Eur Phys J C **33**, s01, s999–s1001 (2004)
Digital Object Identifier (DOI) 10.1140/epjcd/s2004-03-1794-6

EPJ C direct
electronic only

The alignment system of the ATLAS muon spectrometer

C. Amelung, for the ATLAS Muon Collaboration

European Organization for Nuclear Research (CERN), CH-1211 Geneva 23, Switzerland, e-mail: `christoph.amelung@cern.ch`

Received: 14 October 2003 / Accepted: 10 March 2004 /

Abstract. The muon spectrometer of the ATLAS detector at the LHC has been designed to provide a good stand-alone momentum resolution for muons up to about 1 TeV. For this purpose, muon drift tube chambers with very high spatial resolution were developed; in addition, a precise online alignment monitoring system is required. This system is based on optical sensors measuring the individual deformations and the relative positions of muon chambers; temperature sensors are used to monitor their thermal expansion. In the endcap, the alignment system has to make use of additional alignment bars, used as precision reference rulers. In the year 2002, the ATLAS muon collaboration has installed a large-scale test setup of the muon spectrometer barrel and endcap in the H8 test beam line at CERN; one of its aims is to test the concepts and the final prototypes of the components of the alignment system before starting the mass production.

1 Introduction

The world's highest-energy particle collider to date, the LHC (Large Hadron Collider), is under construction at CERN. It will provide colliding proton beams of 7 TeV each with a luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The start-up of LHC operation is currently foreseen for the year 2007. The general-purpose experiment ATLAS [1] is one of the four LHC detectors, with a total length of 44 m, height of 22 m, and a weight of 7000 tons. One of the key components (and the largest by volume) of ATLAS is its muon spectrometer [2], designed to provide a good stand-alone momentum measurement of muons up to the highest energies: p_T should be measured with a resolution of $\Delta p_T/p_T = 10\%$ at $p_T = 1\,\mathrm{TeV}$. The spectrometer consists of MDT (monitored drift tube) chambers, composed of 6–8 layers of cylindrical (30 mm diameter) aluminum drift tubes with a single-tube design resolution of $80\,\mu$m. The high position resolution of the MDT chambers is complemented by fast trigger chambers with a good time resolution.

2 ATLAS muon spectrometer alignment

2.1 The challenge

The MDT chambers are placed in the field of an air-core toroidal magnet, which has the advantage of causing only slight multiple scattering. The drawback of this design is the relatively low magnetic field strength that can be reached: the bending of a 1 TeV muon track is such that the track sagitta varies between $500\,\mu$m in the barrel and 1 mm in the endcap. Consequently, in order to measure the momentum of a 1 TeV muon to 10%, the error on the sagitta measurement must be less than $50\,\mu$m. Each track is detected in three almost equally spaced layers of chambers; thus the MDT resolution contributes a sagitta error of $40\,\mu$m, and the additional error from the chamber alignment must not exceed 30–40 μm. As long-term stability in ATLAS cannot be guaranteed at such small scales, an alignment monitoring system has been designed, which is based on optical and temperature sensors. The information from this system is used in the offline track reconstruction to correct for chamber misalignment; no physical adjustments are made to the chamber positions.

The chambers themselves are high-precision objects by construction: sense wires and tubes are assembled with a precision of $20\,\mu$m. In addition, each chamber has an in-plane alignment system to monitor deformations; thermal expansion is derived from temperature measurements on the chamber. Only the relative alignment of triplets of chambers that can be traversed by the same muon track is of relevance; neither their global position in space, nor the relative alignment of other groups of chambers affects the measured sagitta in first order. The most straightforward solution is thus to install 3-point straightness monitors (RASNIKs) on chambers, parallel to the muon tracks; these devices are also used for the in-plane alignment.

2.2 The RASNIK system

The heart of the RASNIK (Red Alignment System of NIKHEF) system [3] is a mask with a chessboard-like pattern, illuminated by infrared LEDs and projected through a lens onto a CCD. The CCD typically has a size of some mm^2, while the mask has a size of some cm^2, and so the image seen by the CCD corresponds to only a small part of the mask. To determine from the incomplete image its location on the mask, the chessboard pattern is modified in every 9th column and row such that a coarse position information is coded into it. Typical square sizes lie in the range 85–340 μm, and fine position information of the order of some μm is obtained from the many black-white transitions in the image. Longitudinal position information of the order of 10^{-5} times the mask-CCD distance comes from the measured magnification of the image.

The CCD, lens, and mask of the RASNIK form a three-point straightness monitor: the measured quantity is the distance of the mask center from the straight line joining the CCD and lens centers. Thus, by placing each of these elements on a different MDT chamber, the relative chamber alignment, i.e. the false sagitta introduced by their misalignment, can directly be measured and used to correct the measured sagitta of a track traversing the chambers. The dominant contribution to the error of this measurement is the mounting accuracy of the elements on the chambers, of the order of 10 μm. A useful variation of the RASNIK principle is to integrate CCD and lens in a box, i.e. to build a camera. This converts the three-point monitor into a two-point monitor, or proximity sensor.

2.3 From principle to practice

The idea to use RASNIKs in ATLAS for the relative chamber alignment is confronted with a fundamental difficulty. As the alignment is of interest in the coordinates transverse to the muon track, the RASNIK lines have to be projective, i.e. pointing to the ATLAS interaction point. Accommodating four free lines of view for the four corners of each triplet of MDT chambers turns out to be technically impossible. In the barrel region, at least a smaller number of projective lines can be accommodated; in the endcap region, projective lines are impossible to realize at all, because the two cryostats of the endcap toroid magnets block them. Only a very small number of nearly projective lines can pass through special tubes in the cryostats.

As a solution in the barrel region, the reduced system of projective lines is complemented by a system of axial lines, connecting chambers in the same layer to form larger ‘logical’ chambers and thereby compensating for the reduction in the number of projective lines. In the endcap region, the alignment relies instead on large precision reference rulers, the so-called alignment bars, which are aligned with respect to each other using BCAMs, and relative to which chamber positions are monitored in turn.

2.4 The BCAM camera

The BCAM (Boston, or Brandeis, CCD Angle Monitor) is a camera [4], consisting of a CCD and a lens, which looks at a laser diode at a large distance (in the range 0.5 m to 16 m). The CCD-lens distance approximately equals the focal length of the lens, and the image seen by the camera is thus a blurred circular light spot. The measured quantity is the position of this light spot on the CCD, which can be translated into a transverse angle with respect to the BCAM optical axis. Low-precision longitudinal information can be obtained from the relative angle under which two laser diodes appear. BCAMs are attached to alignment bars on platforms with three stainless-steel balls; one or two cameras (facing opposite directions) and two or four laser diodes are integrated in a single BCAM box.

BCAMs can be used in two configurations: a pair of BCAMs is a 2-point angular monitor, where each BCAM measures the absolute angular position of its partner to an accuracy of 50 μrad (limited by the camera calibration and mounting accuracy). A triplet of BCAMs on a straight line is a 3-point straightness monitor, where each of the outer BCAMs measures the relative positions of the two others. This relative measurement has an accuracy of $\sqrt{2} \cdot 5\,\mu$rad (limited by the small systematic effects of the centroid-finding algorithm). In addition, each pair of BCAMs in such a triplet also provides 2-point information.

2.5 Alignment bars

Alignment bars [5] are large precision objects, built inside and around an up to 9.6 m long aluminum tube. BCAMs mounted on platforms on the bars monitor their relative alignment; RASNIK masks for proximity sensors on endcap MDT chambers are mounted in the same way and permit to align the chambers with respect to the bars. The purpose of an alignment bar is to provide a well-defined spatial relationship between all the BCAMs and masks mounted on it: their positions on the bar must be known to 20 μm, the BCAM orientations in addition to 50 μrad. During construction, the bars are calibrated by measuring the positions of mounting balls for BCAMs and masks using a large coordinate-measuring machine (CMM).

Like for MDT chambers, expansion and deformation of alignment bars are monitored by using temperature sensors and in-bar RASNIKs. As the three RASNIKs inside a bar are sensitive to the bar shape only in five points, an interpolation procedure is required; since bars deform by up to 4 mm (much more than chambers) under their own weight and that of the sensors mounted on them, this interpolation must be accurate to 0.5%. Simple interpolation by splines or polynomials produces errors far beyond this; the finally adopted method makes use of the analytic solution of the differential equations describing the deformation of a bar as a function of the known discrete and continuous forces acting on it, by combining it with the RASNIK measurements.

3 Alignment system tests

In the H8 beam line at CERN, a part of one endcap of the ATLAS muon spectrometer, as well as a part of the barrel, have been set up in order to test the alignment concept, and to gain experience with the operation of the complex system of chambers and alignment sensors. Six endcap and six barrel chambers are present and can be illuminated by a muon beam from the SPS accelerator. In addition, six alignment bars, four of 9.6 m length and two 2.6 m long ones, are installed in the endcap setup.

There are two strategies for making use of the data provided by an alignment system. The absolute concept is the straightforward one: to ask that the alignment system provides sagitta corrections at any time and without using any external references. The other concept is relative: assuming that at one moment the sagitta corrections are known (e.g. from the use of straight muon tracks in special runs with the magnetic field switched off, or using muons from Z^0 decays recorded in normal running), the alignment system is used only to follow variations of the sagitta corrections from this point on. The advantage of the latter strategy is that all sensor positioning accuracies and many sensor calibration parameters cancel out in first order. Data for a test of this strategy, with muons from the test beam and measurements from the (partially uncalibrated) system of alignment sensors being recorded simultaneously, have been collected in 2002/2003.

In order to become independent of the beam and of tracking-related systematic effects, the muon beam can be replaced by the so-called muon simulator, a device consisting of a camera looking approximately along the beam line at light sources attached to the MDT chambers. From the relative movements of the light sources, the sagitta variations can be directly extracted. Data for this test have also been collected in 2002/2003 with the endcap setup.

The alignment, i.e. the chamber positions and orientations, is reconstructed from the sensor measurements by a global χ^2 minimization with e.g. MINUIT. By comparing the resulting sagitta variations to those observed using tracks, one obtains r.m.s. differences of typically 10–20 μm both in the barrel and the endcap setup. The comparison to sagitta variations measured by the muon simulator in the endcap setup (Fig. 1) yields an r.m.s. accuracy of 16 μm over a continuous period of 2.5 days, during which daily temperature-induced sagitta variations of up to 500 μm were complemented by artificial variations of up to 5 mm from shifting and/or rotating chambers. The total χ^2/ndf of the alignment fit varies in an acceptable range of 0.9–1.5. The observed resolution of the alignment system of 10–20 μm agrees well with the expectation from simulations for the relative alignment (the sensor mounting accuracies, which do not contribute here, dominate the absolute alignment design resolution of 30–40 μm).

4 Summary

The design of the ATLAS muon spectrometer requires a relative alignment of individual muon chambers to a precision of 30–40 μm. Two large-scale test setups for the barrel and endcap alignment systems have been completed in 2002, and the relative alignment concept has been successfully tested using the data collected in 2002/2003.

Acknowledgements. Many colleagues have contributed to the alignment system test and the results presented here, and their work is gratefully acknowledged. I thank the organizers of the conference for their kind invitation to give this presentation.

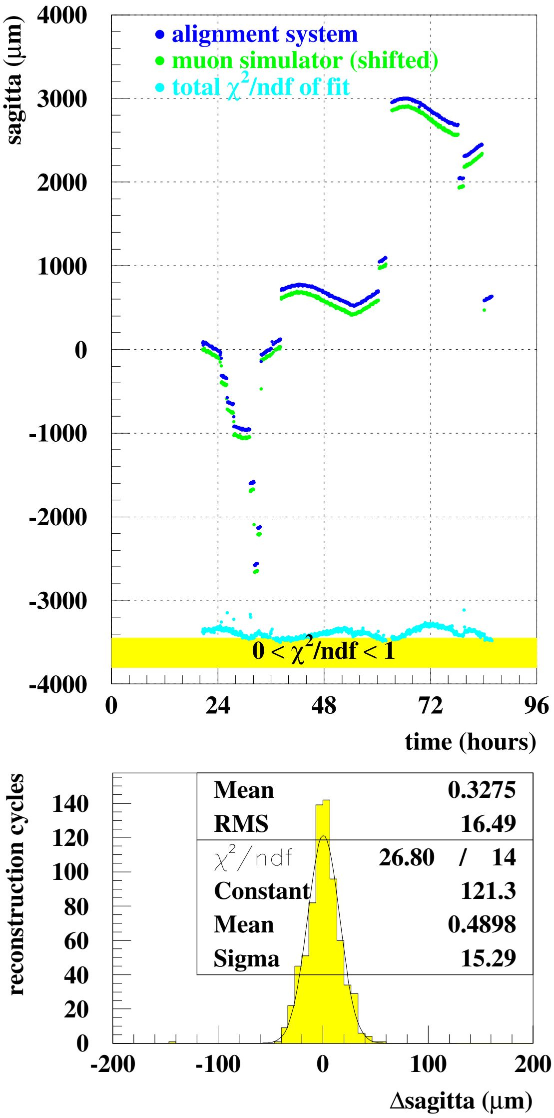

Fig. 1. *Top*: sagitta variations reconstructed from the alignment system (*blue*) and measured by the muon simulator (*green*, shifted by 100 μm for clarity of presentation), over a period of 2.5 days. Smooth variations are temperature-induced, steps come from chamber shifts and rotations. The total χ^2/ndf of the alignment fit is also shown (*cyan*); the *yellow band* indicates the range $0 < \chi^2/\text{ndf} < 1$. *Bottom*: sagitta difference between alignment system and muon simulator

References

1. ATLAS Collaboration: Technical Proposal for a General-Purpose pp Experiment at the LHC at CERN, CERN/LHCC/94-43
2. ATLAS Muon Collaboration: ATLAS Muon Spectrometer Technical Design Report, CERN/LHCC/97-22
3. H. Dekker et al.: The RASNIK/CCD 3-Dimensional Alignment System, Proceedings of the Third International Workshop on Accelerator Alignment, CERN, Geneva (1993)
4. K. Hashemi et al.: ATLAS notes ATL-MUON-2000-024 and ATL-MUON-2000-026
5. A. Schricker: The Alignment System of the ATLAS Muon Spectrometer, doctoral thesis, Tech. Univ. of Vienna (2002)