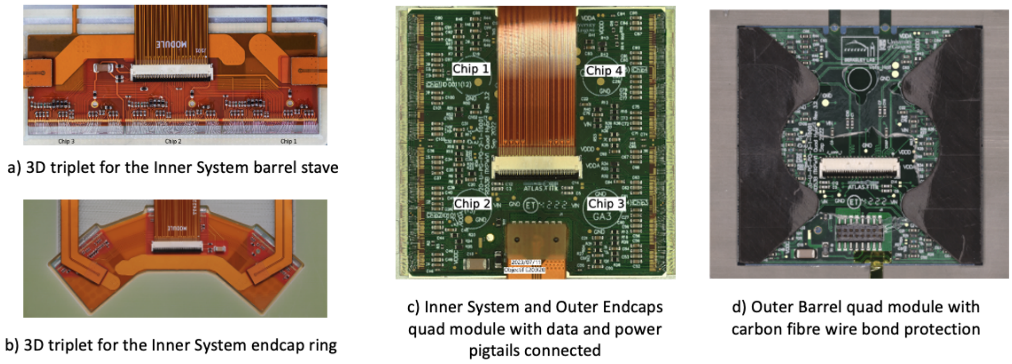


Figure 3: ITk-Pixel modules. a) linear and b) arc-shaped triplet modules for the innermost layer of the IS. c) Picture of a quad module for the IS and OEC. d) Quad module for the OB including the wire bond protection.

3. Modules

In the ITk Pixel detector there are several flavours of hybrid modules depending on where they are located, see Figure 3. In the layer closest to the interaction point (L0), the modules consist of three 3D-sensors bump-bonded to three read-out chips and assembled together by flex PCBs (Printed Circuit board) in triplets, linear-shaped for staves (central area) and arc-shaped for rings. In order to benefit the transversal impact parameter resolution at ITk, the linear triplets have a pixel size of 25 µm × 100 µm, while 3D sensors in the rings have a pixel size of 50 µm × 50 µm like in all the other parts of the Pixel detector. For all the other pixel layers, planar quad modules have been chosen. A quad module is composed of 4 chips bonded to a single n-in-p planar sensor. In the next layer (L1), sensors are 100 µm thick while they are 150 µm thick from L2 to L4. The only difference is that the OB modules add a carbon-fiber protection for the wire bonds. In total, the Pixel Detector will have 8372 silicon modules.

The sensors for the ITk Pixel Detector are at the moment of writing this document under production and have been fully qualified against irradiation. In this document only a couple of results are shown in Figure 4 while more details and results can be found in [6] and [5]. The

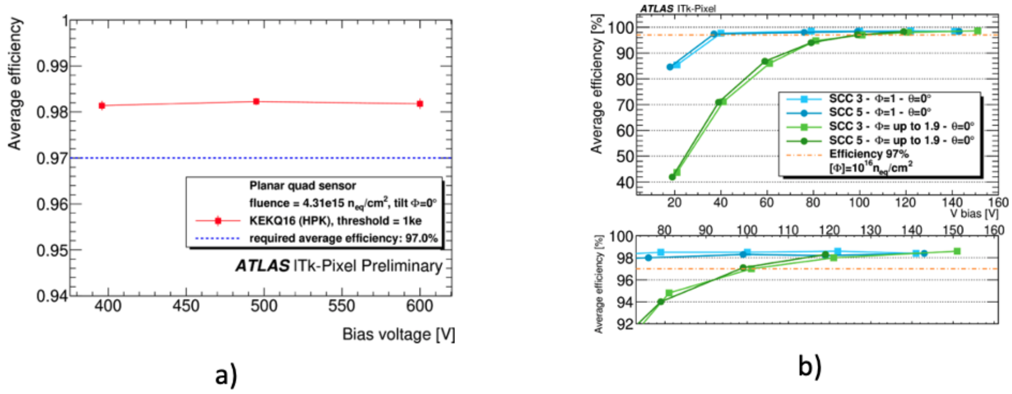


Figure 4: Average efficiency vs bias voltage after irradiation for a) planar quad 150 µm thick sensors [5] and b) 3D sensors [6].

efficiency after irradiation is shown and compared with the requirements for each technology, all sensor flavours meet the requirements.

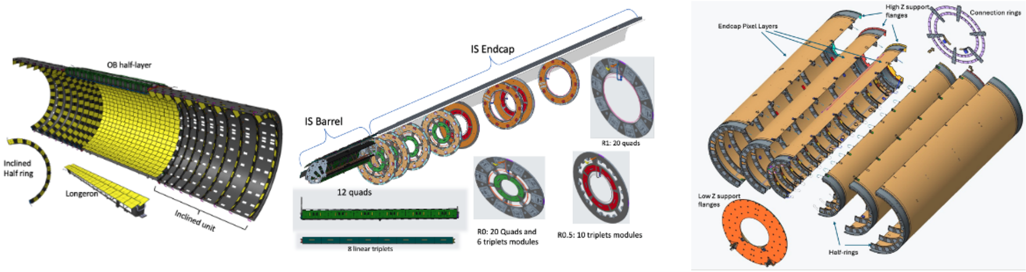
The read-out chip is common to all the pixel modules, and it is the ITkPixV2. It uses a 65 nm technology developed by the RD53 Collaboration [7] and it addresses:

- High luminosity by having high granularity with 152800 (50×50 µm^2) pixels per chip with a total area of 2×2 cm^2 and high data rate: 4 data links per chip at 1.28 Gb/s and incorporates data compression.
- Radiation levels increasing the efficiency implementing low threshold operation and reading charge using Time over Threshold (ToT) and high resistance against irradiation by incorporating leakage current compensation and hardened Single Event Error.
- Services optimisation by integrating shuntLDO regulator for serial powering and data merging from different chips within a module in the flex PCB interface.

Challenges during the Modules R&D phase. The operating temperature of the ITk will be -35 °C, but variations between -45°C and +40°C can be expected during the life of the detector. To qualify the modules' technology for the detector, as a quality assurance they must operate properly after 100 cycles between -55°C and +60°C.

The final module assembly is made of different parts with different materials and coefficients of thermal expansion: thinned down to 150 µm Front-End (FE) chips bump-bonded to thin sensors forming the so-called bare module, a flex PCB is glued on to the bare module and wire-bonded to the FE chip. Finally, modules are glued to the mechanical supports, based on carbon with ≈ 0 Coefficient of Thermal Expansion (CTE). When the final modules are thermal cycled, they undertake big thermo-mechanical stresses that were showing that the sensors' bow can compromise the quality of the connection between the read-out chip and the sensor (bump-bonds), and worsening after thermal cycling. Different strategies have been developed to mitigate this problem:

- Adjusting the copper thickness in the flex, balancing power dissipation and thermal stress.
- Implementing an R&D program with hybridization vendors to address sensor bowing.



a) Outer Barrel half layer b) Inner System Quarter-shell c) Outer Endcap

Figure 5: Layout of sections of the different ITk-Pixel subdetectors: a) half layer of the OB with the two different sections, longerons and inclined rings. b) A quarter shell of the IS layout, with staves and different rings flavours. c) A complete OEC with half-rings.

- Applying Parylene coating helps reduce thermal stress on the bumps.

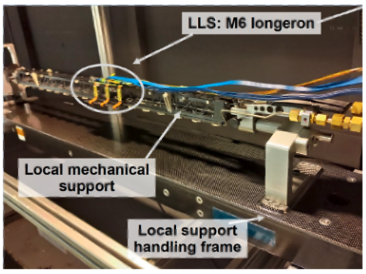
All this issues will be carefully monitored along the remaining pre-production and production.

4. Mechanical structures and Integration

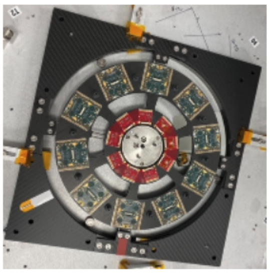
The local [8] and global support structures in the ATLAS ITk Pixel detector are based on carbon materials and while the local supports hold the silicon modules and some services, the global structures support the local supports and all the services. In Figure 5, sections of the global layouts for the different subsystems are shown, A half-layer for the OB a quarter shell for the IS and a whole OEC. One of the biggest challenges on projects as complex and big as the ITk-Pixel project is the integration, which refers to the moment when all components and assemblies are integrated with all the services (cables and pipes). Every final connection between the on-detector services detector and the outside world is made and tested before operating the detector.

5. System test

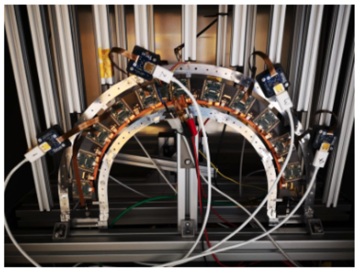
System tests are crucial for the project success. These involve assembling a mini-detector using as many closer-to-final components as possible, including modules, services, and local supports. The setup operates with a cooling system, near-final power and data cables, and data acquisition system, the Detector Control System (DCS) and safety interlocks are also integrated.
Complex tests will help understand the final operation of the full detector in ATLAS such as: multi-module readout, data transmission, grounding and shielding optimisation (identifying any possible interference between components), test the performance at different temperature and checking the robustness of the different connections and interfaces. It is also acting as the best training towards operation of the final detector in ATLAS, this will guarantee that the needed expert are ready for data taking. In Figure 6, pictures of the different subsystem's prototypes for system tests are shown. The first round of tests with prototypes have demonstrated how useful they are for forward developments, from lessons on modules handling up to data acquisition, going through the serial-powering of the modules and monitoring of the operation conditions.



a) OB Longeron



b) IS coupled ring



c) OEC half ring

Figure 6: System tests prototypes for the different subsystems: a) OB longeron, b) IS coupled ring and c) OEC half ring.

6. Project Status and prospect

At the moment of writing this proceeding, sensors and front-end chips are under production and most of the remaining components of the detector are already under pre-production having finalised the prototyping phase. In my opinion, the next big challenges in the project are moving from system test with prototypes to system test with pre-production components, where the community will have the opportunity to understand the functioning of a very complex system with final (or very close to final) components, and exercising the integration of all parts with real components and services form all sub-systems in big mock-ups. The ITk-Pixel community is looking forward for the next problems to solve and challenges to face.

References

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