TOC

THE ALIGNMENT SYSTEM OF THE ATLAS MUON SPECTROMETER

Christoph Amelung
CERN, CH-1211 Geneva 23, Switzerland

1 INTRODUCTION

The world's highest-energy particle collider, the LHC (Large Hadron Collider), is currently under construction at CERN. It will provide colliding proton beams of 14 TeV center-of-mass energy at a luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The start-up of LHC operation is foreseen for the year 2007. Four experiments are being built for the LHC: two of them are multi-purpose detectors (ATLAS and CMS), while the two others have been optimized for more special measurements (LHCb and ALICE). All four experiments are now gradually moving or have already moved from the R&D and prototyping to the mass-production stage. In this phase, tests of final or nearly final components are being performed in order to ensure their functionality before the assembly of the detectors, and in order to learn how to operate the complex systems. This presentation focuses on the ATLAS experiment [1], the largest of the four detectors, with a total width of 44 m, height of 22 m, and a weight of 7000 tons (Fig. 1).

2 ATLAS MUON SPECTROMETER ALIGNMENT

2.1 The muon spectrometer

One of the key components (and the largest by volume) of the ATLAS detector is its muon spectrometer [2]. It has been designed to provide a good stand-alone momentum measurement of muons up to the highest expected energies: the transverse momentum p_T can be measured with a resolution of $\Delta p_T/p_T = 10\%$ even at $p_T = 1$ TeV. The muon spectrometer consists of MDT (monitored drift tube) chambers (Fig. 2), composed of 6–8 layers of cylindrical ($d = 30$ mm) aluminium drift tubes with a design single-tube resolution of 80 µm. The high position resolution of the MDTs is complemented by fast trigger chambers with a good time resolution: RPCs (resistive plate chambers) in the barrel and TGCs (thin gap chambers) in the endcap. In a small endcap region around the beam pipe, MDTs are replaced by CSCs (cathode strip chambers) to cope with the high particle multiplicities expected here.

The MDT chambers are placed in an air-core toroidal magnetic field, which has the advantage of little multiple scattering due to the little material present between chambers. The drawback of this design is the relatively low magnetic field strength that can be reached. For example, a 1 TeV muon track is bent by the magnetic field such that it obtains a sagitta varying between 500 µm at rapidity $\eta = 0$ (in the barrel) and 1 mm at rapidity $\eta = 2$ (in the endcap). Consequently, in order to measure the momentum of a 1 TeV muon to 10%,

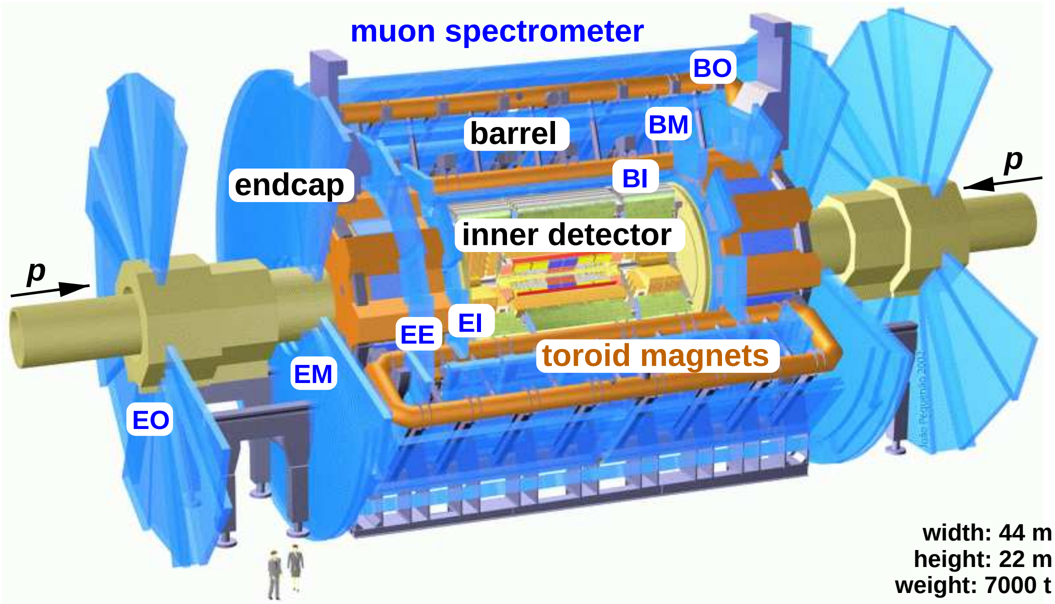

Fig. 1: Virtual reality image of the ATLAS detector. The muon spectrometer (shown in blue) surrounds the inner detector. The eight barrel toroid coils (shown in brown), as well as eight toroidal coils in each of the endcaps, provide the magnetic field.

the error of the sagitta measurement must be 50 μm. Each track is detected in three about equally spaced layers of chambers; thus the MDT resolution contributes a sagitta error of 40 μm, and the additional error from the alignment of the MDT chambers must not exceed 30–40 μm in order to meet the specification.

The MDT chambers themselves are high-precision objects by construction: sense wires and tubes are placed with a precision of 20 μm, which is verified for a sample of 1/7 of them in an X-ray tomograph facility. In addition, each MDT chamber has an in-plane alignment system to monitor deformations; thermal expansion is derived from temperature measurements on the chamber.

In principle, 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 to first order the measured sagitta. The most straightforward solution is thus to install 3-point straightness monitors, RASNIKs, parallel to the muon tracks. These monitors are the subject of the following section.

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 (Fig. 3), which is illuminated by an array of infrared LEDs and projected through a lens onto a CCD. Typical CCD dimensions are of the order of mm, while the mask has a size of the order of cm. As the lens is usually placed somewhere in the middle between mask and CCD, the image projected onto the CCD corresponds to only a

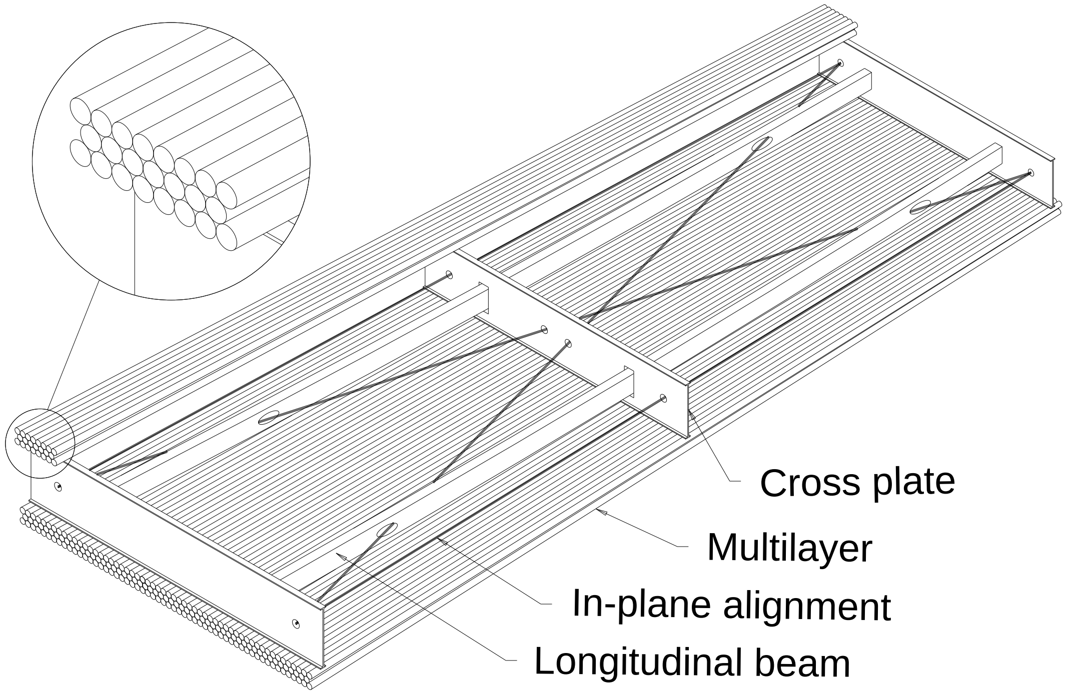

Fig. 2: Drawing of an MDT (monitored drift tube) chamber. Two layers of 3–4 tubes each are glued onto a supporting frame of three cross plates and two longitudinal beams. The elements of the in-plane alignment system are glued to the cross plates.

small fraction of the mask. In order 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 binary coded into it. Typical square sizes lie in the range 85–340 μm, and fine position information is obtained from the large number of black/white transitions in the image.

For a symmetric RASNIK, where the lens is positioned half-way between CCD and mask, transverse position resolutions of the order of 1 μm have been obtained under lab conditions. Longitudinal position information comes from the measured magnification of the image, and the resolution is found to be about $0.03 \times f$ μm (where f, the focal length of the lens, is given in mm, and the distance between CCD and mask is $4f$). A nice feature of the RASNIK is the decoupling of dynamic range and position resolution: the dynamic range can be increased by using a larger mask, without any loss in resolution.

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 centers of the CCD and the lens. Thus, by placing each of these elements on a different MDT chamber, their relative alignment, or equivalently, the false sagitta introduced by their misalignment, can directly be measured and used to correct the sagitta measurement of a muon track traversing the chambers. The dominating contribution to the error of this measurement is the positioning accuracy of the elements, which is of the order of 10 μm.

A useful variation of the RASNIK principle is to integrate CCD and lens in a box, forming

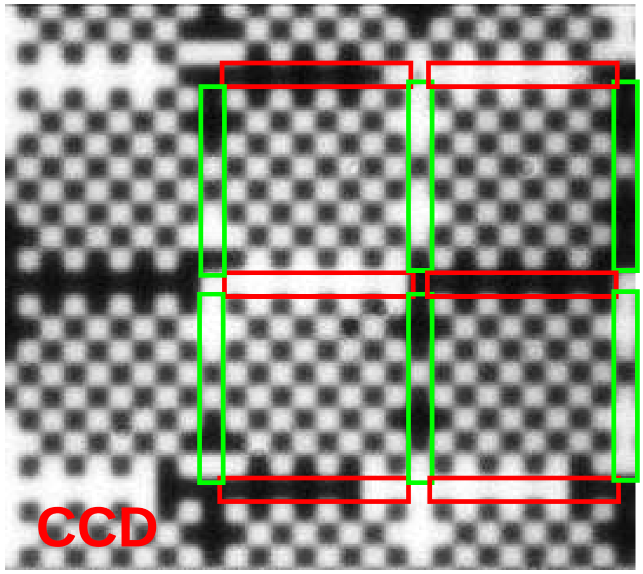

Fig. 3: Image of a RASNIK mask. In every 9th column and row (highlighted in red and green), the chessboard-pattern is modified to encode the coarse position information (by an exclusive-OR of the chessboard-square color with the binary representation of an 8-bit number). Horizontal position information is coded in vertical strips, and vice versa.

a stiff unit, in other words: to build a camera. This converts the three-point monitor into a two-point monitor, or proximity sensor.

2.3 From principle to practice

In practice, the idea to use RASNIKs for the alignment in ATLAS is confronted with some difficulties. As the relative chamber alignment is of interest in the coordinate transverse to the muon track, the RASNIK lines have to be exactly projective, i.e. pointing to the ATLAS interaction point, from where the muons originate. Accommodating four free lines of view for the four corners of each triplet of muon chambers turns out to be technically impossible. In the barrel region, at least a smaller number of projective lines has been accommodated; in the endcap region, projective lines were impossible to realize at all, because the two cryostats of the endcap toroid magnets block them. Only a small number of nearly projective lines can pass through special holes 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, a completely different approach is taken. Here, the alignment relies on intermediate reference objects, the so-called alignment bars, which are aligned relative to each other and relative to which chambers are referred in turn. In total, 96 alignment bars in the two endcaps form a precise reference grid with a relative accuracy of 30 μm in the projective directions, and of 300 μm absolute.

While the alignment concept of the barrel has been the subject of numerous tests, prototypes of the components of the endcap alignment system have been produced and tested only in the recent past. The following sections therefore focus on the endcap alignment system. Before describing alignment bars, the device used to align them relative to each other will be presented: the BCAM.

2.4 The BCAM camera

The BCAM (Boston CCD Angle Monitor) is a camera [4], consisting of a CCD and a lens (Fig. 4), which looks at two laser diodes at a large distance (in the range 0.5 m to 16 m). The distance from CCD to lens is fixed at approximately 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 the center of this light spot on the CCD, which can be translated into a transverse angle with respect to the BCAM optical axis. Some low-precision longitudinal information can be obtained from the relative angle under which the two laser diodes appear. A BCAM is mounted on a platform with three stainless-steel balls, which in turn is attached to an alignment bar.

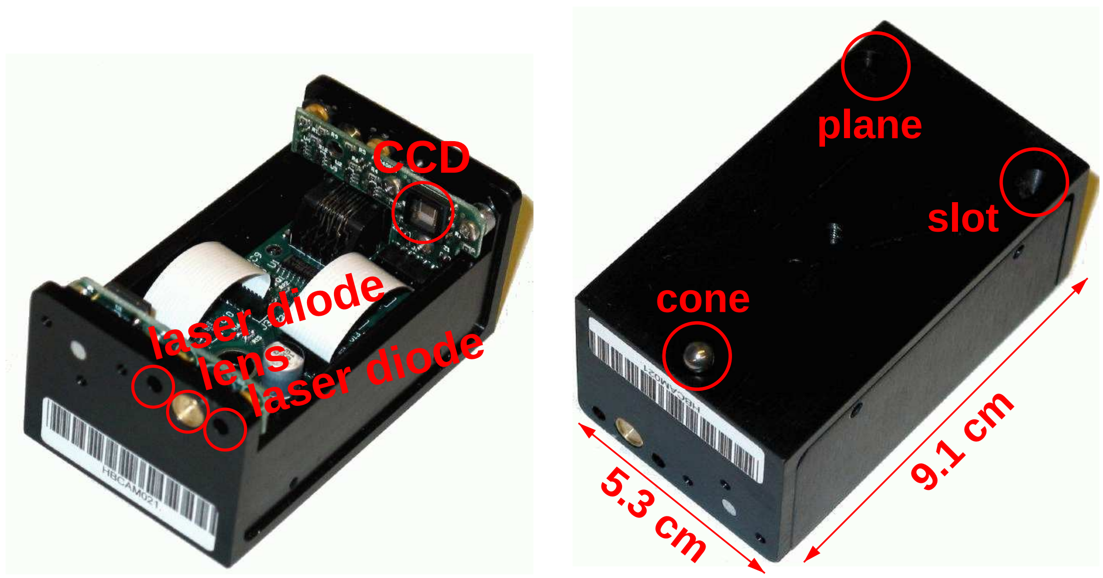

Fig. 4: Photos of a BCAM (after removal of the cover). Left: the CCD, lens, and two laser diodes in the right half of the box are indicated in red; the same arrangement is also present in the left half, with the camera looking into the opposite direction. Right: the BCAM is mounted on three stainless-steel balls on a platform. Differently shaped holes in the BCAM base serve to accommodate the balls.

In one BCAM body, 1 or 2 cameras and 2 or 4 laser diodes are integrated, respectively; in the case of two cameras, they are arranged next to each other facing opposite directions.

BCAMs can be used in two different configurations: a pair of BCAMs is a 2-point angular monitor, and each BCAM can measure the absolute angular position of its partner to an accuracy of 50 μrad (which is limited by the camera calibration accuracy and by the precision to which the relative positions of the three balls can be measured). A triplet of BCAMs on a straight line is equivalent to a 3-point straightness monitor, if one of the outer BCAMs measures the relative angular positions of the two others. This relative measurement has an accuracy of $\sqrt{2} \cdot 5\,\mu$rad (which is limited by the unavoidable systematic effects of the centroid-finding algorithm). In addition, each pair of BCAMs in such a triplet also provides 2-point information, and thus the BCAM 3-point straightness monitor is somewhat superior in information (though not in precision) to its RASNIK equivalent. Both the relative and the absolute accuracy of the BCAM have been demonstrated in the lab with a prototype.

The dynamic range of a BCAM is ±20 mrad, directly related to the size of the CCD and the distance from CCD to lens. There is a trade-off between dynamic range and relative accuracy: if the dynamic range is increased by a factor of two (by shifting the lens towards the CCD), the relative accuracy is deteriorated by the same factor in turn.

2.5 Alignment bars

Alignment bars [5] are large precision objects, built inside and around an up to 9.6 m long aluminium tube (Fig. 5). BCAMs mounted on platforms on the bars measure the positions of the bars in space; RASNIK masks (for proximity sensors on chambers) are also mounted on platforms and permit to align endcap MDT chambers relative to alignment bars.

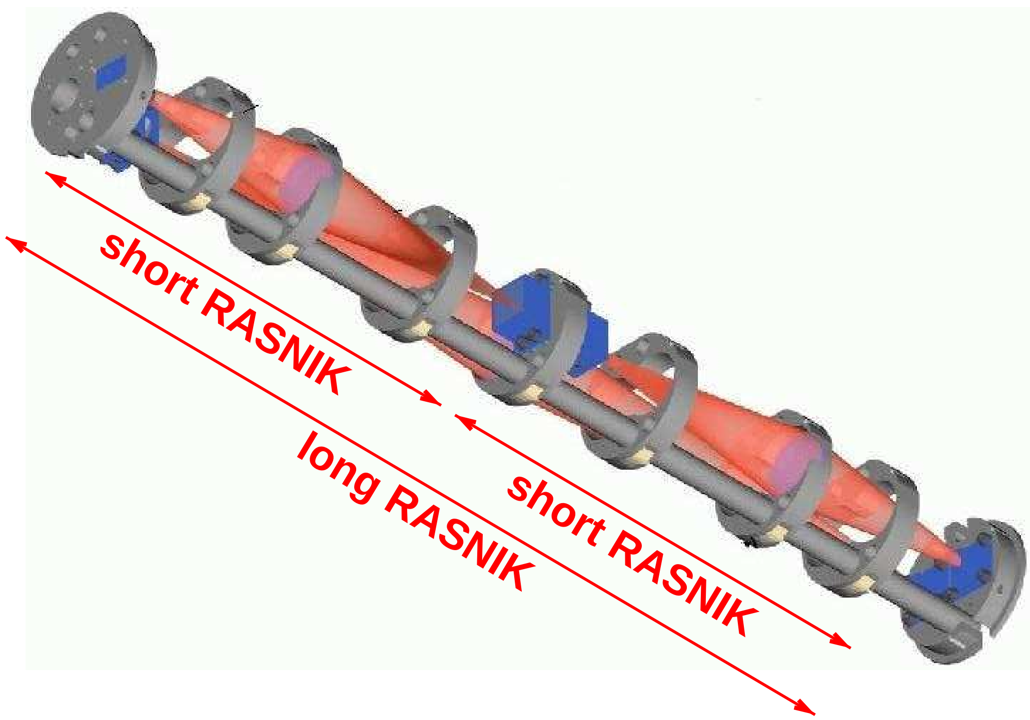

Fig. 5: Schematic drawing of the in-bar instrumentation of an alignment bar. Two short RASNIKs and one long RASNIK are used to monitor shape deformations; temperature sensors are attached to the nine discs. The shown parts are inserted into the alignment bar tube with an inner/outer diameter of 72/80 mm.

Effectively, the purpose of an alignment bar is to provide a stable spatial relationship between all the BCAMs and proximity sensor masks mounted on it. The positions of BCAMs and masks on the bar must be known at any time to 20 μm, the orientations of BCAMs to 50 μrad. A strategy similar to MDT chambers is used to ensure this: the thermal expansion of the bars is monitored by temperature sensors in nine places along the bar, shape deformations are monitored by three in-bar RASNIKs.

However, the three RASNIKs can provide information about the shape of the bar only in three points along the bar (relative to two other points, which define the bar coordinate system), and thus an interpolation procedure is required for points in between these few measured points. It turns out that this is a highly non-trivial problem: for example, interpolation by splines or polynomials has been shown to produce errors far beyond the specification. The solution that has been finally adopted makes intelligent use of the analytic solution of the differential equations describing the bar deformation as a function of discrete and/or continuous forces, and will be explained below.

Unlike MDT chambers, alignment bars are not assembled with high precision, but have to be calibrated instead. This is done with a large CMM (coordinate-measuring machine), where the positions of all balls on the bar are measured with a local (relative) precision of 2–3 μm, and a global (absolute) precision of 10 μm. These position measurements, together with the in-bar RASNIK and temperature sensor readings during the measurements (which are approximately constant), are referred to as the initial shape of the bar. In addition, the RASNIKs have to be calibrated, i.e. the orientations of the sensor coordinate systems relative to the bar coordinate system have to be determined, which is done by a number of controlled deformations of the bar.

In the experiment, only the difference of RASNIK and temperature values with regard to the initial shape measurement is used. All known changes of forces acting on the bar compared to the initial state are taken into account (e.g. the weight of sensors mounted on the bar, or changes in the direction of gravity if the bar is inclined or rotated around its axis). These are used to calculate the expected deformation of the bar. Any remaining unaccounted-for forces (e.g. cables connecting to sensors) are absorbed into three effective forces which are determined using the RASNIK measurements, and which serve as a measured correction to the expected deformation. A lot of care is taken to reduce these unaccounted-for forces: for example, the bars are kinematically supported in their Bessel points to minimize shape compliance, and cables are guided from the sensors along the bar to one of the support points, before they are allowed to leave the bar and to attach to the large support structures. It is found that the unaccounted-for forces do not exceed some Newton, and that the correction to the deformation is of the order of 100–200 μm, the total deformation being as large as 1–2 mm. The systematic error of the interpolation procedure is typically 5% of the correction, and thus about 0.5% of the total deformation.

3 ENDCAP ALIGNMENT TEST

3.1 Alignment test setup

In the H8 test beam area at CERN, an octant of one endcap of the ATLAS muon spectrometer has been set up (Fig. 6) in order to test and validate the alignment concept, and in order to gain experience with the operation of the complex system of chambers and alignment sensors. Six endcap 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, as well as all the required BCAMs and proximity sensors are installed and read out. A similar setup has been built in the same area for a test of the barrel alignment system, the results of which are beyond the scope of this presentation.

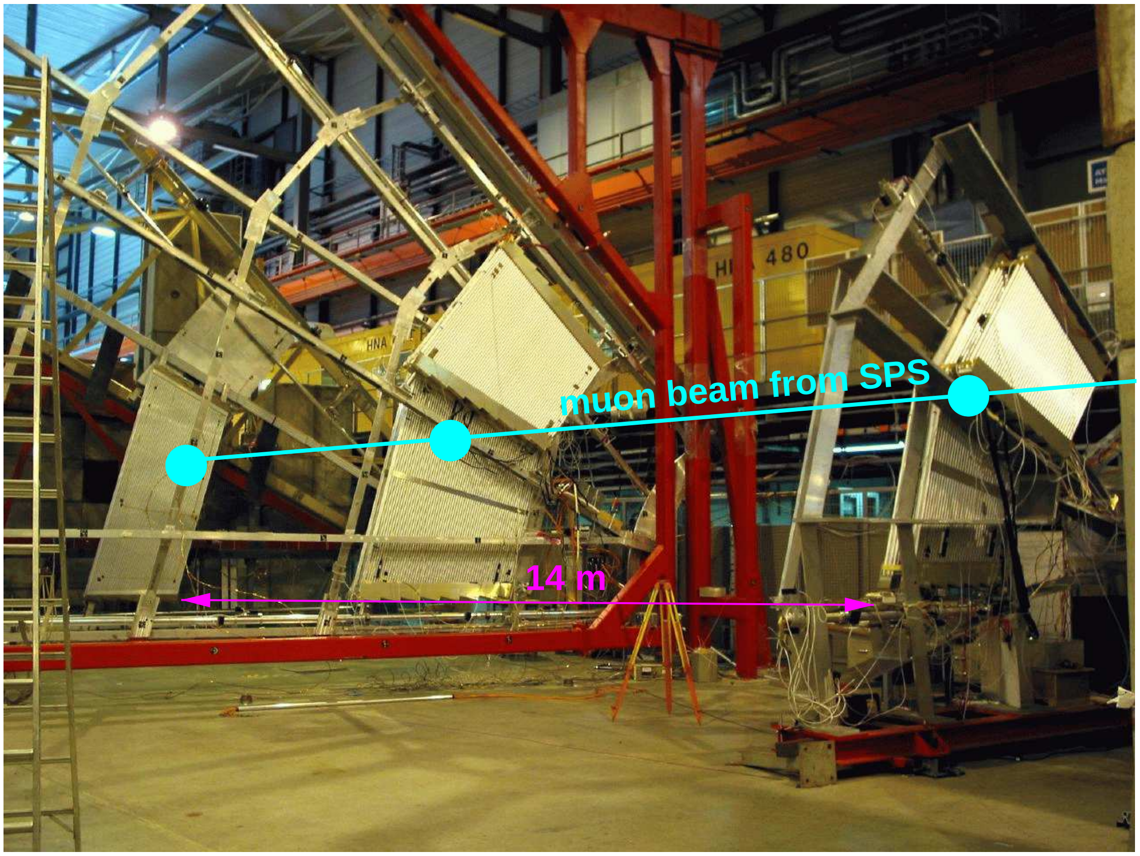

Fig. 6: Photograph of the endcap alignment test setup in the H8 test beam area at CERN. The cyan line indicates the muon beam direction, the circles the points where the beam hits the chambers. The distance between the first and the last chamber is about 14 m.

3.2 Alignment reconstruction and simulation software

On the software side, the program ARAMYS [6] has been developed for the reconstruction of global alignment information from the individual sensor measurements; the program can also be used as a tool to simulate the performance of a given alignment system resulting from the known sensor resolutions. The program implements the description of alignment bar deformations based on forces, as well as chamber deformations. It uses a description of the geometry of the setup and a sensor database generated from various calibration sources. ARAMYS is a compact program currently written in C, and relies on the CERN minimization software MINUIT [7] to find the set of positions and deformations of objects that is in best agreement with a given set of sensor measurements.

A simulation of the alignment test setup has been performed using design intrinsic resolutions and positioning accuracies for all sensors. Averaged over many identical test setups, the r.m.s. width of the false sagitta distribution, i.e. the expecation value of the contribution of the alignment system to the total error of the sagitta measurement, is about 30 µm, with position-dependent variations of about ±25% (Fig. 7).

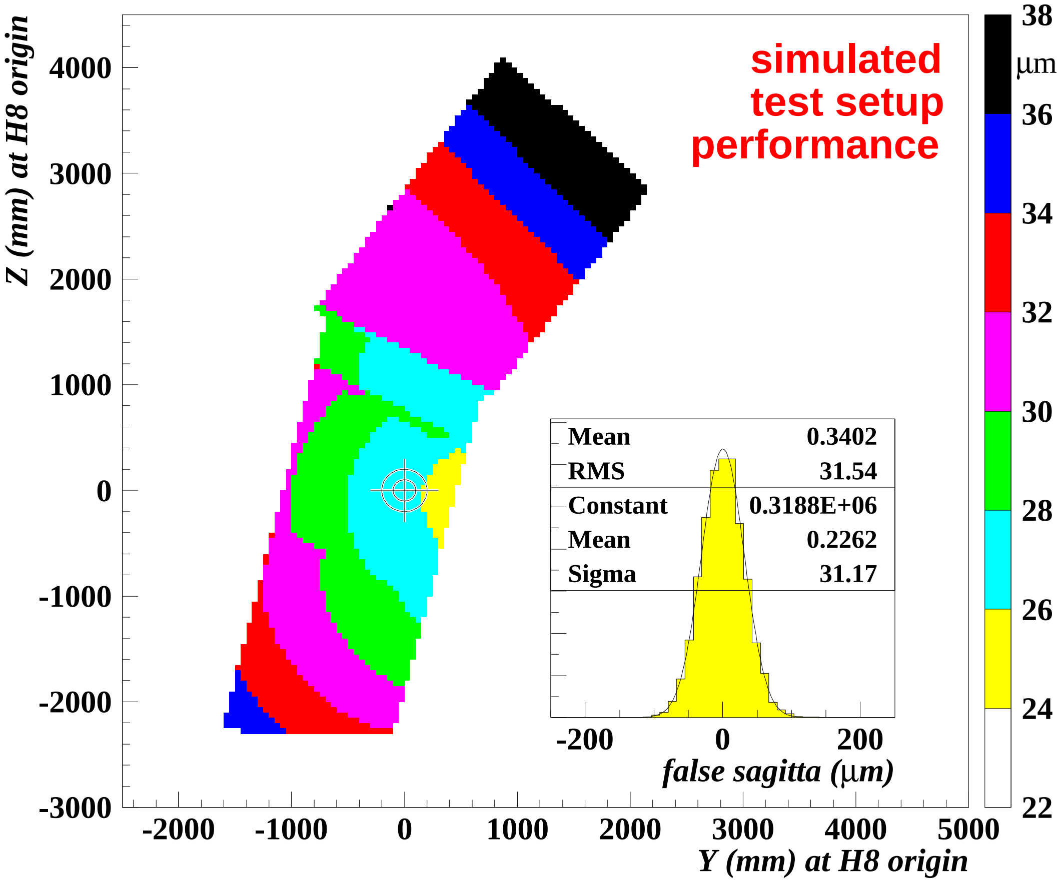

Fig. 7: Simulated performance of the alignment test setup, expressed as the expected r.m.s. width of the false sagitta distribution. Different colors represent the (position-dependent) r.m.s. widths of local false sagitta distributions; the histogram shows the sum of all local distributions. Irregular structures are due to the varying overlaps between different chambers traversed by a muon track. The test beam illuminates the chambers at (and in about $1\,\mathrm{m}^2$ around) $Y = Z = 0$.

3.3 First results of the alignment test

A number of results has been obtained from the preparatory stage and the first data taking in 2002; some of the things learned had an effect on the final design of the ATLAS alignment system. This presentation focuses on the central target of the endcap alignment test: the validation of the alignment system concept.

There are two possible strategies how to make use of the data provided by the alignment system. The absolute concept is the most straightforward one: to ask that the alignment system should provide sagitta corrections at any time and regardless of any other sources of information. The drawback of this concept is that sensor positioning accuracies and calibration parameter uncertainties dominate the quality of the result; it has been found that positioning sensors accurately to some tens of μm is one of the most difficult tasks in the series production. The absolute concept has not been tested in 2002, because calibration data were not available for all classes of sensors. The expected performance for this concept is shown in Fig. 7.

The other concept, called the relative concept or 'plan B', relies on the assumption that at one moment in time the sagitta corrections are known, e.g. from the use of straight muon tracks in special data-taking runs with the magnetic field switched off. The alignment system would then be used only to follow variations of the sagitta corrections from this point on. The advantage of this strategy is that all sensor positioning accuracies and many sensor calibration parameters cancel out, at least to first order. Data for a test of this strategy, with muons from the test beam and alignment sensor data recorded simultaneously, have been collected in 2002 and are being analysed. Alternatively, in order to become independent of the beam and all the possible tracking-related systematic effects, the role of the muon beam can be played by a device called the muon simulator. It consists of a camera (a BCAM), looking approximately along the beam line at light sources attached to the muon chambers in question. From the relative movements of the light sources, the sagitta variations can be directly extracted, and they can be compared to the sagitta corrections as reconstructed by the full alignment system.

The result of such a comparison is shown in Fig. 8. It can be seen that in the bending direction (the coordinate in which the magnetic field bends a charged particle track, and thus the coordinate relevant for the momentum measurement), the alignment system and the muon simulator agree in their predictions of the sagitta correction to an r.m.s. accuracy of about 20 μm, over an integrated time period of four days during which (mostly temperature-induced) sagitta variations of about 500 μm were observed. Given that the muon simulator itself introduces an error of about 20 μm (as estimated from the observed difference in sagitta variations obtained from looking at two different light sources on each chamber), this result is compatible with the assumption that the width of the difference distribution (and the small visible systematic effects) are due to the muon simulator. An independent verification of this assumption will be possible using muon tracks; it is however not yet clear how large the systematic error of the track-based alignment will be.

4 SUMMARY

The design of the ATLAS muon spectrometer requires a relative alignment of individual muon chambers to a precision of 30–40 μm. While this can be achieved by relatively straightforward methods in the barrel region, a more complicated approach has to be taken in the endcap. Here, alignment bars, large precision objects, are used to form an intermediate reference system to which chambers can be aligned. A large-scale test setup for the alignment system has been completed in 2002, and promising results have already been obtained from the first data. More results are expected to come in the next years.

ACKNOWLEDGMENTS

The ATLAS Muon Spectrometer Alignment and its validation in the H8 test beam area are a project of, but not exclusively of, NIKHEF, Amsterdam (Netherlands), CEA Saclay (France), Brandeis University (USA), MPI Munich (Germany), CERN, Geneva (Switzerland), and the University of Freiburg (Germany). Many colleagues from these and other institutions have contributed to the project and the results presented here, and their work is gratefully acknowledged. I thank S. Palestini and A. Schricker for careful proof-reading of the manuscript and providing useful comments, and the organizers of the workshop for their kind invitation to give this presentation.

REFERENCES

[1] ATLAS Collaboration, *Technical Proposal for a General-Purpose pp Experiment at the LHC at CERN*, CERN report CERN/LHCC/94-43.

[2] ATLAS Muon Collaboration, *ATLAS Muon Spectrometer Technical Design Report*, CERN 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 and J. Bensinger, *The BCAM Camera*, ATLAS note ATL-MUON-2000-024;
D. Daniels, K. Hashemi and J. Bensinger, *BCAM Calibration*, ATLAS note ATL-MUON-2000-026.

[5] A. Schricker, *The Alignment System of the ATLAS Muon Spectrometer*, Ph.D. thesis, Technical University of Vienna (2002);
Ch. Amelung and A. Schricker, *Calibration of Alignment Bars for the ATLAS Muon Spectrometer Endcap*, ATLAS internal note ATL-MUON-COM-2002-14.

[6] Ch. Amelung, *Muon Spectrometer Alignment in ATLAS: A Generalized Approach to Simulation*, ATLAS note ATL-MUON-2001-011.

[7] F. James and M. Roos, Comp. Phys. Comm. 10 (1975) 343.

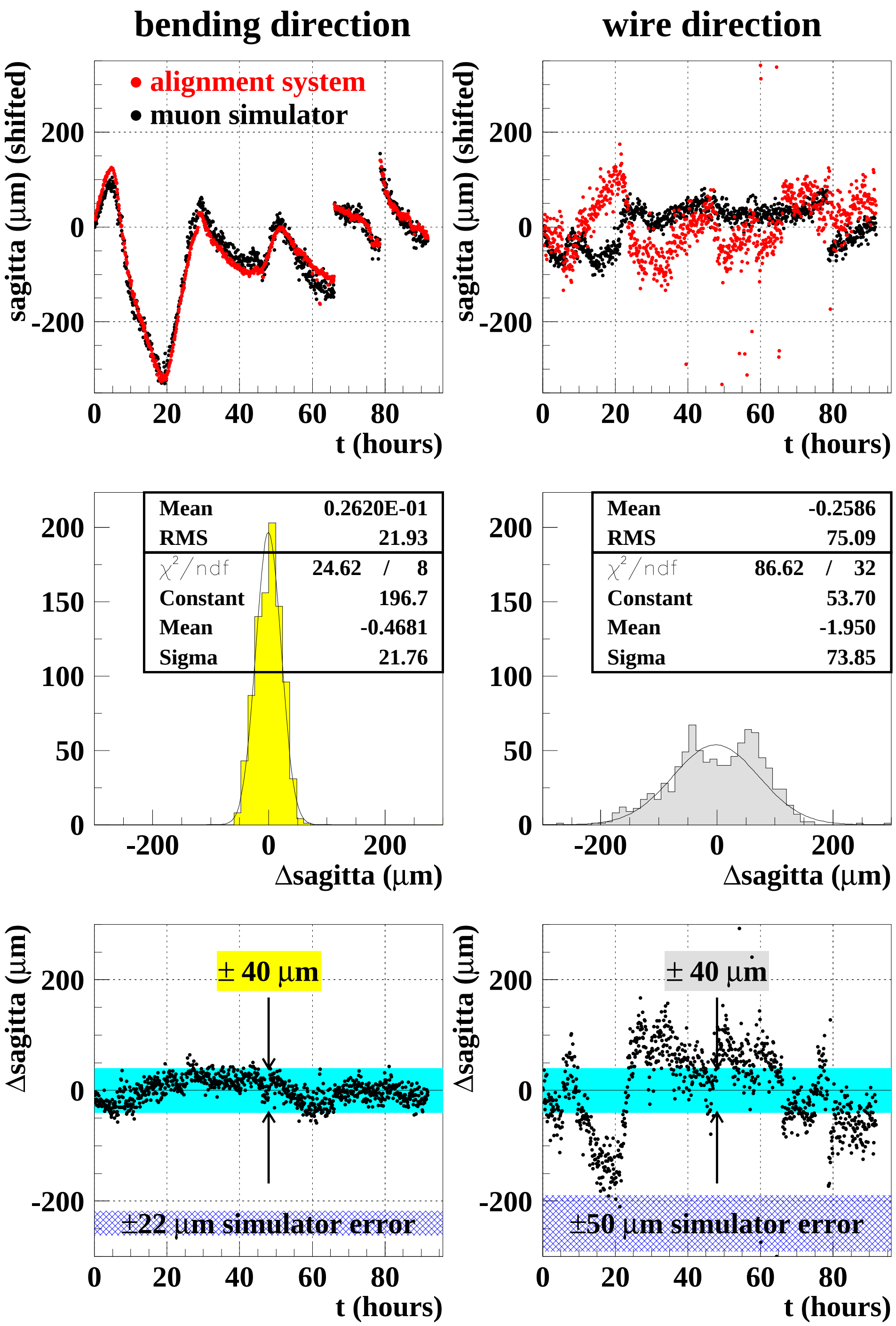

Fig. 8: Comparison of sagitta variations as reconstructed by the alignment system (red) to those measured by the muon simulator (black). The top plots show the sagitta variations vs time, the center plots the difference between the two, and the bottom plots the difference vs time. Plots on the left are for the bending direction (i.e. relevant), plots on the right are for the wire direction (i.e. mostly irrelevant). The blue band in the bottom plots indicates an estimate of the error of the muon simulator measurement.