Monitored Drift Tubes in ATLAS

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Abstract

The precision chamber system of the ATLAS muon spectrometer is described. Particular emphasis is given to the mechanical aspects and to the choice of the operation point of the detector.

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1 The ATLAS Muon Spectrometer

In the ATLAS detector [1] muons will be measured in two completely independent systems, the Inner Tracker and the Muon Spectrometer. The inner tracker has a radius of 1.1 m and is surrounded by a superconducting coil which generates a solenoidal field of 2 T. It is instrumented with pixel detectors, silicon strips and straw tubes with transition radiation detection capability. In this region, muons momenta are measured in a light material but high occupancy environment. The momentum measurement is competitive up to $p_T \sim 50\ GeV/c$.

In the muon spectrometer the measurement is made after the calorimeters and then is limited at low p_T by multiple scattering and energy losses. The ATLAS muon spectrometer is based on three 8-coil air-core toroid magnets, one to cover the barrel region ($|\eta| < 1.2$) and two in the forward regions ($1.2 \leq |\eta| \leq 2.7$) , which generate an approximately toroidal field over a radial distance of the order of 5 m with an average field of 2.6 and 6 Tm in the barrel and endcaps respectively. The muon spectrometer is designed for stand-alone measurement capability.

The muon spectrometer instrumentation consists of precision chambers for coordinate measurements in the bending plane: Monitored Drift Tubes (MDT) [2] and Cathode Strip Chambers (CSC) [3] and trigger chambers: Resistive Plate chambers (RPC) [4] in the barrel region and Thin Gap Chambers (TGC) [5] in the forward regions; the trigger chambers provide bunch crossing identification and measurement of the second coordinate in the non bending plane.

2 The concept of Monitored Drift Tubes

The design consideration with the strongest impact on the design of the ATLAS muon spectrometer is the requirement for stand-alone measurement capability. This safeguards against any unanticipated backgrounds and ensures a good discovery potential in the presence of unexpected event topologies due to unknown physics at the TeV scale. To accomplish a good momentum measurement even at low momenta, this requirement leads to the choice of an air-core magnet system, which however puts high demands on the muon chamber system due to unavoidable field inhomogeneities and the relatively low fields in such systems.

The open structure of the barrel toroid allows to reconstruct the muon momenta from a measurement of the sagitta in three muon stations in front, in the center and behind the magnetic field in the range $|\eta| < 1.4$. In the forward the muon momenta are obtained from a point-angle measurement with one point in front and two point behind the endcap toroid cryostats.

To achieve the required momentum resolution at high momenta (the sagitta for a 1 TeV muon is about 500 μm) two requirements have to be fulfilled: the muon chambers have to provide a position measurement accuracy of about 50 μm per station and the alignment of the three stations with respect to each other has to be known to about 30 μm.

To achieve the first goal a system of high pressure (3 bar absolute) proportional drift tubes - the Monitored Drift Tubes - has been chosen. An MDT chamber consists of six layers of drift tubes, arranged such that three layers of closely-packed tubes (multilayers) are mounted on each side of a support structure. The two multilayers and the support structure form a chamber, see Fig.1.

To fully exploit the drift tubes space resolution wires have to be positioned to better than 10 μm inside a tube and better than 20 μm inside a chamber using high precision assembly methods.

An in-plane alignment system allows to track sag/distortion in each chamber, see Fig.1. The comb plates of the support structure accurately define the positions of the multilayers. They are equipped with RASNIK alignment systems [6]. These systems measure the position, in three coordinates, of the middle component (the lens) with respect to the center point between the outer components (an illuminated coded mask and a CCD with video readout respectively). There are two systems along the chamber edges parallel to the tubes, and two diagonal systems.

It will not be possible to stabilize the geometry of the chambers and their positions in the spectrometer on the scale of a measurement accuracy of 50 μm due to movements induced by variations of temperature or magnetic field. Therefore chamber alignment is achieved off-line using corrections obtained from the measurement of the path of light-rays by light sensitive detectors (See Sect.6).

The chambers layout which has a direct impact on the spectrometer resolution has been optimized with respect to geometrical acceptance, access to the electronics, alignment facilities, field inhomogeneities and chamber construction. Figure 2 shows the MDT system layout. MDT chambers cover almost all the rapidity range but a very small region at high rapidity where the expected rates are higher than 100 Hz/cm^2. In this region, to reduce occupancy, CSC chambers are used because of their finer granularity. The MDT system consists of 880 chambers which covers an area of $\sim$ 5500 m^2; the total number of tubes is $\sim$ 300000, for a total tube and wire length of $\sim$ 1075 Km.

3 The Drift Tubes

The basic detection cell of the MDT's is a drift tube of 3 cm outer diameter and 400 μm wall thickness made with an hard aluminum alloy of the Al Mn type (ALUMAN 100) . The tubes are produced by extrusion and their thickness is then reduced by drawing. The use of this technique allows to satisfy tight tolerances on the outer diameter (+0/-20 μm), wall thickness ($\pm$ 20 μm), eccentricity ($<$ 15 μm).

The tubes are closed at both ends by endplugs which also provide the fixation of the W-Re wire of 50 μm diameter and its connection to preamplifiers and the high voltage supply as well as the gas inlets. They also contain the gas seals of each tube. The wire is stretched in the tubes to the 60% of the elastic limit. The method for wire fixation is not decided yet - under consideration are gluing or crimping of the wire.

The wire is located in the center of the tube by disk-shaped precision wire locators. The wire locators fix the wire position at both ends of the tubes, right in front of the endplugs with a precision of $\sim$ 10 μm. In the long chambers (tube length $> 4m$), an additional wire locator is used for reasons of electrostatic stability in the middle of the tube. The support structure of the chamber makes the tube gravitational sag match the wire sag within 100 μm (see Sect.4). The accurate position of the wire respect to the outer tube surface is guaranteed by the tight tolerances on the tube specifications.

The goal is to fabricate individual tubes and test them for gas tightness and verify electrical properties before their assembly into multilayers. Given the large number of tubes, semi-automatic assembly of the individual tubes with wire, wire locators and endplugs is foreseen. Pilot production of drift tubes has shown a yield of good tubes higher than 99% with a measured leak rate lower than $10^{-5} torr \cdot l \cdot s^{-1}$ corresponding to a pressure drop of $<$ 1 %

per tube every 10 days.

4 Chamber assembly

Tested drift tubes are assembled into units consisting of three layers of closely-packed tubes (multylayers). Essential to the construction of the multilayers is the use of precision jigging to establish and maintain, during assembly and while the adhesive cures, the position ($20\mu m$) of the tubes. At present, prototypes are being constructed using two somewhat different techniques for the assembly of multilayers. In the first approach each layer of tubes is precisely controlled. In a first step tubes in a layer are glued together, then two layers are glued and finally the third layer is added on top. The jigging controls each tube to very high accuracy at those points where the wires are located, namely the wire supports. The second approach puts more emphasis on the jigging for assembling of complete multilayers. Only the top and bottom layers are controlled by jigging and the middle layer is positioned by the tubes. In this case the precision is again guaranteed by the strict tolerances of the tubes.

A final decision on the tube stacking method will be taken on the grounds of full scale prototypes evaluation consisting on precise measurements of the wire positions using X-ray tomography techniques.

An MDT chamber is built from two multilayers mounted to either side of a support structure as shown in Fig.1. Considerations of pattern recognition performance, autocalibration[2], and angular resolution in a single chamber have also guided the decision to separate the two multilayers by a distance of 200-400 mm.

The support structure uses a minimum of material and provides precision positioning of the two multilayers and components of the alignment systems (see Sect. 6). The stiffness of the beams is chosen to permit the desired gravitational sag of the chamber to match the wire sag. The assembly of spacer and the multylayers is again done using high precision jigs.

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[2] Iterative process to determine the r-t relation by fitting tracks to the reconstructed hits.

5 The choice of the operating point

The choice of the operating point for the MDT chambers is driven by few basic requirements: excellent position resolution ($< 100\ \mu m$), sufficiently high lifetime to survive 10 years of operation at LHC, and sufficiently low occupancy of the chambers to allow for efficient pattern recognition in the high background conditions expected at LHC.

The expected deposited charge per unit of wire length accumulated after 10 years of LHC operation can be computed from:

$$Q = r \cdot d \cdot < N_e > \cdot G \cdot e \cdot t \approx 0.067 C/cm$$

where: $r = 100 Hz$ is the maximum expected counting rate in the MDTs, $< N_e > \approx\ 700e$ the average number of primary electrons, $G = 2 \cdot 10^4$ the gas gain (the choice of the gas gain will be justified later), e the charge of the electron and $t = 10^8 s$ the running time of the experiment. In the final setup the integrated deposited charge will be higher due to the higher primary ionization produced by neutrons and photons, which dominate the background and counting rates. Background calculations indicate that these particles have, averaged over the energy spectrum, a primary ionization yield which is higher by a factor 2 than the one for minimum ionizing ones. This gives an integrated deposited charge of $Q = 0.13 C/cm$.

Streamer signals have to be avoided as already small fractions of streamer pulses increase the integrated deposited charge significantly. If the charge in a streamer pulse is 100 times higher than in the proportional avalanche a fraction of 1% streamer would double the integrated charge. Finally a safety factor of 5 is applied to account for uncertainties in the background calculations. We therefore require that the MDT have to be designed to survive $Q = 0.67 C/cm$. Ultra-clean tests made at CERN show gain variations of the order of $10 \div 20\%$ per C/cm.

From the previous discussion on the chamber aging it is clear that one has to keep the lowest possible gain compatible with a good performance. The lowest possible gain is defined by the interplay of noise, discriminator threshold and shaping time. We require a discriminator threshold five times higher than the electronic noise. For a gas gain of $2 \cdot 10^4$ at an electronic noise of $N = 5000$ equivalent electrons, the threshold can be set to be around the 25th electron for a shaping time of 15 ns. As a direct consequence of this choice the single wire position resolution averaged over the drift radius is expected to be of about $80\mu m$. A decrease of the discriminator threshold to the 12th electron, possible with a gas gain of at least $4 \cdot 10^4$, would improve the average resolution by about 30%.

Once the operating parameters fixed, one has to find a suitable gas mixture. To fulfill the ATLAS requirements, the filling gas has to be non flammable for safety requirements, the maximum drift time has to be less than 500 ns to minimize the occupancy. To improve both resolution and autocalibration, the Lorenz angle should be kept below 10^o and, despite the $1/r$ E-field dependence, the r-t relation should be as linear as possible. Finally the streamer rate should be $< 1\%$ to limit aging effects.

At present the best gas candidate is $Ar : N_2 : CH_4$ (91 : 4 : 5) which fulfills all the above requirements. The small percentage of N_2 improves the linearity of the space-time relation as can be seen from Fig.3 where the r-t relation for the preferred gas is shown as calculated by the GARFIELD package[7].

Fig.4 shows the single wire space resolution calculated using GARFIELD. Shown are also the different contributions to the resolution. The main source of uncertainty is, as expected, due to clustersize fluctuations. Test beam measurements on small MDT prototypes are in good agreement with both simulation results.

6 The Global Alignment system

As discussed in Sec.2 to achieve a sagitta measurement at the level of 50 μm one needs a global alignment system. In the case of stiff chambers the corrections to a false sagitta of a particle from chamber displacements can be corrected for using the apparent sagitta of projective (pointing to the vertex) light-rays, see Fig. 5. The accuracy of these corrections is limited by initial chamber displacements in the order of a centimeter and several milliradians and the vertex spread of several centimeters in the direction of the beam. Alignment errors of better than $30\mu m$ are expected after correction, if the position of the track through the chambers is known to about 2 cm. Axial alignment rays, parallel to the beam direction, reduce the dependence on the initial chamber positioning error. In-plane alignment measurements within each chamber are used to correct for deviations from stiffness.

The positions of projective alignment towers with respect to each other and to other subdetectors, necessary for the determination of the invariant mass of multiparticle final states, needs to be known with a precision in the centimeter range. This is achieved by an external survey of the detector. Tower-to-tower alignment as necessary for the reconstruction of low-momentum muons traversing more than one alignment towers is achieved by proximity sensors, measuring displacements between adjacent chambers. These also allow to combine more than one chamber per layer to form a projective tower, thus reducing the number of required light paths and adding redundancy to the alignment system.

In the endcaps, the cryostat of the endcap toroids would obstruct any light path, thus making complete projective alignment impossible. Therefore a different solution is adopted for this region: precise carbon-fiber bars are projectively aligned with only 8 alignment rays and the chamber alignment is done with respect to the bars.

7 Spectrometer performance

Assuming a single tube space resolution of $\sim 80\ \mu m$, one obtains a multilayer resolution of $\sim 50\ \mu m$ and a chamber space resolution of $\sim 35\ \mu m$. Adding to this a $\sim 30\ \mu m$ contribution due to the global alignment, the design $\sim 50\ \mu m$ sagitta resolution is obtained. On these grounds a full simulation of the spectrometer gives the results shown in Fig.6. At $p_T = 100\ GeV/c$, the structures seen in the resolution curve are due to regions where only a two station measurement is possible and to multiple scattering in the magnet struts. At the highest momenta the multiple scattering effects become negligible.

8 Prototypes and Milestones

The ATLAS MDT system will be built by a worldwide Collaboration. Given the very large number of chambers to be built, the production will be shared between many production sites: Dubna, Frascati, MPI Munich, NIKHEF, Pavia, Protvino, Roma I and Thessaloniki for the Barrel chambers and the Boston Consortium (Brandeis, Boston, Harvard, MIT, Tufts) and Seattle for the forward chambers.

Two full scale prototypes have been already tested on a beam at CERN and more prototypes are expected to be ready by the end of 1996. Three of these prototypes will form a full size tower to be exposed to cosmic rays for a demonstration of the alignment scheme. The series production is expected to start around 1999 to end in late 2003 in time for installation in the experimental area.

9 Conclusions

The ATLAS MDT system is a very ambitious muon detector aiming for a precision of 50 μm in a huge system: 45 m long, 22 m in diameter and covering an area of $\sim$ 5500 m^2. It has excellent stand-alone capability and almost hermetic coverage up to $|\eta| = 2.7$. Quite advanced prototype studies show that the challenge can be met, allowing to explore the exciting physics scenario opened by LHC.

References

[1] The ATLAS Collaboration; ATLAS, technical proposal for a general-purpose pp experiment at the Large Hadron Collider at CERN; CERN/LHCC/P2, December 1994.

[2] The ATLAS Muon Group; Monitored Drift Tubes for Muon Spectroscopy in ATLAS, ATLAS Internal Note MUON-NO-044, June 1994.

[3] GEM Technical Design Report, SSCL-SR-1219, 1993. See also J. Hauser, These Proceedings

[4] A. Di Ciaccio, These Proceedings

[5] K. Nagai, These Proceedings

[6] H. Dekker et al., "The RASNIK/CCD 3-dimensional alignment system". Proceedings of the 3rd Conference of Accelerator Alignment, CERN/Annecy, October 1993. Page 147.

[7] R. Veenhof, Garfield, a drift-chamber simulation program. User's guide, CERN, 1966.

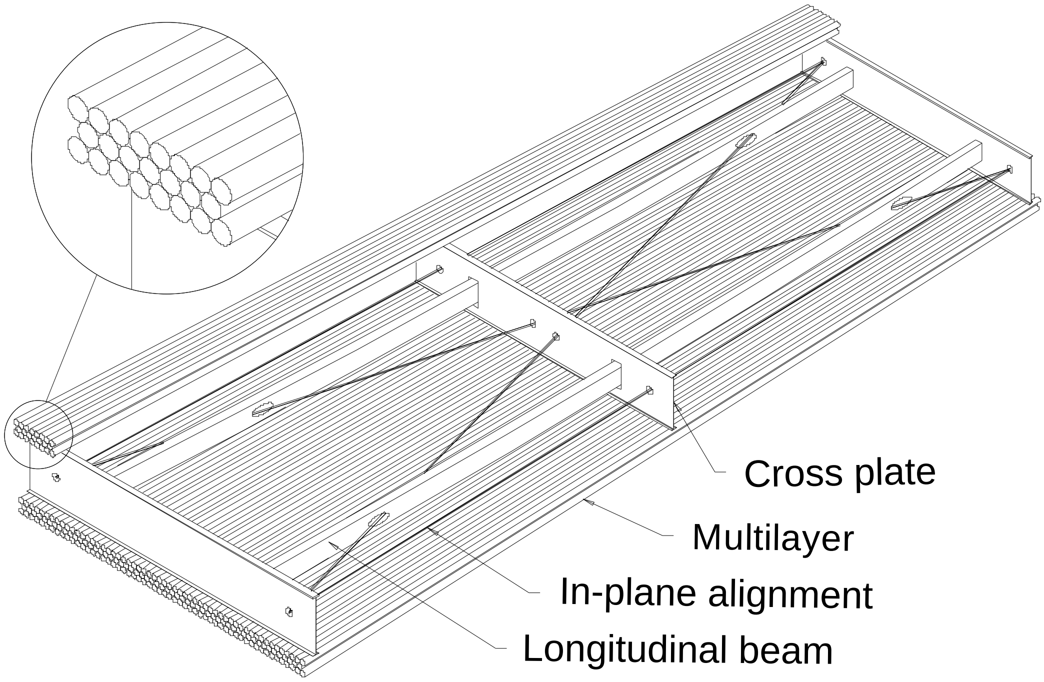

Figure 1: MDT chamber with part of the top multilayer removed to show the chamber support. Also shown is the arrangement of the in-plane alignment rays used to monitor internal deformations of the chamber (see Section 4).

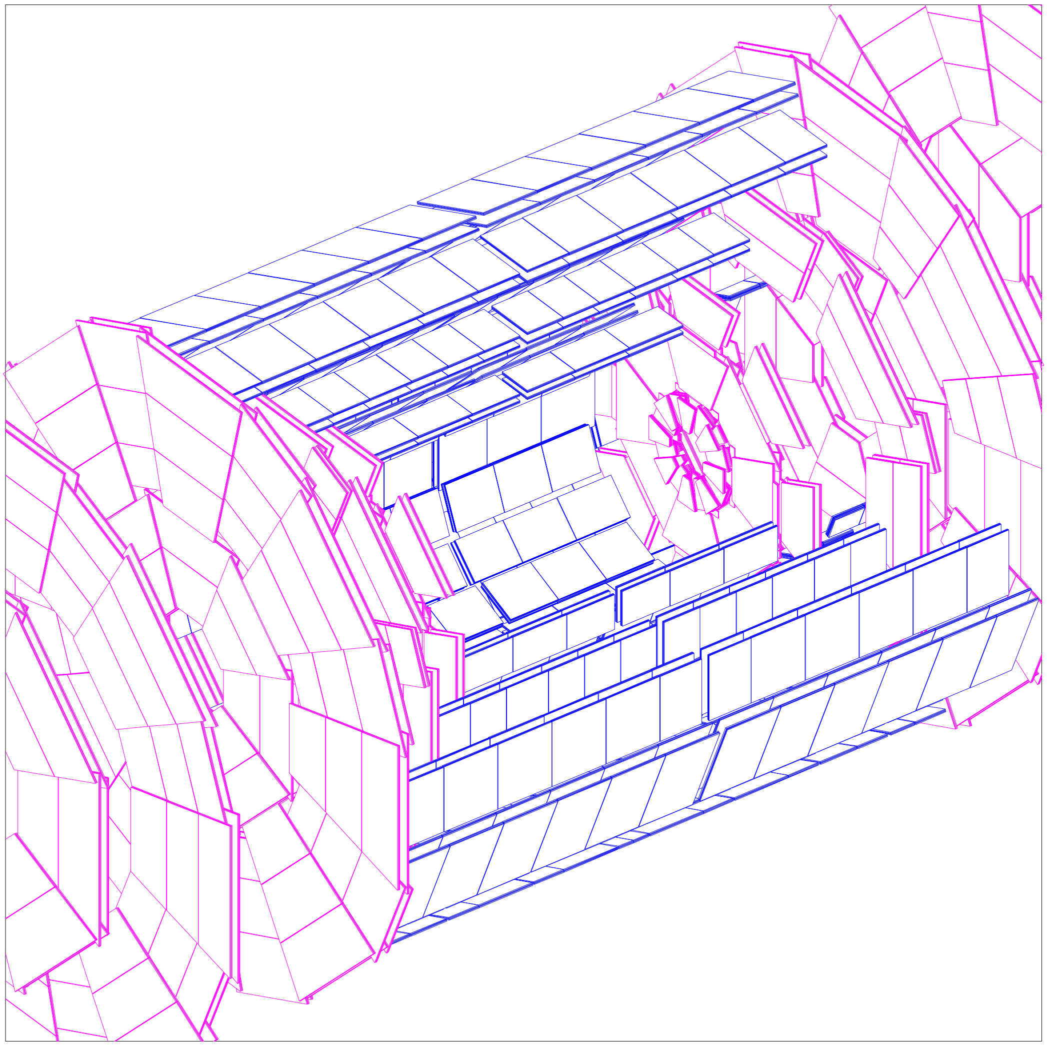

Figure 2: Layout of the MDT system

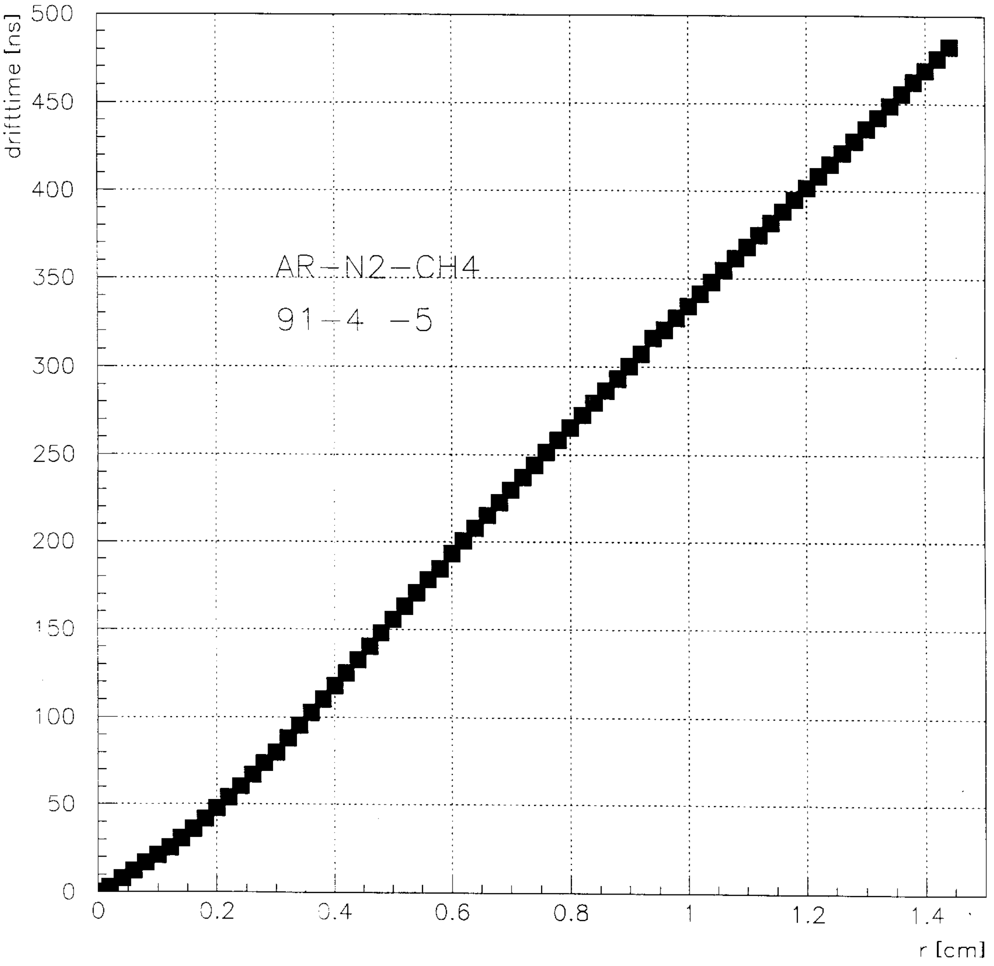

Figure 3: r-t relation for $Ar : N_2 : CH_4$ (91 : 4 : 5) gas mixture (GARFIELD simulation).

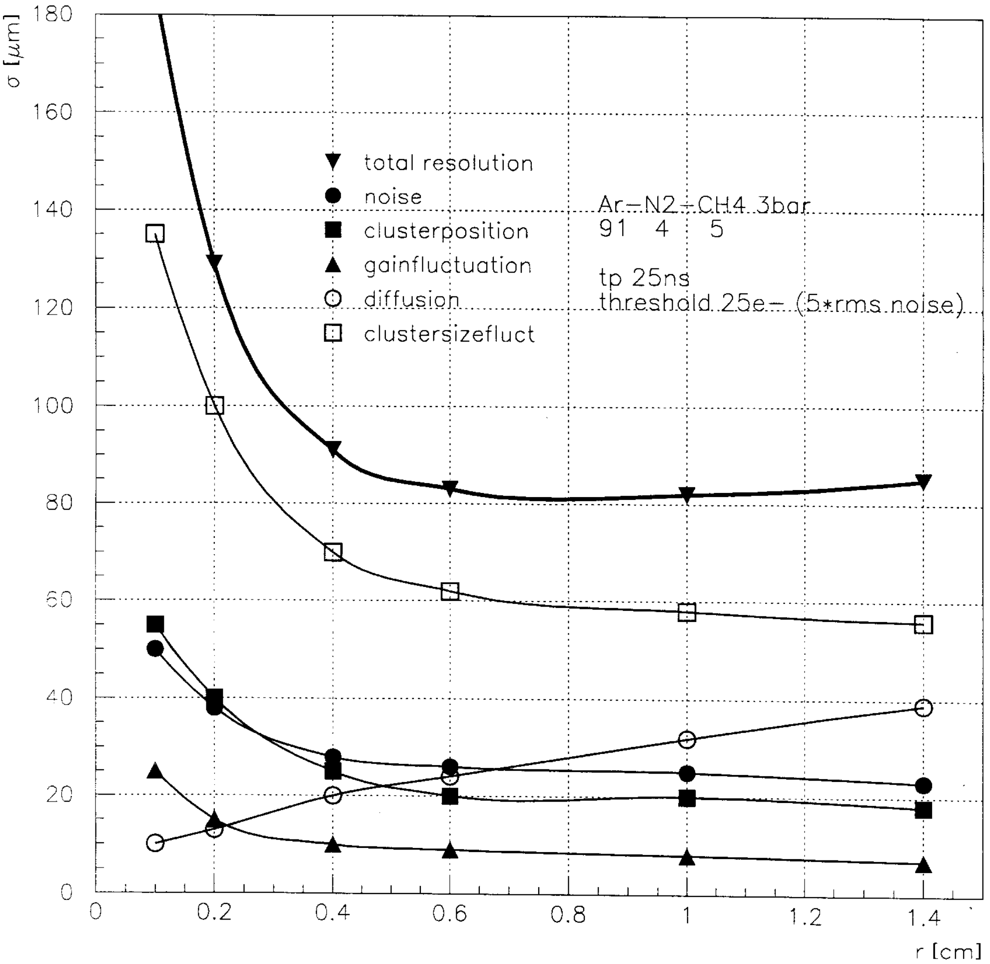

Figure 4: Results of a Garfield calculation for the single wire space resolution of a MDT tube. The different contributions to the resolution are shown.

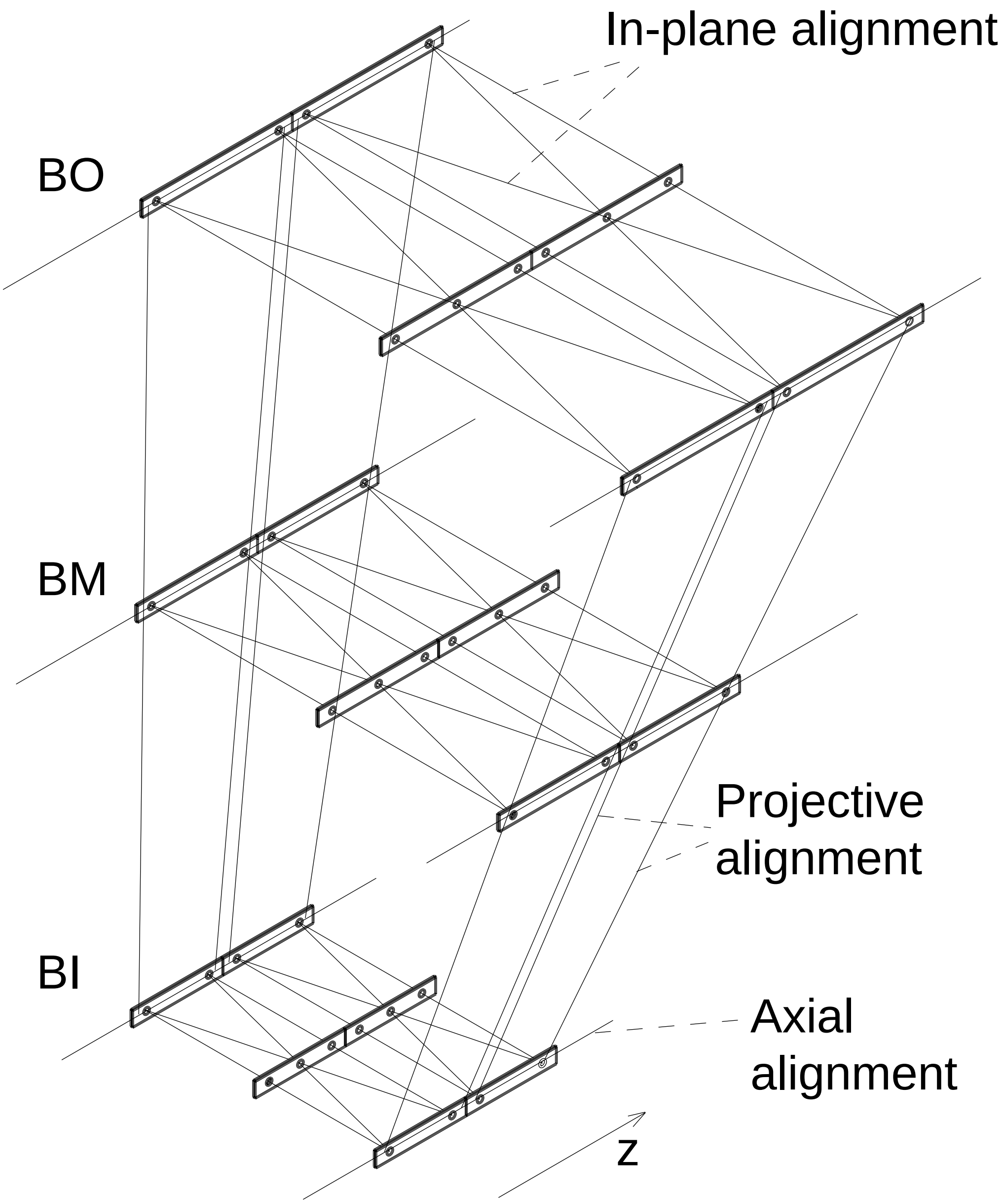

Figure 5: Arrangement of the alignment rays for two adjacent projective towers of the barrel spectrometer. Muon chambers are represented by their cross plates only.

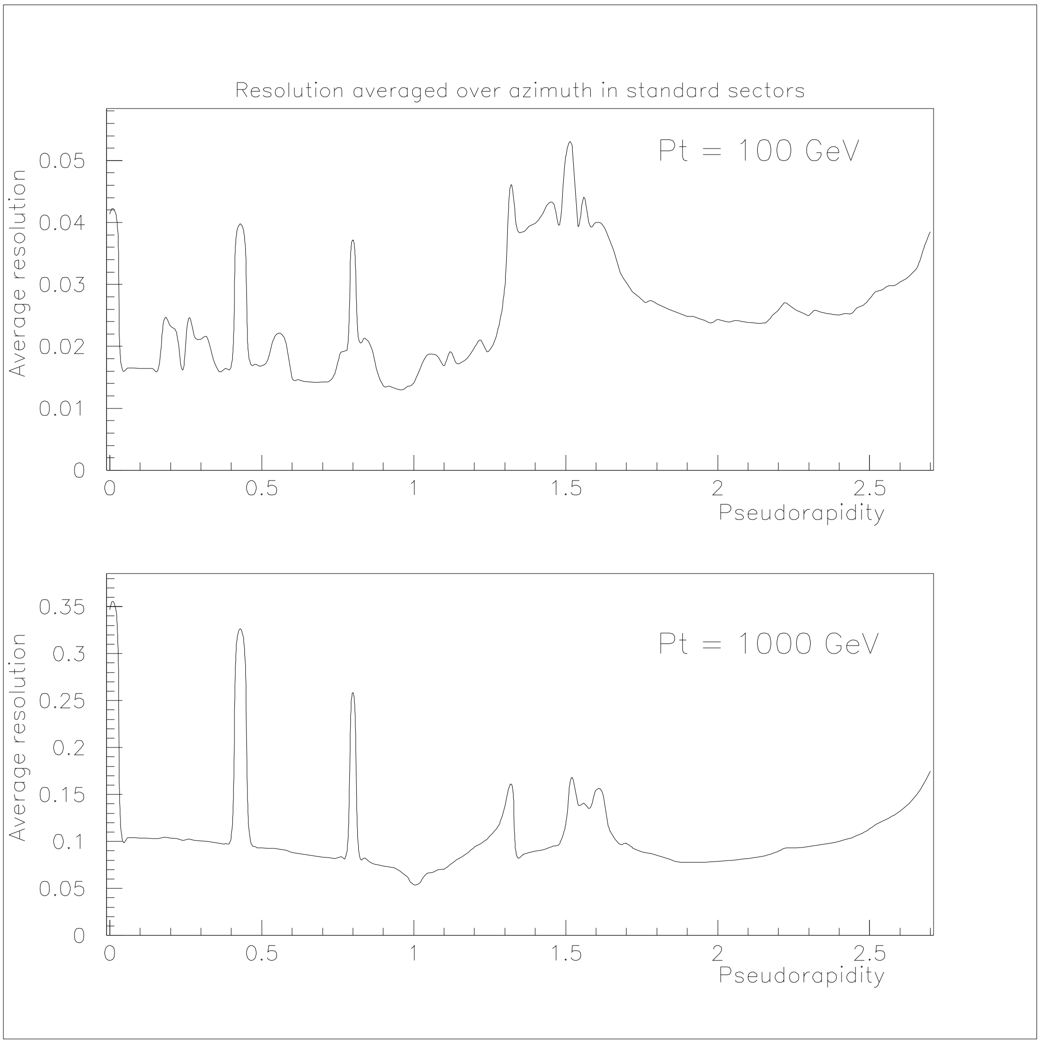

Figure 6: Momentum resolution averaged over the azimuthal angle of the muon spectrometer for $p_T = 100\ GeV/c$ (top curve) and $p_T = 1\ TeV/c$ (bottom curve). See text for details.