Commissioning and performance of the ATLAS Transition Radiation Tracker with first high energy pp and Pb-Pb collisions at LHC

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Abstract—**The ATLAS Transition Radiation Tracker (TRT) is the outermost of the three sub-systems of the ATLAS Inner Detector at the Large Hadron Collider at CERN. It consists of close to 300000 thin-wall drift tubes (straws) providing on average 30 two-dimensional space points with 0.12-0.15 mm resolution for charged particle tracks with $|\eta| < 2$ and $p_T > 0.5\,\text{GeV}$. Along with continuous tracking, it provides particle identification capability through the detection of transition radiation X-ray photons generated by high velocity particles in the many polymer fibers or films that fill the spaces between the straws. Custom-built analog and digital electronics is optimized to operate as luminosity increases to the LHC design. In this article, a review of the commissioning and first operational experience of the TRT detector will be presented. Emphasis will be given to performance studies based on the reconstruction and analysis of LHC collisions. The first studies of the TRT detector response to the extremely high track density conditions during the November 2010 heavy ion LHC running period will be presented. These studies give interesting insight to the expected performance of the TRT in future high luminosity LHC proton-proton runs.**

I. INTRODUCTION

THE ATLAS experiment[1] is one of the two general purpose detectors at the Large Hadron Collider (LHC) at CERN. The LHC is a hadron storage ring with a 27 km circumference allowing the collision of protons and lead ions in four interaction points. For protons it will have beam energies as high as 7 Tev and luminosities as high as $10^{34}\text{m}^{-2}\text{s}^{-1}$ with a bunch spacing of 25 ns. Beams were first injected at energies of 450 GeV in September 2008 followed by a 14 month shutdown period for repairs. As of November 2009 there had been collisions at $\sqrt{s} = 900\,\text{GeV}$ for a short time before the commissioning for $3.5\,\text{TeV}$ beam energy began in 2010. First events at this energy were seen on March 30, 2010, and have been provided ever since with constantly increasing luminosity reaching values as high as $8 \times 10^{32}\text{m}^{-2}\text{s}^{-1}$ so far. The $\sqrt{s} = 7\,\text{TeV}$ program is scheduled to be continued throughout 2011 and 2012. In 2013 there will be a shutdown allowing the LHC to be repaired and reach its design parameters afterwards.

The ATLAS detector is a hermetic 4π multi purpose detector located 100 m underground at one of the four LHC interaction points. It employs appropriate detection techniques for studying the remnants of high energy proton collisions at the full solid angle up to TeV energies. Viewed from the outside, its most striking feature is a muon system consisting of eight air-core toroid coils providing a $1.4\,\text{T}$ magnetic field for muon detection and measurement. Further inside is a multilayer calorimetric system. It employs various energy measurement techniques depending on the actual location inside the detector (and hence the projected energy and particle density during operation). The calorimeter encloses a superconducting solenoid magnet which provides a $2\,\text{T}$ magnetic field for the Inner Detector.

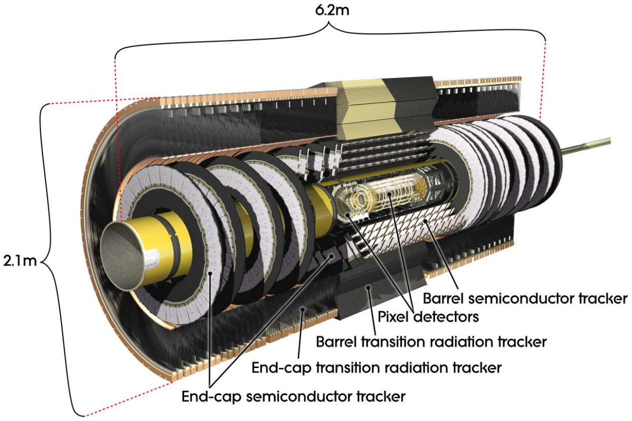

Figure 1. Cut-away image of the ATLAS Inner Detector.

The Inner detector covers the range of $|\eta| < 2.5$ and provides tracking for charged particles with a transverse momentum $p_T > 0.5\,\text{GeV}$. It consists of three subsystems. The innermost layer is the Pixel detector containing three layers in the central region and three disks in each end-cap with over 80 million $400\,\mu\text{m} \times 50\,\mu\text{m}$ sized pixels for precise tracking and vertexing in a very high occupancy environment. It extends from the beam pipe outwards to a radius of 122.5 mm. Enclosing the Pixel detector is the Silicon Tracker (SCT) consisting of four layers and two times nine disks respectively of silicon strips with a pitch of $80\,\mu\text{m}$. Each detector layer consists of two strip layers tilted by 40 mrad with respect to each other. Hence the SCT is able to provide four precision space points for each track traversing its volume which extends outwards to a radius of 514 mm.

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II. THE TRANSITION RADIATION TRACKER

The TRT is the outermost tracking detector in the ATLAS Inner Detector volume and extends to a radius of 1082 mm from the interaction region. Its design was driven by the need to get continuous tracking with a long lever arm and electron identification in the pseudorapidity range $|\eta| < 2$. It was also designed to provide a point resolution of $130\,\mu$m and withstand the challenging LHC environment with a high particle density and accumulated radiation dose.

A. *Design*

In contrast to the other inner tracking detectors, the TRT is not a semiconductor detector but a gaseous detector. It consists of 4 mm diameter straw tubes wound from a multilayer film reinforced with carbon fibers and containing a 30 μm gold plated tungsten wire in the center[5]. The straw wall is at -1.5 kV while the wire is kept at ground. Thus the charge clusters created through primary ionization undergo avalanche multiplication near the wire. The straw is filled with a gas mixture of 70% Xe, 27% CO_2 and 3% O_2. Gas composition and high voltage are chosen to ensure that the maximum drift time for hits close to the wall is below 50 ns with a gas amplification factor of 2.5×10^4. The gas gain is continuously monitored by the Gas Gain Stabilization System and the high voltage is adjusted to keep the gain value stable. The system achieves a stabilization of the gain factor on a 2% level compensating changes in temperature, pressure and gas composition.

For electron identification the TRT exploits Transition Radiation (TR), soft X-ray photons emitted by charged particles traversing a boundary between material layers of varying refractive index. The emitted photons are detected in the straw tubes by absorption on xenon atoms and subsequent ionization. In this way TR deposits a much higher energy in a single straw than an ionizing particle usually does. In ATLAS, normally only electrons reach a velocity which is needed to generate Transition Radiation thus the detection of a TR photon indicates the traversing of an electron. The emission of TR happens in dedicated radiators which are interleaved with the straws. By introducing multiple layers of radiator material and choosing their spacing in the right way, the emission of TR can be stimulated coherently amplifying the yield of emitted transition radiation.

The Barrel region covers the range $|\eta| < 1$ and comprises 52544 straws parallel to the beam axis arranged in 73 layers[2]. Each straw has a length of 144 cm and the outermost 64 straw layers are electrically split in the middle so both sides can be read out independently. The innermost nine layers are split in three parts with only the outer 31.2 cm being read out while the middle parts remains inactive. This design was chosen to ensure the hit rate of a single readout channel is kept below 20 MHz at LHC design luminosity. As a radiator a matrix of oriented polymer fibers was chosen filling the TRT volume and embedding the straws. Mechanically the Barrel consists of three layers of 32 modules which provide stabilization and cooling for the straws they contain. The modules are arranged in a non-projective geometry to avoid dead gaps.

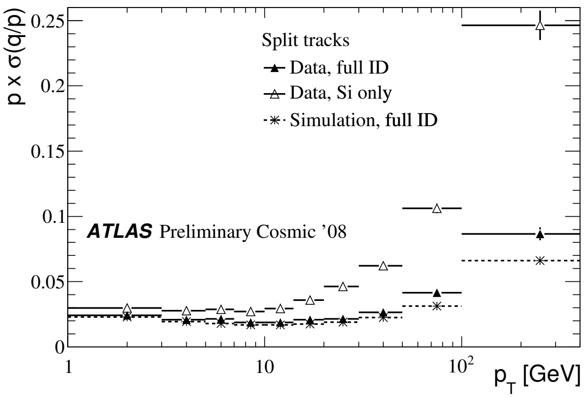

Figure 2. Momentum resolution of the ATLAS tracking system with and without using the TRT information for 2008 cosmic data.

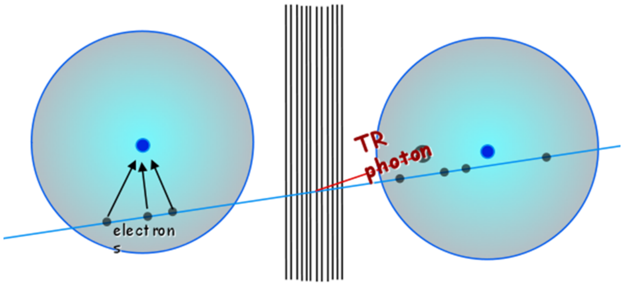

Figure 3. Working principle of the TRT. Primary ionization clusters are generated by traversing charged particles and absorbed transition radiation photons.

The end-cap region covers the range $1 < |\eta| < 2$. Each end-cap contains 122880 37 cm long straws in 160 layers[3]. The straws are oriented radially and are mechanically and electrically arranged in 20 wheels of eight layers. Thin polymer foils are interleaved with the wheels and serve as radiators.

In total each track traversing the detector volume crosses approximately 35 straws (except in the gap region between end-cap and barrel) with a point resolution of $130\,\mu$m over a distance of roughly half a meter. With these measurements the TRT significantly improves the momentum resolution for charged tracks as can be seen in Fig. 2.

B. *Signal formation and digitization*

A charged particle crossing a straw causes primary ionization in the drift gas thus creating charge clusters as depicted in Fig. 3. In the electric field of the straw the electrons drift towards the wire where they are multiplied in an electric avalanche. A Transition Radiation photon, created in one of the radiator layers, is absorbed in the Xe gas and creates primary ionization as well (however more than most traversing charged particles). The individual straws are directly coupled to the ASDBLR[1] frontend chip where the electric pulses are amplified, shaped and the slow ion drift tail of the signal is suppressed[4]. In this way the net signal is the superposition of several smaller signals each generated when a primary

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[1] Amplifier-Shaper-Discriminator with Baseline Restoration

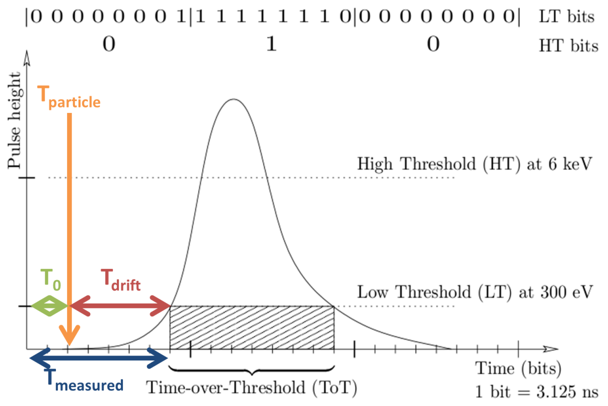

Figure 4. Digitization and timing of a TRT pulse. The colored arrows are depicting different timings important for the reconstruction of a physical hit.

cluster reaches the wire. An illustration is shown in Fig. 4. The ASDBLR moreover contains two independent discriminators set to different thresholds. The lower one is set to approximately 300 eV which is well below the median energy deposition of a minimum ionizing particle. The upper one is set to 6 keV and thus primarily sensitive to energy deposition by a TR photon. Those thresholds are tuned with reference to the electronic noise and a test pulser on the ASDBLR chip once a week during special calibration runs. In practice the low threshold is set in a way to give a uniform noise detector occupancy of 2% while the high threshold is tuned to give a uniform probability for high threshold hits over the detector.

The ASDBLRs are coupled to DTMROC[2] digitization chips. For each triggered event, 75 ns (i.e. three bunch crossings) of the signal are digitized with different timing characteristics.

The low threshold signal (LT) is digitized in bins of 3.125 ns width. Its leading edge (i.e. the first bin in a readout window which is high) corresponds to the arrival of the first cluster at the wire determining the drift time and hence the distance of closest approach of the track to the wire. The trailing edge contains the same information about the last ionization cluster and can be used for pileup suppression among other things. The time over threshold (ToT, i.e. the time between leading and trailing edge) contains information about the distance the particle traveled through the straw, its deposited energy etc. and can be used for particle identification. By design the maximal pulse length of a "real" signal is about 50 ns so the readout timing has to be adjusted with respect to the collision timing in a way those 50 ns are contained within the readout window. This has been done using cosmic and single beam events with an achieved precision below 1 ns. The high threshold signal (HT) is only sampled three times per readout window. The mere presence of a HT hit indicates a possible electron so no further timing is required. The tracking is done by the LT hits.

Fig. 4 shows also some timings relevant for the readout. The readout window is adjusted relative to the LHC clock in a way that the pulse is completely contained in the readout window. This adjustment is made in hardware during special calibration runs once per week. The "physical" time of arrival of a particle T_{particle} is not coincident with the start of the readout window but has an offset T_0 due to time of flight and signal propagation time along the straw. This offset is calibrated offline for every run and chip (see Sec. IV)[6]. The measured time T_{measured} contains the drift time T_{drift} and this offset.

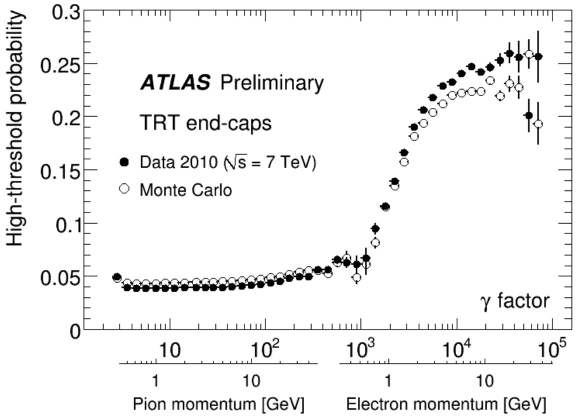

Figure 5. Probability of a TRT high-threshold (HT) hit as a function of the Lorentz factor, $\gamma = \frac{E}{m}$, for the TRT end-cap region, as measured in 7 TeV collision events.

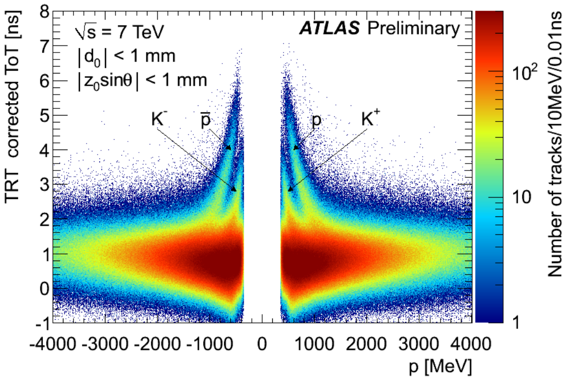

Figure 6. Estimator for specific charged particle energy loss based on the Time over Threshold (ToT) measured by the TRT. The estimator demonstrates the capability to use ToT as an observable for particle identification for heavily ionizing particles. The tracks are required to have at least one pixel, at least six SCT, and at least 15 TRT hits.

III. PARTICLE IDENTIFICATION

The TRT offers two different ways of identifying particles. For separating pions from electrons the fraction of high threshold hits on a track can be used. As described above the probability for generating a transition radiation photon and a subsequent high threshold hit is much higher for electrons than for pions. An example plot for the onset of transition radiation can be seen in Fig. 5. At high values of γ (above $\gamma = 1000$), a nearly pure sample of electrons is obtained from photon conversions. For low values of γ, all selected tracks in the event are used and are assumed to have the mass of the charged pion. As expected from the production of transition radiation

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[2] Digital Time Measurement Read-Out Chip

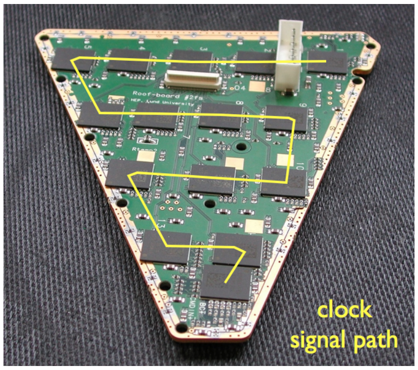


Figure 7. Signal path of the timing signal along one frontend board. Readout chips are fed serially so the timing offset has to be calibrated.

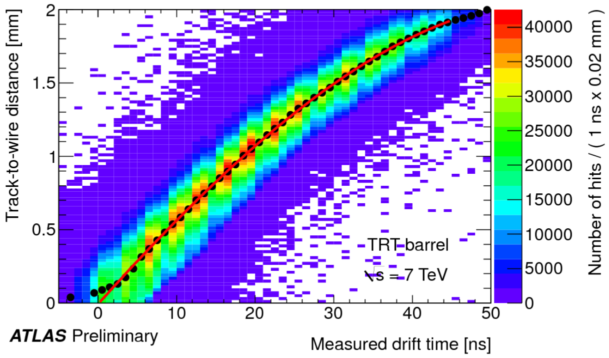


Figure 8. Example for a r-t calibration curve. The track-to-wire distance computed from the track fit is plotted versus the measured drift time. Dots show time-slice-wise fit means of the distributions while the red curve represents the calibration used.

(TR), the probability of a HT hit increases for particles with a γ-factor above 1000, which enables the TRT to separate electrons from pions over a momentum range between 1 GeV and 150 GeV. The data shows a higher TR detection than the one predicted by the MC, which was tuned to test beam data.

The second possibility of identifying particles in the TRT is by the specific energy deposit dE/dx in the gas volume. As an estimator for this quantity, the measured time over threshold (i.e. the time between leading and trailing edge) is taken as a starting point. After applying various corrections to accommodate for physical variation (e.g. the actual length the track was passing through the straw) a good estimator for the specific energy loss can be achieved as demonstrated in Fig. 6. Proton and kaon bands are clearly visible and distinguishable.

The amount of data collected to date allows for detailed studies of the HT onset as well as the energy deposit behavior of different particle species. Different possible methods for corrections are being studied so significant improvements in particle identification are expected soon.

IV. CALIBRATING THE TRT

Calibrating the TRT is essential for ensuring its high precision and reliability. By design each drift-type detector measures a time which has to be converted into one or more spatial coordinates. This conversion requires a mapping which is often highly sensitive to external effects and hence has to be calibrated regularly.

There are two different quantities requiring a regular offline calibration with collisions data. T_0, the time between the beginning of the readout window and the physical arrival of a particle originating from the bunch crossing associated with that window. And the relation between the measured (and corrected) drift time and the distance of closest approach of the track to the wire (r-t relation).

In hardware, the timing of the readout window can only be tuned for single readout boards in fixed steps of 0.5 ns. Within a given board there is still a timing spread of up to 3 ns. For the desired resolution however a precision in the order of 100 ps has to be achieved. One of the main effects requiring offline calibration is illustrated in Fig. 7. The timing signal is distributed to the different DTMROCs on a readout board serially resulting in a small offset between neighboring chips. Routinely the offset is measured for every straw in each run and a calibration is run on the level of single chips. Straws connected to one chip were found to show no major variations in timing. Experience shows that calibration constants have to be updated every few weeks. The main reasons for such frequent updates are linked to the slow drifts of the time reference provided by the LHC and replacements of single hardware components in the readout or triggering chain.

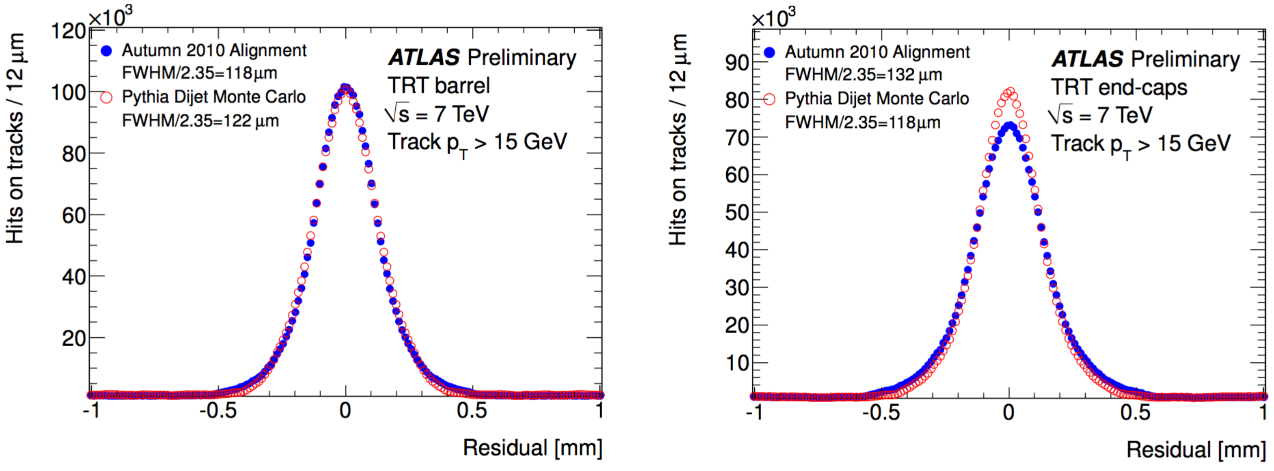
The r-t relation is measured by comparing the measured drift time with the distance of closest approach computed from the overall track fit. An example can be seen in Fig. 8. This relation is affected by changes in the high voltage or the gas composition and by the presence or absence of the magnetic field. Since both quantities are calibrated iteratively and in parallel and are related to each other, one point has to be fixed in the r-t relation to ensure fit convergence. Currently this is taken to be the drift radius of 1 mm at a drift time of 18 ns. In last year's running, the r-t relation proved to be very stable under nominal running conditions.

V. PERFORMANCE IN PROTON COLLISIONS

For quantifying the tracking performance of the TRT there are two key quantities: The spatial resolution and the average straw efficiency.

For estimating the spatial resolution, the unbiased track residuals are computed. For tracks with $p_T > 15\,\mathrm{GeV}$ the distribution of the difference of the measured track-to-wire distance and the same quantity computed from the track fit is used. The straw being considered is excluded from the track fit to avoid any bias. Distances and times are assigned a sign depending on which side of the wire itself they lie. The residual is expected to be approximately a Gaussian distribution centered at zero with a width which is equal to the average spatial resolution of the TRT straws convoluted with the track fit error. The residual distributions for both barrel and end-caps for $7\,\mathrm{TeV}$ running are show in Fig. 9. In the barrel region, the resolution of $118\,\mu\mathrm{m}$ even exceeds the resolution measured in Monte Carlo with a perfectly aligned detector. For the end-cap a width of $132\,\mu\mathrm{m}$ is measured.

The excellent performance of the barrel is a consequence of the LHC incident in 2008. ATLAS used the enforced break to



(a) Barrel

(b) End-cap

Figure 9. Unbiased residuals for the TRT for $\sqrt{s} = 7\,\mathrm{TeV}$ collisions. Tracks are required to have $p_T > 15\,\mathrm{GeV}$, and at least 6 hits in the Silicon detectors. Solid blue circles show collisions data using the latest alignment while open red circles show Monte Carlo studies assuming a perfectly aligned detector.

conduct an extensive program of cosmic ray studies. During these studies the TRT served as main trigger for ATLAS. Since the wheel structures in the end-caps are more or less parallel to the preferred direction of cosmic rays only limited studies for the end-caps could be performed while significant study could be made of the barrel.

A significant improvement in the resolution could be gained by the latest efforts in alignment using the 2010 7 TeV data[7]. In general ATLAS employs three levels of alignment for the Inner Detector. At the first level only whole detector structures (e.g. TRT barrel) are aligned with respect to each other. Level 2 alignment includes also the relative alignment (e.g. single 8-plane wheels in the TRT end-caps). At the end of 2010 for the first time the amount of data collected was sufficient to perform a level 3 alignment on the TRT, i.e. aligning each single straw individually adding 701696 degrees of freedom to the alignment procedure.

Apart from improving the overall performance, the level 3 alignment also accounts for some systematic deviations that are not accessible when aligning modules and wheels. Fig. 11a shows the mean of the residual distribution contributed per 4-plane half wheel in one end-cap. One clearly sees an alternating pattern. This kind of pattern can be explained by a slight elliptic deformation of the half-wheels. When addressing the alignment of every single straw such deformations can be accounted for so the same distribution after the straw-by-straw alignment is much more uniform (Fig. 11b).

The straw efficiency is computed similarly to the residuals. For each straw in a given part of the detector, the efficiency of finding a hit if a track traverses the straw volume in a given distance from the wire is measured and averaged over the whole detector partition. The first and last straws on a track are excluded from the efficiency calculation. Known non-functional straws (∼2%) are also exlcuded. The tracks are required to have at least one pixel hit, six SCT and 15 TRT hits, as well as $p_T > 1\,\mathrm{GeV}$, $|d_0| < 10\,\mathrm{mm}$ and $|z_0| < 300\,\mathrm{mm}$ to assure a good extrapolation into the TRT.

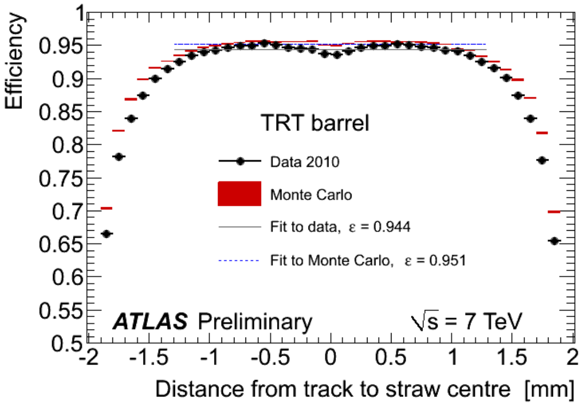


Figure 10. This plots show the TRT hit reconstruction efficiency as a function of distance of closest approach of the track to the straw center. The hit reconstruction efficiency is defined as the number of straws with a hit on track divided by the number of straws crossed by the track. The efficiency for data (MC) is found to be 94% (95%) in the plateau region which is defined by the solid lines. The threshold in the Monte Carlo is tuned to the data collected during the 900 GeV center of mass collision data.

As an example the efficiency curve in the barrel for 7 TeV running is shown in Fig. 10. While showing a plateau with an overall efficiency of 94.4% this value drops due to geometric and reconstruction reasons at the edges of the straw. This efficiency is maintained throughout the whole detector and has not changed compared to the 2009 runs at lower beam energy.

VI. PERFORMANCE IN HEAVY ION COLLISIONS

At the end of 2010 the LHC was run for several weeks with lead ions (instead of protons) at $2.76\,\mathrm{GeV}/A$. Although ATLAS was not designed with heavy ion physics in mind, the whole detector was operated and data was being recorded and analyzed. Being the tracking detector with the lowest granularity in ATLAS, the TRT was especially challenged by the harsh conditions of high energy ion-ion collisions.

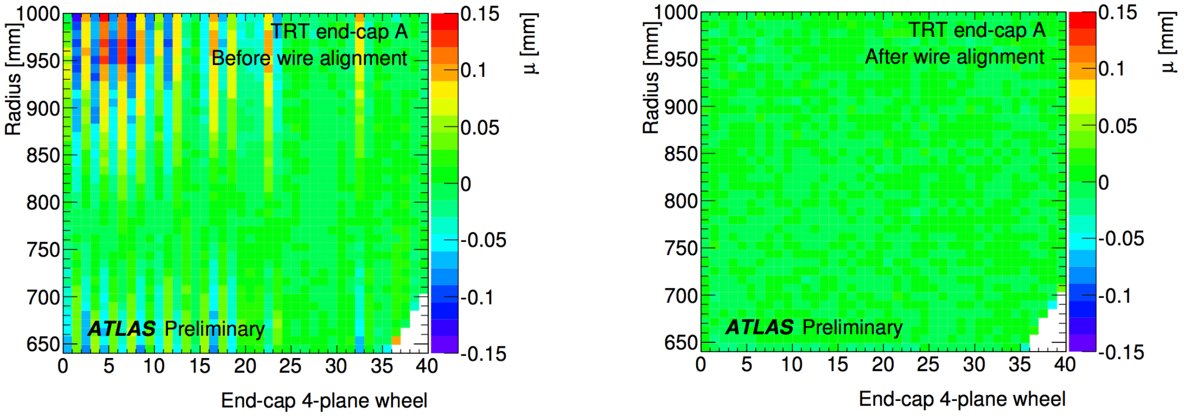


Figure 11. Shift of the residual distribution for individual half-wheels in end-cap A before and after performing level 3 alignment. The observed pattern is the result of a slight elliptic deformation of the half-wheels which are mounted together back-to-back to form a full wheel. This can be addressed by performing a straw-by-straw alignment.

Depending on the overlap of the nuclei events with several thousand charged tracks resulting in detector occupancies as high as 95% could be observed.

For an efficient tracking under these conditions the way of reconstructing tracks has to be modified. In the heavy ion reconstruction algorithms only tracks seeded by hits in the SCT/Pixel detectors are taken into account and extrapolated outwards into the TRT volume while for pp running tracks found in TRT are also extrapolated inwardly and matched to SCT/Pixel hits. Moreover the extrapolating algorithm has to be modified to work with a higher rate of tracks overlapping in a given straw and the higher track density in general. Given the sensible choice of the parameters mentioned, the TRT is able to provide an essential contribution to the momentum resolution and lower the fake track finding rate over the whole p_T range significantly.

VII. SUMMARY

The TRT is an excellent detector improving ATLAS tracking with its long lever arm and the high number of hits per track. Already in this early phase of LHC running the TRT exceeds its design performance goals. Its capability in discriminating electrons from pions is an integral component of the ATLAS electron identification algorithm.

During LHC heavy ion running the detector has proved suited to even the very high occupancies well above what is expected for LHC design luminosity. Thus giving us confidence the TRT is ready for at least ten more years of LHC running to be recorded.

ACKNOWLEDGMENT

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REFERENCES

[1] The ATLAS collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 (2008) S08003.
[2] E. Abat et al., *The ATLAS TRT Barrel Detector*, JINST 3 (2008) P02014.
[3] E. Abat et al., *The ATLAS TRT end-cap detectors*, JINST 3 (2008) P10003.
[4] E. Abat et al., *The ATLAS TRT electronics*, JINST 3 (2008) P06007.
[5] E. Abat et al., *The ATLAS Transition Radiation Tracker (TRT) proportional drift-tube: Design and Performance*, JINST 3 (2008) P02013.
[6] The ATLAS collaboration, *Calibration of the ATLAS Transition Radiation Tracker*, (2011) (ONLINE) http://cdsweb.cern.ch/record/1330712/files/ATLAS-CONF-2011-006.pdf
[7] The ATLAS collaboration, *Alignment Performance of the ATLAS Inner Detector Tracking System in 7 TeV proton-proton collisions at the LHC*, (2010) (ONLINE) http://cdsweb.cern.ch/record/1281342/files/ATLAS-CONF-2010-067.pdf