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The ATLAS ITk Pixel Detector. The biggest challenges from design to construction

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Abstract: As a part of the ATLAS Phase-II upgrade, the current Inner Detector of the experiment will be replaced with a new all-silicon Inner Tracker (ITk) designed to face the challenging environment associated with the high number of collisions per bunch crossing expected during the High-Luminosity phase of the Large Hadron Collider. Along the lifetime of this project, from design to prototyping stages, many difficulties have been encountered and unforeseen problems had to be solved. In this proceeding, an overview of the ITk Pixel Detector layout and the most demanding tasks faced with up to now are described.

Keywords: Detector design and construction technologies and materials; Particle tracking detectors; Voltage distributions

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Contents

1 Introduction

The expected luminosity of the Large Hadron Collider during the High-luminosity phase (HL-LHC) will be $\mathcal{L} = 7.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, corresponding to a 5-fold increase with respect to current values, and the number of protons in the bunches will increase from 1.5×10^{11} to 2.2×10^{11}.

The radiation in the region close to the ATLAS experiment [1] interaction point is expected to reach unprecedented values: an ionizing dose of 5 MGy and a non-ionizing fluence of 1×10^{16} $n_{\mathrm{eq}}/\mathrm{cm}^2$. As it is planned, the data taking has to continue for 10 years in such conditions and the aim for the ATLAS experiment is to collect up to $4000\,\mathrm{fb}^{-1}$ of proton-proton collisions data at centre-of-mass energy $\sqrt{s}$ =14 TeV.

In order to reach the tracking performance required by the ATLAS physics programme for HL-LHC, the ATLAS Inner Detector (ID) [1], consisting of a silicon pixel and silicon strip detectors as well as a Transition Radiation Tracker (TRT), will be replaced by a new detector — the Inner Tracker (ITk). The ITk will be an all-silicon tracking detector made of two subsystems: a Pixel Detector [2] surrounded by a Strip Detector [3].

2 ATLAS ITk Pixel

The ITk Pixel Detector will consist of five barrel layers and a number of end-cap rings, resulting in about $13\,\mathrm{m}^2$ of instrumented area. The design of the new detector (figure 1) will allow to cover the range of pseudorapidities up to $|\eta| = 4$.

It is possible to divide the detector into three subsystems: Outer Barrel (OB), Outer End-cap (OEC) and Inner System (IS) (figure 2). In the baseline scenario, the outer pixel barrel and endcap detector will be operated during all HL-LHC period, while the inner barrel and end-caps will be replaced after $2000\,\mathrm{fb}^{-1}$ [2].

At the expected high level of pile-up ($\langle\mu\rangle = 200$), it is very important to reduce the material budget as much as possible to lower the effects of multiple scattering in the detector media. In figure 3 a comparison of material budgets between the current ATLAS Inner Detector and ITk is shown.

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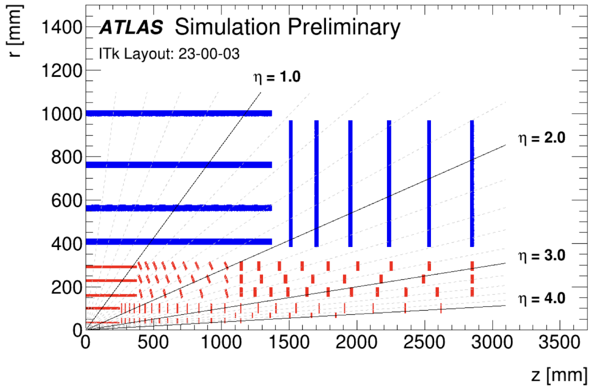

Figure 1. ITk layout of one quadrant (only active detector elements) of the detector: the active elements of the Strip detector are shown in blue, and those of the Pixel Detector are shown in red [4]. Reproduced from [4]. CC BY 4.0.

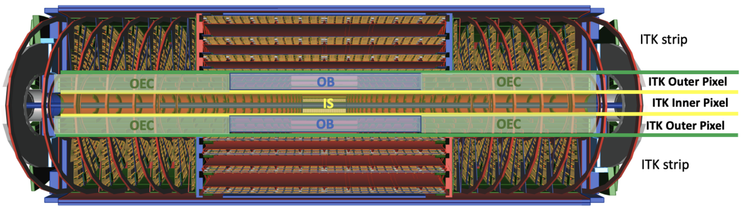

Figure 2. The full ATLAS ITk layout [4] where the different sub-detectors forming the pixel sub-system are highlighted: the Inner System (IS) in yellow, the Outer Barrel (OB) in blue and two Outer End-caps (OECs) in green [5]. Reproduced with permission from [5].

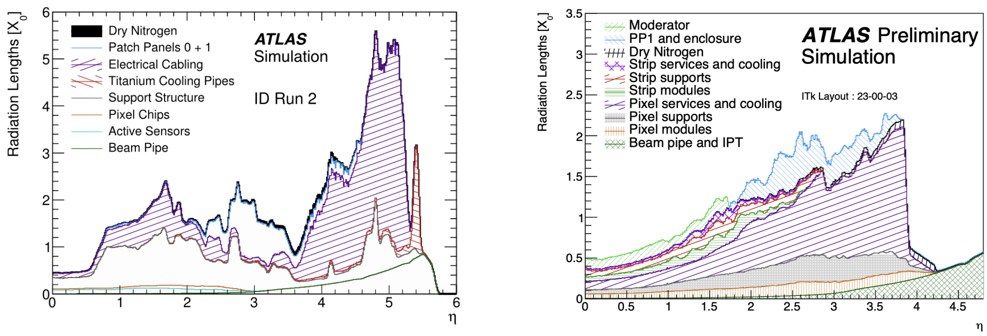

Figure 3. Radiation length X_0 versus the pseudorapidity $|\eta|$: ATLAS ID during LHC Run2 (on the left) [2] and ATLAS ITk [4] (on the right). Reproduced from [2]. CC BY 4.0.

3 Major challenges of the ITk project

From the mechanical point of view, the detector structure has to be robust and light providing support to the whole system, including local supports for modules and electronics, cables to power the detector and to drive the data in and out of the volume, and cooling.

All material and structures are designed to withstand all the possible conditions along the life of the detector. A customized CO_2 bi-phase cooling system driven through titanium pipes will allow the operation of the detector down to −35 °C.

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The environmental conditions at different locations within the pixel system will be monitored and linked to an interlock system that will protect the detector from major damages in case of any malfunction. Achieving that requires that the operation conditions of every pixel module are monitored by a Detector Control System (DCS).

3.1 Local supports

Local support structures will consist of lightweight carbon fibre composite and have to mechanically support the silicon modules and some of the services including titanium cooling pipes.

Different geometries of local supports were optimized for the various layers and regions of the detector. For the Inner System it is planned to use two layers of staves and double-sided rings in the end-caps. Outer Barrel local supports will consist of three layers of longeron and inclined rings. Outer End-cap local supports will be constructed using three layers of end-cap rings composed by two half-rings.

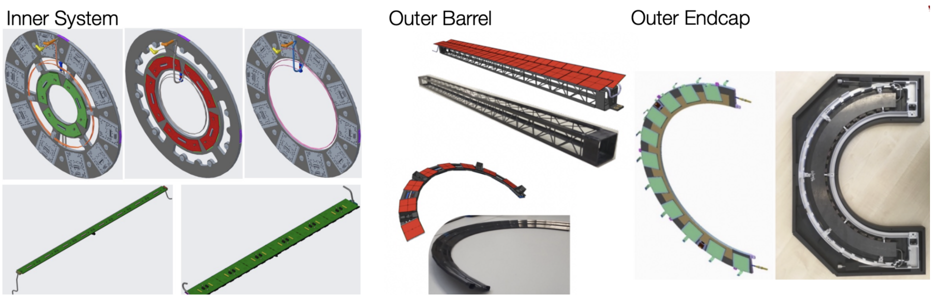

Figure 4. Lightweight local support carbon fibre structures with pixel modules (from left to the right): for the Inner System, Outer Barrel and Outer End-cap [6]. Reproduced with permission from [6].

3.2 Serial powering and data transmission

Every pixel module needs to be powered and monitored using a DCS system providing Low Voltage to power up the ASIC and High voltage to bias the silicon sensors. To accomplish this, a new serial powering scheme (figure 5) has been developed [6]. Among its advantages a reduction of material budget and power loss on cables can be found. In addition, serial powering minimizes the required space. In the chosen scheme, up to 14 modules are connected in series while in each module the readout chips are connected in parallel, so that the total current is the same in each module. At the same time, each module has its own ground thus only the last module in a chain has the same ground as the serial powering chain itself. Floating grounds of the serial powered modules are one of the challenges since it makes the construction more complex in comparison to the standard parallel powering scheme.

High-speed transmission parallel lines (TwinAx cables) running at 1.28 Gb/s per data link are used to drive the data from the front-end chip to an opto-electrical conversion system. The optosystem features custom designed radiation-hard electronics devoted to signal equalization, aggregation (to 10.24 Gb/s) and opto-electrical conversion. The data transmission scheme is illustrated in figure 5.

3.3 ITk Pixel modules

ITk pixel modules are made using hybrid technology during which silicon sensors are bump-bonded to the readout ASICs. The readout chip is based on the 65 nm technology developed by the RD53

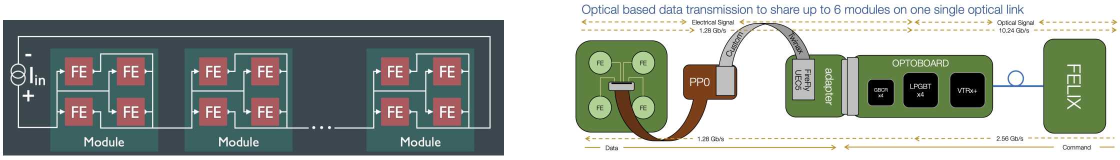

Figure 5. Serial powering scheme (on the left) [6] and data transmission scheme (on the right) [7]. Reproduced with permission from [7].

collaboration [8]. Three different types of modules will be used in the ITk Pixel Detector: quad modules, linear triplet modules and ring triplet modules (figure 6). Quad modules are made of a single $4 \times 4\,\mathrm{cm}^2$ planar sensor bump bonded to four read-out chips. Triplet modules are made of three single chips each one bonded to a $2 \times 2\,\mathrm{cm}^2$ 3D sensor. Triplets will be used in the innermost layer because of better radiation hardness, which will allow them to carry on the data-taking during the planned period.

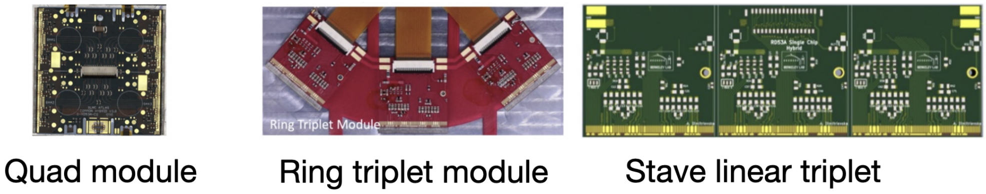

Figure 6. ITk pixel modules (from left to right): quad module, ring triplet module, stave linear triplet [6]. Reproduced with permission from [6].

Both planar and 3D sensor technologies use n-implants in p-substrates with a generally thinner active thickness compared to the current pixel detector. As a consequence, charge and hit efficiencies are saturated at lower bias voltages, which leads to a reduction of dissipated power. At the moment, a market survey is finished for both technologies and pre-production is ongoing [9]. The parameters of ITk pixel modules and their placement on the detector layers are reported in table 1.

Table 1. Layers and properties of modules in ITk Pixel [4]. Reproduced from [4]. CC BY 4.0.

Layer	Module type	Sensor type	Sensor thickness (μm)	Pixel size (μm^2)
L0 barrel	triplet	3D n-in-p	270	25×100
L0 ring	triplet	3D n-in-p	250	50×50
L1	quad	planar n-in-p	100	50×50
L2–L4	quad	planar n-in-p	150	50×50

4 Conclusion

This contribution provides an overview of the pixel subsystem of the Inner Tracker — the project for the Phase-II upgrade of the ATLAS Inner Detector. The description of the ITk pixel layout is given. Major challenges in the design of the detector due to the unprecedented radiation and pile-up conditions during the High-Luminosity phase of the Large Hadron Collider are described.

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References

[1] ATLAS collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, 2008 *JINST* **3** S08003.

[2] ATLAS collaboration, *Technical Design Report for the ATLAS Inner Tracker Pixel Detector*, CERN-LHCC-2017-021, ATLAS-TDR-030 (2017) [DOI:10.17181/CERN.FOZZ.ZP3Q].

[3] ATLAS collaboration, *Technical Design Report for the ATLAS Inner Tracker Strip Detector*, CERN-LHCC-2017-005, ATLAS-TDR-025 (2017).

[4] ATLAS collaboration, *Expected Tracking Performance of the ATLAS Inner Tracker at the HL-LHC*, ATL-PHYS-PUB-2019-014 (2019).

[5] F.J. Munoz, *Carbon Based Local Supports for the ATLAS ITk Pixel Detector*, *PoS* **Pixel2022** (2023) 077.

[6] L. Vannoli, *ATLAS ITk Pixel Detector Overview*, ATL-ITK-SLIDE-2023-123 (2023).

[7] J. Chan, *Serial powering for ATLAS ITk pixel modules*, ATL-ITK-SLIDE-2022-674 (2023).

[8] RD53 collaboration, (2023), http://rd53.web.cern.ch/rd53.

[9] L. Meng, *ATLAS ITk Pixel Detector Overview*, in the proceedings of the *International Workshop on Future Linear Colliders (LCWS 2021)*, Online Conference, Switzerland, 15–18 March 2021 [ATL-COM-ITK-2021-017] [arXiv:2105.10367].

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