New Methods for the Alignment of the ATLAS Muon Spectrometer

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***Abstract*— The ATLAS muon spectrometer consists of three layers of precision drift-tube chambers in an air-core toroid magnet system with an average field of 0.4 T. The muon momenta are determined with high accuracy from the measurement of the sagitta of the muon tracks in the three chamber layers. In order to achieve the required momentum resolution of the muon spectrometer of better than 4% for transverse momenta below 400 GeV/c and of 10% at 1 TeV/c, the relative positions of the muon chambers are measured by a system of optical sensors with an accuracy of 30 μm. In order to verify the correctness of the optical alignment, a method has been developed to measure the relative chamber positions with muon tracks which are recorded during the operation of the experiment. For this purpose, an independent estimate of the muon momenta is needed. This is not provided with sufficient accuracy by the track measurement in the inner detector because of energy loss fluctuations in the calorimeters. For muons of $p_T < 40$ GeV/c, however, the momenta can be determined with high-enough precision independently of the relative misalignment of the chambers from comparison of the local track direction measurements in the individual chamber layers. This method allows for monitoring of the chamber positions with an accuracy of about 30 μm in time intervals of a few hours during LHC operation.**

***Index Terms*— ATLAS detector, muon spectrometer, drift tubes, alignment, tracks, muon.**

I. Introduction

In the muon spectrometer of the ATLAS detector at the Large Hadron Collider (LHC), three layers of large drift tube chambers, the Monitored Drift Tube (MDT) chambers, are used for precision tracking in the 0.4 T toroidal field of superconducting air core magnets. The MDT chambers consist of two triple or quadruple layers (multilayers) of aluminium drift tubes with 30 mm diameter and 0.4 mm wall thickness mounted on either side of an aluminium space frame. The high 20 μm mechanical positioning accuracy of the sense wires inside a chamber and the spatial resolution better than 35 μm allows for the precise measurement of muon momenta up to the TeV scale. If the three layers of MDT chambers are aligned with an accuracy of 30 μm, a momentum resolution better than 10% is achived up to $p_T = 1$ TeV/c.

The alignment accuracy is achieved by a system of optical alignment sensors monitoring the relative movement of the chambers with 10 μm precision. The determination of the positions of the chambers on the level of 30 μm requires the muon tracks. The initial absolute calibration of the optical alignment monitoring system is planned with straight muon tracks recorded at the beginning of the LHC operation when the toroid magnet will be switched off for the alignment task. [1]

We describe a new method which will be used to check the absolute alignment of the barrel muon spectrometer continuously with curved muon tracks of low momenta. Those will be provided in a dedicated single-muon data stream at the output of the level-2 6 GeV muon trigger at a rate of $\sim$1 kHz during the operation of the LHC for $L = 10^{33}$ cm^2 s^{-1}.

II. Momentum measurement in the Muon Spectrometer

In the muon spectrometer, muon momenta are determined from the curvature of the muon trajectories. Fig. 1 shows a schematic of a muon traversing a so-called ”tower” of three muon chambers in the barrel part of the muon spectrometer. The muon momentum is best measured from the sagitta s which is the distance of the track point in the middle muon chamber from the straight interconnection of the track points in the inner and outer chambers. At momenta below 100 GeV/c, however, a similar accuracy is achieved from the deflection angle α which is the angle between the muon direction in the inner chamber and the muon direction in the outer chamber. The incoming and outgoing directions are measured by the muon chambers in addition to the track points which are used for the sagitta measurement. At very low momenta, $p_T < 6$ GeV/c, the spatial resolution in the middle chamber is good enough to measure the curvature of the muon trajectory within the middle chamber with an accuracy of about 30%.

The three ways of measuring the muon momenta are complementary and the basis of the alignment of the barrel muon spectrometer with curved tracks. The three methods have a different sensitivity to the misplacement of the chambers within a barrel tower and lead to different momentum resolutions (see Table I):

- The sagitta measurement is sensitive to displacements of the chambers orthogonal to the thought straight projective line connecting the primary vertex with the centres of the muon chambers. The momentum resolution of about 5% at $p_T < 20$ GeV/c is dominated by multiple scattering.
- The deflection angle measurement is insensitive to the initial chamber displacements, but is sensitive to rotations of the inner and outer muon chambers around the tube axis. It provides the same momentum resolution as the sagitta measurement for $p_T < 100$ GeV/c.

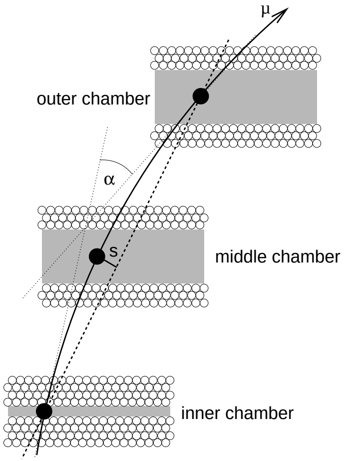

Fig. 1. Schematic of the detection of a muon in the barrel part of the muon spectrometer. The muon momentum is best measured from the sagitta s. Below 100 GeV a similar momentum resolution is achieved from the deflection angle α.

- The curvature measurement inside the middle chamber is only affected by the precision of the chamber geometry. It is limited by the spatial resolution of the chamber and can be applied up to $p_T \sim 6$ GeV/c where a momentum resolution of 30% is achieved.

TABLE I

COMPARISON OF MOMENTUM MEASUREMENT METHODS

Momentum from	Sensitivity to	$\frac{\Delta p}{p}\|_{p=6(20)\ \mathrm{GeV/c}}$
Sagitta	Chamber misplacements	5%(3.5%)
Deflection angle	Chamber rotations	5%(3.5%)
Curvature in chamber	Mechanical chamber precision	30%(100%)

III. A PROCEDURE TO ALIGN BARREL TOWERS WITH CURVED MUON TRACKS

The three momentum measurement methods allow for the following two-step alignment procedure for barrel towers with curved tracks:

1) The momentum measurement p_{middle} of the middle chamber is used to determine the rotation of the inner chamber with respect to the outer chamber. The rotation angle is obtained from the difference $1/p_{middle} - 1/p_{def.\ angle}$ where $p_{def.\ angle}$ denotes the momentum as measured with the deflection angle. 10^5 tracks of $p_T < 6$ GeV/c are needed for an accuracy of 3 mrad, 10^6 tracks of $p_T < 6$ GeV/c for an accuracy of 1 mrad. The mechanical precision of the muon chamber limits the achievable rotation angle accuracy to about 5 mrad. It is therefore planned to use the straight muon tracks available at the start-up of the LHC to determine the orientation of the multilayer with sufficient precision to allow for an unbiased momentum measurement by the middle chamber.
2) The momentum obtained from the deflection angle is used to extrapolate the track segment measured in the middle chamber from the middle to the inner and to the outer chamber. This extrapolation allows us to determine the orientations and positions of the inner chamber and the outer chamber with respect to the middle chamber. An alignment accuracy of 30 μm (100 μm) requires the knowledge of the rotation between the inner and the outer chamber with an accuracy better than 1 mrad (3 mrad).

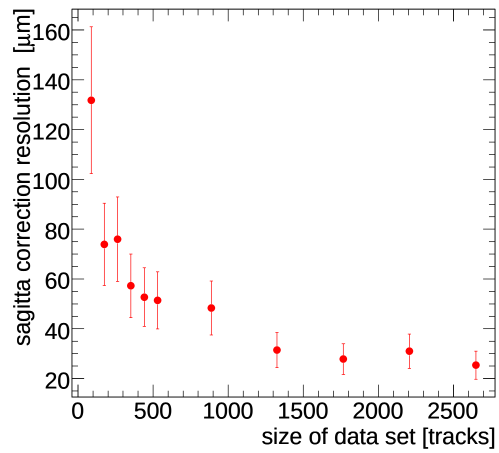

Fig. 2. Accuracy of the sagitta correction after the alignment of a barrel tower with a certain number of curved muon tracks of $p_T > 20$ GeV/c. The numbers are obtained with a Monte-Carlo simulation of the full ATLAS detector after the determination of the rotation angle of the inner and outer chambers with 10^6 single muon tracks of $p_T = 6$ GeV/c.

Figure 2 shows the accuracy of the sagitta correction after the first step of the alignment procedure with 10^6 6 GeV muon tracks and the second step of the alignment procedure with 20 GeV muon tracks. Only about 100 muon tracks of p_T =20 GeV/c are needed to obtain a sagitta alignment correction with 100 μm accuracy. The target alignment accuracy of 30 μm is achieved with 1500 muon track of p_T=20 GeV/c.

Given the fact that the majority of muons passing the 6 GeV muon trigger have transverse momenta close to 6 GeV/c and about 0.5% of the trigger muons have transverse momenta $>$ 20 GeV/c, the dedicated muon data stream will allow us to check the absolute alignment of barrel towers with 30 μm (100 μm) accuracy every 3 days (5 hours) during the operation of the LHC at $L = 10^{33}$ cm^{-2} s^{-1}.

IV. SUMMARY AND OUTLOOK

We described three methods to measure momenta in the barrel of the ATLAS muon spectrometer. These allow us to align towers of three muon chambers with curved low-momentum muon tracks with an accuracy down to 30 μm. The rate of low-momentum muons at the LHC will permit the control of the absolute alignment of barrel towers with 30 μm accuracy every three days.

The presented alignment method proves that the barrel of the ATLAS muon spectrometer can be aligned with curved tracks. The same information which is used by our alignment method is implicitly used by methods which minimize the χ^2 of the reconstructed tracks by varying the alignment of the muon chambers. Our first Monte-Carlo studies applying such a method show similar results for the alignment of barrel towers as the presented algorithm.

REFERENCES

[1] The ATLAS Muon Collaboration, *ATLAS Muon Spectrometer – Technical Design Report*, CERN/LHCC 97-22, Geneva 1997.