Concepts for the mechanical realisation

of the ATLAS muon chamber alignment

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Summary

This paper describes how alignment systems can be implemented in the ATLAS muon chambers and chamber towers [1]. The calibration procedures are explained, and concepts for the mechanical realisation are presented.

Jargon, abbreviations and conventions

Barrel	cylindrical part of muon spectrometer
BI	Barrel Inner muon chamber
BM	Barrel Middle muon chamber
BO	Barrel Outer muon chamber
Cross Plate	precision plate defining the positions of the tube units and the alignment systems. There are outer and middle cross plates
FB	forward/backward (chambers)
FI	forward inner chamber
FM	forward middle chamber
FO	forward outer chamber
IP	Interaction Point
Large chambers	muon chambers central between magnet coils
Octant	1/8 section (in angle ϕ) of the muon spectrometer; one octant contains 13 barrel towers and 2 FB towers
RASNIK	Red Alignment System NIKhef
RASNIK block	rectangular block with either a mask, lens or CCD
Small chambers	muon chambers between large chambers (in angle ϕ)
Superlayer	stack of four layers of tubes, closely glued together
Tower	Assembly of BI, BM and BO chamber whose corners are in line with the IP.
Transfer block	high-precision link between the RASNIK block and the cross plate
TI	Transient Inner chamber
TM	Transient Middle chamber
TO	Transient Outer chamber
Tube unit	a group of tubes, glued together
2D	two-dimensional
3D	three-dimensional

Errors, uncertainties and tolerances

An engineering tolerance is defined as the largest deviation from the ideal value that can be tolerated. It is indicated by '+/-' or 'δ ='. If RMS values are given, it is explicitly noted 'RMS', or the 'σ' sysmbol is used. If to be compared we assume the relation:

$$\delta = 2\ \sigma$$

Coordinate systems

Unless otherwise mentioned, the Chamber Coordinate System is used.
Coordinate systems:

| Abb.	Coordinate system	Coordinates	Origin
CCS	Chamber Coordinate System	X: direction of tubes	Chamber centre
		Y: perp. to ch. plane	
		Z: dir. of cross plates	
TCS	Tower coordinate system	Follows CCS	Origin in BM centre
OCS	Octant Coordinate System	Follows CCS	Origin in IP
ACS	ATLAS (muon) Coor. System	CCS of (top,+Z) OCS	Origin in IP
RCS	RASNIK Coordinate System	X: horiz. of video image	
		Y: vert. of video image	
		Z: optical axis	

1 Introduction
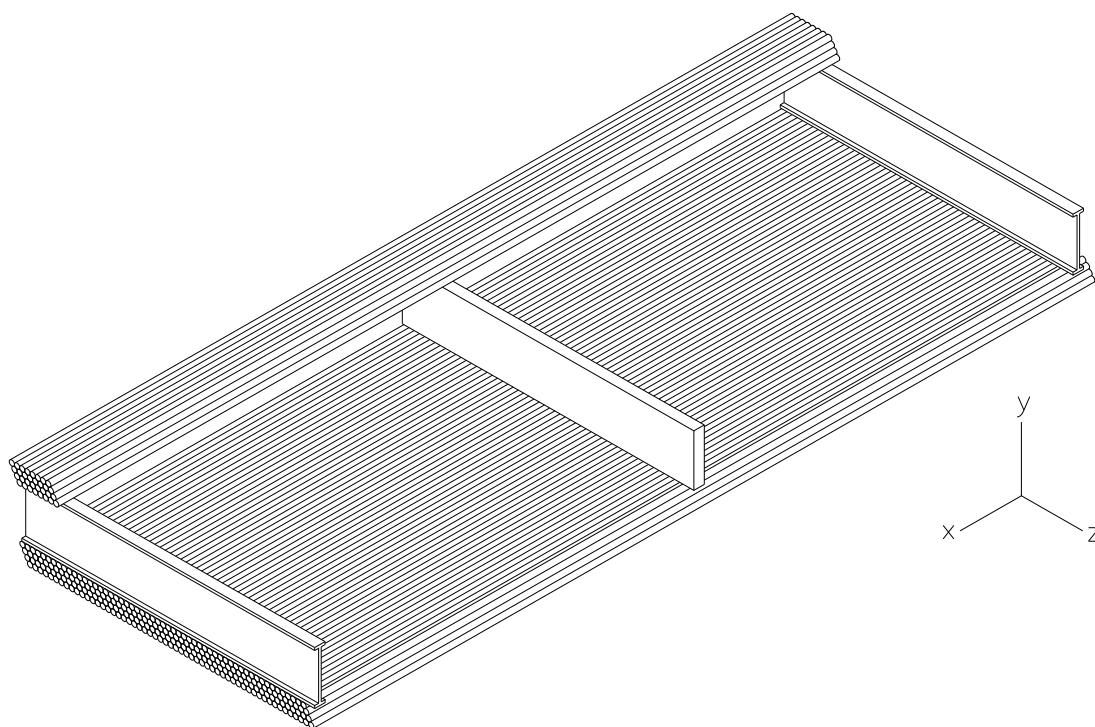
Figure 1: *The assembly of tube units and cross plates*

In order to accurately measure the curvature of high-momentum muon tracks, the relative position in Y and Z of the wires close to stiff tracks should be known to better than 30 μm (RMS). Given the large total volume, the temperature gradients and the fact that the magnet coils which carry the chambers move several mm when activated, the chambers can not be fixed within the required precision in their ideal positions. Instead, their relative position will be monitored continuously [2] [3] [4].

Not only the relative position of chambers within a muon tower is important. Since the chambers are made of aluminium, their thermal expansion may be different in an environment with temperature gradients. Partial displacements due to temperature differences which influence the sagitta should, if possible, be compensated for by the same alignment systems.

In this paper we explain some possible alignment principles. Their mechanical realisation is discussed. The systems are integrated with the central high-precision reference objects of the MDTs: the cross plates (see fig. 1).

It has been shown that the combination of in-plane and projective alignment systems can provide sagitta corrections for chamber displacements, chamber rotations and chamber deformations due to a linear variation of the chamber temperature [5]. Mainly for reasons of redundancy the proximity, axial or praxial systems are added. The pattern recognition procedure may require an additional 'longitudinal' alignment system.

2 Principles of alignment for the barrel chambers

We first distinghuis **local** and **global** alignment. Local alignment systems measure *relative* positions of different chambers or chamber parts, whereas global alignment systems measure the *absolute* position of chambers with respect to the ATLAS Coordinate System. Within local alignment we distinghuis: in-plane, axial, radial, projective, proximity, praxial and longitudinal alignment.
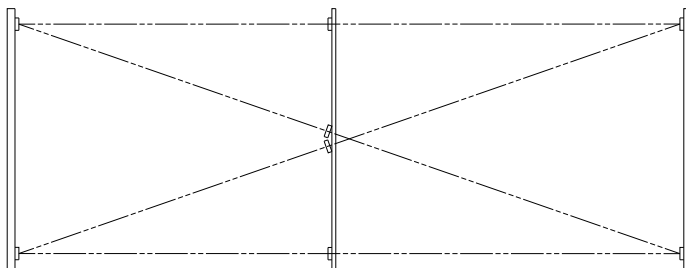

Figure 2: *The in-plane alignment systems. Top view of the chamber cross plates.*

2.1 In-plane alignment

Principle. In-plane alignment systems measure the deformation of individual chambers like sag, torque and, to a certain extend, thermal expansion. Since all wires within a chamber are accurately positioned with respect to the cross plates, it is sufficient to measure the relative positions of the three cross plates within a chamber. This problem has been solved in the muon chambers of L3 [6]. A possible configuration of the in-plane RASNIK alignment systems is shown in fig. 2, using two 'parallel' and two 'diagonal' systems. The edge and the diagonal systems share the same CCDs and mask/light sources. Shifts in the position of the middle cross plate with respect to the outer two is monitored by the two edge systems. The shift in Z of the middle cross is measured twice, while the shift in Y and the rotation over the X axis (the tube direction) follows from the Y values of the edge systems.

The torque of the chamber can be defined as the relative rotation around the X axis of the two outer cross plates. The diagonal systems can monitor this rotation by taking the difference between the two Y values. The average of the Y and Z values of the diagonal systems are also measures for the shifts in Y and Z of the middle cross, thus providing for redundancy in the data. A shift in X of the middle cross plate causes a change in the Z values of the diagonal systems. The correlation between the diagonal Z coordinates and the X (3rd) coordinate of all systems again provides redundancy. The relative rotation of the RASNIK mask with repect to the CCD can be accurately obtained from the image analyses. This

offers an independant 4-fould measurement of the chamber torque. This is of special interest if one of the two CCDs would fail after a period of succesful operation. The consistency of the data is a measure for the errors of the in-plane alignment.

Mechanical realisation. The cross plates can be put in their ideal position on the alignment station (see section 4.1), which can handle the three cross plates of any chamber type. The X, Y and Z (offset) values of the RASNIK systems are read out and stored in a database. Given the large range and excellent linearity, the RASNIK components can be fixed with tolerances of mm onto the cross plates.
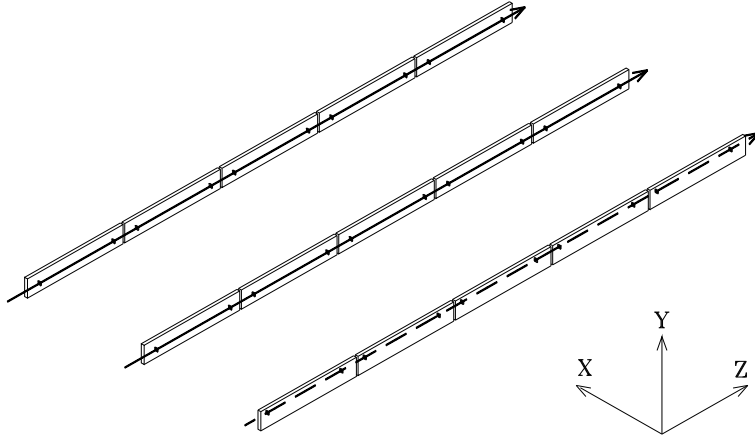
Figure 3: *Axial alignment*

2.2 Axial alignment

Principle. Axial alignment is shown in fig. 3, where only the cross plates of some neighbouring BM chambers in an octant are shown. The axis of an axial alignment system runs parallel to the p-p beam axis. Sensors are positioned at the corners of the chambers: their position is accurately known with respect to the wires of the chamber. Each (large) chamber is crossed by two systems running close and parallel to each of the outer cross plates. The X and Y position of the chamber corners with respect to the axis of the alignment system can be measured. A third system along the middle cross plates could be applied in addition. As a result, the chamber rotations around the X, Y and Z axes can be obtained, as well as chamber translations in the X and Y direction. If 2D alignment systems are applied like the transparent Si diode arrays [8], no Z information is obtained. If the CCD/RASNIK system or the stretched wire system [9] is used, the position of the chambers corners is known in three coordinates, albeit with different accuracy in different directions.

Mechanical realisation.

Axial alignment can be realised by systems which are capable of monitoring the positions of many sensors with respect to one straight reference line. Examples are the transparent Si strip detectors placed in an infra-red laser beam [8], the stretched wire systems [9], and the glass-plate 'light ratio' system with a He-Ne laser [10].

The sensors on the cross plates should be mounted with high precision with respect to the Y reference surfaces for positioning the tube units (see fig. 4). This can be done, for instance, by three precision pins which act as a stop for the piece which carries the sensor. The X position of the piece can be set by a rod (see section 2.4). In turn, the position of the sensor should be known accurately with respect to the surfaces of the block. This can be
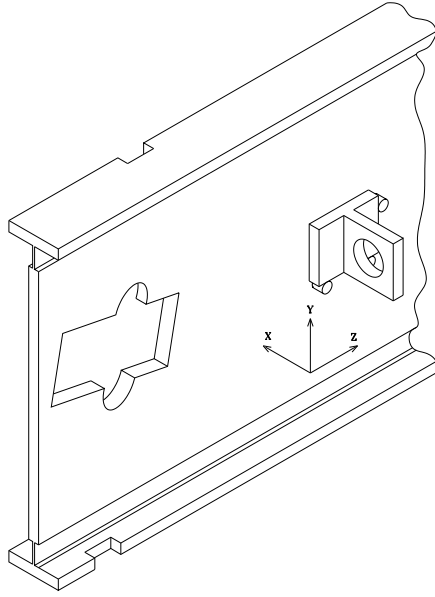
Figure 4: *The mounting of the sensors for axial alignment on the cross plate. The hole for the transfer block (see section 2.4) is also shown.*

realised optically if the Si or stretched wire systems are used. The offsets can be measured and stored in a database.

A total of up to 26 sensors are to be placed in one light beam that crosses all chambers in Z within an octant. In order to minimise lever arms, the sensors should be positioned as near as possible to the centre-line of the cross plate. In the design stage, the effects of rotation of the cross plates around the Z axis should be kept in mind.

Per chamber a third system may run close to the middle cross plate. An octant has therefore six or nine systems. If one system cannot span the entire length in Z (BO: 26 m), a subdivision into more systems is possible. In principle the RASNIK multi-lens system is usable. As an alternative, a chain of 'leapfrog' RASNIK systems can be applied.
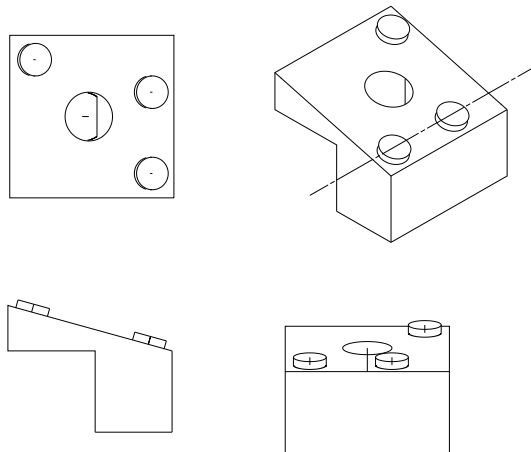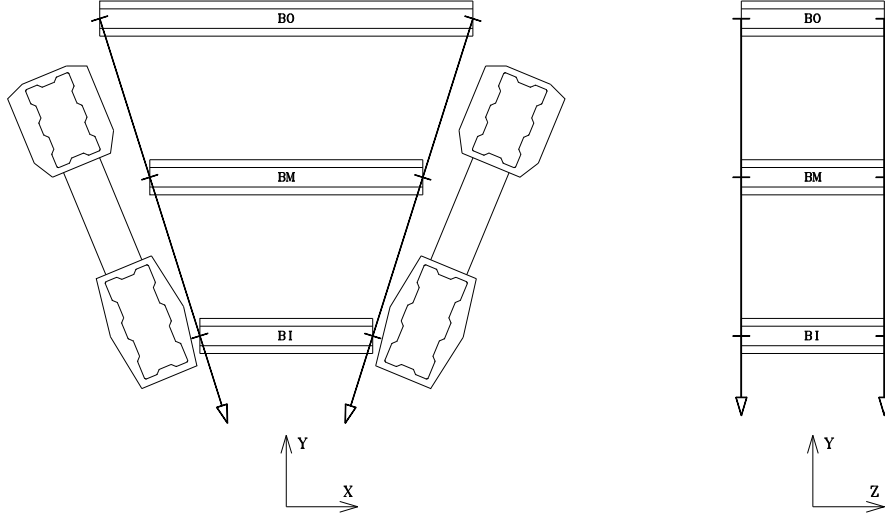

Figure 5: *The transfer block*

Figure 6: *Radial alignment*

2.3 Radial alignment

Principle. The optical axis of a radial alignment system is directed towards the pp beam and makes a 90° angle with it. The four corners of a muon chamber assembly shown in fig. 6 can be equipped with radial alignment systems. As a consequence, the BI, BM and BO chamber have the same dimension in Z. This dimension can be (relatively easily) chosen such that the light beams are not obstructed by construction elements of the magnet cryostat.

Radial 3D alignment systems combined with axial 3D alignment systems provide enough information to apply sagitta corrections if the relative positions of the axes of the systems are known.

Radial alignment is problematic in the region where there is no BI chamber coverage in Z.

Mechanical realisation. The radial alignment systems run (almost) parallel to the nearby coil pancake, thus making an angle ϕ somewhat less than 22.5 ^{o} with the cross plate surface. This can be realised by means of the 'transfer' block and 'RASNIK' block shown in fig. 5 and fig. 7. The transfer block is pressed against three dowel pins, fixed on the cross plate, as shown in fig. 8. These dowel pins are positioned simultaneously with the precision references for the tube units.

On the slanted surface of the transfer block, again three dowel pins are fixed, which define the position of the RASNIK block carrying either a mask, a lens or a CCD. See section 4.2 for the alignment of the RASNIK blocks.

The relevant dimensions of the transfer blocks of one type should be identical within 10 μm (RMS). Their absolute precision is of less importance. The dowel pins on the transfer blocks can be glued in position with a template.

The blocks for the BM chamber have a hole for the passage of the light beam.

2.4 Projective alignment

Principle. The axis of a projective alignment system points towards the interaction point. The alignment systems are placed at the four tower corners. The straightness of a muon track is compared directly with the reading of the alignment systems. By interpolation,
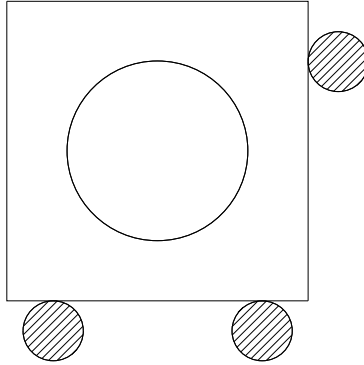
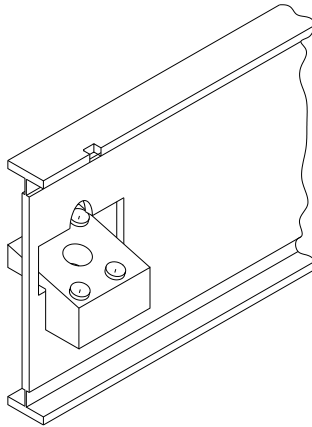Figure 7: *The RASNIK block, positioned by the dowel pins of the transfer block*

Figure 8: *The transfer block for radial alignment systems, mounted on the cross plate*

sagitta corrections can be calculated throughout the muon 'tower' shown in fig. 9. If the 2nd coordinate (X) of the muon track is known with sufficient precision, sagitta corrections are possible throughout the tower.

Mechanical realisation. The mechanics of projective alignment is identical to radial alignment (see section 2.3), except that the transfer block is rotated around the X axis by an angle θ. Three dowel pins at each side of the cross plate define the two θ angles associated with the cross plate. The dowel pins define the position in Y and Z of the transfer block, as well as θ, as is shown in fig. 10. As a consequence, the slanted surface has an angle smaller than 22.5 $^{\circ}$, and depends on θ. The transfer blocks are therefore different for different towers; there are even two types per tower. In total there are 10 different types, and 96 pieces of each type. Blocks of one type need to be identical within 10 μm: their absolute geometry has much larger tolerances. At the slanted side three dowel pins are positioned which define the position of the RASNIK blocks, as described for the radial alignment.

The high precision in both transversal coordinates (< 1 μm) allows freedom of the RASNIK systems in the rotation around the optical axis. This rotation is fixed by the dowel pins on the transfer block. We propose to position the pins such that the RASNIK Y coordinate does not change if chambers are moved in X. As a consequence, the Y vector of the CCD is perpendicular to the wires and the line through the two 'Y' dowel pins of fig. 5 runs parallel to the cross plate.
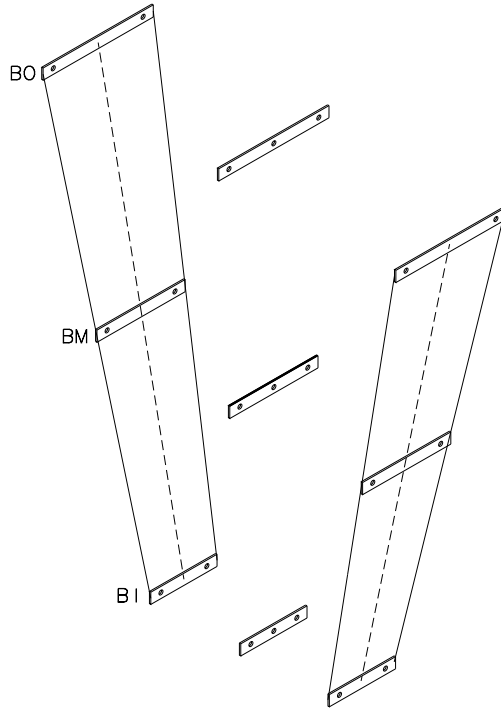
Figure 9: *Projective alignment in the tower geometry*

Fig. 11 shows a side view of the cross plate and the transfer block for the projective alignment. The light beam crosses the cross plate. Locally, some tubes should be shorter in order to create a passage for the light beam. This is the case for the bottom superlayers of the large BM and BO chambers, and for both the superlayers of the BM and BO small chambers. The coverage for muon detection is therefore not affected. A region of 0.6 percent of the solid angle is only covered with a point-angle momentum measurement due to the chamber holes..

If a fifth and a sixth system are added to the tower (see the dotted lines in fig. 12), more redundancy is obtained and the sag of the cross plates (supposed to be less than 10 μm) is verified.

As mentioned before, the Y and Z positions of the transfer blocks is determined by dowel pins on the cross plates. Since the cross plates do not need to be very accurate in X, special care is needed for the X position of the transfer blocks. In practice, the transfer blocks can be simply fixed against the outer cross plates. When mounted in the chamber assembly station, the cross plates are positioned such that the distance in X between two opposite transfer blocks fits the length of a reference rod (see fig. 13).

2.5   Proximity alignment

Principle. By means of proximity alignment systems the distance between the corners of two Z-adjacent chambers is measured. This provides knowledge of the Z coordinates of all the wires. If connected to external references, the proximity systems contribute to global alignment.

Mechanical realisation. Fig. 14 shows a proximity alignment system where RASNIK is used. Due to the short distance between the mask and the CCD, the resolution of the lens
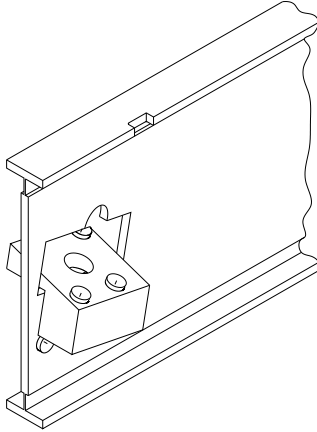
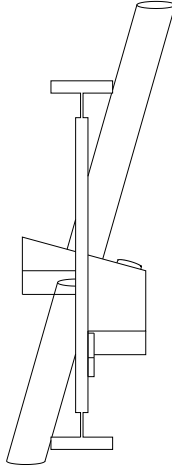Figure 10: *Projective alignment: the transfer block is tilted with angle θ*

Figure 11: *Side view of the cross plate. The shielding tube around the light beam is also shown*

displacement in the direction of the optical axis is about 2 μm. Together with the two transverse coordinates (resolution better than 1 μm), a 3D translation sensor is obtained. As a result, the relative shifts is measured, in 3D, of the two adjacent cross plate corners.

The displacement of the lens in the direction of the optical axis equals the difference of the Y positions of the adjacent chamber corners and would be a verification for Si-based axial alignment systems.

2.6 Praxial alignment

Praxial alignment combines the RASNIK proximity system and a 'local' axial system. It is shown in fig. 15. With this system not only the relative shift of the adjacent cross plate corners is measured, but also the relative rotation around the X and Z axis. The only not-measured parameter of the six parameters describing the relative position of two cross plates is the rotation around the Y axis (the system has its optical axis as a 'pivot'). This parameter is of lesser importance and sufficient information is available from the projective systems.
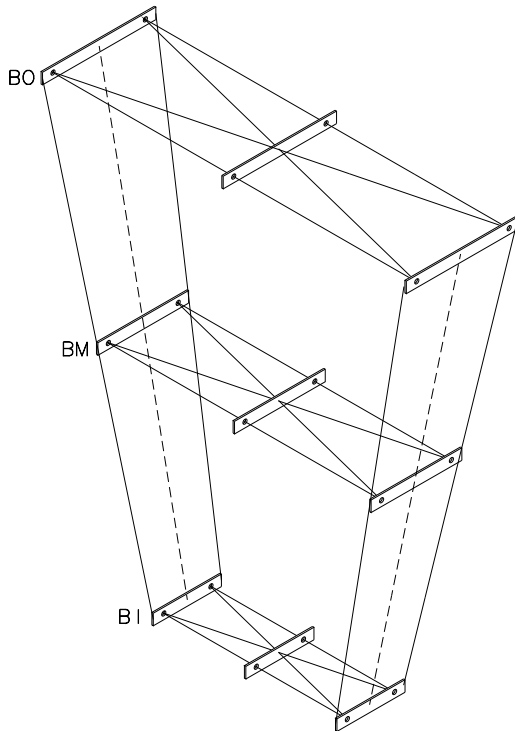
Figure 12: *The in-plane and projective alignment systems of a muon tower*

2.7 Longitudinal alignment

Principle. If, within a muon tower, the BO chamber is shifted in Z and the BI chamber is shifted by a same amount in -Z, no change in any of the alignment systems will occur. This is consistent with the non-sensitivity of the muon sagitta for this particular displacement. The pattern recognition procedure requires, however, knowledge of the relative Z positions of BI and BO. This is due to the fact that tracks are found by extrapolating track segments from BI, through BM, to BO. The road width depends on the uncertainty of the relative Z positions of the BI and BO chambers (BM is linked via projective alignment). A large road width decreases the efficiency of the pattern recognition procedure. The Z alignment between BI and BO should be known to better than 1 mm in order not to reduce the efficiency. Longitudinal alignment can be realised by mounting a RASNIK system between BM and BO, near rapidity 0. Both the mask and lens are mounted on BM, while the CCD is mounted on BO. The relative shift between BM and BO is thus measured.

2.8 Global alignment

By means of global alignment systems the position of muon towers is measured with respect to the outside world (the ATLAS coordinate system). This can be realised by means of a survey of four light sources placed near the outside corners of each BO chamber. Ideally, a total of 80 towers and 320 light sources can be included in the survey. Due to the overlap in the octants, their relative position is accurately known, and therefore the relative positions of the light sources. This information, together with the survey data and data from tracks in the Inner Detector can provide an accurate knowledge of the tower position with respect to external ATLAS survey marks. The light sources are mounted in pieces which can be
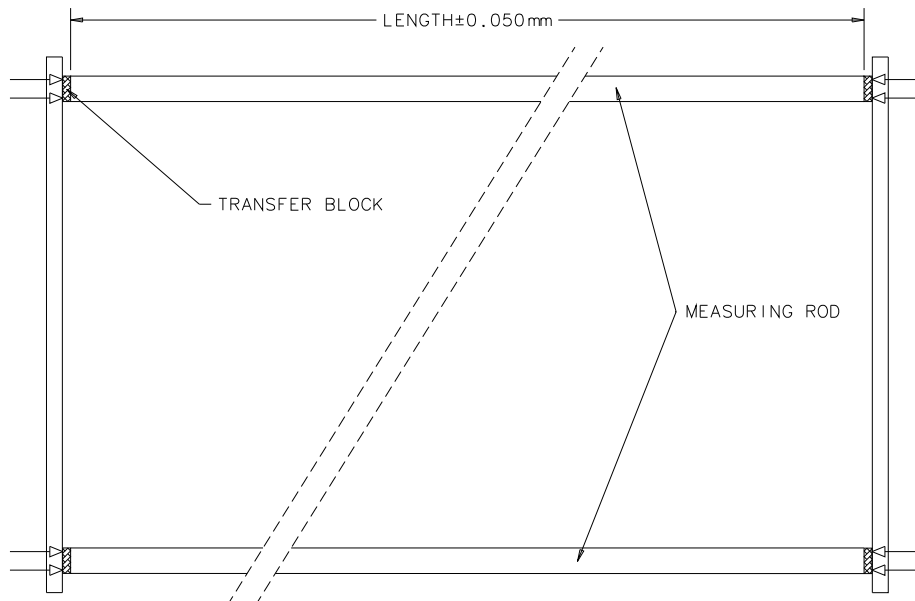
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Figure 13: *Positioning the transfer blocks in X*

accurately positioned, in Y and Z, on the tubes. The X positions of the pieces can be defined by a template. Tolerances in the X, Y and Z positions are in the order of 0.5 mm. Additional global alignment data can be obtained by linking the axial alignment systems to the ATLAS coordinate system. This can be realised by adding axial sensors with well-known positions in the ATLAS coordinate frame.

3   Requirements

In the projective alignment scheme, the chambers are segmented to form projective triplets (towers) which contain the trajectory of high energy muons. An example of chamber seg-
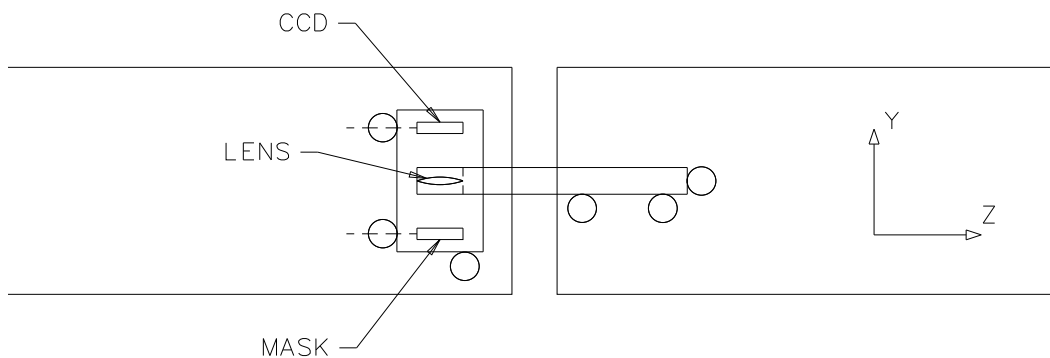

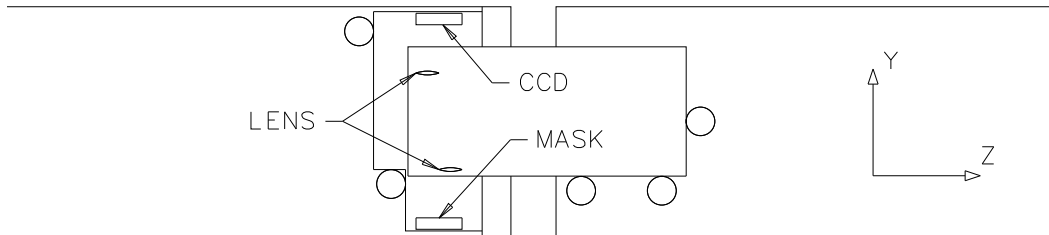Figure 14: *RASNIK as proximity system*

Figure 15: *The double-lens RASNIK praxial system.*

mentation and layout of the light rays is shown on figure 16 for both the barrel and end cap regions.

From the false sagittas observed with the light rays a correction to the measured sagitta of a muon track can be calculated which depends on the track position inside the tower. The ATLAS spectrometer aims at a precision on this correction of better than 30 μm for a magnitude of the chambers displacements of the order of 5 mm in translation and 4 mrad in rotation. It has been shown [5] that, for the barrel part, a projective scheme involving 4 straightness monitors per tower, working in 2 dimensions (along the z and x axis), provides enough information for the sagitta correction. The contributions to the error on this correction are dominated by the uncertainty on the optical sensor positioning (to be better than 20 μm in Y and Z and 100 μm in X) and the departure from the perfect projective geometry. The latter is mainly induced by the finite vertex spread in z ($\sigma_z \sim 50 mm$) and renders the sagitta correction more sensitive to the size of the initial angular displacements. A control of the chamber rotations below the level of 1 mrad would permit positionning tolerances of the order of 10 mm. Such a control could be achieved by a set of at least 2 axial beams per chamber layer running in the z direction which connect the positions of the MDT cross plates. Additional optical sensors accurately placed on radial stiff rods would ensure the relative positionning of the axial beams of different chamber layers.

In the forward region, the projective scheme is not applicable due to the presence of the end cap toroid cryostat. Making use of the 3D measurement capabilities of the RASNIK system, a set of 6 light beams (8 for redundancy) arranged in a non-projective way provides enough information to fully reconstruct the spacial positions of 2 chambers with respect to the third one, used as a reference. For an acceptable sagitta correction, one RASNIK system has to be sensitive to a displacement of the TM/FM chamber along the light beam axis (i.e. the z axis) of the order of $200\mu m$ for a 13 m distance between TI/FI and TO/FO.

As the projective scheme leads to additional constraints on the design of the barrel MDT chambers, alternative approachs involving the crossination of radial and axial system could be considered. So far, none of them has been studied in any detail. The global approach followed by the SDC collaboration [7], based on a crossination of radial RASNIK type systems, Range Only Monitors and proximity sensors, has not yet been shown to provide the accuracy required for the ATLAS spectrometer.

So far only the alignment of the large chambers of the barrel spectrometer has been considered. For the small chambers, the segmentation and therefore the projective light ray locations are imposed by the design of the magnet coil. The struts connecting two neighbouring coils become an obstacle for many of these light rays. In addition, due to the overlap between the small and the large chambers, the passage of the light beams through the large
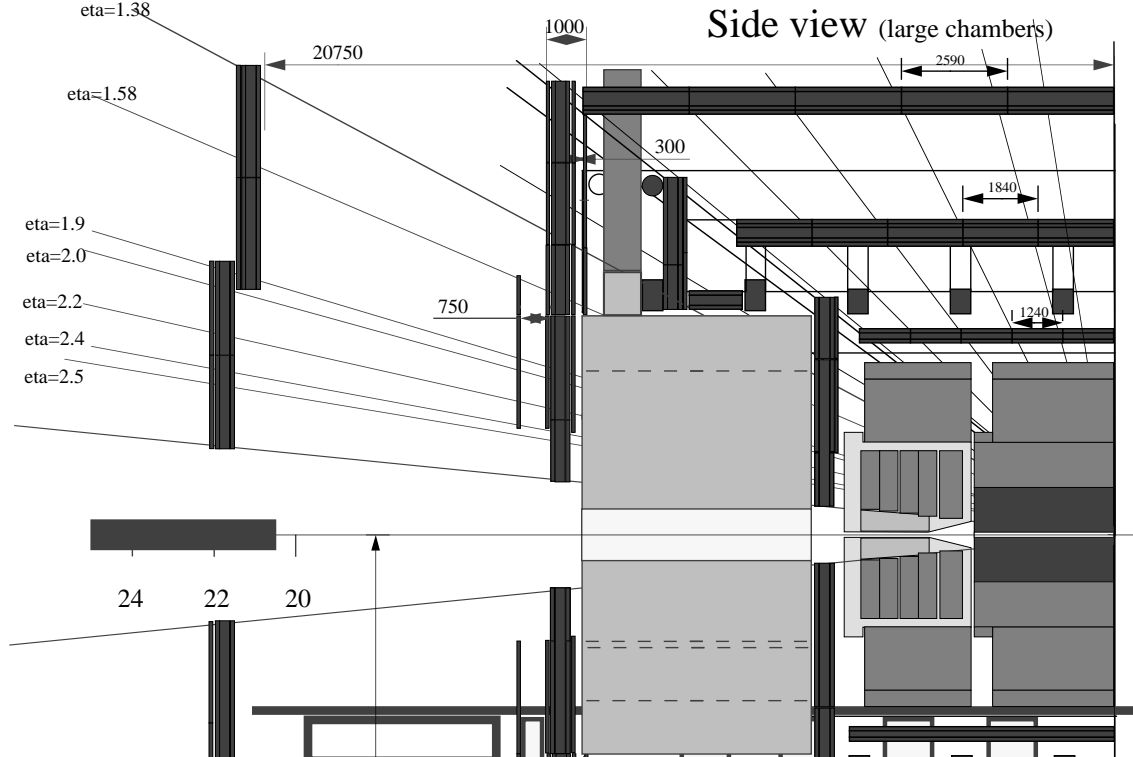
Figure 16: *Layout of the chambers in the r-z plane. It shows the segmentation of the large chambers in the barrel and the trajectories of the light rays: projective in the barrel and non projective in the end caps.*

chambers would lead to unpleasant complications in the MDT design. Due to this over-lap, however, many muons of known momentum (measured in the calibrated towers of large chambers) will be available for the alignment of the towers of small chambers. The imple-mentation of a second set of alignment systems for the towers of small chambers is therefore not necessary.

4 Calibration of offsets: alignment stations

The offsets of the RASNIK blocks are measured in an alignment station as shown in fig. 18. It consists of three position-adjustable supports for the blocks. Each support has six individually adjustable stops which define the position of a block in space. The principle of the alignment procedure is shown in fig. 17. Three gauge blocks, one with a mask, one with a lens and one with a CCD are put on the supports of the alignment station. The mask, lens or CCD are mounted at random on the blocks. After reading the X and Y coordinates of the image on the CCD, all three blocks are put upside down on their supports: the shift of the image on the CCD equals four times the misalignment of the middle support with respect to the outer two [2]. Successive gauge block rotations and adjustments of the position of the supports results in an alignment error of less than a few μm, in both the coordinates perpendicular to the optical axis.
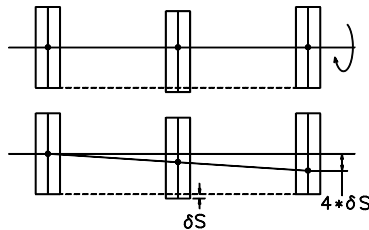
Figure 17: *Principle of the alignment procedure.*

During this alignment procedure one has to take care that the relative rotations of the calibration blocks is small. For the adjustment of the two 'vertical' stops and for the 'bottom longitudinal' stop a bubble level can be applied. For the two 'top longitudinal' stops a crossination of a straight edge and a 90 ^{o} hook can be used.

After the alignment procedure, the alignment station is used for measuring the offsets of mask, lens or CCD RASNIK blocks. For each individual block the (offset) values for the three coordinates of the lens are read out and stored in a database.

We propose to define a set of three RASNIK blocks as 'reference' blocks. For production, the offsets of blocks are measured with respect to these reference blocks. For instance, the offsets of blocks with CCDs are measured using the 'lens' and 'mask' reference blocks. This allows the use of any crossination of CCD, lens or mask block, instead of making sets of three non-separatable blocks.

4.1   The calibration of the cross plates

In fig. 19 the calibration of the in-plane alignment systems is shown. The supports for the cross plates are adjusted by means of three gauge blocks with dimensions close to the size those of a cross plate. If the cross plates are then fixed on the supports, they have their ideal relative position. The offsets of the four RASNIK systems is read out and stored in a database. By defining a set of reference cross plates one can avoid non-separable sets of three plates, as in the case of the RASNIK blocks.

4.2   The calibration of the RASNIK blocks

Ideally, three 'projective' cross plates are put on an alignment station in a similar way as for the in-plane alignment of the cross plates. Given the non-symmetry of the projective cross plates, and their relative displacement in X it is virtually impossible to develop an alignment procedure for a suitable alignment station. The alignment for RASNIK blocks, however, is simple, given their rectangular shape. As a consequence, the RASNIK blocks for the projective alignment need to be positioned with high precision on the cross plates; this in contrast with the in-plane alignment components which can be fixed with a tolerance of mm.

5   The cross plates

The tube units of fig. 1 are mounted on three 'cross plates' (two outer plates and one middle plate; the latter may not be needed for the for the small chambers). The cross plates are
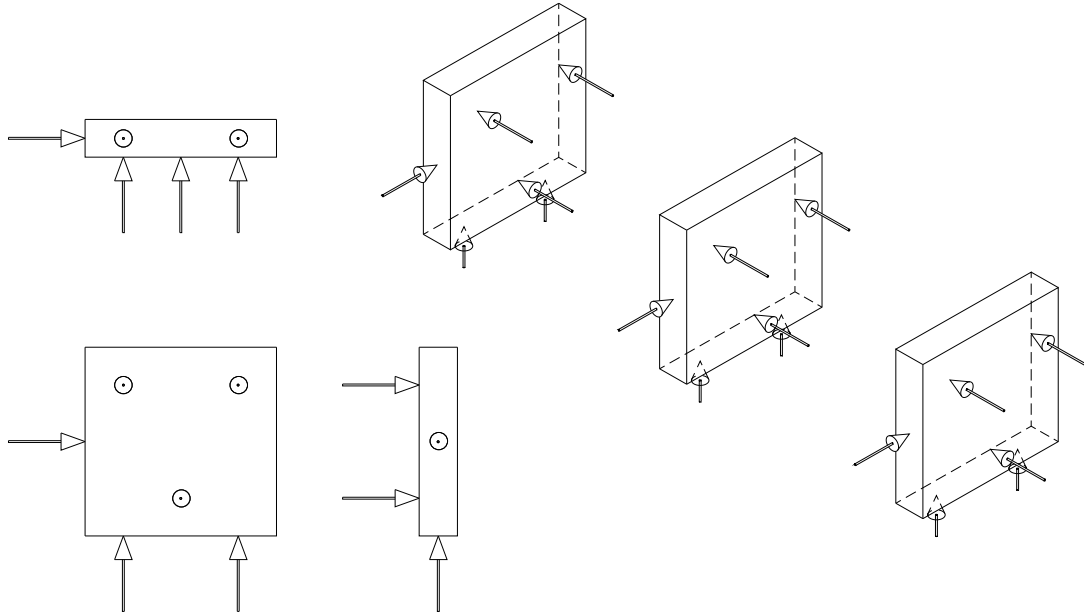
Figure 18: *The principle of the 6-fold supports of an alignment station*

equipped with reference stops and reference planes which accurately define the positions of the tube units in Y and Z.

A concept for the outer cross plates is shown in figure 20. The plates have an I-beam shape; the top and bottom constrictions allow a different thermal expansion of the top and bottom tube units. The middle cross plate has the shape of a box girder and fixes the top and bottom tube units relatively in X.

Given the tolerances of 20 μm in the positions of the references for the tube units and the transfer blocks, it looks attractive to construct the cross plates by means of a template. If made from the same material as the cross plate, the template thermal expansion cancels. Furthermore, the absolute dimensions of the template may vary while the differences between the cross plates can be minimal.

The reference surfaces on the cross plate may well be realised by casting epoxy between the cross plate body and the (mirror image) reference surfaces on the template.

6   Conclusions

The combination of projective alignment and in-plane alignment offers a redundant system which would allow tolerances in chamber positions and rotations up to 15 mm and 2 mrad, respectively. These tolerances can be 'distributed': a larger tolerance in the position requires a smaller tolerance in rotations, and vice-versa.

If proximity systems are applied then the absolute Z positions of the wires are known, greatly contributing to the global alignment and redundancy.

If an BO chamber is rotated around its X axis, and the BI chamber of the same tower is rotated proportionally in the opposite direction then nothing is observed by the projective systems. The sagitta for tracks from the IP are not affected, but an error is introduced for muons which originate away from the IP. The additional information from axial alignment
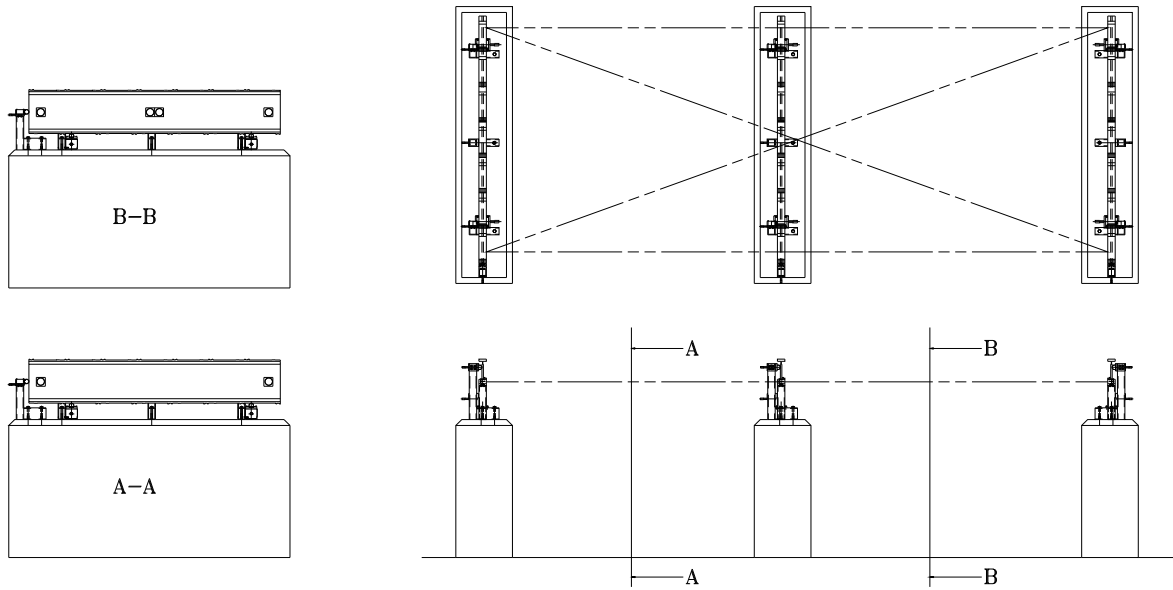
Figure 19: *Alignment station for the cross plates. Typical cross dimensions for the BO chambers are 0.4 x 2.5 m^2*

systems can cancel this error. In addition, axial systems would increase the redundancy.

The proposed integration of the alignment systems on the cross plates minimises errors due to lever arms. The transfer blocks can be placed anywhere in Z on the cross plates: this freedom can be used to choose the Z dimension of the cross plates to minimise the number of different chamber types and/or superlayer tube units. With this schema, the FB chambers closest to the barrel can be equipped with projective systems as well, and an overlap in alignment systems for the barrel and FB chambers can be realised. Furthermore, it allows to use one BI chamber for two muon towers adjacent in Z.

The proposed realisation of the alignment does not require expensive hardware like marble tables or precision equipment.
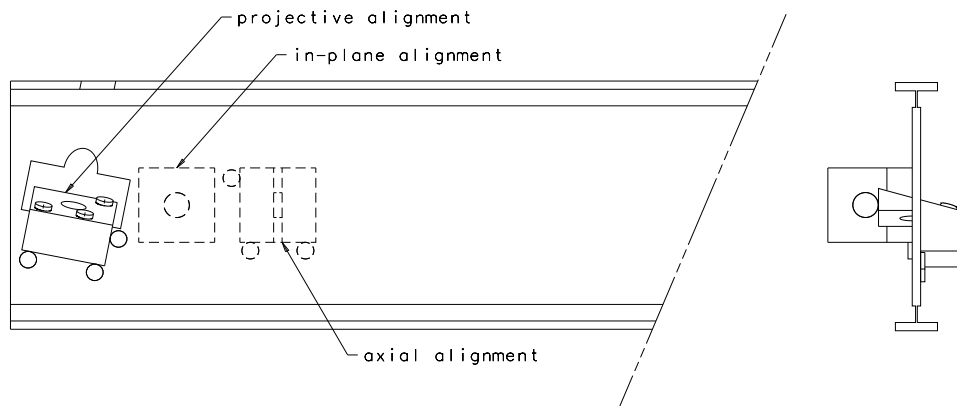

Figure 20: *The outer cross plate*

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We propose therefore to construct a prototype muon tower (DACHA) and to equip this tower with RASNIK in-plane alignment systems, with RASNIK projective alignment systems (4-fold), with RASNIK praxial systems and with Si axial alignment systems.

Projective alignment is not possible for the FB chambers. There, a crossination of 'pseudo' projective and radial alignment is possible according to the same principles as the barrel chambers.

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