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The design and layout of the Phase-II upgrade of the Inner Tracker of the ATLAS experiment

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In the high luminosity era of the Large Hadron Collider (HL-LHC), the instantaneous luminosity is expected to reach unprecedented values, resulting in about 200 proton-proton interactions in a typical bunch crossing. To cope with the resultant increase in occupancy, bandwidth and radiation damage, the ATLAS Inner Detector will be replaced by an all-silicon system, the Inner Tracker (ITk), aiming to provide tracking coverage up to $|\eta| < 4$. The ITk consists of an inner pixel and an outer strip detector designed to provide a tracking performance at least as good as the current detector, but in the HL-LHC environment. In this talk, the updated layout of the detector for the pixel technical design report is presented, and the expected detector and tracking performance is discussed.

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Introduction

The High-Luminosity Upgrade of the Large Hadron Collider (HL-LHC) [1] is going to accelerate and collide protons at $\sqrt{s} = 14\,\text{TeV}$ with the unprecedented instantaneous luminosity of $\mathcal{L} = 7.5 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ corresponding to an average of 200 inelastic collisions per bunch-crossing.

By the end of its operation, the HL-LHC is expected to deliver $4000\,\text{fb}^{-1}$ to both ATLAS and CMS experiments. The large amount of data will allow the two collaborations to probe the Standard Model of Particle Physics to a precision level never achieved before. Nevertheless, the HL-LHC poses serious challenges to the experiments working in its harsh operating conditions and it is clear that a detector re-design and the implementation of new technical solutions are necessary.

In this document, the latest developments on layout of the Phase-II upgrade of the Inner Tracker (ITk) of the ATLAS experiment are presented together with its predicted physics performance. The presented results were published in the ATLAS ITk Pixel TDR [2].

1. Layout of the Inner Tracker

In order to preserve or improve the physics performance of the current ATLAS Inner Detector (ID), the ITk must have an increased radiation hardness, a higher granularity, a reduced material budget, and a pseudorapidity[1] coverage up to $|\eta| < 4$.

A schematic view of the current ITk layout is shown in Fig. 1 (left). The ITk Pixel layout, shown in red, is an evolution of the concepts developed in the ITk Strip TDR [3]. It follows the same guiding principles of an extended barrel stave with inclined sensors in the forward region of pseudorapidity, which requires less sensors while reducing the material traversed by particles and ultimately improving tracking performance. Rings are used instead of disks in both endcaps, which again help to reduce the number of sensors while improving coverage. Two pixel pitches are still under consideration: 50×50 and $25 \times 100\,\mu\text{m}^2$. The Strip Detector, shown in blue, has four barrel layers and six end-cap petal-design disks, both having double modules each with a small stereo angle to add $z(R)$ resolution in the barrel(end-caps), respectively.

Particular care was put in the detailed simulation of engineering components like stave supports and services. The resulting improved description of the material distribution allows for a better understanding of how the material affects tracking performance. Figure 1 (right) shows a comparison of the material distribution expressed in terms of radiation length (X_0) versus η for the ID and the ITk, demonstrating that up to a factor five reduction can be achieved, which in turn is going to improve tracking performance especially for particles with low transverse momentum.

2. Expected tracking performance of the ITk

In this section, a selection of ITk tracking performance studies from Ref. [2] is presented.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

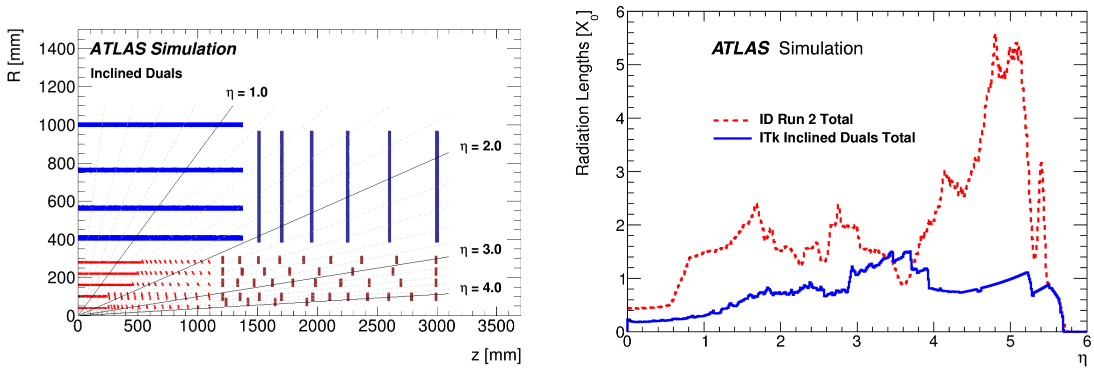

Figure 1: **Left:** Schematic view of the Inclined Duals layout showing the sensors position in one quadrant of the (r,z)-plane. Pixel (Strip) sensors are shown in red (blue) [2]. **Right:** Comparison of ID (red dashed line) and ITk (blue solid line) material budget in terms of X_0 versus η [2].

2.1 Tracking reconstruction efficiency and resolution

One of the most important criteria to evaluate the performance of tracking detector is its efficiency, defined as fraction of prompt particles which are associated with reconstructed tracks. For pions and electrons, the probability to reconstruct their tracks is limited by their interaction with the detector material. As shown in Fig. 2 (left), the material reduction of the ITk leads to a better track reconstruction efficiency. Such higher efficiency of the ITk is combined with a low fake rate, below 10^{-5}, defined as the fraction of tracks that could not be associated with a truth particle.

The reconstructed tracks can be parameterized by the transverse (d_0) and longitudinal (z_0) impact parameters with respect to the primary interaction point, the transverse momentum (p_T), and the polar (ϕ) and azimuthal (θ) angles at the vertex. Their resolutions are evaluated from simulation by comparing the reconstructed values for a given particle with the true value.

The z_0 resolution is shown in Fig. 2 (right). The ITk is performing significantly better than Run2 ID mainly due to the decreased pixel pitch in z direction. These improvements guarantee the necessary pile-up rejection capabilities to cope with the HL-LHC operating conditions. The ITk maintains a d_0 resolution which is similar to the one of the Run2 ID even if its innermost layer is at a larger radius (39 mm, instead of 33 mm). As for the p_T resolution, the ITk shows a factor two improvement with respect to the current ID, mainly due to the higher precision of the Strip detector as compared to the current transition radiation tracker of the ID and due to the reduced material.

2.2 Vertex reconstruction

Once tracks are reconstructed, they are used to reconstruct and identify the hard-scatter and pile-up vertices. The ITk reconstruction shows a primary vertex position resolution with nearly no dependency on local pile-up density. As for the reconstruction efficiency, it is nearly one for top-pair events with an average of 200 pile-up interactions, whereas an efficiency above 90% is found for the more challenging process vector-boson fusion $H \rightarrow \nu\nu\nu\nu$. For both topologies, an identification efficiency compatible with Run2 performance is expected in the HL-LHC pile-up environment.

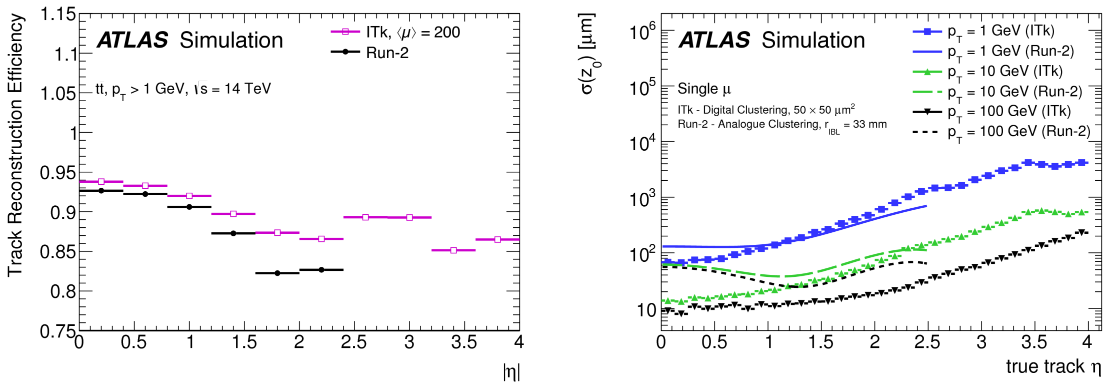

Figure 2: **Left:** Track reconstruction efficiency of the ITk for a top-pair sample with an average of 200 pile-up events. Results for the current ID with a Run2-like pile-up distribution are also shown [2]. **Right:** Track z_0 resolution versus η for $50 \times 50\,\mu\mathrm{m}^2$ pixels. Results are shown for single muons of 1, 10, and 100 GeV in p_T. The resolutions for the current ID are overlaid [2].

2.3 Physics object performance

The excellent tracking capabilities of the ITk lead to several improvements in physics performance, as detailed in Ref. [2]. Important examples are: an excellent hard-scattered identification efficiency (above 80% in the whole $|\eta|$ range) for a typical working point of 50 in pile-up jet rejection; improved resolution (10%) of missing transverse momentum thanks to a more efficient association of soft tracks to the hard-scatter vertex; enhanced flavor tagging, maintaining the great Run2 performance and extending the pseudo-rapidity coverage to $|\eta| < 4$.

Conclusion

The latest developments on the ITk layout have been presented and its expected performance was discussed. The ITk is going to maintain or improve the performance of the current ID in the harsher HL-LHC environment. Further details and many additional studies can be found in Ref. [2].

Acknowledgments

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References

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