Commissioning and performance of the ATLAS Inner Detector with the first beam and cosmic data

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Abstract

The ATLAS experiment at the CERN Large Hadron Collider (LHC) started data-taking in Autumn 2008 with the inauguration of the LHC. The Inner Detector is a tracking system for charged particles based on three technologies: silicon pixels, silicon microstrips and drift tubes. The detector was commissioned and calibrated in the ATLAS cavern. Cosmic muons data are used for timing the different components of the system, measuring detector performance on particles and cross-checking the calibration results. Cosmic ray data serve also to align the detector prior to the LHC start up, exercising the alignment procedure to be repeated during the accelerator's operation. Tracking performance after this early alignment is suitable for initial LHC collisions.

Key words: Tracking detectors, Silicon detectors, Alignment

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1. Introduction

The Inner Detector is the tracking device for the ATLAS experiment [1] at CERN's Large Hadron Collider [2]. The active region of the Inner Detector extends from 50 mm up to 1066 mm from the beam axis and operates within a solenoidal magnetic field of 2 T parallel to the beam direction.

The system has been designed to provide a momentum resolution in the plane perpendicular to the beam axis ($R\Phi$ plane) of $\sigma_{p_T}/p_T = 0.05\% p_T [\text{GeV}] \oplus 1\%$. It includes three complementary sub-detectors: the Pixel Detector, the SemiConductor Tracker (SCT) and the Transition Radiation Tracker (TRT). Each sub-detector consists of a central barrel part and two end-caps. Both the Pixel Detector and the SCT are silicon based and have an acceptance in the pseudorapidity range $|\eta| < 2.5$.

The Pixel Detector [3] consists of 3 barrel layers, the innermost one located 50.5 mm from the beam, and 3 disks in each end-cap. Typical pixel size is $50 \mu\text{m} \times 400 \mu\text{m}$ with an expected resolution of $10 \mu\text{m}$ in the $R\Phi$ plane and $110 \mu\text{m}$ in the Rz plane.

The SCT [4] consists of 4 barrel layers and 9 disks in each end-cap. Modules are built from two wafers of $80 \mu\text{m}$ pitch strips at a 40 mrad stereo angle, providing a point resolution of $17 \mu\text{m}$ in the $R\Phi$ plane and $580 \mu\text{m}$ in the Rz plane.

The TRT [5] is the outermost sub-detector. It is built of 4 mm straw tubes embedded in polypropylene fibres (barrel) or foils (end-caps) as material for transition radiation. Within the TRT acceptance, $|\eta| < 2$, a track gets typically 30 measurements with $130 \mu\text{m}$ resolution in the $R\Phi$ plane. Besides providing continuous tracking, the transition radiation emitted by highly relativistic particles is used for electron identification in the range $0.5 \text{ GeV} < E < 150 \text{ GeV}$.

Installation of the Inner Detector in the ATLAS cavern started in 2006; the last sensitive device to be inserted was the Pixel Detector in 2007. Connection of the services was completed in April 2008. The system has been operational since August 2008, after the evaporating cooling system [6] was completely commissioned.

The Pixel Detector is now operative at 98.5%, the SCT at 99%, and the TRT at 98%. In section 2 the data-taking conditions in Autumn 2008 are described. Sub-detector calibration and characterization with cosmic rays is summarized in section 3. The alignment procedure and tracking performance of the whole system are shown in section 4.

2. Autumn 2008 data-taking

The Inner Detector took part in the ATLAS data-taking in Autumn 2008, both with LHC single beams and cosmic rays. During this period, the SCT and the Pixel Detector end-caps had a reduced coverage, 97% and 85% respectively, resulting from leaky cooling circuits. Most of these will be operated in 2009.

During the initial running of the LHC, the so-called *beam splash* events were produced by beam scraping on collimators approximately one hundred meters from the experimental hall. They generated a large number of particles crossing the detector with trajectories almost parallel to the beam axis. To prevent risk of damage due to beam losses, only the SCT end-caps and the TRT were active during this data-taking. The collected data were used for timing the SCT end-caps within one bunch spacing time of 25 ns and the TRT with a precision of 2 ns.

Cosmic ray data were collected during a global ATLAS run in September and October 2008, with and without the solenoid turned on. This was followed by detector calibration and characterization and by a week of data-taking dedicated to the Inner

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Figure 1: Efficiency of second level trigger tracking reconstruction algorithms as a function of the track distance from the beam axis. IDScan and SiTrack are pointing algorithms to be used also for LHC collisions, TRT is a specialized algorithm used in cosmic data-taking.

Detector system, without the magnetic field. The full data samples consists of 4.9 million tracks with the solenoid off and 2.7 million tracks with solenoid on. Within the SCT and the Pixel Detector acceptance there are respectively 1150 and 230 thousand tracks with solenoid off and 880 and 190 thousand tracks with solenoid on.

The Inner Detector coverage for cosmic rays is only a small fraction of the acceptance covered by the ATLAS first level trigger, which itself is based on the muon spectrometer and calorimeter triggers. In order to improve the trigger rate for particles crossing the Inner Detector, different tracking algorithms are used at the second level trigger. The efficiency for these triggers is measured with respect to the offline reconstruction algorithm and is shown in figure 1 as a function of the distance of the track from the beam axis. IDScan and SiTrack [7] are algorithms aiming to select pointing tracks, i.e. tracks coming from the LHC interaction region, and will be used also during LHC collisions. They show a good efficiency within the acceptance of the innermost SCT layer located at 300 mm from the beam axis. To increase the acceptance for non-pointing tracks a special trigger, based on the TRT standalone track reconstruction, was implemented.

3. Calibration and characterization

Before data-taking, the sub-detectors are calibrated to tune their response to charged particles and provide a good uniformity. This is particularly relevant for the silicon part, due to the high number of channels (80×10^6 in the Pixel Detector and 5×10^6 in the SCT).

Pixel thresholds are tuned to $4000 e^-$, with a typical noise of 165 ENC, resulting in a very high value of threshold over noise and a noise occupancy $< 2 \times 10^{-10}$, after masking a fraction of only 10^{-4} of the channels. The Pixel Detector measures the collected charge through the Time over Threshold (ToT) technique. The ToT, measured in clock cycles of 25 ns, is tuned to 30 for a charge deposition of $20000 e^-$, the most probable value

Figure 2: Pulse height distribution for pixel hits associated to tracks with incidence angle with respect to the normal to the detector surface $|\alpha| < 0.2$ rad.

Figure 3: Noise occupancy of SCT modules in cosmics data-taking. The design requirement of 5×10^{-4} is the upper limit of the displayed range.

expected for a minimum ionizing particle. Given the tuning capability of the pixel front-end electronics, thresholds are uniform within $40 e^-$ and the ToT response is constant within 2%. The calibration is validated by the good agreement of the pulse height distribution with Monte Carlo expectation (figure 2).

The SCT operates at a nominal threshold of 1 fC. Due to the lower threshold over noise ratio with respect to the pixel detector, a control of the noise level is critical for operation. In cosmic data-taking, the noise occupancy is 5×10^{-5} (figure 3), well below the design requirement of 5×10^{-4} . The measurement of noise as a function of the depletion voltage shows also the possibility to operate below full depletion. This option was chosen during single beam running at the LHC, where the STC operated at 20 V bias instead of the nominal 150 V, since it was a safer condition in case of beam losses.

The measurement of the angle between the charge drift direction and the electric field, due to the Lorentz force on charge carriers, is a fundamental calibration for silicon trackers, because it may cause shifts of the collected charge position larger

than the device resolution. Preliminary measurements using cosmic muons are $(12.26 \pm 0.03)^\circ$ for pixels and $(3.93 \pm 0.03)^\circ$ for strips (statistical errors only). The difference is due to the higher mobility of electrons (collected in pixels) compared to holes (collected in strips).

The TRT is characterized by its capability to identify highly relativistic particles via their detection through transition radiation. This is achieved by using a double threshold: a lower one for tracking and a high one for signals compatible with transition radiation photons. The onset of the transition radiation is visible in cosmic ray data from the excess of high-threshold hits for high energy muons (figure 4). Low-threshold hits associated to a track have a probability of coming from noise of less than 1%.

After these calibrations, the efficiency is measured by extrapolating reconstructed tracks to the sensitive detectors and checking for the presence of hits. Considering only components switched on for the readout, the observed value is $> 99.7\%$ for the Pixel Detector, between 99% and 99.6% for the SCT, depending on the layer or disk, and 97.2% for the TRT.

4. Alignment and tracking performance

Initial information about detector alignment comes from survey data and is improved with the track-based alignment. The track-based alignment is performed by minimization of the *residuals*, the distances between the positions measured by the detector and the reconstructed track. An optical system is also used to monitor SCT deformations [8].

Different methods have been developed in ATLAS [9]. The main alignment technique is the *global- χ^2* method, which considers all the correlation terms between the measurement points, and therefore between all the detector components, along a track. This method requires the inversion of a $6N \times 6N$ matrix, where N is the number of aligned objects and 6 is the number of parameters to describe a rigid translation and rotation of the objects. At the first alignment stage, N is a small

Figure 4: Fraction of high threshold hits on cosmic muon tracks as a function of $\gamma = E/m$ in the TRT barrel. The onset of transition radiation at high energies is in agreement with expectations from test beam data.

number of macro structures, like barrel and endcaps, or layers and disks, and major misalignments between these structures are corrected. In further refinements, the granularity of the alignment is gradually increased up to individual silicon modules (1744 in the Pixel Detector, 4088 in the SCT). For the last alignment step only two translations in the measurement plane have been taken into account.

For cross-check other methods have been developed. The *local- χ^2* technique neglects the correlation between different silicon wafers but requires only the inversion of $N \times N$ matrices; the *robust alignment* technique exploits overlapping regions between nearby detector modules, where extrapolation errors between two measured points are negligible.

Figure 5 shows the residuals of the precise measurements in the $R\Phi$ plane after the alignment procedure. The results of the Gaussian fit to these residuals provides widths of $24 \mu\text{m}$, $30 \mu\text{m}$ and $174 \mu\text{m}$ for the Pixel Detector, the SCT and the TRT respectively. These widths contain contributions from the intrinsic detector resolution, extrapolation error, misalignments and other tracking systematics. The latter components can be estimated by comparing the observed width with the one computed on simulated events, where the exact detector geometry is known. Along the η direction, Pixel Detector residuals have a width of $131 \mu\text{m}$, compatible with the $127 \mu\text{m}$ expected for cosmic rays.

Tracking performance is mainly defined by the resolution of the track parameters: d_0 , distance of closest approach to the origin in the $R\Phi$ plane (perigee), z_0 , z coordinate of perigee, ϕ_0 , azimuthal angle of particle momentum at perigee, θ , polar angle of particle momentum, and Q/p_T , the reciprocal of the transverse momentum, multiplied by the charge. This is estimated for cosmic ray events by splitting a reconstructed track which crosses the whole Inner Detector, in two halves, as shown in figure 6a. Each half track has a set of measurements similar to particles from the LHC collisions. The resolution distribution of the differences between the upper and lower halves $k_{\text{up}} - k_{\text{low}}$, where k is any one of the above track parameters, has a width $\sigma_{k,\text{up-low}} = \sqrt{\sigma_{k,\text{up}}^2 + \sigma_{k,\text{low}}^2}$. On average the upper and lower segment resolutions are equal and the average resolution on a track parameter is derived from the differences: $\sigma_k = \sigma_{k,\text{up-low}} / \sqrt{2}$.

As an example, figure 6b shows the distribution of d_0 differences and table 1 summarizes the achieved resolutions for tracks with $p_T > 2 \text{ GeV}$. The results are compared with the simulation for the case of perfect alignment. The achieved resolution after the cosmic alignment is already within 50% of the expectations in case of perfect alignment. This is not far from the design goal of having a performance degradation lower than 20% due to alignment accuracy [10].

5. Conclusions

The ATLAS Inner Detector successfully collected single beam and cosmic ray data in Autumn 2008. These data are used for detector timing, calibration and characterization. The number of working channels is above 98% and have an intrinsic efficiency above 99.5% for most of components. The noise

Figure 5: Residuals between the measured points in the $R\Phi$ plane and the reconstructed track after alignment: Pixel Detector (a), SCT (b) and TRT (c). For the residuals in the silicon detectors, tracks are required to pass within the innermost pixel barrel layer acceptance and to have a transverse momentum > 2 GeV. For the TRT residuals, the acceptance is widened, requiring only the outermost pixel layer, and no momentum cut is applied. The widths include contributions from detector resolution, alignment uncertainties and extrapolation error.

Figure 6: To estimate tracking parameter resolutions, cosmic tracks are split, as sketched in (a). The d_0 difference between the two split tracks is shown in (b). Tracks have been reconstructed using only silicon detectors, are requested to have a transverse momentum $p_T > 2$ GeV and to cross the innermost layer of the Pixel Detector.

Table 1: Resolution for tracks reconstructed in the silicon detectors after alignment and comparison with expectation from the simulation of a perfectly aligned detector. Track selection is the same in figure 6

	Cosmic muons	Monte Carlo
$\sigma(d_0)$	$35 \mu\text{m}$	$23 \mu\text{m}$
$\sigma(z_0)$	$117 \mu\text{m}$	$107 \mu\text{m}$
$\sigma(\phi_0)$	0.28 mrad	0.21 mrad
$\sigma(Q/p_T)$	3.5 TeV^{-1}	2.8 TeV^{-1}

rate is well below the design requirements. The barrel part is aligned using cosmic ray tracks and demonstrates tracking performance adequate for initial data-taking.

Early collision data will be used to cover remaining commissioning issues which cannot be assessed using cosmic rays, due to the kinematics of the events: vertex reconstruction and alignment of regions scarcely illuminated by cosmic rays, mainly in the end-caps. The commissioning work already performed will guarantee a smooth start of data-taking with the first LHC collisions and will allow the expected detector performance to be reached quickly.

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