

The ATLAS TRT and its Performance 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 almost 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 $p_T > 0.5$ GeV/c. 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 talk, a review of the commissioning and first and current operational experience of the TRT detector and its performance at LHC will be presented. Emphasis will be given to performance studies based on the reconstruction and analysis of LHC collisions. A comparison of the TRT response and the particle identification in pp and Pb-Pb collisions will be presented. The results are also compared with the expected performance.

1. 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 proton collisions, designed center of mass energy is $E_{CM} = 14$ TeV, interaction rate is $f = 40$ MHz which corresponds $T = 25$ ns bunch spacing and instantaneous luminosity $L = 10^{34}$ cm⁻²s⁻¹. Beams were first injected at energies of 450 GeV on September 2008 followed by a 14 month shutdown period for repairs. As of November 2009 there had been collisions at $E_{CM} = 900$ GeV for a short time before the commissioning for 3.5 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 2×10^{33} cm⁻²s⁻¹ so far. At the end of 2010, the LHC delivered a short run of Pb-Pb collisions at centre-of-mass energy of nucleons at $E_{CM} = 2.76$ TeV. In Pb-Pb collisions, $10 \mu\text{b}^{-1}$ data have been delivered by LHC.

Currently, the LHC is running at $E_{CM} = 7$ TeV with $T = 50$ ns bunch spacing and has delivered a total of 1.05 fb^{-1} , and ATLAS has recorded 1.01 fb^{-1} in the 2010 and 2011 7 TeV proton collisions. The $E_{CM} = 7$ 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.

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2. The ATLAS Detector

The ATLAS detector is a hermetic 4π multipurpose 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 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 1.4T 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 2T magnetic field for the Inner Detector.

The Inner detector covers the range of $|\eta| < 2.5$ and provides tracking and particle identification for charged particles ($e-\pi$) with a transverse momentum $p_T > 0.5$ GeV/c. The inner detector consists of pixel and silicon micro-strip detectors surrounded by a Transition Radiation Tracker (TRT). A schematic view of the inner detector is shown in Figure 1.

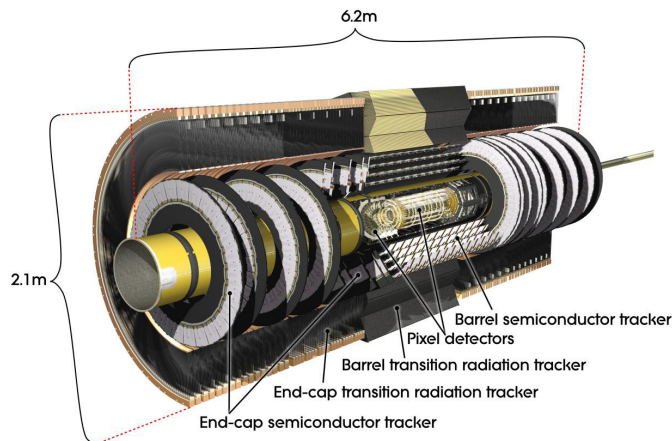


Figure 1. Cut-away image of the ATLAS Inner Detector.

The calorimeter system, covers the pseudorapidity range $|\eta| < 4.9$ and uses a variety of techniques. The electromagnetic calorimeter is a lead liquid argon (LAr) detector in the barrel region and in the forward region copper LAr technology is used; it provides $e-\gamma$ trigger, identification and measurement. The hadronic calorimeter with scintillator tiles or LAr as the active material and with either steel, copper or tungsten as the absorber material, provides trigger, jet measurements and missing transverse energy measurement. Finally the Muon Spectrometer is based on the magnetic deflection of muon tracks in the large superconducting air-core toroid magnets, instrumented with separate trigger and high-precision tracking chambers covering the pseudorapidity range up to $|\eta| < 2.7$.

The trigger system of ATLAS comprises of three levels: the first level (L1), which is fully hardware, is implemented in the calorimeters and the Muon Spectrometer. The other two levels, the level two (L2) and the Event Filter (EF) are software based: the L2 accepts data from defined Regions Of Interests (ROI) of L1 and the EF which provides a full event reconstruction on computer farms [2].

3. The Transition Radiation Tracker

The ATLAS Transition Radiation Tracker (TRT) is the outermost of the three sub-systems of the ATLAS inner detector. It extends to a radius of 1082 mm from the interaction region. Its design was driven by the need to get continuous tracking with long lever arm and electron identification in the pseudorapidity range $|\eta| < 2$. It was also designed to provide a point resolution of 130 μm and withstand the challenging LHC environment with a high particle density and accumulated radiation dose [3].

3.1. TRT design

TRT is 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 [4]. Keeping the wire at ground, the potential difference between the straw wall and the wire is 1.5 kV. Therefore the charge clusters created through primary ionization, as depicted in Figure 2, undergo avalanche multiplication near the wire with a amplification factor of 2.5×10^4 . The straw is filled with a gas mixture of 70% Xe, 27% CO₂ and 3% O₂. Gas composition and high voltage are chosen for stability and transition radiation performance.

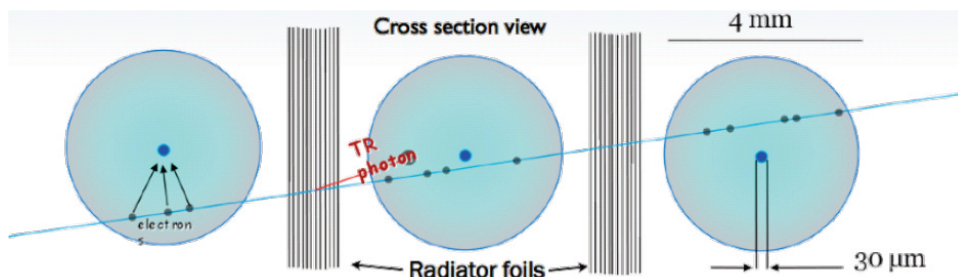


Figure 2. Working principle of the TRT. Primary ionization clusters are generated by traversing charged particles and absorbed TR photons.

For electron identification the TRT exploits Transition Radiation (TR), soft X-ray photon emitted by a charged particle when traversing the boundary between materials with different dielectric constants $(\epsilon_1, \epsilon_2)^2$. 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 TRT barrel covers $|\eta| < 1$ and comprises totally 105088 readout channels parallel to beam axis arranged in 73 layers. Each straw has a length of 144 cm. The design was chosen to ensure the hit rate of a single readout channel is kept below 20 MHz at LHC design luminosity[5]. The end-cap regions cover the range $1 < |\eta| < 2$. Each end-cap contains 122880 39 cm long straws oriented radially in 160 layers[6].

Each charged track traversing the detector volume crosses on average 30 straws with a point resolution of 130 μm 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 Figure 3.

3.2. Signal formation and digitization

A particle crossing a straw causes some primary ionization centers to create electrons which drift to the anode wire where electrons are multiplied in an electric avalanche. Hence a measurable signal can be generated. A Transition Radiation photon, created in one of the radiator layers, is absorbed in the

² Note that the emitted TR energy and intensity are proportional to $\epsilon_1 - \epsilon_2$ and particle Lorentz factor, $\gamma = E/m$, respectively. In addition, TR emission angle with respect to the particle direction is proportional to $1/\gamma$.

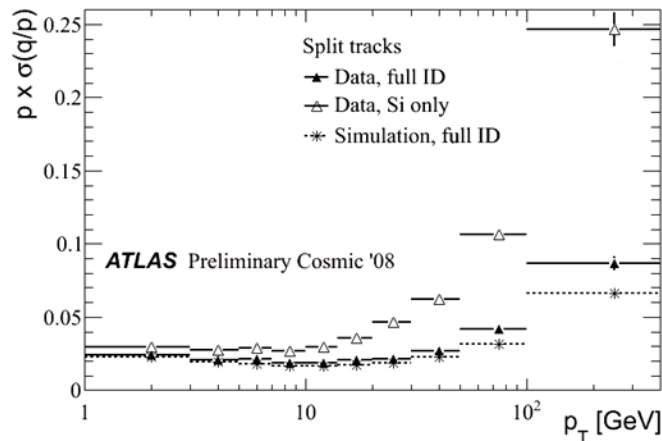


Figure 3. Momentum resolution of the ATLAS tracking system with and without using the TRT information. Contribution of TRT at high energy can be seen clearly

Xe gas creating primary ionization as well. This additional ionization from TR increases the electric pulse height obtained in the straw tube. To measure the signal, the individual straws are directly coupled to the ASDBLR (Amplifier-Shaper-Discriminator with Baseline Restoration) frontend chip. Here electric pulses are amplified, shaped and the slow ion drift tail of the signal is suppressed [7]. The ASDBLR moreover contains two independent discriminators set to different thresholds: a low threshold (300 eV) for registering the passage of minimum ionizing particles and a high threshold (6 keV) to flag the absorption of transition radiation X-rays.

The ASDBLRs are coupled to DTMROC (Digital Time Measurement Read-Out Chip) digitization chips. For each triggered event, 75 ns (i.e. three bunch crossings) of the signal are digitized with different timing characteristics. Note that the time resolution of TRT is about 3 ns. Leading edge of the pulse gives information about the drift time of the electrons to the wire and hence the distance of closest approach of the track to the wire. So, this information is used for tracking of the charged particle passing through the straws.

An example of digitization and timing of TRT pulse is shown in Figure 4.

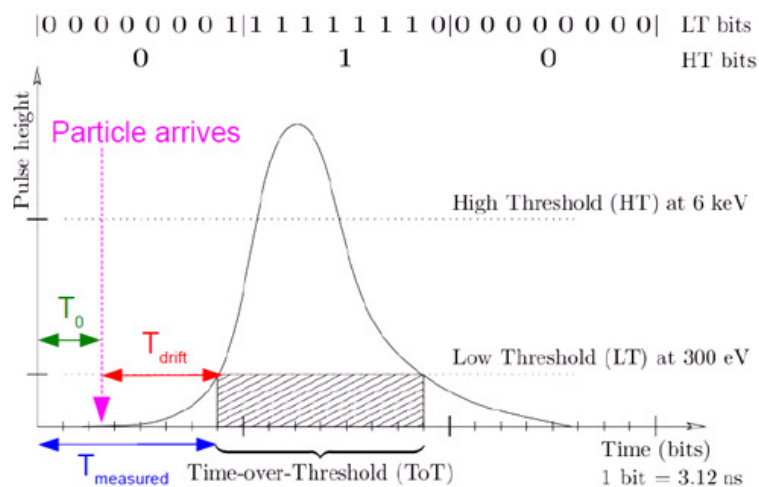


Figure 4. Digitization and timing of a TRT pulse.

3.3. TRT calibration

By design each straw measures a time which has to be converted into spatial coordinates. We need a calibration function which relates the measured time and track's closest distance to the wire. In TRT, to do that two calibration procedures are applied. One is the R-t relation which converts drift time to a measured drift radius. For all TRT straws, one R-t relation is used for Barrel and one for end-cap. The other one is the T_0 calibration 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. T_0 calibration is performed in hardware level. Each calibration is performed regularly after every run.

An example R-t curve can be seen in Figure 5.

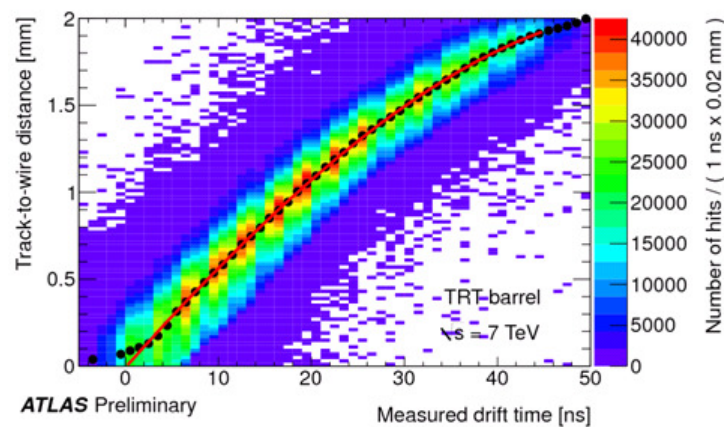


Figure 5. Example for a R-t calibration curve.

3.4. Particle identification with TRT

The TRT offers two different ways of identifying particles.

For separating electrons from charged pions, the fraction of high threshold hits on a track can be used. As indicated in Figure 6, the probability (which depends on particle γ value) for generating a transition radiation photon and a subsequent high threshold hit is much higher for electrons than for pions³. With this way, TRT separates electrons from pions over a momentum range between 1 GeV/c and 150 GeV/c.

TRT also provides particle identification information in the form of dE/dx measurements for charged particles. As an estimator for this quantity, the measured time over threshold, ToT , (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 Figure 7. Proton and kaon bands are clearly visible and distinguishable. Using ToT technique, particle identification with TRT can be used for the charged particles whose momentum is less than 10 GeV/c[3].

3.5. TRT performance in proton and heavy ion collisions

For quantifying the tracking performance of the TRT there are two key quantities: The spatial resolution and the average straw efficiency. The alignment and calibration procedures yield the resolutions of 118 μm for barrel and 132 μm for end-cap hit resolutions in 7 TeV proton collisions.

³ Consider a particle with momentum $p = 10$ GeV/c crossing a total of 30 straws. Using binomial theorem and assuming the probability is constant for all straws one can calculate expected number of HT hits. For example, for the electron hypothesis expected number of high threshold hits is 6 while for the pion hypothesis it is 1.2.

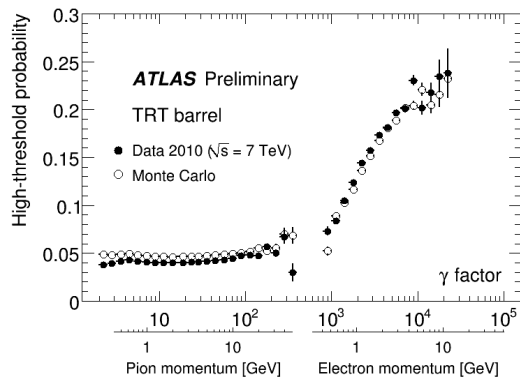


Figure 6. Probability of a TRT high-threshold hit as a function γ factor as measured in 7 TeV collision events.

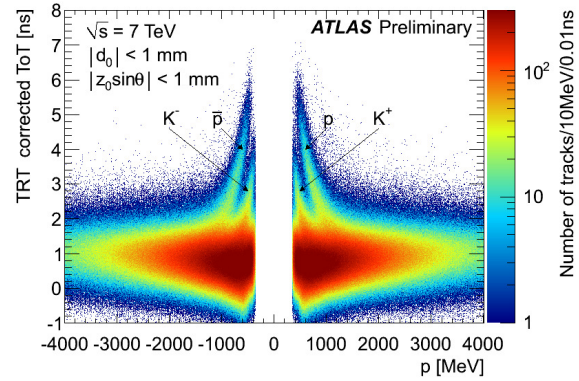


Figure 7. Shown are the TRT corrected ToT versus track momentum. One can see the different populations from different particles.

An example resolution distributions are shown in Figure 8 for the barrel and in Figure 9 for the end-cap regions for the data and Monte Carlo studies which assume the perfectly aligned detector.

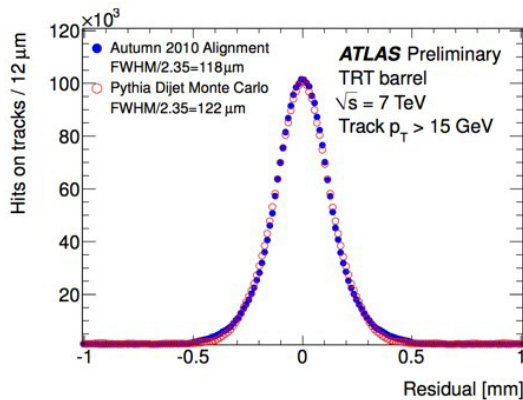


Figure 8. Residual distribution for the barrel.

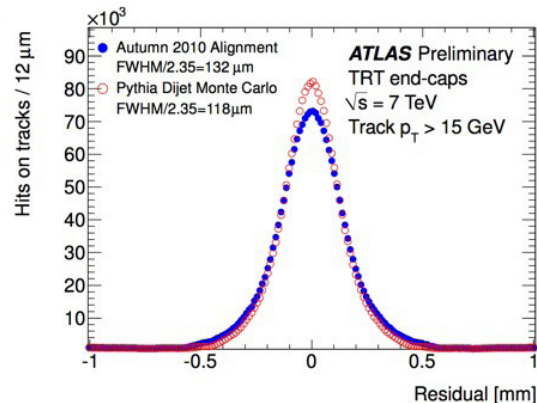


Figure 9. Residual distribution for the end-cap.

The straw hit efficiency is defined as number of hits on straw divided by number of tracks passing that straw. As an example the efficiency curve in the barrel for 7 TeV running is shown in Figure 10. Inefficiency at outer straw radius is due to reconstruction effects and smaller electric signal pulse size.

Although ATLAS was not designed with heavy ion physics in mind, the whole detector was operated and data was being recorded and analyzed. The TRT was especially challenged by the harsh conditions of high energy ion-ion collisions. Depending on centrality of the events, several thousand charged tracks resulting in detector occupancies as high as 95% could be observed. However, even in high occupancy, TRT contributes to the tracking information[3].

4. Summary

The TRT is an excellent detector improving ATLAS tracking with its long lever arm and the high number of hits per track. It also provides discrimination between electrons and charged pions. During LHC stable beams in 2010 and 2011 TRT achieved 100% data taking efficiency. The alignment and

calibration procedures resulted in $\sim 120(130)$ μm hit resolution in Barrel(End-cap). Barrel hit resolution is better than the design expectations.

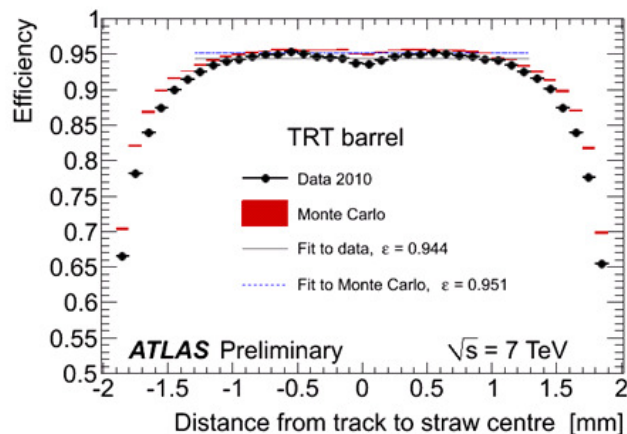


Figure 10. Example efficiency curve for the barrel.

The results obtained from heavy ion collisions indicate that the TRT provides useful tracking information even in high occupancy. Thus giving us confidence that the TRT is ready for at least ten more years of LHC running to be recorded.

5. Acknowledgement

The ATLAS collaboration wishes to thank CERN for the efficient commissioning and operation of the LHC during this initial high-energy data-taking period as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the TRT colleagues making the detector perfect.

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