ATLAS Transition Radiation Tracker (TRT): Straw Tubes for Tracking and Particle Identification at the Large Hadron Collider

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Abstract

The ATLAS Transition Radiation Tracker (TRT) is the outermost of the three inner detector tracking subsystems and consists of $\sim$300000 thin-walled drift tubes ("straw tubes") that are 4 mm in diameter. The TRT system provides $\sim$30 space points with $\sim$130 micron resolution for charged tracks with $|\eta| < 2$ and $p_T > 0.5$ GeV/c. The TRT also provides electron identification capability by detecting transition radiation (TR) X-ray photons in an Xe-based working gas mixture.

Compared to Run 1, the LHC beams now provide a higher centre of mass energy (13 TeV), more bunches with a reduced spacing (25 ns), and more particles in each bunch leading to very challenging, higher occupancies in the TRT. Significant modifications of the TRT detector have been made for LHC Run 2 mainly to improve response to the expected much higher rate of hits and to mitigate leaks of the Xe-based active gas mixture. The higher rates required changes to the data acquisition system and introduction of validity gate to reject out-of-time hits. Many gas leaks were repaired and the gas system was modified to use a cheaper Ar-based gas mixture in some channels. A likelihood method was introduced to optimize the TRT electron identification.

ATLAS Transition Radiation Tracker (TRT): Straw Tubes for Tracking and Particle Identification at the Large Hadron Collider

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Abstract

The ATLAS Transition Radiation Tracker (TRT) is the outermost of the three inner detector tracking subsystems and consists of ~300000 thin-walled drift tubes ("straw tubes") that are 4 mm in diameter. The TRT system provides ~30 space points with ~130 micron resolution for charged tracks with $|\eta| < 2$ and $p_T > 0.5$ GeV/c. The TRT also provides electron identification capability by detecting transition radiation (TR) X-ray photons in an Xe-based working gas mixture.

Compared to Run 1, the LHC beams now provide a higher centre of mass energy (13 TeV), more bunches with a reduced spacing (25 ns), and more particles in each bunch leading to very challenging, higher occupancies in the TRT. Significant modifications of the TRT detector have been made for LHC Run 2 mainly to improve response to the expected much higher rate of hits and to mitigate leaks of the Xe-based active gas mixture. The higher rates required changes to the data acquisition system and introduction of validity gate to reject out-of-time hits. Many gas leaks were repaired and the gas system was modified to use a cheaper Ar-based gas mixture in some channels. A likelihood method was introduced to optimize the TRT electron identification.

Keywords: gaseous detectors, transition radiation detector, tracking, particle identification

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1. Introduction

The ATLAS Inner Detector (ID) is the innermost part of the ATLAS experiment [1] and has three main subcomponents: the silicon based Pixel and SemiConductor Tracker (SCT) detectors, and the Transition Radiation Tracker (TRT) based on gaseous type of detectors called straws [2]. The design of the ID is schematically presented in Figure 1.

The TRT detector consists of about 300,000 straw tubes that are 4 mm in diameter, made out of Kapton and having at their centre a 31 μm diameter gold-plated tungsten wire. In the barrel the straws are placed parallel to the beam-line and cover from 560 to 1080 mm in radius and $|z| < 720$ mm. The two endcaps where straws are arranged perpendicular to the beam-line cover $827 < |z| < 2774$ mm and $617 < R < 1106$ mm.

When charged particles cross the TRT straws they ionise active gas mixture and produce about 5-6 primary ionisation clusters per mm of path in the gas. Having the straw wall at high negative voltage creates an electric field so the primary electrons are accelerated towards the central anode and liberate more electrons producing a detectable current signal. The signal generated inside the straws is then amplified, shaped and finally discriminated.

At the begin of LHC and ATLAS operation the only gas used in the TRT detector was xenon based gas mixture. However, due to the large, irreparable gas leaks which developed in the gas system part of the TRT detector is now flushed with a gas mixture composed primarily of much cheaper argon. The xenon based gas mixture is crucial to letting the TRT combine tracking capabilities with particle identification (PID) based on transition radiation (TR) photon detection. The PID functionality gives significant discrimination power between electrons and charged pions with energy in the range 1 GeV < E < 100 GeV enhancing the electron selection criteria in ATLAS.

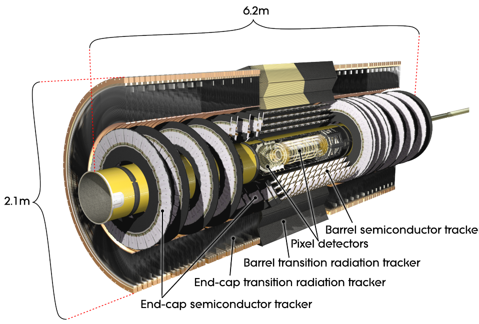

Figure 1: A schematic view of the ATLAS Inner Detector [3].

2. TRT performance at high pile-up and occupancy

2.1. Signal digitization at high rates

The TRT electronics is equipped with two adjustable discrimination thresholds which provide real time information about whether each threshold is met. The output the TRT electronics is a 27-bit word recorded for each straw over 75 ns. The 27-bit word consists of three 9 bits words collected every 25 ns, in each of these words 8 least significant bits represents the

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signal amplitude with respect to the low threshold (LT). The information about LT is used for tracking purposes. The 9-th bit is set if signal exceeds the high threshold (HT) at any time within 25 ns window and is used for PID. A schematic view of the signal and corresponding 75 ns readout window is shown in Figure 2.

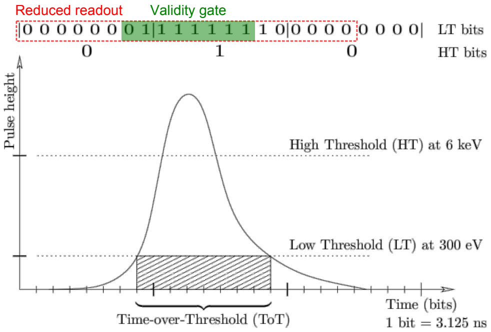

Figure 2: The TRT straw pulse and electronic LT and HT response. Reduced readout word format (in read) together with "validity gate" (in green) are also shown.

Data acquisition and tracking conditions become very challenging when the detector runs at the high occupancy levels due to the increasing numbers of protons per bunch and the reduction in bunch spacing provided by the LHC accelerator. Therefore to keep data rate at the acceptable level the readout schema has been changed. There are only 23 bits transferred per straw (reduced readout) and a "validity gate" have been used to remove out of time hits. The validity gate restricts the signal appearance within certain time window. The reduced readout also takes into account only the middle HT bit and employs a Huffman lossless compression algorithm significantly reducing the needed bandwidth to transfer out of the detector all data.

2.2. High occupancy studies

The TRT straw occupancy as a function of $<\mu>$ (up to 70) for a special run with "fat bunches" has been studied. In these special runs, single bunch was circulating in each of the two LHC rings resulting in no pile-up from adjacent bunches. In Figure 3 the occupancy as function of $<\mu>$ is shown for the TRT barrel. The occupancy is defined as the probability to have LT hit within a readout window (precisely it is a number of fired straws divided by the total number of straws in the region). The occupancy increases linearly from about 24% at $<\mu> = 45$ to 35% at $<\mu> = 70$.

2.3. Position resolution

The drift-time measurement provided by recording the time at which the ionization signal exceeds the LT (leading-edge time) is used to determine the position of the tracks. The relationship between the measured drift-time and the distance between the closest approach of the track to the anode wire is known as the R-t relationship. Knowledge about the drift-time measurement and leading-edge calibration is crucial for obtaining the precise drift-radius and therefore good position accuracy. A detailed model of the drift-tube including: ionization of the gas, electron drift velocity, energy fluctuations, signal propagation, shaping and discrimination has been developed to make a precise simulation and comparison with measured data. Figure 4 shows the track position measurement accuracy versus η for high values of $<\mu>$ actual data are compared with the simulation. The simulation underestimates the track position measurement accuracy in the barrel by about 6 μm.

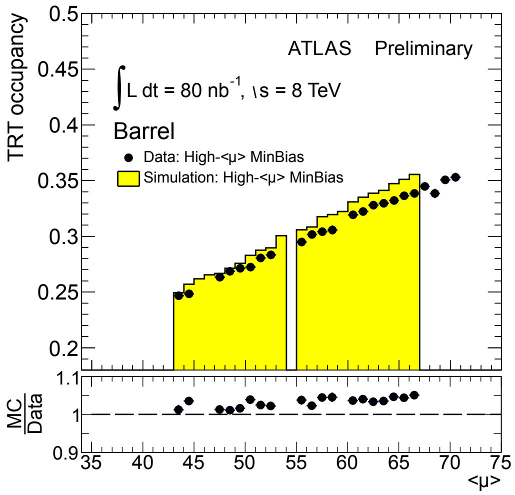

Figure 3: TRT straw occupancy as a function of h μ in the barrel for "fat bunch" runs (no pile-up from adjacent bunches) during 2012 at $\sqrt{s} = 8$ TeV. Data (solid circles) and simulation (filled histograms) [4].

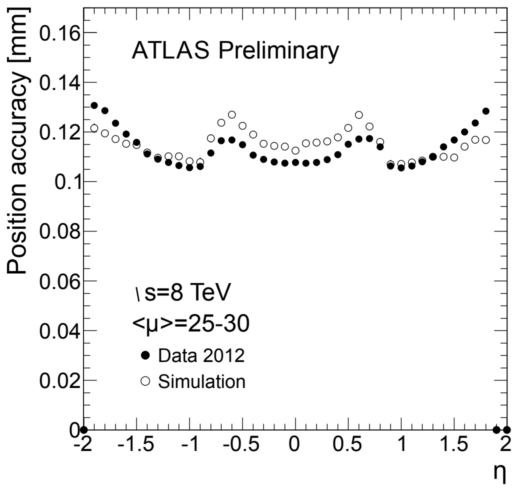

Figure 4: Track position measurement accuracy in the straw as a function of pseudorapidity (η) for muons $p_T > 30$ GeV. Data (solid circles) and simulation (open circles) are shown for 2012 running at $25 \leq \mu \leq 30$ [4].

2.4. Tracking properties

For any tracking detector finding and measuring tracks in the dense environment at high occupancy from pile-up events is very challenging. The ATLAS track-finding algorithm first finds tracks in the Pixel and SCT detectors and later adds TRT hits extending the track out to the colorimeter region. Therefore, the track extension fraction which is the relative number of tracks in which a track reconstructed in precision trackers have a continuation in the TRT detector is very important parameter. Figure 5 shows the TRT track extension fraction versus total TRT occupancy for minimum bias events with $40 < \langle\mu\rangle < 70$. In this Figure, all tracks down to 500 MeV are reconstructed. Practically, no dependence on the TRT occupancy is observed and the simulation describes measured data well.

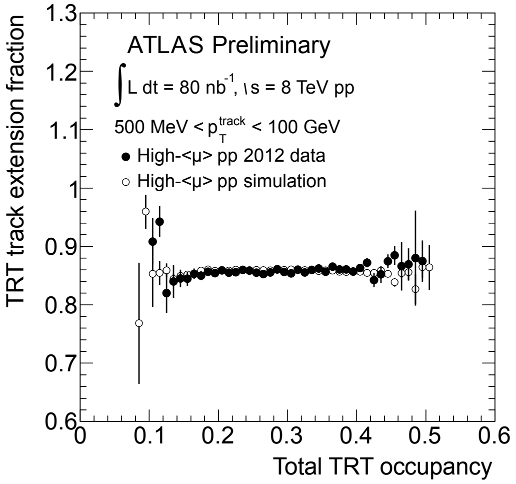

Figure 5: TRT track extension fraction as a function of total TRT occupancy from minimum bias events at $40 < \mu < 70$ [4].

3. TRT gas leaks and argon based gas mixture studies

During Run 1 large leaks appeared in some of the tubing used to supply the active gas to the detector due to mechanical stress and corrosion caused mainly by ozone. It has been decided to use an argon based gas mixture in places where the xenon losses too high and therefore unaffordable. The xenon leaks at the level of ∼150 l/day leading to high operation costs (the price of xenon is at ∼10 CHF/l) which will be too high to sustain over the expected duration of Run 2. The affected parts of the TRT detector which are operating with argon are: the innermost barrel layer – M0 (1/4 of the barrel), end-cap A wheel A6 and end-cap C wheel A4 (2 out off 28 end-cap wheels). However, this configuration may further be changed if new leaks develop or the cost of xenon becomes unacceptable.

Studies to evaluate the impact of argon usage have been performed. The tracking results presented below have been performed. These tracking results have been obtained after applying the alignment calibration procedure which calculates the TRT wire positions with mean accuracy of $\sim 1\mu$m. The TRT R-t dependency obtained for the barrel from 900 GeV collision data with all TRT straws filled with argon gas is shown in Figure 6. In this case the tracks are required to have $p_T > 0.5$ GeV, at least one silicon hit, and at least ten TRT hits. The relation is very similar to the one obtained with xenon and provides the precise drift time information necessary for track reconstruction.

In order to verify the spatial resolution of the TRT detector achievable using argon-based gas mixture, the hit residual distribution has been prepared. That distribution for barrel obtained from the same data as above is presented in Figure 7. The residual is the difference between the drift radius extracted from the drift time and the track radial position, measured from the track fit to all hits on the track except the one in the straw being considered.

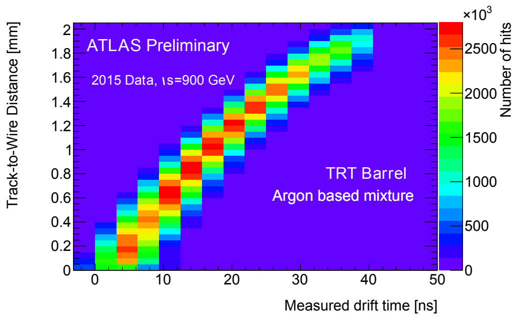

Figure 6: The R-t dependency for the barrel with all TRT straws filled with Ar-based gas mixture [5].

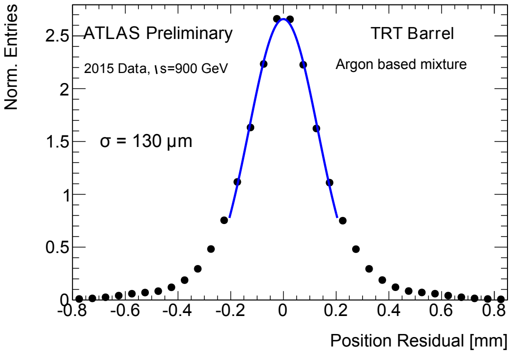

Figure 7: The TRT unbiased hit residual distribution for the barrel for tracks of $p_T > 0.5$ GeV with at least one SCT hit and at least 10 TRT hits [5].

The residual σ is at the level of 130 μm at low intensity.

4. Particle identification

The TRT offers particle identification by separating electrons from charged pions using the fraction of HT hits on track. The HT probability as a function of Lorentz γ-factor for TRT barrel is shown in Figure 8 for electrons and muons from J/ψ and Z decays. Only the most energetic muons have large enough γ-factors to emit TR, thus they are useful for mapping the turn-on curve. As expected, the turn-on of TR is seen to occur in the γ-factor range from 10^3 to 10^4. The simulation well agrees with the measured data.

The pion rejection factor is a key parameter which describes the TRT particle identification power. Figure 9 shows the pion misidentification probability for HT fraction criteria that give 90% electron efficiency as a function of the $|\eta|$. The detector performance is better then the simulation-based expectations, especially in the end-cap region ($|\eta| > 0.8$).

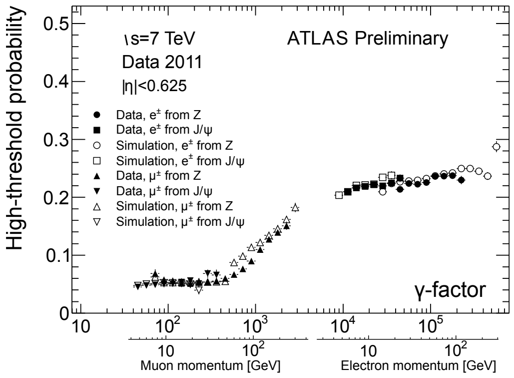

Figure 8: The probability to exceed the high threshold for electrons and muons from J/ψ and Z decays as a function of the Lorentz γ-factor for tracks with in the TRT barrel region. Data (solid symbols) and simulation (open symbols) are presented [4].

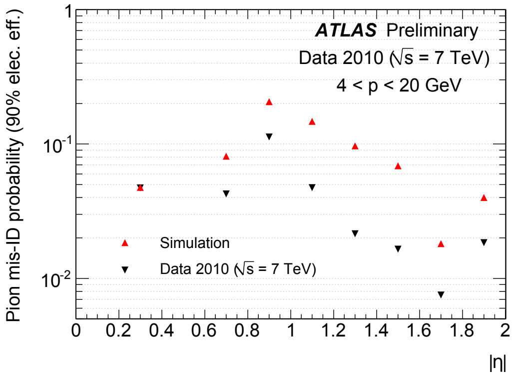

Figure 9: Pion misidentification probability for HT fraction criteria that gives 90% electron efficiency in different TRT regions (data are presented in bins of $|\eta|$) [5].

4.1. *Performance of the PID with high pile-up*

The HT fraction gives relatively simple discrimination for the electron identification, however HT hits can be generated by δ-rays or by any charged particle due to fluctuations in energy deposition. These additional HT hits not caused by TR decrease the pion separation power. Moreover, in the high occupancy conditions due to the larger number of tracks in the detector and higher energy deposition in the straws the HT probability increases. The HT probability for MIPs grows faster than for electrons therefore the PID performance decreases. Figure 10 shows the HT probability for electrons as as function of the average number of interactions per bunch crossing. Clear indication of the growth in HT probability is visible for increasing number of interactions per bunch crossing ($<\mu>$).

In order to improve the TRT PID ability a likelihood method has been proposed. After parameterizing the HT probability, a likelihood can be constructed for each track under the assumption that the candidate track comes from an electron ($\mathcal{L}^e$) or MIP such as a muon ($\mathcal{L}^\mu$) with the following formula:

$$\mathcal{L}^{e,\mu} = \Pi_{\text{TRT hits}} \begin{cases} p_{HT}^{e,\mu} & \text{if HT hit} \\ 1 - p_{HT}^{e,\mu} & \text{else} \end{cases} \tag{1}$$

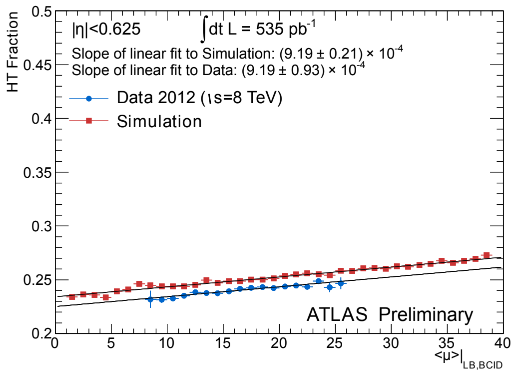

Figure 10: The HT probability as a function of average number of interactions per bunch crossing for electrons [5].

where: $p_{HT}^{e,\mu}$ – probability to exceed HT for electron or MIP with the track. These two likelihoods can then be used to evaluate an electron probability $\mathcal{P}^e$ in a following way:

$$\mathcal{P}^e = \frac{\mathcal{L}^e}{\mathcal{L}^e + \mathcal{L}^\mu} \tag{2}$$

That method is especially important for the PID when argon and xenon based gas mixtures are used simultaneously in different parts of the detector (current TRT operation mode). Argon has lower TR absorption probability than xenon, therefore HT probability across the detector varies significantly resulting in a necessity of using a better approach than simple HT fraction – a likelihood method seems to be the best option to keep PID as efficient as possible.

5. Conclusion

The TRT detector performs very well despite high pile-up, extreme occupancy, problems with gas leaks (mixed argon/xenon operation mode) and significantly contributes to the overall ATLAS tracking and electron identification. The problems with gas leaks do not affect the tracking properties, however discrimination between electrons and charged pions is affected.

Acknowledgements

We acknowledge our TRT project colleagues for their tireless efforts to operate the TRT well. The ATLAS collaboration wishes to thank CERN for the efficient operation of the LHC during the data-taking periods.

References

[1] The ATLAS Collaboration, *JINST* 3 S08003, 2008.
[2] The ATLAS TRT collaboration, *JINST* 3 P02013, 2008.
[3] *http://www.atlas.ch/photos/inner-detector-combined.html*
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