TRANSITION RADIATION TRACKER FOR ATLAS PROJECT

**O.L. Fedin, E.G. Danilevich, A.E. Khristachev, L.G. Kudin, S.N. Kovalenko, V.P. Maleev,
A.V. Nadtochy, S.K. Patrichev, Yu.F. Ryabov, D.M. Seliverstov, V.A. Schegelsky,
E.M. Spiridenkov, A.Yu. Zalite**

1. Introduction

PNPI is participating in the ATLAS project in creation of the Transition Radiation Tracker (TRT). TRT is one of the three sub-systems of the Inner Detector of the ATLAS experiment [1]. Besides TRT, the ATLAS Inner Detector includes the Pixel Detector and the Semi-Conductor Tracker (Fig. 1). TRT is designed to operate in a 2T solenoidal magnetic field at the design LHC luminosity (10^{34} cm^{-2}s^{-1}). TRT provides a combination of continues tracking, based on individual drift-tubes (straws), and of electron identification based on registration of the transition radiation (TR) photons which are produced in the radiators foils interleaved between the straw layers. The TRT geometry provides registration of the charged particles with p_t>0.5 GeV/c and with pseudo-rapidity $|\eta|$<2.1. TRT contributes to the accuracy of the momentum measurement in the Inner Detector by providing at all luminosities precise measurements in the R-φ plane. The accuracy of this R-φ measurement, expressed as an average over all drift-time measurements in the straws, is required to be close to 30 μm statistically and not worse than 50 μm if one includes systematic uncertainties. It means that the accuracy of one straw measurement should be about 180 μm. TRT contributes to the electron identification together with the ATLAS liquid argon electromagnetic calorimeter. Electron identification at LHC is much more difficult than at existing hadron colliders, and it has been demonstrated that the TR-signature is needed to identify a clean sample of inclusive electrons in the p_t-range between 20 and 40 GeV/c. The TR-signature is crucial for extraction of the signals from decay processes with huge combinatorial background of charged-particles pairs and also for identification of soft electrons in b-quark jets.

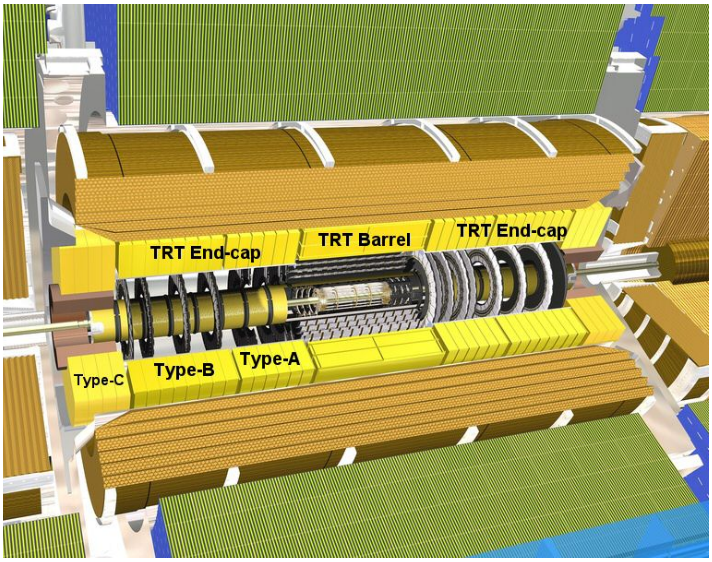

Fig. 1. ATLAS Transition Radiation Tracker

2. Straw design and basic properties

The operating conditions in the ATLAS experiment at LHC demand stringent requirements on the straw properties [2]. All choices of materials, the straw design, the active gas and the operating point were made to ensure safe and efficient operation in the high radiation environment. A large tube diameter would assure a high hit efficiency but it would not be able to collect all electrons in the short bunch crossing time of 25 ns. The straw diameter was chosen to be 4 mm as a reasonable compromise between speed of response, number of ionization clusters, and mechanical and operational stability. The straw tube wall is made of 35 μm thick multilayer film which is produced on the base of 25 μm Kapton film. On one side of the Kapton film an aluminium layer of 0.2 μm thickness is deposited. The Al-layer provides good electrical conductivity. The aluminium layer is then protected against damage from cathode etching effects and from occasional discharges by a 5–6 μm thick graphite-polyimide layer containing 55% of carbon. The other side of the film is coated with a 4–5 μm polyurethane layer acting as a heat-seal compound. The straw is manufactured by winding two 10 mm wide tapes on a precisely tooled rod at temperature of ~260°C. The Kapton film alone has poor mechanical properties. The straw would be affected by thermal and humidity variations. In order to improve the straw mechanical properties, they were reinforced along its length with four sets of thin carbon fibre bundles. The C-fibres were bounded to the tube outer surface at 90° with respect to each other, using a special machine (Straw Reinforcement Machine – SRM), which was designed at CERN. The SRM is a semi-automatic device. After a group of naked straws is loaded into the drum, the carbon fibre pass over a series of rollers, and an impregnation pot wets the fibres with epoxy resin ensuring uniform resin distribution and tension. A specialized workshop has been organized at PNPI for the straw reinforcement (Fig. 2). The PNPI SRM workshop has produced ~110,000 long reinforced straws (1650 mm length). Stringent quality control steps were implemented in the straw reinforcement process. They include fibre delamination tests and straw geometry measurements (straightness, inner and outer diameters and local deformations or defects). The production yield was 98% at the production rate of ~6000 straws per month.

Fig. 2. View of Straw Reinforcement Machine at PNPI

The anode wire for the TRT straws was chosen to be of golden-plate tungsten 30 μm in diameter. To achieve high registration efficiency of the TR photons, a xenon-based gas mixture is used. The xenon fraction of 70% marks the balance between transition radiation performance, operational stability and electron collection time. The optimal gas composition was found to be 70%Xe+27%CO_2+3%O_2. The TRT is typically operated at 1530 V, corresponding to a gas gain of 2.5×10^4 for the chosen gas mixture [3]. The energy deposition in the straw is the sum of ionization losses of charged particles (~2 keV in average) and of the larger deposition due to TR photon absorption (>5 keV).

At the LHC design luminosity, the straw counting rate is very high, about 12 MHz [4]. This counting rate comes from the ionizing particles, slow neutrons and low-energy photons. The heat dissipation is directly proportional to the straw counting rate and estimated to be 10–20 mW per straw at the LHC design luminosity. The temperature gradient along each straw should not exceed 10°C to keep straw operation stability and gas gain uniformity. To evacuate the dissipated heat, a flow of CO_2 gas along the straw is used. The flow of CO_2 also evacuates any xenon gas which could leak out of the straws and thereby reduce the transition radiation registration efficiency.

3. Straw preparation

To use the straws for the TRT modules assembly, it should pass through several steps of the preparation procedure (a general view of the straw preparation workshop is shown in Fig. 3). Each of the reinforced straws is 1650 mm long, and at the first step they need to be cut into few short straws (four ~400 mm long straws for the A/B type modules, or three ~500 mm long straws for the C type modules). The straw pre-cutting is not precise and is chosen only for convenient work. The pre-cut straws pass through the test for the inner surface conductivity because high voltage distribution and signal propagation along the straw depend on it. Then a conductive past is put on one edge of the straw to provide conductivity between the inner and outer surfaces. After that an end-piece (which provides gas distribution into the straw, wire fixation, and fixation of the straw in the wheel) is glued on the straw. At the final step, the straw is cut precisely with an accuracy of ~100 μm.

Fully equipped straws passed several quality tests. First of all they were checked for gas-tightness under overpressure of 1 atm. If the pressure drop was more than 0.1 mbar/bar/min, the straws were rejected. Then the straws were checked for straightness, and simultaneously their length was measured. The straws with the sagitta less than 200 μm and the length deviated from the specification by not more than 100 μm are used for the TRT modules assembly. At the last step, a visual inspection of the straws was done to check for any damages, bubbles in glued parts, runs of glue *etc*.

Fig. 3. Straw preparation workshop at PNPI

The described procedures require unique devices which were designed and produced in collaboration of PNPI with CERN. A special workshop was organized at PNPI to accomplish this task. The straw preparation team has produced and tested more than 170,000 straws for the A/B wheels, and more than 47,000 straws for the C-type wheels. The production yield was 96% at production rate of 320 straws/day.

4. Design and construction of the TRT endcaps

The TRT design [5] follows the tight requirements in terms of rigidity, stability, minimum amount of material, as well as other requirements typical for any tracking system in a collider experiment. TRT consists of one barrel and two endcap parts. The full length of the detector is 6.8 meters. The diameter is about 2 meters.

Each of the two endcap TRT parts consists of two sets of identical and independent modules (wheels). They are called the 8-plane wheels, because they contain eight planes of radially oriented straws. Each TRT endcap contains two different types of wheels called A and B.

Twelve 8-plane wheels of type A per side are located closest to the interaction point between $827 < Z < 1715$ mm. Each wheel contains 6144 straws positioned in eight successive layers spaced by 8 mm along Z. Each layer contains 768 straws in the azimuthal plane. The free space of 4 mm between successive layers is filled with 15 μm thick polypropylene radiator foils. The distance between straws in the azimuthal plane varies from 5.2 mm at the inner radius of 640 mm to 8.4 mm at the outer radius of 1010 mm. The A-type wheels were assembled at PNPI.

Eight 8-plane wheels of B-type per side are located between $1719 < Z < 2725$ mm. The B-type wheels are identical to the A-type wheels except for the spacing between the successive straw layers which is increased to 15 mm. This free space is filled with larger number of radiators foils. The B-type wheels were assembled at JINR in Dubna.

Originally the TRT endcap was designed with extension the rapidity region up to $|\eta| = 2.5$ ($Z < 3363$ mm) by using the third ring of wheels (C-type wheels). They should contain 4608 straws positioned in eight successive layers spaced by 8 mm along Z (as for the A-type wheels). Each layer, however, should contain only 576 straws in the azimuth plane, a smaller number than for the A/B-type wheels. The C-type straws should be longer by 14 cm than the straws of A/B-type to extend the η-coverage of the TRT. The construction of the C-type wheels has been staged, and they will not be assembled at present.

The endcap TRT therefore comprises a total of 245,760 straws with a quite uniform occupancy. A typical track will cross between 32 and 45 straws.

5. Wheel design and assembly

The 8-plane wheel is assembled from two back-to-back 4-plane wheels, which are the basic assembly unit for the detector. A 4-plane TRT module is assembled in the first stage.

The straws are inserted and glued (Fig. 4) into precisely drilled holes in the inner and the outer C-fibre rings, which serve as support structures for the straws. To ensure optimal uniformity in the number of straws crossed by particles as a function of azimuth, each straw in a given layer is angularly displaced with respect to its neighbor in the previous layer by 3/8 of azimuthal spacing between straws in the same layer. The straws themselves are reinforced and are part of the mechanical structure of the module. The straw straightness is required to be remained better than 300 μm, because their operational stability strongly depends on the displacement of the anode wire from the tube axis. Each straw is therefore visually inspected after insertion and after gluing. The problematic straws were replaced. The assembled 4-plane mechanical structure (C-fibre rings and straws) passed through inspection and quality-control measurements (dimensions and gas tightness of the mechanical structure).

Fig. 4. Assembly of TRT wheels at PNPI. Straw insertion and gluing into the carbon support rings

Flex-rigid printed circuit boards (Wheel Electronic Board – WEB) are used to distribute high-voltage to the straw cathode and to readout signals from the anode wires. There are 32 separate WEBs per one wheel. The flex-rigid printed circuit board contains two flexible layers of the circuit made from polyamide film. Each flex circuit contains holes with inward-printing petals. The first layer of the flex circuit is used to provide a reliable high-voltage connection to the straw cathode. The high-voltage plastic plugs are inserted through the petals into the straw making contact with the inner straw walls. The signal connection is done in an analogous way using the second flexible layer and the custom-designed copper crimp-tubes inserted through the petals in the second layer. These copper crimp-tubes are used to fix the anode wires on the outer radius (Fig. 5). The other custom-designed copper crimp-tubes with isolation are used to fix the anode wires on the inner radius. The WEB transmits the signals to the front-end electronics boards through three connectors each corresponding to 32 channels.

Fig. 5. Assembly of TRT wheels at PNPI. 4-plane wheel prepared for the wire stringing

A third C-fibre ring at the outer radius is glued to the rigid part of the WEB. On the opposite side of the rings fixed to the WEB, the glass-fibre boards are glued. They provide a sturdy box-like support. This box-like structure serves as an outer gas manifold for the 4-plane wheel. The inner gas manifold is made of reinforced polyamide material and glued to the inner C-fibre ring. The gas flows into one of the two 4-plane wheels, assembled together as an 8-plane wheel, through this outer gas manifold along the straws into the inner gas manifold and through eight plastic connecting elements into the second 4-plane wheel, where it traverses the straws in the opposite direction and is collected in its outer gas manifold.

The whole 8-plane wheel is covered with a thin metal-clad polyamide membrane on each side at the inner radius, which provides a signal-return path from the inner radius of the straws to the outer radius where the electronics ground is defined. The wheels are held together as a stack through a set of axial metallic tie-rods.

A specialized workshop has been organized at PNPI for the wheels assembly. The wheels assembly process includes not only mechanical assembly but also components preparation and final and intermediate tests, resulting in establishment of a passport for each wheel.

Each component used for wheels assembly, when received from a manufacturer or produced in-house, has to be checked for conformance and cleaned before use. Some of the components go through several stages of assembly before going into wheels (straws, flex-rigid printed-circuit boards, inner gas manifolds). The quality control is performed after each essential stage of assembly.

The tight tolerance for the TRT, which is placed in-between the SCT and Liquid Argon calorimeter, is required to comply with the given dimensional envelopes. The critical dimensions of the endcap wheels (such as the inner and the outer radii, the thickness of the endcap wheels) are checked and compared to the specifications.

In the gas leak test, the assembled 4-plane or 8-plane wheels are filled with 20 mbar over-pressured argon. The leak rate is evaluated by measuring the pressure drop in the closed detector gas volume over a sufficiently long period of 4–8 hours. After applying temperature and volume corrections, only a leak rate of smaller than 1 mbar/min/bar is accepted.

The tension of the wires is measured during the stringing process itself and after completion of the module. This test is repeated also after reception of the modules at CERN. Control of the wire tension is necessary to avoid instabilities from the wires gravitational suffering and electrostatic sag. This required special attention since all wires in the TRT modules are crimped. All straws with less than 55 g wire tension, that is with tension loss greater than 5 g, were disconnected. A device based on the acoustic feed-back loop is used to accurately determine the wire tension. The wire is excited acoustically, and the characteristic frequency is measured by capacitance-oscillation sensing. The device was developed and produced at PNPI. Typically, one wire out of 3072 (one per 4-plane module) was neutralized because of the wire tension lower than the specification.

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, when two 4-plane wheels are assembled together in a 8-plane wheel. For the binary gas mixture 70%Ar and 30%CO_2 used in this test, the high voltage is 1480 V. The voltage was applied to the wheel during several weeks. The current drawn should remain below 150 nA for groups of about 200 straws.

The problematic wires out of specification were removed and restrung when ever possible during assembly of the modules. Part of them were neutralized (disconnected from the high-voltage group by unsoldering the protection resistor), since the design of the endcap does not permit restringing of the wires after assembly of the module. Basically, all tests were repeated after transportation of the modules to CERN, before the modules enter the stage of final assembly to the super-modules equipped with front-end electronics.

6. The wheels tests and acceptance criteria

The most stringent requirement for accepting the assembled wheels [6] is the need for a stable and robust operation of the TRT detector over many years of running at the LHC. The aspired goal was to achieve a full detector with less than 1% of dead channels, although up to 3% are acceptable with respect to physics performance. Therefore all assembled TRT wheels are passed through various tests and the quality control procedures. The careful testing and analysis helped to detect non-obvious problems in the production cycle.

All the module characteristics are recorded in the production data base. In the large scale project like the TRT, the modern database is needed not only for trivial follow up of the component stores, but also to document more complicated test results, and to provide possibilities to trace the reasons of the detector failure. Even after many years of running, information on the batch of components used, on the person names

Fig. 6. View of the 8-plane wheel prepared for the tests on the WTS with radioactive source ^{55}Fe

involved into production and tests, environment conditions during the tests can be extracted from the TRT Data base.

The verification of the straw straightness, or wire offset (eccentricity) with respect to its nominal position within the straw, is the most critical 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. The actual overall wire offset can arise from several sources, *e.g.* the mechanical positioning of the crimp tube in the straw plastic end-pieces, bent or non-cylindrical straws, *etc.*

The technical difficulty in direct determination of wire positions in 370,000 straws demands an indirect way to access eccentricity and other geometric deformations of the straws. The method is based on the measurements of the gas gain uniformity along the straw tube. The verification is performed by installing the 8-plane wheel under test in a vertical position in the automated setup (called Wheel Test Station) equipped with an array of ^{55}Fe radioactive sources – see Fig. 6.

The WTS is rather complicated setup, it includes all complexities starting from precise mechanics, sophisticated electronics, computing and data acquisition system, on-line and off-line programming up to a dedicated data base. PNPI provided main contributions to this project from design to construction of the WTS key elements.

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 signal amplitude, obtained from the straws filled with a 70%Ar and 30%CO_2 gas mixture, is read out at six points along the full length of each individual straw. For a perfectly straight straw with an anode wire exactly centered at the straw ends, the amplitude of the signal should be uniform along the full length of the straw. With the help of calibration curves, the wire eccentricity can be extracted from the change in the gas gain and from deterioration of the peak width. The calibration curves have been determined in experiments with controlled deformation of the straw tubes. The gas gain variation is defined by the difference of the largest and the smallest gain points. In addition, the shape of the measured peak provides an indication of the nature of the anomaly. After applying safety factors accounting for uncertainties, it was decided that straws with amplitude variations greater than 9% are subject to critical review and possibly to face disconnection. The results of all acceptance tests are stored in production database and summarized in so-called electronic endcap wheel passports.

The wheels were assembled on time according to the plans of the TRT collaboration. Less than 1% of the channels were dead. After delivery to CERN, the wheels were tested again with the results reproducing well the measurements at PNPI.

7. Integration and commissioning

During 2004–2006, stacking of all endcap wheels with their electronics into the TRT endcaps has been performed. The endcap services were connected to the detector after rotating the endcap stacks from their original horizontal position to the vertical position within a service support structure and the Faraday cage.

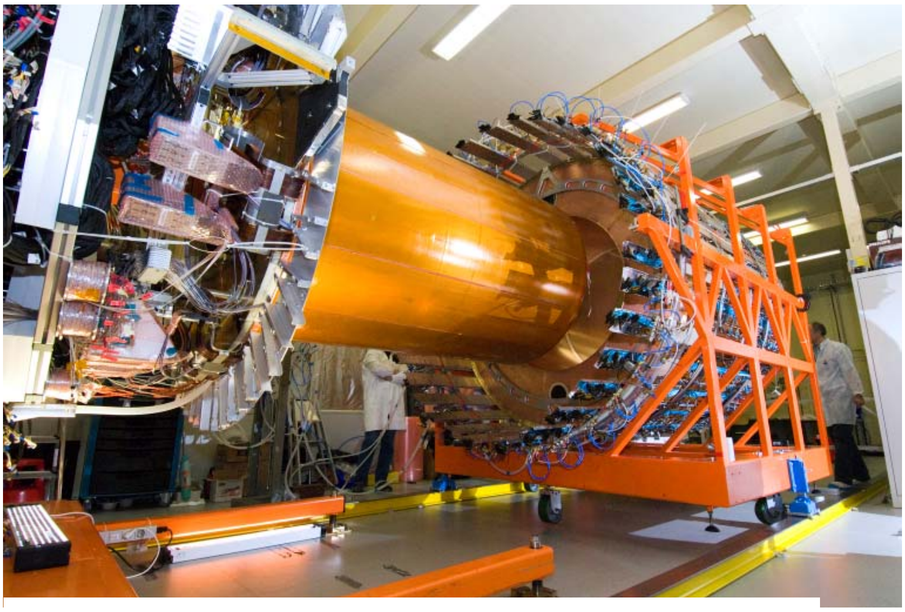

Fig. 7. View of the TRT endcap during integration with the SCT endcap at CERN

Before final installation in the ATLAS cavern in the beginning of 2007, the TRT has been fully characterized and qualified as an operational system separately and together with the silicon-strip detector (SCT). Common survey, mechanical and geometrical test, services test and system test have been done. The dedicated cosmic runs, stand-alone and combined with the SCT, have been performed. The major goal of the cosmic rays studies was to test combined operation of the SCT and the TRT (Fig. 7) and to check the inter-detector effects. To represent and analyse the readout data from the TRT detector, a program called Event Display was written by the PNPI team.

PNPI physicists made principal contribution to the TRT detector description for the GEANT4 detector simulation. Currently, studies of the TRT performance for electron identification are in progress within the Physics e/gamma group. PNPI physicists participate also in the work of the Top-physics group and the Jet/EtMiss working group.

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