Performance of the ATLAS Inner Detector at the LHC

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Abstract. Since the LHC startup in 2009, the ATLAS inner tracking system has played a central role in many ATLAS physics analyses. Rapid improvements in the calibration and alignment of the detector allowed it to reach nearly the nominal performance in the timespan of a few months. The tracking performance proved to be stable as the LHC luminosity increased by five orders of magnitude during the 2010 proton run, while the performance was only slightly degraded in the extremely dense heavy ion collisions.

1. Introduction
The ATLAS Inner Detector [1] started recording collisions from the LHC [2] beams in November 2009. Since then, approximately 600 million events have been recorded, reconstructed offline, and used to understand and improve the performance of the tracking system in great detail. The Inner Detector consists of three components: a pixel detector with very high granularity and precision, surrounded by a silicon strip tracker (SemiConductor Tracker, SCT), and finally the Transition Radiation Tracker (TRT), a tracker based on drift tubes (straws). The Pixel and SCT cover the pseudorapidity\(^2\) range up to \(|\eta| < 2.5\), while the TRT extends up to \(|\eta| < 2.0\). The Inner Detector is immersed in a solenoid field of about 2 T, which allows a measurement of the momenta of the particles. Table 1 summarizes the specifications of the subcomponents in the tracking system.

| Detector | #channels | #hits per track | \(R-\phi\) resolution | \(R-z\) resolution |
|----------|-----------|-----------------|-----------------------|-------------------|
| Pixel    | 80M       | ~3              | < 10 \(\mu\)m         | ~ 100 \(\mu\)m    |
| SCT      | 6.3M      | ~4 (modules)    | 17 \(\mu\)m           | ~ 800 \(\mu\)m    |
| TRT      | 320k      | ~30             | 130 \(\mu\)m          | -                 |

\(^1\) On behalf of the ATLAS Collaboration
\(^2\) Pseudorapidity is defined as \(\eta = -\ln \tan(\theta/2)\), where \(\theta\) is the polar angle
2. Operation and performance

The Inner Detector is fully operational since September 2008, when the first cosmic tracks were detected in the Pixel Detector. A very large fraction of the detector is functional: approximately 97% of the Pixel Detector, 99% of the SCT Detector, 98% of the TRT Detector. The remaining dead channels are stored and corrected for in the offline reconstruction. The efficiencies were found to be nearly 100% for the Pixel and SCT Detectors, about 95% for the TRT. The noise rates are $10^{-13}$ for the Pixel Detector, $<5\cdot10^{-4}$ for the SCT, around 2% for the TRT [3]. These values are equal or better than the design specifications [4]. The data is continuously monitored offline, e.g. to assess the impact of occasional operational issues on the tracking performance. Only a small fraction of data had to be discarded due to holes in the tracking acceptance.

Apart from the efficiencies at the hit level, the track reconstruction and vertex reconstruction efficiencies were also studied [5]. The track reconstruction efficiency was taken from the simulation, with the systematic errors estimated from data/MC disagreements. In the initial phase the agreements were generally very good, except in the forward region $|\eta| > 2.2$ were some material was found to be missing in the detector description. The tracking efficiency as a function of $p_T$ is shown in Figure 1. The highest efficiency is obtained for high-$p_T$, central tracks. The vertex efficiency was obtained in a data driven way, using an event sample enriched with collisions. In Figure 2 it can be seen that the vertexing efficiency is practically 100% for vertices with three or more tracks.

![Figure 1. Tracking efficiency as a function of $p_T$ [5].](image1)

![Figure 2. Vertex reconstruction efficiency as a function of the number of tracks [5].](image2)

3. Alignment

To be able to complete the ATLAS physics program, the relative positions of the sensors in the Inner Detector need to be known within 10 micrometers or better. The tolerances used during the assembly of the detector were much larger than that, therefore the full alignment needs to be obtained by studying the data [6]. The starting point during the LHC startup was the alignment obtained using cosmic-ray data in 2008 and 2009. The performance using this alignment was reasonable in the barrel part, but clearly more limited in the endcaps where statistics with the cosmic-ray data were low. The first collision runs at 7 TeV greatly increased the number of available tracks, allowing a more detailed alignment to be performed, eventually down to the level of individual sensors. Figure 3 shows that the measurement precision of the TRT was practically at the level of the simulation (which assumes a perfect alignment and calibration), after just a few months of data taking. In addition to the improved alignment, the precision
of the Pixel Detector also benefitted greatly from the corrections for distorted sensor surfaces, which were enabled in time for the autumn 2010 reprocessing of the data. Figure 4 shows the improvement in the pixel resolution in this reprocessing, compared to the initial processing in spring 2010.

Figure 3. Hit residuals in the TRT barrel, compared between data and simulation [6].

Figure 4. Hit residuals in the Pixel barrel, using the initial alignment (spring 2010) and an updated alignment (autumn 2010) [6].

4. Particle identification
The Inner Detector can distinguish between several particle types, depending on the momentum of the particle. In particular the separation between electrons and pions plays a very important role in many physics analyses that require electrons. Compared to pions, electrons are much more likely to produce transition radiation in the TRT radiator material. This radiation often produces large energy deposits in the straw (≈10 keV, compared to 2 keV for a MIP). By counting the number of straws on track with a large energy deposit (‘high threshold hits’), the probability of this particle being an electron can be determined. The large number of straws per track makes for a powerful discriminant. Figure 5 shows the probability for a straw on track to pass the high threshold as a function of momentum, for electrons and pions. More information about the performance of the TRT may be found in Ref. [7].

In addition to detecting electrons, both the TRT and Pixel Detector can also distinguish between pions, kaons and protons at low momentum using their specific energy loss $dE/dx$, as shown in Figure 6. The deuteron band is also visible in the right half of the plot. The $dE/dx$ based particle identification is used mainly to tag decays of Standard Model hadrons (e.g. the $\Lambda$ and $\phi$ particles) [8], but also to search for stable, highly ionizing, supersymmetric particles [9].

5. Material studies
The material budget of the Inner Detector was studied using hadronic interactions and photon conversions. These are sensitive to the thickness of the material in interaction lengths and radiation lengths, respectively. Figure 7 shows the positions of the reconstructed hadronic interactions. The beam pipe can be seen near $R = 30$ mm, while the structure near $R = 50$ mm is the first layer of the Pixel Detector. The radius of the interactions in the beam pipe varies as a function of $\phi$, due to the beam pipe being displaced with respect to the nominal beam line. This shift has since been implemented in the detector description used in the simulation and reconstruction. Figure 8 shows the positions of reconstructed photon conversions in the central
6. Conclusions

The ATLAS Inner Detector has met or exceeded the expectations since the LHC startup in 2009. For the most part the performance (efficiency, resolutions) is in very good agreement with the simulation. The performance stayed almost constant as the LHC luminosity increased by six orders of magnitude. The Inner Detector will continue to play a central role in the fulfillment of the ATLAS physics program.

7. References

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