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Tracking properties of the ATLAS Transition Radiation Tracker (TRT)

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Abstract. The tracking performance parameters of the ATLAS Transition Radiation Tracker (TRT) as part of the ATLAS Inner Detector (ID) are described for different data taking conditions in proton-proton collisions at the Large Hadron Collider (LHC). These studies are performed using data collected during the first (Run 1) and the second (Run 2) periods of LHC operation and are compared with Monte Carlo simulations. The performance of the TRT, operating with xenon-based (Xe-based) and argon-based (Ar-based) gas mixtures and its dependence on the TRT occupancy is presented. No significant degradation of position measurement accuracy was found up to occupancies of about 20% in Run 1. The relative number of reconstructed tracks in ID that also have a extension in the TRT was observed to be almost constant with the increase of occupancies up to 50%. Even in configurations where tracks are close to each other, the reconstruction algorithm is still able to find the correct TRT hits and properly reconstruct the tracks.

1. Introduction

The ATLAS detector [1] at the LHC is a general-purpose detector designed to make precision measurements of known physics processes and to probe new physics at the energy frontier of the LHC. At the centre of the detector is an optimised, multi-technology tracking detector (Inner Detector, ID) [2] embedded in a 2T axial magnetic field produced by a solenoid. It is designed to provide a high-precision reconstruction of charged particle trajectories.

The ID covers the pseudorapidity range $|\eta| < 2.5$ and has full coverage in ϕ . It consists of a silicon pixel detector at the innermost radii (pixel), surrounded by a silicon microstrip detector (SCT), and a straw-tube detector called the Transition Radiation Tracker (TRT). The TRT combines continuous tracking capability with particle identification based on transition radiation (TR), which arises when ultra-relativistic charged particles cross a boundary between media with different dielectric constants. Responses to the charged particle crossing the detector recorded in individual detector elements ("hits") are used to reconstruct tracks inside the tracker and ultimately to estimate their tracking parameters. The precise measurement of the particle trajectories is fundamental for almost all data analyses in ATLAS. In this paper, the TRT tracking performance for different TRT straw occupancies in proton-proton (pp) collisions during Run 1 (2009-13) and Run 2 started in 2015 is presented. The straw occupancy is defined as the probability to have the straw signal above a given threshold value in the TRT read-out window of 75 ns, equivalent to three bunch crossings at the nominal LHC running conditions with 25 ns bunch spacing.

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2. Operation during the first data-taking period at LHC

The TRT is a straw tracker composed of 298,304 carbon-fibre reinforced kapton straws, 4 mm in diameter and held at a potential of -1530 V, with respect to a 31 μ m diameter gold-plated tungsten wire at the centre referenced to ground [3]. The TRT has two different geometrical arrangements of straws: a barrel section where 52,544 straws are aligned parallel to the direction of the beam axis (z) [4] and two end-cap sections, each with 122,880 straws that are aligned perpendicular to the beam axis and point outwards in the radial direction [5]. The TRT acceptance range is $|\eta| < 2.0$.

The TRT operates as a drift chamber: when a charged particle traverses a straw, it deposits about 2.5 KeV in the active gas (Xe-based mixture), creating 5-6 primary ionisation clusters per mm of path length. The electrons then drift towards the wire and cascade in the strong electric field very close to the wire, producing a detectable signal. The signal on each wire is then amplified, shaped, and discriminated against two adjustable thresholds [6]: Low Level (LL) and High Level (HL). The LL threshold is used to measure an electron drift time for the tracking. The HL threshold is used to identify large energy deposits. Separation of particle types is based on the probability of a particle's signal in a straw to exceed the HL threshold, which is different for electrons which produce TR, and other particles with Lorentz factors below 1000 which do not produce TR.

2.1. Low occupancy conditions

To suppress the effect of the occupancy, baseline TRT performance studies are first performed at relatively low straw occupancy conditions (average occupancy value is lower than 20%) with the pp data collected with a 50 ns bunch interval.



Figure 1. Position residual distribution in the TRT end-caps for high energy muons with $p_T > 30 \text{ GeV}$ [7].



Figure 2. Straw track position measurement accuracy for high energy muons with $p_T > 30$ GeV as a function of $\langle \mu \rangle$ [7].

The spatial position of charged particle tracks in the TRT detector is determined by using drift-time measurements. The TRT records the time at which the ionisation signal first exceeds the LL threshold (so-called leading-edge time) and later this time can be translated into a drift circle radius, making use of the relation between drift time and drift distance, called the r-t relation. The r-t relation is obtained from data using the measured drift time and the actual drift radius calculated as the distance of closest approach of the reconstructed track to the anode wire (so-called track-to-wire "distance"). The leading-edge time of the signal is corrected for the different timing effects due to clock propagation, signal travelling in wires, electronic delays and the time of flight of the particle.

There are two basic straw performance parameters which define the TRT tracking properties: the straw efficiency and the straw track position measurement accuracy. The straw efficiency is defined as the probability for the straw to produce a signal above the LL threshold for a particle traversing the straw gas volume. This efficiency decreases for the highest value of the track-to-wire distance, but on average is about 96% for a typical straw channel and is practically constant through the entire detector.

The straw track position measurement accuracy is defined in an iterative procedure as the width σ of a Gaussian fit to the peak of the position residual distribution. The position residual is defined as the difference between the measured drift radius and the track-to-wire distance. It is shown in figure 1, for an average number of interactions per bunch crossing $\langle \mu \rangle$ of 5-10. Figure 2 shows the averaged straw track position measurement accuracy in the straw as a function of $\langle \mu \rangle$ for the TRT, comparing data with simulation. For data the average straw track position measurement accuracy in the straws over the entire TRT is within the range of 105 μ m to 115 μ m.

2.2. High occupancy conditions

At an LHC design luminosity of 10^{34} cm⁻¹s⁻¹ a TRT straw occupancy reaches 50-60%. High detector occupancies are more challenging for track reconstruction. It can cause a degradation of the track parameter resolution due to incorrect hit assignments, a decrease of hit efficiencies, and an increase in the fake-rate of tracks from random hit combinations. The global TRT tracking capabilities are studied using a special LHC high intensity proton-proton collision fills with $\langle \mu \rangle$ up to 70 and bunch interval equal to 24300 ns (no pile-up from adjacent bunches). Figure 3 shows the correlation between the occupancy and $\langle \mu \rangle$ for the TRT barrel.

The TRT track extension fraction is the relative number of tracks reconstructed in the silicon detectors that also have a extension (more than 18 TRT hits) in the TRT. This variable reflects the quality of the standard ATLAS track-finding algorithm and is shown in figure 4. The track extension fraction is almost constant for occupancies up to 50%.





Figure 3. TRT straw occupancy in barrel as a function of $\langle \mu \rangle$. The bottom plot shows the ratio between simulation and data [7].

Figure 4. The TRT track extension fraction as a function of the total TRT occupancy with $40 \le \langle \mu \rangle \le 70$ [7].

One of the most challenging tasks for any tracking detector is finding and reconstructing tracks in regions with high track density as in energetic jet cores. To understand the TRT performance in such harsh conditions the TRT tracking constants at high pile-up conditions are characterized as a function of jet track density and compared with simulations.

Events with at least one high energy jet are selected. Tracks are required to have hits in silicon detectors and $p_T > 2$ GeV. Tracks are associated with jets if the distance in η - ϕ space between the track and the jet, ΔR (trk, jet)= $\sqrt{\Delta \eta^2 + \Delta \phi^2}$, is less than the distance parameter used in the jet reconstruction (R = 0.4) [8]. Since the jet track density increases nearer the core of the jet and depends on jet p_T , data are studied as a function of ΔR (trk, jet) and for three jet p_T regions. Figure 5 shows the TRT track extension fraction as a function of ΔR in jet cores, averaged over the entire $\langle \mu \rangle$ range ($40 \leq \langle \mu \rangle \leq 70$). The TRT track extension fraction is observed to be practically constant even within the dense cores of the most energetic jets. Data and simulation are also in reasonable agreement.



Figure 5. TRT track extension fraction as a function of ΔR in jet cores [7].



Figure 7. Straw position measurement accuracy for tracks with $p_T > 20$ GeV as a function of $\langle \mu \rangle$ [9].



Figure 6. TRT precision hit fraction on tracks as a function of ΔR in jet cores [7].



Figure 8. Precision hit fraction for tracks with $p_T > 20$ GeV as a function of $\langle \mu \rangle$ [9].

Figure 6 shows the TRT precision hit fraction as a function ΔR in jet cores averaged over the entire $\langle \mu \rangle$ range. The precision hit fraction is defined as the number of precision TRT hits (those hits with an useful drift time measurement) divided by the total number of hits on the selected track. A precision hit is defined as a hit for which the track-to-wire distance is within 2.5 times the drift circle uncertainty. Even in the core of the most energetic jets the precision hit fraction is practically the same as that outside of the jet core. This implies that even if two tracks are very close to each other, the reconstruction algorithm is able to find the correct hits and properly reconstruct the tracks.

3. Operation during the second data-taking period at LHC

The second period of LHC operation introduced the routine use of 25 ns intervals between proton collisions, resulting in increase of pile-up from adjacent bunches. Moreover, starting in 2012 a gradually increasing number fleaks were detected in TRT and because of the high cost of xenon gas, some TRT modules were filled with a significantly less expensive Ar-based gas mixture. An Ar-based gas mixture was considered as an alternative to the Xe-based gas mixture one for the TRT operation at the detector design stage. All needed TRT software calibrations are done to match these new pile-up and gas geometry conditions. These changes include r-t relation and leading-edge time calibrations, optimization of spatial measurements errors and many others. High levels of agreement between simulation and data were observed for precision hit fraction and track measurement accuracy as function of $\langle \mu \rangle$ for TRT barrel and end-caps. Figure 7 and figure 8 show these distributions for tracks with $p_T > 20$ GeV in TRT barrel.

4. Conclusions

Studies of the TRT basic performance at relatively low and high occupancy based on pp collisions during the first and second LHC data-taking periods has been presented. These studies include analysis of the TRT tracking performance using both Xe- and Ar-based gas mixtures. It was observed that the straw efficiency is larger than 96% and the track measurement accuracy is better than 120 μ m for Run 1 data-taking period conditions with 50 ns bunch spacing and is better than 130 μ m for Run 2 data-taking period conditions with 25 ns bunch spacing in 2015.

Additional studies include the track characteristics at high occupancy, and in jet cores as a function of jet p_T and the track distance $\Delta R(trk, jet)$ from the jet axis. The relative number of reconstructed tracks in ID that also have a extension in the TRT was observed to be almost constant with the increase of occupancies up to 50%. Even in configurations where tracks are close to each other, the reconstruction algorithm is still able to find the correct TRT hits and properly reconstruct the tracks. The simulation was found to describe the data generally well.

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