The Muon Spectrometer of the ATLAS Experiment

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The muon spectrometer of the ATLAS experiment at CERN LHC is reviewed. Background conditions, design performance, Level-1 trigger scheme and the different tracking detectors are presented. Results from recent tests on the performance of the MDT chambers and of the alignment system are discussed.

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1. INTRODUCTION

The requirement of high quality in the measurement of muons has characterized very significantly the design of the ATLAS detector. The muon spectrometer [1] includes three large superconducting air-core toroids, precision tracking chambers for accurate momentum resolution, and an effective trigger system based on chambers with fast response. Emphasis has been given to reliability and stand-alone high performance over the large range in transverse momentum (p_T) required by the physics program of ATLAS.

Fig. 1 shows the general ATLAS layout [2], with Barrel chambers (pseudorapidity $\eta < 1$) arranged in three cylindrical layers, and End-Cap chambers (extending to $\eta = 2.7$) mounted on wheels normal to the detector axis. The detector size is about 22 m in diameter and 44 m in length.

In the following sections, we shall review the background conditions, and discuss the momentum resolution and its implications on physics searches. Next, we shall illustrate the characteristics of the main components of the spectrometer, including brief discussions on trigger, quality control and alignment. Finally, the last sections are devoted to results from beam-tests performed last summer.

2. BACKGROUND AND MUON RATES

In the muon spectrometer, the background is mostly due to photons and neutrons, with energy typically below 1 MeV and 100 keV respectively. The values of the fluence are estimated to be of the order of 1 kHz/cm^2 across most of the detector, increasing by about a factor 20 in the inner station of the End-Cap. The corresponding hit rates for tracking detectors are expected to be roughly in the range 20–500 Hz/cm^2 (with non-negligible contributions from muons and charged hadrons), and they impose constraints on the detector design, both in terms of performance (efficiency, resolution), and for long-term stability (aging).

The rate due to muons depends strongly on threshold on transverse momentum: at the luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ the total rate for $p_T >$ 8 GeV/c is ≈30 kHz, reducing to ≈1 kHz above 20 GeV. In this range, muon production is dominated by decays of beauty, charm, and light mesons. Further above, W decays become relevant.

3. DESIGN PERFORMANCE

The ATLAS muon spectrometer is designed for excellent resolution at large transverse momentum. Fig. 2 shows the different contributions to the resolution in p_T; above 300 GeV/c the main contributions are from the accuracy of the detectors and the precision in their alignment. In Fig. 3 the measurement in the Inner Detector of ATLAS is included for the over-all determination of the transverse momentum: the resolution from the muon spectrometer dominates for

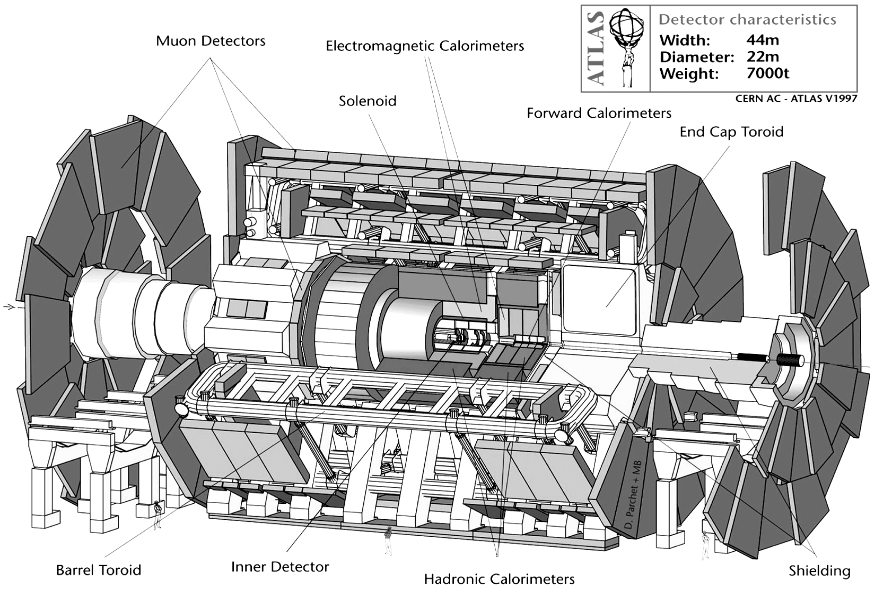

Figure 1. View of the ATLAS detector.

$p_T > 50$ GeV/c.

As an example, Fig. 4 [3] shows the discovery potential for Standard Model Higgs, expressed in terms of standard deviation significance, as a function of the Higgs mass. The momentum resolution, and in particular the triggering capability of the muon spectrometer are very relevant for the searches $H\rightarrow ZZ^*\rightarrow 4\,\mu$, $H\rightarrow WW^*\rightarrow \mu\nu\mu\nu$ and ttH. For Higgs mass above 170 GeV/c^2, the excellent momentum resolution at large values of p_T makes the muon spectrometer a main instrument for the discovery and the measurement of the Higgs mass in the channel $H\rightarrow ZZ\rightarrow 4\,\mu$.

4. SPECTROMETER MAGNETS

The Barrel Toroid is formed by eight superconducting coils, each of them with a coil area of 5×26 m^2. The magnetic field extends between the inner and the outer tracking stations, and is in the range of 0.5 to 2 T. The field integral seen across the toroid by energetic muons is in the range of 2 to 4 T m.

In each End-Cap, the magnetic field is provided by eight superconducting coils, closed in an insulation vessel extending to about 10 m in diameter, located between the first and the second station of tracking chambers. The field is in the range of 1 to 2 T, and the field integral is between 2 and 8 T m. necessary for

Currently, the superconductors are ready, and the assembly of the coils is nearly complete. Most of the effort is now on the integration of the mechanical structures.

5. MUON TRIGGER

The Level-1 muon trigger looks for large transverse momentum muons by reconstructing tracks that point approximately to the interaction point, both in the r-ϕ and in the r-z projection, the latter being close to the bending plane determined by the toroids.

Two thresholds are foreseen (at about 6 and 20 GeV/c respectively), and they are implemented using data from sets of trigger chambers located on different tracking stations, as shown in Fig. 5. The trigger acceptance extends to

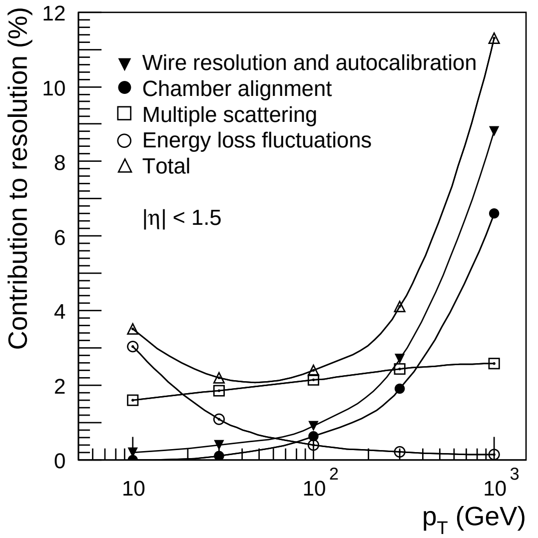

Figure 2. Contributions to p_T resolution in the muon spectrometer.

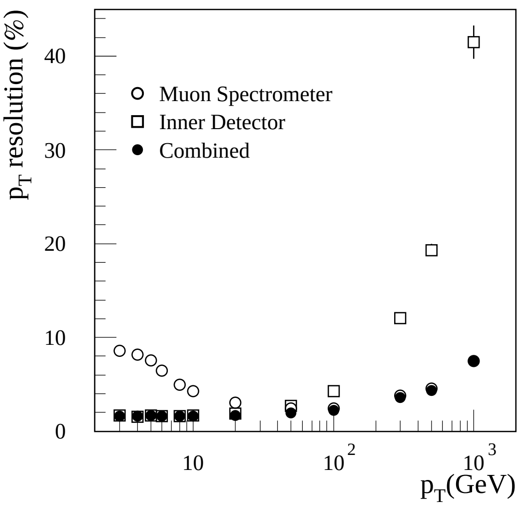

Figure 3. Muon transverse momentum resolution with track reconstruction in the ATLAS Inner Detector and in the muon spectrometer.

$\eta = 2.4$.

Because of the different rates in the Barrel and in the End-Cap, two different detectors have been chosen. They are both characterized by fast response, needed to handle background and to associate tracks to the LHC bunch crossing.

5.1. RPC chambers

Resistive Plate Chambers, operated in avalanche mode, are used in the Barrel. Each chamber uses two gas volumes, Bakelite plates, and four planes of read-out strips. Two layers of chambers are installed in the middle station, and provide the trigger for the low-p_T threshold. A third layer of RPC is installed on the outer chamber station, and is used, together with the other planes, for the high-p_T threshold.

RPCs operated in realistic background conditions in the GIF facility at CERN have shown time resolution below 2 ns, corresponding to trigger resolution better than 3 ns [4].

Currently, series production has started, with about 30 % of the gas volumes completed. An extensive test of production chambers is underway at the GIF facility; among the goals is establishing the operation of the detector with recirculation and in-line purification of the chamber gas.

5.2. TGC chambers

In the End-Cap, the Level-1 muon trigger is provided by Thin Gap Chambers. These are multi-wire chambers operated in saturated mode. The anode-to-anode pitch is equal to 1.8 mm, and the anode to cathode gap is 1.4 mm. The cathode is coated with graphite, and external pick-up strips provide the coordinate along the sense wires. The chamber gas is a mixture (55%-45%) of carbon dioxide and *n*-pentane. Three multi-layers of chambers (one triplet and two doublets) are located in the middle tracking station. Additional TGCs are part of the inner station and are used to increase the tracking ability.

Currently, nearly 50 % of the RPCs have been built by collaborating institutes in Israel, Japan and China.

Tests performed at high rate have shown single-plane time resolution of about 4 ns rms, with 98 % efficiency, corresponding to a trigger efficiency of 99.6 % [5].

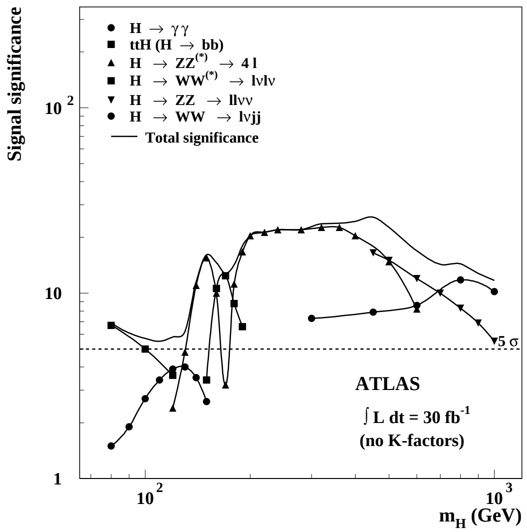

Figure 4. Expected statistical significance, expressed in units of Gaussian standard deviation, for the search of the Standard Model Higgs boson. Contribution of different channels are shown, for an integrated luminosity of 30 fb^{-1}.

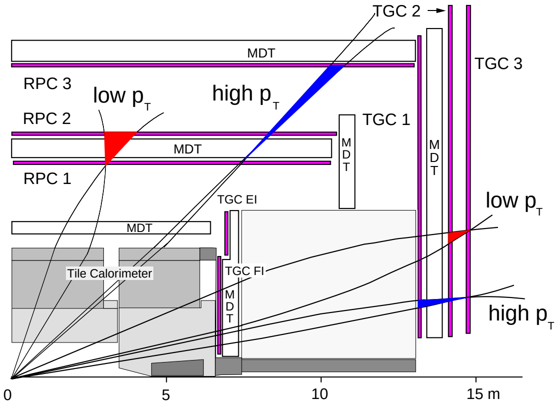

Figure 5. Scheme of Level-1 Muon Trigger. The low-$\mathrm{p_T}$ trigger requires coincidences, in both projections, between two trigger stations. The high-$\mathrm{p_T}$ trigger requires additional coincidences with the third station. The momentum resolution are about 20 % and 30 % respectively, limited by multiple scattering and energy fluctuation in the central calorimeter, and, for the high-$\mathrm{p_T}$ threshold, by the length of the interaction region.

6. PRECISION CHAMBERS

6.1. MDT Chambers

The precision measurement of muon momentum is performed, in almost all the spectrometer, by the Monitored Drift Tubes (MDTs). These are drift chambers formed by aluminum tubes with 3 cm diameter and length in the range 0.9 to 6.2 m. On each chamber the tubes are arranged in two multi-layers, each formed by three or four layers of tubes, as shown in Fig. 6. The MDT chambers use a mixture of Ar-CO_2 (93%-7%), kept at 3 bar absolute pressure, and are operated with a gas gain of 2×10^4. These parameters were chosen in order to match well the running conditions of ATLAS: the MDTs can sustain high rates without aging [6], and with little sensitivity to space charge; the single tube resolution is below 100 μm for most of the range in drift distance, and the resolution of a multi-layer is approximately equal to 50 μm. (Recent measurements on MDT performance are discussed in Section 8.4.)

In order to exploit such tracking accuracy on chambers covering surfaces up to 10 m^2, an extremely accurate mechanical construction is needed. Furthermore, precise monitoring of the operating conditions is required for best performance. Among these issues is the knowledge of the actual chamber geometry. The MDTs are supported at three points via kinematical mounts, which do not apply undesired forces that might cause deformations to the detectors. The aluminum frame supporting the multi-layers is equipped with straightness monitors (of RASNIK type, discussed in Section 7.1) that control sagging and torsion of the detector ("in-plane" alignment). The chambers are also equipped with temperature monitors (in order to correct for the thermal expansion of the tubes, and for the temperature of the gas), and with magnetic field sensors, in order to predict the E×B effect on drift time.

The construction of the 1174 MDTs of the

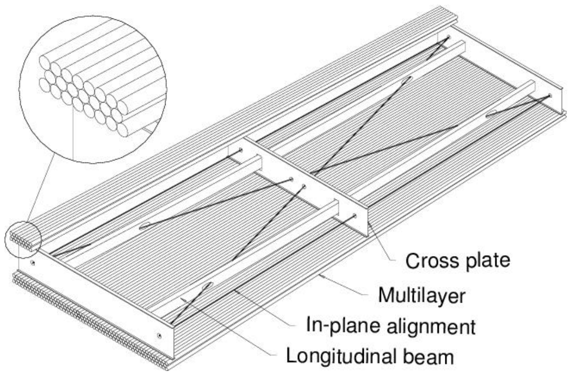

Figure 6. Scheme of a Monitored Drift Tube chamber.

muon spectrometers is done by collaborating institutes, in thirteen production sites (or production consortia) in Europe, Asia and North America. Currently, more than 50 % of the chambers have been mechanically assembled.

6.2. Control of the construction accuracy

The mechanical accuracy achieved in the construction of the MDT chambers is checked in the Tomograph facility at CERN.

The Tomograph [7] makes use of two collimated X-ray beams mounted on a common head moved across the chamber, under interferometric control. Scintillation counters determine when the beams cross a sense wire, as shown in Fig. 7; the use of two, non-parallel beams allows an accurate measurement of the position of almost all wires, in two dimensions, on different cross sections of the MDT chambers. The accuracy of the instrument, determined on a gauge chamber and monitored with a calibrated ruler, is equal to few μm rms.

While the measurement of all MDT chambers is beyond the reach of a single quality control facility, the Tomograph analysis was crucial to establish whether the production sites had reached the required accuracy in the construction of preproduction chambers. The specifications require 20 μm rms deviation in the position of the sense wires, with reference to wire pitch in a layer, and inter-layer distances. The values of these parameters were fixed for each production site after the experience with pre-series production. The Tomograph is now used to monitor the stability of construction quality by analyzing about 15 % of the chambers from the production lines.

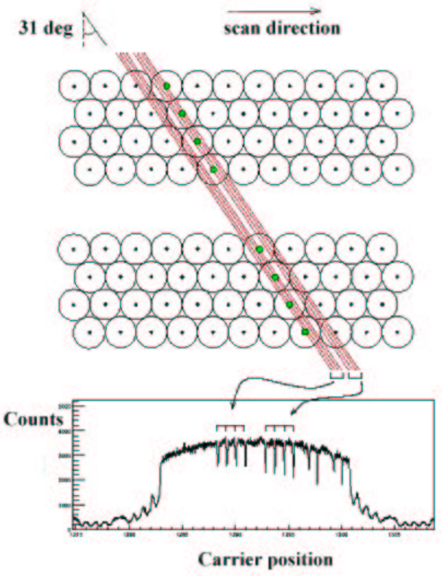

Figure 7. Scheme of the Tomograph measurement. The plot shows counts for different positions of the moving head. The absorption lines, for one of the two beams only, correspond to the X-ray beam position shown on top over the chamber cross section.

6.3. CSC Chambers

The background rate in the $2 < \eta < 2.7$ region of the inner station of the End-Cap is large enough to demand the use of a precision detector with higher granularity. A MWPC with strip read out is used (the Cathode Strip Chambers). The sense wire pitch is 2.54 mm, and the pitch of the read-out strip is 5.08 mm. The track resolution in the bending plane is 60 μm. The production of the 32 chambers of this kind used in ATLAS is about to start at BNL.

7. ALIGNMENT

An excellent alignment of the spectrometer is necessary to fully exploit the intrinsic accuracy of the precision chambers.

Additional complexity is due to the lightness of the mechanical support structures, which are subject to significant and non-trivial deformations in case of temperature changes, or simply when the magnets are turned on or off.

As a consequence, the spectrometer cannot be aligned directly with straight muons collected at zero magnetic field; a specific system, based on optical elements, has been designed to determine and to monitor the relative position of the tracking chambers.

7.1. Barrel chambers alignment

The basic elements are the RASNIK [8] optical straightness monitors. They are formed by three elements along a view-line: an illuminated target-mask at one end, a lens in the middle, and a CCD sensor at the other end. The system provides a very accurate measurement of the relative alignment of the three systems (rms resolution of about 1 μm).

In the ATLAS barrel, most of the chambers belonging to the odd-numbered azimuthal sectors are equipped with two platforms supporting "projective" RASNIKs lines, pointing to the interaction region. Other elements of the alignment include "axial" lines, running along the chambers within a sector, and the "praxial" sensors, connecting adjacent chambers, both based on different implementations of the RASNIK scheme. Additionally, chambers belonging to different sectors and stations are monitored by a lower accuracy system (the "reference" system), based on CCD cameras and LED targets, which determine positions in three dimensions, by means of triangulations, to an accuracy of about 0.4 mm. The RASNIK elements, which need to be calibrated, are mounted on platforms by means of precision, three-balls mechanics, and the platforms are accurately fixed to the MDT chambers (with a procedure verifiable by the Tomograph). In this way the optical alignment is transferred to the position of the sense wires. Chambers in the even-numbered sectors are pre-aligned by the reference system, and precisely aligned to odd-numbered sectors using muon tracks in the regions of overlap. The design accuracy of the alignment system correspond to 30 μm rms error in the measurement of the sagitta of muon tracks.

7.2. End-Cap chambers alignment

In the forward region the use of many projective alignment lines is not possible because of the presence of the cryostat of the toroid magnet. Hence, the alignment of the spectrometer is performed by first aligning a set of reference devices, the "alignment bars", and then transferred to the tracking chambers. The alignment bars [9] are built from aluminum tubes, with diameter of 80 mm and length up to 9.6 m. Internally, they are equipped with RASNIKs, which monitor the transverse shape, and with temperature sensors, which control the longitudinal thermal expansion. Eight bars are mounted on each tracking station of the End-Cap, oriented radially along the edge of wedge-shaped sectors. On the outer surface, the bars are equipped with alignment devices called BCAM [10], formed by a precision CCD camera and by LEDs acting as targets for other BCAMs. Through the BCAMs, each bars looks at the two adjacent bars on the same station, along several view-lines, and to the two corresponding bars in the other stations, along two or three projective lines. Globally, this provides a set of measurements used for a redundant determination of the relative position of all the bars. The alignment is finally transferred to the precision chambers, which are equipped with "proximity" sensors (telescopes formed by a CCD and a lens) looking at RASNIK-masks mounted on the alignment bars. Like in the case of the Barrel, the calibration of all alignment devices is necessary, including the shape of the alignment bars. The resolution of the BCAM is equal to 50 μrad (including calibration and positioning accuracy), reducing to 5 μrad when used to measure angular differences in the polar lines. The alignment resolution contributes about 40 μm to the uncertainty in the measurement of tracks sagitta.

8. RECENT TEST-BEAMS RESULTS

8.1. System test in the H8 beam

Sets of MDT chambers from the Barrel and the End-Cap have been installed in the beam-area H8 at CERN in order to test the performance and develop the integration of the muon spectrometer. In the Barrel set-up, six chambers from an odd-numbered sector have been mounted in a geometry reproducing two tracking towers. In the End-Cap set-up, six chambers reproduce parts of one octant of the three tracking stations; each station is equipped with two alignment bars. In the nominal position, the beam crosses the chambers with position/angle corresponding to energetic muons in ATLAS at 75 and 15 deg polar angle, respectively for the Barrel and the End-Cap set-ups. A dipole magnet allows to change this angle by about ±3 deg. Preliminary results from alignment tests performed in summer 2002 are discussed in the sections 8.2 and 8.3. While improvements in the analysis are expected, and further tests are planned for next year (e.g.: with a wider coverage of the chamber with the test beam, using fully calibrated alignment devices, and including tracking from the trigger chambers), the current results provide already now a significant test of the detector performance and a validation of the alignment system.

8.2. Tests of Barrel alignment

A full alignment test was not possible because several optical devices could not be calibrated in time for the beam period. However, significant tests of the alignment system could be done studying the relative position of different components of the system. For instance, geometrical variations due to temperature gradients are tracked simultaneously and independently by the alignment system and by the track reconstruction program. Similarly, alignment information from optical devices and from tracks can be compared for controlled displacements of chambers. Fig. 8 [11] shows the result of a preliminary analysis based on sets of data corresponding to different positions of a chamber in the central tracking station. The offset of 130 μm is due to the use of uncalibrated alignment devices. The alignment system can track large movements of the middle chamber with an accuracy of about 20 μm rms.

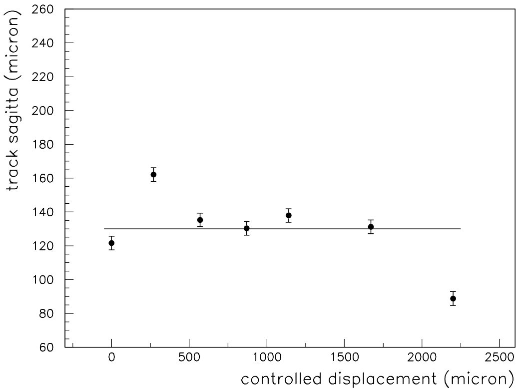

Figure 8. Alignment test for Barrel MDTs: the displacement applied to the middle chamber is reported on the horizontal axis. Track reconstruction, including data from the optical alignment system, provides the misalignment of the middle chamber relative to the outer ones, as shown on the vertical axis. The spread of the data points is equal to about 20 μm.

8.3. Test of End-Cap alignment

While analyses using together the alignment system and the reconstruction of tracks are not yet available, interesting results have been obtained using an additional optical system: a polar alignment monitor, formed by a BCAM looking at LED targets mounted on three chambers of the three stations, along a line of view directed to the virtual interaction point and relatively close to the beam line. The readings from this device ("muon simulator"), provide a monitor on the relative alignment of the three chambers, and can be compared to the prediction from the alignment system. Fig. 9 [12] shows the comparison over a time interval of five days. The coordinate shown is the difference between the central chamber and the interpolation between the external ones, for the direction along the bending plane. The significant movement is induced by large temperature variations in the experimental

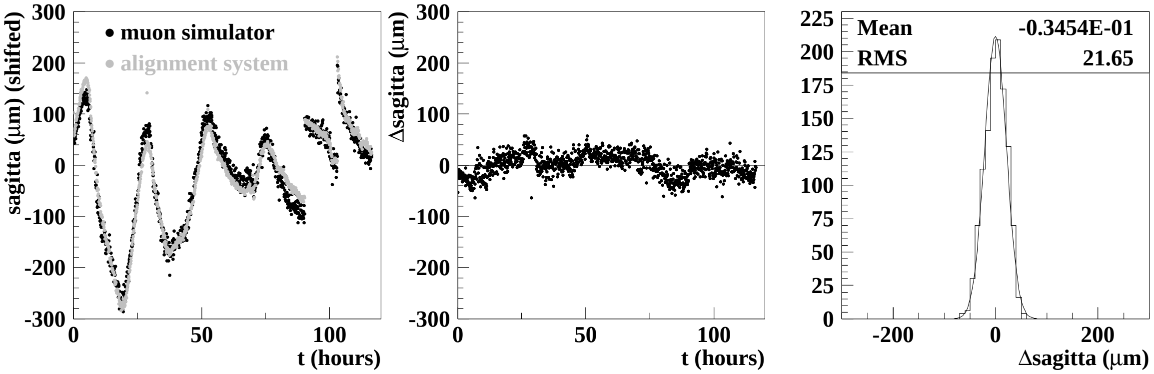

Figure 9. Comparison of the measurement of the muon simulator with the prediction based on the End-Cap alignment system. The three plots show respectively the data and the prediction across five days, the corresponding residuals, and their distribution integrated over time.

hall. Because of lack of calibration of alignment devices, an absolute comparison of the two sets of data is not possible, and the time averages of the two datasets have been set to zero. On the full data sample, the alignment reconstruction from optical devices tracks the reading of the muon simulator with a rms deviation of 22 μm (which tends to be smaller on short time scale). Despite the limitations of this measurement, the test is very significant since the full geometrical reconstruction from the alignment system was used for this analysis.

8.4. MDT tests in high background rate

The GIF facility at CERN [13] allows testing of detectors with muon beams and with background comparable (or larger) to the one expected in LHC. The photon counting rate provided by the ^{137}Cs source can be adjusted to be of the order of 100 Hz/cm^2 for testing running conditions in LHC (including tests of front-end and trigger electronics), while higher rates are used for aging studies. The program completed in summer 2002 includes tests with MDT chambers. Fig. 10 [14] shows the single tube resolution as function of the impact radius, for different background rates, obtained with a chamber of type BIS. The maximum intensity corresponds to about 400 Hz/cm^2, higher than the maximum expected for MDT chambers in ATLAS, which should be better approximated by the curve at 51 kHz ($\approx$ 100 Hz/cm^2), and is reached only in a small region of the spectrometer. At high rates, there is a significant accumulation of space charge from positive ions, which, because of its fluctuations, adds a contribution to the drift distance resolution, noticeable in particular for large drift times. Fig. 11 [15] shows the multi-layer resolution obtained with a MDT of type BOS (three layers of tubes). For this data, the muon beam was normal to the chamber plane, and the resolution can be shown as a function of the drift distance in the first layer. In very high background conditions the multi-layer resolution is in the range 40–100 μm, to be compared to the 40–60 μm range observed at low rate, which is expected to be representative for most of the chambers of the spectrometer.

9. CONCLUSIONS

At about two years from the beginning of installation of muon chambers on the ATLAS detector, the construction of the muon spectrometer is well underway, and tests of the different tracking detectors have shown that the tight design requirements on construction and tracking accuracy are met. Significant efforts are currently taking

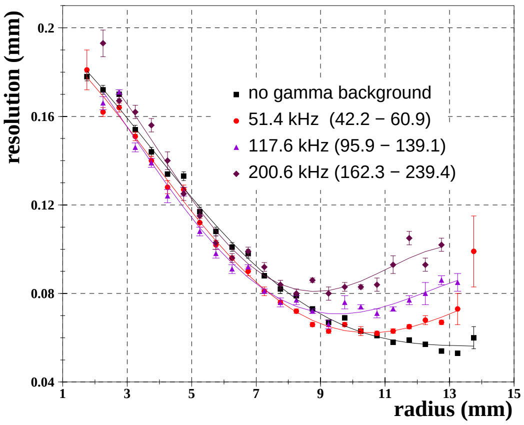

Figure 10. Space resolution in MDT tubes vs. drift distance, for different values of the background rate.

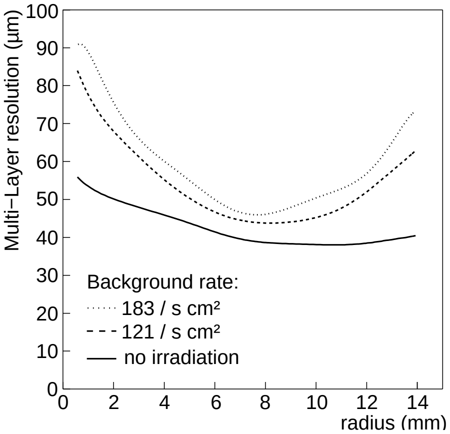

Figure 11. Space resolution of a MDT multi-layer, for tracks normal to the chamber and different background intensities, as a function of the drift distance on the first layer.

place on system tests, which allow to verify the performance and to develop the integration of the different components of the spectrometer.

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