Alignment of the ATLAS Muon Spectrometer with Tracks and Muon Identification at High Background Rates

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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 muons of p<40 GeV/c the momenta can be determined with high-enough precision independently of the relative misalignment of the chambers from the 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.

During the operation of the experiment the chambers will be exposed to a high flux of neutrons and g rays which may lead to occupancies of up to 20%. Even higher occupancies are expected for a possible luminosity upgrade of the LHC. We investigated on test-beam measurements at the Gamma-Irradiation Facility at CERN how pattern recognition algorithms can cope with the increased hit rates.

1 Introduction

The ATLAS muon spectrometer consists of three layers of precision muon drift-tube chambers in an air-core toroid magnet system with an average field strength of 0.4 T providing a bending power of 3 Tm. The muon chambers are

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built of two triple or quadruple layers of pressurized drift tubes with a spatial resolution of 80 μm per tube. As the anode wires of the tubes are positioned with 20 μm accuracy within a chamber, each chamber provides a track-point measurement with an accuracy better than 40 μm. If, in addition, the relative positions of the chambers in the muon spectrometer are known with 30 μm accuracy, muon momenta can be measured with an accuracy of better than 4% for transverse momenta below 400 GeV/c and of 10% at 1 TeV/c. The relative chamber positions are monitored continously with the required accuracy by a system of optical sensors. We present a method which permits the monitoring of the optical alignment of the muon spectrometer based on muon tracks.

Our method relies on the efficient reconstruction of straight muon segments in each chamber of the layers of muon chambers in the spectrometer. During the operation of the experiment the chambers will be exposed to a high flux of neutrons and γ rays which may lead to occupancies of up to 20%. Even higher occupancies are expected for a possible luminosity upgrade of the LHC. We investigated on test-beam measurements at the Gamma-Irradiation Facility (GIF) at CERN how pattern recognition algorithms can cope with the increased hit rates.

2 Alignment of the ATLAS muon spectrometer with tracks

Muons traversing a so-called "tower" of precision chambers leave a nearly straight segment in each of the chambers. These segments can be used to calculate a superpoint in each chambers which is the position of the muon trajectory in the middle of each chamber (see Fig. 1). As the muons fly on a curved path through the spectrometer due to the presence of the toroidal magnetic field, the superpoint of the middle chamber does not lie on the straight interconnection of the superpoints of the outer chambers. The sagitta s, i.e. the distance of the superpoint of the middle chamber from the straight interconnection of the superpoints of the outer chambers, is a measure for the muon momentum. $s \approx \frac{500\ \mu\text{m GeV/c}}{p}$ in the barrel part of the spectrometer where p denotes the muon's momentum. The superpoints are measured with $\leq$40 μm accuracy leading to a sagitta resolution of $\leq$50 μm. Thus the muon's momentum can be determined with $\leq$10% accuracy for $p \leq$1 TeV/c.

The sagitta is – by definition – very sensitive to a misalignment of the three chambers detecting a muon. It is therefore monitored continously with 30 μm by an optical alignment system. At the same time does the sagitta itself provide no handle to check the optical alignment. An independent momentum measurement 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. But one can make use of the fact that a muon chamber can measure the direction of the muon trajectory in addition to the superpoint (cf. Fig. 1). One can determine the momenta of low-energy muons with $p_T < 40$ GeV/c in the muon spectrometer with a resolution of a few percent by comparing the muon directions at the entrance and the exit of the muon spectrometer. The deflection angle $\alpha_{out} - \alpha_{in}$ is independent of the chamber's misalignment and thus allows for monitoring relative chamber positions. Fig. 2 shows the resolution of the extrapolation of a single segment from the middle to the outer chambers as a function of the muon momentum which is determined by the deflection angle. The resolution is about 5 mm for $p_T \geq 6$ GeV/c. Hence the misalignment of the chambers can be measured with 30 μm with about 30,000 muon tracks.

Unfortunately this accuracy is only achieved if the momentum measurement is unbiased on the level of 5 MeV/c or – equivalently – the deflection angle $\alpha_{out} - \alpha_{in}$ is not biased by a relative rotation of the outer and inner chambers about the tube axes by more than 0.01 mrad. Yet another independent and, in particular, unbiased momentum measurement is needed. An unbiased momentum measurement of ≈20% statistical precision per 6 GeV muon can be obtained from the curvature of the muon trajectory in the middle chamber due to the high mechanical precision of the chamber. We conclude that 50,000 muons of 6 GeV/c momentum have to be collected to measure the relative rotation of the outer and inner chambers and the relative misalignment of all the chambers of a tower with the required accuracy. 50,000 muons per tower can be provided by a planned single muon data stream of 2,5 kHz rate within 3 hours of ATLAS operation at the LHC.

3 Muon reconstruction at high rates

We mentioned in the introduction that the efficient reconstruction of muon segments, which is required by our alignment algorithm, must be guaranteed also in the presence of the high n-γ background in which the muon spectrometer will be operated. Monte-Carlo calculations [1] predict nominal counting rates of up to 40 kHz per tube in a six-layer and up to 60 kHz in an eight-layer chamber. The calculations have an uncertainty of a factor 5 in the predicted rates such that five times higher background counting rates may be encountered in ATLAS at full luminosity of the LHC.

Previous publications [2][3][4] show that, in a six-layer chamber, a segment reconstruction efficiency ≥97% at the nominal background rates can be achieved with ≤ 0.1 fake segments per event. At a couting rate of 200 kHz per tube (five time the maximum nominal rate), the efficiency drops to 90% if the number of fake segments is kept below 0.25 per event. The efficiency can be almost recuperated by accepting 3.5 fake segments per event. This effect is caused by the fact that, at a rate of 200 kHz per tube, in 10% of the tracks only two out six muon hits are detected while the other four are masked by background hits. As any two hits can be interconnect by a straight line it is very difficult to distinguish the correct combination of two hits from the wrong ones.

This problem can be overcome if the dead time of the tube read-out is reduced from its present value of 800 ns (equal to the maximum drift-tube of the tubes) to its minimum of 200 ns, as the reduction of the dead time reduces the probability of masking a muon hits by a background hit.

We studied the segment reconstruction efficiency as a function of the background counting rate and the dead time of the drift-tube read-out with test-beam data which were recorded in a 100 GeV muon beam with an ATLAS 6-layer muon drift-tube chamber in the GIF at CERN in 2003 [3]. A silicon tracking detector was used as external reference in the test-beam set-up.

We followed the standard track-reconstruction procedure of ATLAS in our analysis: We restricted the track search to the 3 cm wide region defined by the beam trigger and searched inside that region for muon hits within a 500 μm straight road. The segment reconstruction efficiencies which were obtained in our analysis are presented in Fig. 2. The dashed curve shows the reconstruction efficiency obtained with the standard dead time of 800 ns and the requirement of a low fake rate. It agrees with the quoted result [4]. The solid line represents the efficiencies obtained with the reduced dead time of 200 ns with the same requirements on the fake rate. Efficiencies above 95% are reached even at the highest background rates including the safety factor of 5. An efficiency of 90% is achieved at ten times the maximum nominal rate. Such rates can be encountered after the possible luminosity upgrade of the LHC. Our results indicate that a large fraction of the ATLAS muon chambers can be operated at an upgraded LHC.

4 Summary

We developed an algorithm based on muon tracks which allows us to monitor the relative positions of drift-tube chambers in a tower of the ATLAS muon spectrometer with an accuracy of 30 μm. The algorithms makes use of the direction capability of muon chambers which permits the determination of the muon momenta independently of the standard three-point sagitta measurement. The algorithm requires 50,000 muons of $p_T \geq 6$ GeV/c which will be recorded within 3 hours by the ATLAS experiment at the LHC. Our algorithm is complementary to the precision optical alignment monitoring system of the ATLAS muon spectrometer.

In addition we proved with test-beam data taken at the Gamma Irradiation Facility at CERN, that a high muon tracking efficiency $\geq 90\%$ can be achieved even at background rates of up to 400 kHz per tube, if the read-out electronics of the tube is operated with a dead time which is small compared to the maximum drift time.

5 Figure captions

Fig. 1: The muon momentum can be determined either most precisely from a three point track-sagitta measurement or from the deflection angle $\alpha_{out} - \alpha_{in}$ of the muon trajectory in the muon spectrometer.

Fig. 2: Segment reconstruction efficiency for a six-layer ATLAS muon drift-tube chamber as a function of the background counting rates for two different dead-time settings of the read-out electronics as measured in the GIF.

References

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Fig. 1

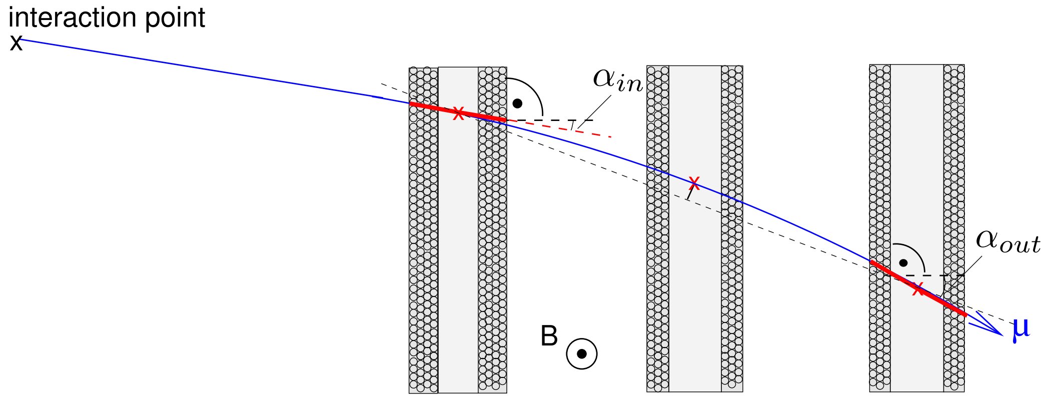
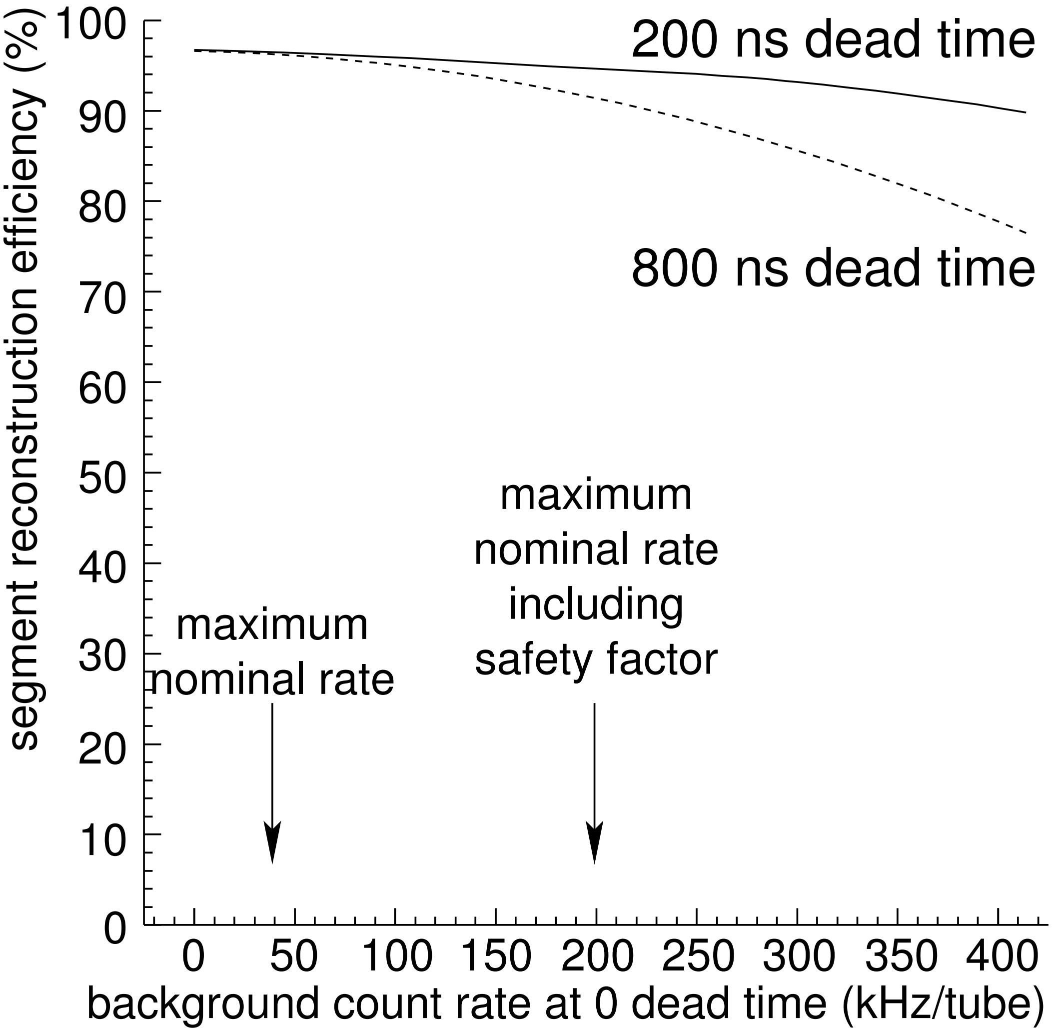


Fig. 2



segment reconstruction efficiency (%)
100
90
80
70
60
50
40
30
20
10
0
200 ns dead time
800 ns dead time
maximum
nominal rate
including
safety factor
maximum
nominal rate
0
50
100
150
200
250
300
350
400
background count rate at 0 dead time (kHz/tube)