ATLAS EXPERIMENT

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1. Introduction

LHC offers a large range of physics opportunities, among which the most important being the measurements that will lead to an understanding of the mechanism of electroweak symmetry breaking. The origin of mass at the electroweak scale is a major focus of interest for the ATLAS. Other important goals are the search for heavy *W*- and *Z*-like objects, for supersymmetric particles, for compositeness of the fundamental fermions, as well as investigations of *CP* violation in *B*-decay and detailed studies of the top quark. The ATLAS detector design was guided by a broad spectrum of detailed physics studies.

2. The ATLAS detector

The ATLAS Collaboration has proposed to build a general-purpose collider detector [1], which is able to operate at highest possible luminosity (10^{34} cm^{-2}s^{-1}) with as many signatures as possible (e, γ, μ, jet, E_T^{miss}, b-tagging). Emphasis is also put on the performance necessary for the physics accessible during initial lower luminosity (10^{33} cm^{-2} s^{-1}) using in addition more complex signatures (τ and heavy-flavour tags from secondary vertices). The basic design criteria of the detector include the following:

- Very good electromagnetic calorimetry for electron and photon identification and missing transverse energy (E_T^{miss}) measurements.

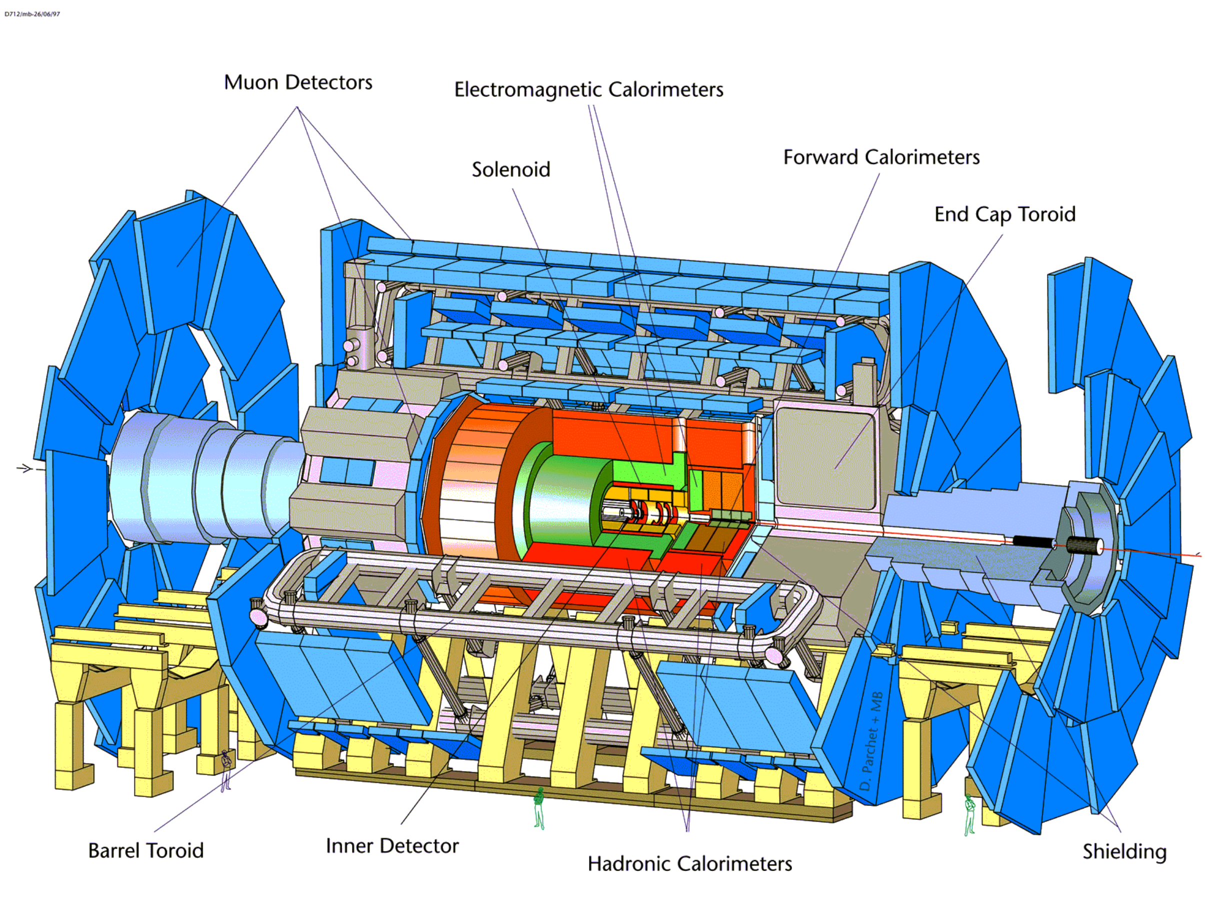

Fig. 1. Overall layout of the Atlas Detector

- High-precision muon momentum measurements, using the external muon spectrometer alone.
- Efficient tracking at high luminosity for high-p_T lepton momentum measurements, electron and photon identification, τ-lepton and heavy-flavour identification, and full event reconstruction capability at lower luminosity.
- Large acceptance in pseudorapidity (η) with almost full azimuthal angle (ϕ) coverage everywhere.
- Triggering and measurements of particles at low-p_T thresholds, providing high efficiencies for most physics processes of interest at LHC.

The overall detector layout is shown in Fig. 1.

3. Magnet and Muon spectrometer

The magnet configuration is based on the inner super-conducting central solenoid (CS) around the inner detector cavity and large superconducting air-core toroids consisting of independent coils arranged in an eight-fold symmetry outside the calorimetry. The air-core toroids consists of the Barrel Torroid (BT) and of two Endcap Toroids (ECTs) inserted at the ends of BT. The CS provides a central field of 2 T with a peak magnetic field 2.6 T at the superconductor itself. The peak magnetic fields on the superconductors in the BT and ECT are 3.9 and 4.1 T respectively.

The concept of the magnet configuration offers:

- Almost no constraints on the calorimetry and inner detector allowing noncompromised technological solutions;
- A high-resolution, large-acceptance and robust stand-alone muon spectrometer.

The quality of the muon track reconstruction has been one of the guiding design criteria for the ATLAS experiment. The conceptual layout of the muon spectrometer [2] is based on the deflection of muon tracks in the large superconducting air-core toroid magnets. The muon spectrometer (Fig. 2) is equipped with a separate dedicated trigger and high-precision tracking chambers. To provide magnetic field that is mostly orthogonal to the muon track and to minimize the degradation of resolution due to multiple scattering, a system of three large superconducting air-core toroid magnets is used. Over the range $|\eta| \leq 1$, the magnetic bending is provided by the large barrel toroid. For $1.4 \leq |\eta| \leq 2.7$, the muon tracks are bent by two smaller endcap magnets inserted into ends of the barrel toroid. Over $1.0 \leq |\eta| \leq 1.4$, usually referred as the transition region, the magnetic deflection is provided by a combination of the barrel and endcap fields.

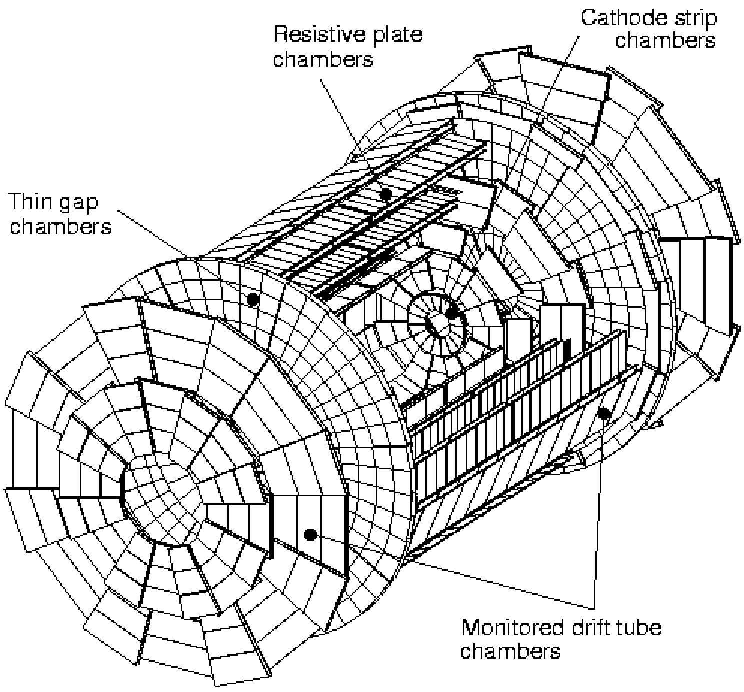

Fig. 2. View of the muon spectrometer

This concern is reflected by choice of the main components of the muon spectrometer: a system of three large superconducting air-core toroid magnets, precision tracking detectors with ~ 60 μm intrinsic resolution, and a powerful dedicated trigger system. The emphasis is given to reliable, high resolution, stand-alone performance over a p_T range from 5 GeV to $\geq$ 1000 GeV. Good momentum resolution is essential for the detection of decays such as $H \to ZZ^* \to 4\ell$ or $Z' \to \mu\mu$ above large background. The physics benefits of a momentum resolution $\Delta p_T/p_T \approx 2\cdot10^{-2}$ at 100 GeV and $\Delta p_T/p_T \approx 10^{-1}$ at 1000 GeV. The *B*-physics program benefits from the detection and measurement of muons with transverse momenta down to $p_T \approx 5$ GeV. Four different chamber technologies are employed: Monitored Drift Tube chambers (MDTs) and Cathode Strip Chambers (CSCs) for the precision measurement; Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs) for triggering.

In the barrel region, tracks are measured in chambers arranged in three cylindrical layers around the beam axis. In the transition and endcap region, the chambers are installed vertically, also in three stations. Over most of the η-range, Monitored Drift Tubes (MDTs) provide a precision measurement of the track coordinates. At large pseoudorapidities and close to the interaction point, Cathode Strip Chambers (CSCs) with a higher granularity are used in the innermost plane over $2 \leq |\eta| \leq 2.7$. The trigger system covers the pseudorapidity range $|\eta| \leq 2.4$. Resistive Plate Chambers (RPCs) are used in the barrel and Thin Gap Chambers (TGCs) in the endcap regions. The trigger chambers for the ATLAS muon spectrometer serves a three-fold purpose:

- bunch crossing identification, requiring a time resolution better than the LHC bunch spacing of 25 ns;
- trigger with well-defined p_T cut-offs in moderate magnetic fields, requiring granularity of order of 1 cm;
- measurement of the second coordinate in the direction orthogonal to that measured by the precision chambers, with a typical resolution of 5−10 mm.

The MDT chambers are aluminum tubes of 30 mm diameter and 400 μm wall thickness, with a 50 μm diameter central W-Re wire. The tubes are operated with non-flammable mixture 93% Ar and 7% CO_2. The MDTs provide a single-wire resolution of ~ 80 μm when operated at high gas pressure (3 bar) together with robust and reliable operation thanks to the mechanical isolation of each sense wire from its neighbours.

The CSC is a multiwire proportional chamber with cathode strip readout and with a symmetric cell in which the anode-cathode spacing is equal to the anode wire pitch. The precision coordinate is obtained by measuring the charge induced on the segmented cathode by the avalanche formed on the anode wire. The anode wire pitch is 2.54 mm and the cathode readout pitch is 5.08 mm. The position resolution of better than 60 μm has been measured in several prototypes. Other important characteristics are a small electron drift time (~ 30 ns), a good time resolution (7 ns), a good two-track resolution, and a low neutron sensitivity.

The RPC is a gaseous detector providing a typical space-time resolution of 1 cm × 1 ns with digital readout. The 2 mm thick bakelite plates are separated by polycarbonate spacers of 2 mm thickness, which define the size of the gas gap. The spacers are glued on both plates at 10 cm intervals. A 7 mm wide frame of the same material and thickness as a spacer is used to seal the gas gap at all four edges. The outside surfaces of resistive plates are coated with thin layers of graphite paint which are connected to the high voltage supply These graphite electrodes are separated from the pick-up strips by 200 μm thick insulating films which are glued on both graphite layers. The readout strips are arranged with a pitch varying from 30 to 39.5 mm.

The TGCs are multiwire proportional chambers in which the anode wire pitch is larger than the cathode-anode distance. Signals from the anode wires, arranged parallel to the MDT's wires, provide the trigger information together with readout strips arranged orthogonal to the wires. These readout strips are also used to measure the second coordinate. To form the trigger signal, several anode wires are grouped together and fed to a common readout channel. The TGCs are operated with a highly quenching gas mixture of 55% CO_2 and 45% n-pentane (n-C_5H_{12}). The main dimensional characteristics of the chambers are a cathode-cathode distance (gas gap) of 2.8 mm, a wire pitch of 1.8 mm, and a wire diameter of 50 μm. The operating high voltage is 3.1 kV.

4. Calorimeters

A view of the ATLAS calorimeters is shown in Fig. 3. The calorimetry consists of an electromagnetic calorimeter (EM) covering the pseudorapidity region $|\eta| < 3.2$, a hadronic barrel calorimeter covering $|\eta| < 1.7$, hadronic endcap calorimeters covering $1.5 < |\eta| < 3.2$, and forward calorimeters covering $3.1 < |\eta| < 4.9$.

The EM calorimeter must be able to identify and accurately reconstruct electrons and photons over wide energy range. The EM calorimeter is a lead liquid argon (LAr) detector with the accordion-shaped kapton electrodes and the lead absorber plates over its full coverage. The EM calorimeter is divided into the barrel and two endcaps. The barrel EM calorimeter is contained in a barrel cryostat which surrounds the Inner Detector. The solenoid, which supplies the 2T magnetic field to the Inner Detector, is integrated into the vacuum of the barrel cryostat and is placed in front of the EM calorimeter. The EM calorimeter consists of two identical half-barrels, separated by a small gap (~ 6 mm) at $z = 0$. Two endcap cryostats house the end-cap EM calorimeter. Each endcap calorimeter is mechanically divided into two coaxial wheels. The outer wheel covers the region $1.375 < |\eta| < 2.5$ and the inner wheel covers the region $2.5 < |\eta| < 3.2$.

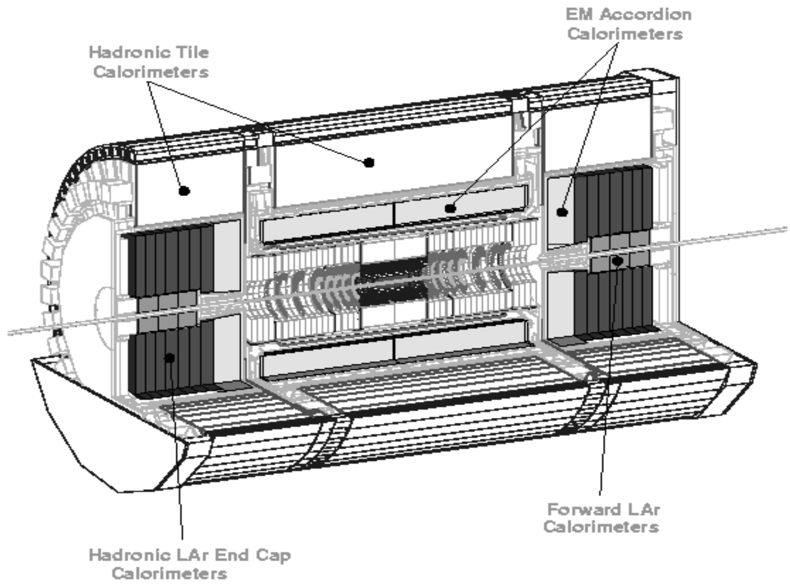

Fig. 3. Three-dimensional cutaway view of the ATLAS calorimeters

The major goals of the hadronic calorimeter are to identify jets and measure their energy and direction, to measure the total missing transverse energy (E_T^{miss}). The hadronic calorimeters use different techniques best suited for the widely varying requirements and radiation environment over the large η-range. The major design criteria of the hadronic calorimeter is its thickness. The calorimeter should provide good containment for hadronic showers and reduce punch-through into the muon system to a minimum. The total thickness of the calorimeter is 11 interaction lengths (λ) at $\eta = 0$, including about 1.5λ from the outer support. Approximately 10λ of the active calorimeter are enough to provide good resolution for high-energy jets. The large η-coverage will also guarantee good E_T^{miss} measurements, which is important for many physics signatures and, in particular, for SUSY particles search. Over the range $|\eta| < 1.7$, the iron scintillating-tile technique is used for the barrel and the extended barrel tile calorimeters and for partial coverage of the gap between them with the intermediate tile calorimeter (ITC). This gap provides space for cables and services from the innermost detectors. The tile calorimeter is a sampling calorimeter using iron as the absorber and scintillating tiles as the active material. The tiles are placed radially and staggered in depth. The structure is periodic along z. The tiles are 3 mm thick, and the total thickness of the iron plates in one period is 14 mm. Two sides of the scintillating tiles are read out.

Over the range $\sim 1.5 < |\eta| < 4.9$, the LAr calorimeters are chosen – two hadronic endcap calorimeters (HEC) and two high-density forward calorimeters (FCAL). Both the HEC and the FCAL are integrated in the same cryostat as that housing the EM endcaps. Each HEC consists of two independent wheels, of outer radius 2.03 m. The upstream wheel is built of 25 mm copper plates, while the outer wheel uses 50 mm plates. In both wheels, the 8.5 mm gap between consecutive copper plates is equipped with three parallel electrodes, splitting the gap into four drift spaces of about 1.8 mm.

The FCAL consists of three sections. The first one is made of copper, while the other two are made of tungsten. In each section, the calorimeter consists of a metal matrix with regularly spaced longitudinal channels filled with concentric rods and tubes. The rods are at the positive high voltage while the tubes and matrix are grounded. The LAr in the gap between is the sensitive medium.

5. Inner detector

The layout of the Inner detector (ID) is shown in Fig. 4. It combines high-resolution detectors at the inner radii with continuous tracking elements at the outer radii, all contained in the central solenoid (CS) which provides a nominal magnetic field of 2 T [3].

The momentum and vertex resolution requirements from physics call for high-precision measurements to be made with fine-granularity detectors, using silicon microstrip (SCT) and pixel technologies. The highest granularity is achieved around the vertex region using semi-conductor pixel detectors. The total number of precision layers must be limited because of the material they introduce and because of their high cost. Typically, three pixel layers and eight strip layers (four space points) are crossed by each track. A large number of tracking points (typically 36 per track) is provided by the straw tube tracker (TRT), which provides continues track-following with much less material per point and lower cost. The combination of the two techniques gives very robust pattern recognition and high precision in both ϕ and z coordinates

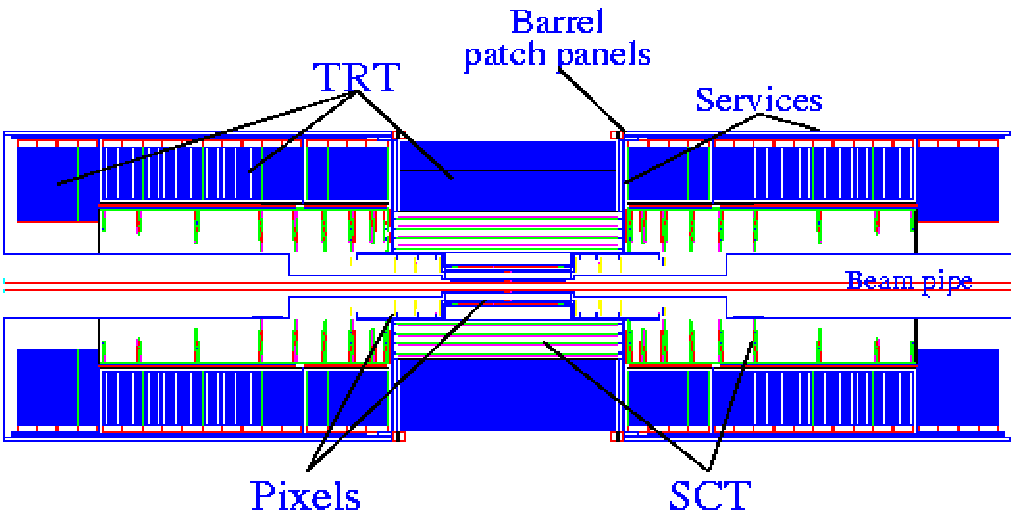

Fig. 4. View of the ATLAS Inner detector

The pixel detector consists of three barrel at radii of ~ 4 cm, 10 cm, and 13 cm, and of five disks on each side, between radii of 11 cm and 20 cm, which complete the angular coverage. The pixel modules are identical in the barrel and in the disk. Each module is 62.4 mm long and 21.4 mm wide, with 61,440 pixel elements read out by 16 chips. The modules are overlapped on the support structure in order to give hermetic coverage. The thickness of each layer is expected to be about 1.7% of the radiation length at normal incidence.

The SCT detector is designed to provide eight precision measurements per track in the intermediate range, contributing to the measurement of the momentum, the impact parameter and the vertex position, as well as providing a good pattern recognition by the use of high granularity. The barrel SCT uses eight layers of silicon microstrip detectors to provide precision points in the $R\phi$ and z coordinates, using small angle stereo to obtain the z-measurement. Each silicon detector is 6.36×6.40 cm^2 with 768 readout strips of 80 μm pitch. Each module consists of four single-sided *p-on-n* silicon detectors. The detector contains 61 m^2 of silicon detectors, with 6.2 million readout channels. The spatial resolution is 16 μm in $R\phi$ plane and 580 μm in z, per module containing one $R\phi$ and one stereo measurement. Tracks can be distinguished if separated by more than ~ 200 μm.

Both the pixel and the SCT systems require a very high dimensional stability, cold operation of the detectors, and removal of the heat generated by the electronics and the detector leakage current.

The Transition Radiation Tracker (TRT) is based on the use of straw detectors. The straw tube is a drift tube which can operate at the very high rates expected at the LHC due to their small diameter (4 mm) and the isolation of the sense wire within an individual gas volume. The electron identification capability is added by employing xenon gas mixture to detect transition-radiation photons created in a radiator between the straws. Each straw is 4 mm in diameter and it is equipped with a 30 μm diameter gold-plated W-Re wire. The barrel contains about 50,000 straws of 144 mm length. Each straw in the barrel is divided in two parts at the centre, in order to reduce occupancy, and is read out at each end. The endcap contains 320,000 radial straws with the readout at the outer radius. The total number of electronics channel is 420,000. Each channel provides a drift-time measurement, giving a spatial resolution of 170 μm, and two independent thresholds. These allow the detector to discriminate between tracking hits, which pass the lower threshold (~ 200 eV), and transition-radiation hits, which pass the higher one (~ 6 keV). The TRT is operated with the non-flammable gas mixture of 70% Xe, 20% CO_2 and 10% CF_4, with a total volume of 3 m^3.

The TRT barrel is built of the three types of modules covering the radial range from 56 to 107 cm. The 32 modules of each type contain 329, 520 and 793 straws, respectively. The first six radial layers are inactive over the central 80 cm of their length in order to reduce their occupancy.

Each of two TRT endcaps consists of 18 eight-plane wheels. The 14 wheels (6 wheels of type A and 8 wheels of type B) nearest to the interaction point cover the radial range from 64 to 103 cm. The last four wheels (type C) extend to the inner radius of 48 cm. The wheel of type A contains 12288 straws, type B – 6144 straws, and type C – 9216 straws.

The primary concept of the TRT design is to obtain good performance at the high occupancy and counting rate. In the barrel the rate of hits above the lower threshold varies with radius from 6 to 18 MHz. In the endcaps the rate varies with z from 7 to 19 MHz. The maximum rate of hits above the higher TR-threshold is 1 MHz.

The TRT provides an additional discrimination between electrons and hadrons, with *e.g.* a pion rejection factor at p_T = 20 GeV varying with η between 20 and 100 at 90% electron efficiency.

6. The PNPI contribution

PNPI is participating in the ATLAS program in several projects: Inner Detector – Transition Radiation Tracker (TRT), Muon Detector – Cathode Strip Chambers (CSC) and DAQ/DCS subproject. The most essential contribution is in the TRT detector. PNPI should assemble 48 endcap wheels of type A each containing four layers of straws. Each wheel consists of 3072 straws. Approximately 50% of the endcap straws will be in these wheels.

Four specialized workshops have been organized at PNPI for the TRT detector assembly – a straw reinforcing area, a straw preparation area, an assembly area, and a wheel test station.

To improve the rigidity of the straws, a special "straw reinforcement" procedure is applied. This procedure consists in reinforcing the straw tubes with stiff carbon filaments glued along the length of the straw. The CERN/TA1 group has designed a Straw Reinforcement Machine (SRM). The SRM (Fig. 5) is a semi-automatic device. After a group of naked straws is loaded into the drum, the four stiff carbon filaments are accurately gluing on the surface of the straw. The PNPI SRM workshop has produced 110 000 long straws (165 mm length) and successfully finished the works in the beginning of March, 2002. The part of the produced straws will use for the TRT barrel assembly at Hampton University (USA).

Fig. 5. View of Straw Reinforcement Machine at PNPI

The Straw Preparation Workshop (SPW) should produce more than 150 000 short straws (372 mm length) for the wheels of type A. The long straws are cut, the end-pieces glued in, and then the straws are stringently tested. The straightness of the straw is controlled to better than 300 μm. The gas tightness control is extremely precise, the pressure drop in the closed straw should be < 0.01% per minute. The straws are also tested on conductivity, glue quantity *etc*. The SPW is already producing more than 320 straws per day. Already more than 100 000 straws have been produced.

The assembly of TRT detector modules consists of several steps. A 4-plane TRT module is assembled at the first stage. The basic assembly tooling consists of two circular assembly tables. The first of these tables serves to support the straw support carbon ring during the insertion of the straws and radiators. The second table is used to assemble active wheel electronics board (WEB) and passive WEB elements into the complete rings. Then anode wires are installed in the straw Fig. 6. To fix a wire in the straw special pins and crimping tool are used. The modules are stringently tested during the assembly. Each module should pass through several high voltage tests, the gas-tightness test, the contact test and the measurements of the wire tension after crimping of the anode wires.

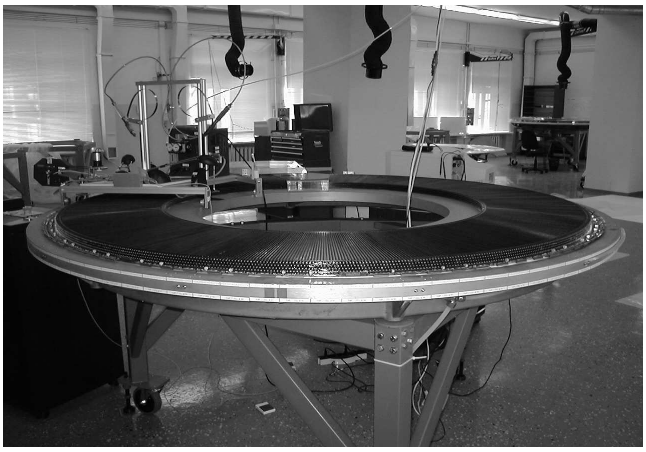

Fig. 6. View of the 4-plane module installed on the assembly table for the wiring

Two 4-plane wheels are ready; an 8-plane module is assembled. Such a module has stand-alone functionality, and extensive tests can be performed with the Wheel Test Station (WTS). A view of the 8-plane wheel prepared for the tests is shown in Fig. 7. The goal of these tests is to check the gas gain uniformity along the straw. The Fe^{55} sources are used to irradiate straws in a different positions along the straw, producing up to 50 000 spectra per wheel. Special electronics have been developed at PNPI to provide the required high data-taking rate. One 8-plane module can be automatically tested in less than 24 hours.

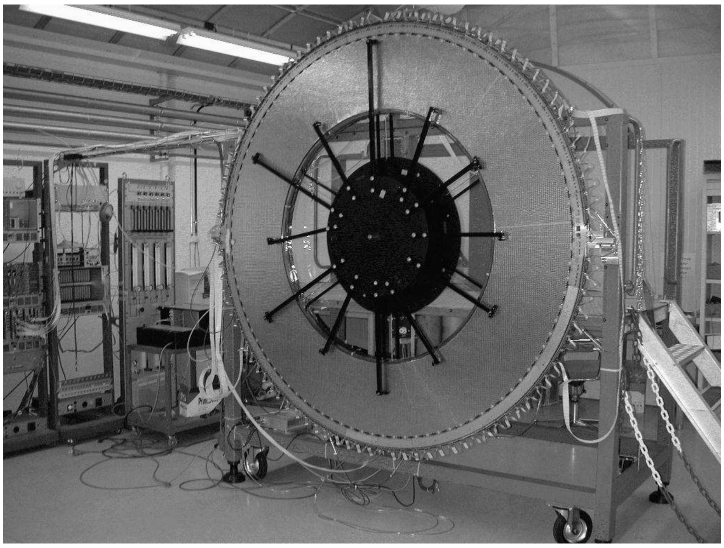

Fig. 7. View of the 8-plane wheel prepared for the tests with radioactive source Fe^{55}

The wire position in a set of several 8-plane modules can be tested with a monochromatic *X*-ray beam. This idea was developed at PNPI [4]. A special *X*-ray tube with a praseodymium anticathode produces a 36 keV *X*-ray. Using a silicon crystal monochromator followed by a narrow collimator, a monochromatic *X*-ray beam is shaped with a small divergence (< 50 microradians) and small width (< 50 μm). The method consists of measuring the straw tube counting rate while scanning on the narrow *X*-ray across the straw. This rate increase strongly when the beam hits the wire. This is due to an additional secondary emission of photoelectrons, Auger electrons and fluorescence from the anode wire when the *X*-ray beam hits the wire. The straw tube is monitored on a computer-controlled gantry that allows automatic scanning of the entire area of the detector. The straw wire positions have been determined with an accuracy of several microns.

Fig. 8 shows a photograph of the *X*-ray scanner installed in front of the wheel for the wire position measuring inside the straw tubes.

PNPI has participated in implementation of the prototype of the ATLAS-DAQ system (DAQ-1), mainly in the Back-End software [5]. The most important contributions include implementation of the Configuration Data Base with the library of remote access to CDB and a program package for inter process communications in DAQ-1 with user requirements for the diagnostic system of DAQ-1.

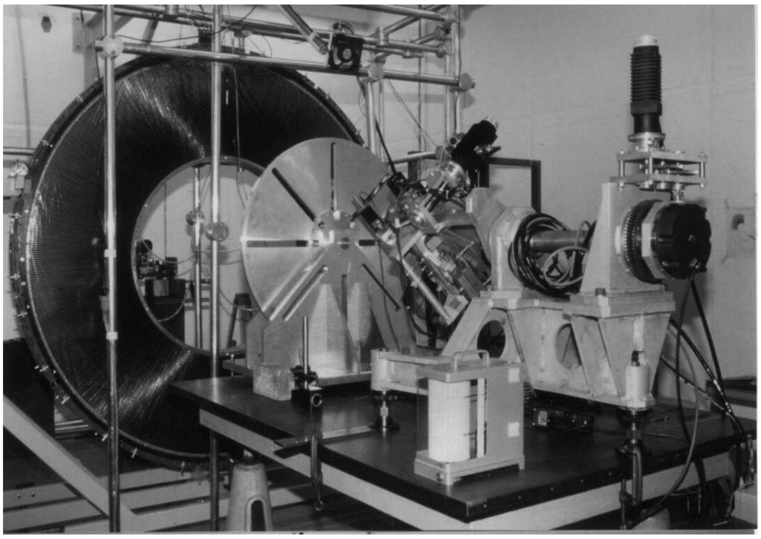

Fig. 8. *X*-ray scanner installed in front of view of the wheel

In the ATLAS-DCS group, PNPI specialists have performed several subprojects:

– design and implementation of CAN-Open servers in HV slow control systems in ATLAS sub-detectors (participation in the LAr Calorimeter test beam);

– program interface in SCADA system (System of Control and Data Acquisition).

PNPI is participating in the development of the TRT ATLAS software. The geometry description of the TRT end-caps and the barrel (partly) has been performed in XML. Several versions of the TRT endcap and barrel geometry description in GEANT-4 (using Placement, Replicas and Parametrized Volumes) were made. The visualization of setup and tracks/hits is done using DAWN. The optimization of the TRT endcap and barrel geometry description in GEANT-4, which led to a substantial decrease of necessary amount of memory, is performed. For ionization cluster formation PAI model is introduced and tested. The hit formation is performed and the framework of digitization program is worked out. The drift-distance to drift-time conversion and signal shaping are included in the digitization program.

PNPI collaborates in the design and construction of the Cathode Strip Chambers for ATLAS Muon spectrometer. The beam test of the CSC prototypes demonstrated the excellent position resolution of 40 μm per layer which is less than 1% of the readout pitch [6]. The double muon track resolution of about 2 mm was achieved for the prototype with readout pitch of 5 mm [7]. The timing resolution for the entire four-layer detector was 3.6 ns (r.m.s.), which is adequate for the fully efficient beam crossing identification in the ATLAS experiment.

The following PNPI team of physicists and engineers is participating on this stage of ATLAS project: O.L.Fedin, Yu.F.Ryabov, D.M.Seliverstov, V.A.Schegelsky, L.V.Bakanov, A.E.Christachev, A.Yu.Zalite, Yu.K.Zalite, V.M.Fillimonov, A.V.Gelamkov, Vl.Vas.Ivanov, V.Y.Ivanov, E.A.Ivanov, S.V.Katunin, A.G.Kazarov, N.V.Klopov, S.E.Kolos, S.N.Kovalenko, V.P.Khomoutnikov, A.G.Krivchitch, L.G.Kudin, A.K.Kyrianov, V.P.Maleev, A.V.Nadtochi, E.G.Novodvorski, S.B.Oleshko, S.K.Patrichev, I.B.Soloviev. In addition, about 15 technicians are involved in construction of TRT detector.

References

[1] ATLAS Collaboration, Technical Proposal for a General Purpose *pp* Experiment at the Large Hadron Collider at CERN, CERN/LHCC/94-43, LHCC/P2, 15 December 1994.

[2] ATLAS Collaboration, Muon Spectrometer Technical Design Report, vol. **1**, CERN/LHCC/97-22, May 1997.

[3] ATLAS Collaboration, Inner Detector Technical Design Report, CERN/LHCC/97-16, April 1997.

[4] T.Akesson, A.Smirnov *et al.*, Nucl. Instr. Meth. **A463,** 129 (2001).

[5] I.Alexandrov, A.Kazarov, S.Kolos, Yu.Ryabov, I.Soloviev *et al.*, IEEE Trans. Nucl. Sci. **47,** No **2** (2000).

[6] G.Bencze *et al.*,Nucl. Instr. Meth. **A357,** 40 (1995).

[7] V.Gratchev *et al.*, Nucl. Instr. Meth. **A365,** 576 (1995).