ATLAS Transition Radiation Tracker (TRT): Straw Tube Gaseous Detectors at High Rates

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Abstract

The ATLAS Transition Radiation Tracker (TRT) is the outermost of the three tracking subsystems of the ATLAS Inner Detector. The ATLAS detector is located at LHC/CERN. We report on how these gaseous detectors (“straw tubes”) are performing during the ATLAS 2011 and 2012 runs where the TRT experiences higher rates than previously encountered. The TRT contains around 300000 thin-walled proportional-mode drift tubes providing on average 30 two-dimensional space points with an intrinsic resolution of approximately $120\,\mu$m for charged particle tracks with $|\eta| < 2$ and $p_T > 0.5\,GeV$. Along with continuous tracking, the TRT provides electron identification capability through the detection of transition radiation X-ray photons. During the ATLAS 2012 proton–proton data runs, the TRT is operating successfully while being subjected to the highest rates of incident particles ever experienced by a large scale gaseous tracking system. In the second half of 2012, the TRT has collected data in an environment with instantaneous proton–proton luminosity around $0.8 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. While shadowing effects caused by up to 40 simultaneous proton–proton collisions per bunch crossing are noticeable, the TRT performs significantly better than design. It also contributes to the combined tracking system p_T resolution and to electron identification. During LHC heavy ion running in 2011, the TRT contributed to measuring track p_T even in events where overall occupancy exceeded 50 %.

Keywords: ATLAS, Transition Radiation Tracker, TRT, Performance

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1. Introduction

The ATLAS experiment [1] is one of the four large particle detectors at the Large Hadron Collider (LHC) at CERN. It is a multi-purpose detector and consists of three main components: Inner Detector, calorimeters, and Muon Spectrometer. The Inner Detector in turn comprises three subsystems: the silicon Pixel detector, the Semiconductor Tracker (SCT), and the Transition Radiation Tracker (TRT). Immersed in a solenoidal magnetic field of 2 Tesla, the Inner Detector measures trajectories and momenta of charged particles with $p_T > 0.5$ GeV up to a pseudorapidity of $|\eta| = 2.5$.

2. Design of the TRT

The TRT is a straw-tube tracker. It consists of drift tubes with a diameter of 4 mm that are made from wound Kapton and reinforced with thin carbon fibres. In the centre of each tube there is a gold-plated tungsten wire of $31\,\mu$m diameter. With the wall kept at a voltage of -1.5 kV and the wire at ground potential, each tube acts as a small proportional counter. The tubes are filled with a gas mixture of 70 % Xe, 27 % CO_2, and 3 % O_2.

The TRT barrel region contains 52 544 straw tubes of 1.5 m length, parallel to the beam axis. They cover a radius from 0.5 m to 1.1 m and a pseudorapidity range of $|\eta| < 1$. The central wires are electrically split and read out at both ends of the straw. The endcaps contain radial 0.4 m long straws that are arranged perpendicularly to the beam axis. Each side consists of 122 880 straws, covering the geometrical range $0.8\,\mathrm{m} < |z| < 2.7\,\mathrm{m}$ and $1 < |\eta| < 2$. The endcap straws are read out at their outer end.

When a charged particle traverses the TRT, it ionises the gas inside the straws. The resulting free electrons drift towards the wire, where they are amplified and read out. The front-end electronics samples the incoming signal in 24 time bins of 3.12 ns and compare it against a threshold corresponding to 300 eV, resulting in a 24-bit pattern that gets buffered in a digital pipeline and then passed on to the central ATLAS data acquisition. The maximum readout rate of the system is currently 80 kHz, with a foreseen upgrade to 100 kHz.

The spaces between the straws are filled with polymer fibres (barrel) and foils (endcaps) to create transition radiation, which may be emitted by highly relativistic charged particles as they traverse a material boundary. This effect depends on the relativistic factor $\gamma = E/m$ and is strongest for electrons, which means it can be used for particle identification (section 6). Typical photon energies are 5–30 keV. These soft X-rays can be absorbed by Xe atoms, depositing additional energy in the gas and leading to significantly higher readout signals. Such signals are detected by comparing them against an additional high threshold of 6 keV that is sampled in three 25 ns time bins alongside the pattern described before.

This design makes the TRT complementary to the silicon-based tracking devices: the intrinsic single-point resolution of $120\,\mu$m is larger than that of the silicon trackers, but this is com-

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pensated by the large number of hits per track (typically more than 30) and the long lever arm. Furthermore, the high sampling frequency of the wire signals enables the TRT to provide timing information on the nanosecond level.

3. Luminosity and Pile-Up

The instantaneous luminosity is one of the key figures of a particle collider: integrated over time and multiplied with the cross-section of a given process, it immediately determines the number of events and thus the statistics available for physics analyses. The LHC reached peak luminosities between 6 and almost $8 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ of proton–proton collisions during most of 2012. In order to achieve such luminosities, both revolving beams consisted of 1368 proton bunches that contained around $1.5 \cdot 10^{11}$ particles each. Furthermore, the LHC also delivered lead–lead and proton–lead collisions during dedicated running periods in 2011 and 2013. The TRT successfully took data in all of these beam configurations.

High luminosities are desirable, but with the typical beam conditions of 2012, 25–35 proton–proton collisions happen on average during each bunch crossing. This number, often denoted by μ, determines the in-time pile-up that is seen in each recorded event, and which poses a demanding challenge to the tracking and vertexing algorithms used for event reconstruction.

Closely related to μ is the number of primary vertices that are actually found after event reconstruction. Up to values of $\mu \approx 15$ the dependence is strictly linear, but for higher pile-up the reconstruction finds slightly less vertices than a simple linear extrapolation would suggest [2].

The bunch spacing influences the out-of-time pile-up that is seen by the detectors. In 2012 the LHC operated with a bunch spacing of 50 ns, which could be handled without problems by all detectors, including the TRT. In 2015 the LHC bunch spacing is likely to be reduced to 25 ns, which will shift the out-of-time pile-up much closer to each recorded event. However, data from test runs taken at the end of 2012 showed that the shorter bunch spacing is still manageable despite the more challenging conditions.

4. Tracking Performance

The TRT readout data merely contain time information, which needs to be calibrated to be useful for tracking [3]. The first step is the T_0 calibration, defining the offset between the start of the readout and the arrival of particles. It accounts for the time of flight, the signal propagation, and clock offsets. Its results are subject to small daily variations on the level of 100 ps, which are mainly caused by a drift of the central ATLAS clock.

The $R(t)$ calibration relates the measured drift time with a particle's distance of closest approach to the readout wire. It depends on the properties of the active gas (mixture, pressure, temperature), the voltage that is applied to the tube, and the magnetic field. The $R(t)$ relation is modelled by a third-order polynomial, as shown in Fig. 1. The resulting coefficients turn out to be very stable on the time scale of months. This is due to the TRT's "Gas Gain Stabilization System", which automatically adjusts the applied voltages to compensate for small variations of the other gas parameters. Precise monitoring of the composition of the gas mixture also contributes significantly to the long-term stability of the $R(t)$ fit parameters.

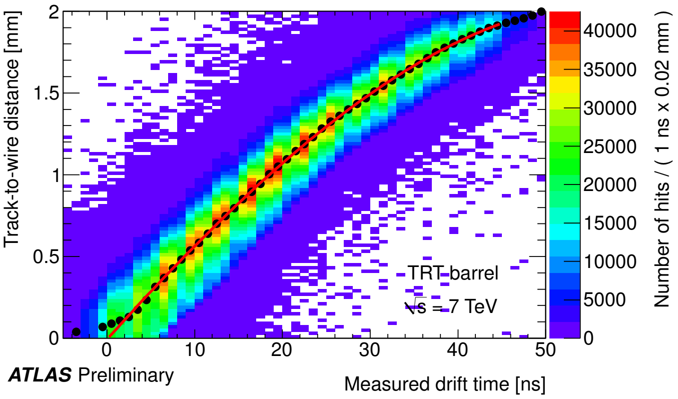

Figure 1: The $R(t)$ relation for the TRT barrel. The red line shows the relation that is used to determine the drift distance based on the measured drift time [3].

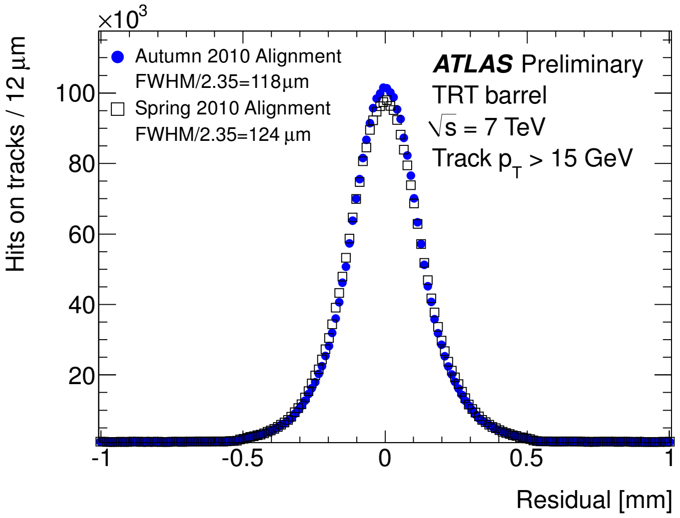

Figure 2: Unbiased tracking residual distributions for the TRT barrel, comparing the alignment of spring 2010 (open squares) with the improved alignment of autumn 2010 (solid circles) [4].

Figure 2 shows the resulting performance in terms of the unbiased tracking residual distribution for proton–proton collisions at low luminosity: using the alignment results of autumn 2010 and applying a cut of $p_T > 15\,\mathrm{GeV}$, residual widths of $118\,\mu\mathrm{m}$ (barrel) and $132\,\mu\mathrm{m}$ (endcaps, not shown) are achieved [4]. Providing an average of 30–40 such position measurements, the TRT contributes significantly to the tracking performance of the Inner Detector as a whole, particularly at high p_T. Figure 2 also points out the importance of the overall detector alignment: the residuals improve significantly by applying an improved set of alignment constants.

5. Tracking with Pile-Up

For proton–proton collisions at high luminosity, the TRT encounters straw occupancies between 10 and 60 %, strongly depending on the region of the detector [6]. Figure 3 shows that those values increase linearly with the number of vertices per event, as expected. The highest occupancies are seen in the inner barrel, the lowest are seen in the foremost part of the endcaps. The occupancy of high-threshold hits behaves similarly, but its absolute value is about one order of magnitude smaller than what is seen in Fig. 3.

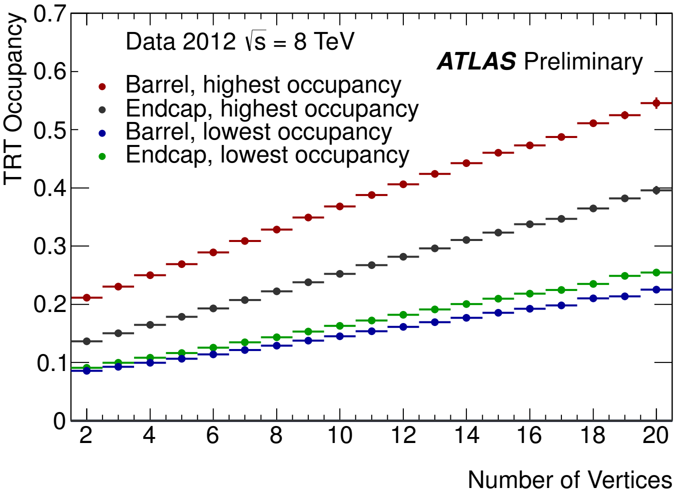

Figure 3: TRT occupancy vs. number of reconstructed primary vertices per event, shown separately for the barrel and endcap regions with highest and lowest occupancy [6].

Being a very simple quantity, the raw occupancy does not yet account for the drift time information that is associated to each hit. This means that occupancy values like the ones seen in Fig. 3 (or Fig. 6 below) are not as severe as they may seem at first sight, and the TRT is still able to provide tracking information even when its raw occupancy is very high.

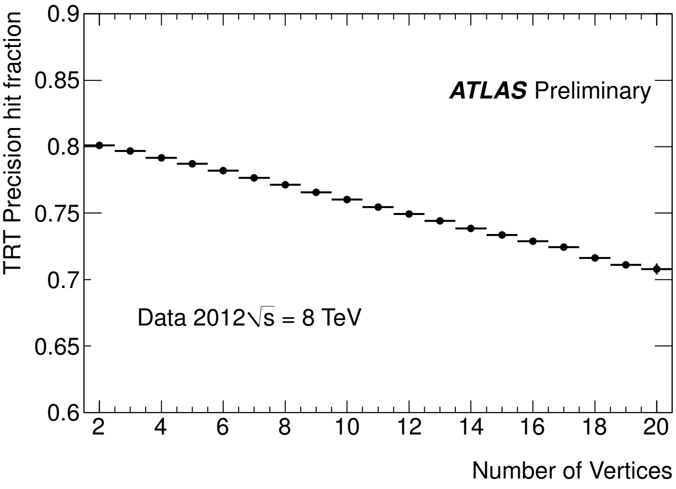

Figure 4: Fraction of TRT hits with good timing information (“precision hits”) vs. number of reconstructed primary vertices per event [2].

Hits with good timing information are called “precision hits”—they are the most useful for tracking. Not all hits are precision hits: the timing information may be deteriorated or lost due to random gaps in the ionisation pattern, the emission of δ-electrons, overlapping tracks, or out-of-time pile-up, for instance. The fraction of precision hits is around 0.8 at low pile-up and decreases linearly to 0.7 for a pile-up of 20 vertices per event [2], as shown in Fig. 4.

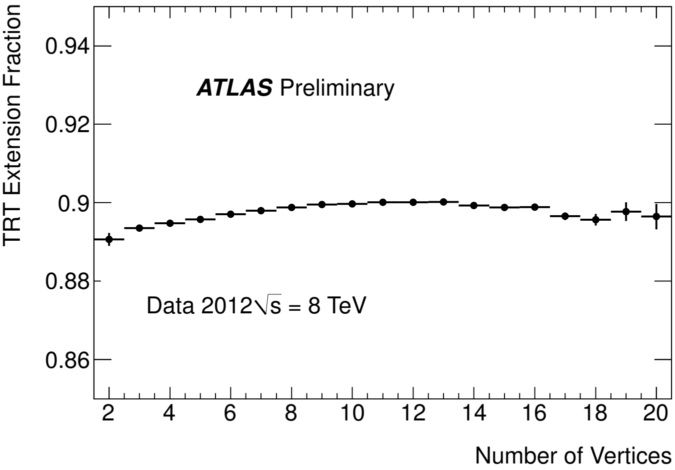

Figure 5: Fraction of tracks from the Inner Detector tracking where a track extension into the TRT could be found vs. number of reconstructed primary vertices per event [2].

Even though significant, this reduction does not have a severe impact due to the large number of hits per track: figure 5 shows that the fraction of silicon-seeded tracks that can be extended into the TRT remains almost flat at 0.9, essentially independent of the pile-up. Similarly, the total number of TRT hits that contribute to reconstructed tracks from the Inner Detector tracking hardly changes with pile-up [2].

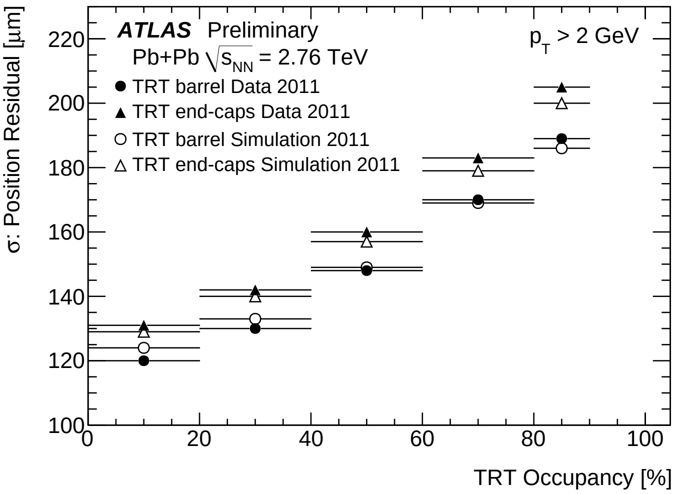

Figure 6: TRT position residual vs. TRT occupancy, using tracks with a transverse momentum above 2 GeV from lead–lead collision events [6].

Figure 6 shows the TRT position residuals for different occupancies, using tracks from lead–lead collisions that were recorded in late 2011. The residuals get worse for higher occupancies because less hits with good timing information are available: the earliest of two (or more) overlapping tracks that hit the same straw will always be used for reconstruction, whereas the later one(s) will always be lost. However, the deterioration of the position residuals is still moderate: even in extreme lead–lead events with an overall TRT occupancy above 80 % the residuals remain around 200 μm, compared to an intrinsic value of 120 μm at very low occupancy [6]. This means that the TRT is still able to provide additional position information to the Inner Detector tracking even in the densest of events that have been recorded so far.

6. Particle Identification

The fact that the emission of transition radiation is much more likely for an electron than for a pion of the same momentum can be used to discriminate these particle types [5]. Figure 7 shows the high-threshold turn-on curve, i. e. the probability of getting a high-threshold hit as a function of a particle's relativistic γ factor. This probability is low for pions over a large momentum range (and almost entirely due to Landau fluctuations), but it rises quickly for electrons with momenta of only few GeV. This allows electron–hadron discrimination over a wide energy range.

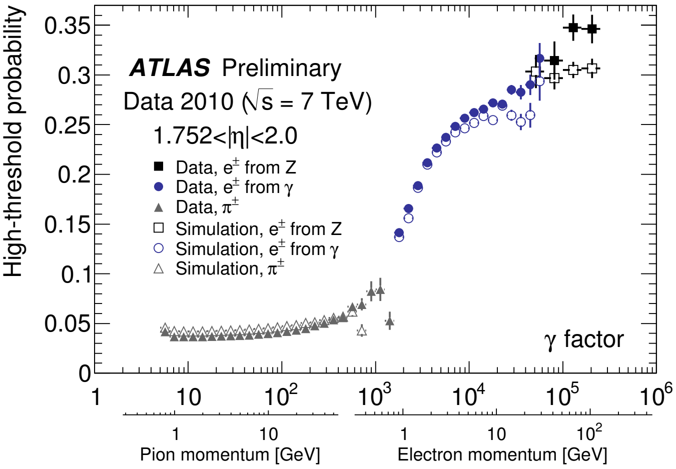

Figure 7: The high-threshold turn-on curve, shown for the outer endcap wheels [5].

Closely related to the high-threshold probability is the high-threshold fraction, i. e. the fraction of high-threshold hits per track, which is a prime quantity to discriminate electron and pion tracks. Figure 8 shows that the high-threshold fraction is almost immune to pile-up [6], which means that it can still be used to identify electrons even at high pile-up. Figure 8 is produced from tag-and-probe electron candidates at the Z peak, which makes it comparable to the rightmost data points in Fig. 7.

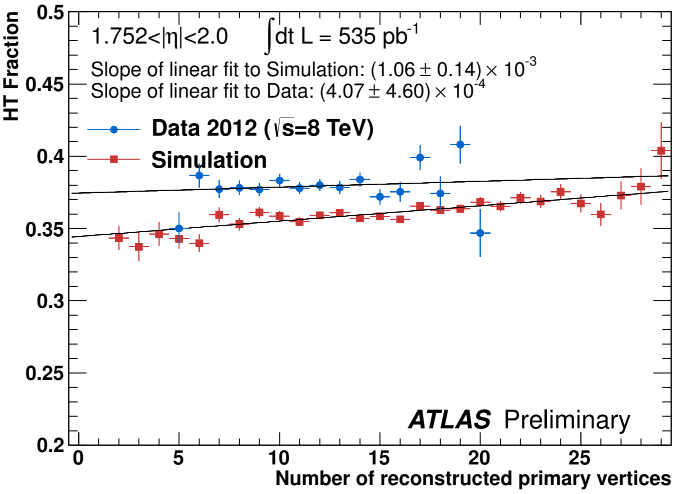

Figure 8: The fraction of high-threshold hits per reconstructed track vs. number of reconstructed primary vertices per event, shown for the outer endcap wheels [6].

7. Summary

The ATLAS TRT provides tracking and identification of charged particles. At high luminosities as they were routinely delivered by the LHC in 2012, some areas of the TRT have to cope with occupancies well above 50 %. Nevertheless, both tracking and particle identification still work reliably under those conditions even though the the TRT is susceptible to in-time and out-of-time pile-up. Most TRT hits provide useful drift time information, most tracks can be extended from the silicon detectors into the TRT, and the high-threshold hits that are caused by transition radiation can be used to identify electron tracks.

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