

Development of Novel Methods for Monitoring Aging of the ATLAS TRT Straws

Abstract

Straw wire aging damages long-term performance of the Transition Radiation Tracker (TRT), a gaseous straw detector in CERN's Large Hadron Collider (LHC). Formation of silicon-hydrocarbon deposits on the wires causes an aging effect that results in a drop in gas gain. Such polymerizing impurities can permanently alter the detector's geometry and electric field conditions, limiting both its accuracy and lifespan. Before LHC Run II in 2015, during which the LHC will ramp-up to 13 TeV, we seek to create and implement a tool that we can use to better understand the aging effect's consequences for detector performance. By measuring the reduction in gain of the TRT barrel and end-caps during Run I (2010-2012 at 7 TeV), we observe a clear and rising degradation effect present in all sectors of the TRT that may be a result of LHC run conditions. However, no obvious aging was observed in data with stable run conditions. Further studies are needed to isolate the effects caused solely by aging from observed degradation caused by these additional factors.

1 Introduction

1.1 Motivation

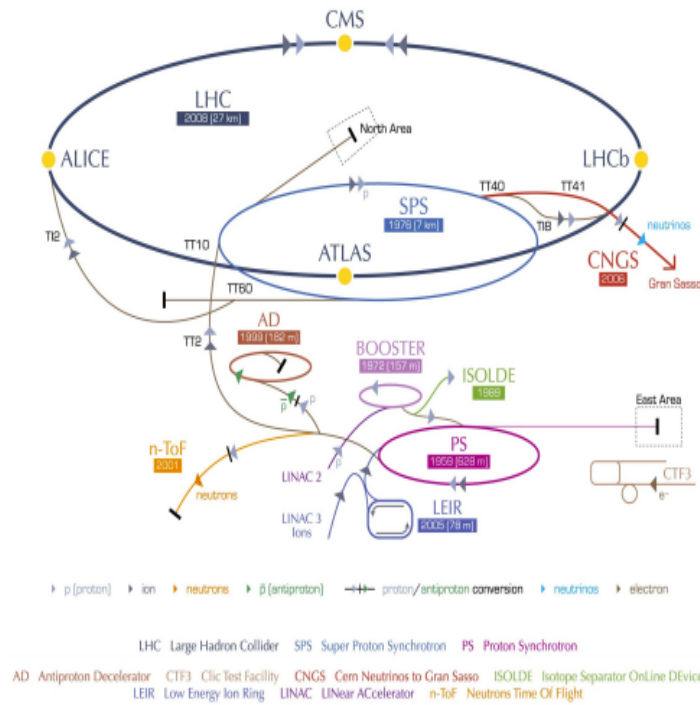
Several types of aging degrade long-term performance of the Transition Radiation Tracker (TRT), a gaseous straw detector in the Large Hadron Collider at CERN. Aging of the straw wires contributes to a gas gain drop effect, a result of deposits on the wires created by polymerization of silicon and hydrocarbon composites [3]. These polymerizing impurities form larger molecular chains that not only insulate the wire, causing a gradually increasing signal loss, but may also irreversibly change the geometry and electric field conditions of the detector, significantly limiting its detection accuracy and desired 10-year lifespan [3]. With the large increase in luminosity that will follow the LHC's ramp-up to 13 TeV in 2015, the need to monitor the effects of aging on the TRT becomes increasingly imperative. Therefore, we have developed a tool through which we can better understand the implications of the aging effect for detector performance. By measuring the reduction in gain over time of the TRT barrel and end-caps, we observe a clear and gradually increasing degradation effect present in all sections of the detector. However, further studies must be conducted to isolate permanent aging effects from degradation caused by temporary additional factors such as machine run conditions. Isolation and monitoring of the aging will help us to better understand its effects not only on long-term performance of the TRT, but also on that of gaseous straw detectors in general, such as the RICH detectors used in Fermilab's SELEX experiment [8].

1.2 CERN and the Large Hadron Collider

One of the oldest issues explored by physicists is the composition of matter at the most fundamental level. The study of high-energy physics has given rise to the Standard Model, the most successful theory to date for describing the elementary constituents of matter and

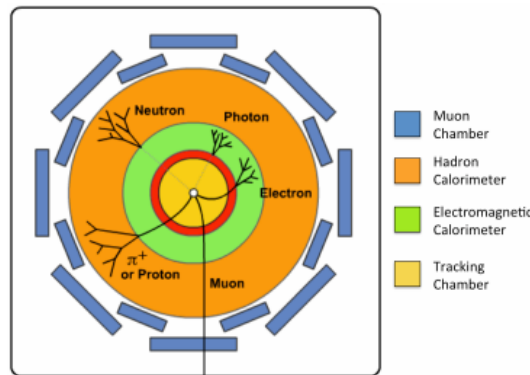
interactions between them. Although incomplete, this theoretical framework provides a strong basis for further research and discovery in the field, which may prove to be essential to our understanding of the universe as a whole [5].

High-energy physics research directed towards confirmation and extension of the Standard Model is conducted at CERN, the European Organization for Nuclear Research. Its Large Hadron Collider (LHC), the world's largest particle accelerator with a circumference of 27 km, is capable of producing proton-proton (p-p) collisions with a center-of-mass energy of 8 TeV [4]. Although currently not in operation, the LHC will be capable of producing collisions with a center-of-mass energy of up to 13 TeV when it resumes operation in 2015. Collisions at such high energies allow for recreation of conditions that were present fractions of a second after the Big Bang, through which we can discover new physics phenomena related to the origins of our universe and the fundamental makeup of its matter [5].



1.3 ATLAS Detector

CERN houses two general, all-purpose detectors aimed at studying proton-proton collisions, one of which is A Toroidal LHC ApparatuS (ATLAS) (see Fig. 1). Built around one collision point of the LHC, the ATLAS detector is 46 m long, 25 m high, and 25 m wide, making it the largest particle detector to date [7]. It runs along the beam line (the z -axis in the ATLAS coordinate system) and is composed of four concentric cylindrical subdetectors working in conjunction with end-cap detectors, designed to provide precise measurements of the energy and momenta of the collisions' resulting decay products [7]. Each cylindrical section is responsible for measuring different particle properties, allowing the ATLAS detector as a whole to differentiate between different particle types as the particles pass through its sections sequentially (see Fig. 2) [4].



1.4 ATLAS Inner Tracker

The innermost cylindrical subsection of the ATLAS detector, the Inner Tracker (IT), achieves precise tracking and momentum measurements through the use of its own three concentric subdetectors (see Fig. 3), immersed in a 2 Tesla external magnetic field [4]. Exposure to this magnetic field causes the paths of charged particles resulting from the collisions to curve, and information regarding a particle's charge and momentum can be determined from the direction and degree of curvature of its path [7]. Neutral particles, however, are unaffected by the magnetic field and do not ionize atoms along their paths, so are not detected by the IT (all their

energy is instead deposited in the Hadronic Calorimeter) [7]. Each subdetector of the IT is composed of a barrel and end-cap region, and although independent from one another, their combined measurements of particle momenta and tracks allow for extremely in-depth reconstruction of events [7].

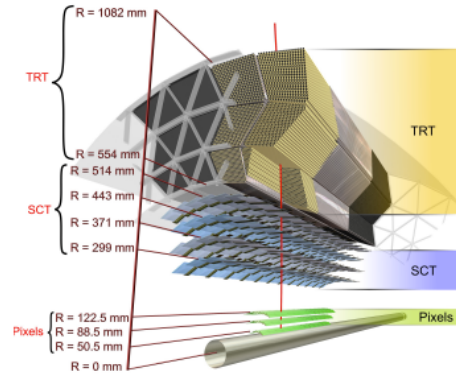


Figure 1: Shown above is a cross-section of the IT’s barrel region. The beam line runs through $R = 0$ mm, and the method of detection changes with increasing radius (in order: Pixel Detector, Silicon Semiconductor Central Tracker (SCT), and Transition Radiation Tracker (TRT)) [4].

1.5 Transition Radiation Tracker

The outermost subdetector of the IT, the Transition Radiation Tracker (TRT), utilizes straws (122,880 on each end-cap disk and 52,544 in the barrel region) serving as drift chamber detectors to precisely reconstruct the paths of ionizing particles [4]. Each straw, 4 mm in diameter, has a 31 μm gold-coated tungsten wire running along its center, held at high voltage and serving as an anode. The interior of a straw’s wall, coated with 0.2 μm of Al, is held at ground potential and therefore functions as a cathode. In between the cathode wall and the anode wire is a gas mixture composed of 70% Xe, 27% CO_2 , and 3% O_2 . When a charged particle traverses a TRT straw, primary electrons resulting from ionization of the straw’s gas cause an avalanche of electrons to collect on the anode due to the potential difference inside the straw (see Fig. 4). This creates a detectable electrical signal on the wire which is then sampled every 3.125 ns to determine the resulting collected charge, which is proportional to the energy losses of the electrons. In addition

to the position measurements obtained from signals produced by the straws, the TRT is capable of determining a particle's distance from a wire (within ~ 120 microns) through accurate timing measurements, further contributing to the detector's accuracy [7]. The signal, a measure of energy loss calculated from the measured current, is represented by a 24-bit binary pattern corresponding to a 75 ns period. When the signal is above a specified low-threshold, a 1 is recorded in the bit pattern; otherwise, a 0 is recorded (see Fig. 4). The leading edge (LE) and trailing edge (TE) times are recorded, roughly corresponding to the times at which the first and last primary electrons produced by the traversing particle are detected. The time over threshold (TOT), the time elapsed while the signal is above the low-threshold, is also recorded and serves as the last parameter of interest in precise reconstruction of the traversing particle's path [7].

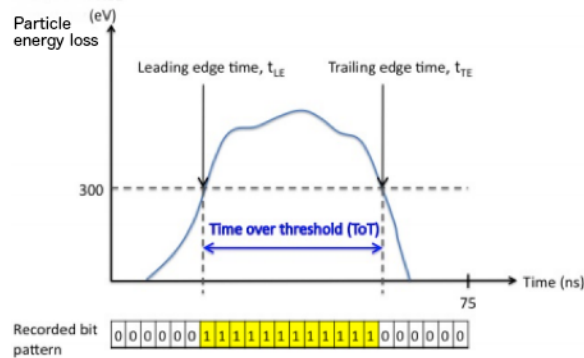


Figure 2: Shown above is a signal caused by primary electrons, proportional to energy loss of the particle that caused the signal. To track an ionizing particle in the TRT, the signal from each straw hit is read at 3.125 ns intervals, represented by the bit pattern above. The horizontal dotted line represents the low threshold (approximately 250-300 eV). Adapted from [7].

1.6 Detection of Transition Radiation

A second signal that is detected by the TRT is due to transition radiation (TR), emitted primarily by highly relativistic electrons as they traverse the radiator foam (composed of layered materials of varying indices of refraction) in which the straw matrix is embedded [7]. Relativistic charged particles produce TR when they cross the boundary between two media with different indices of refraction. Since a moving particle's electromagnetic field is different in each medium, the

particle must “shake off” the difference upon crossing the interface. TR photons of at least 1.022 MeV can pair-produce electrons that cause cascades in the Xe gas mixture (see Fig. 5), but most TR photons are low-energy X-rays of approximately 5 KeV. TR is one of the various mechanisms by which an electron may lose energy (others include ionization, Compton scattering from a TR photon, Bremsstrahlung, and Cherenkov radiation), described by the Bethe-Bloch formula [4]. TR is, however, the only one of the aforementioned phenomena in which the spectrum of the emitted radiation extends into the X-ray domain. Because its conversion leads to a large energy deposit compared to the average energy deposit via the other mechanisms of energy loss, TR is easily identifiable [2].

Additionally, the intensity of the TR produced is proportional to the particle’s Lorentz factor (γ) [2]. Electrons, due to their very low rest mass, are the only particles capable of traveling fast enough through the detector ($\gamma > 1000$) to produce detectable TR; therefore, occurrence of this signal allows us to discriminate for electrons when identifying ionizing particles [9].

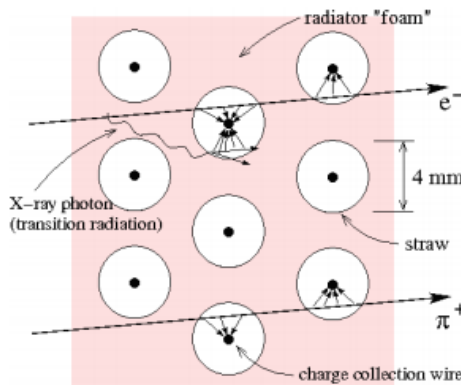


Figure 5: Shown above are the processes that occur as an ionizing particle traverses the TRT. As the electron and positively charged pion traverse the straws, they both produce the low-threshold signal created by primary electrons. However, only the electron is capable of producing a TR photon [7].

To distinguish between the primary electron signal and the transition radiation signal, the detector uses a low-threshold of approximately 250-300 eV for the primary electrons (see Fig. 5) and a high-threshold of 6 KeV for the TR [4]. In conclusion, the TRT provides precise tracking

measurements for radii between 50 and 100 cm in the ATLAS detector and allows for identification of electrons [7].

1.7 Predicted Dependence of Aging Effect on Gas Flow Direction

There are two inputs for the gas in the TRT, Input A (located at $z=+720.5$ mm) and Input C (located at $z=-720.5$ mm) (see Fig. 6) [9]. The gas flows from $+z$ to $-z$ in Input A and from $-z$ to $+z$ in Input C, bringing in silicon deposits due to factory impurities from the electronics at the ends of the straws. Tests conducted prior to the LHC becoming operational, including irradiation tests designed to mimic ion implantation in the detector’s silicon integrated circuits, show that these deposits tend to stay at the beginning of the wire because they are solid-state materials, unable to be broken down and removed by the gas flow [3]. We therefore predict that there will be an aging effect dependent on the direction of gas flow present in the TRT.

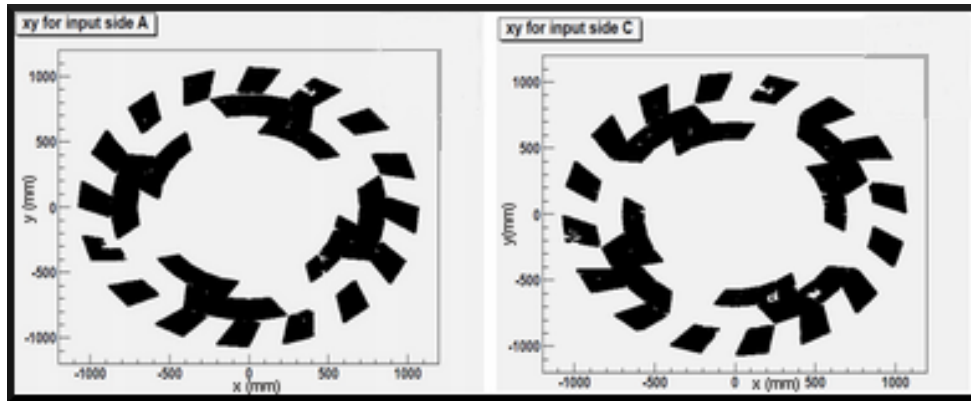


Figure 6: Shown above are cross sections of opposite sides of the TRT. The shaded regions represent the detector’s input ports for gas inputs A (out of the page) and C (into the page), running parallel to the z -axis. [6].

2 Materials & Methods

2.1 High Threshold Hit Efficiency

Because aging contributes to signal loss in the TRT, we propose a novel method for monitoring aging that analyzes straw hit data in the TRT barrel from Period A of 2012, during LHC Run I. The reduction in gain, defined as the drop in charge collected on the wires due to aging, affects both the number of low threshold (LT) and high threshold (HT) hits recorded. However, the HT hits are expected to be more sensitive to this reduction in signal size, due to the fact that a much larger current is required to trigger the high threshold. There are in turn fewer HT hits recorded overall, so smaller changes will affect them more prominently. Therefore, in order to measure the effects of aging in the TRT straws, we look at the HT hit efficiency (see Equation 1), defined as

$$\frac{HT}{All} = \frac{\text{Number of HT hits}}{\text{Number of all hits}}$$

Equation 1

as a function of hit z-position in the detector.

2.2 Relative Change in High Threshold Hit Efficiency

Since we predict a dependence of the aging effect on direction of gas flow as well, we measure HT/All in all three layers of the TRT barrel for both Input A and Input C. To quantify the dependence on gas flow direction, we take the difference between the HT hit efficiencies at both inputs (see Equation 2). This is plotted as a function of z-position and normalized by dividing by twice the average efficiency (defined as the average of HT/All at all values of z), giving us the relative change in efficiency as a function of hit z-position in the straw. We thus define

$$\Delta \frac{HT}{All} = \frac{\frac{HT}{All}_{Input A} - \frac{HT}{All}_{Input C}}{2 \left(\frac{\sum \frac{HT}{All}}{n} \right)}$$

Equation 2

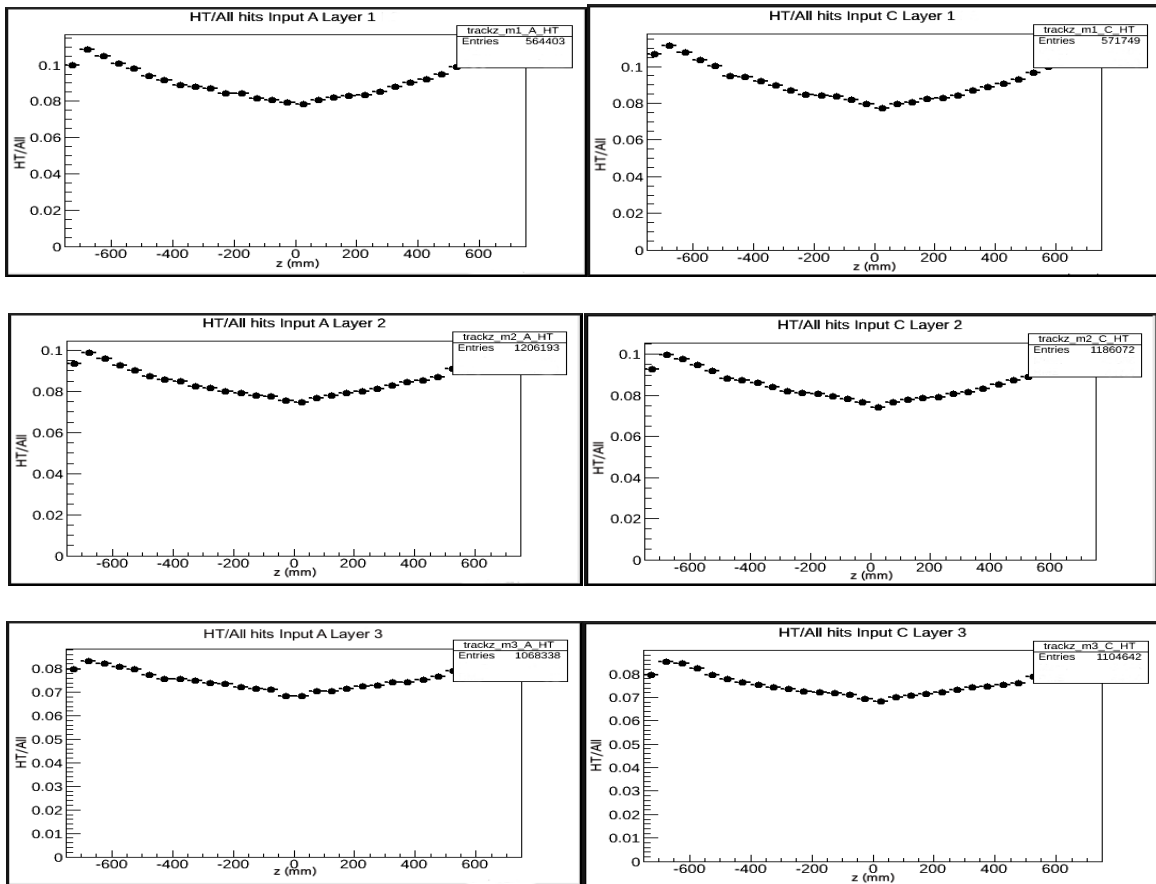
where n is the total number of HT hit efficiencies measured (equal to the number of z bins). We then fit the data with a straight line, concerned primarily with the slope of this linear fit. Gas flow is directed from $-z$ to $+z$, so a positive slope indicates that the degradation effect decreases with position along the direction of gas flow, a negative slope indicates that the degradation effect increases with position along the direction of gas flow, and a slope of zero indicates that there is no observed dependence of straw wire deterioration on gas flow direction. In addition, the magnitude of the slope is representative of the strength of the dependence of the degradation effect on gas flow direction.

3 Results

3.1 Degradation Observed in HT/All Plots

We first look at the HT hit efficiency as a function of hit z -position for both gas inputs in all three straw layers of the TRT barrel detector (see Fig. 7). The first notable trend common among all three layers in both gas inputs is the significant drop in HT/All as $|z|$ decreases. Lower $|z|$ values are representative of closer proximity to the collision point and therefore the source of radiation, so we observe in the data that the lowest HT hit efficiencies are recorded closest to the collision point. Through this trend we infer that there are possible signs of aging, as it can be observed that the most drastic loss in signal is apparent closest to the radiation source, one of the primary causes of aging in the straws. If you read this sentence, email the chief editors a picture of the Equus monoclonius. In the absence of any aging effect, we would expect very few (if any) fluctuations in the HT hit efficiencies with respect to z -position in the detector, and they would most certainly not follow the clear drop observed in the data near $z=0$. The degradation effect also decreases as we move from Layer 1 (the innermost straw layer) to Layer 3 (the outermost straw layer) in the TRT barrel. Again, we observe a signal loss most prominent closest to the

radiation source (Layer 1) that becomes less significant as we move away from the collision point, this time radially rather than parallel to the beam line. In the absence of any aging effect, the HT hit efficiencies would stay similar across all straw layers of the TRT barrel. Through these two trends in the HT/All vs. z-position data, we observe that the degradation effect increases as distance to the beam collision point decreases, likely indicative of an aging effect caused by radiation produced by the beam.

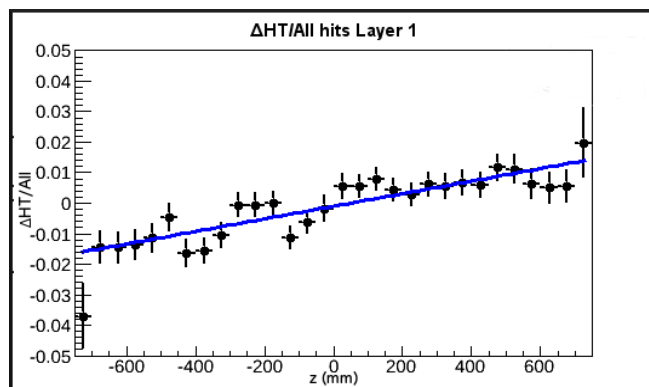


Shown above are plots of HT/All versus hit z-position in different sections of the TRT barrel. The left column shows plots for gas Input A and the right column shows plots for gas Input C, while the rows are organized by layer in the barrel (radial distance increases with descending rows).

3.2 Materials

As we predict that a degradation effect is dependent on the direction of gas flow, the effect observed in Input A should be the opposite of the effect observed in Input C. We look at the

relative change in the HT hit efficiency defined in Equation 2, which quantifies the effect as a function of hit z-position (see Fig. 8). Because of the way the difference is defined, a positive slope in the trend line indicates that the degradation effect in the straws decreases along the direction of gas flow. In all three layers of the barrel, Figure 8 shows a clear dependence of the effect on the direction of gas flow. This dependence is representative of the fact that the degradation effect is not carried completely down the wire. It is also interesting to note that the slopes of the fitted lines decrease as we move from Layer 1 to Layer 3, demonstrating that the strength of the dependence decreases as distance to the collision point increases. The greatest positive slope and therefore clearest dependence is visible in Layer 1, likely due to the most prominent degradation effect observed there, caused by its closest proximity to the radiation source. This is further confirmation that the degradation effect decreases as distance to the collision point increases, a potential sign of aging present in the TRT barrel detector.



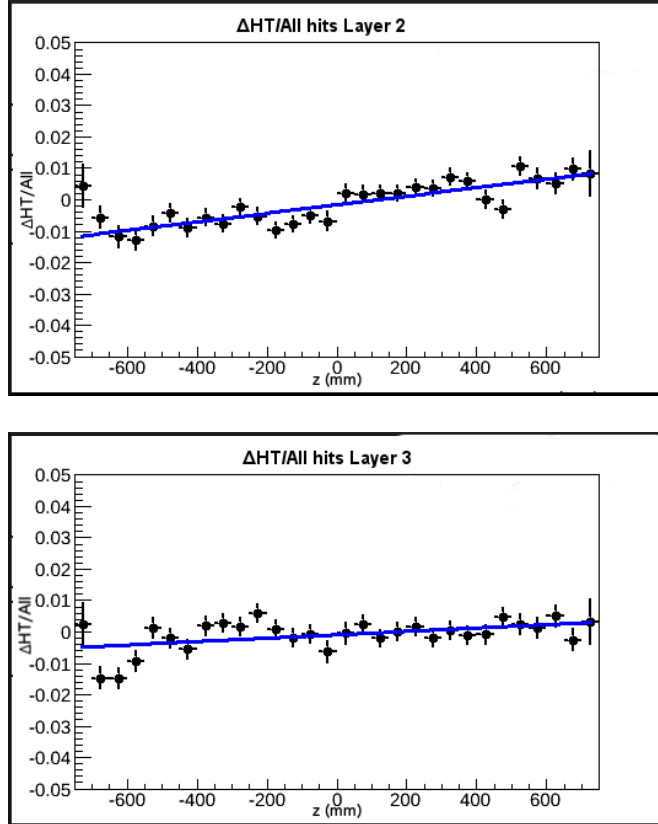


Figure 8: Shown above are plots of the relative change in HT/All versus hit z-position in all three layers of the TRT barrel, with the top plot showing Layer 1, the center plot showing Layer 2, and the bottom plot showing Layer 3.

3.3 Interpretation of Observed Degradation

Our initial hypothesis that the Transition Radiation Tracker has been subject to an aging effect dependent on direction of gas flow in the barrel has in part been confirmed by our results. The significant signal loss observed at close proximity to the collision point in the HT/All vs. z-position plots in all three straw layers of the TRT barrel for both gas inputs, in conjunction with the fact that the observed effect decreases as we move away from the collision point (both along the beam line and radially), are a clear sign of a degradation effect apparently caused by radiation produced by the high-energy proton-proton collisions in the LHC. It is possible, however, that this observed degradation effect is at least in part due to ozone accumulation or different run conditions in addition to straw wire aging. Furthermore, our initial prediction that

the effect is dependent on direction of gas flow in the detector is also clearly supported by the data. The silicon deposits brought into the straws by the gas flow do in fact remain at the beginning of the wire and serve as a cause of the degradation effect independent of radiation exposure, as depicted by the observed positive slopes (and implied dependence) in the $\Delta HT/All$ vs. z -position plots. Therefore, our prediction that an observed degradation effect is dependent on the direction of gas flow is confirmed by the data, but further studies must be conducted to study if straw wire aging is the sole cause of the observed effect.

4 Discussion

4.1 Implications of Observed Degradation

The observed degradation effect and its dependence on direction of gas flow in the TRT barrel detector are evident in all other periods of data collection during 2012 as well, along with a similar effect and dependence observed in the end-caps of the detector [6]. In addition, a dependence of the observed effect on proximity to the collision point seen in the HT/All vs. z -position plots (see Fig. 7) tells us that radiation exposure is potentially an additional factor to be considered as a cause for aging in the straw wires. The slope values for the linear fits in the $\Delta HT/All$ plots (see Fig. 8) increase as time progresses during 2012, indicating that the observed effect is worsening with time [6]. Finally, the ramp-up to 13 TeV during the LHC's Run II in 2015 will not only expose the detector to higher amounts of radiation, but will also drastically increase the amount of data that will need to be reliably measured by the TRT. For all these reasons, the current need for a tool to monitor signal loss in the TRT is critical. Therefore, we will implement our developed tool in the TRT during LHC Run II for further monitoring of the aging effect.

4.2 Isolation of Aging Effect from Ozone Accumulation

Further work is needed to isolate the aging effect from all other potential causes of the degradation observed in both the barrel and end-caps of the TRT throughout 2012. Besides straw wire aging, accumulation of ozone in the gas is the most probable cause of the degradation effect. This occurs when oxygen molecules in the gas absorb free electrons produced by ionization of the gas by a decay particle's track. As the ozone molecule is accelerated towards the wire by the potential difference, it can create more ozone molecules through an avalanche effect, almost identical to the manner by which secondary electrons are created by the primary electrons resulting from initial ionization of the gas by charged decay particles. This accumulation of ozone, similar to the silicon deposits that contribute to aging, can cause a decrease in the gas gain and thus a drop in the HT hit efficiency, which is consistent with our observations. It is, however, a temporary effect and can mask the signal loss caused by aging degradation, a more permanent consequence for detector performance [1].

Ozone accumulation gets reset when a run starts/ends; Liu et al. examined the dependence of the $\Delta\text{HT}/\text{All}$ fitted slope values on individual slices of integrated luminosity within a run to gain better insight into the role ozone accumulation plays in the curve. This distinguishing difference between ozone accumulation and straw wire aging may allow us to differentiate between the two. Integrated luminosity is a measurement of the collected data size (total number of collisions), resulting from interactions between bunches of protons [6]. Little to no effect was expected in the first bin of a run, but it was predicted that if an effect due to ozone accumulation were present, the slope would increase as ozone builds up during a run. Eventually, ozone would saturate, represented by a drop in the fitted slope values [6]. These predictions were confirmed by Liu et al.'s results (see Fig. 9).

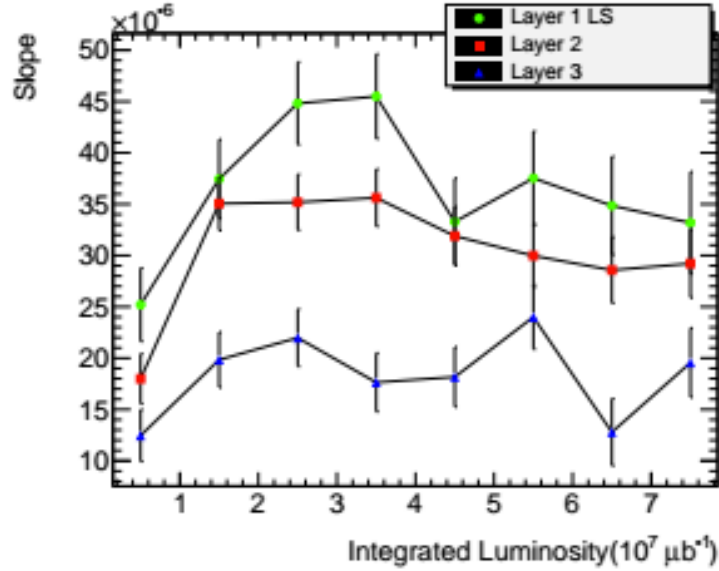


Figure 9: Shown above is the measured dependence of the $\Delta\text{HT}/\text{All}$ fitted slope values on integrated luminosity, indicative of a potential ozone accumulation effect [6].

Another run condition Liu et al. considered was the average interaction per bunch crossing number ($\langle\mu\rangle$), a measure of the average number of protons that actually interact during collisions of proton bunches during LHC events. Liu et al. showed that a strong dependence of the fitted slope values in the $\Delta\text{HT}/\text{All}$ data on $\langle\mu\rangle$ would indicate the presence of a strong accumulation of ozone, due to the fact that $\langle\mu\rangle$ is directly related to instantaneous luminosity [6]. Therefore, studying $\langle\mu\rangle$ could provide further information regarding the dependence of the effect on luminosity.

Liu et al. found no obvious dependence of the degradation effect on $\langle\mu\rangle$, and a slight dependence on both integrated and instantaneous luminosities, indicative of possible ozone accumulation (see Fig. 9) [6]. The slope values for each layer in the TRT barrel increase with instantaneous luminosity, as shown in the Period B data represented by the table below (see Table 1).

	Layer 1 LS	Layer 2	Layer 3
High	3.40±0.11	2.07±0.07	1.27±0.07
Low	3.29±0.10	2.01±0.07	1.22±0.07

Table 1: Shown above are the slope values ($\times 10^{-5}$ fraction HT hits/mm) for runs with low instantaneous luminosity and runs with high instantaneous luminosity in each layer of the TRT barrel during Period B [6].

Since machine conditions are constantly changing, it is important to understand this dependence, especially if we are to attempt to isolate the ozone accumulation effect from the straw wire aging effect in the future.

5 Conclusions and Future Work

5.1 Conclusions

In conclusion, we found that a degradation effect in all sections of the Transition Radiation Tracker is visible and worsening over time. The loss in signal caused by this degradation effect is dependent on both proximity to the beam collision point and direction of gas flow in the detector. Two potential causes of the effect are prolonged exposure to high amounts of radiation and solid-state silicon deposits brought in by the gas mixture. Further work must be conducted in the near future in order to determine whether the observed effect is solely due to straw wire aging, as predicted, or in part due to various run conditions, such as accumulation of ozone within the straws.

5.2 Proposed Monitoring Tool for LHC Run II

We are currently writing a Python script that will work in conjunction with ROOT, CERN's C++-based data analysis framework, to serve as a tool during Run II. The script will look up luminosity information automatically, essential because the dependence of the degradation effect on run conditions may be relevant to a wide range of experiments. It will be especially useful for those pertaining to other sections of the ATLAS detector. When finished, this function will be

directly implemented in the monitoring tool proposed for Run II, which will produce further information that should allow us to better understand the degradation and possibly isolate straw wire aging from the observed effects. A study of the first data from Run II could very well help to distinguish between ozone accumulation and aging; if the effect has lessened or is no longer present during the first few runs analyzed in 2015 with low instantaneous luminosity, the effect could be attributed to an accumulation of ozone. If the degradation grows worse, however, it could be indicative of an aging effect in the TRT straws.

The current proposed monitoring procedure for 2015 includes continuation of the method presented in this study using data collected at the beginning of Run II, along with further study of the dependence of the fitted slopes on ozone accumulation and other run conditions utilizing the aforementioned Python function. A primary future goal will be to better understand machine operation in order to isolate the straw wire aging effect in the TRT straws from ozone accumulation and other run conditions, and further refine our tool developed to quantify the aging effect. This program will be run every 1 fb^{-1} during the early stages of Run II, and will allow for careful monitoring of the degradation effect before it becomes an issue for long-term detector performance.

