An Efficient Method to Determine the Space-to-Drift-Time Relationship of the ATLAS Monitored Drift Tube Chambers

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***Abstract*—The ATLAS experiment at the Large Hadron Collider (LHC) at CERN is currently being assembled to be ready to take first data in 2008. Its muon spectrometer is designed to achieve a momentum resolution of better than 10% up to transverse muon momenta of 1 TeV. The spectrometer consists of one barrel and two endcap superconducting air-core toroid magnets instrumented with three layers of precision drift chambers as tracking detectors and a dedicated trigger system. Detailled studies have been performed with a new approach of the autocalibration, a method to determine the space-to-drift-time relation of the ATLAS MDT chambers, and are presented.**

I. Introduction

The ATLAS muon spectrometer is based on three superconducting air core toroid magnets–one for the barrel and one for each of the two end caps. With a mean bending power of 3 Tm in the barrel and 5 Tm in the end caps, muon tracking chambers with an accuracy better than 40 μm are required to achieve the spectrometers design resolution of $\Delta p_T^\mu / p_T^\mu < 2-3\%$ for $p_T^\mu < 200$ GeV/c and $\Delta p_T^\mu / p_T^\mu < 10\%$ for $p_T^\mu = 1$ TeV/c. Three layers of Monitored Drift Tube (MDT) chambers are used as precision trackers in the muon spectrometer. Each MDT chamber consists of two multilayers of three or four layers of drift tubes glued to both sides of an aluminum support frame (cp. fig. 1). Each of the layers include up to 72, 1–6 m long tubes, a chamber has a maximum number of 432 drift tubes.

For muon momenta larger than 300 GeV/c, the calibration of the space to drift time relationship of the MDT chambers is—beside the spectrometer alignment—the main contribution to the momentum resolution (cp. fig. 2) and has to be known with an accuracy better than 20 μm. The space to drift time, r(t), relation depends on the operating and environmental parameters of the chambers like the temperature, gas mixture, magnetic field, and the background radiation, thus necessitating an hourly recalibration of the spectrometer.

II. Analytical Autocalibration

With current status of the simulation programs it is not possible to calculate the r(t) relation from the operating and environmental data with sufficient accuracy. Therefore, the calibration is performed with the chamber data itself. Using

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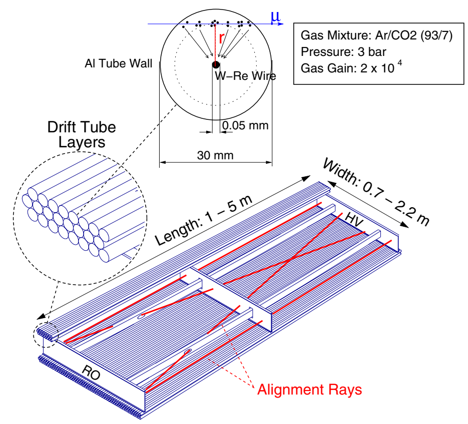

Fig. 1. Schematic view of a barrel Monitored Drift Tube (MDT) chamber

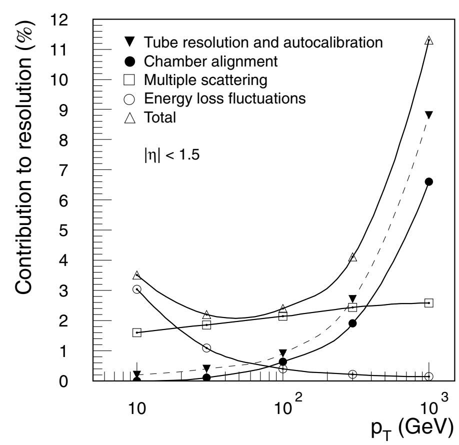

Fig. 2. Contributions to the transverse momentum resolution of the ATLAS barrel muon spectrometer [1]

the redundant measurement of muon tracks in the tube layers of MDTs, the r(t) relation can be improved by an iterative method (autocalibration). The best performing algorithm which reaches an accuracy better than 20 μm across the whole spectrometer is the so-called analytical autocalibration. It uses an initial r(t) relation with an accuracy of about 200 μm, which can be obtained for example by integrating the drift time spectrum [2], to reconstruct straight muon tracks in an MDT chamber or, dependending on the muon momentum, in

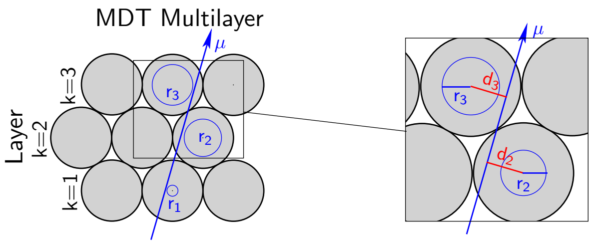

Fig. 3. Reconstruction of a straight muon track in an MDT multilayer

one multilayer.

The method uses the track residuals

$$\Delta(t_k) = r(t_k) - d_k \tag{1}$$

(k:=number of hit tube, see fig. 3) to correct the r(t) relation from the i-th iteration. The idea of this method is, not only to correct the r(t) relation by the mean value of residuals of several thousands of muon tracks (conventional autocalibration), but to find the systematical deviation $\epsilon(t)$ from the true r(t) relation,

$$r(t_k) = r^{true}(t_k) + \epsilon(t_k). \tag{2}$$

$\epsilon(t_k)$ includes the full dependence of all tube hits on a muon track. A dependence between the measurable residual $\Delta(t_k)$ and $\epsilon(t_k)$ has thus to be found. The distance between the k-th anode wire to the reconstructed track d_k depends on all driftradii which were used reconstruct the track. Assuming a linear dependence (cp. fig. 4),

$$\begin{aligned} d_k &= \sum_l a_l r(t_l) \\ &= \sum_l a_l (r^{true}(t_l) + \epsilon(t_l)) \\ &= r^{true}(t) \sum_l a_l \epsilon(t_l) \end{aligned}$$

the k-th residual of a single track can analytically be described as:

$$\Delta_k(t) = \sum_l m_{k,l} \epsilon(t_l), \tag{3}$$

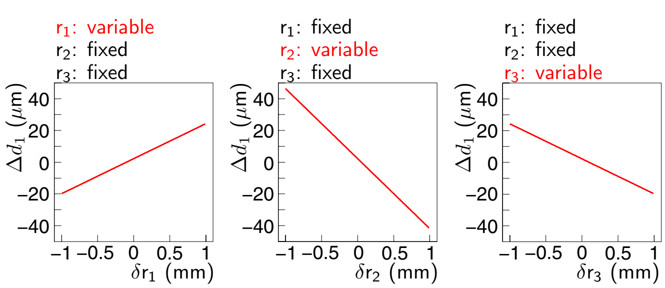

Fig. 4. Check of the linear dependence of the distance to track d_1 on the systematical error of the track hits with simulated data. Δd_1 is the change of the distance between the track and the first anode wire. For the test, two drift radii were fixed while varying the third in a small range and recording the change of d_1. The linear dependence is clearly visible.

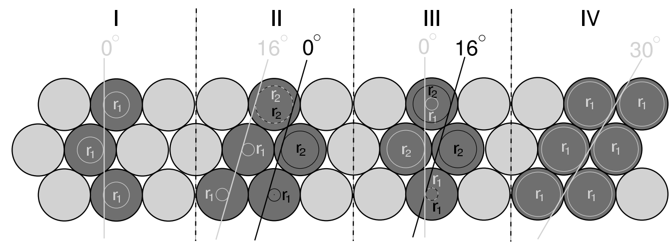

Fig. 5. Examples of track configurations for which certain drift radii can be calculated exactly. In case I and IV all hit tubes on the track have the same driftradii. Hence a potential error in the r(t) relation can be corrected with only one muon track. Case II and III show examples of higher order fixed points where two tracks are used to define two driftradii

with

$$\begin{aligned} m_{k,l} &= a_l \quad \text{for} \quad k \neq l \\ m_{k,l} &= (1 - a_l) \quad \text{for} \quad k = l \end{aligned}$$

With eq. 3 an analytical approximation for the track residuals has been found which cannot be directly calculated as the equation is in general underdetermined (see appendix in [3] for mathematical prove). $\epsilon_i(t)$ has thus to be parametrized,

$$\epsilon(t) \rightarrow \kappa(t) = \sum_{g=0}^{G} \beta_g t^g, \tag{4}$$

to gain the maximum possible information one gets from the residuals with this method. The parameters β are determined by minimizing

$$\chi^2 = \sum_{tracks} \sum_k \frac{\left[\Delta_k^{measured} - \Delta_k(t)\right]^2}{\sigma\left(\Delta_k^{measured}\right)^2}. \tag{5}$$

A detailed derivation of equation 3, including statistical errors on the drift time measurement, and a the matrix elements $m_{k,l}$, can be found in [3]. The space drift time relation $r^i(t)$ is then being corrected with the correction function $\kappa^i(t)$,

$$r^{i+1} = r^i(t) - \kappa^i(t),$$

in the i-th iteration of the autocalibration. When the spread of $\kappa^i(t)$ is in the order of 1 μm and stable on two following iteration steps, it is assumed that the method converged and that the algorithm found the best possible r(t) relation. For further details, see [4].

This approach of the autocalibration needs, as the conventional method as well, a spread of the incident track angles to converge. Hence, only one r(t) relation per MDT chamber will be determined. Each chamber has a specific range of track angles depending on its position in the spectrometer. The spread of these track angles is important for the performance of the algorithm, as specific track configurations exist, for which the driftradius can be determined exactly. These so-called fixed points are to constraint the algorithm to significantly improve its accuracy. Fig. 5 shows examples of different types of fixed points.

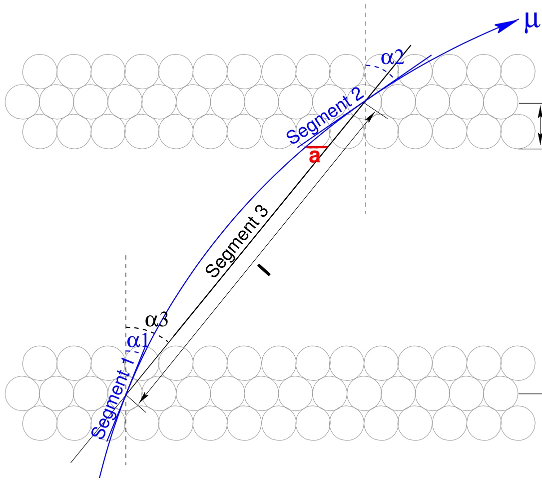

Fig. 6. Illustration of the three possible track segments in a MDT chamber. a describes the magnitude of the deviation of segment 2 and segment 3 and thus the influence of taking a straight track segment over both multilayers instead of a bent one on the accuracy of reconstruction.

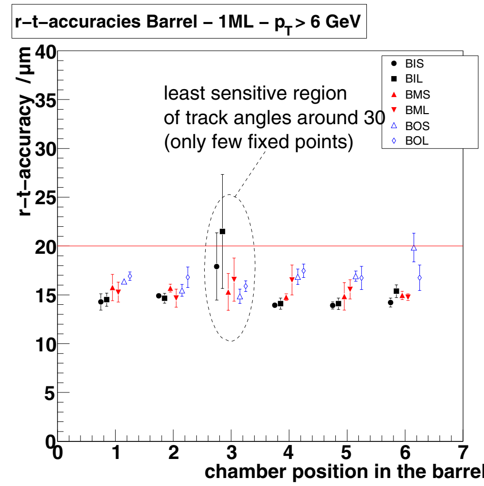

Fig. 7. r(t) accuracies achieved for the different types of barrel chambers using muons with $p_T > 6$ GeV for the calibration and separate track segments per multilayer. Points denote the chambers of the inner (I), middle(M) and outer (O) layer.

III. Performance Tests

The performance of the new autocalibration method has been tested by a Monte Carlo study. Two samples of single muons have been simulated at two different trigger thresholds—one sample with a transverse momentum p_T >6 GeV and the other one with p_T >20 GeV in the muon spectrometer. The results for the barrel chambers presented in this paper are representative for the spectrometer as the track intervals in the endcap chambers are similar. The calibration in the barrel is more complex, as the chambers are mounted in the magnetic field of the toroid. The muon tracks are thus bent within the single chambers which leads, particularly for calibrating at the lower trigger threshold, to an additional difficulty. The track of a muon with 6 GeV has a sagitta of $\sim$500 μm within an MDT chamber, more than one magnitude larger than the claimed r(t) accuracy of 20 μm. But the sagitta does not correctly describe the influence of using a straight track instead of a bent one. In fig. 6 three possible track segments are shown. Segment 1 and 2 are segments reconstructed in both multilayers separately. Segment 3 is the one which is reconstructed with all tube hits on the track. The parameter a describes the deviation of using segment 3 instead of segments 1 and 2 for the calibration,

$$a = s \cdot \left[\sin \frac{eBl}{2p} + \alpha_3 - \sin \alpha_3\right] \quad (6)$$

where s and d depend on the MDT chamber geometry. With typical chamber values in the equation, a calculates to $\sim$150 μm for 6 GeV and $\sim$50 μm for 20 GeV muons. The track segments used for the autocalibration are thus reconstructed in both MDT multilayers separately for the lower threshold. Nevertheless the aim is to use both multilayers for the reconstruction of the track segments, as the number of fixed points increases with the number of hits on the track [3]. The calibration with muons from the 20 GeV trigger threshold achieves much higher accuracies by using the reconstruction across both multilayers, even if the parameter a is still larger than the claimed r(t) accuracy. For the study, an initial r(t) relation was used with a parabolic deviation from the true r(t). The amplitude of the parabola was chosen to 500 μm. Testbeam measurements showed, that a typical starting r(t) relation from the integration method differs with a similar shape but with slightly smaller amplitude from the true r(t) relation. An ensemble test with 5 independent samples of 2000 tracks per chamber was performed to test the algorithm. Fig. 7 shows the mean accuracies and the RMS of the ensembles for muons with an transverse momentum $p_T > 6$ GeV of a representative part of all barrel chambers. The slightly worse performance of the inner and middle chambers at position 3 originate from the interval of track angles for these chambers which is spread around 30°. Residual based calibration methods are least sensitive in this region of track angles due to the chamber

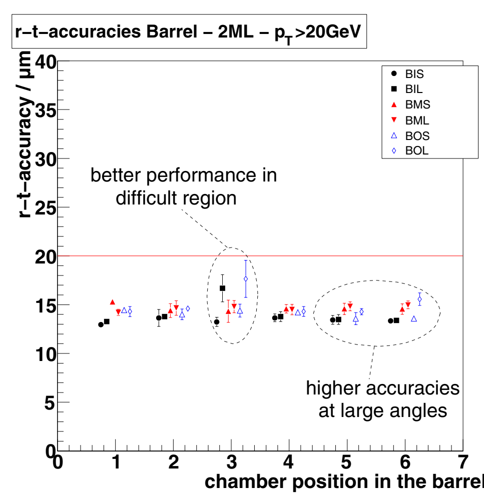

Fig. 8. r(t) accuracies achieved for the different types of barrel chambers using muons with $p_T > 20$ GeV for the calibration and track segments over both multilayers. Points denote the chambers of the inner (I), middle(M) and outer (O) layer.

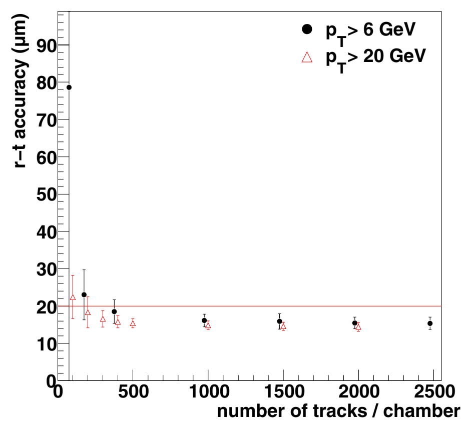

Fig. 9. Accuracy of the r(t) relation in dependence of the number of tracks used for the calibration. The mean value of all barrel chambers for both trigger thresholds is shown.

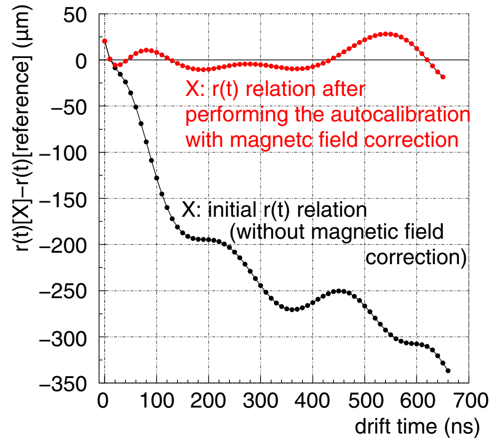

Fig. 10. Differenc between the the r(t) relations with and without magnetic field, measured in the ATLAS toroidal field. The black line shows the change of the r(t) relation caused by the magnetic field. The red curve is the difference after applying the B-field correction—the r(t) relations diverging less than 20 μm.

geometry. As the residuals of tracks with an incident angle of 30° are per definition zero, these tracks provide no information about the systematical error of the r(t) relation. In addition there are only two fixed points in this angular interval—one of them is shown in fig. 5 IV. In fig. 8 the accuracies achieved for the 20 GeV trigger threshold are shown using track segments across both multilayers. Especially in the insensitive region around 30° the performance of the method is significantly improved. The accuracies at larger angels—chamber positions 5 and 6—are slightly better compared to the results using muons with $p_T > 6$ GeV as well. Fig 9 shows the mean accuracies of all barrel chambers as function of the number of tracks per calibration for both trigger thresholds. Only a few hundred tracks are necessary for the method to improve the starting r(t) relation significantly. With 1000 tracks, the values are already well below 20 μm and are not improved with a larger number of tracks. The method did not converge using less than 100 tracks per calibration.

IV. Influence of the Magnetic Field

The magnetic field also influences the drift path of primary electrons, as the Lorentz force deflects them on their way to the anode wire, leading to longer drift times. As the toroid field is not homogeneous across the MDT chambers, the r(t) relation has to be corrected for the effect of the magnetic field **B** to reach the necessary precision: in test beam measurements a shift of the maximum drift time of 70 ns/($\mathbf{B}^2$/T^2) has been observed [5], [6], leading to deviations of up to 500 μm from the rt-relation without magnetic field. A model [5], [6] for the dependence of the drift time $t(r, B)$ as a function of the magnetic field has been developed and yields an accuracy of better than 1 ns. The model has been tested with simulations [4] and with cosmic muons. Fig.10 shows the difference between the r(t) relation with and without magnetic field, measured with a MDT chamber in the ATLAS toroidal magnetic field in November 2006 [7]. For both r(t) relations, the autocalibration has been performed, the one gained without magnetic field serves as the reference r(t) relation. Differences between the r(t) relations of the order of 300 μm for large drift times occur. Applying the correction function on the drift times, the differences can be reduced to less than 20 μm. This first test of the magnetic field correction of the drift times with cosmic muons in ATLAS shows an excellent performance of the modelled correction function.

V. Summary

The performance of a new approach of autocalibration has been successfully tested with simulated data. The r(t) calibration of all ATLAS muons chambers was studied with muons of two different trigger thresholds and two slightly different approaches to optimize the accuracy of the algorithm. The method reaches accuracies well below 20 μm and will be used as calibration algorithm in the ATLAS muon spectrometer. A model to correct the r(t) relation in presence of magnetic fields has been confirmed with the first cosmic ray data taken with the ATLAS barrel toroid at the nominal field strength.

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