The Transition Radiation Tracker of the ATLAS Experiment

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***Abstract*—The transition radiation tracker (TRT) is one of the three subsystems of the inner detector of the ATLAS experiment. It combines electron identification capability with charged-particle track reconstruction. A total of 420 000 electronic channels provide continuous tracking with many projective measurements per track. This paper gives details of some features of the TRT, from performance requirements to the consequences of its operation in the LHC environment. Some technical choices and operating conditions have been recently changed, the most significant one being the active gas. Presently, a large fraction of barrel and end-cap modules have been assembled in the United States and Russia, respectively. A strict quality assessment has been implemented at the assembly sites and at CERN upon arrival of the modules. The acceptance tests include dimensional surveys, wire-tension measurements, gas-tightness tests, high-voltage training, and gas-gain uniformity measurements along each individual straw. First estimates of the module quality are presented based on the analysis of these tests.**

***Index Terms*—Gas detectors, tracking, transition radiation.**

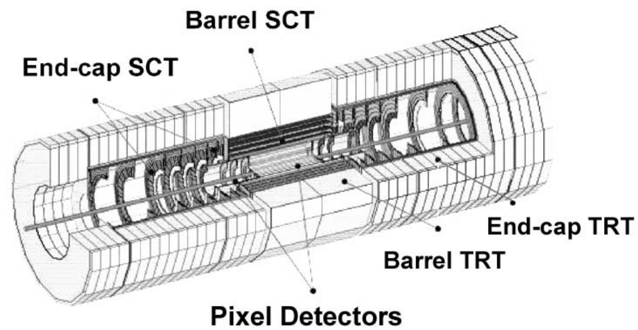

Fig. 1. Perspective view of the ATLAS inner detector. The TRT covers the most external part of the tracker. The barrel contains 52 544 axial straws of about 150 cm length, and the two end-caps contain 319 488 radial straws of 39 to 55 cm length. Barrel straws are electrically divided in two halves and read out at both ends, whereas the end-cap straws are read out and serviced at the outer radius of the detector.

I. Introduction

The transition radiation tracker (TRT) is part of the inner detector of the ATLAS experiment. Fig. 1 shows a schematic layout of the Inner detector: pixel sensors at the innermost radius, followed by layers of silicon-strip sensors, all enclosed by the TRT end-cap wheels and barrel modules covering the most external and largest volume [1]. The TRT is a straw drift-tube detector that combines electron identification capability with the traditional charged-particle track reconstruction in gaseous detectors. The straws have a 4 mm diameter and operate in proportional mode with a $70\%\mathrm{Xe}-27\%\mathrm{CO_2}-3\%\mathrm{O_2}$ gas mixture and an avalanche gain of 2.5×10^4. Particle identification is achieved by efficiently converting in the Xenon-based gas mixture the transition radiation (TR) photons that are emitted when a charged ultrarelativistic particle crosses the interface between different media, polypropylene (random fibers or foils) and CO_2 gas for the TRT. Thus the energy deposition in the TRT is the sum of ionization losses of charged particles ($\sim$2 keV on average) and of the larger deposition due to TR photon absorption (>5 keV). A low-threshold discriminator, set nominally at 200 eV, detects with high efficiency the dE/dx depositions from minimum ionizing particles. A higher-threshold discriminator, set nominally at 5 keV, is optimized for electron/pion separation. Electron tracks contain more high-threshold hits than pion tracks, and a clean electron/pion separation can be achieved by counting the number of high-threshold hits along a reconstructed track.

At the LHC design luminosity of $10^{34}\ \mathrm{cm^{-2}s^{-1}}$, the straw counting rates are very large with an estimated average of about 12 MHz and a maximum of close to 20 MHz for the innermost barrel straws and longest end-cap straws. While most of this counting rate comes from ionizing tracks, slow neutrons and low-energy photons also contribute at a significant level. At such high counting rates, the drift-time accuracy and efficiency are appreciably degraded, but the momentum resolution, pattern recognition and level-2 trigger are preserved with adequate performance thanks to an innovative design of the front-end electronics.

After 10 yr of operation, the most exposed straws will have accumulated a radiation dose of about 10 Mrad, and a neutron fluence of up to $2 \times 10^{14}\ \mathrm{n/cm^2}$. These numbers include a 50% safety factor for uncertainties in the calculations. This total expected dose translates into unprecedented ionization currents and integrated charges ($\sim$10 C/cm of wire) for a large-scale gaseous detector. The straws have been shown to survive in accelerated aging tests these radiation doses and neutron fluences without any significant degradation neither of their mechanical and electrical properties nor of their performance [2], [3].

II. Detector Construction

A. Module Design and Construction

As shown in Fig. 1, the TRT consists of one barrel and two end-cap parts. The barrel covers $\pm$75 cm along the direction of the beam line. It consists of three radial sections, each containing 32 identical modules. The innermost modules contain

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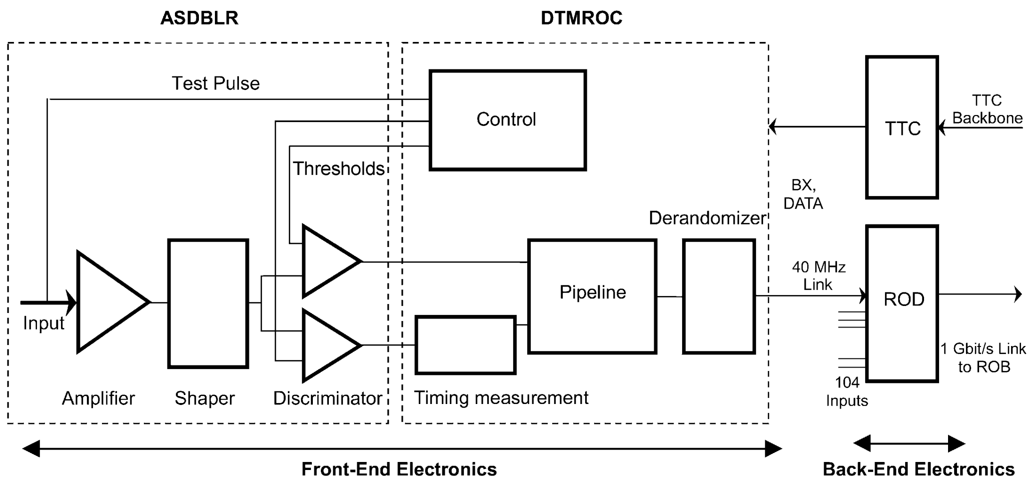

Fig. 2. Schematics of the on-detector signal processing chain for the ATLAS TRT detector.

320 straws each, the middle ones 570 straws each, and the outer ones 800 straws each. The full barrel thus contains ~53 000 150 cm long reinforced straw tubes. Each wire is electrically divided in its middle and read out at both ends. The space between the straws is filled up with a low-density polypropylene/polyethylene fiber radiator to produce transition radiation. Each module is housed in a carbon-fiber reinforced plastic shell that provides stiffness and conducts part of the heat generated by the irradiated straws. The end-cap TRT contains three different types of wheels, called A, B and C. Each end-cap contains ~160 000 radial straws. The type-A and type-B wheels have 37 cm long straws, grouped into eight-plane wheels, each plane containing 768 straws. The type-C wheels, the most distant from the interaction point, contain each 576 straws of 55 cm length per layer. The layers of straws are interleaved with radiator stacks consisting of ~15 polypropylene foils, each 15 μm thick, separated from each other by a 200 μm thick spacer.

Because of their different geometries, the barrel and end-cap modules are structurally different, but nevertheless follow the same tight requirements in terms of rigidity, dimensional stability, minimum amount of material and other features characteristic of any inner tracker in a collider experiment. Specific details about the construction of end-cap and barrel modules can be found elsewhere [4]. The assembly procedures have been optimized for fast and reliable mass production. The production strategy and quality assurance methods have been established to efficiently share the construction between different production sites. The quality control procedures and specifications to be met during the course of production are an integral part of the assembly process. A production database and user-friendly web interface support the storage of parts, the input-quality control data for all components, as well as the identification and storage of all test results obtained during the assembly itself.

The straws themselves are reinforced and are part of the mechanical structure of the module. They are glued to the light support structures (thin C-fiber rings and glass-fiber tension plates for the end-cap and barrel, respectively) without any mechanical constraints and are required to remain straight to better than 300–400 μm after assembly. Gold-plated tungsten wires of 31 μm diameter are crimped (end-cap) or pinned (barrel) at both ends of each straw; both technologies have proven to be reliable and clean, based on extensive validation tests. The crimping tubes, supported by injection-molded plastic pieces, are used both for locating and fixing the wire at the center of the straw (end-cap). A negative high voltage is applied to the straw, while the wire is kept at ground potential. Special care had therefore to be taken in the design to guarantee sufficient electrical insulation between the straws and the mechanical structures. For a nominal gas gain of 2.5×10^4, the high voltage is approximately 1530 V for the standard operating gas mixture.

At LHC rates, significant heat is generated in the straws as the positive ions created by the ionizing particles drift to the cathode. The heat dissipation is directly proportional to the straw counting rate and is estimated to be 10 to 20 mW per straw at design luminosity. Considering the basic requirements on straw operation stability and gas-gain uniformity, the temperature gradient along each straw should not exceed 10°C. To meet this specification and to remove the heat, a CO_2 flow along the straws is used in the end-cap wheels; fluorinert liquid used to cool the barrel front-end electronics maintains the barrel module shells at an approximately constant temperature. The flow of CO_2 takes away any Xenon gas which would leak out of the straws, thereby potentially polluting the radiator space.

The space availability for electronics, cables and service pipes is very limited and the amount of material that is introduced has to be kept as low as possible. Thin cables and pipes, connections and the necessary electrical breaks between the detector and the surface are optimized to meet those requirements [1].

B. *Front-End Electronics*

The front-end electronics of the TRT detector is designed for fast and efficient signal-shaping of the output signal of the TRT straws. An 8-channel analog ASDBLR chip and a 16-channel digital DTMROC chip provide on-detector signal processing, time digitization, pipe-lining and data sparsification (Fig. 2) [5].

The ASDBLR design is based on a largely differential circuit with a short shaping time of 7.5 ns. This value optimizes trade-offs between signal-to-noise and accuracy. In order to cope with the high occupancies, the chip incorporates a precise ion-tail cancellation network in the shaper circuit. Still, large signals or the overlapping ion tails from the pile-up of many signals

TABLE I
TESTS AND ACCEPTANCE CRITERIA FOR THE END-CAP WHEELS AT THE PRODUCTION SITES AND AT CERN AFTER TRANSPORT. THE CORRESPONDING TABLE FOR BARREL MODULES IS VERY SIMILAR

Test	Specification /Acceptance criteria
Dimensional survey	Within specified envelopes
Gas tightness	Pressure drop< 1 mbar/min/bar
Wire tension (T)	55 g < T < 80 g Wire slippage over time< 5 g
High-voltage test in CO_2 at 2 kV	Current < 50 nA for all groups of 32 straws
High-voltage conditioning in 70%Ar-30%CO_2 at nominal gas gain	Current < 150 nA for all groups of 192 straws
Gas-gain uniformity	Wire offset < 400μm for all straws connected to high-voltage Wire offset < 300 μm for 95% of all straws (goal)
Cooling fluid (C_6F_{14}) tightness	Leak rate < 10^{-5} cm^3/min at 3 bar
Ventilation gas (CO_2) tightness	Pressure drop < 1 mbar/min at 5 mbar

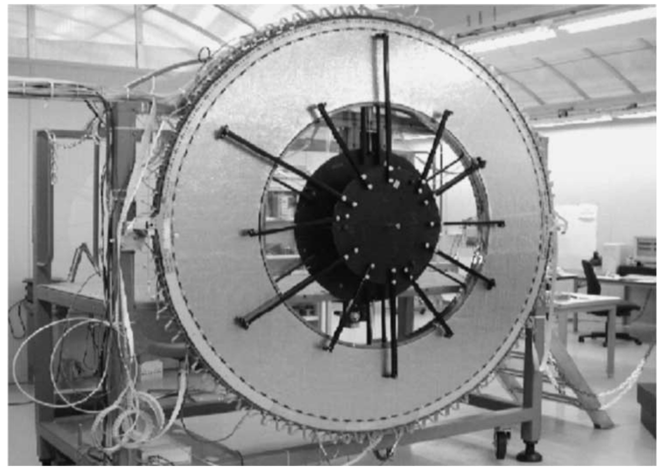

Fig. 3. One end-cap wheel being measured in the WTS. The automatic rotation of six arms equipped with ^{55}Fe sources allows reading out the signal amplitude (in a $70\%\mathrm{Ar} - 30\%\mathrm{CO_2}$ gas mixture) at six points along the full length of each individual straw. This measurement provides a complete characterization of each wheel in less that one day. The gas gain along each straw is measured in order to derive the wire eccentricity and to ultimately identify problematic channels. A second set of ^{55}Fe sources in reference positions (the shortest arms in the picture) provide online corrections for gas-gain variation due to environmental fluctuations.

result in a continuous shaper output current with a fluctuating level several times as large as the desired minimum operating threshold. This would severely degrade performance, efficiency and drift-time accuracy, and would also introduce significant dead time. A differentiating baseline restorer network reduces these effects by allowing efficient detection of near-threshold signals following larger signals.

The DTMROC chip receives and time-encodes the output information of two ASDBLR chips (16 channels), stores data in a memory pipeline and supplies Level-1 formatted data to the back-end electronics located off-detector. It uses the ATLAS 40 MHz system clock. A specially designed ternary receiver intercepts the current step outputs separating out the low and high-threshold discriminator levels. Two shaped test-pulse outputs are provided for calibration and commissioning of the detector.

All the analog and digital ASICs have been produced and the front-end boards are in the preproduction stage. The TRT back-end electronics modules are in the advanced prototype stage and are routinely used in test-beam measurements and system tests.

III. MODULE TESTS AND ACCEPTANCE CRITERIA

The most stringent requirement for accepting assembled modules, which contain from 320 (barrel) to 3000 (end-cap) straws, is the need for a stable and robust operation of the whole system over many years of running at the LHC. In addition to the quality control and tests performed during module production, all completed TRT modules are submitted to a set of measurements before they are packaged to be sent to CERN and again upon arrival at CERN. The measurements follow similar procedures and tooling to those used during assembly. For the final evaluation of each module, the critical points and specifications summarized in Table I are considered. While these tests are very similar for barrel modules and end-cap wheels, this section will focus on the end-cap case as a specific example.

All the module characteristics are recorded in the production database and all the measurements are compared with the values obtained during production. The final information is included in the electronic passport of each module. Wires out of specification in the barrel modules are removed and restrung whenever possible. For the end-cap modules, the problematic wires are neutralised (disconnected from the high-voltage group by unsoldering the protection resistor), since their design does not permit direct restringing of wires.

The verification of the straw straightness or wire offset with respect to its nominal position is the most essential test of the full set of acceptance criteria. For a wire offset of more than 400 μm, the local increase of electric field substantially modifies the gas gain. Under such conditions, the rate of discharges and large-amplitude signals increases significantly, making the straw very unstable under standard LHC running conditions. Therefore, such wires are disconnected from the high-voltage supply at this stage. The measurement is performed for the end-cap case by installing eight-plane wheels in the final vertical position in the Wheel Test Station (WTS); the barrel modules are measured in an equivalent set-up adapted to their particular geometry. Fig. 3 shows the WTS with an eight-plane end-cap wheel under test. The ^{55}Fe sources are mounted on arms placed at six different radii on a star-shaped support. Through an automatic rotation of the arms, the ^{55}Fe signal amplitude in a $70\%\mathrm{Ar} - 30\%\mathrm{CO_2}$ gas mixture, is read out at six points along the full length of each individual straw. For a perfectly straight straw with a tensioned wire exactly centered at the straw ends, the amplitude of the signal should be very uniform along the full length of the straw. The actual overall wire offset will arise from several different sources, e.g., the precision and play in the straw plastic end-pieces, the crimp tubes, etc. However, the main cause for

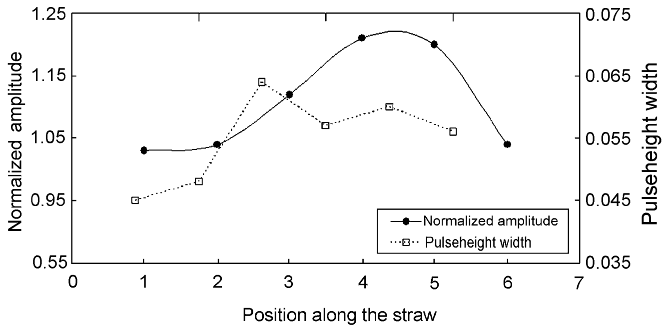

Fig. 4. Typical variations of the normalized amplitude (mean) and width of the Gaussian fit of each $^{55}\mathrm{Fe}$ spectra taken along six points of a bent straw. The observed variation in the middle of the straw indicates a wire eccentricity of more than 400 $\mu\mathrm{m}$.

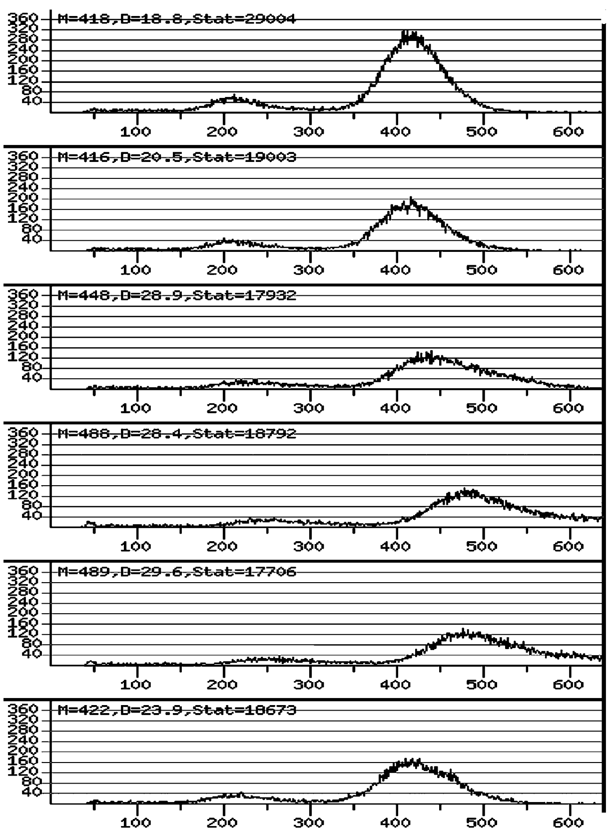

Fig. 5. Each $^{55}\mathrm{Fe}$ pulse-height spectra corresponds to each of the six measured points along the bent straw of Fig. 4.

wire offset is a bent or noncircular straw. Fig. 4 shows the typical pattern of gas-gain amplitude variation and the correspondent increase in pulse-height width for the six measured points in a bent straw. This particular straw, a very rare case, is a candidate for disconnection since the gas-gain variation is above 20%. Fig. 5 shows for the same straw the recorded $^{55}\mathrm{Fe}$ pulse-height spectra at each measured point.

The goal is to have 95% of the straws measured with an eccentricity below 300 $\mu\mathrm{m}$, which corresponds to approximately 5.5% variation in signal amplitude for the chosen gas. All wire offsets should stay below 400 $\mu\mathrm{m}$ eccentricity, corresponding to less than 10% gas-gain variation. Fig. 6 shows the distributions of gas-gain variation for the first four end-cap wheels produced in Russia (3072 channels each) after they have been transported

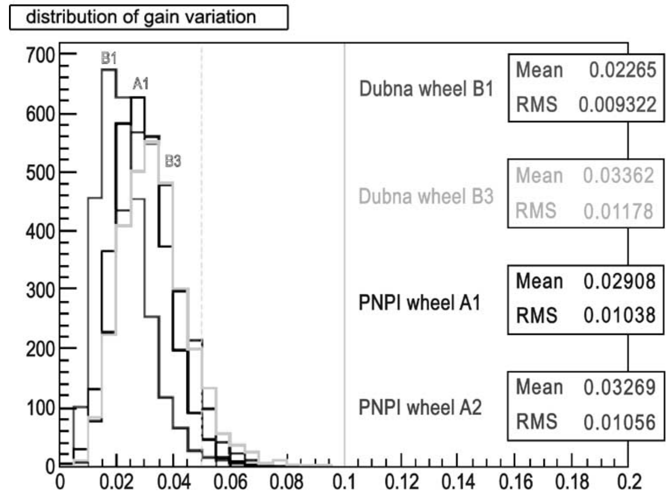

Fig. 6. Distributions of gas-gain variations measured for each of the 3072 straws in the first four end-cap wheels produced in Russia, after they have been transported to CERN. Typically less than 0.1% of the straws display a wire offset above 400 $\mu\mathrm{m}$ (corresponding to a total gas-gain variation of 0.1 on the horizontal axis), and are subsequently neutralized.

and received at CERN. All four wheels displays a gas-gain uniformity with a rms of about 1%. Typically, less than 0.1% of the straws display a wire offset above 400 $\mu\mathrm{m}$ and are subsequently neutralised. The reproducibility of the gas-gain variation measurements between the production sites and CERN, as well as between repeated runs, is better than 1%, thanks in particular to a careful control and monitoring of environmental conditions.

As part of the quality assurance and control, the wire tension is measured during the stringing of each straw plane and after the completion of the module at the production sites. This test is repeated after reception at CERN. A device based on an acoustic feed-back loop is used to accurately and reliably determine the wire tension. The wire is excited acoustically and the characteristic frequency is measured by capacitance-oscillation sensing. Wires with a tension lower than 55 g or higher than 80 g, or with a tension loss of more than 5 g are replaced or neutralised. Fig. 7 shows the distribution of the tension difference between the measurements taken at a few months' interval at the production site and after reception at CERN for the example of one end-cap four-plane wheel. The mean value of this difference is 1.44 g, and a total of 13 wires show a tension loss above 5 g. For the time being, these wires are kept in place and controlled regularly. Disconnection will be possible at a later stage, during the final stacking of wheels. Typically, one wire out of 3072 is neutralised because of a wire tension lower than the specification of 55 g.

High-voltage tests are carried out at three different steps during assembly to identify and repair problematic elements. A final high-voltage conditioning is performed at CERN, when two four-plane wheels are assembled together into an eight-plane wheel. The high-voltage for the binary gas mixture $70\%\mathrm{Ar} - 30\%\mathrm{CO_2}$ used in these tests is 1480 V, that corresponds to a gas gain 2.5×10^4. Voltage is applied to the wheel during several weeks. The current drawn should remain below 150 nA for groups of about 200 straws. In the last 3 d of this test, the voltage is increased to 1550 V (gas gain 10×10^4). Problematic groups exceeding that value are studied

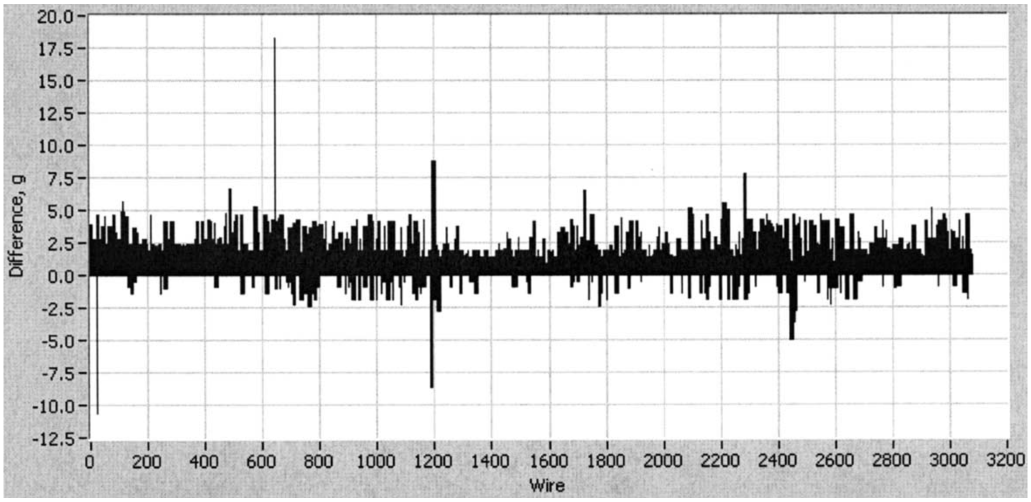

Fig. 7. Distribution of wire-tension difference between the measurements taken at a few months' interval at the production site (PNPI, Russia) and after reception at CERN for all 3072 wires of an end-cap wheel. Negative values account for errors during the measurements and give an estimate of the systematics when comparing measurements taken at the production sites and at CERN.

in detail; defective straws are identified and trained up to full recovery. Unsuccessful training leads to the disconnection of the individual problematic straw. Typically, this also happens for only one straw out of 3072.

One of the key components of the end-cap wheels, both mechanically and electrically, is the so-called active web, which provides the interface between electronics and mechanics. The active web is a multilayer flex-rigid printed circuit board, which carries the high voltage to the straws and transmits the signal from the wires to the front-end electronics. During early production, these circuits have displayed some defects, which affect the connection and readout of typically 10 to 15 straws out of a complete four-plane wheel (3072 straws). The total number of problematic (i.e., dead or unstable) channels after all tests are carried out adds up to about 0.5% to 1%, a fraction which is expected to decrease in the future. The intrinsic complexity of the barrel modules with 1.5-m-long straws, equipped with wire joints to electrically break the wire and wire locators inside the straw volume, results in a similar percentage of problematic channels.

All barrel modules (96 total plus nine spares) have been assembled and 60% have been fully tested before shipment to CERN. The end-cap wheel assembly in Russia is 75% complete in terms of straw assembly, but serious delays in the production of the aforementioned active web circuits, which are also part of the mechanical assembly and have to be in place when wire stringing is carried out, have delayed wire stringing and completion of wheel assembly. A total of ten wheels (out of 80 needed for the inner end-caps) have been delivered to CERN to-date.

IV. Integration and Commissioning

During 2004, the integration of all barrel modules with their electronics into the Inner Detector barrel support structure has to be performed. In parallel, the stacking of all wheels of one of the two inner end-caps will take place, followed in 2005 by the stacking of the second inner end-cap. The type-C wheels for the outer end-caps are staged and are not discussed further here.

Before their final integration, all the barrel and end-cap modules which will be stored, sometimes for a significant amount of time, may have to undergo once again some of the tests described in Table I. Only after successfully passing all these tests, will the modules be considered ready for installation.

Barrel modules will be assembled together into a complete unit in a C-fiber rigid support structure. The front-end electronic boards as well as all relevant services (signal cables, low and high voltage, gas, cooling, etc.) will be connected to the modules and tested. Toward the end of 2004, the barrel TRT should be considered ready for integration with the barrel semiconductor tracker (SCT). The end-cap wheels will be assembled together by horizontally stacking completed eight-plane wheels together with their front-end electronic boards. The end-cap services will be connected to the detector after rotating the end-cap stacks from their original horizontal position to a vertical position within a service support structure and Faraday cage.

Before final installation in the ATLAS cavern at the end of 2005, the TRT will be fully characterized and qualified as an operational system, separately, and together with the silicon-strip detector (SCT). Common survey, mechanical and geometrical tests, services tests and system tests are foreseen. The final commissioning before data taking will consist of dedicated cosmic ray runs and possibly beam-halo runs while the LHC is commissioned with single beams.

V. TRT Performance

A. Gas Mixture

The TRT collaboration has recently replaced its original $70\%\mathrm{Xe} - 10\%\mathrm{CO_2} - 20\%\mathrm{CF_4}$ gas mixture by a new $70\%\mathrm{Xe} - 27\%\mathrm{CO_2} - 3\%\mathrm{O_2}$ baseline gas mixture. The new mixture does not generate under irradiation chemically aggressive $\mathrm{CF_4}$-subproducts while keeping aging phenomena in the harsh LHC environment still at a minimum [6]. As compared to a more standard binary mixture, the addition of oxygen enlarges substantially the operational safety margin, i.e., the high-voltage plateau, without changing significantly the TRT

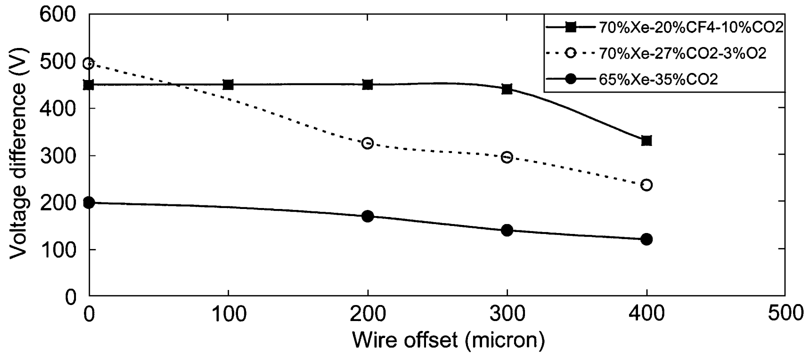

Fig. 8. Voltage difference between the working point and the discharge point for different gas mixtures measured as a function of the wire offset in the straws. The behavior in $Ar - CO_2$ 65–35 and in the same mixture with the addition of 20% CF_4 or 3% oxygen are compared.

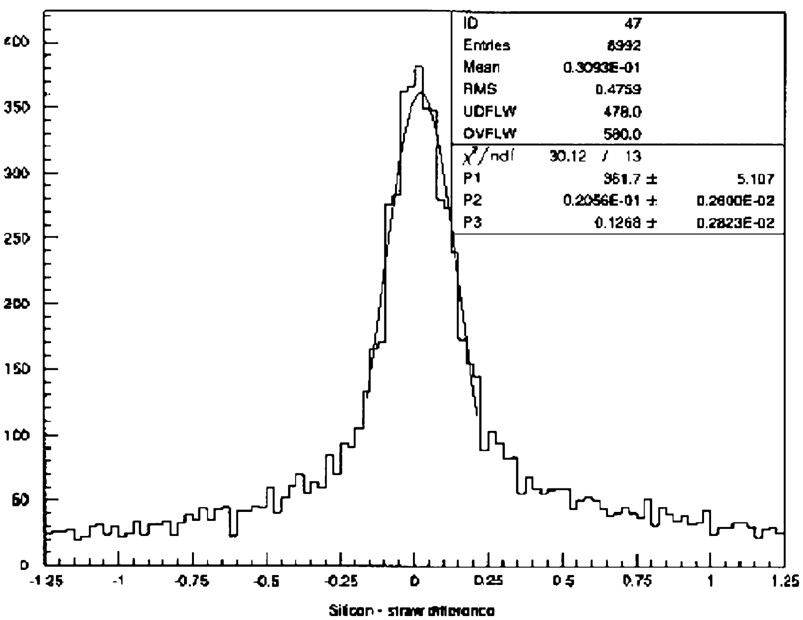

Fig. 9. For 20 GeV test-beam pions and a straw counting rate of 18 MHz, distribution of the residuals obtained from the straw drift-time measurements, with respect to the beam track, after conversion of the straw drift-time measurement to a radial distance from the straw center. The drift-time accuracy obtained is 127 μm and the efficiency is 51%.

performance. Fig. 8 shows as a function of wire offset the voltage difference between the working point and the discharge point for the old baseline mixture with 20% CF_4, the new baseline mixture with 3% oxygen and an $Ar - CO_2$ binary mixture. For large wire offsets of 400 μm, a margin of 220 V is obtained with the new baseline mixture, to be compared with 120 V for the binary mixture. After taking into account safety factors, such as the effect of temperature variations in the detector volume and the effect of highly-ionising particles, the realistic margin of operation is about 170 V, to be compared with 50 V for the binary mixture. In terms of aging, no degradation has been observed in laboratory tests for total accumulated charges of up to 11 C/cm with the new baseline mixture.

B. Performance

The performance of the ASDBLR and DTMROC chips has been successfully demonstrated with several prototype barrel and end-cap modules in system tests [7], [8]; electron identification [3], [9] and tracking [4], [10] performances have been studied under a variety of operating conditions in beam tests. Fig. 9 shows as an example the residual distribution obtained from the straw drift-time measurement, after conversion to a radial distance from the straw center. The measurements in Fig. 9 have been taken during beam tests with 20-GeV pions and with the straws irradiated at a counting rate close to 20 MHz. The drift-time accuracy and efficiency, defined from the distribution shown in Fig. 9 as the rms σ of a Gaussian fit to the peak and the fraction of selected measurements lying within a $\pm 2.5 \times \sigma$ around the peak position are, respectively, 127 μm and 51% at this maximum straw counting rate. Without any background counting rate, these values improve to 102 μm and 80%, respectively. These results were in fact obtained with the final version of the analog front-end chip, but with a simplified digital readout yielding a somewhat worse efficiency for small pulses. Using the full electronics readout chain on a sector prototype equipped with 384 channels, the drift-time efficiency at low counting rate was found to be 88% in good agreement with expectations from Monte Carlo simulations.

VI. Summary

The TRT is a large-size high-rate detector presently being assembled for the ATLAS experiment. The design is a compromise between many contradictory requirements. The straws as detector elements have been thoroughly validated and optimized for satisfactory operation in the LHC environment. Extended campaigns of measurements, system tests and beam tests have demonstrated the excellent performance and robustness of straws with their front-end electronics. By October 2003, 60% of the barrel modules and 20% of the end-cap wheels are considered as operational. The TRT is now moving into integration in 2004, and will be integrated with the SCT (silicon-strip detectors) during 2005. The installation of the overall inner detector in ATLAS is planned for the end of 2005-beginning of 2006.

Acknowledgment

The TRT detector has been designed and is being built by a large group of people around the world. This presentation gives an overview of the design and present status. Therefore, the author would like to thank and acknowledge all members of the TRT collaboration for their contribution to it.

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