

## Dissertation

# The Alignment System of the ATLAS Muon End-Cap Spectrometer

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# Kurzfassung

Der geplante Large Hadron Collider (LHC) am CERN wird die einzigartige Möglichkeit bieten, physikalische Prozesse in einem Energiebereich, der weit über den gegenwärtiger Experimente hinausreicht, zu studieren. Der ATLAS Detektor (eines der beiden Universalexperimente am LHC) wurde entworfen, um das Entdeckungspotential des LHC für „neue Physik“ völlig auszunützen. Eine wesentliche Voraussetzung dafür ist, daß sein Muon-Spektrometer Muonen mit einem Transversalimpuls von  $p_T = 1 \text{ TeV}$  mit einer Impulsauflösung von  $\sim 10\%$  messen kann. Um dies zu erreichen, entschied sich die ATLAS Kollaboration, die Kombination aus Driftkammer-Systemen und einem Magnet-system aus supraleitenden Spulen derart zu optimieren, daß der Gesamtbeitrag zum Meßfehler der Muontrajektorien kleiner als  $30 \mu\text{m}$  r.m.s. sein wird. Diese geforderte Impulsauflösung in dem Meßvolumen von annähernd  $20.000\text{m}^3$  kann nur erreicht werden, wenn die Position jeder einzelnen Driftkammer mittels optischer Systeme laufend vermessen wird. Die im Vorwärtsbereich geforderte absolute Positionsbestimmung der Driftkammern wird durch ein Referenzsystem aus 80, bis zu 9.6 m langen, hochpräzisen Linealen (*Alignment Balken*) erreicht, welche die Position und Orientierung der auf ihnen montierten Sensoren auf  $30 \mu\text{m}$  in Querrichtung,  $20 \mu\text{m}$  in Längsrichtung und mit einer Winkelauflösung von  $50 \mu\text{rad}$  ständig zur Verfügung stellen müssen.

Diese Arbeit beschreibt die Entwicklung des Konzepts und die technische Realisierung dieser Alignment Balken. Nach Motivierung der Anforderungen und einer einleitenden Erklärung der angewendeten Techniken zur globalen Positionsbestimmung, wird die optische und thermische Instrumentierung, sowie das daraus resultierende Design der Alignment Balken vorgestellt. Die Kalibrierung dieser Balkeninstrumentierung, in Verbindung mit der Vermessung der Balkenform mit einer Koordinatenmeßmaschine ermöglicht es, die absolute Formänderung an diskreten Punkten am Balken zu messen. Ein analytisches Modell zur Beschreibung des Balkenverhaltens wird hergeleitet, um die aktuelle Balkenform zwischen den Meßpunkten beschreiben zu können. Die geforderte Präzision der Formbeschreibung wird durch die Einführung *virtueller Kräfte*, die aus den Messungen der Balkeninstrumentierung errechnet werden, erreicht. Die durchgeführten Messungen an 6 gebauten Prototypen und die erreichte Präzision der Bestimmung der Balkenform unter Laborbedingungen werden gezeigt.

Um das Zusammenspiel dieser Balken und die eingangs geforderte Positionierungsgenauigkeit von Kammern zu verifizieren, wurde eine eigenständige Einheit (ein Oktant) des Vorwärtsbereichs des Muonspektrometers aufgebaut und erfolgreich getestet.

Schließlich führte die gewonnene Erfahrung zu einem Entwurf, das die gestellten Anforderungen an die Alignment Balken erfüllt, und zu einem Handbuch, daß die Schritte vom Zusammenbau bis zur Installation im ATLAS Detektor beschreibt.





# Abstract

The Large Hadron Collider at CERN will offer an unparalleled opportunity to probe fundamental physics at an energy scale well beyond that reached by current experiments. The ATLAS detector is being designed to fully exploit the potential of the LHC for revealing new aspects of the fundamental structure of nature.

The muon spectrometer itself must measure with a momentum resolution of  $\sim 10\%$  for muons with a transverse momentum of  $p_T = 1 \text{ TeV}$ , to fully exploit the advantages offered by the open superconducting air core muon toroid magnet system. At this level of momentum resolution the muon spectrometer relies heavily on the ability to master the alignment of the large muon chambers spaced far apart. The overall contribution of the alignment to the total sagitta error must be less than  $30 \mu\text{m}$  r.m.s. In order to meet the stringent alignment requirements the positions of the muon chambers are constantly monitored with optical alignment technologies. The end-caps of this spectrometer are therefore embedded in an alignment grid that must allow for an absolute position measurement of the chambers. This alignment grid employs up to 9.6 m long precision rulers (alignment bars) which have to provide the position and orientation of all alignment sensors permeating the end-caps. Simulation studies have shown that the shape of these bars must be known to  $30 \mu\text{m}$  r.m.s. and the length must be known to  $20 \mu\text{m}$  r.m.s.

The principles of alignment and survey techniques used to do this are introduced and the current activities concerning the alignment strategy for the ATLAS muon end-cap spectrometer are presented. After consideration of the motivation and requirements, the measurement strategy and the design of the alignment bars is given. An optical and thermal in-bar instrumentation is used to provide shape information of discrete points on the bar. The strategy to calibrate the in-bar instrumentation and to measure an initial bar shape with a large coordinate measuring machine, leads to the analytic shape model that allows to interpolate between the discrete number of measured points to describe any other bar shape. Expressing these changes with *virtual loads* that account for all forces acting on the bar, finally leads to the required precision. The basic principles are explained and detailed design and test results are presented.

As part of the process one octant, the smallest independent unit of the end-cap alignment system, has been erected in the H8 test beam area to evaluate the systems performance of the proposed alignment strategy. Measurements are presently carried out with this prototype setup and initial results will be presented.

Finally, work done during the development of the alignment bars led to a proposal for the final ATLAS alignment bars and to a manual describing the process from assembling until installation.



# Acknowledgements

It is a pleasure to be able to thank the many people who have helped to make the last three years so enjoyable and rewarding. First and foremost, I would like to thank Chris Fabjan, my supervisor and former group leader, for his continuous support and guiding my studies with precision and enthusiasm. He is an enormous source of encouragement and motivation.

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Thanks to Thomas, Werner, Edda, Harald, Sabine, Stefan, Karsten and all the others of the ~Austrian “Mittagsrunde” for making lunch time so enjoyable and relaxing.

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To Simone.



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# Chapter 1

## Introduction

### 1.1 The Standard Model

The experimental discoveries and theoretical developments of the last 50 years have led to the development of the Standard Model of particle physics. The uniting principle of modern fundamental physics is that of symmetry. In addition to the familiar space-time symmetries and discrete symmetries, it appears that Nature exhibits local gauge symmetries. There exists a deep connection between local gauge symmetries and physical interactions: the phase variation permitted by local symmetry is reconciled by a field which is considered to be the mediator of interactions between matter particles. The Standard Model is a gauge field theory with local gauge invariance. It describes all of the known fundamental particles and their interactions via three of the four known forces of nature: electromagnetism, the weak force and the strong force. Gravity is by far the weakest of the four forces, and is not described within Standard Model.

There are three types of particle described in the Standard Model: spin- $\frac{1}{2}$  fermions (matter particles), spin-1 gauge bosons (which mediate interactions between matter particles), and a spin-0 Higgs boson (which is a consequence of spontaneous symmetry breaking; [HIG:64]). The up and down quarks, the electron, and the electron neutrino are all that is needed to make up normal matter. For reasons unknown, this pattern is repeated three times, that is, for three “generations”, each generation containing two quarks, a lepton and a neutrino (see Table 1.1).

| gen 1                                        | gen 2                                            | gen 3                                              | T    | T <sup>3</sup>                                       | Y    | Q                                                    |
|----------------------------------------------|--------------------------------------------------|----------------------------------------------------|------|------------------------------------------------------|------|------------------------------------------------------|
| $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$ | $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$ | $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$ | +1/2 | $\begin{smallmatrix} +1/2 \\ -1/2 \end{smallmatrix}$ | -1   | $\begin{smallmatrix} 0 \\ -1 \end{smallmatrix}$      |
| $e_R$                                        | $\mu_R$                                          | $\tau_R$                                           | 0    | 0                                                    | -2   | -1                                                   |
| $\begin{pmatrix} u \\ d' \end{pmatrix}_L$    | $\begin{pmatrix} c \\ s' \end{pmatrix}_L$        | $\begin{pmatrix} t \\ b' \end{pmatrix}_L$          | +1/2 | $\begin{smallmatrix} +1/2 \\ -1/2 \end{smallmatrix}$ | +1/3 | $\begin{smallmatrix} +2/3 \\ -1/3 \end{smallmatrix}$ |
| $u_R$                                        | $c_R$                                            | $t_R$                                              | 0    | 0                                                    | +4/3 | +2/3                                                 |
| $d'_R$                                       | $s'_R$                                           | $b'_R$                                             | 0    | 0                                                    | -2/3 | -1/3                                                 |

**Table 1.1:** Fermion multiplet assignments and quantum numbers T (weak isospin), T<sup>3</sup> (third component of weak isospin), Y (hypercharge) and Q (electric charge).

The electromagnetic force is described in extremely good agreement with experiment by quantum electrodynamics (QED), a gauge field theory with local gauge invariance. It describes the interaction between particles carrying electric charge via a massless spin-1 gauge boson – the photon.

The electromagnetic and weak forces are described in the Standard Model in the “unified” framework of the electroweak model. Experimental evidence suggested that the weak force should be mediated by three massive vector bosons  $W^\pm$  and  $Z^0$ . One of the major stumbling-blocks in the development of a field theory description of the weak force was a way of permitting the gauge bosons to be massive, but also maintaining the renormalisability essential for a predictive theory. The only known solution to this problem is the so-called Higgs mechanism (one massive scalar particle, whose mass is not specified in the theory).

The strong force is described in the Standard Model by quantum chromodynamics (QCD), a gauge field theory with unbroken local symmetry. There are eight gauge bosons (gluons) which mediate the interactions of particles carrying a quantum number, known as color. The quarks have three possible color states and the gluons have eight. At high energy scales (and hence smaller distances), the strong force becomes weaker (“asymptotically free”). Conversely, at lower energies (and hence longer length scales), the force between particles becomes stronger, which may explain the fact that colored objects have not been observed in isolation. It is suspected that this so-called “color confinement” is exhibited by QCD.

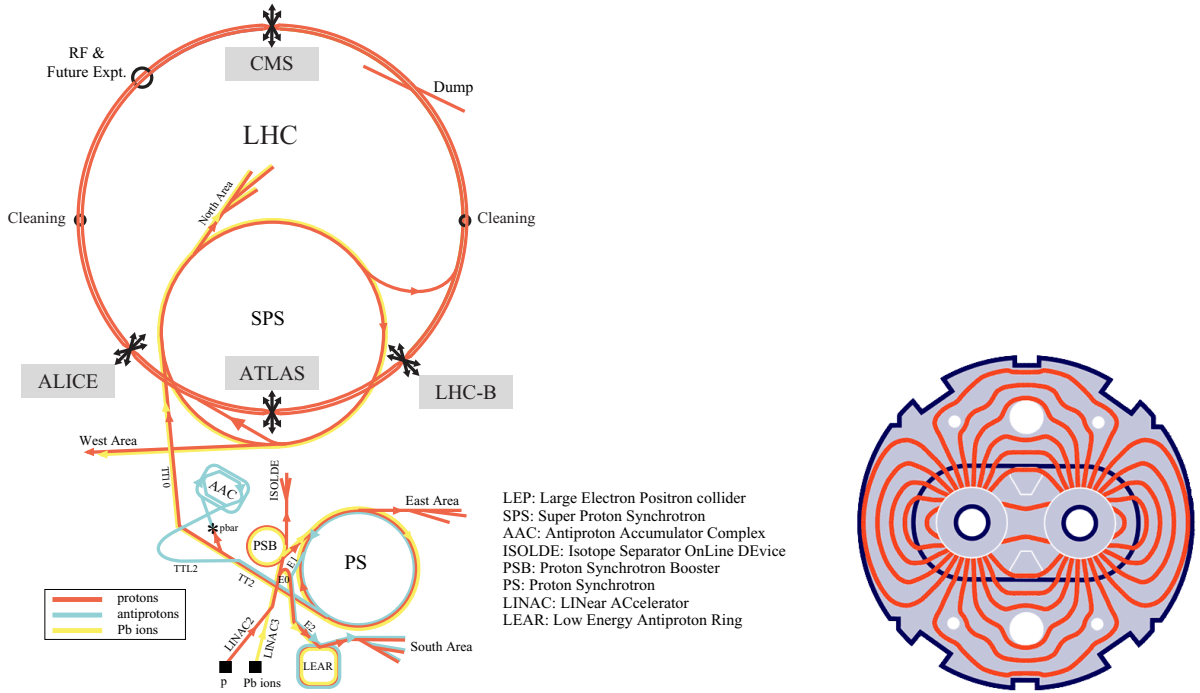
At the time of writing, no experimental result has been conclusively shown to disagree with the predictions of the Standard Model. There is perhaps one exception the indication of neutrino masses which are not part of the model and would require an extension. The most significant confirmation of the approach taken in the Standard Model is surely the discovery in 1984 of the  $W^\pm$  and  $Z^0$  at the expected masses. The top quark was discovered 1995, leaving the Higgs boson as the only remaining particle of the Standard Model which has not been found. Resolution of the puzzle of electroweak symmetry breaking is currently one of the most burning issues in High-Energy Physics, and is one of the main reasons for constructing the Large Hadron Collider.

## 1.2 The Large Hadron Collider

In December 1994, delegates representing the 19 member states of CERN [CE] unanimously approved a resolution permitting the construction of the Large Hadron Collider (LHC), [JAR:90]. The LHC, a high-luminosity proton-proton collider constructed from more than thousand superconducting magnets, will be installed in CERN’s existing 27-kilometer circular tunnel built for the Large Electron-Positron (LEP) collider. It will allow to explore particle physics up to energies that dominated the universe only  $10^{-12}$  seconds after the Big Bang, when the whole universe was not bigger than a pin-head and the temperature was about  $10^{16}$  K.

### 1.2.1 Design Parameters of the LHC

The LHC will be a  $p\bar{p}$  collider with a center of mass energy  $\sqrt{s}$  of 14 TeV and a design luminosity of  $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . In order to achieve the requirements within the constraint of the 27 km circumference LEP tunnel, the magnet system consisting of 1232 dipole magnets with a strength of 8.4 T, must operate in superfluid helium at temperatures below 2 K. The magnetic channels will be housed in the same yoke and cryostat, a unique configuration that not only saves space but also gives a 25% cost saving compared to two separate rings (Figure 1.1-right).



**Figure 1.1:** *left:* schematic view of the CERN accelerator complex; *right:* illustration of the cross-section of the magnetic channels for LHC.

The LHC will be filled with protons delivered from the SPS and its pre-accelerators at 450 GeV. Two superconducting magnet channels will accelerate protons to 7-on-7 TeV, after which the beams will counter-rotate for several hours, colliding at the experiments, until the beam degradation is such that the machine has to be emptied and refilled.

At the interaction points, the bunches will have a transverse radius of  $16 \mu\text{m}$  and the length of the bunch will be 30 cm. This means that the position of the vertex has a rather large spread of  $\sim 5.5 \text{ cm}$  r.m.s. along the beam direction.

## 1.3 Physics at LHC

Since one of the prime reasons for building the LHC is to solve the puzzle of the electroweak symmetry breaking, considerable attention has been paid during the design pro-

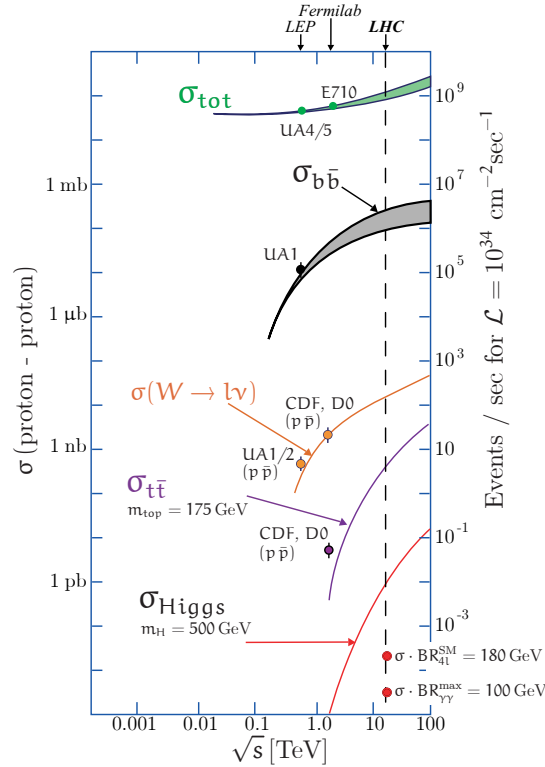
cess to the sensitivity of Higgs signatures. The LHC is designed to explore all the range of “allowed” Higgs masses and more, hence the planned experiments either must find the Higgs boson or contradict the Standard Model. In this Section the Higgs production and decay channels for the whole range of Higgs masses will be discussed.

At the LHC heavy fermions (bottom and top-quarks) will be produced in large quantities. Hence, beside the Higgs search also B physics as well as the study of top-quark production and decay will be interesting issues for the LHC physics program.

All these examples for LHC physics are used as benchmark processes for the detector design. In this Section these benchmark processes and their impact on the design of the four LHC detectors will be discussed briefly.

### 1.3.1 Particle Production Rates

In Figure 1.3 some important production cross sections and interaction rates are shown as a function of the center of mass energy  $\sqrt{s}$ . The total cross section is estimated to be between 90 and 130 mb. This means that on average there will be about 20 interactions in the center of the detectors per bunch crossing at full luminosity. Small-angle elastic and inelastic proton-proton scattering will be the most numerous and hence dominate the 20 underlying events per bunch crossing.

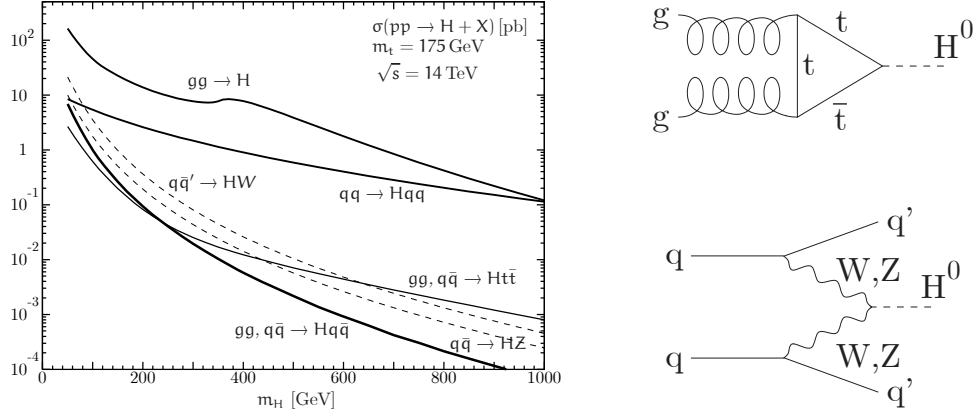


**Figure 1.2:** The cross-section of some characteristic processes [JAR:90], [ZÜR:00]. The center of mass energy of LHC is indicated at the top. At  $\sqrt{s} = 14 \text{ TeV}$  the production of the Higgs is eleven orders of magnitude less frequent than small-angle p p scattering.

## Higgs Production

Assuming a Higgs mass of 500 GeV, the production cross section of the Higgs will be typically 1 pb. This corresponds to  $10^5$  produced Higgs bosons per year (or 1 Higgs boson every 2 minutes). The cross section increases rapidly for a low mass Higgs.

The most dominant production mechanisms are the gluon-gluon fusion and the  $WW$  ( $ZZ$ ) fusion. Figure 1.3-right shows the Feynman diagrams for these two processes. Less important production channels are  $t\bar{t}$  fusion and  $W$  or  $Z$  Bremsstrahlung [JAR:90].



**Figure 1.3:** *left:* Higgs boson production cross sections at the LHC for the various mechanisms as function of the Higgs mass [DJO:02]; *right:* the most dominant channels for the Higgs production; *top:* gluon-gluon fusion; *bottom:*  $WW$  and  $ZZ$  fusion.

## Higgs Decay

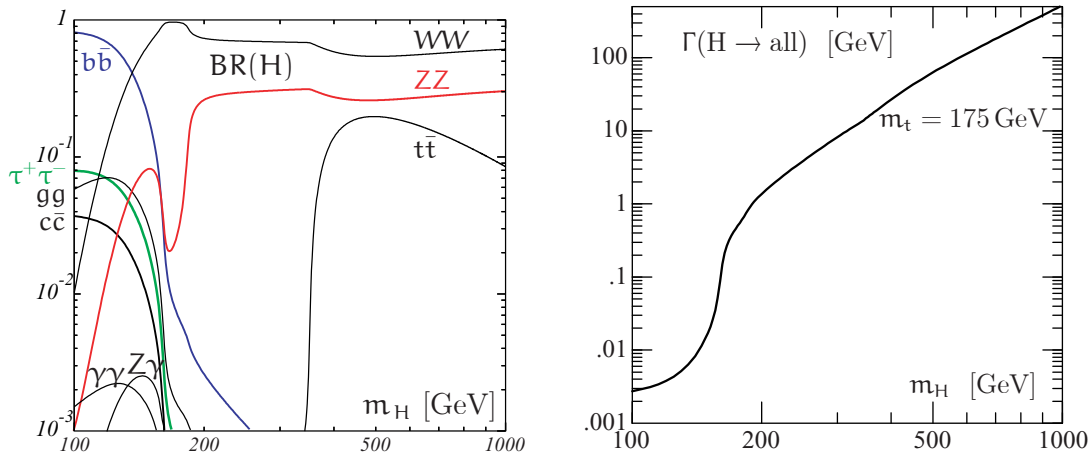
In Figure 1.4-left the branching ratios are shown as a function of Higgs masses for a range between 100 and 1000 GeV. Only a few decay channels of the Higgs boson are accessible to experimental observation since most of the decay channels have either small branching ratios or are obscured by a large background of events. Statistics will be the limiting factor in the detection of the Higgs boson, in particular for Higgs masses approaching 1 TeV.

### 1.3.2 Higgs Search

The most prominent benchmark processes for the detector design at LHC are the different Higgs decay channels for the Higgs mass range from 80 GeV to 1 TeV. (The only current available information on the Higgs mass is the lower limit  $m_H > 114.1$  GeV established at the upgraded LEP2 [LE:01].) The significance of Higgs signals expected for ATLAS is shown in Figure 1.5.

- **Low Mass ( $80 \text{ GeV} < m_H < 120 \text{ GeV}$ ):**

For a Standard Model Higgs boson in this mass range, the decay modes important



**Figure 1.4:** Decay branching ratios (*left*) and total decay with (*right*) of the Standard Model Higgs boson as a function of its mass [DJO:02].

for discovery are  $H \rightarrow \gamma\gamma$  and  $H \rightarrow b\bar{b}$ .

$H \rightarrow \gamma\gamma$  places severe demands on the performance of the electromagnetic calorimeter. Excellent energy and angular resolution will be required to observe the narrow peak above the irreducible prompt  $\gamma\gamma$  continuum. Powerful particle identification capability will be needed to reject the large jet background and, for  $m_H \sim m_Z$ , the potentially dangerous resonant background from  $Z \rightarrow e^+e^-$  processes. For a SM Higgs boson in the mass region below the threshold for  $H \rightarrow WW$  and  $H \rightarrow ZZ$ , the branching ratio for  $H \rightarrow b\bar{b}$  is essentially 100% (see Figure 1.4-left), since in this scenario the b-quark is the heaviest accessible particle.

The first years of running at low luminosity will not be sufficient for statistically significant discovery in any single channel.

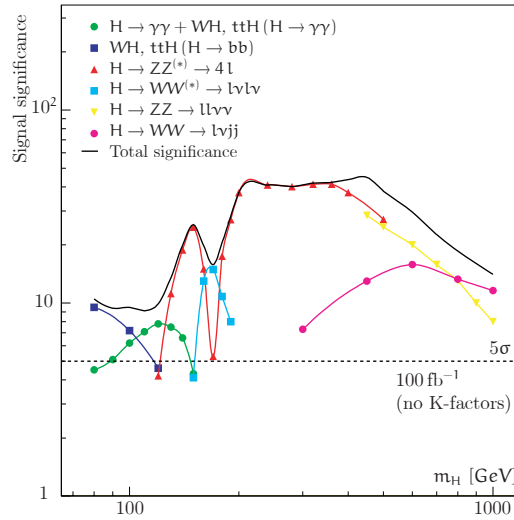
- **Intermediate Mass ( $120 \text{ GeV} < m_H < 800 \text{ GeV}$ ):**

In this mass region the decay  $H \rightarrow ZZ^{(*)} \rightarrow l^+l^-l^+l^-$  provides a very clean signature of a Higgs boson. For the range  $m_H < 2m_Z$  (i.e. below 180 GeV) one of the two Z bosons is virtual. For a Higgs mass of 150 GeV one expects  $\sim 550$  such events per year. The four leptons have a high transverse momentum ( $5 \text{ GeV} < p_T < 50 \text{ GeV}$ ). The natural Higgs width  $\Gamma_H$  is small in this regime (see Figure 1.4-left) and the background is mainly coming from prompt muons, decay muons, hadronic punch-through, neutrons and muon-induced electromagnetic secondaries. To achieve a good acceptance for such kind of events, the geometrical and kinematic acceptance for leptons has to be optimized, and the significance of the signal will depend on the four-lepton mass resolution.

- **High Mass ( $m_H > 800 \text{ GeV}$ ):**

For a heavy Higgs boson the channel  $H \rightarrow ZZ \rightarrow l^+l^-\nu\bar{\nu}$  becomes six times more frequent than  $H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$  but cannot be completely reconstructed because of the escaping neutrinos. Also the channels  $H \rightarrow WW$ ,  $ZZ \rightarrow l^\pm\nu 2\text{jets}$ ,  $2l^\pm 2\text{jets}$  provide promising signatures for a heavy Higgs boson.





**Figure 1.5:** Significance for the Standard Model Higgs boson discovery in various channels at the LHC with high luminosity [JAC:00]

- **SUSY Higgs:**

In the Minimal Supersymmetric Extension of the Standard Model (MSSM), two Higgs doublets are required, resulting in five physical states. This physical particle spectrum contains charged Higgs bosons ( $H^\pm$ ), two neutral scalars ( $h$ ,  $H$ ) and one pseudoscalar ( $A$ ). The mass of the lightest of these scalars depends upon the top quark mass, the ratio of the vacuum expectation rates  $v_2/v_1 \equiv \tan \beta$ , and the masses of other supersymmetric particles. The MSSM Higgs searches require efficient secondary vertex detection for  $\tau$ -leptons and  $b$ -quarks as well as high resolution calorimetry for jets and missing transverse energy.

- **Strongly interacting Higgs:**

A Higgs of high mass  $m_H > 1 \text{ TeV}$  is very broad and leads to strong scattering of gauge boson pairs.

### 1.3.3 Other Proton-Proton Physics Issues

This section is intended to give some further examples of benchmark processes that had an impact on the detector design besides the Higgs search.

#### Supersymmetric Searches

If **SU**per**SY**mmetric (SUSY) particles exist, they will be produced and detected at the LHC for masses up to 2 TeV. The lightest SUSY particle is stable, but hardly interacting with matter. Hence the search for super-symmetric particles sets stringent requirements on the hermeticity of the detector.

## Top-quark Physics

The LHC will provide a large number of top quarks. The  $t\bar{t}$  cross section will be about 1 nb (see Figure 1.2). This high statistics of top-quarks will allow to obtain a top mass resolution limited merely by theoretical uncertainties rather than statistics. Furthermore it will be possible to study the top decay channels in detail, such as  $t \rightarrow bH^+$  or  $t \rightarrow Zc$ .

## B-Physics

The very large cross-section for b-quark at the LHC will allow a wide range of precision measurements performed in the rich field of B-Physics. The ATLAS program will include studies of CP violation using the decays  $B_d \rightarrow J/\Psi K_s$ ,  $B_d \rightarrow \pi\pi$ , and  $B_s \rightarrow J/\Psi \Phi$ . Other topics are the measurement of  $B_s$  mixing, searches for rare decays such as  $B_d \rightarrow \mu\mu$  and  $B_s \rightarrow \mu\mu$ , the study of B-baryon decay dynamics and spectroscopy of rare B hadrons.

B-Physics will be experimentally easiest during the first few years of LHC operation when the luminosity will be low and hence the effect of pile-up will be reduced. The vertex detector, located close to the beam axis, is expected to survive this initial phase.

## Other Searches

New heavy gauge bosons  $W'$  and  $Z'$  could be accessible to the LHC for masses up to 5–6 TeV. Therefore high resolution lepton measurement and charge identification are needed even in a  $p_T$  range up to a few TeV.

Also searches for leptoquarks and investigations of quark and lepton compositeness will be performed at LHC.

### 1.3.4 Experiments at LHC

In order to exploit the full discovery potential of LHC, two general-purpose proton-proton experiments (ATLAS and CMS) and two specialized experiments (ALICE and LHCb) will be installed at the four interaction points (see Figure 1.1).

The main difference between the two general-purpose experiments lies in their magnet configurations for muon spectroscopy. The choice of the magnet system strongly influences the geometry of the detector.

- **ATLAS:**

The ATLAS (**A** Toroidal LHC Apparatu**S**, [ATL:94], [TDR:97]) experiment is characterized by the following magnet configuration: A super-conducting solenoid will be installed around the inner detector, and large super-conducting air-core toroids consisting of independent coils will be arranged outside the calorimetry. This concept makes almost no constraints on calorimetry and inner detector, allowing noncompromised technological solutions and a high-resolution, large-acceptance and robust muon spectrometer with excellent stand-alone capabilities.

The ATLAS experiment will be explained in greater detail in the next section.

- **CMS:**

The CMS (Compact Muon Solenoid, [CMS:94]) experiment is based on a single, large, super-conducting solenoidal magnet (14m long and 3m inner radius) generating a uniform magnetic field of 4T. The choice of a strong field leads to a compact design for the muon spectrometer without compromising the momentum resolution when combining information from muon system and inner detector.

CMS will be 14 m high, 20 m long, and will have a weight of  $\sim 12000$  tons.

- **ALICE:**

The existing L3 detector will be converted into the ALICE (A Large Ion Collider Experiment, [ALI:95]) experiment to investigate Pb-Pb collisions. This heavy-ion detector will be used to study physics of strongly interacting matter at extreme energy densities.

- **LHCb:**

This dedicated B physics experiment [LHC:98] at the LHC will be built in the DELPHI pit. It is an open-geometry single-arm forward collider detector which is designed to fully exploit the B physics potential of the LHC. The large Lorentz boost of accepted B-mesons allows precise decay-time measurements, which are complemented by excellent particle identification and efficient muon triggers.

## 1.4 The ATLAS Detector

The ATLAS collaboration proposed to build a general-purpose proton-proton detector designed to exploit the full discovery potential of the LHC [ATL:94]. The collaboration submitted a Letter of Intent in 1992, a Technical Proposal in 1994 and Technical Design Reports for each of the subsystems including most of the final specifications. Construction started in 1998 and the experiment should be mostly ready for the start of LHC; staging scenarios for some detector components are under discussion.

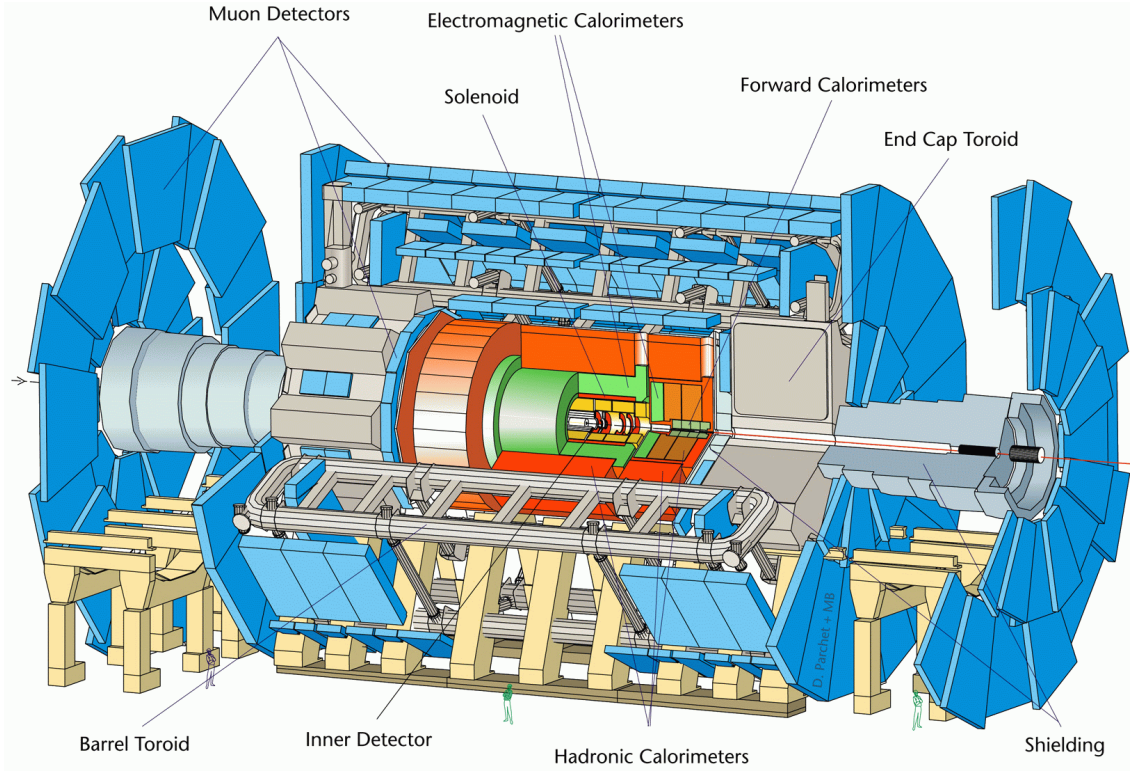
As pointed out in Section 1.3, many of the interesting physics questions at the LHC require high luminosity. A variety of signatures is important to achieve robust and redundant physics measurements allowing for internal cross checks. The goal of exploiting the full physics potential of LHC and the requirements introduced in Section 1.3 lead to the following basic design considerations:

- very good electromagnetic calorimetry for electron and photon identification and measurements, complemented by hermetic jet and missing  $E_T$  calorimetry;
- efficient tracking at high luminosity for lepton momentum measurements, for b-quark tagging, and for reliable electron- photon-separation, as well as  $\tau$  and heavy-flavor vertexing and reconstruction capability of some B decay final states at lower luminosity;
- stand-alone, precision muon momentum measurements up to the highest luminosities, and very low  $p_T$  trigger capability at low luminosity;

- large acceptance and maximum  $\eta$ <sup>1</sup> coverage.

### 1.4.1 Overall Detector Concept

Figure 1.6 shows a 3-D view of the design of the whole ATLAS detector. The geometry is the familiar tracker-calorimeter-muon chamber onion skin configuration.



**Figure 1.6:** 3D view of the ATLAS detector.

The layout is largely determined by the configurations of the magnetic fields. A superconducting solenoid surrounds the inner tracking cavity. On the outside of this is the calorimeter which is itself surrounded by superconducting air-core toroids consisting of independent coils with eight-fold  $\phi$ -symmetry. This magnet configuration makes it possible to build a high-resolution, large-acceptance, robust stand-alone Muon Spectrometer with minimal constraints on the calorimeter and Inner Detector.

The Inner Detector is contained within a cylinder of 6.8 m length and 1.15 m radius and is surrounded by a solenoid providing a 2 T magnetic field parallel to the beam axis. High performance pattern recognition, momentum and vertex measurements, and enhanced electron identification are achieved by combining “discrete” high-resolution pixel and strip detectors in the part of the tracking volume closest to the interaction point with “continuous” straw-tube tracking with transition radiation capability in the outer part.

<sup>1</sup>The pseudo rapidity  $\eta$  is defined as  $\eta \equiv -\ln \tan(\theta/2)$ , where  $\theta$  is the polar angle with respect to the beam line.

Highly granular liquid argon (LAr) electromagnetic sampling calorimetry is employed in the pseudorapidity range  $|\eta| < 3.2$ . This will give excellent performance in terms of energy and position resolutions. The LAr technology is also used for the end-cap hadronic calorimeter, sharing cryostats with the electromagnetic end-cap calorimeter. The same end-cap cryostats also house the LAr forward calorimeters which cover the pseudorapidity range  $3.2 < |\eta| < 4.9$ . The LAr calorimetry is contained in a cylinder with an outer radius of 2.25 m and extends to 6.65 m along the beam axis. The hadronic calorimetry is based on a scintillating tile technique and is situated in a cylinder outside the LAr cryostats, extending to an outer radius of 4.25 m and a length of 6.10 m. It is divided into a barrel cylinder and two “extended barrel” cylinders. The total weight of the calorimeter system, including the solenoid flux return iron yoke, which is integrated into the tile calorimeter support structure, is about 4000 tons.

The Muon Spectrometer surrounds the calorimeters. The air-core toroid system, with a long barrel and two inserted end-cap magnets, generates a large field volume and strong bending power with a light and open structure. Multiple scattering effects are therefore minimal, and an excellent muon momentum resolution is achieved with three stations of high-precision tracking chambers. For triggering, the muon instrumentation is equipped with fast resistive plate chambers (RPCs).

The overall dimensions of the ATLAS detector are defined by the Muon Spectrometer. The outer chambers of the barrel are at a radius of about 11 m. The length of the barrel toroid coils is 13 m, and the third layer of the forward muon chambers, mounted on the cavern wall, is located at 21 m from the interaction point. The total weight of the ATLAS detector is about 7000 tons.

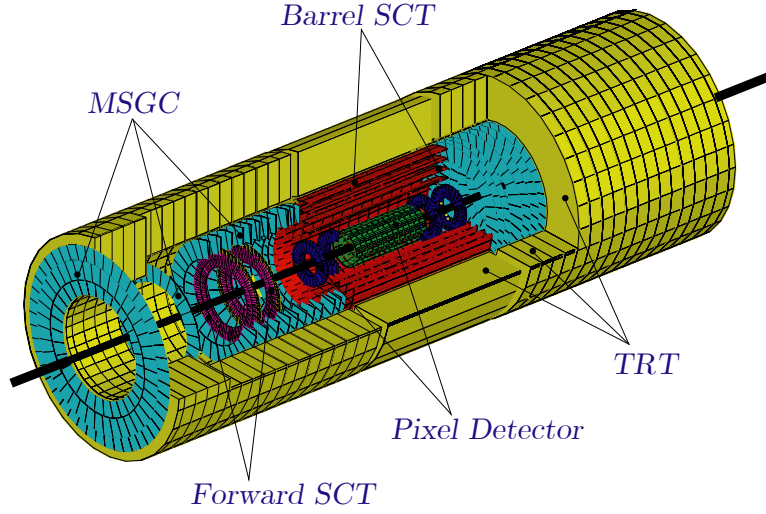
### 1.4.2 The Inner Detector

The purpose of the Inner Detector [ATI:97] is to make high-precision measurements of kinematic parameters of charged tracks moving in a solenoidal magnetic field with maximal capability for pattern recognition, particle identification and triggering. The ATLAS Inner Detector is shown in Figure 1.7.

The *silicon pixel vertex detector* consists of three barrel layers of 140 million pixels (of dimensions  $50\text{ }\mu\text{m}$  in  $r$ - $\phi$  direction and  $300\text{ }\mu\text{m}$  in the direction along the beam line) and four disks on each side between radii of 11 cm and 14 cm. This high resolution allows to reconstruct the track origin with sufficient precision to find secondary decay vertices. The detectors and the front-end-readout chips must withstand over 300 kGy of ionizing radiation and over  $5 \cdot 10^{14}$  neutrons/cm<sup>2</sup> in ten years of operation.

The *silicon strip detectors* – **S**emi **C**onductor **T**racker (SCT) – with a pitch of  $80\text{ }\mu\text{m}$  are mounted in four barrel layers at radii of 30, 37, 45 and 52 cm in order to provide four precision measurements per track in the intermediate radial range, contributing to the measurement of momentum, impact parameter and vertex position. The spatial resolution will be  $\sigma_{r,\phi} = 18\text{ }\mu\text{m}$  and  $\sigma_z = 580\text{ }\mu\text{m}$ .

The *Transition Radiation Tracker* (TRT) consists of 420,000 proportional drift tubes with a diameter of 4 mm. It is divided into a barrel part and several forward wheels.



**Figure 1.7:** ATLAS inner detector consisting of a silicon pixel vertex detector system, the semi conductor tracker (SCT) and the transition radiation tracker (TRT). The whole inner detector has a length of 6.8 m and a radius of 1.15 m.

The detector is optimized for the detection of photons created as transition radiation in stacks of thin radiators between the tubes. The single-wire resolution will be  $170\ \mu\text{m}$  and the efficiency will be  $> 50\%$  even for the highest rates (15 MHz). Two different discriminator thresholds will be used to distinguish between tracking hits (only lower threshold) and transition-radiation hits (both thresholds).

### 1.4.3 Calorimetry

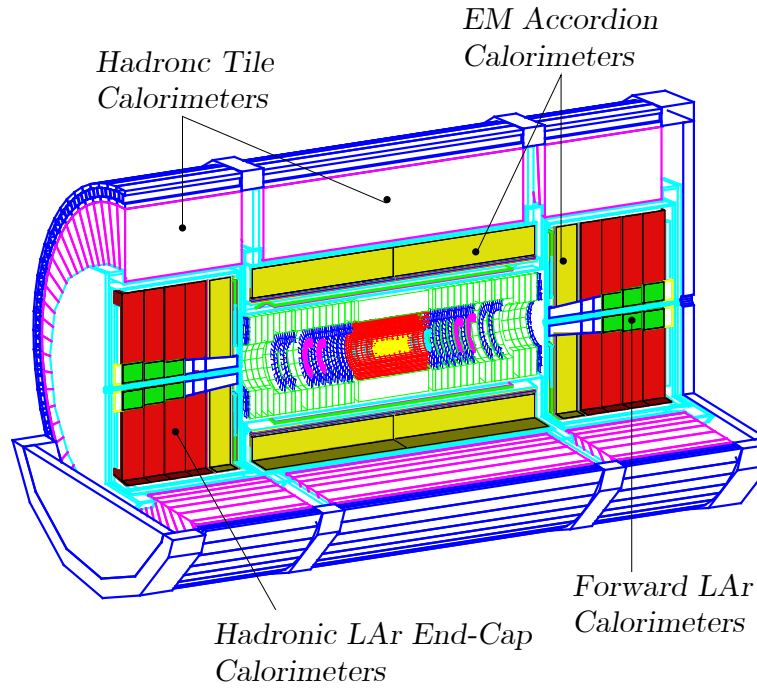
The ATLAS calorimetry [ATC:96] is shown in Figure 1.8. It consists of an electromagnetic and a hadronic calorimeter. A barrel cryostat around the inner cavity contains the barrel electromagnetic **L**iquid **A**rgon (LAr) calorimeter and the coil of the solenoid magnet. Two end-cap cryostats enclose the electromagnetic and hadronic end-cap calorimeters as well as the integrated forward calorimeter.

- **The Electromagnetic Calorimeter:**

The electromagnetic calorimeter is a lead-LAr detector with accordion-shaped Kapton electrodes and lead absorber plates over its full coverage<sup>2</sup>. The LAr sampling technique is radiation-resistant and provides long-term stability of the detector response, excellent hermeticity, good energy resolutions, and relatively easy detector calibration. The total thickness of the electromagnetic calorimeter is  $> 24 X_0$  in the barrel part and  $> 26 X_0$  in the forward region. The segmentation of the calorimeter will be  $\Delta\eta \times \Delta\phi \approx 0.025 \times 0.025$ ; the design energy resolution will be  $\Delta E/E = 10\%/\sqrt{E} \oplus 1\%$  ( $E$  in GeV). The energy-scale precision will be  $0.1\%$  and the measurement resolution of the shower direction in  $\theta$  will be  $\sim 50\text{ mrad}/\sqrt{E}$  ( $E$  in GeV).

<sup>2</sup>Barrel part:  $|\eta| < 1.475$ ; end-cap parts:  $1.375 < |\eta| < 3.2$





**Figure 1.8:** Layout of the ATLAS calorimetry system.

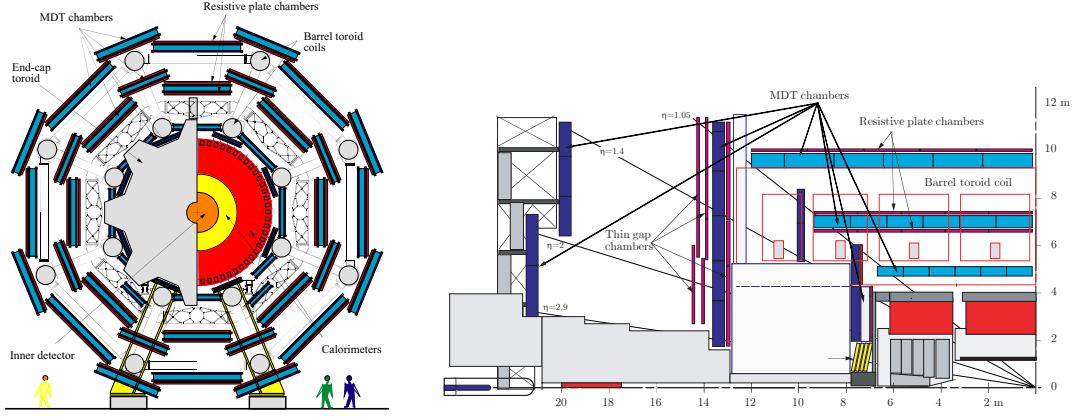
- **The Hadronic Calorimeter:**

For the hadronic calorimetry, different techniques and devices are employed, as best suited for the different requirements and the radiation environment in the respective regions. The total thickness is 11 hadronic interaction lengths ( $\lambda$ ) at  $\eta = 0$ , including  $1.5\lambda$  of the outer support. In the range of  $|\eta| < 1.6$  a sampling calorimeter is used with iron as absorber material and scintillating tiles (3 mm thick) as active material (TILE Calorimeter). The signals produced are read out on both sides of the scintillating tiles by wavelength shifting fibres into two separate photomultipliers. The segmentation of the hadronic calorimeter will be  $\Delta\eta \times \Delta\phi \approx 0.1 \times 0.1$ . In the range of  $1.5 < |\eta| < 4.9$  a hadronic LAr calorimeter is used. The end-cap hadronic calorimeter extends up to  $|\eta| < 3.2$  and is a copper-LAr detector with parallel plate geometry. The high-density forward calorimeter covers the region of  $3.2 < |\eta| < 4.9$  with the front face about 5 m from the interaction point. The detector is based on rods filled with LAr in a copper and tungsten matrix. The expected energy resolution for the hadronic calorimeter is  $\Delta E/E = 50\%/\sqrt{E} \oplus 3\%$  for  $|\eta| < 3$  and  $\Delta E/E = 100\%/\sqrt{E} \oplus 10\%$  for  $3 < |\eta| < 4.9$ .

#### 1.4.4 The Muon Spectrometer

The Muon Spectrometer dominates the size of the ATLAS experiment. It is based on the magnetic deflection of muon tracks in a system of three large super-conducting air-core toroid magnets instrumented with separate trigger and tracking chambers. The momentum resolution of the muon spectrometer relies heavily on the ability to master

the alignment of the large muon chambers spaced far apart. Figure 1.9 shows two cuts through the Muon Spectrometer.



**Figure 1.9:** *left:* transverse view of the ATLAS Muon Spectrometer. For the barrel and for the end-caps a 16-fold segmentation in azimuth has been chosen that follows the eightfold symmetry of the magnet structure; *right:* side view of one quadrant of the ATLAS experiment.

The design and performance of the Muon Spectrometer must satisfy the following requirements:

- the largest possible discovery reach for expected and unexpected new physics, with minimal systematic biases;
- good discrimination against high levels of charged and neutral particle background from minimum-bias events and radiation;
- safe and reliable operation in difficult environmental conditions for the full anticipated lifetime of the LHC.

Based on some selected benchmark processes discussed in Section 1.3 the important parameters that need to be optimized for maximum physics reach are [TDR:97]:

- *Resolution:* momentum and mass resolutions at the level of 1% are essential for the reconstruction of narrow two- or four-muon final states on top of high background levels, such as the intermediate mass Higgs, and for reliable charge identification. A transverse momentum resolution that is constant over the full rapidity range is desirable.
- *Second-coordinate measurement:* a measurement of muon tracks in the non-bending projections with an r.m.s. spatial resolution of 5–10 mm is required for safe track reconstruction and reliable momentum determination.



- *Rapidity coverage of track reconstruction:* all physics channels profit from a pseudorapidity coverage up to  $|\eta| \approx 3$  and good hermeticity, in particular rare high-mass processes.
- *Trigger selectivity:* transverse momentum thresholds of 10–20 GeV are adequate for high-mass states, which will be in the focus of LHC physics at nominal luminosity. Lower thresholds of  $p_T \approx 5$  GeV are required for CP violation and beauty physics.
- *Trigger coverage:* adequate trigger efficiencies can be obtained with a pseudorapidity coverage smaller than that of the precision chambers. The actual requirements are mostly determined by processes at the opposite ends of the LHC mass scale: the need for good acceptance for rare high-mass Higgs particles, and the need for very high statistics to study small rate asymmetries due to CP violation in the B sector. A trigger coverage of  $|\eta| < 2.4$  is found to be sufficient.
- *Bunch-crossing identification:* the LHC bunch-crossing interval of 25 ns sets the scale for the required time resolution of the first-level trigger system.

Achieving a resolution  $\Delta p_T/p_T \sim 10\%$  for  $p_T = 1$  TeV dictates the combination of the bending power in the central rapidity region, and of the precision with which the muon instrumentation must be able to measure the sagitta of the particles.

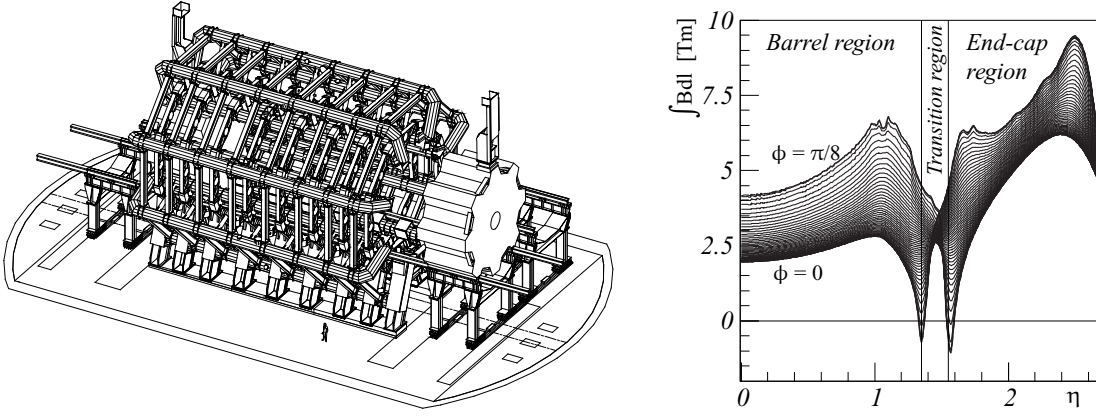
## Magnet System

The magnet system for the Muon Spectrometer (Figure 1.10) consists of three air-core super-conducting toroids with an open structure to minimize the contribution of multiple scattering to the momentum resolution. The toroidal design of the magnet system made it possible to design a high-resolution, large-acceptance and robust stand-alone muon spectrometer. A combined optimization of the magnet field strength and its radius, constrained by magnet fabrication costs and by space limitations in the experimental cavern, led to the air-core toroid magnet configuration providing a bending power (at  $\phi = 0$ ) between  $\int B \, dl = 2 \text{ Tm}$  at  $\eta = 0$  and up to  $\int B \, dl = 9 \text{ Tm}$  at  $|\eta| = 2.8$ . The average toroidal magnetic field will be  $\sim 0.5 \text{ T}$ . An advantage of the toroidal magnetic field is the fact that the bending power increases with higher pseudo-rapidities.

The barrel toroid extends over a length of 25 m, with an inner bore of 9.4 m and an outer diameter of 20.1 m. The two end-cap toroids have a length of 5 m, an inner bore of 1.64 m and an outer diameter of 10.7 m. Each toroid consists of eight flat coils arranged radially and symmetrically around the beam axis. The barrel-toroid coils are contained in individual cryostats, whereas the eight end-cap toroid-coils are assembled in a single large cryostat.

## Muon Instrumentation

The ATLAS Muon Spectrometer will measure the trajectories of particles at three stations of chambers.



**Figure 1.10:** *left:* 3D view of the super-conducting air-core toroid magnet system; *right:* toroid bending power  $\int B dl$  of the azimuthal field component as a function of  $\eta$ .

In the barrel ( $|\eta| < 1$ ) they will be arranged in three cylinders, concentric with the beam axis at radii of about 5 m, 7.5 m and 10 m. In this  $\eta$ -region the particles are measured near the inner and outer field boundaries, and inside the field volume, in order to determine the momentum from the sagitta.

The end-cap chambers will cover the pseudorapidity range  $1 < |\eta| < 2.7$  and are arranged in four disks at distances of 7 m, 10 m, 14 m and 21 m from the interaction point. In the forward region, for  $|\eta| > 1.4$ , the magnet cryostats do not allow the positioning of chambers inside the field volume. Instead, the chambers are arranged to determine the momentum with the best possible resolution from a point-angle measurement.

The ATLAS muon spectrometer utilizes four different chamber technologies:

- **Precision Chambers:**

For the precision measurement of muon tracks in the principal bending direction of the magnetic field, **M**onitored **D**rift **T**ube (MDT) chambers are used nearly everywhere. The layout of the MDT chambers will be explained in Section 1.4.5. Only in the innermost ring of the end-cap inner-station ( $2 < |\eta| < 2.7$ ), where particle fluxes are highest, **C**athode **S**trip **C**hambers (CSCs) are utilized (see Figure 1.9, right). CSCs are multiwire proportional chambers with cathode strip readout and with a symmetric cell in which the anode-cathode spacing is equal to the anode-wire pitch. A spatial resolution of  $60 \mu\text{m}$  has been measured. A transverse coordinate is obtained from the strips parallel to the anode wires, which form the second cathode of the chamber.

- **Trigger Chambers:**

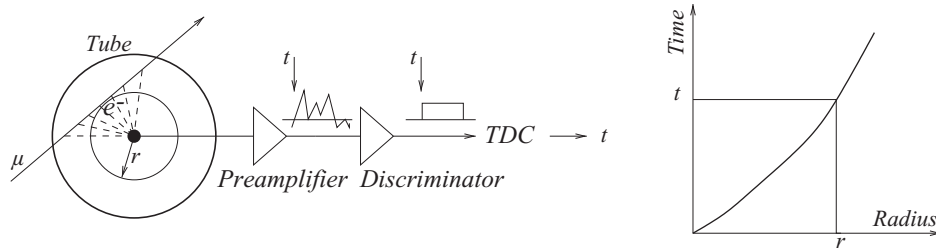
These chambers will provide the trigger function, the bunch crossing identification and the measurement of the “second coordinate” (coordinate along the magnetic field lines). In the barrel, this information is provided by three stations of **R**esistive **P**late **C**hambers (RPCs). They are located on both sides of the middle MDT station, and either directly above or below the outer MDT station. These chambers

are gaseous parallel plate chambers with a typical space-time resolution of  $1\text{ cm} \times 1\text{ ns}$ . Each chamber is made of two rectangular detector layers, each one read out by two orthogonal series of pick-up strips: The  $\eta$ -strips are parallel to the MDT wires and provide the bending view of the trigger detector. The  $\phi$ -strips, orthogonal to the MDT wires, provide the second-coordinate measurement which is important for the off-line pattern recognition.

In the end-caps, three stations of **Thin Gap Chambers** (TGCs), located near the middle MDT station will be installed. The TGCs have a structure similar to multiwire proportional chambers, with the difference that the anode-wire pitch (1.8 mm) is larger than the cathode-anode distance (1.4 mm). Signals from the anode wires, arranged parallel to the MDT wires, provide the trigger information together with readout strips arranged orthogonal to the wires, that also provide a measurement of the second coordinate.

#### 1.4.5 Muon Precision Drift Chambers

The sagittas of muon tracks are measured by precision chambers (**M**onitored **D**rift **T**ubes) in an inner, middle and outer station. The basic elements of these chambers are drift tubes with a diameter of 3 cm and a  $50\text{ }\mu\text{m}$  central wire that is connected to high voltage. The principle of operation is shown in Figure 1.11. A muon crossing the



**Figure 1.11:** Principle of the drift tube operation. The electron-drift time is measured and converted to a distance via a space-time relation (rt-relation).

drift tube ionizes the detector gas along its track, the electrons are drifting towards the wire in the electric field and are multiplied in an avalanche process close to the wire due to the high field. The movement of the ions induces a current on the wire that is read out at one end of the tube by a current-sensitive preamplifier. After discriminating the signal, a **T**ime to **D**igital **C**onverter (TDC) stores the arrival time of the pulse, thus measuring the drift time of the ionization electrons. The drift time is then converted to a distance by a space-time relation (rt-relation). The rt-relation is obtained by a so-called auto-calibration procedure. The performance of the MDT chambers in a high-rate environment and the dependence on the environmental parameters is documented in [ALE:99].

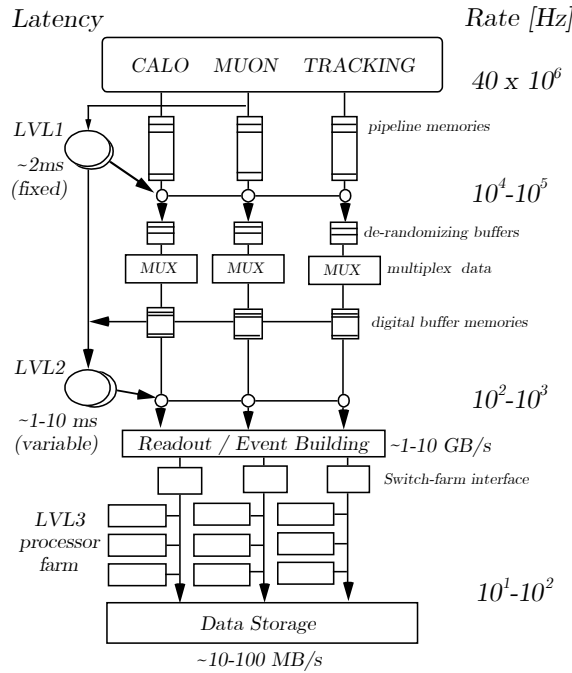
The MDT chambers consist of two multilayers separated by a support structure. Each multilayer combines three or four<sup>3</sup> layers of tubes (see Figure 1.13-left). An X-ray tomo-

<sup>3</sup>3 layers in the middle and outer station, 4 layers in the inner station.

graph is used to measure the wire positioning accuracy on about 12% of all chambers and hence provides quality feedback to the chamber production sites. In total 1194 MDT chambers (370000 readout channels) will cover an area of 5500 m<sup>2</sup>.

### 1.4.6 The Trigger Scheme

The role of the trigger system is to select bunch crossings containing "interesting" interactions. The data-acquisition system (DAQ) will be able to record events only at a rate of  $\sim 100$  Hz (10–100 MB/s). Hence the task of the trigger is to reduce the vast interaction rate of  $10^9$  Hz to approximately 100 Hz of interesting events.



**Figure 1.12:** The ATLAS three-level trigger architecture.

The ATLAS trigger is organized in three trigger levels (LVL1, LVL2 and LVL3) as shown in Figure 1.12. The LVL1 trigger uses reduced-granularity data from a subset of detectors. The LVL2 trigger uses full-granularity, full-precision data from most of the detectors, but examines only regions of the detector flagged at LVL1 as containing interesting information. The LVL3 trigger uses the full event data for the final selection of events for off-line analysis.

The LVL1 trigger accepts data at the full LHC bunch-crossing rate of 40 MHz (every 25 ns). The latency, which is the time to form and distribute the LVL1 trigger decision, is 2  $\mu$ s and the maximum output rate is limited to 100 kHz by the capabilities of the sub-detector readout systems and the LVL2 trigger. During the LVL1 processing, the data from all parts of the ATLAS detector are held in pipeline memories. The LVL1 trigger must identify unambiguously the bunch crossing containing the interaction of interest and should introduce negligible dead-time.

The LVL2 trigger reduces the rate from about 100 kHz after LVL1 to 1 kHz. To minimize the latency, only data from regions of interest, defined by LVL1, are transferred to the trigger processors. Also, data from different regions of interest are processed in parallel where possible.

After an event is accepted, the full data are sent to the LVL3 processors via the event builder. At LVL3 a complete event reconstruction is possible with decision times up to about 1 s. The LVL3 system must achieve a data storage rate of 10–100 MB/s by reducing both the event rate and the event size. Only for some special triggers, such as Higgs boson candidates, the full event data of about 1 MB will be recorded.

## 1.5 The Alignment System of the Muon Spectrometer

The requirements on the momentum resolution of the spectrometer call for an accuracy of the relative positioning of chambers traversed by a muon track that matches the intrinsic resolution and the mechanical tolerances of the precision chambers. Over the large global dimensions of the spectrometer, however, it is not possible to stabilize the dimensions and positions of the chambers at the sub-millimeter level. Therefore, chamber deformations and positions are constantly monitored by means of optical alignment systems and are corrected for in the off-line analysis. Thus the chamber mounting precision is moderate of the order of  $\sim 10$  mm for displacements. In turn the reduced resolution of the chambers along the wire implies that the chambers need to be oriented within  $\pm 2$  mrad.

In the barrel and transition regions (up to pseudorapidity  $|\eta| = 1.3$ ), high energy muons with  $p_T = 1$  TeV/c show a sagitta of  $\sim 500$   $\mu\text{m}$  in the average magnetic field of 0.5 T, so a momentum resolution of 10 % requires a sagitta measurement accuracy of 50  $\mu\text{m}$ , using three MDT chamber stations with a lever arm between extreme stations larger than 5 m.

In the end-cap region, the measurement proceeds from a point-angle measurement (equivalent to a sagitta measurement) with distances between extreme chambers of the order of 14 m and a bending power of the order of 6 Tm. At a pseudorapidity  $\eta = 2$ , the sagitta of a  $p_t = 1$  TeV particle is about 1 mm. The target maximum alignment contribution to the sagitta error is 30  $\mu\text{m}$ .

Independently to the optical survey, alignment with straight muon tracks is also foreseen for both parts of the spectrometer.

### 1.5.1 In-Plane Alignment System

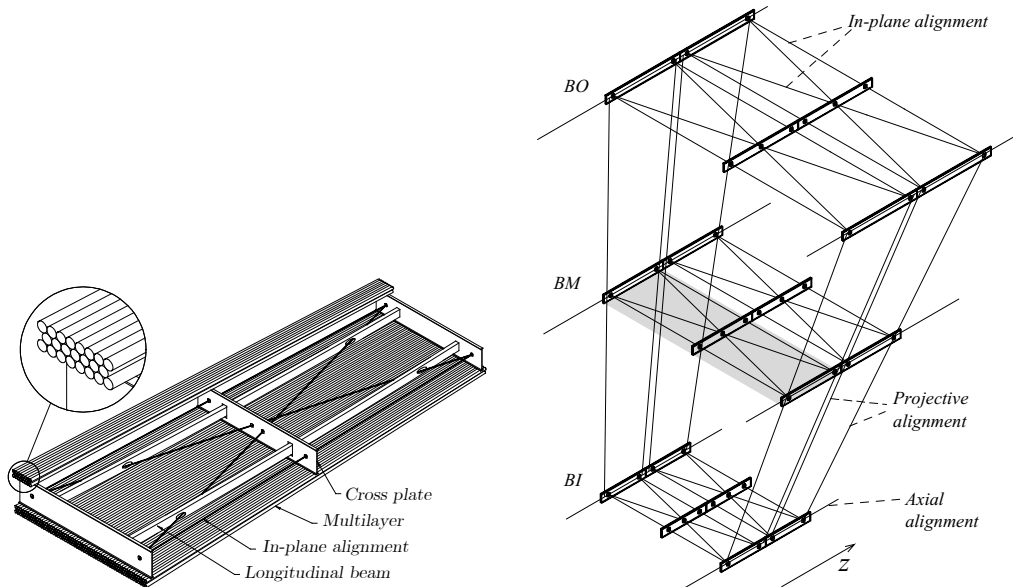
Muon chambers are equipped with an in-plane alignment system, which is needed to monitor wire displacements with an accuracy of 10  $\mu\text{m}$ . These displacements are inferred from relative movements of the cross-plates (Figure 1.13-left) which form part of the chamber support structure. In large chambers a system of four straightness monitors allows to monitor deformations out of the chamber plane. Smaller chambers are equipped with a simpler system consisting of one straightness monitor. Chamber deformations induced by thermal expansion are not detected by the straightness monitors and thus monitored with temperature sensors.

The global alignment scheme assumes the chambers as perfectly rigid planar bodies and uses the monitored wire displacements at the time of the off-line sagitta correction.

### 1.5.2 The Barrel Alignment System

The arrangement of the light rays for the alignment of barrel towers is shown in Figure 1.13. Chamber dimensions and positions are such that they form triplets with a projective geometry as seen from the interaction point. In this projective layout, and in linear approximation, the correction to the measured sagitta of the muon trajectory is a function of six chamber-displacement parameters. Four projective light rays provide an over-constrained measurement of chamber movements [TDR:97]. A PRAXIAL alignment system emerged in order to reduce the number of projective rays to the number of natural passages in the detector. The main goal is to allow the merging of six adjacent chambers into one single unit which can be handled by the projective system. The merging of chambers of a given layer is achieved by overlapping straightness monitors running in the  $z$  direction along the two sides of the large MDT chambers. The distance and orientation along  $z$  between two adjacent chambers is measured by 3D proximity sensors.

In addition to the relative alignment system, a reference system will be implemented to allow for an absolute positioning of the chambers to  $400\text{ }\mu\text{m}$ , which is mandatory for the pattern recognition, when calibrating the system with tracks in the high rate environment.



**Figure 1.13:** *left:* two multilayers of MDT tubes each consisting of three or four layers are glued to a support frame ("spacer structure") to form a chamber; *right:* the projective alignment system in the barrel region.

### 1.5.3 The End-Cap Alignment System

The projective philosophy used in the muon barrel system cannot be used in the end-cap spectrometer. The large number of lines of sight that are necessary would require too many penetrations of the end-cap toroidal magnets. Therefore one has to resort to an alignment strategy with a minimum number of nearly projective light rays connecting the chamber layers.

In the end-cap, a reference grid is setup with alignment bars using a quasi-projective alignment system. The bars are considered self-aligning precision rulers. The shape of each bar is determined by calculation, calibrated by the readings of the internal monitors. The relationship between the bars is then established by a network of polar and azimuthal sensors which measure the bearing angle of light sources on the other parts of the system<sup>4</sup>. Chambers are then referred to the alignment grid using proximity sensors. For this purpose each small and large chamber pair is considered as logical unit.

The optical alignment system must measure the relative position of the inner, middle and outer muon station with an accuracy such that the maximum alignment contribution to the sagitta measurement is  $< 30 \mu\text{m}$  r.m.s. The position of muon chambers will be monitored, and used for the off-line sagitta correction.

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<sup>4</sup>The bars are connected by polar monitors in  $(z, \theta)$  planes and by azimuthal monitors which control their relative positions within the chamber planes  $(r, \phi)$ .





## Chapter 2

# The End-Cap Alignment System

### 2.1 Introduction

This chapter will give an overview of the alignment concept that is used to position objects in space by means of different sensors. The three types of optical alignment sensors that are implemented in the end-cap alignment will be discussed in detail, followed by a description of the layout of the end-cap alignment. The contribution of each sensor to the global alignment will be discussed.

### 2.2 Motivation

For many interesting channels expected at the LHC, good sensitivity will require precise measurement of the kinematic parameters of high- $p_T$  charged tracks. In order to do this the muon spectrometer is designed to make precise position measurements of points on these tracks as they curve through a magnetic field. The precision with which this can be done is dependent upon both the intrinsic measurement precision of the detector elements employed and the accuracy with which their locations are known. The intrinsic precision of a detector is simply a property of its design. The positioning accuracy with which it was positioned at assembly and the stability of its location subsequently. The overall process of accurately determining the position of detector elements both before and after assembly is known as **alignment**.

Since precision with which the positions of detector elements must be known during running will in general be higher than that which can be inferred from knowledge of the detector just after assembly, it will be necessary to determine the location of each element during operation of the detector. This may be done either indirectly using the track data, or directly using a **survey system**. Survey measurements must be made with a precision sufficient for the total combined precision to be within the specifications derived from the physics requirements.

$$\sigma_{\text{total}} = \sigma_{\text{intrinsic}} \oplus \sigma_{\text{survey}} < \sigma_{\text{required}}$$

Survey measurements will be combined geometrically to produce a three-dimensional

picture of the locations of the detector elements. It is useful to factorize the alignment problem into the local or internal alignment. These rigid bodies, leaving then 6 degrees of freedom for the location relative to the other subdetectors.

## 2.3 The General Concept of Alignment

Determining the alignment of objects in space means to determine the spatial relationship of a number of local coordinate systems (LCS) to one global coordinate system (GCS), i.e. to determine for each LCS its position, represented by the coordinates  $x, y, z$  of its origin in the GCS, as well as its orientation, represented by the angles of three subsequent rotations around the  $x, y, z$  axes,  $\alpha, \beta, \gamma$ . Points on objects, e.g. the positions of active detector elements, may be defined in any of the LCSs.

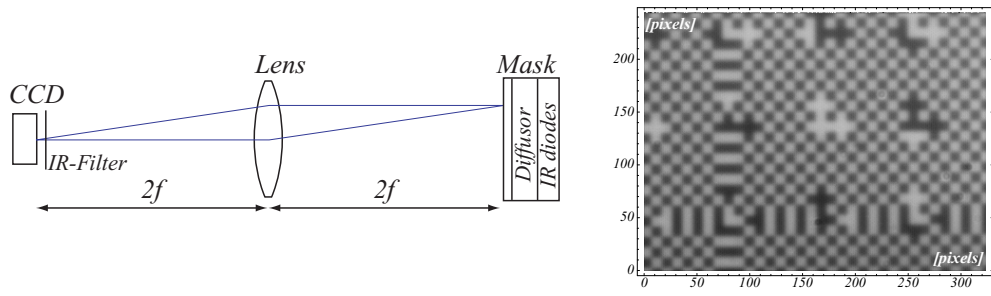
Information about the spatial relationship between pairs (or groups) of coordinate systems is obtained from alignment sensors. They relate points in different coordinate systems by providing a measurement related to their relative positions and/or orientations. If the cumulative information from all sensors is sufficient to unambiguously constrain all degrees of freedom of the problem, the alignment can be determined; if the problem is over-constrained, this can be exploited to improve the overall precision of the alignment.

## 2.4 Alignment Sensors

Three different types of optical alignment sensors are implemented in the end-cap alignment system. All sensor types are based on the same electronics components but implemented differently, to serve the individual needs. In either system an image which is generated by an illuminated mask or a light spot is focused through a projection lens to an image sensor. The image captured by a charge coupled device (CCD) with  $240 \times 360$  active elements is then analyzed and yields a measurement (relative to a calibration value) in the local coordinate system of the sensor.

### 2.4.1 RASNIK (Straightness Monitor)

The RASNIK scheme [RAS:00] is a three-point imaging system consisting of an illuminated mask, a projection lens and a CCD sensor. Three-dimensional positioning is obtained from an analysis of the mask image on the CCD. Figure 2.1-right shows the chessboard-like mask image where every ninth row and column contains information about the global position on the mask of the small part projected onto the CCD. The encoded positions are interpreted relative to the orientation of the CCD. Hence the CCD provides the orientation of the local coordinates system of this sensor.



**Figure 2.1:** *left:* sketch of a RASNIK system which focusses the mask image 1:1 onto the CCD; *right:* typical image of the non-repeating coded mask used in the CCD-RASNIK system.

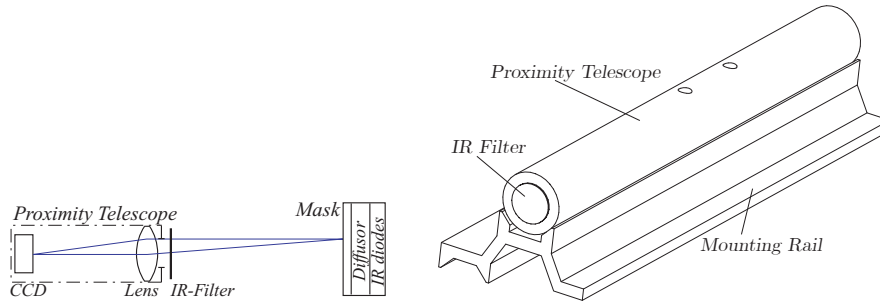
When mounting each of the three RASNIK components individually, the system behaves as a straightness monitor, measuring any change in position perpendicular to the optical axis. Movements of the lens by a distance  $d$  in a direction perpendicular to the axis defined by the mask and the CCD cause a displacement of the image of the mask by a distance  $2d$ . Such movements can be determined to typically  $1\text{ }\mu\text{m}$ . Changes in the lateral positions lead to different magnifications of the chess board pattern; typical accuracies of a few tens of  $\mu\text{m}$  in the axial direction have been obtained<sup>1</sup>. Optimal performance requires a sharp image of the mask on the CCD. This imposes a constraint on the distances between the CCD, lens and mask depending on the focal length of the lens.

The accuracy at typical operating distances between CCD and mask of several meters is mainly limited by atmospheric turbulence along the optical path. RASNIK systems are used for the in-plane alignment of the chambers, and the shape monitoring of alignment bars.

### 2.4.2 Proximity Monitors

The proximity monitor is a RASNIK-based system where, CCD and lens are combined into one unit (telescope) facing the same type of illuminated mask as shown in Figure 2.1. Each proximity telescope needs to be adjusted to its operating distance, which is done by moving the lens at the time of calibrating the telescope. The system provides the optical connection between the large and the small chambers, and between the chambers and the alignment bars. The transverse coordinate resolution of a proximity monitor is  $1\text{ }\mu\text{m}$ . According to the mounting requirements of the chambers, the monitor allows for displacements in longitudinal direction to within  $\pm 20\text{ mm}$ . The dynamic range transverse to the optical axis is depending on the mask size and the individual magnification of the system.  $30 \times 30\text{ mm}^2$  masks have been chosen and thus fulfill the required range of  $\pm 10\text{ mm}$ . Measurements in the axial direction are transferred from the measurement of the magnification, here the resolution is  $5 \cdot 10^{-5}$ .

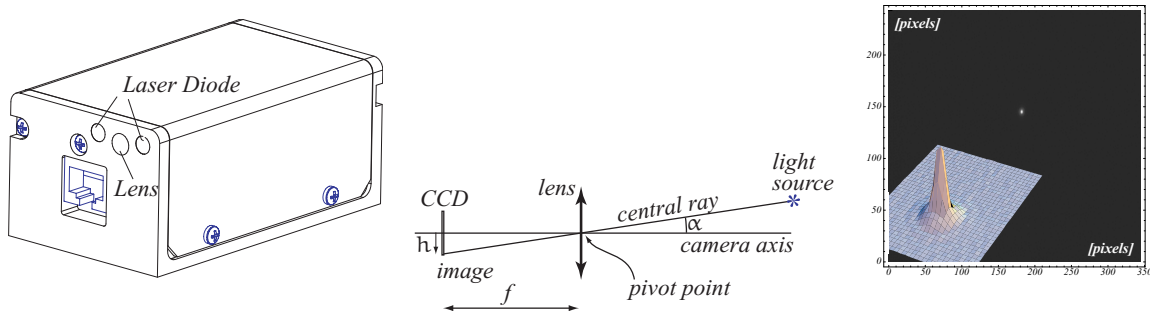
<sup>1</sup>The accuracy in axial direction is depending on the relative distances CCD-lens and lens-mask.



**Figure 2.2:** Proximity monitor consisting of the telescope and the mask; *left*: sketch of the proximity system; *right*: sketch of the proximity telescope mounted on its rail.

### 2.4.3 BCAM (Angle Monitor)

The **B**oston **C**CD **A**ngle **M**onitor [HAS:00] is a simple fixed focus camera which consists of a thin lens and a CCD image sensor. The main difference to the two systems above is the light source this camera is facing. A BCAM is analyzing the relative position of the center of a light spot that is projected onto the CCD, thus the BCAM measures angles, in contrast to the RASNIK based systems that measure positions. When looking at point-like sources the images need not to be in focus since the quantity of interest for the reconstruction - the center of intensity - does not change when defocussing. In comparison to the two systems above, BCAMs need not to be adapted to the individual source distances, which makes the technical implementation of this system very easy and general. But owing to this concept, displacements in axial direction cannot be measured with one light spot. The intrinsic sensor resolution is  $5 \mu\text{rad}$  over a dynamic range of  $40 \text{ mrad}$ . For a focal length of  $\sim 75 \text{ mm}$  this resolution corresponds to a center-finding precision on the CCD of  $0.4 \mu\text{m}$ . The center finding precision relies on a correctly captured intensity distribution of the light spot, which demands owing to the operating principle of a CCD an exposure time well below the saturation. BCAM cameras are



**Figure 2.3:** *left*: schematic drawing of a BCAM; *middle*: measurement principle; *right*: CCD image and intensity distribution of a light spot.

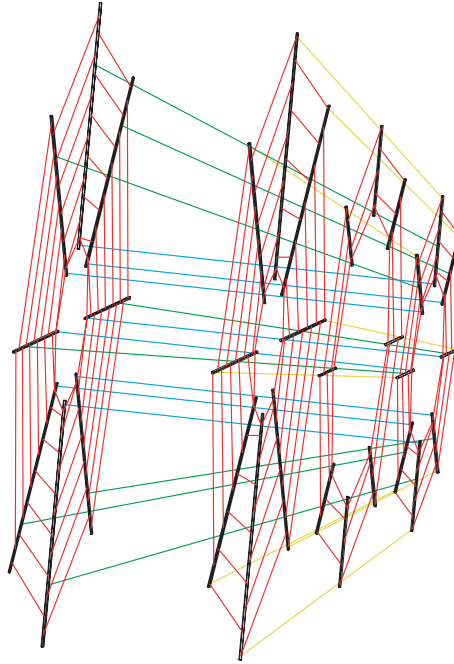
mounted to a three-ball pattern relative to which the location of the camera pivot point and its viewing direction are calibrated. In addition each BCAM houses two light sources

whose positions are also calibrated relative to the camera mount. The calibration error, which also includes the mounting accuracy to the three-ball mount is of the order of  $50\text{ }\mu\text{rad}$  for orientation and  $20\text{ }\mu\text{m}$  for shifts. All BCAMs in the end-cap alignment system are mounted onto alignment bars and are used to monitor displacements along polar and azimuthal lines.

## 2.5 Alignment Concept in the End-Cap Spectrometer

### 2.5.1 Reference Grid

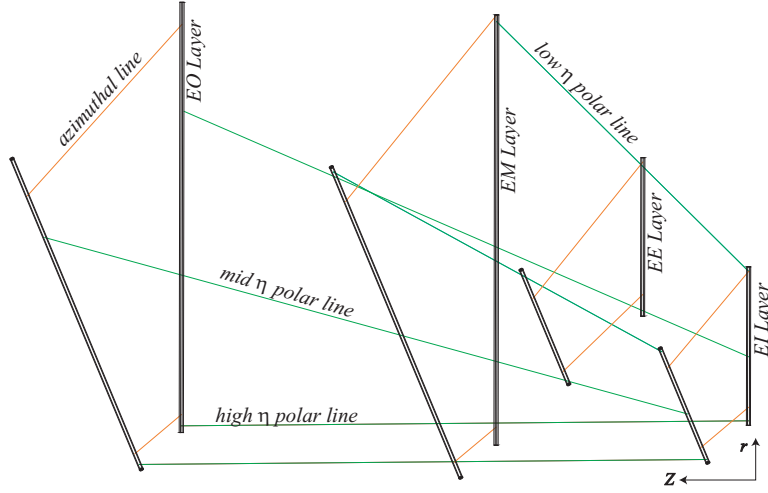
To obtain a position measurement of the four wheels of muon chambers, the end-cap alignment system needs, in addition to the three sensors presented above, one more ingredient: precision rulers to which these sensors are mounted to. These rulers (alignment bars) have to provide the relative positions and orientations of the sensors they are carrying. The network of alignment rays and bars that permeates the end-cap is shown in Figure 2.4. Once the positions of all bars are established, the chambers can be referred to this reference grid.



**Figure 2.4:** Alignment bars and alignment rays used in one end-cap of the muon spectrometer.

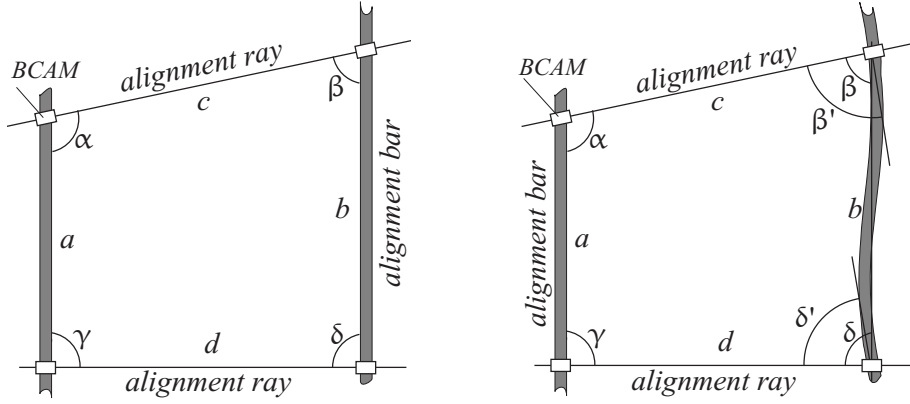
Eight radially arranged bars per layer are optically connected with azimuthal lines to control the relative positions of bars within the chamber ( $r, \phi$ ) planes. The different layers are then optically connected by polar lines to allow for a position measurement in the ( $z, \theta$ ) planes. The smallest independent cell of this grid (Figure 2.5) can be formed from two alignment bars per layer which are connected by at least two polar- and two

azimuthal lines.



**Figure 2.5:** Alignment bars and alignment rays used in one octant of the end-cap spectrometer.

This unit can be further subdivided into four-sided shapes: alignment quadrangles, which are useful to illustrate the basic principle of the end-cap alignment (2.6-left).

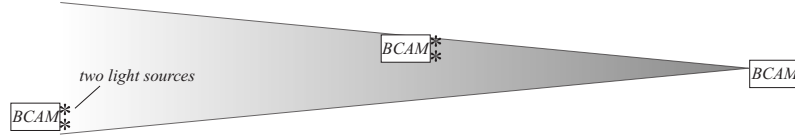


**Figure 2.6:** Measurement principle of an alignment quadrangle [HAS:00]. Distances  $a$  and  $b$  are known and the polar lines are not parallel, so the distances  $c$  and  $d$  can be deduced. *left:* idealized; *right:* relative angle deviations are derived from the reconstructed shape of the alignment bar.

In order to determine the relative position of two alignment bars ( $c$ ,  $d$ ) the angles  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $\delta$  and the distances between the light rays  $a$ ,  $b$  have to be provided by the alignment bars.

The detector layout prevents to have projective polar lines such that they would intersect at the interaction point of the detector. Thus to measure the track sagitta with such a quasi-projective layout of light rays, BCAMs have to provide absolute position

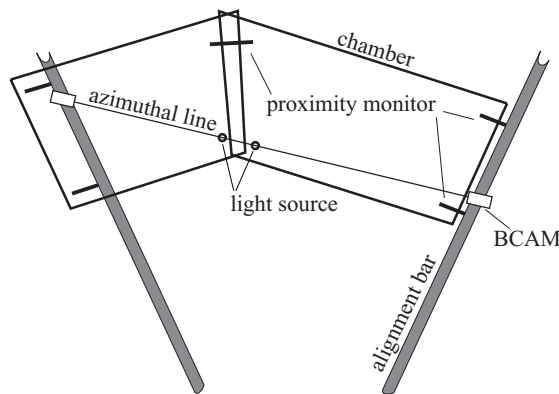
measurements with an accuracy of  $50\ \mu\text{rad}$ . The precision required to measure the track sagittas is then achieved by relative measurements, which are almost parallel to muon tracks. Owing to the measurement principle of BCAMs, each polar BCAM is facing two or three partner BCAMs in the same alignment corridor, thus obtaining light ray sagittas by measuring the relative bearing angle of light sources in different layers, this relative measurements are accurate to  $5\ \mu\text{rad}$ . Figure 2.7 shows such an arrangement of three polar BCAMs in one alignment corridor.



**Figure 2.7:** Three polar BCAMs facing each other in one alignment corridor.

### 2.5.2 Chamber-Bar Alignment

Rings of sixteen (eight small and eight large) chambers build an eightfold azimuthal symmetry in each layer. Pairs of one small and one large chamber are considered as a logical unit. Two proximity telescopes on the 'bar-sides' of each chamber pair face their corresponding masks which are mounted on the alignment bars. The optical connection between a small and a large chamber is maintained by one proximity monitor and by an azimuthal BCAM pair of which each BCAM measures not only the position of its partner but also that of light sources mounted on the chambers. This additional line per chamber pair is mandatory to control the out-of-plane movement in the overlap region [AME:01]. Figure 2.8 illustrates the connection between chambers and bars and the connection between the large and the small chamber of a pair.



**Figure 2.8:** Alignment of chambers relative to bars.

### 2.5.3 Calibration of the Forward Alignment System

The possibility of improving the performance of the alignment system by calibration with tracking data has been studied in [OST:97]. As the end-cap alignment does, contrary to the barrel, not rely on a direct comparison of the track sagitta with the light ray sagitta, the calibration procedure will not correct for as large sensor mispositionings as in the barrel. For projective tracks the systematic deviation of the measured sagitta of a track (false sagitta) due to a chamber misalignment is a function of  $\phi$  (track polar angle) and  $\theta$  (azimuthal angle of track). Thus the individual contribution of each sensor to the sagitta error cannot be disentangled. Hence a map of false sagittas is created by measuring straight muon tracks, to serve the off-line sagitta correction.

## 2.6 Alignment Reconstruction Software

The alignment reconstruction software (ARAMYS, [AME:01]) has been developed to – in a first step – simulate the performance of the alignment system for the ATLAS muon spectrometer. The concept of the program is simple and general, which makes its application to a specific alignment problem easy. The alignment of the different detector elements involved is reconstructed from the measurements provided by alignment sensors as the result of a  $\chi^2$  minimization performed by MINUIT.

The program can accommodate in a uniform way all kinds of optical sensors as well as quantities derived from other measurements, e.g. from temperatures or optical survey. Owing to its concept, it is open to many applications. Sensors are treated as point like objects. They have at least a sensor position associated with them, defined in a LCS, as well as a position of a source they look at. They may or may not in addition look at one or many auxiliary positions defined in additional LCSs.

Simulation runs employ a Monte Carlo algorithm, where all measurements are randomly smeared to reflect their resolutions. A single run of the alignment simulation program corresponds to the following steps:

- Set up the nominal geometry by positioning all LCSs in space. Randomly displace them off their nominal positions and orientations within the initial positioning accuracy.
- Set up all sensor coordinate systems, by positioning each of them in its sensor position.
- Randomly displace the sensor coordinate systems according to the mounting accuracy of the sensors.
- Simulate the sensor readout
- Discard the true geometry (actually, it has to be stored for the purpose of comparison between true and reconstructed positions)
- Reconstruct the positions from the sensor readout.



- Calculate a user-defined figure of merit (or generate a distribution) from the reconstructed LCS positions and orientations, possibly by comparing them to the true positions and orientations.

Usually many runs are performed in order to average over the individually determined figures of merit and thus become independent of the starting conditions, i.e. the random number generator seed, and of the statistical fluctuations owing to the Monte Carlo method.

Simulation runs have been performed to optimize the alignment layout for the end-cap. The program was very useful to obtain the individual contributions of the sensors involved to the overall measurement error of the track sagitta and to match the resolution and positioning requirements of the individual sensor types such that their error contribution to the reconstructed track sagitta is of the same order.

## 2.7 Contributions of this Thesis

When I joined the collaboration at the start of my thesis there was a vague idea how alignment bars could look like. After experiencing major problems with a first prototype made from carbon fiber, there was little knowledge about how to proceed to reach the enormous precision requirements. Due to my work the following major issues concerning alignment bars have now an answer:

### Design and layout of the alignment bar

This thesis will explain the design that allows to mount all the necessary sensors into the alignment bar, and thus transforms an almost 10 m long tube into a precision ruler. The question how to support such a bar properly is also discussed.

### Calibration of the alignment bar instrumentation

The way from a bar design to the use of its instrumentation to predict the relative positions of a small number of points on this bar will be described in detail. It includes the calibration of the in-bar instrumentation and the measurements needed to obtain the initial shape of the bar.

### Reconstruction of the bar shape

Alignment sensors are distributed over the whole bar, thus knowing the relation of the small number of points on the bar obtained from the in-bar instrumentation is not sufficient. I developed a novel way of describing the bar shape by means of virtual loads which are derived from the in-bar instrumentation. This procedure described in Section 6.4 lead to the required precision in the bar shape and its first derivative, which permits to predict the position and orientation of the alignment sensors.

## **Demonstration of the end-cap alignment**

To demonstrate the performance of the end-cap alignment the smallest independent cell (one octant of one end-cap spectrometer) has been set up in the H8 test beam area at CERN. Measurements and tests have been performed to understand the behavior of this system. Quantifying the global positioning accuracy and to learn for the final ATLAS design are among the major issues.

## **Proposed design for the ATLAS alignment bars**

All this led to a proposal for the design for the final ATLAS alignment bars, as well as to many detailed solutions allowing to fulfill the requirements. The proposal is discussed in Chapter 9, followed by a manual that describes the process from assembling until installing the alignment bars (Section 9.3).

## Chapter 3

# Environment and Requirements for the Alignment Bars

### 3.1 Introduction

In Section 1.3 the detector requirements that are necessary to achieve maximum physics reach were derived from the LHC research program. In Section 1.5 those thoughts were translated into requirements for the ATLAS muon spectrometer and in greater detail for its alignment system. This chapter will introduce the operational environment of the alignment system of the end-cap spectrometer and will afterwards concentrate on the requirements for the alignment bars.

### 3.2 Operational Environment

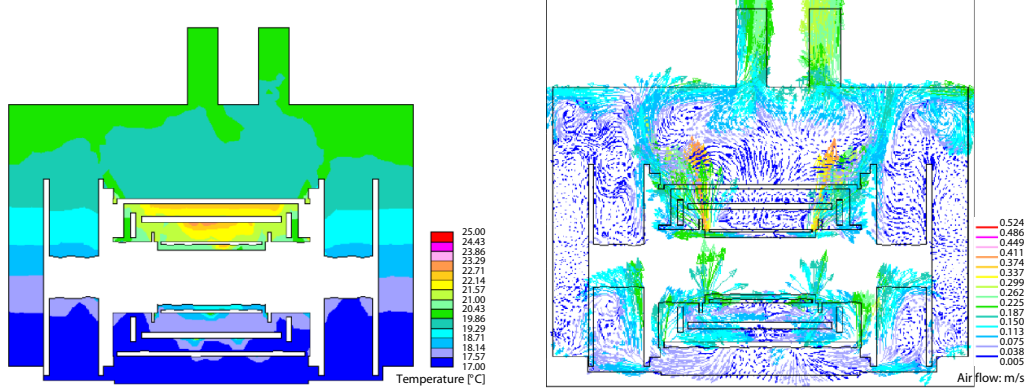
#### 3.2.1 Vibrations

The spectrum of seismic vibrations in the LEP/LHC tunnel has been measured [BAL:93]. Under adverse conditions, r.m.s. amplitudes are at the 0.01 - 0.03  $\mu\text{m}$  level in the 1-10 Hz range, arguably too low to be of concern. Vibrations potentially induced by compressors, pumps, liquid helium flow in the toroid coils, air currents, etc., are a potentially more serious problem. Initial studies and measurements on LEP detectors (L3 and ALEPH) and their extrapolation to LHC experiments indicate that vibrational amplitudes at the level of 10  $\mu\text{m}$  r.m.s. cannot be excluded [COL:96].

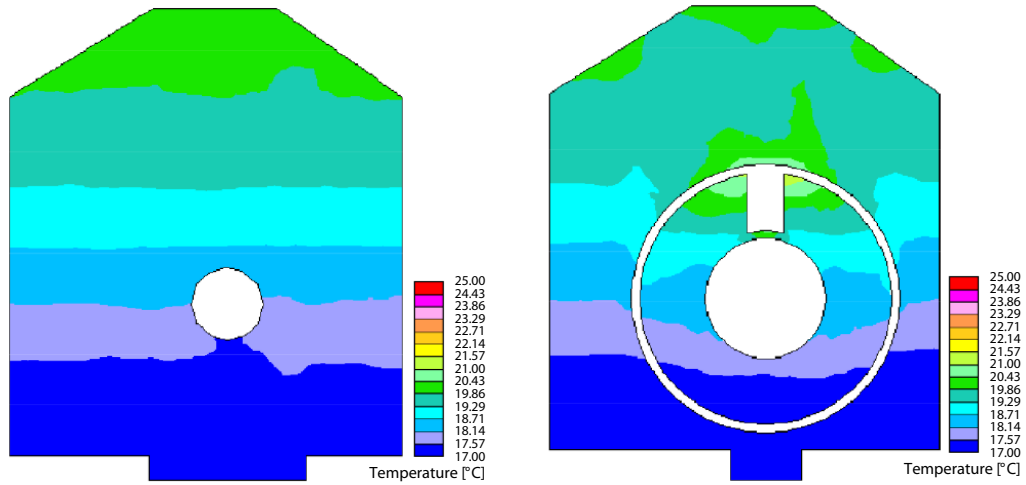
#### 3.2.2 Temperature Environment

Temperature differences across the muon spectrometer are estimated to be about 3 K once a stable state has been reached after start-up of operation. They are induced by electronic racks distributed on the structure that surrounds the barrel toroid and are the primary heat source on the outer periphery of the spectrometer; on-chamber electronics

dominate in the muon spectrometer volume, while toroid coils represent a significant heat sink. As the muon instrumentation completely encloses the magnets, forced-air ventilation is impractical. Recent FEA calculations of the expected temperature distribution in the ATLAS cavern [GRA:02] are shown in Figures 3.1 and 3.2.



**Figure 3.1:** Simulated temperature distribution and air flow in the ATLAS cavern; cut in the vertical plane trough the center of the detector; *left*: simulated temperature distribution [ $^{\circ}\text{C}$ ]; *right*: simulated velocity field of the air flow [ $\text{m/s}$ ].



**Figure 3.2:** Simulated temperature distribution in the ATLAS cavern; *left*: temperature distribution [ $^{\circ}\text{C}$ ] in the vertical plane between EM and EO layer; *right*: temperature distribution [ $^{\circ}\text{C}$ ] in the vertical plane between EI and EM layer.

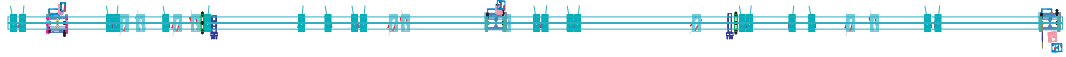
### 3.3 Design and Performance Requirements

The tight limits on the shape reconstruction impose the main performance numbers for alignment bars. These numbers set the boundaries for the reconstruction of the chamber positions and thus of the sagitta measurements in the end-cap spectrometer.

### 3.3.1 Design Requirements

Accounting for the design properties these bars have to fulfill, one has to keep in mind that even though the muon spectrometer defines the envelope of the ATLAS detector, the space these bars are mounted in is very tight. Bars are located between the small and large chamber pairs and have to serve the alignment system. In other words, all the necessary optical lines have to meet their corresponding sensors mounted on the bars. The structures to which the different layers of the spectrometer are mounted to have to carry huge load.

- Alignment bars have to carry all the sensor platforms and the alignment devices needed to establish the reference grid for the end-cap alignment. As an example Figure 3.3 is showing a drawing of an alignment bar foreseen for the EM layer. This bar has to carry 34 sensor platforms and sensors. Hence the bars have to be stable and strong.



**Figure 3.3:** Drawing of an alignment bar foreseen for the EM layer of the spectrometer.

- The bar must be manageable by persons and owing to the huge load the structures have to carry, the bars proper weight must not exceed 60 kg.
- Due to dynamic range of the alignment sensors, the profile of the bar has to accomplish that each sensor platform on the alignment bar has to be individually aligned with a mounting precision of  $\leq 1$  mrad.

### 3.3.2 Performance Requirements

Simulation studies have shown that, in order to reach the design sagitta precision [TDR:97], the contribution of the alignment system to the overall sagitta error must be less than  $30\text{ }\mu\text{m}$  r.m.s. The alignment reconstruction software ARAMYS (see Section 2.6) has been used to translate this requirement into a more specific wording:

#### Absolute Length Scale

The quasi-projective layout of the end-cap alignment system requires that the radial positions of the muon chambers are known very precisely. The chambers position is related to the positions of the proximity masks on the bar, where else the radial position of the bars in the global coordinate system is mainly defined by measurements of the polar BCAMs. Thus a mispositioning of these two sensor groups along the bar enters directly in the sagitta reconstruction.

Alignment bars are considered as precision rulers and therefore have to provide an absolute length scale over their full length of up to 9600 mm. The radial position of proximity masks and polar BCAMs on the bar has to be known to within  $\leq 20 \mu\text{m}$  in the bar coordinate system.

### Precision in Shape Prediction

The shape requirements are only set by the alignment sensors. Differences for these requirements are induced by the implementation of the involved sensors. As an example, azimuthal BCAMs measure the absolute bearing angle of a light source. The mounting precision of a BCAM is  $50 \mu\text{rad}$ , thus looking at a light source which is i.g. 5 m away the absolute position of the source can be measured to not better than  $150 \mu\text{m}$  and consequently the BCAM position needs not to be known much better than that. On the other hand, the same sensor used as a polar BCAM measures the relative bearing angle of two or tree light sources. Here the intrinsic sensor resolution of  $5 \mu\text{rad}$  is dominating the required positioning precision, and consequently the BCAM position needs to be known to  $20 \mu\text{m}$ .

The knowledge of the viewing direction ( $d\vartheta$ ) of all BCAMs is of major importance, while the rotation of a proximity mask is not even measurable. Table 3.1 lists the positioning and orientation requirements translated into the bar coordinate system for each individual sensor category.

| Bar coordinate system: | x<br>⊥ to chamber layer | y<br>   to chamber layer | z<br>along the bar | $d\vartheta$       |
|------------------------|-------------------------|--------------------------|--------------------|--------------------|
| Polar BCAMs:           | $150 \mu\text{m}$       | $150 \mu\text{m}$        | $20 \mu\text{m}$   | $50 \mu\text{rad}$ |
| Azimuthal BCAMs:       | $150 \mu\text{m}$       | $150 \mu\text{m}$        | $150 \mu\text{m}$  | $50 \mu\text{rad}$ |
| Proximity masks:       | $60 \mu\text{m}$        | -                        | $20 \mu\text{m}$   | -                  |

**Table 3.1:** Maximum contributions of the positioning error of the individual sensors to maintain the design sagitta precision; the numbers are based on a simulation using the design values for the sensor resolutions.

The required precision in reconstructing the viewing direction of the BCAMs ( $d\vartheta$ ) can be translated to an overall knowledge of the bar shape to  $30 \mu\text{m}$  relative to the bar coordinate system.

BCAMs and proximity monitors are distributed over the whole bar. The shape of an alignment bar is mainly determined by the radial positioning requirements of the proximity masks and the orientation requirements of the BCAMs. Two numbers can be extracted from that:  
Each point on the bar has to be known to  $30 \mu\text{m}$  perpendicular to the bar, and to  $20 \mu\text{m}$  along the bar.

### 3.4 Strategy to Meet the Requirements

As no manageable object of almost 10m length is stiff enough, one has to resort to a strategy where the object shape is continuously monitored and corrected for.

Absolute positioning precision is required, meaning that from the moment the alignment system will be used, the bar shape has to be known. A calibration of the bar, in the sense that the knowledge of the bar position in the global coordinate system permits to determine all sensor coordinate systems related to this bar, is inevitable.

The bar will be equipped with overlapping straightness monitors (RASNIKS) to provide the shape information at discrete points along the bar. The number of points has to be sufficient to allow for a complete reconstruction of the bar shape in the bar coordinate system. The implemented RASNIK monitors can not provide an absolute length measurement, thus the bar length has to be measured differently. Since thermal expansion is the dominant contributor to changes in length, the bar temperature will be measured.

In order to interpolate the bar shape and length between points where sensors provide measurements, it must be possible to treat the bar as a free body. This can only be ensured by kinematically supporting the bar.

Calibrating the bar means to measure once all the necessary elements on the bar. The sensors on the bar are exchangeable and are calibrated relative to three-ball patterns that provide accurate mounting. One thus has to measure the three-ball patterns which define the sensor platforms on the bar. Like that, at the point of calibration the bar can be treated as an object carrying  $3n$  balls, which can be precisely measured by a coordinate measuring machine. The relation between the in-bar sensor readings and deformations of the bar is carried out by a calibration of the in-bar instrumentation.

Alignment bars will be instrumented with sensors to monitor the bars shape and length.

Bars will be mounted such that they can act as a free body.

Each bar will be calibrated; subsequently, the in-bar sensor instrumentation will serve as an input to interpolate the bar shape and length, thus allow to predict the positions of the  $3n$  balls, and hence the position and orientation of the  $n$  sensors on the bar.





## Chapter 4

# Alignment Bar Design

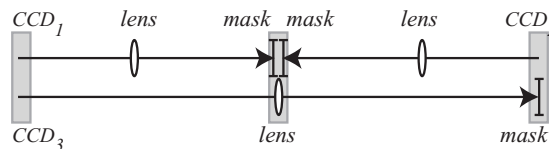
### 4.1 Introduction

Following the strategy specified in Section 3.4, a design is required to facilitate the mounting of temperature sensors and straightness monitors into the alignment bar. This in-bar instrumentation must then provide enough information to allow predicting the bar shape.

This chapter will discuss the realization of the in-bar instrumentation and show the design of the first six prototypes that have been built.

### 4.2 Bar Shape Monitoring

To describe first- and second-mode deformations of a tube that is supported in two points, a minimum number of 5 points related to each other has to be known. In view of the precision requirements, RASNIK straightness monitors are capable of measuring deformations to the micron level over the approximate bar length of 10 m. Since one RASNIK system can measure relative displacements of three points, two more RASNIK systems are needed to relate 5 points to each other. Figure 4.1 shows this concept of three overlapping RASNIK systems, where one “long” RASNIK goes over the full bar length, and two “short” RASNIKs extend over one half length of the bar each.

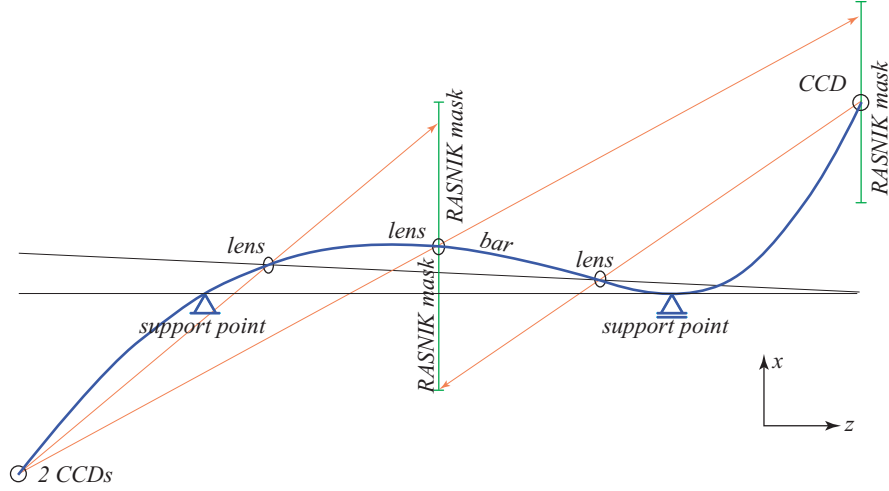


**Figure 4.1:** Layout of the optical in-bar instrumentation, consisting of three overlapping RASNIK systems.

The relation between the three systems is obtained by mounting two elements of different

RASNIKS on the same support. As indicated in Figure 4.1, two CCDs on one end of the bar as well as the masks for the short RASNIKS and the lens for the long RASNIK are mounted together. On the other side of the bar, one CCD and the mask of the long RASNIK move together.

RASNIKS analyze the portion of the mask that is projected onto the CCD. One way of illustrating this is to draw a center ray from the CCD through the lens to the mask. The intersection between the ray and the mask then corresponds to the analyzed coordinate. Figure 4.2 illustrates the readout scheme for the in-bar RASNIKS.



**Figure 4.2:** Readout scheme of the optical in-bar instrumentation. The deviations on the RASNIK masks provide position information about the three elements of the long RASNIK relative to the straight line defined by the lenses of the two short RASNIKS

Deviations on the RASNIK mask from the “zero-reading” provide the position information of three points (CCD, lens and mask of the long RASNIK) relative to the straight line defined by the positions of the lenses of the short RASNIKS. The lenses of the short RASNIKS and the support points need not necessarily coincide.

One RASNIK system measures the following quantity (transverse to the optical axis):

$$x_{\text{RAS}} = (1 + m^{-1})(x_{\text{lens}} - x_{\text{CCD}}) - (x_{\text{mask}} - x_{\text{CCD}})$$

where the magnification  $m$  can be written as the ratio of the distances of the RASNIK elements along the optical path:

$$m = \frac{z_{\text{CCD}} - z_{\text{lens}}}{z_{\text{lens}} - z_{\text{mask}}}.$$

The three RASNIK systems are coupled:

$$\begin{aligned} x_{\text{CCD},1} &= x_{\text{CCD},3} \\ x_{\text{mask},1} &= x_{\text{mask},2} = x_{\text{lens},3} \\ x_{\text{CCD},2} &= x_{\text{mask},3} . \end{aligned}$$

The positions of the elements of the long RASNIK relative to the lenses of the short RASNIKS can now be written as:

$$\begin{aligned}
 x_{\text{CCD},3} &= \frac{1}{1 + m_1 + m_3(1 + m_2)} [(1 + m_1)(1 + m_3(1 + m_2)) x_{\text{lens},1} \\
 &\quad m_1 (x_{\text{RAS},1} + m_3 ((1 + m_2) x_{\text{lens},2} + (1 + m_2) x_{\text{RAS},1} + x_{\text{RAS},3}))] \\
 x_{\text{lens},3} &= \frac{(1 + m_1) x_{\text{lens},1} - m_1 x_{\text{RAS},1} + m_3 (x_{\text{lens},2} + m_2 x_{\text{lens},2} - m_2 x_{\text{RAS},2} + x_{\text{RAS},3})}{1 + m_1 + m_3(1 + m_2)} \\
 x_{\text{mask},3} &= \frac{1}{1 + m_1 + m_3(1 + m_2)} [(1 - m_2)(1 + m_1 + m_3) x_{\text{lens},2} - \\
 &\quad m_2 ((1 + m_1) x_{\text{lens},1} - m_1 x_{\text{RAS},1} - (1 + m_1 + m_3) x_{\text{RAS},2} + m_3 x_{\text{RAS},3})] \quad (4.1)
 \end{aligned}$$

When setting  $x_{\text{lens},1} = x_{\text{lens},2} = 0$ , equations 4.1 reduce to:

$$\begin{aligned}
 x_{\text{CCD},3} &= m_1 \frac{-x_{\text{RAS},1} - m_3 (x_{\text{RAS},1} + m_2 (x_{\text{RAS},1} - x_{\text{RAS},2}) + x_{\text{RAS},3})}{1 + m_1 + m_3(1 + m_2)} \\
 x_{\text{lens},3} &= \frac{m_3 (x_{\text{RAS},3} - m_2 x_{\text{RAS},2}) - m_1 x_{\text{RAS},1}}{1 + m_1 + m_3(1 + m_2)} \\
 x_{\text{mask},3} &= m_2 \frac{m_1 (x_{\text{RAS},1} - x_{\text{RAS},2}) - x_{\text{RAS},2} - m_3 (x_{\text{RAS},2} + x_{\text{RAS},3})}{1 + m_1 + m_3(1 + m_2)}.
 \end{aligned}$$

Like that the positions of  $x_{\text{CCD},3}$ ,  $x_{\text{lens},3}$  and  $x_{\text{mask},3}$  are described relative to the straight line that is defined by the two lenses for the short RASNIKS (see Figure 4.2).

The bar shape is monitored with three overlapping RASNIK systems. By that the minimum number of measured points is obtained, to describe first and second order deformations of the alignment bar.

### 4.3 Design Concept

One issue of the design concept is that all the instrumentation needed to predict the length and shape of the alignment bar is inside the bar. This ensures that all components are sufficiently protected and no parts of this instrumentation are blocking space for the sensor platforms which have to be mounted on the bar.

A round aluminium tube with 80 mm outer diameter and 72 mm inner diameter was chosen (Anticorodal 6004 thermal treated supplied by the company Menzinken, intrinsic straightness  $\leq 1 \text{ mm/m}$ ). Using a round tube has the advantage that the sensor platforms which are mounted to the bar can be aligned within the required angular precision of  $\leq 1 \text{ mrad}$ . Also the resistance against deformation is isotropic, which reduces uncertainties in predicting the shape. The decision of choosing aluminium as tube material was based on the following requirements:

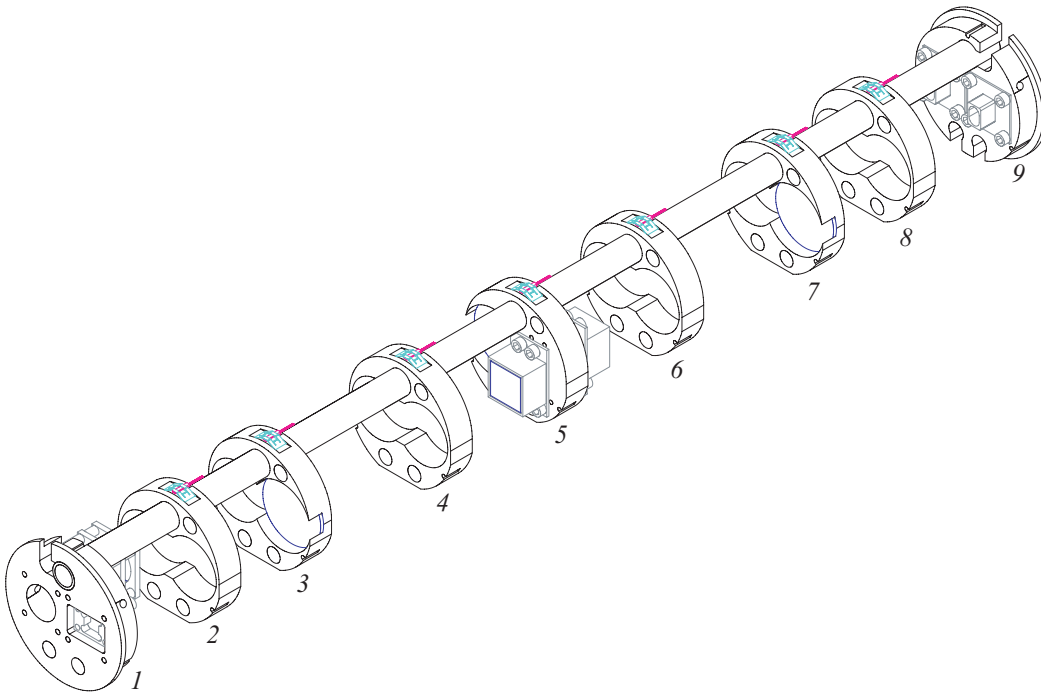
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No sensitivity to humidity  
 good thermal conductivity  
 Easy mechanical handling  
 Availability in the dimensions preferred  
 good stiffness- to weight-ratio

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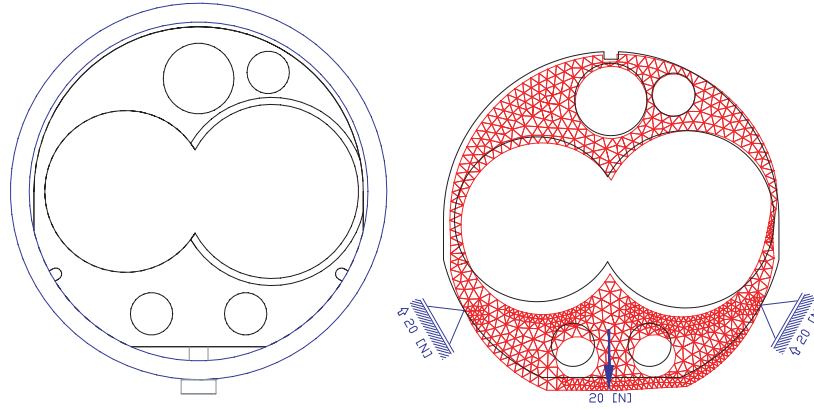
### 4.3.1 The In-Bar Skeleton

All optical components and the temperature sensors that are inside the tube are mounted on a skeleton which is inserted into the alignment bar. Each disc of this skeleton is rigidly connected to the bar. The tube ends are closed with end-stations. The skeleton shown in Figure 4.3 is designed such that all the in-bar sensors can be mounted and connected while the skeleton is outside the bar. After being inserted into the tube the skeleton is rigidly attached to the bar with one screw per disc, such that the discs align themselves to the inner wall of the tube. This way of attaching the skeleton to the tube addresses the need of minimum influence on the mechanical bar properties. The thin aluminium rod which connects the discs allows enough freedom to avoid blocking the discs if the bar changes its shape. This thin rod is also used to guide the cables that have to be led through to the ends of the bar. The discs of the skeleton are made of the same material as the bar and have been designed such that most of the machining can be performed in one go using a numerically controlled milling machine. The skeleton for the 9.6 m long bars consists of 7 discs and two end stations. For the 2.6 m long bars three discs and two end stations are used.



**Figure 4.3:** Drawing of the skeleton that is inserted into the alignment bar (distance between discs scaled 10:1.)

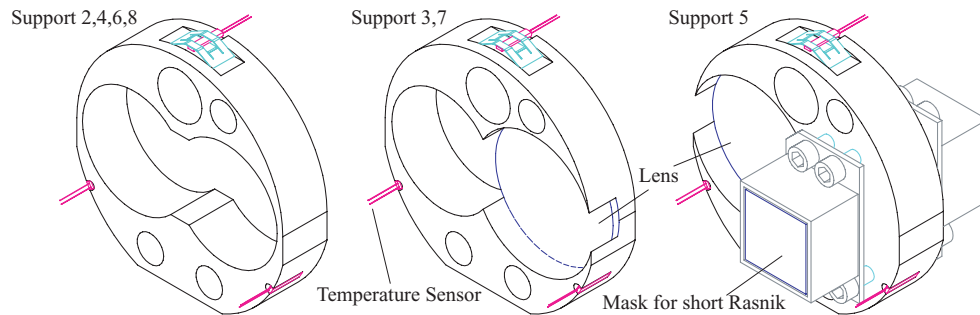
Figure 4.4 shows that only the lower part of a disc touches the inner wall of the tube, making the insertion of the skeleton into the tube easy.



**Figure 4.4:** *left:* one disc screwed to the tube; *right:* FE model of the deformation of one disc due to the screwing to the tube. (max. deformation  $5\text{ }\mu\text{m}$  for 20N pulling force)

### In-bar RASNIK system

The three RASNIK systems are mounted on the skeleton which therefore consists of three different types of inner stations.

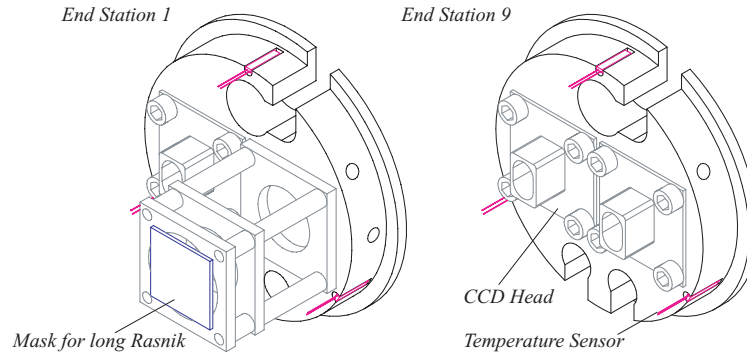


**Figure 4.5:** The three different types of discs.

Two discs (3,7) hold the lenses for the short RASNIK systems. These lenses are glued to a small support on the disc, thus allowing for a maximum optical surface.

Disc 5 holds the lens for the long RASNIK, which is also glued to the discs, and the masks for the short RASNIKS, which are screwed to the support. These masks are the standard masks which are also used for the in-plane alignment.

The discs in between the ones keeping the RASNIK elements are shown in Figure 4.5-left. Their task is to carry temperature sensors and the cables connecting the stations to avoid that the cables sag and thus block the optical path.

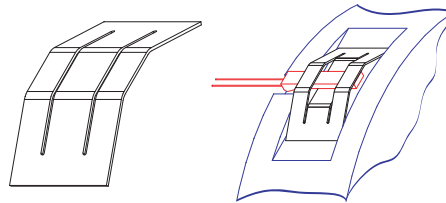


**Figure 4.6:** *left:* end-station 1 rotated by  $180^\circ$ ; *right:* end-station 9.

The end-stations carry all CCDs and the mask for the long RASNIK. A collimator in front of each CCDs is used to minimize the degradation of the image contrast due to reflections on the inner wall of the tube. The CCDs have to be close to the bar end in order to be close to the electronics driving the RASNIK system, which should be replaceable.

### Temperature Sensors

Each disc contains 3 temperature sensors that are mounted such that the sensors are in thermal contact to the inner wall of the tube. Two sensors are automatically forced to the wall when screwing the disc to the tube. The third sensor is mounted on a CuBe spring (Figure 4.7) in order to make it touch the inner wall of the tube.



**Figure 4.7:** CuBe spring; *left:* without temperature sensor; *right:* attached to the disk with temperature sensor.

Since the temperature has to be measured with an error less than 0.1 K and the difference in cable length is equal to the length of the bar, the sensors are connected with a 4-wire scheme: two wires drive the thermal resistor at constant current and two wires are used to measure the voltage drop at the sensor. This arrangement allows to disregard the length dependent resistance of the wires when measuring the voltage using a voltmeter with high resistance. The thermal resistors consist of a thin platinum film which is supported on a ceramic substrate.

All sensors needed to measure the bar shape and temperature are mounted to a skeleton which is inserted into the alignment bar. These sensors are referred as the in-bar instrumentation.

## 4.4 Bar Mounts

At the level of accuracy needed to reconstruct the bar shape, it is essential to understand the impact of the constraint forces introduced by the bar mounting that is used.

### 4.4.1 Mount Position

Alignment bars are supported in two points. In view of the bar shape, the position for this two support points can be optimized. Various definitions of such distinctive support positions (Bessel points) exist. The definition used here is the one, where the overall deformation of the bar is minimized, which is the case, when the middle of the bar and the ends of the bar sag by the same amount. For a tube that is deformed by its proper weight, these positions are at 22.3% of the bar length from the ends each.

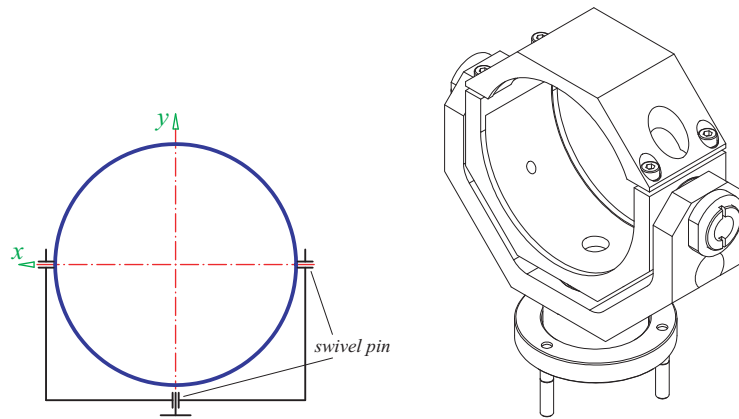
### 4.4.2 Kinematic Mounting

A *kinematic mount* of a free body has to be designed such that all six degrees of freedom are singly constrained, to assure that movements will be prevented, while at the same time no stress is introduced. To meet this requirement, mounts have to permit certain degrees of freedom to the object they are keeping in position. In consideration of that, mounts can be classified by the **degrees of freedom** (DOF: 3 linear motions, 3 rotations) they are permitting. Also, the solution of problems in statics postulates that constraint forces, namely those external forces required to maintain the position of the free body, can be calculated from the six conditions of equilibrium:

$$\sum_{i=1}^n F_i = 0, \quad \sum_{i=1}^n M_i = 0,$$

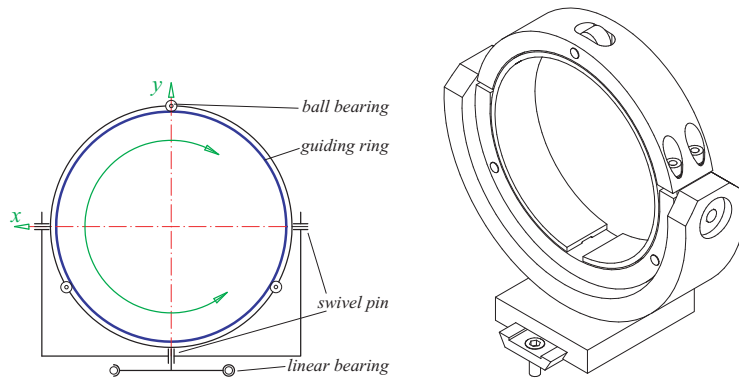
where  $F_i$  and  $M_i$  are all external forces and torques acting on the free body.

To locate an object like a bar in a kinematically stable position, a combination of two different mount types is needed. One mount permits rotations around two perpendicular and intersecting axes normal to the bar ( $x$ - and  $y$ -axis) and therefore constrains the following 4 DOF: rotation around the bar symmetry axis ( $z$ -axis) and the three linear motions. This type of mount is called “gimbal mount” (Figure 4.8).



**Figure 4.8:** Mount permitting 2DOF, rotation around  $x$ -,  $y$ -axis; *left*: schematic drawing; *right*: conceptual drawing of the gimbal mount used for the alignment bar.

Thus, permitting the remaining 4 DOF of the alignment bar, the second mount has to allow for free rotation in any direction and linear motion along the bar axis (Figure 4.9). The freedom of rotation around the bar axis is ensured by the three ball-bearings which are guiding a ring that is glued to the bar. The motion along the bar axis is carried out by a linear bearing which is fixed to the supporting frame.



**Figure 4.9:** Mount with 4DOF, rotation around  $x$ -,  $y$ - and  $z$ -axis, linear motion in  $z$ -direction possible. *left*: schematic drawing; *right*: conceptual drawing.

Both mount types restrain motion perpendicular to the bar axis. Such an arrangement of mounts allows the alignment bar to act as a free body, because no additional forces or torques are applied; each force restraining one DOF acts in the center of symmetry of the bar<sup>1</sup>.

For the reconstruction of the bar shape it is essential to know the position of the support points along the bar to an accuracy of 0.05% of the total bar length. Therefore, the

<sup>1</sup>For a cylindric object like the alignment bar is, the center of symmetry coincides with the location of the neutral fiber.

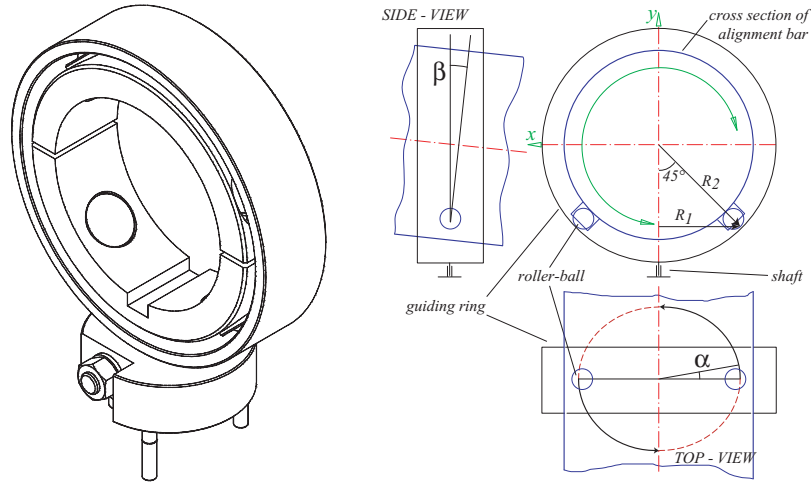


point of support in the mount permitting 4DOF has to move together with the bar, as it is the case for the mount shown in Figure 4.9. In turn, the mounting precision of this mount relative to the support frame does not need to meet this level of accuracy.

Alignment bars are supported with two kinematic mounts, allowing for the necessary degrees of freedom such that the bar can act as a free body.

#### 4.4.3 Simplified Loose Bearing (4DOF Mount)

Producing a mount where every motion is decoupled is very expensive. A study of the effects caused by a simplified loose bearing is shown in Figure 4.10. The two roller-ball-like bearings mounted on the bar rest in a guiding ring. This setup permits rotations around all three axes, as well as the required linear motion along the bar axis such that the point of support moves together with the bar. One disadvantage of this kind of mounting is that the two roller-balls tend to roll to the bottom of the guiding ring, since they are in an unstable condition of equilibrium. To prevent the guiding ring from turning, it has to be blocked once it is aligned to the bar (Figure 4.10:  $\alpha \rightarrow 0$ ).



**Figure 4.10:** Drawing and scheme of the simplified loose bearing (4 DOF mount).

Forces induced by the proper weight of the bar do not act in the center of symmetry if  $\alpha$  and  $\beta$  are non-zero (see Figure 4.10). These forces cause the two torques  $M_y(\alpha)$  and  $M_x(\beta)$ .

#### The Torque $M_y(\alpha)$

The torque  $M_y$  bends the bar in the (horizontal)  $x$ - $z$  plane. As a conservative approach, the balls on which the bar rests can be reduced to points. For this case, the torque  $M_y$

can be written as

$$M_y = -F_A \frac{\partial}{\partial \alpha} \left[ R_2 - \sqrt{R_2^2 - R_1^2 \cos^2 \alpha} \right],$$

with  $R_1 = \frac{R_2}{\sqrt{2}}$ ,

$$M_y = F_A \frac{\cos \alpha \sin \alpha R_2}{\sqrt{4 - 2 \cos^2 \alpha}}. \quad (4.2)$$

The torque  $M_y$  is proportional to the angle  $\alpha$  in the small-angle approximation:

$$\begin{aligned} M_y &= F_A \frac{\partial}{\partial \alpha} \left[ R_2 - \sqrt{R_2^2 - R_1^2} - \frac{R_1^2 \alpha^2}{2 \sqrt{R_2^2 - R_1^2}} + O(\alpha^4) \right] \\ &= F_A \frac{R_2}{\sqrt{2}} \alpha + O(\alpha^3). \end{aligned} \quad (4.3)$$

### The Torque $M_x(\beta)$

The simplified mount also affects the shape of the bar in the (vertical)  $y$ - $z$  plane. This torque

$$M_x = F_A \frac{R_2}{\sqrt{2}} \sin \beta \quad (4.4)$$

is in the small-angle approximation of the same order of magnitude as the torque  $M_y$  (4.3). Therefore the same considerations as discussed for the torque  $M_y$  are valid for  $M_x$ .

The influence of these torques on the shape reconstruction are negligible, and will be discussed in Section 6.5.2.

The simplified loose bearing induces torque which size is dependent on the orientation of the guiding ring of this mount relative to the bar.

# Chapter 5

## Calibration of the Alignment Bar

### 5.1 Introduction

The strategy specified in Section 3.4 imposes that the shape and the length of each alignment bar is measured once, and that from then on any change in length and shape is followed by the in-bar sensors. In Section 4.2 the in-bar RASNIK system was introduced which provides information about the bar deformation. The in-bar sensors need to be calibrated and, material properties related to changes in shape have to be measured once.

The tubes for the alignment bars as delivered by the manufacturer have an undefined shape. Their straightness is specified to be better than 1 mm/m, two orders of magnitude worse than the level of accuracy needed. In order to use a shape model to describe the bar shape (which assumes an initially straight bar), the initial shape of the bar needs to be known; after that, any deformations are well described by the model, as they are superimposed linearly to the initial shape. To derive any other shape of the alignment bar from the readings of its in-bar instrumentation, a calibration procedure is required. The bar calibration must therefore provide two sets of data:

- an initial shape of the bar, which is defined as the positions of all relevant points mechanically connected to the bar, and
- a prescription how to move these points when the readout values of the in-bar sensors change.

Together with the measured material properties and initial temperature values, the ball positions and RASNIK readout values represent the initial bar shape.

This chapter describes the procedures used to calibrate the in-bar instrumentation, and explains the measurements performed to obtain the initial shape of an alignment bar.

## 5.2 Measurement of Material Properties

Two material properties have to be known:

- As changes of the bar length are obtained from the bar temperature, by assuming purely thermal expansion, the expansion coefficient of the bar needs to be known.
- The resistance against deformation, i.e. the product of Young's modulus and the second moment of inertia, is needed to quantify changes in the bar shape due to additional weights (e.g. sensors).

### 5.2.1 Thermal Expansion Coefficient

The thermal expansion of an object like the alignment bar can be described as:

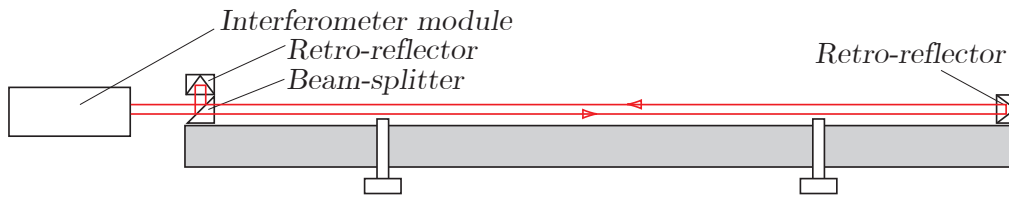
$$\delta L(T) = \alpha \int_0^L (T(z) - T_0) dz, \quad (5.1)$$

where  $\alpha$  is the thermal expansion coefficient of the bar material, and  $T_0$  is the temperature that is associated to the length  $L_0$ . As the bar temperature is measured at discrete points along the bar, the simplest way of describing the bar length is to reduce (5.1) to:

$$\delta L(T) = \alpha \sum_{i=1}^{n-1} (\bar{T}_i - T_0) l_i, \quad n = \text{number of sensors}.$$

Here,  $\bar{T}_i$  is the average temperature of two adjacent stations,  $(T_i + T_{i+1})/2$ , and  $l_i$  is the distance between stations.

Once the bar is equipped with its in-bar instrumentation, the expansion measurement is performed using a laser interferometer and the in-bar temperature sensors. The expansion coefficient  $\alpha$  can be extracted by comparing the change distance inbetween the retro-reflector (prism) and the beam-splitter (semi-transparent mirror) of one arm of the interferometer to the measured temperature.



**Figure 5.1:** Setup of the expansion measurement using a laser interferometer and the temperature sensors of the in-bar instrumentation.

Temperature variations of a few degrees (e.g. day-to-night variations) are sufficient to measure the thermal expansion coefficient of the bar material.

To obtain a precision in length prediction of  $20 \mu\text{m}$  r.m.s. over the bar length of approximately 9.6m, the temperature sensors have to measure temperature changes to  $0.1^\circ\text{C}$ .

Absolute precision is not required, since the thermal expansion of the bar material is linear in the operating temperature range; measuring temperature changes relative to the initial measurement of the bar is sufficient.

The expansion coefficient of the bar is about  $22 \mu\text{m K}^{-1} \text{m}^{-1}$ ; given for the expected temperature range of the order of  $\pm 10^\circ\text{C}$ , the expansion coefficient  $\alpha$  of the bar has to be known to within  $\pm 1\%$ . The measurements performed are discussed in Section 7.2, p.75.

### 5.2.2 Resistance against Deformation

The product of Young's modulus ( $E$ ) and the second moment of inertia ( $I$ ) can be extracted from the controlled deformation measurements. The second moment of inertia only depends on the shape of the cross section of the object being deformed and can be calculated using:

$$I = \int_r^R \xi \, dA.$$

For a hollow cylinder, like the bar is,  $I$  is isotropic and reduces to:

$$I = \frac{\pi}{64} (R^4 - r^4) \quad (5.2)$$

The measurements performed to extract the resistance against deformation will be shown in Section 7.3.1.

## 5.3 Calibration of the Bar Shape

The measurement of the initial shape of the alignment bar and the calibration of the in-bar instrumentation is performed with a large 3D coordinate measuring machine (CMM, a picture is shown in Appendix A).

The comparatively large outer diameter of the bar, as well as its non-negligible deviation from perfect circularity, makes it impractical to measure the shape directly on a CMM. Instead, small steel balls of a few mm diameter glued to the bar are used to define all relevant points on the bar. In addition, there may be further balls fixed to the bar, e.g. those on the sensor support platforms. In this procedure the real (mechanical) bar shape remains unknown; it is only known that the points on the bar move together in a well-defined way according to the mechanical properties of the bar, which is fully sufficient. In other words, use is made of the mechanical properties of the bar only where changes of the bar shape are concerned; no attempt is made to obtain its real shape, this information is used nowhere.

### 5.3.1 Calibration of the in-bar RASNIKS

The calibration is needed to relate the three individual RASNIK coordinate systems to one coordinate system, which normally is the bar coordinate system in which the point

positions of the sensor platforms are measured. Each of the three RASNIK systems has to be calibrated individually. In detail, the calibration of one in-bar RASNIK proceeds as follows:

- Balls are glued on the bar approximately in those places where the disks of the in-bar skeleton are supporting the RASNIK elements. The precision required for this is moderate, of the order of a few mm.
- The positions of all balls on the bar are measured with the CMM, relative to an appropriately chosen bar coordinate system (defined by some of the balls on the bar such that the  $z$  axis points approximately along the bar axis, and  $x$  and  $y$  are transverse to it). The in-bar RASNIKS are read out continuously during the measurement process, in order to ensure that variations in bar shape are small; afterwards, the readout values are averaged and stored together with the ball positions.
- The bar is deformed such that the readout values of the RASNIKS change significantly, i.e. with a magnitude that is of the same order as the deformation expected in the experiment. This can either be done by changing the direction of gravity (i.e. by rotating the bar around its axis), or by applying one or many external forces, or by a combination of the two. The above measurements are repeated for each deformation. While only one deformation measurement is strictly needed for the calibration, making a number of further deformations is advisable in order to cross-check the calibration result, and is needed in order to quantify its quality.
- The ball positions and the measured RASNIK values are converted into relative ones by subtracting their values each. From here on, “ball positions” and “RASNIK values” will refer to these relative measurements.

In order to obtain the relationship between ball positions and RASNIK values, quantities are computed from the measured positions of those balls that are near the respective RASNIK elements:

$$\begin{aligned} x_{\text{CMM}} &= (1 + m_{\text{CMM}}^{-1}) (x_{\text{ball,lens}} - x_{\text{ball,CCD}}) - (x_{\text{ball,mask}} - x_{\text{ball,CCD}}) \\ y_{\text{CMM}} &= (1 + m_{\text{CMM}}^{-1}) (y_{\text{ball,lens}} - y_{\text{ball,CCD}}) - (y_{\text{ball,mask}} - y_{\text{ball,CCD}}) \end{aligned}$$

where

$$m_{\text{CMM}} = \frac{z_{\text{ball,CCD}} - z_{\text{ball,lens}}}{z_{\text{ball,lens}} - z_{\text{ball,mask}}}$$

Simultaneously, the value that has been measured by the RASNIK is known to be

$$\begin{aligned} x_{\text{RAS}} &= (1 + m_{\text{RAS}}^{-1}) (x_{\text{RAS,lens}} - x_{\text{RAS,CCD}}) - (x_{\text{RAS,mask}} - x_{\text{RAS,CCD}}) \\ y_{\text{RAS}} &= (1 + m_{\text{RAS}}^{-1}) (y_{\text{RAS,lens}} - y_{\text{RAS,CCD}}) - (y_{\text{RAS,mask}} - y_{\text{RAS,CCD}}) \end{aligned}$$

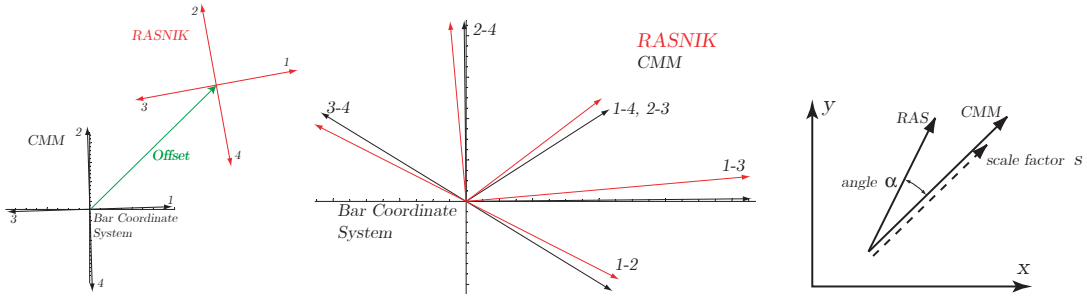
where in this case  $m$  represents the magnification of the optical system

$$m_{\text{RAS}} = \frac{z_{\text{RAS,CCD}} - z_{\text{RAS,lens}}}{z_{\text{RAS,lens}} - z_{\text{RAS,mask}}}.$$

Since the balls necessary to measure the positions of the RASNIK elements are located close to them,

$$m_{\text{CMM}} \approx m_{\text{RAS}}.$$

Before relating the individual RASNIK coordinate system to the bar coordinate system, simple corrections may be necessary for the orientation of the mask: rotations in steps of  $90^\circ$ , and reverting the orientation of one of the coordinate axes<sup>1</sup>. After applying this corrections to the RASNIK values, combinations of all measurements are built by subtracting each measurement from all the others. The so obtained  $\frac{1}{2}n(n-1)$  possible combinations can be expressed as the vectors  $(x_{\text{CMM}}, y_{\text{CMM}})$  and  $(x_{\text{RAS}}, y_{\text{RAS}})$  in the two-dimensional  $x$ - $y$  plane. The calibration then consists of making them coincide by a rotation around the origin, with angle  $\alpha$ , and by multiplication with a scaling factor<sup>2</sup>,  $s$  (see Figure 5.2).



**Figure 5.2:** *left:* RASNIK-measured values for 4 different deformations and related CMM values; *middle:*  $\frac{1}{2}n(n-1)$  combinations built from the measured values; *right:* illustration of the two RASNIK calibration parameters, the rotation angle  $\alpha$  describing the rotation of the RASNIK coordinate system with respect to the bar coordinate system, and the scaling factor  $s$  describing the ratio of length scales between the two coordinate systems. For clarity of presentation, the deviation of  $s$  from the ideal value of 1 has been strongly exaggerated (it is typically less than 1%).

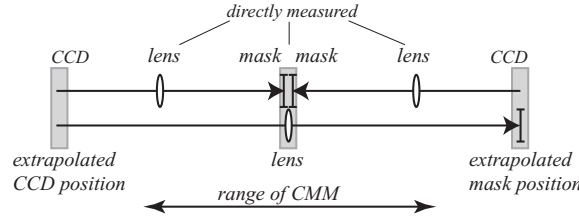
The angle  $\alpha$  and the scaling factor  $s$  are computed as the mean values of all combinations, weighted by the lengths of the individual vectors. These two calibration constants per RASNIK fully characterize the bar, in conjunction with the set of numbers describing the initial shape. Using these values, any change in the RASNIK readings  $(x_{\text{RAS}}, y_{\text{RAS}})$  can be translated into a change in the quantity  $(x_{\text{CMM}}, y_{\text{CMM}})$ , from which the changes of positions of the balls at RASNIK elements can be derived, which in turn serve as the input to the shape reconstruction procedure for changes of all the other relevant point positions, which are finally superimposed to the initial shape.

All three elements for short RASNIKS can directly be measured with the CMM. To obtain a calibration for the long RASNIK (which exceeds the range of the CMM), the

<sup>1</sup>Reverting the orientation of a coordinate axis becomes for instance necessary, where the axis of the RASNIK coordinate system is antiparallel to the bar axis in the bar coordinate system, which is at least for one RASNIK the case.

<sup>2</sup>The scaling factor serves mainly to absorb the initial inaccuracy of gluing balls to the bar in places where RASNIK elements are inside the bar, i.e. the approximation made in assuming  $m_{\text{CCD}} \approx m_{\text{RAS}}$ . Further explanation is given in Section 6.6.1, p.71. Typical values are  $s = 0.99 \dots 1.01$ .

middle of the bar is measured and the positions of masks and CCD are extrapolated using the measurements of the already calibrated short RASNIKS.



**Figure 5.3:** Extrapolation of the positions of the CCD and the mask for the long RASNIK.

The calibration of the in-bar RASNIKS provides the necessary parameters to relate the individual RASNIK coordinate systems to one bar coordinate system, in which all the ball patterns are measured.

Six bars have been calibrated, results of the RASNIK calibration of the first two bars are listed in Table 5.1.

| bar       | RAS<br># | $\alpha$<br>[rad] | $s$   | $\langle \Delta x \rangle$<br>[ $\mu\text{m}$ ] | $\langle \Delta y \rangle$<br>[ $\mu\text{m}$ ] | $\sigma_x$<br>[ $\mu\text{m}$ ] | $\sigma_y$<br>[ $\mu\text{m}$ ] |
|-----------|----------|-------------------|-------|-------------------------------------------------|-------------------------------------------------|---------------------------------|---------------------------------|
| EO<br>up  | 1        | 0.797             | 1.008 | -3.4                                            | -0.4                                            | 6.7                             | 2.8                             |
|           | 2        | 0.789             | 0.998 | 0.5                                             | -1.2                                            | 2.8                             | 2.7                             |
| EO<br>low | 1        | 0.779             | 0.995 | -6.4                                            | 18.5                                            | 25.6                            | 26.4                            |
|           | 1        | -0.031            | 1.010 | 5.0                                             | -1.4                                            | 9.5                             | 7.3                             |
|           | 2        | -0.029            | 0.996 | -2.6                                            | -1.8                                            | 5.1                             | 4.3                             |
|           | 3        | -0.031            | 0.997 | -4.4                                            | 6.9                                             | 8.7                             | 13.0                            |

**Table 5.1:** Calibration results for two of the tested bars. The table lists:  $\alpha$ , the rotation angle between the RASNIK and the bar coordinate systems;  $s$ , the scaling factor between the two;  $\langle \Delta x, y \rangle = \langle x, y_{\text{ball}} - x, y_{\text{RAS}} \rangle$  the mean difference between CMM-predicted and actual RASNIK readings, and  $\sigma_{x,y}$ , the r.m.s. of the difference (assuming a mean difference of zero).

### 5.3.2 Initial Shape Measurement

The initial shape can be understood as the positions of all ball mechanically connected to the bar, measured in the same coordinate system as the one which in-bar instrumentation is referred to. The initial shape includes also the deformation due to gravity. To extract the gravitational deformation from the initial shape the bar can be measured in two different orientations. Measurements of this kind have been performed to prove the analytic shape model; this is discussed in Section 6.3.1



Due to the limited range of the CMM, the bar has to be measured in two portions. These two portions have to be put together in order to obtain the full bar shape.

Three balls glued to the bar define the local bar coordinate system. These balls are located near the middle of the bar and separated such that they can be reached by the CMM in each measurement. Thus when combining the two portions of the bar the measurement of the same local coordinate system can be used. At the precision needed, it is inevitable that the bar changes its shape when moving it relative to the CMM, in order to measure the second portion. The calibrated in-bar instrumentation is used to correct for this change in deformation.

During the measurement, the bar has to be blocked in the middle and the ends. This is necessary since the probe head of the CMM touches the object it measures with a triggering force of about 0.07 N ( $\sim 7$  g). At the extremities of the bar, this force corresponds to a deformation of the bar of the order of 30  $\mu\text{m}$ . In order to avoid any influence on the bar shape, the blocking of the bar is controlled with the readings of the in-bar instrumentation.

The initial shape of the bar is the set of all measured balls mechanically connected to the bar, in combination with the measured values of the calibrated in-bar instrumentation.



# Chapter 6

## Bar Shape Reconstruction

### 6.1 Introduction

The shape of alignment bars changes from the initial shape measurement, when they are mounted in the detector, where the discrepancy can reach a few mm. An algorithm is needed to interpolate these changes in shape between the points measured by the in-bar instrumentation. The algorithm used to interpolate the bar deformation and the reconstruction of the bar shape (i.e. the positions of the balls glued to the sensor platforms) will be described in this chapter.

Calling that a force of only 0.07 N ( $\sim 7$  g) acting at the end of the bar causes a deformation of about 30  $\mu\text{m}$ , it is clear that such little forces cannot be accounted for. Thus looking for a way to interpolate the bar shape in-between the measured points provided by the in-bar instrumentation is a possible solution.

### 6.2 Description of the Length

The length of alignment bars changes for two reasons:

- the bulk effect is the change in bar-length due to temperature variations.
- a smaller effect is the change in length due to the bar's proper weight, if the bar is mounted in an inclined orientation.

#### 6.2.1 Thermal Expansion

To address the predictability of the bar length in an inhomogeneous temperature environment, the bar temperature is measured in 9 positions along the bar. The linear model

$$\delta L_{\text{Bar}}(T) = \alpha_{\text{Bar}} \sum_{i=1}^8 \left( \frac{T_i + T_{i+1}}{2} - T_{\text{ref}} \right) L_i \quad (6.1)$$

to predict the changes in length is sufficient if the temperature gradient along the bar is less than  $0.5 \text{ K m}^{-1}$ . Here  $T_i$  is averaged temperature over the three sensors at the position  $i$  of the bar.  $T_{\text{ref}}$  is the temperature the bar had when its initial length  $L_i$  was measured. The difference between two adjacent stations  $L_i$  corresponds to the distance between the sensor  $i$  and the sensor  $i + 1$ .  $\alpha_{\text{Bar}}$  is the thermal expansion coefficient of the used bar material.

## Simulation

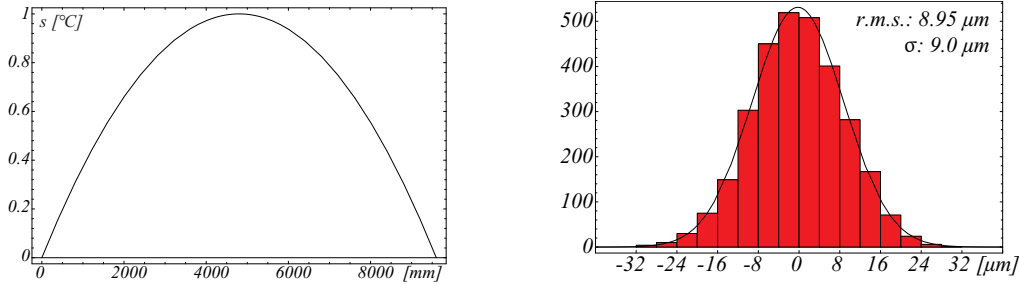
Changes in bar length in an ambient temperature environment and due to linear thermal gradients are accurately described by the linear model (Equation 6.1). The predictability of the bar length under nonlinear thermal gradients can be estimated using a Monte Carlo simulation. The function describing the thermal gradient is evaluated at the discrete points where the temperature is measured and the expansion of the bar is reconstructed from this information. This can then be compared to the true bar length derived from the full integrated temperature distribution:

$$\delta L_{\text{Bar}}(T) = \alpha_{\text{Bar}} \int_0^L dz T(z) - T_{\text{ref}}. \quad (6.2)$$

Two different scenarios have been simulated under the assumption that the expansion coefficient of the bar material is known precisely and the temperature sensors are accurate to  $0.1 \text{ K}$  r.m.s. For the first simulation the function

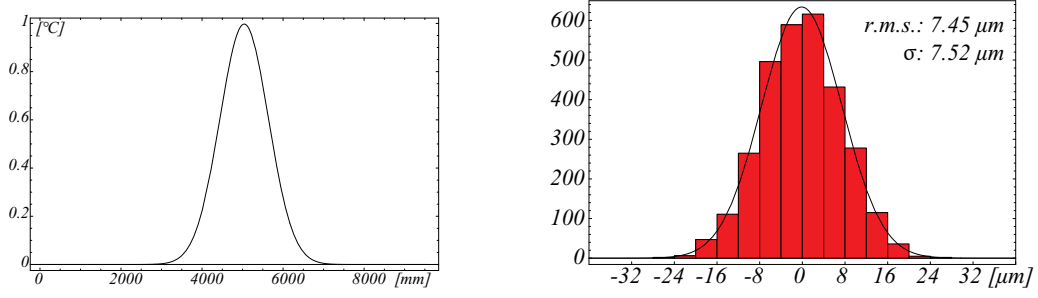
$$T(z) = 4 \frac{s}{l} (z - \frac{z^2}{l}) \quad (6.3)$$

with a randomly changing amplitude  $s$ , such that  $\bar{s} \approx 0.5 \text{ K m}^{-1}$  was used.



**Figure 6.1:** Simulated error in length prediction of a nonlinear thermal gradient; average gradient  $0.5 \text{ K m}^{-1}$  r.m.s., 9 sensors equally spaced along the bar. *left:* gradient function used for the simulation; *right:* difference between linear model and integrated temperature distribution.

To simulate the effect of a local heat source, a Gaussian distribution with constant shape (amplitude  $1 \text{ K}$ ,  $600 \text{ mm}$  f.w.h.m.) randomly placed along the bar has been chosen. The obtained accuracy in predicting the bar length is shown in Figure 6.2.



**Figure 6.2:** Simulated error in length prediction of a nonlinear thermal gradient, 9 sensors equally distributed along the bar; *left*: gradient function used for the simulation; *right*: difference between the linear model and integrated temperature distribution.

### 6.2.2 Elastic Stretching

Changes in length due to the bar's proper weight are a minor contributor and can be calculated using Hooke's Law. Once the weight distribution and the inclination of the bar is known, the expansion,  $u$ , of the bar under its own weight can be calculated using:

$$A E u''(z) = -q \quad (6.4)$$

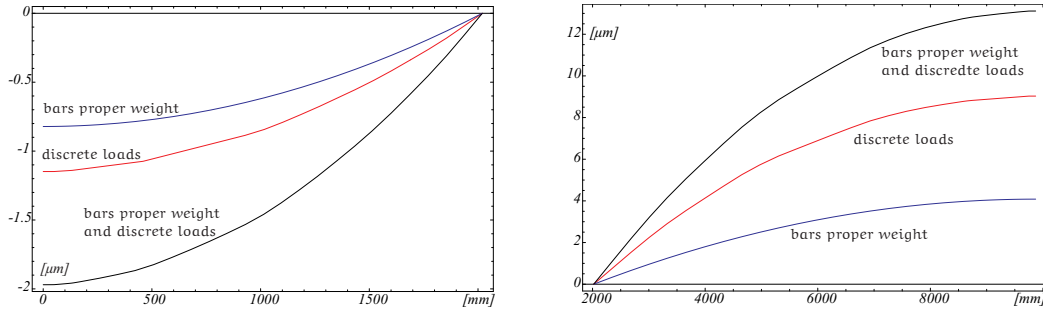
where  $A$  represents the area of the tube cross section,  $E$  is Young's modulus and  $q$  the load distribution. The boundary conditions

$$\begin{aligned} u(z_0) &= 0 \\ u'(l) &= 0 \end{aligned}$$

reflect the fact that the gimbal mount is restraining linear motion at  $z = z_0$  and that the end of the bar ( $z = l$ ) is not exposed to forces. Discrete forces from the sensors and platforms mounted to the bar can be added using Dirac's delta distributions. Thus Equation 6.4 can be solved:

$$u(z) = -(A E)^{-1} \int_{z_0}^l q(z - z_0) + \sum_{i=1}^n F_i \delta(z - z_i + z_0) dz \quad , n \dots \text{number of forces.} \quad (6.5)$$

Figure 6.3-right shows the expected expansion of an ATLAS-like bar due to its proper weight and the discrete loads, mounted in the EM layer and inclined by 67.5 degrees. The contributions to the expansion from the bars proper weight and from the discrete loads of the sensors and platforms are plotted separately. Here the bars proper weight also includes the loads from the sensor cables and the in-bar instrumentation.



**Figure 6.3:** *left:* compression of a bar under its own weight supported at the gimbal mount at  $z_0 = 2020$  mm; *right:* elastic stretching of a bar under its own weight and supported at the gimbal mount at  $z_0 = 2020$  mm.

The upper part of the bar ( $z = 0$  until  $z = z_0$ ) is compressed under its own weight. For this plot, Young's modulus in Equation 6.5 has to be replaced by the compression modulus, which is for the material used 75.2 GPa ( $\sim 4.2\%$  larger than Young's Modulus [DUB:01]). Figure 6.3-left shows this compression for a bar mounted in the EM layer.

## 6.3 Description of the Shape

### 6.3.1 Analytic Bar Shape Model

The ideal alignment bar can be considered as a straight tube, perfect in circularity with a constant cross-section. The deformation of such an ideal bar, when exposed to external forces, can be calculated using Bernoulli's suppositions [ROS:93], that cross-sections of the bar remain planar and perpendicular to the neutral line of the bar independent of its deformation. These suppositions are sufficiently precise for tall objects and provide exact solutions for simple bending. Assuming a tall object where the product of Young's modulus and the second moment of inertia remains constant, the deformation  $w(z)$  due to external forces can be written as:

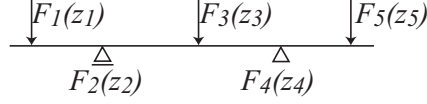
$$EIw^{(4)}(z) = q(z), \quad (6.6)$$

where  $E$  is Young's modulus,  $I$  is the moment of inertia, and  $q(z)$  represents a load distribution. Equation 6.6 is linear in  $w$ , thus its solutions can be superimposed. Consequently, the different contributions to the deformation of the alignment bar can be calculated separately: the description of the deformation of the bar due to the presence of discrete forces and the description of its deformation due to a continuous load distribution (like the weight of the bar itself).

### Discrete Forces

Alignment bars are supported in two points and exposed to discrete forces which can act anywhere over the full length of the bar. The various discrete forces are caused by

the mass of the sensor platforms and the sensors mounted onto the platforms. The most general case that needs to be considered is a tube which is supported in two points and exposed to three external forces, as shown in Figure 6.4. The evaluation of this case will be shown below. The calculations can then easily be extended to an arbitrary number of forces by superimposing results for three external forces as often as required.



**Figure 6.4:** Straight tube supported in two points and exposed to three external forces  $F_1$ ,  $F_3$ ,  $F_5$  and two forces  $F_2$ ,  $F_4$  responding in the support points.

Figure 6.4 shows that in total five forces are deforming the bar: three external forces ( $F_1$ ,  $F_3$ ,  $F_5$ ) and the two forces ( $F_2$ ,  $F_4$ ) responding in the support points. The two responding forces can be calculated using the kinematic conditions of equilibrium (Equation 6.7), i.e. that the sum of all torques as well as the sum of all forces have to be zero:

$$\sum_n M_n = 0, \quad \sum_n F_n = 0, \quad n \in [1, 5]. \quad (6.7)$$

To calculate the deformation of the bar, Equation 6.6 has to be applied to each section between two adjacent forces. Hence the six resulting equations can be written as:

$$EI w_i'''(z) = \sum_{n=0}^i F_n(z_n) \quad i \in [0, 5], \quad (6.8)$$

where  $i$  denotes one of the six sections of the bar, and  $F_0 = 0$ . The Equations 6.8 are coupled using the following static boundary conditions:

$$\begin{aligned} w_2(z_2) &= 0 \\ w_4(z_4) &= 0 \\ w_i(z_i) &= w_{i+1}(z_i) \\ w_i'(z_i) &= w_{i+1}'(z_i). \end{aligned} \quad (6.9)$$

Since no external torque is introduced into the system, the remaining kinematic boundary conditions can be written as:

$$\begin{aligned} w_0''(0) &= 0 \\ w_5''(l) &= 0 \\ w_i''(z_i) &= w_{i+1}''(z_i). \end{aligned} \quad (6.10)$$

The solutions of the differential equations 6.8 are 6 polynomials of maximum third order. To obtain a continuous function over the full length of the tube, these polynomials can be combined using Heaviside distributions,

$$w(x) = \frac{1}{EI} \sum_{i=0}^5 w_i \Theta[(z_{i+1} - z)(z - z_i)], \quad (6.11)$$

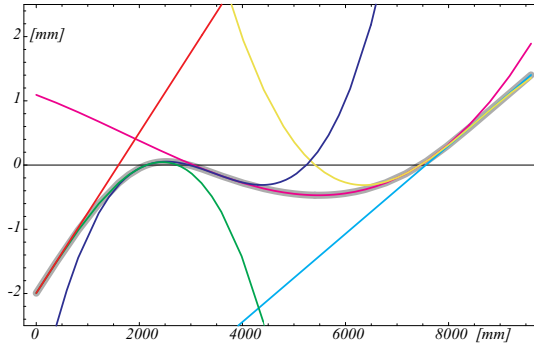
where  $z_0 = 0$  and  $z_6 = l$ . The deformation  $w(z)$  is a function of the positions of the support points  $(z_2, z_4)$ , and the three external forces  $(F_1(z_1), F_3(z_3), F_5(z_5))$ :

$$w = \frac{1}{6(z_4 - z_2)EI} [w_0\Theta[z(z_1 - z)] + w_1\Theta[(z - z_1)(z_2 - z)] + w_2\Theta[(z - z_2)(z_3 - z)] \\ + w_3\Theta[(z - z_3)(z_4 - z)] + w_4\Theta[(z - z_4)(z_5 - z)] + w_5\Theta[(z - z_5)(l - z)]] \quad (6.12)$$

where

$$\begin{aligned} w_0 &= (z_2 - z_4)(z_2 - z_1)(2z_2z_4 - z_2z - 2z_4z - z_1(z_2 - 3z) - z_1^2)F_1 + \\ &\quad (z_2 - z)[(z_2 - z_3)(z_4 - z_3)(z_2 - 2z_4 + z_3)F_3 + (z_2 - z_4)^2(z_4 - z_5)F_5], \\ w_1 &= (z_2 - z)[(z_2 - z_4)(2z_2z_4 - z_2z - z^2 - z_1(z_2 + 2z_4 - 3z))F_1 + \\ &\quad (z_2 - z_3)(z_4 - z_3)(z_2 - 2z_4 + z_3)F_3 + (z_2 - z_4)^2(z_4 - z_5)F_5], \\ w_2 &= (z_2 - z)[(z_4 - z)(z_2 - 2z_4 + z)(z_2 - z_1)F_1 - \\ &\quad (z_4 - z_3)(2z_2(z_4 - z) + z^2 - 2z_4z_3 + z_3^2)F_3 - (2z_2 - z_4 - z)(z_4 - z)(z_4 - z_5)F_5] \\ w_3 &= (z_4 - z)[(z_2 - z)(z_2 - 2z_4 + z)(z_2 - z_1)F_1 - \\ &\quad (z_2 - z_3)(2z_2z_4 + z(z - 2z_4) - 2z_2z_3 + z_3^2)F_3 - (z_2 - z)(2z_2 - z_4 - z)(z_4 - z_5)F_5], \\ w_4 &= (z_4 - z)[(z_2 - z_4)^2(z_2 - z_1)F_1 + (z_2 - z_3)(2z_2 - z_4 - z_3)(z_3 - z_4)F_3 - \\ &\quad (z_2 - z_4)(2z_2z_4 - z(z_4 + z) - z_5(2z_2 + z_4 - 3z))F_5], \\ w_5 &= (z_4 - z)(z_2 - z_4)^2(z_2 - z_1)F_1 + (z_4 - z)(z_4 - z_3)(z_3 - z_2)(z_4 - 2z_2 + z_3)F_3 + \\ &\quad (z_2 - z_4)(z_4 - z_5)(2z_2(z_4 - z) - z_4z - z_5(z_4 - 3z) - z_5^2)F_5. \end{aligned} \quad (6.13)$$

Figure 6.5 illustrates the contributions of the individual polynomials to the solution for an arbitrarily chosen deformation.



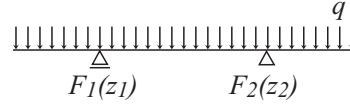
**Figure 6.5:** Illustration of the six individual solutions for the six sections of the bar.

## Continuous Load

The algorithm to calculate the deformation of a bar due to a continuous load distribution, e.g. its own weight, is similar to what was shown above. Figure 6.6 illustrates that the



continuous load distribution  $q$  has to be in kinematic equilibrium with the two responding forces ( $F_1$ ,  $F_2$ ) in the support points.



**Figure 6.6:** Straight tube supported in two points and exposed to a continuous load distribution  $q$ .

The three resulting equations:

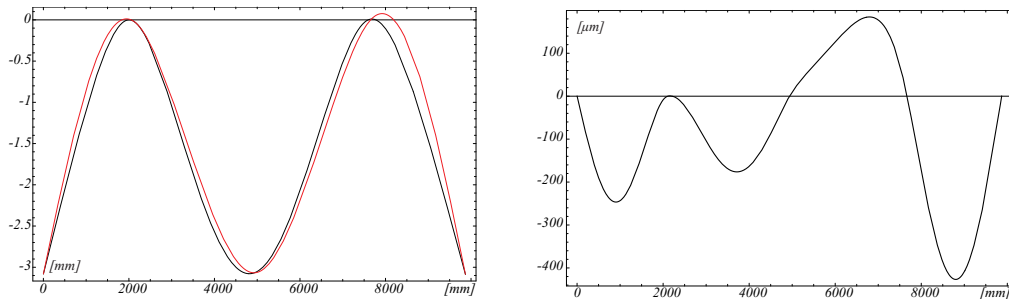
$$EIw_i(z)''' = qz + \sum_{n=0}^i F_i(z_i), \quad i \in [0, 2], \quad (6.14)$$

are again coupled using static and kinematic boundary conditions. The result is:

$$w = \frac{q}{24EI} \{ (z - z_1) [4z_2^2 l - z_2^3 - 2z_2 l^2 + z^3 + z_1^2 (z - z_2) + z_1 (2l^2 + z^2 - z_2^2 - 4z_2 l)] \Theta[z(z_1 - z)] + \frac{(z_1 - z)(z_2 - z)}{z_1 - z_2} [z_1^3 - z_2^3 + 4z_2^2 l - 2z_2 l^2 + z_1^2 z - z_2^2 z + 4z_2 l z - 2l^2 z - z_2 z^2 + z_1 (4l^2 + z^2 - 8z_2 l)] \Theta[(z - z_1)(z_2 - z)] + (z_2 - z) [z_1^3 + z_1^2 z_2 + 2z_2 l^2 + z_1 (z_2^2 - 8z_2 l + 4l^2) - z(z_2^2 + 4z_2 l - 6l^2) - z^2(z_2 + 4l) - z^3] \Theta[(z - z_2)(l - z)] \}.$$

## 6.4 Shape Correction (Virtual Load Model)

In Section 4.2 in-bar sensors have been introduced, implemented to monitor changes in the bar deformation. From the moment the initial shape is measured, the calibrated in-bar sensors provide shape information in 5 discrete points along the bar. Since alignment sensors are positioned all over the bar, the shape of the bar between these measured points is of major interest. Different simple models to interpolate the shape fail regarding the required precision. Figure 6.7 shows the interpolation error when using a cubic spline fit, (which even has a mathematical structure similar to the analytic solution).



**Figure 6.7:** Comparison between a cubic spline interpolation and the mechanical shape model; *left:* deformation calculated for an ATLAS-like EM-bar; *right:* difference between analytic model and cubic spline fit

The way out is to introduce the mechanical properties of the bar into the interpolating function and resort to a shape prediction that allows to handle the possible changes based on the forces acting on the bar. The concepts to describe the bar shape by means of forces acting on the bar have been derived in Section 6.3.1. This can now be used the other way round to calculate forces for a known deformation. The deformation is measured in five points along the bar, thus three forces or three loads can be used to describe the changes in deformation<sup>1</sup>. These “*virtual forces*” or “*virtual loads*” then represent the missing load distribution absorbed in three effective parameters.

The analytic solution of this idea can be calculated as follows: depending on the positions of the individual RASNIK elements, the corresponding polynomials  $w_i$  (Equations 6.13) can be inserted into the three Equations 4.1 (p.41) describing the relative position of 5 points along the bar as a function of the RASNIK readings  $(\alpha, \beta, \gamma)$ . Thus, the RASNIK readings can be expressed as a function of three linear load distributions,  $\alpha, \beta, \gamma = f(q_1, q_2, q_3)$ . Extracting the virtual loads  $q_i$  and inserting them into Equation 6.12 yields three equations for the linear loads as functions of the RASNIK readings  $q_i = f_i(\alpha, \beta, \gamma)$ . The free parameters in the three resulting equations are the measured values from the in-bar RASNIKS.

A general solution, allowing for the short-RASNIK lenses to be not placed in the support points, grows very large due to the number of bar parameters involved (9 parameters defining the locations of the RASNIKS, 2 defining the support points).

A more general way to solve this problem is to numerically fit the equation

$$x = d + z k + w(z) \quad , w(z) \dots \text{Equation 6.12} \quad (6.15)$$

to the five points derived from the in-bar instrumentation. The fit is in practice as accurate as the analytical solution, since the number of free parameters is equal to the number of data points.

To describe first and second mode deformations of the bar, two mechanical models are appropriate:

- Three discrete forces can be placed such that one force is acting at each end of the bar, and one force is acting in the middle between the two support points (which is not necessarily the middle of the bar).
- Three linear loads, in the bar sections from the ends to the support points, and inbetween the support points.

Using linear loads to describe the changes in deformation has practical advantages, e.g. the contribution of the proper weight of the bar to the deformation needs not to be accounted for separately: It is absorbed into the virtual load model.

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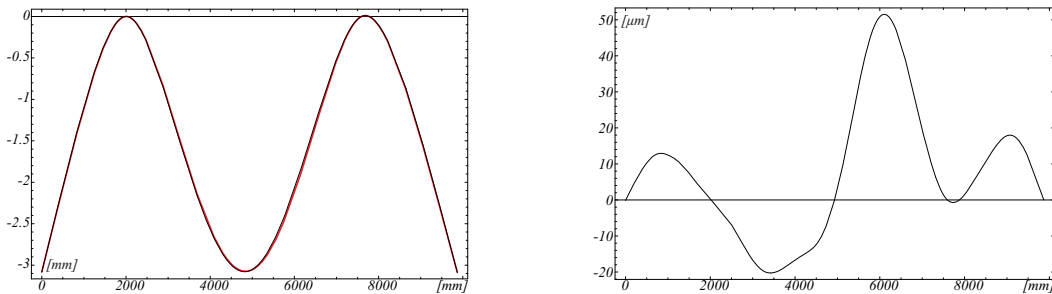
<sup>1</sup>In total 5 forces are acting on the bar, three can be chosen freely, and the two forces responding in the support points have to be in kinematic equilibrium.

### 6.4.1 Inclined Positions

The initial shape of all alignment bars has to be measured in horizontal positions. For bars which are mounted in inclined positions the change in shape due to the effective scaling of gravity transverse to the bar has to be taken into account. Various loads contribute to the bar deformation:

- the weight of the tube itself
- the weight of the in-bar instrumentation
- the weight of the sensor platforms
- the weight of the sensors and the cables connecting the sensors (both are attached to the bar only after the initial shape measurement).

To describe the change in deformation from the initial shape measurement to the situation where the bar is mounted in inclined position, the load distribution on the bar has to be known. Local deformations induced by discrete masses like the sensor platforms cannot be measured by the in-bar instrumentation, and thus it is not sufficient merely using the in-bar sensors to reconstruct the bar shape. Figure 6.8 shows the interpolation error when describing the deformation of an ATLAS-like EM bar only with three linear loads. Still, compared to Figure 6.7, the interpolation error is already reduced by one order of magnitude.



**Figure 6.8:** *left:* relative deformation of an ATLAS like bar; calculated with 35 discrete forces, acting in the positions of the platforms; same deformation expressed with three linear loads; *right:* deformation due to discrete forces subtracted from the deformation reconstructed with three linear loads; This example corresponds to measuring the bar in horizontal position, and inclining it by  $90^\circ$ .

A proper solution is to model the deformation in two steps:

- Discrete forces are introduced by the sensors and the platforms. The weight of these is measured once and serves to calculate the expected change in deformation, using Equation 6.11.

- In a second step any remaining forces not accounted for are absorbed in the virtual load model, which uses the in-bar sensor readings as input. The quantity of discrete forces absorbed into the virtual loads is expected to be small, and thus the interpolation error is also small.

Both solutions are superimposed to describe the actual change in deformation.

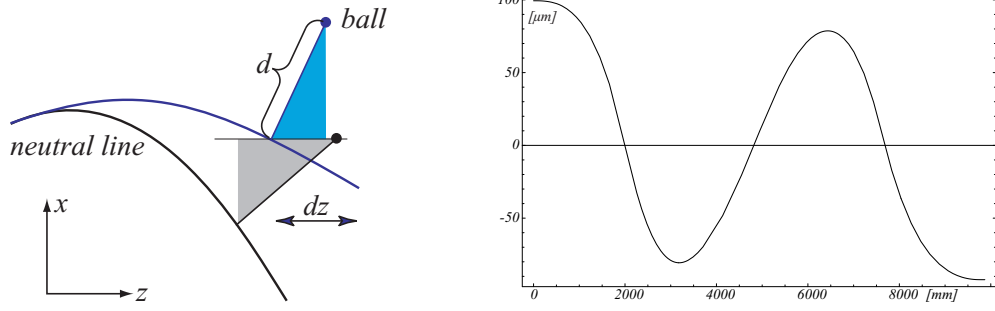
While the first step needs to be performed only once, the second one is continuously applied to follow the changes in the experiment.

The shape reconstruction of an inclined bar is performed as follows: calculate a first estimate of changes in deformation, based on the known mass distribution of sensors and platforms. Correct sensor values by the deformation calculated with the first estimate. Use the corrected in-bar sensor readings as input for the virtual load fit and superimpose the estimated deformation and the virtual load fit to obtain the actual change in bar deformation.

#### 6.4.2 Reconstruction of Platform Positions

Section 6.4.1 describes a possible way to calculate the deformation responsible for the changes of the bar shape. To reconstruct from this deformation the bar shape, which is the position of all relevant points mechanically connected to the bar, one has to perform one more iteration before superimposing the changes to the initial shape.

The analytic bar shape model describes changes of the neutral line of the bar. For a tall cylindrical object, like the alignment bar, the neutral line can be assumed to be in the center of the bar. Objects that are mounted at a certain distance from the neutral line shift along the bar axis when the bar changes its shape. Since cross-sections of the bar remain planar and perpendicular to the neutral line when the deformation of the bar changes, the shifting of objects mounted to the bar scales linearly with their distance from the neutral line. Figure 6.9 shows this shift for a ball that is glued to the outer wall of the bar ( $\sim 48$  mm away from the bar center).



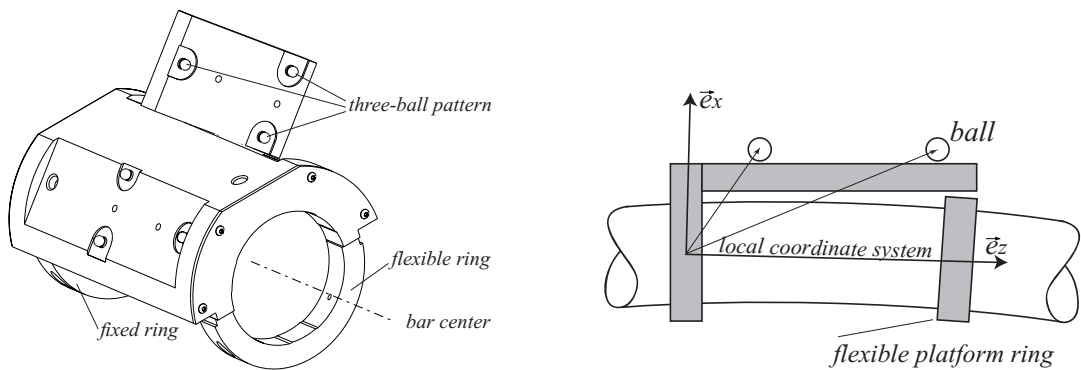
**Figure 6.9:** Shifting of a point related to the bar along the bar axis; *left*: illustration; *right*: shift of a ball mounted at a distance of 48mm relative from bar center, calculated for the deformation shown in Figure 6.8-left.

For **balls directly glued** to the bar like the balls defining the bar coordinate system, or the positions of the RASNIK elements, the shifting along the bar axis can be calculated using the first derivative of the function  $f(z)$ , describing the total change in deformation:

$$\phi = \arctan\left(\frac{\partial}{\partial z}f(z)\right),$$

$$\begin{pmatrix} z \\ x \end{pmatrix}_{\text{new}} = \begin{pmatrix} z \\ f(z) \end{pmatrix} + \begin{pmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{pmatrix} \begin{pmatrix} 0 \\ d \end{pmatrix}. \quad (6.16)$$

**Sensor platforms** are mounted with two rings onto the bar; for large platforms, one ring is flexible. Thus deformations of the bar are not transferred directly to the three-ball patterns on the platform. Positions of platforms are defined by the two platform rings. A large sensor platform used to mount one radial and one polar BCAM to the bar is shown in Figure 6.10.



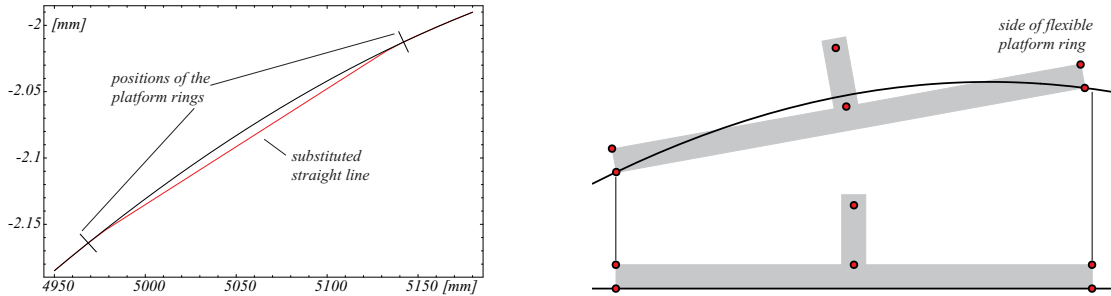
**Figure 6.10:** *left*: drawing of a polar/radial alignment platform; *right*: illustration of the platform and the implementation of a local coordinate system.

To reconstruct the positions of the three ball patterns glued to a platform, a local coordinate system is fixed to the positions of the two platform rings. Bar deformations are then

translated to changes in position and orientation of the local coordinate system, which serve to reconstruct the new ball positions. The corrections have to be applied in both coordinates perpendicular to the bar axis. Since the angular corrections are small, the transformations can be considered as commutative, and hence applied individually. The calculation of the transfer matrix performs as follows: the origin of the local coordinate system is fixed in the center of the platform ring that is not flexible. The unit vector  $\vec{e}_z$  of the local coordinate system is defined by the approximate centers of the two platform rings, one vector,  $\vec{p}_y$ , approximately perpendicular to  $\vec{e}_z$ , points in the  $y$  direction of the bar coordinate system. The outer product of these two vectors defines the unit vector  $\vec{e}_x$ , which in turn can be used to define  $\vec{e}_y$ . The transfer matrix is then calculated relative to the unitary system provided by the bar coordinate system.

$$\begin{aligned}\vec{e}_z &= \text{defined by centers of platform rings} \\ \vec{p}_x &= (1, 0, 0)^T \\ \vec{p}_y &= \|\vec{e}_z \times \vec{p}_x\| \\ \vec{e}_x &= \|\vec{p}_y \times \vec{e}_z\| \\ \vec{e}_y &= \|\vec{e}_z \times \vec{e}_x\|\end{aligned}$$

The fact that the platforms remain straight can also be implemented by modifying the function  $f(z)$ , such that the sections where platforms are mounted on the bar are replaced by straight lines. Figure 6.11 illustrates the modification for a part of  $f(z)$ :



**Figure 6.11:** Reconstruction of ball patterns glued to a platform; *left*: modified function  $f(z)$  describing the total change in deformation; *right*: illustration of the platform reconstruction for an exaggerated deformation.

The behavior of platforms mounted on the bar is accounted for in the bar shape model by locally substituting the analytic shape with a straight line.

## 6.5 Understanding of False Shape Effects

Torque that acts on the bar, influences its shape in two different ways. Torque applied perpendicular to the bar axis deforms the bar; Torsion (i.e. torque applied parallel to the bar axis) twists the bar.

The influence of these effects, which are unaccounted for in the shape reconstruction is discussed here.

### 6.5.1 Torsion

Due to the concept of the initial shape measurement, i.e. measuring three-ball patterns related to the bar, the alignment sensors can be mounted to the bar after the CMM measurement. Some sensors induce, besides a deformation, a twist of the bar. The torsion ( $\phi$ ) of a cylindrical object can be calculated as:

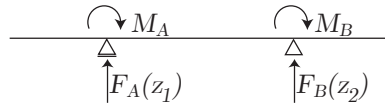
$$\phi = \frac{\Gamma L}{2\pi G \int_r^R \xi^3 d\xi}$$

where  $L$  is the torsion length,  $G$  the shear modulus, and  $\Gamma$  the torque induced by the sensor weight acting in a certain distance from the bar center. The maximum possible torsion is obtained with a BCAM mounted at the end of the bar. For this case the torsion is  $28 \mu\text{rad}$ , about  $1/2$  of the mounting precision required for BCAMs. Torsion cannot be measured at the required accuracy with the in-bar instrumentation. Torsion of a real alignment bar is influenced by the deviation of the bar from a straight line and decreases with the inclination of the bar.

### 6.5.2 Torque

Torque is induced from the simplified bar mount which has been described in Section 4.4.3. Torque deforms a bar in a qualitatively different way than loads. The error in the shape reconstruction when describing a bar deformed by torque with the virtual load model is discussed here.

The elastic line  $w(z)$  of the bar due to torques  $M_A$  and  $M_B$  in the support points can be calculated with the solutions of the differential equations (6.17):



**Figure 6.12:** Torques  $M_A$  and  $M_B$  acting on a straight tube.

$$\begin{aligned} w_1^{(4)}(z) &= q(z), \\ w_2^{(3)}(z) &= \int q(z) dz - F_A, \\ w_3^{(3)}(z) &= \int q(z) dz - F_A - F_B. \end{aligned} \tag{6.17}$$

If no linear load is applied,  $q(z) = 0$ . Torque is introduced with the boundary conditions:

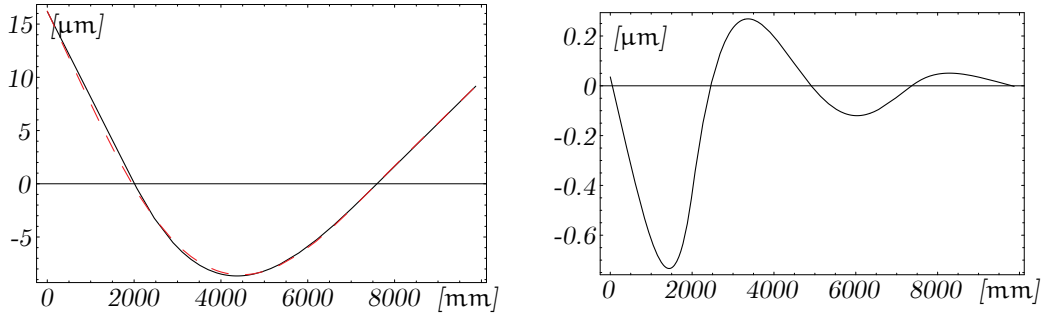
$$\begin{aligned} w_1''(0) &= 0, \quad w_1(a) = 0, \quad w_3(b) = 0, \\ w_1(a) &= w_2(a), \quad w_1'(a) = w_2'(a), \quad w_1''(a) = w_2''(a) + M_A, \\ w_2(b) &= w_3(b), \quad w_2'(b) = w_3'(b), \quad w_2''(b) = w_3''(b) + M_B, \end{aligned}$$

the elastic line  $w(z)$  can be written as:

$$-E I w(z) = w_1 \theta(a - z) \theta(z) + w_2 \theta(b - z) \theta(z - a) + w_3 \theta(l - z) \theta(z - b). \quad (6.18)$$

### Influence on shape reconstruction

In Section 4.4.3 the torque induced by the simplified loose mount has been derived. Assuming this mount is misaligned by 20 mrad, the induced torque for an ATLAS-like EM bar is 0.229 Nm. Figure 6.13 shows the deformation of the bar due to this torque, compared to the deformation calculated with the linear load model under the assumption that the deviations provided by the in-bar instrumentation are known exactly.



**Figure 6.13:** *continuous line:* bar shape due to a torque  $M_A = 0.229$  Nm; *dashed line:* reconstructed bar shape with 3-load model; *right:* residual error in shape reconstruction.

The error in prediction reduces to the difference in the shapes between the two elastic lines. This uncertainty in reconstructing the shape is moderate and of the order of less than  $1 \mu\text{m}$ .

Torque induced by the simplified loose bearing is moderate given that any misalignment of the loose bearing relative to its alignment bar stays below 20 mrad. Even this unlikely situation of misalignment in either direction causes errors in prediction of the bar shape of less than  $1 \mu\text{m}$ .

### 6.5.3 Friction in the Kinematic Mounts

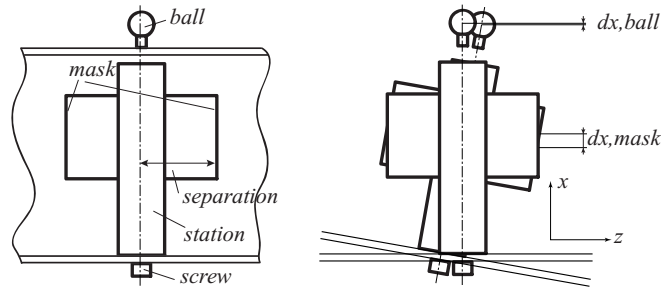
Forces that extend or contract the bar (due to friction of the bearings in longitudinal direction) can be described using Hooke's Law. The friction coefficient of the roller balls used in the simplified mount is  $\eta \simeq 0.007$ , which causes changes in length of  $0.03 \mu\text{m}/\text{m}$ .



## 6.6 Accuracy and Dynamic Range Studies

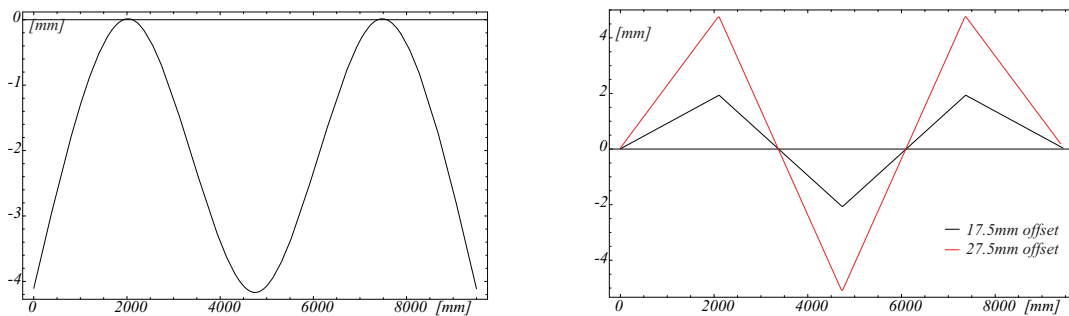
### 6.6.1 Calibration Accuracy

When calibrating the in-bar instrumentation with the CMM, besides statistical errors introduced by the CMM<sup>2</sup>, systematic errors are induced from measuring the deviation of RASNIK elements by means of balls glued to the outside of the bar. Even if the balls are glued exactly at the point the station is fixed to the tube, the separation between the RASNIK elements mounted to one station induces a systematic error when changing the bar shape. This becomes more clear by looking at Figure 6.14 ( $dx_{ball}$  vs.  $dx_{mask}$ )



**Figure 6.14:** Systematic error induced from the mounting of RASNIK elements onto their supports; *left*: sketch of a section supporting two RASNIK masks; *right*: illustration of the relative displacement of the mask due to a change in deformation of the bar.

To first order the RASNIK elements move in  $x$  direction corresponding to the displacement measured at the ball glued close to the station, but the bar also changes its relative angle in this point. Depending on the separation of the elements relative to the support, shifts ( $\delta x$ ) result. Figure 6.15-right is illustrating that this effect is dependent on the position these elements are mounted along bar, and scales with their distance relative to the support.



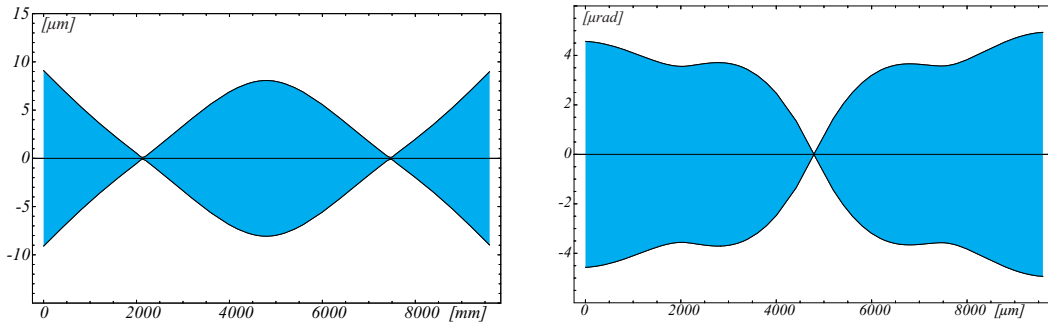
**Figure 6.15:** *left*: deformation of an alignment bar; *right*: corresponding systematic error in measuring the mask position with the CMM.

<sup>2</sup>The precision of the coordinate measuring machine is expected to be of the order of 3-5  $\mu\text{m}$  for relative measurements. [MAA:00]

### 6.6.2 Expected Accuracy

The expected accuracy in measuring changes in deformation with the in-bar instrumentation can be derived from the errors obtained from the RASNIK calibration. To define an envelope of false shapes, the calibration errors, which are related to positioning accuracies on the mask, can be smeared with the analytic shape model. The mean values of the calibration performed on six bars and normalized to movements on the mask are  $6\text{ }\mu\text{m}$  for short RASNIKS and  $13\text{ }\mu\text{m}$  for long RASNIKS.

The obtained envelope is zero at the points defining the bar coordinate system. For the plot shown in Figure 6.16 the support points of the bar have been chosen to define the bar coordinate system and the errors of the worst obtained calibration ( $10\text{ }\mu\text{m}$  for short RASNIKS and  $25\text{ }\mu\text{m}$  for long RASNIKS) have been used.

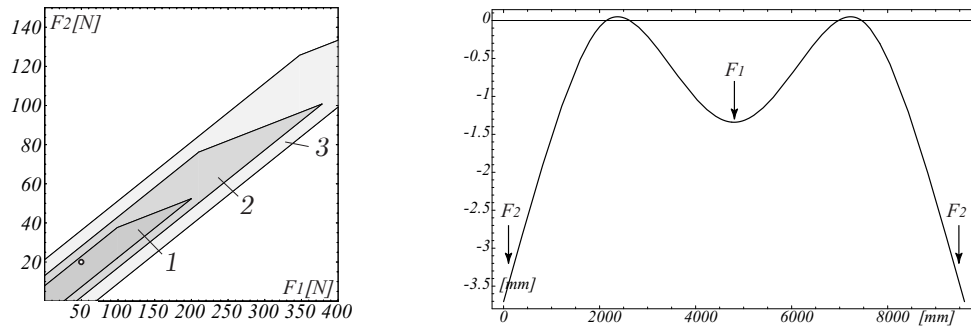


**Figure 6.16:** *left:* envelope of false shapes due to a calibration accuracy of the in-bar instrumentation of  $10\text{ }\mu\text{m}$  for the short RASNIKS and  $25\text{ }\mu\text{m}$  for the short RASNIK; *right:* resulting error in the viewing angle of an alignment sensor mounted to the bar.

The contribution to the error in predicting the bar shape with the measurements of the in-bar RASNIKS depends on their calibration accuracy. Even for the worst obtained calibration, this contribution is less than  $10\text{ }\mu\text{m}$ .

### 6.6.3 Dynamic Range

The analytic shape model can also be used to quantify the dynamic range of the in-bar instrumentation. The dynamic range can be understood as all possible deformations where all RASNIK systems still see their masks and hence provide shape information. Figure 6.17 shows the dynamic range expressed as external forces ( $F_2, F_1, F_2$ ) that can act on the bar. The reduction of the range due to the deformation of the bar under its own weight is already included.



**Figure 6.17:** Dynamic range of the in-bar instrumentation of the alignment bar; *left*: expressed as a function of forces acting at the ends and the middle of the bar; 1. alignment bar prototype built for the H8 test; 2. range due to larger RASNIK masks (20 mm  $\rightarrow$  30 mm); 3. range due to increased masks and larger bar diameter (72/80 mm  $\rightarrow$  72/84 mm); *right*: deformation corresponding to the force combination indicated with a point in the plot shown left.

The range of the in-bar instrumentation is mainly affected in two ways:

- Tubes delivered from the manufacturer have an intrinsic straightness of better than 1 mm/m. In the worst case, the tube can thus have a bow with a sagitta of 5 mm, which affects the range of the in-bar instrumentation, such that the range of possible deformation is no longer symmetric.
- Lenses used for the RASNIK systems show a non-negligible centricity error. This error is introduced at the manufacturing process and shows the same effect as a combination of two perfect plano-convex lenses and a prism. Depending on the orientation of the lenses mounted into the bar, this centricity error can be used to compensate for the bow mentioned above.

In view of these limiting factors, calculating the range as a function of the magnification and the mask size of the three RASNIK systems represents the upper limit of the dynamic range of the system used. The dynamic range must be larger than the expected deformation. The ideal case of mounting a bar, namely supporting it at its Bessel points<sup>3</sup> is very unlikely to be reached. Even if the weight distribution for the final ATLAS bars is known, there is limited space on the supporting frame to choose the support position. Thus it has to be guaranteed that even for shifts of the mounts the in-bar instrumentation works. An estimate of the possible shifts is given in Section 9.2.4.

<sup>3</sup>Various definitions of the Bessel point exist. The definition used here is where the location of the support points allows for minimum deformation of the tube. This is obtained if the points at the ends and the point in the middle of the bar have the same displacements relative to a straight line defined by the support points.



# Chapter 7

## Performance of a Single Alignment Bar

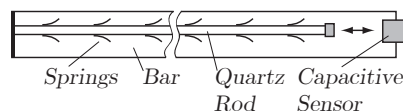
### 7.1 Introduction

Six alignment bars (four 9.6 m and two 2.6 m long ones) based on the design presented in Chapter 4 have been built for the H8 test stand. All bars have been shipped to Freiburg (Germany) in order to calibrate the in-bar instrumentation and to measure the initial shape with a large coordinate measuring machine. After learning how to handle and to measure these bars with the coordinate measuring machine, various tests have been performed to evaluate the calibration and reconstruction routines.

This chapter will first show the measurements performed to test the prediction of the bar length under different thermal conditions, and will afterwards concentrate on the measurements that have been performed to verify the shape reconstruction.

### 7.2 Length Prediction

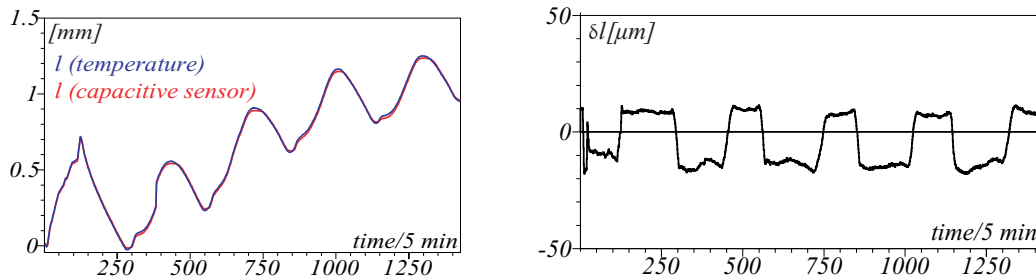
In order to compare the predicted bar length to a measurement, the first alignment bar was equipped with an additional quartz rod, guided by the tube that is connecting the inner stations and supported by springs placed in various positions along this tube. The expansion of the bar relative to the expansion of the quartz rod was measured with a capacitive sensor which provides relative distances accurate to  $1\text{ }\mu\text{m}$ . Figure 7.1 illustrates the setup.



**Figure 7.1:** Illustration of the length measurement using a quartz rod, guided inside the bar, and comparing the expansion of the quartz to the expansion of the bar.

### 7.2.1 Ambient Temperature Environment

To study the predictability of the bar length in an ambient temperature environment, day - to - night temperature variations have been used. It turned out that measuring the expansion of the alignment bar relative to the quartz rod is affected by a systematic error. Stress induced by friction at the points where the rod is supported causes the rod to expand and contract, depending on the temperature trend. Figure 7.2 shows the obtained hysteresis which is of the order of  $20\text{ }\mu\text{m}$ . The force necessary to explain this hysteresis agrees with the force that was measured when trying to pull the quartz rod out of the bar with a spring balance.



**Figure 7.2:** Change in bar length over 4 1/2 days in an ambient temperature environment ranging from  $18^{\circ}\text{C}$  to  $27^{\circ}\text{C}$ ; *left*: predicted from temperature measurement; *right*: measurement with quartz rod and capacitive sensor subtracted from predicted length.

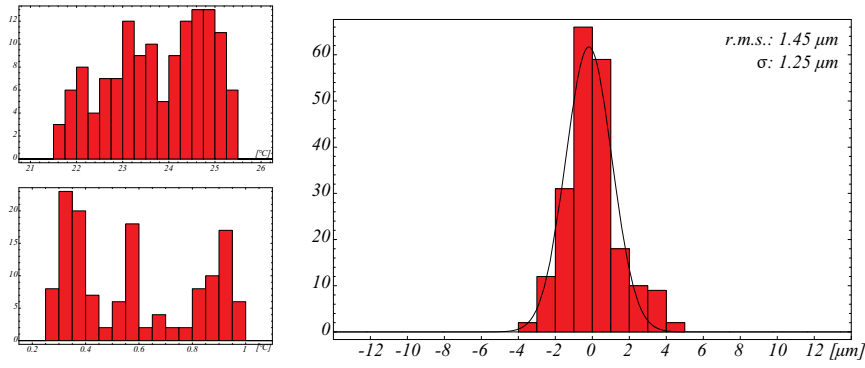
After correcting for this effect, an error in length prediction of  $3.4\text{ }\mu\text{m}$  r.m.s. is obtained for an ambient temperature ranging from  $18^{\circ}\text{C}$  to  $27^{\circ}\text{C}$ .

A second test was performed using the laser interferometer as described in Section 5.2.1 (p.50). A residual error in predicting the bar length of  $1.5\text{ }\mu\text{m}$  r.m.s. has been obtained for temperatures between  $21.5^{\circ}\text{C}$  and  $25.5^{\circ}\text{C}$ . Here the maximum difference in temperature along the bar was between  $0.3^{\circ}\text{C}$  and  $1^{\circ}\text{C}$  (Figure 7.3).

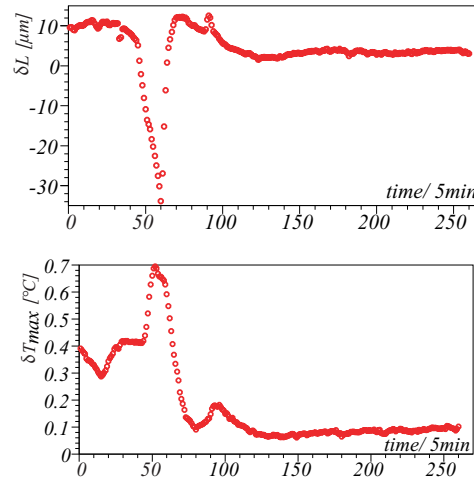
The measurement with the quartz rod and the measurement with the laser interferometer have been used to determine the expansion coefficient of the alignment bar, which is  $22.0 \pm 0.3\text{ }\mu\text{m K}^{-1}\text{m}^{-1}$ ; 6.4% less than the number provided by the manufacturer of the aluminium tube.

### 7.2.2 Temperature Gradients

To test the maximum temperature gradient the linear model in combination with the temperature measurement inside the bar is able to handle, hot-air blowers with a total heating power of  $5 \times 1\text{ kW}$  have been placed close to one end of the bar. After 5 hours of heating, a difference of 5 K along the bar was reached. Figure 7.4 shows that the error in predicting the length starts to deteriorate when the temperature difference  $\delta T$  between two adjacent stations exceeds 0.6 K. Two stations are separated by  $\sim 1.2\text{ m}$ , thus a gradient of  $0.5\text{ K m}^{-1}$  can be predicted to within  $20\text{ }\mu\text{m}$  r.m.s.



**Figure 7.3:** *right:* prediction of the bar length at ambient temperatures ranging from 21.5°C to 25.5°C, subtracted from the interferometer measurement; *left-top:* histogram of the average bar temperature; *left-bottom:* histogram of the maximum temperature difference on the bar that has been observed during this measurement.



**Figure 7.4:** *left:* predicted length subtracted from the measurement with the quartz rod and the capacitive sensor; *right:* maximum temperature difference between two adjacent stations.

In an ambient temperature environment, changes in bar length can be predicted with an error of 1.5 - 3.5  $\mu\text{m}$  r.m.s. For non-linear thermal gradients above  $0.5 \text{ K m}^{-1}$ , the error in predicting the bar length exceeds 20  $\mu\text{m}$  r.m.s.

## 7.3 Shape Prediction

When deriving the algorithm to reconstruct the bar shape in Section 6.3.1, three steps have been presented, which have to be verified.

- Changes in deformation of an alignment bar are predicted using the discrete forces from the weight of the sensor platforms and the corresponding sensors.
- In a second step the in-bar instrumentation is used to correct the prediction to the actual deformation. This correction is based on the virtual-load model.
- Finally the function describing the total change in deformation is modified to reflect the behavior of the platforms, and superimposed to the initial shape.

Section 7.3.1 and 7.3.2 will discuss the measurements performed to verify the analytic shape model. Section 7.3.3 will explain the measurements performed to verify the reconstruction of the bar shape, followed by a discussion of the results.

All measurements related to the bar shape have been performed in Freiburg using a large CMM which can measure in a volume of 6.5 m × 1.5 m × 1.2 m. Besides the three ball patterns on platforms, additional steel balls have been glued directly on the bar, to allow for measurements in between the platforms, in particular to define a bar coordinate system, and to measure the positions of the RASNIK elements of the in-bar instrumentation.

### 7.3.1 Controlled Deformation

The Equations 6.12 (p.62) describing the deformation of the bar scale with the product of Young's modulus and the second moment of inertia. The second moment of inertia (Equation 5.2, p.51) can easily be calculated from the outer and the inner diameter of the bar. The Young's modulus is a material constant and has to be measured once.

Controlled deformations of the bar are performed such that the bar shape is measured, then the bar is deformed by attaching a known weight in a discrete point and the shape is measured again. The induced deformation is obtained by subtracting the first measurement from the second measurement. Measurements of that kind have been used to extract Young's modulus, and to verify the analytic shape model. The Young's modulus is extracted by numerically fitting the predicted deformation  $w(z)$  to the measured deformation, with the free parameter  $E$ .

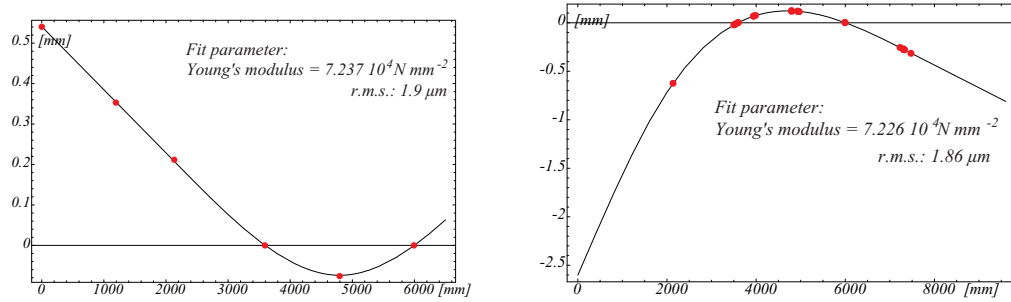
$$\begin{aligned}
 w(z) = z k + d + \frac{F}{48 (B - A) E I} \{ & (2A - l) (2A - 4B + l) (l - 2B) (A - z) \theta(z (A - z)) \\
 & + (2B - l) (A - z) (l^2 - 4Bl + 8A (B - z) + 4z^2) \theta((2z - l) (A - z)) \\
 & + (2A - l) (4A - 2B - l) (l - 2B) (B - z) \theta((l - z) (z - B)) \\
 & - (2A - l) (B - z) (A (8B - 4l) + l^2 + 4z (z - 2B)) \theta((B - z) (z - l/2)) \} ,
 \end{aligned} \tag{7.1}$$

see Figure 7.5.

Here  $A$  and  $B$  are the positions of the support points and  $F$  is the applied force. The additional term  $zk + d$  serves to move the coordinate system of  $w(z)$  (which is defined by the support points of the bar,) into the measured bar coordinate system, (which is defined by steel balls glued at  $z \sim 3400$  mm and  $z \sim 6000$  mm along the bar). The Young's modulus was measured of two bars from two different production series of the



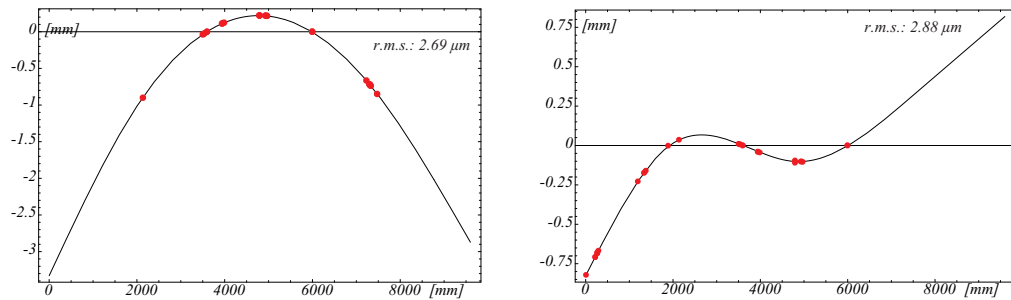
tubes. It is  $(7.232 \pm 0.007) 10^4 \text{ N mm}^{-2}$  (4.5 % larger than the number provided by the manufacturer).



**Figure 7.5:** Measurements performed to derive Young's modulus; *left*: measured and predicted deformation due to 500 g at  $l=4800\text{mm}$ ; *right*: deformation due to for 997.54 g at  $l=5\text{ mm}$ .

The product of the Young's modulus and the second moment of inertia can be derived by fitting the predicted deformation to the measured deformation of the bar. The Young's modulus is  $(7.232 \pm 0.007) 10^4 \text{ N mm}^{-2}$  (4.5 % larger than the number provided by the manufacturer), assuming a value of  $I = 1.367 \cdot 10^{-6} \text{ mm}^4$ .

Using the measured value of  $E$  one can now predict deformations, as shown in Figure 7.6. The observed differences between the predicted and the measured deformation of the order of  $3 \mu\text{m}$  r.m.s verify that the analytic shape model can be used to predict simple deformations.



**Figure 7.6:** Predicted deformation compared to the measured deformation for *left*: 997.54 g at  $l=5\text{ mm}$  and 687.71 g at  $l=9505\text{ mm}$ ; *right*: 997.54 g at  $l=5\text{ mm}$ , 691.06 g at  $l=4752.5\text{ mm}$  and 687.71 g at  $l=4875.5\text{ mm}$

### 7.3.2 Deformation of an Ideal Alignment Bar

Another test to verify that the analytic shape model is capable of predicting the deformation of a real alignment bar, is to compare the calculated deformation of an ideal

alignment bar to the measured deformation of a real alignment bar. The numbers in Table 7.1 describe one of the alignment bars (H8, EM-up). For the calculation of the deformation due to discrete forces, the platforms mounted on the bar are assumed as point-like weights having the center of gravity in their middle.

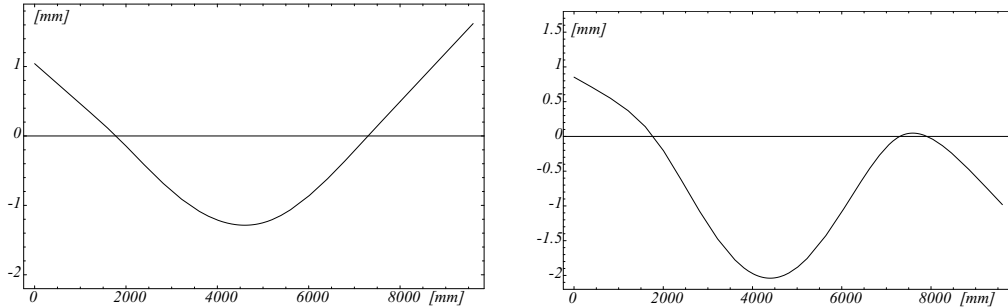
|                            |  |            |                         |  |  |  |  |  |  |
|----------------------------|--|------------|-------------------------|--|--|--|--|--|--|
| outer diameter             |  | D          | 80.2 mm                 |  |  |  |  |  |  |
| inner diameter             |  | d          | 71.7 mm                 |  |  |  |  |  |  |
| Young's modulus            |  | E          | 7.232 Nmm <sup>-2</sup> |  |  |  |  |  |  |
| density                    |  | $\rho$     | 2.7 g cm <sup>-3</sup>  |  |  |  |  |  |  |
| location of support points |  | $x_2, x_4$ | 1780 mm, 7299 mm        |  |  |  |  |  |  |
| bar length                 |  | l          | 9600 mm                 |  |  |  |  |  |  |

|          |      |        |        |        |        |        |        |        |        |
|----------|------|--------|--------|--------|--------|--------|--------|--------|--------|
| Weight   | [g]  | 1591   | 541.8  | 489    | 813    | 813    | 1653   | 541.8  | 489    |
| Location | [mm] | 1131.0 | 1705.1 | 2287.5 | 2483.7 | 3364.1 | 5074.7 | 7062.8 | 7774.1 |

**Table 7.1:** *top:* mechanical properties of the H8 EM-upper bar; *bottom:* weights and positions of sensor platforms mounted to this bar.

The deformation of the ideal alignment bar when exposed to eight external forces, which are simply the gravitational forces due to the mass of the platforms (Table 7.1) and the deformation due to the proper weight of the bar are shown in Figure 7.7.



**Figure 7.7:** *left:* straight tube supported in two points and exposed to the eight external forces from Table 7.1; *right:* straight tube supported in two points and deformed due to the continuous load distribution that describes the proper weight of the bar.

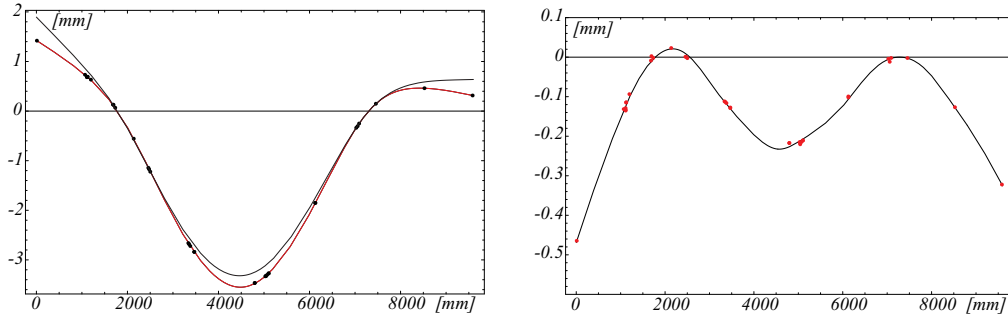
In order to compare the predicted deformation to a CMM measurement, the gravitational sag has to be extracted from the CMM measurement of the bar shape, which is always a combination of the *original shape* of the bar and its *deformation* due to gravity. To disentangle these two contributions, two measurements of the bar in two different orientations are needed. For a coordinate system fixed to the bar the following relations hold:

$$\begin{aligned} \text{bar shape in } 0^\circ \text{ orientation:} & \quad \text{original shape} + \text{gravitational sag} \\ \text{bar shape in } 180^\circ \text{ orientation:} & \quad \text{original shape} - \text{gravitational sag} \end{aligned}$$

By subtracting the measurement of the  $0^\circ$  orientation from the measurement of the  $180^\circ$  orientation, one obtains two times the gravitational sag, while adding these two

measurements yields two times the original shape. The same considerations are valid for a  $0^\circ$  and a  $90^\circ$  measurement:  $0^\circ + 90^\circ = \text{original shape}$ , and  $0^\circ - 90^\circ = \text{gravitational sag}$ . For a bar coordinate system that has the  $x$  or  $y$  axis aligned to the direction of gravity, the gravitational sag changes in this case from one coordinate to the other.

The comparison of the superposition of the two deformations from Figure 7.7 to the measured deformation of the alignment bar shows that the deformation of the measured bar is larger than predicted by several tens of a mm (Figure 7.8-left).



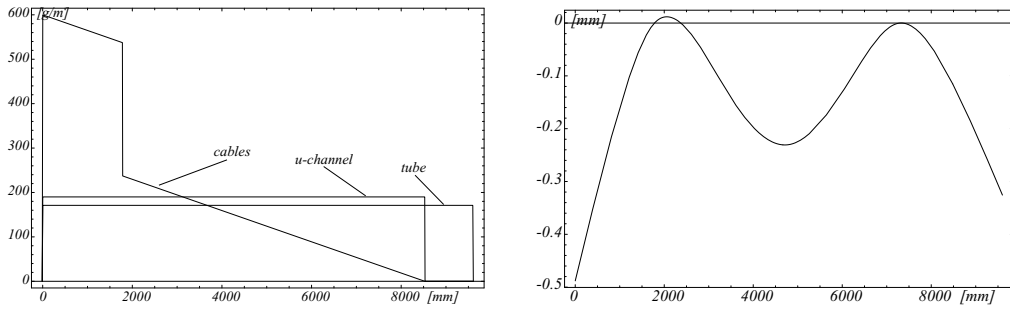
**Figure 7.8:** *left:* deformation of an ideal alignment bar due to its proper weight and eight discrete forces; *dots:* CMM measurement ( $0^\circ - 180^\circ$ )/2 of the associated real alignment bar; *red:* line to guide the eye; *right:* difference between measurement and prediction.

The observed difference (Figure 7.8-right) can be explained with the loads of the in-bar instrumentation, which have been omitted up to now. The load of this in-bar instrumentation, which is transferred to the bar by the nine disks of the skeleton can be split into the following parts:

- The load of the cables connecting the temperature sensors. These cables get thicker towards the end ( $l=0$ ) of the bar and are guided back on the outside of the bar to the closest support point.
- The small tube connecting the nine discs of the skeleton.
- one u-channel guiding the cables for the temperature sensors which is carried by 8 discs.
- The weight of the nine discs.

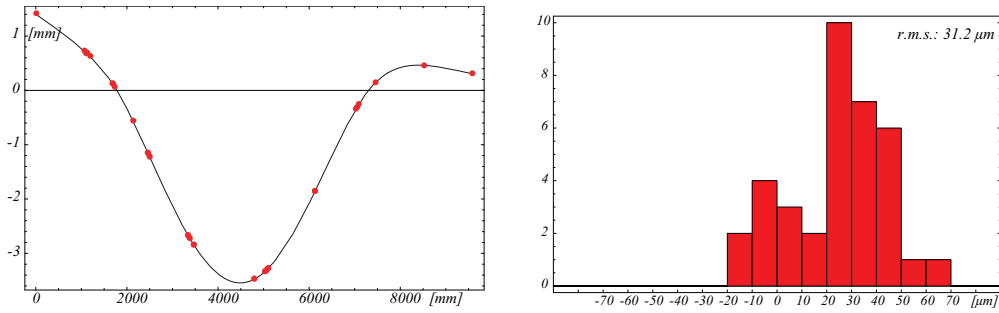
The resulting load is in agreement with the expected deformation if one assumes 190g for each disc, and 100g/m for each of the three cables<sup>1</sup>. The weights of the u-channel (190 g/m) and the small tube (171 g/m) are taken from the specifications of the supplier. The load distribution and the corresponding deformation of the bar is shown in Figure 7.9.

<sup>1</sup>Each disc is assembled from different components and has different a mass; also the cables have different lengths.



**Figure 7.9:** *left:* contributions of the different parts of the in-bar instrumentation, the discrete loads from the nine discs are not shown; *right:* corresponding deformation of the bar.

The total weight transferred to the bar in the positions of the discs adds to 6788 g. Figure 7.10 shows the predicted deformation due to the weight of the sensor platforms, the proper weight of the bar and the load transferred from the in-bar instrumentation, in comparison to the measured deformation of the associated bar.



**Figure 7.10:** *left:* deformation of an ideal alignment bar due to its proper weight, the corresponding sensor platforms and the estimated weight of the in-bar instrumentation; *dots:* CMM measurement ( $0^\circ - 180^\circ$ )/2 of the associated alignment bar; *right:* difference between measurement and prediction.

The difference between the calculated deformation of an ideal alignment bar and the measured deformation of the corresponding real bar (Figure 7.10-right) is close to the required precision, which shows that the analytic bar shape model is adequate to describe deformations of real alignment bars, provided that an effective correction for the loads that have not been accounted for (e.g. lenses, screws, plugs, electronics, sensors,...) is added to the shape prediction.

The analytic shape model is adequate to describe changes in deformation of a real alignment bar from a known mass distribution.

### 7.3.3 Bar Shape Reconstruction

The number of parameters required to calculate the deformation of an ideal alignment bar can be reduced when using the virtual load model (Section 6.4) to describe the deformation of a real alignment bar. The proper weight of the bar as well as the load distribution due to the in-bar skeleton can be absorbed into virtual loads. The remaining parameters that have to be known, are besides the measurements provided by the in-bar instrumentation, the loads of the sensor platforms and sensors and the approximate inclination of the bar relative to the orientation in which its initial shape was measured.

The forces acting on the bar scale with gravity, thus the most interesting test in terms of predicting the bar shape is to measure an alignment bar in the horizontal position ( $0^\circ$ , i.e. the initial shape measurement), rotate the bar around its axis into a different orientation, and compare the calculated shape to the shape measurement in this orientation.

Two scenarios have been set up:

- Measure the alignment bar in the  $0^\circ$  orientation, turn the bar into the  $180^\circ$  orientation and compare the predicted shape to the CMM measurement in this orientation. In terms of forces acting on the bar this means to invert gravity in the vertical plane. This reproduces a worst-case scenario for the ATLAS alignment bars, since they can only be measured in horizontal position and are mounted in inclined positions ( $\sim 22.5^\circ \pm (45, 90, 135, 180)^\circ$ ).
- Rotate the bar by  $90^\circ$  and compare the predicted platform positions to the measurement. In terms of forces this case is comparable to switching off gravity in the vertical plane and switching it on in the horizontal plane.

The measurement program has been performed with all six alignment bar prototypes in either of the two scenarios and can be described as follows:

- Measure the initial bar shape in one orientation (the CMM measurement which the calibrated RASNIKS and the temperature readings are referred to).
- Calculate the bar deformation due to the weight of the sensor platforms.
- Use the values provided by the in-bar instrumentation<sup>2</sup> in the new orientation to refine the deformation with virtual loads and modify the resulting deformation to accommodate the behavior of the sensor platforms.
- Superimpose the resulting deformation to the initial shape measurement.
- Compare the shape prediction to the CMM measurement in the other orientation.

<sup>2</sup>Due to the limited dynamic range of the in-bar instrumentation of the alignment bar prototypes, one of the three in-bar RASNIKS was sometimes not analyzable in the other orientation. **The shape correction with virtual loads was then based on the CMM measurements of the points the RASNIKS would normally measure;** these cases are indicated in the text.

All CMM measurements have been performed in a bar coordinate system defined by three balls glued to the bar. The 9.6m long bars had to be measured in two parts, 0-6200 mm and 3400-9600 mm. Three points in the overlap region defining the coordinate system of the bar and the RASNIK readings have then been used to combine two measured parts to one bar-shape in one orientation.

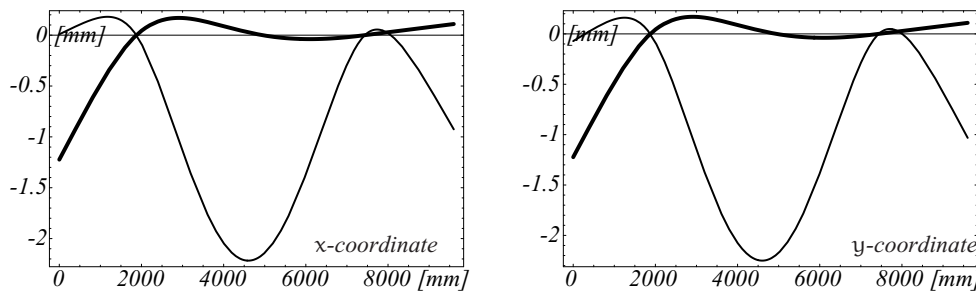
The shape reconstruction will now be discussed for one  $0^\circ - 90^\circ$  measurement and for one  $0^\circ - 180^\circ$  measurement. For better illustration all plots show the difference between the initial shape measurement and the measurement in the new orientation (i.e. the deformation<sup>3</sup>).

### Prediction of a Bar rotated by $90^\circ$

According to the scaling of the masses when rotating the bar, the predicted change in deformation due to the weight of the platforms has to be applied in both coordinates perpendicular to the bar. All the loads that have been unaccounted for in the prediction will be absorbed into virtual loads. To do so, RASNIK values calculated from the deformation due to the weight of the platforms (Figure 7.11, thick line) have to be subtracted from the measured RASNIK values of the in-bar instrumentation. These corrected RASNIK values serve to calculate the deformation in 5 points and hence the virtual load model. The three virtual loads derived for this case are:

|               | 0 – support A | supports A–B | support B – l |
|---------------|---------------|--------------|---------------|
| x coordinate: | 38.715 N/m    | 32.493 N/m   | 34.274 N/m    |
| y coordinate: | 40.555 N/m    | 33.653 N/m   | 35.685 N/m    |

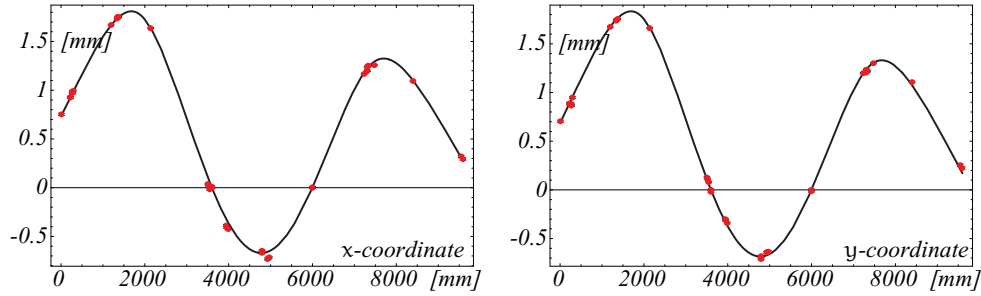
The difference in deformation (Figure 7.11, thin line) can now be superimposed to the prediction (Figure 7.11, thick line) and hence applied to the initial shape measurement.



**Figure 7.11:** *thick line:* deformation due to the mass distribution of the sensor platforms mounted onto the bar; *thin line:* deformation calculated with the virtual load model and the values of the in-bar instrumentation, when rotating the bar by  $90^\circ$ .

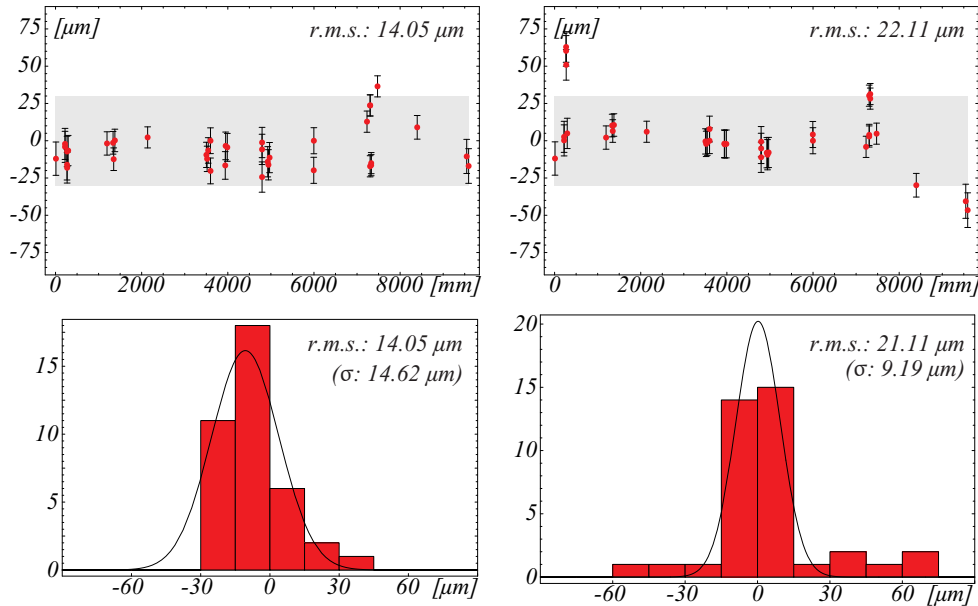
<sup>3</sup>The bar shape is defined by the positions of all balls in the bar coordinate system. These positions range in the coordinates perpendicular to the bar from approx. -40 mm to 125 mm. Thus showing the obtained changes of approx. 3-5 mm on this scale is not illustrative.

Figure 7.12 shows the result of this procedure in comparison to the CMM-measured deformation.



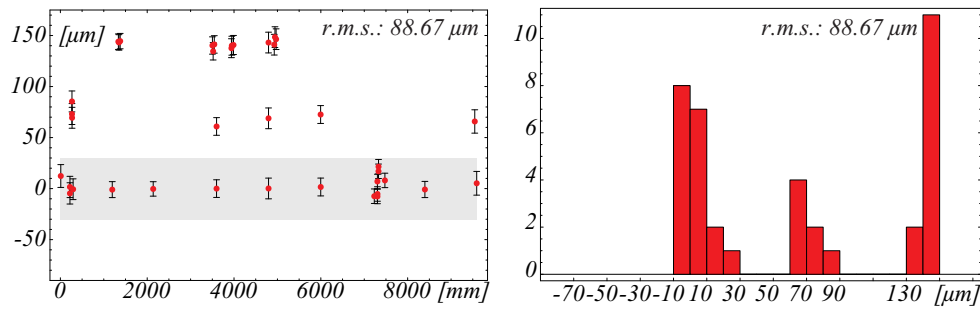
**Figure 7.12:** dots: measured deformation (CMM 90° - CMM 0°); thick line: predicted bar deformation due to the mass distribution of the sensor platforms on the bar and the three virtual loads calculated with the measurement of the in-bar instrumentation.

The difference between the prediction and the measurement for the coordinates perpendicular to the bar is shown in Figure 7.13. The grey band in the plots indicates the allowed  $1\sigma$  region of  $\pm 30\ \mu\text{m}$ .



**Figure 7.13:** Predicted shape subtracted from the CMM measurements (CMM 90° - CMM 0°); left: x-coordinate; right: y-coordinate.

The error in predicting the ball positions in the coordinate along the bar is shown in Figure 7.14. The difference between prediction and measurement in the coordinates perpendicular to the bar is below the required  $30\ \mu\text{m}$  r.m.s. The error along the bar axis is much too large and shows systematic effects, which will be discussed in Section 7.3.4.

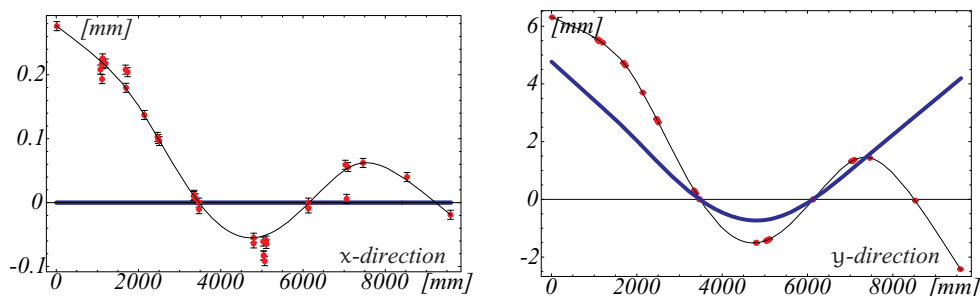


**Figure 7.14:** z-coordinate (along the bar) of predicted ball positions subtracted from the CMM measurements ( $\text{CMM}90^\circ - \text{CMM}0^\circ$ ).

### Prediction of Bars rotated by $180^\circ$

When rotating the bar by  $180^\circ$ , the deformation of the bar mainly changes sign in the coordinate aligned with gravity. Thus the change in deformation predicted from the weight of the platforms has to be applied twice, while the coordinate perpendicular to the direction of gravity should show no change. This is almost the case for the deformation shown in Figure 7.15; the small deformation in the other coordinate is due to the fact that the bar coordinate system was not perfectly aligned to the direction of gravity. This “misalignment” of the coordinate system is neglected and absorbed into virtual loads. Figure 7.15-left shows the deformation calculated with the virtual load model in comparison to the measurement. The plot on the right side shows the prediction due to the platform weights (thick line) and the virtual load corrected deformation in comparison to the measurement. The loads calculated with the virtual load model are:

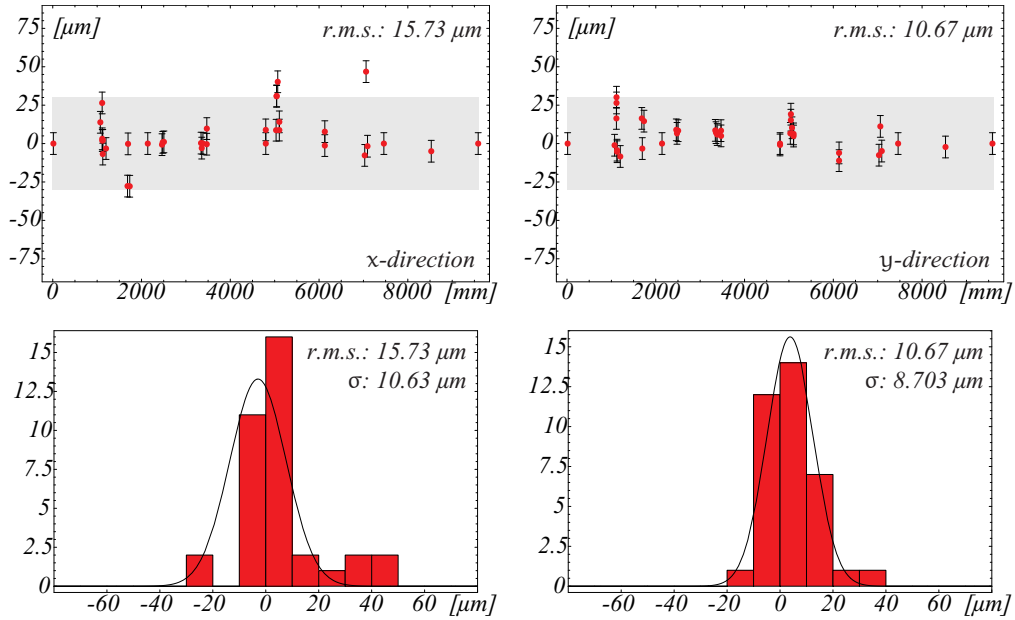
|               | 0 – support A | supports A–B | support B – l |
|---------------|---------------|--------------|---------------|
| x-coordinate: | 2.197 N/m     | 2.099 N/m    | 1.907 N/m     |
| y-coordinate  | 78.251 N/m    | 65.793 N/m   | 63.675 N/m    |



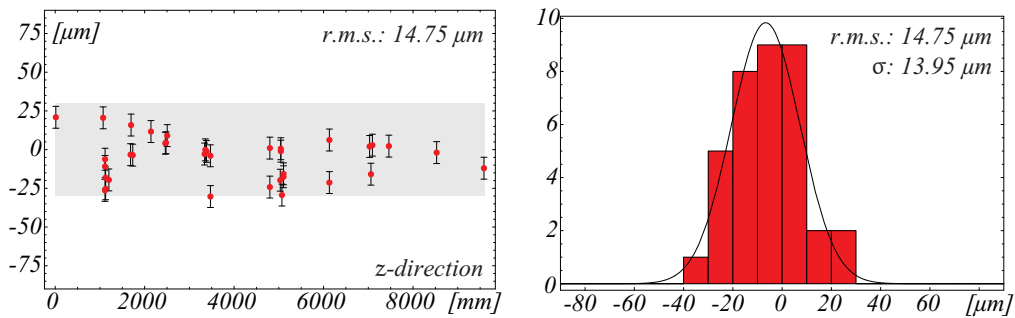
**Figure 7.15:** dots: measured ball positions ( $\text{CMM } 180^\circ - \text{CMM } 0^\circ$ ); thick line: deformation due to the mass distribution of the sensor platforms mounted onto the bar; thin line: predicted bar deformation. Here the the CMM measured positions of the RASNIK elements had to be used as input for the virtual load model.



The difference between the predicted and the measured ball positions is shown in Figure 7.16 for the coordinates perpendicular to the bar, and in Figure 7.17 for the coordinate along the bar. For this measurement the prediction in all three coordinates meets the specified accuracy.



**Figure 7.16:** Predicted ball positions subtracted from the measurements ( $\text{CMM180}^\circ - \text{CMM0}^\circ$ ); *left*, x-coordinate; *right*, y-coordinate.



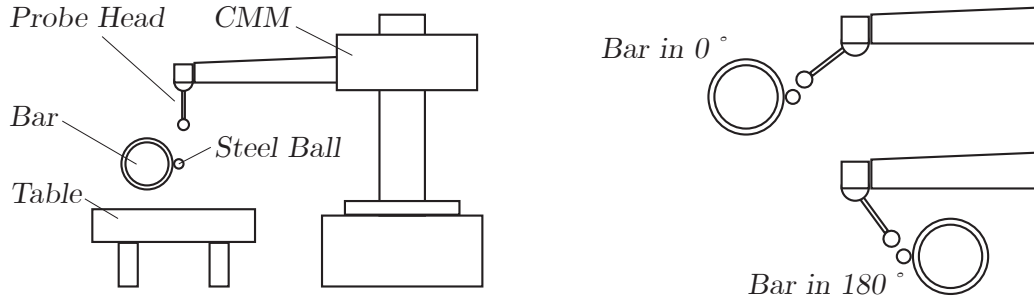
**Figure 7.17:** Predicted ball positions in the coordinate along the bar subtracted from the measurements ( $\text{CMM180}^\circ - \text{CMM0}^\circ$ ).

### 7.3.4 The CMM Measurement Problem

The results above show, that the difference between prediction and measurement is mostly small, but for some cases larger than  $100 \mu\text{m}$ . These inconsistencies between the prediction and the measurement have been traced to an improper operation of the

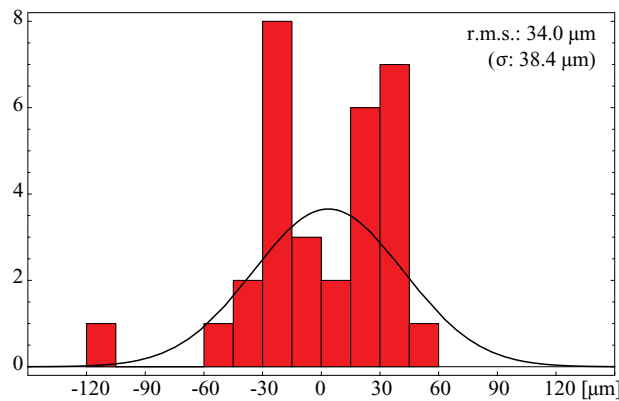
CMM. The structure of deviations between prediction and measurement indicated offsets for certain combinations of measured ball positions:

When measuring the bar with a CMM, different probe head orientations have to be used in order to reach the balls glued to the platforms (illustrated in Figure 7.18).



**Figure 7.18:** Different probe head orientations are used to measure the positions of the same balls glued to the bar, when rotating the bar; *left*: illustration of the setup at the CMM; *right*: two different probe head orientations.

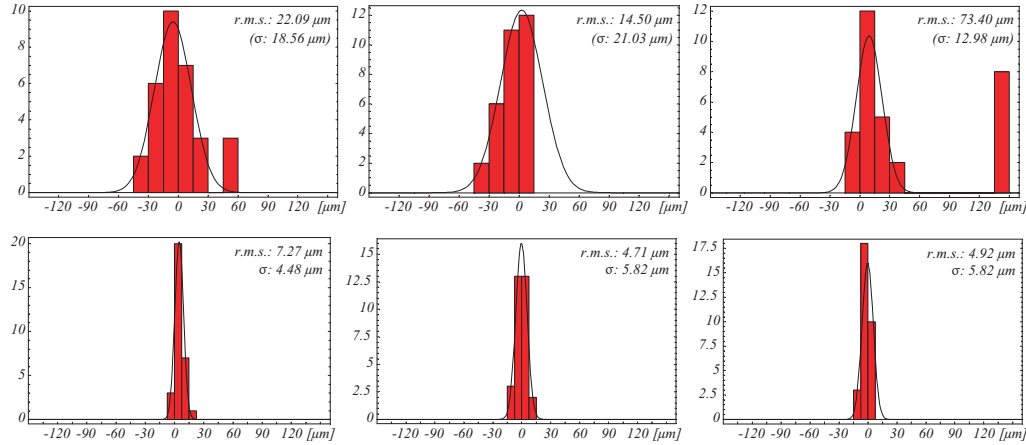
It turned out that when measuring the position of a ball with two different probe head orientations, a constant offset between these two measurements appears<sup>4</sup>. To prove this assumption, the position of a reference sphere was measured with all probe head orientations used to measure the bars. Ideally, the position of the center of this sphere should be reproducible within the nominal machine error of 3-5  $\mu\text{m}$ . The following plot (Figure 7.19) shows the measured offsets when using different probe head orientations, which has an r.m.s. width of 34  $\mu\text{m}$  instead.



**Figure 7.19:** Combined error  $\delta x \oplus \delta y \oplus \delta z$  of the relative differences in measuring the center of one reference sphere with the 31 different probe head orientations that have been used for the bar measurements.

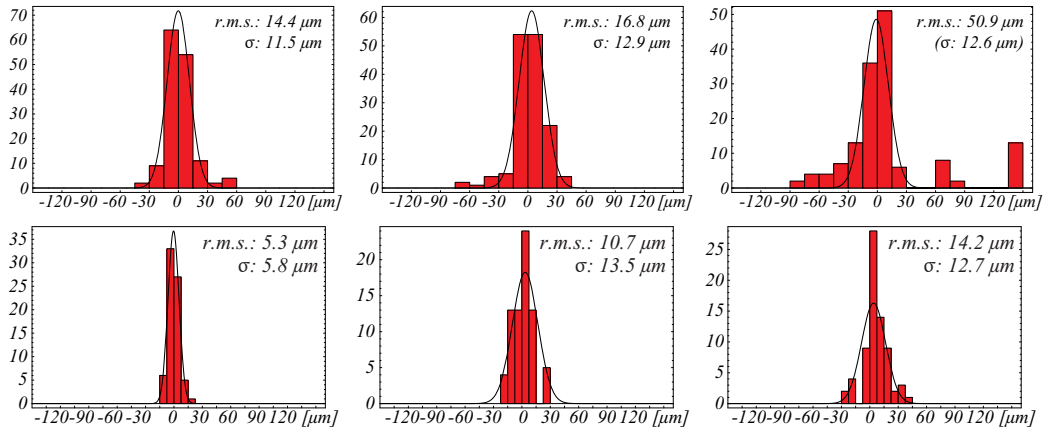
<sup>4</sup>In contradiction to the measurements where the bar is purely deformed and remains in one orientation, the probe head orientation needs to be changed when the bar is rotated.

After discovering this malfunction the CMM has been recalibrated and three bars have been measured again. The plots below show the difference between the predicted and measured ball positions for one 2.6 m long bar before and after the re-calibration and for two 9.6 m long bars which have been measured after the re-calibration.



**Figure 7.20:** 2.6 m long bar; difference between predicted and measured ball positions (CMM $0^\circ$ -CMM $180^\circ$ ); *left*: x-coordinate; *middle*: y-coordinate; *right*: z-coordinate; *top*: before re-calibration; *bottom*: after re-calibration of the CMM. The large differences prior to recalibration point to the difficulty associated with proper CMM operation.

Figure 7.21 shows the combined errors of the predicted ball positions for all 6 bars before the CMM was re-calibrated in comparison to the two long bars that have been re-measured ( $0^\circ$  -  $180^\circ$  orientation) after the calibration.



**Figure 7.21:** Difference between prediction and measurement; *left*: x-coordinate; *middle*: y-coordinate; *right*: z-coordinate; *top*: all 9.6 m long bars before the re-calibration; *bottom*: the one 9.6 m long bar that has been re-measured after the re-calibration of the CMM.

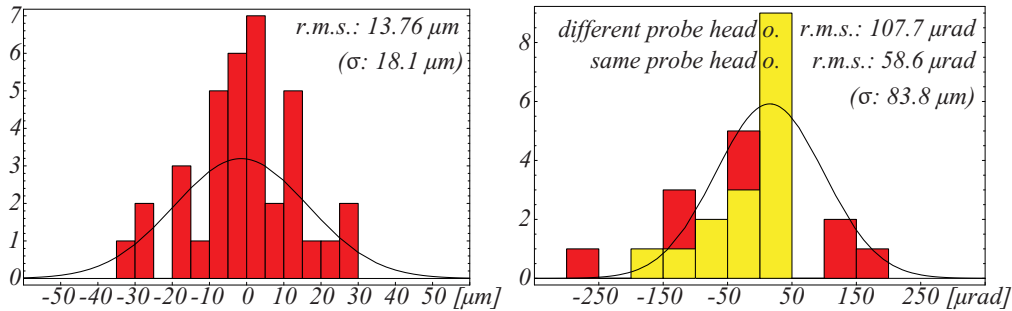
The accuracy obtained with the three re-measured bars (Figure 7.20-bottom and Figure 7.21-bottom) shows that:

It is sufficient to use the weight of the sensor platforms that are mounted onto the bar and to use the in-bar RASNIKS in combination with the virtual load model to predict the bar shape to better than  $30\text{ }\mu\text{m}$  r.m.s.

### 7.3.5 Pivot Point and Viewing Direction

The three balls defining the position (pivot point) and the orientation of a BCAM are separated by 45 mm and 74 mm, and match the three mounting grooves on each sensor, which are shaped as cone, v-groove and plane. The precision of the measurement of this three-ball pattern is mainly constrained by the accuracy of the ball resting in the cone of the BCAM relative to the other two balls. To achieve the required angular precision of  $50\text{ }\mu\text{rad}$ , this ball position has to be measured accurate to  $3.4\text{ }\mu\text{m}$ , relative to the two others. This high precision is needed locally and can only be reached when the probe head remains in one orientation while measuring the individual three ball pattern. The distribution of the ball patterns that have been measured without changing the orientation of the probe head is  $58.6\text{ }\mu\text{m}$  r.m.s. (Figure 7.22-right, yellow).

The difference between the predicted and the measured pivot point position and the difference between the predicted and the measured viewing direction for the two long bars that have been re-measured is shown in Figure 7.22-left.



**Figure 7.22:** *left:* predicted pivot point position subtracted from the position measurement; *right:* predicted viewing direction subtracted from the viewing direction retrieved from the CMM measurement (*yellow:* errors in viewing direction, where the three-ball pattern has been measured with one probe head orientation; *red:* angles where the probe head orientation was changed while measuring the three-ball pattern).

## Chapter 8

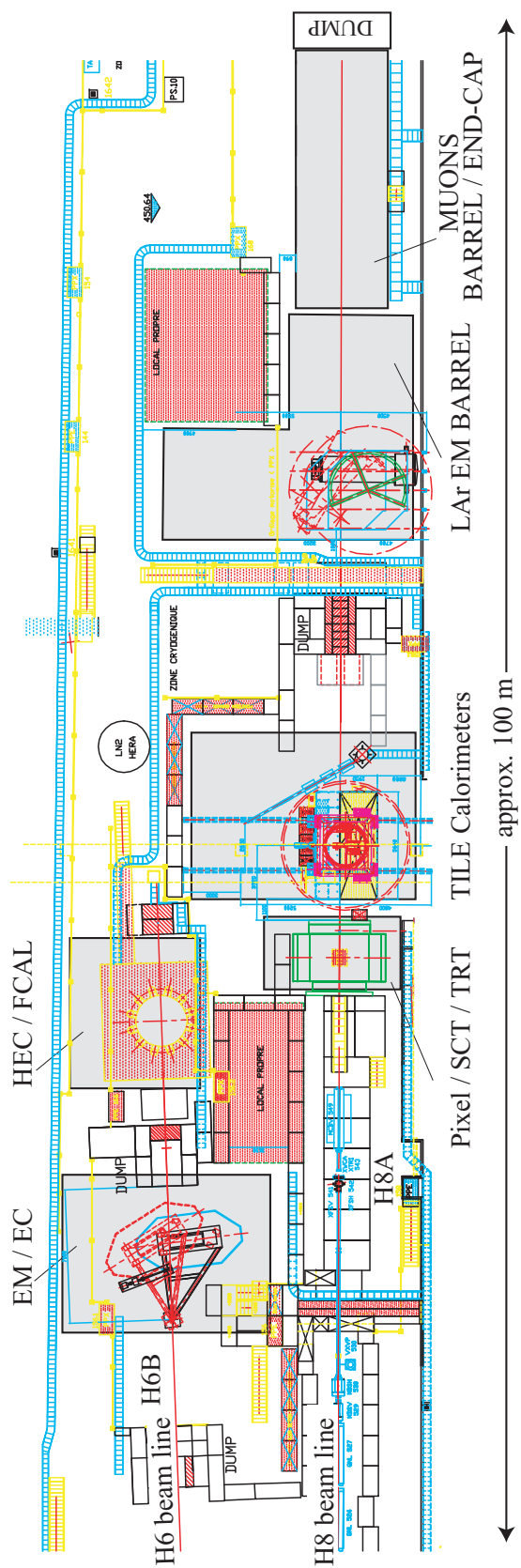
# Alignment System Test in H8

### 8.1 Introduction

To achieve the physics program, very demanding requirements on the muon system as a whole, have been placed. The precision chambers not only have to be built to very high standards of performance, both mechanical and electronic, but their positions in the spectrometer must be known at the level of the resolution of the chambers themselves. This requires a sophisticated and extremely precise alignment system. The large size of the ATLAS muon system also presents a host of technological problems; precision of tens of microns, on a scale of tens of meters, a sophisticated trigger, a complicated magnetic field, a large piece count, complex structural supports, carefully choreographed installation, and intricate routing of services to name just a few. One cannot go from a single or few chambers test to full-scale implementation of the muon system without a meaningful system test on a reasonable scale. Extensive tests of the various components of the muon system already have been found to perform adequately. However, many detailed problems only show up in an integrated system on an adequate scale. To confront these potential problems, H8 is intended as a multi-step program to validate besides the muon system the whole detection chain before installation.

### 8.2 Setup

At the end of the beam line in the H8 test beam area one eighth of the muon end-cap spectrometer has been erected. At the time of writing one of the end-cap test stands was installed, mainly dedicated to test the alignment concept. Another important benefit of running the end-cap test stand (phase 2) will be the opportunity to test the alignment devices readout and control system with real chambers and calibrated alignment sensors, in preparation for expanding the hardware and software to the scale needed for ATLAS.



**Figure 8.1:** Locations of the individual component test stands in the H6 - H8 test beam area.



### 8.2.1 EO, EM, EI Octants

The current setup for the H8 test stand consists of three support structures that emulate 1/8 of one end-cap of the ATLAS muon spectrometer. In Figure 8.2 a picture of the three end-cap support structures is shown.



**Figure 8.2:** Picture of the three octants of the H8 test stand; (from left to right: EO-layer, EM-layer, EI-layer). The six alignment bars in this setup are marked with a red circle.

On each structure two alignment bars (equipped with sensors, measured and calibrated) are mounted. Together with two phantom chambers per structure the minimum number for a meaningful alignment test is attained. The phantom chambers are equipped with proximity sensors and in-plane alignment sensors to detect motion with respect to the alignment bars. Phantom chambers reflect the mechanical behavior of muon chambers, but cannot detect particles. Thus an additional optical ray (muon simulator) traversing the three chamber layers was installed to emulate the measurement of one track.

The goals to be achieved with this set-up are:

- Get experience with the installation of chambers and alignment bars on realistic structures.

- Verify the consistency of the alignment mounting procedure with the positioning accuracy required by the optical system.
- Gain experience with readout and control of the alignment devices and test the alignment devices and DAQ in an environment similar to the one of the ATLAS experiment (long wire data acquisition (LW/DAQ), large temperature gradients, time dependent temperature variations)
- Check the capability of the alignment system to correctly reconstruct controlled movements of individual components (e.g. one alignment bar is therefore mounted on a micrometer stage).
- Use the redundancy of the alignment system to perform an absolute consistency check of the alignment system.
- Use an independent optical straight line reference to perform a relative test of the proximity part of the alignment system.

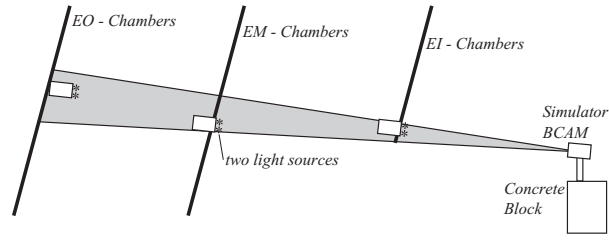
### 8.2.2 Alignment Sensor Readout System

Two different types of sensors have to be read out: temperature sensors and optical devices. The electronics used to process the temperature is based on ELMBs and hence different to the electronics used to readout the optical sensors. It is foreseen to merge the temperature readout in the electronics used for the optical sensors. For the time being the Pt100 sensors are read out with the PVSS SCADA system used at CERN as the agreed common program for DCS. The optical devices are driven and read out using a custom VME driver board, controlled by a small server program written in C and running under Windows NT on an embedded PC in the VME crate. The server communicates via the DIM protocol ([GAS:00]; based on TCP/IP calls) with a computer running the PVSS SCADA system. The optical readout system is controlled using this PVSS computer, which allows for graphical display of results, data archiving and run control, as well as flexible testing of individual sensors and groups of sensors. The images of the optical sensors are analyzed by the server program running in the VME crate and the results, consisting of two-dimensional position coordinates and (in the case of RASNIKS) the magnification and rotation of the mask image with respect to the mask, are sent to the PVSS computer. These data are then stored both in the PVSS native archive format, which can be used for plotting alignment bar and chamber information on-line with the PVSS interface, and in the form of simple ASCII text files that are used by the alignment reconstruction code [AME:01].

### 8.2.3 Muon Simulator

The muon simulator is intended to provide information about the relative positions of one phantom chamber per layer. Thus 4 BCAMs have been installed such that the light sources which are integrated in the three BCAMs mounted on a chamber each, provide





**Figure 8.3:** Illustration of the measuring principle of the muon simulator.

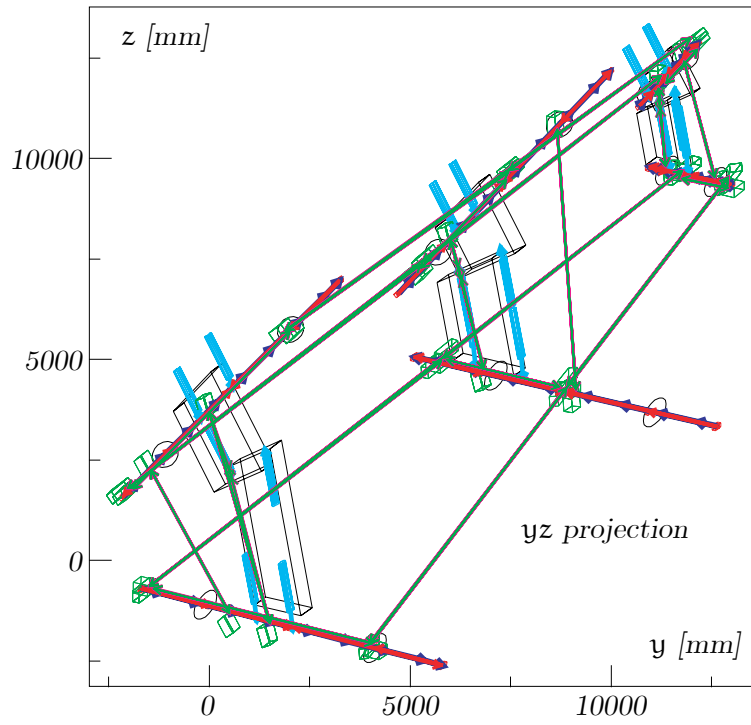
position information relative to a BCAM mounted on a concrete block. Figure 8.3 illustrates the setup.

By comparing the motions of the light sources on the chambers relative to the simulator BCAM, this setup can be understood as one straight line reference.

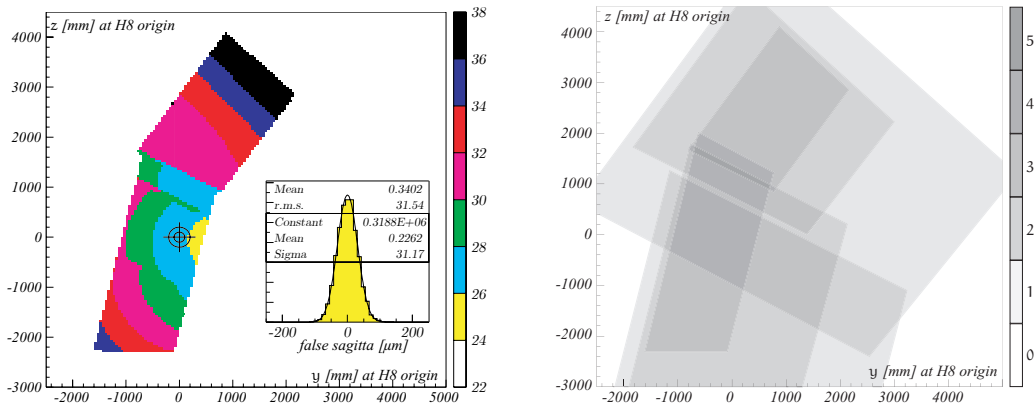
#### 8.2.4 Simulation of the Setup

To obtain information about the precision one can expect from the measurements performed with the H8 test stand, the setup has been simulated with ARAMYS. Figure 8.4 shows an output created from the simulation program, where the six chambers, all alignment elements and the optical sensor lines are indicated. For the simulation the design values of the individual sensors have been used to calculate the contribution to the overall sagitta measurement, which is shown in Figure 8.5-left, expressed as the sagitta error at the position a muon would traverse the EO layer. The reason for the inhomogeneous distribution of this sagitta error can be explained with Figure 8.5-right, where all the six chambers are shown in the projection a muon would see the setup, before traversing the EI layer. Here one can see the increase in resolution for the regions that are covered by more than three chambers.

The simulated contribution of the alignment system to the overall sagitta error in the main bending direction has a distribution of  $32\text{ }\mu\text{m}$  r.m.s.



**Figure 8.4:** Visualization of the simulated H8 setup as provided from ARAMYS. (From left to right: EO-layer, EM-layer, EI-layer.)

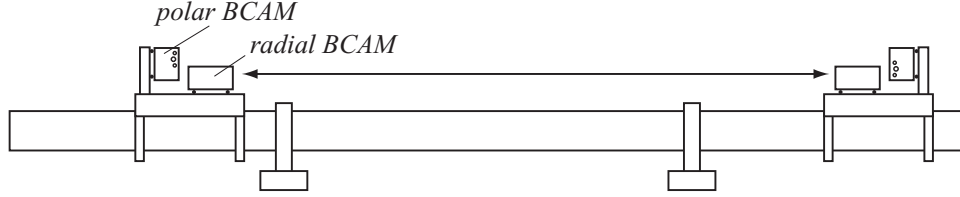


**Figure 8.5:** Simulation of the sagitta measurement; resolution in the main bending direction, normalized to the detected position in the EO layer; *left*: contribution to the overall sagitta error, indicated at the position a muon would traverse the EO layer; *right*: projection of all six chambers, grey values are added and indicate the number of chambers a muon would see.

## 8.3 Measurements

### 8.3.1 Intrinsic Sensor Resolution (BCAM on Bar)

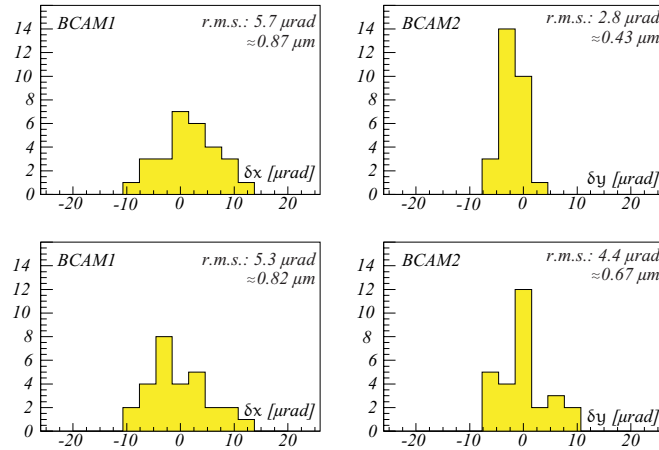
The alignment bars for H8 are equipped with one additional set of BCAMs (radial BCAMs) which are looking along the bar and provide the angular relation of the polar BCAMs that are mounted to the same platform. Figure 8.6 illustrates the pair of radial BCAMs which is separated by  $\sim 5$  m.



**Figure 8.6:** Illustration of the two radial BCAMs mounted on the alignment bar.

As the bar shape is monitored with the in-bar sensors the change in angle of this polar/radial platforms can be retrieved from the first derivative of the bar shape. Hence the measurements of the radial BCAMs are redundant and can be used to evaluate the intrinsic sensor resolution of a BCAM, by comparing the angles predicted from the in-bar instrumentation to the angles measured with the BCAMs.

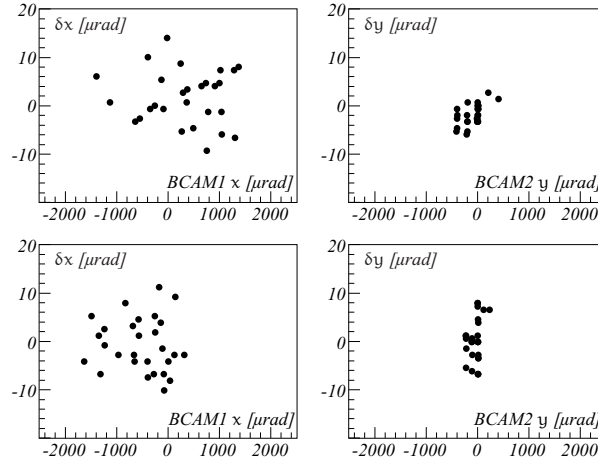
For this test the bar was deformed in one coordinate (x-coordinate), the angular change at the positions the BCAMs are mounted was calculated from the readings of the in-bar instrumentation and compared to the actual measurement of the two radial BCAMs. Figure 8.7 shows the difference between the prediction and the measurement.



**Figure 8.7:** Relative angles measured with the radial BCAMs, compared to the angles obtained from the first derivative of the bar shape. The bar shape has been retrieved from the readings of the in-bar instrumentation; *left*: x-direction (direction of the deformation); *right*: y-direction (almost no change in deformation).

The intrinsic BCAM resolution can be extracted from the deviations in the  $y$ -direction (almost no change in deformation) and is of the order of  $4\text{ }\mu\text{rad}$ . The prediction in  $x$ -direction (direction of deformation) agrees with the BCAM measurement to the order of  $6\text{ }\mu\text{rad}$ .

Relative changes in the viewing direction of the BCAMs of  $\sim 1300\text{ }\mu\text{rad}$  have been reached. Systematic effects that scale with the deformation have not been observed. Figure 8.8 shows that the precision in predicting the BCAM measurement is not correlated to the deformation of the bar, which indicates that the bar shape model and its first derivative describe bar deformations well, and that the behavior of BCAM platforms is understood.



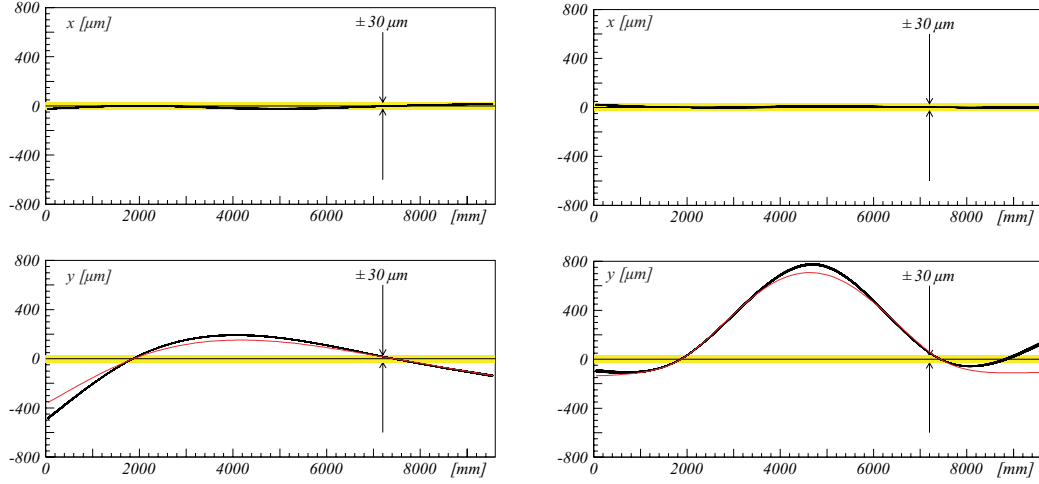
**Figure 8.8:** Difference between predicted and measured angle vs total change in angle.

### 8.3.2 Bars in Inclined Positions

Before mounting the bars to the structures in H8, they have been placed in horizontal position and connected to the readout system. This functionality check was also used to obtain information whether some elements of the in-bar RASNIKS displaced during the transport. The measurements from the in-bar instrumentation led to a shape which differs by less than  $30\text{ }\mu\text{m}$  compared to the shape, the bar had during the measurement of the initial shape. At the level of accuracy one can expect from this test, this is an indication, that the RASNIK elements inside the bar “survived” the transport.

Normally the bars are then mounted to the structure and equipped with the alignment sensors (i.e. BCAMs and proximity masks). To test the predictability of the change in shape when mounting a bar in an inclined position, one long bar, which is mounted at  $\sim 45^\circ$  was first equipped in horizontal position, to compare the prediction based on the additional load of the alignment sensors to the measurement of the in-bar instrumentation. For this prediction, the load of the additional cables which are connecting the alignment sensors on the bar has not been taken into account. Figure 8.9-left shows this prediction in comparison to the deformation measured with the in-bar instrumentation.

Both deformations are referred to the deformation the bar had, when its initial shape was measured. For the prediction of the bar shape in its inclined position, all loads acting on the bar have been scaled with the inclination angle. Figure 8.9-right shows the difference in deformation between the prediction and the measurement of the bar in its inclined position.



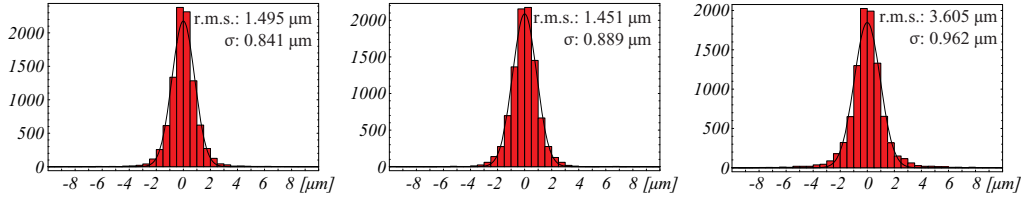
**Figure 8.9:** Predicted deformation (red) of a completely equipped bar, compared to the deformation reconstructed from the measurements of the in bar instrumentation (black). Both deformations are scaled relative to the deformation the bar had, when its initial shape was measured. *left:* bar in horizontal position (*top:* deformation horizontal, *bottom:* deformation vertical) *right:* bar in  $\sim 45^\circ$  inclined position (expressed in the same bar coordinate system as used left).

Regarding the fact, that for the prediction of the deformation in horizontal and in inclined position, the load of the cables connecting the alignment sensors, has been neglected, the predicted deformations are in reasonable agreement to the deformations measured with the in-bar instrumentation.

### 8.3.3 Vibrations

The setup in H8 has also been used to address the stability of alignment bars in the vibrational environment of the test beam area. The EO structure is mounted to a wall built from concrete blocks, which are used as beam dump. Similar as in the ATLAS cavern, where the EO structure will be attached to the cavern walls, while the EM structure is freely standing; equal to the EM structure in the H8 setup. In terms of stability of the alignment bars, the interesting part is the spread of the RASNIK data of the in-bar instrumentation, due to the presence of vibrations. Thus the short term variations of the data, for which vibrations are responsible (“high frequency”), taken from a continuous run over 70 hours have been used to quantify the vibrational influence. Figure 8.10 shows this spread of the three different in-bar RASNIKs, totalized for all four long alignment bars mounted to the EO and the EM structure. The spread is less

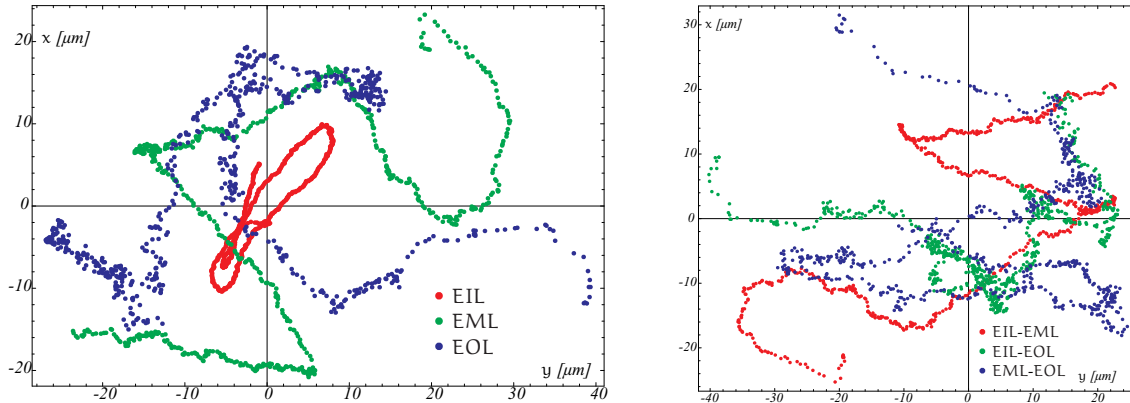
than  $4\text{ }\mu\text{m}$  r.m.s., which can be translated into an uncertainty in knowing the shape to  $2\text{ }\mu\text{m}$  r.m.s. and thus is not of concern.



**Figure 8.10:** Averaged high frequency part of all long alignment bars (EO and EM); *left*: short RASNIKS S1; *middle*: short RASNIKS S2; *right*: long RASNIKS.

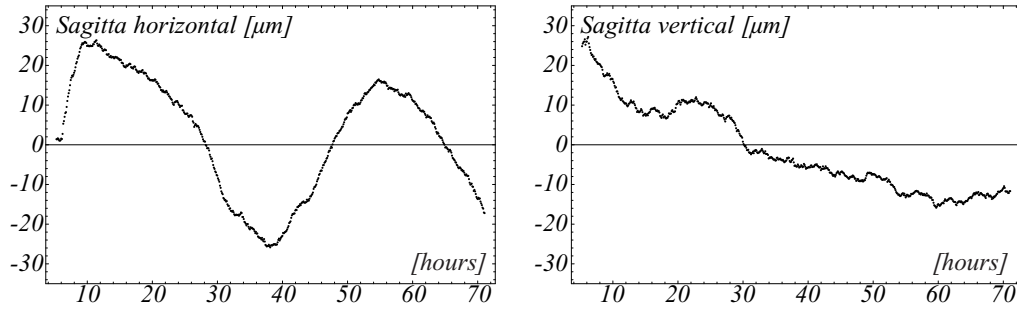
### 8.3.4 Movement of Chambers

Relative movements between the three chamber layers (EI-EM-EO) as seen from the muon simulator are shown in Figure 8.11. Here the high frequent part of the data was removed with a moving average of 50 successive measurements. Figure 8.11-right shows the movement of the EIL chamber relative to the EML and the EOL chamber as well as the movement of EML relative to EOL.



**Figure 8.11:** Movement of the three phantom chambers, measured with the straight line reference of the muon simulator ( $x$  vertical,  $y$  horizontal); *left*: movements of the three large chambers relative to the simulator BCAM mounted on a concrete block; *right*: relative movements between chambers (EIL-EML, EIL-EOL, EML-EOL).

This chamber movements can be expressed as the contribution to the sagitta error one would obtain without an alignment system. Figure 8.12 shows this movements over 70 hours. During the first 13 hours the temperature changed by  $0.8^\circ$ , which corresponds to a change in sagitta of  $25\text{ }\mu\text{m}$ . The resolution of the muon simulator is discussed in Section 8.3.5.

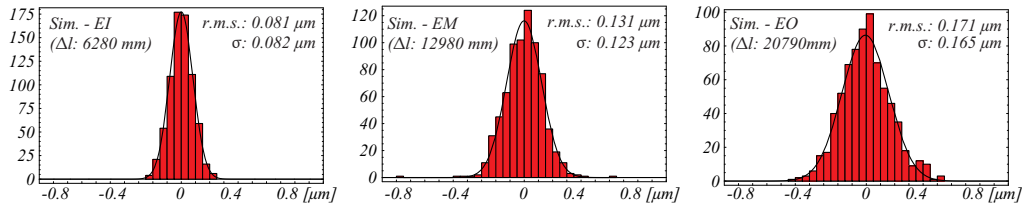


**Figure 8.12:** Contribution to the sagitta error due to relative movements of the three chamber layers over 70 hours; *left*: horizontal; *right*: vertical.

### 8.3.5 Temperature Effects

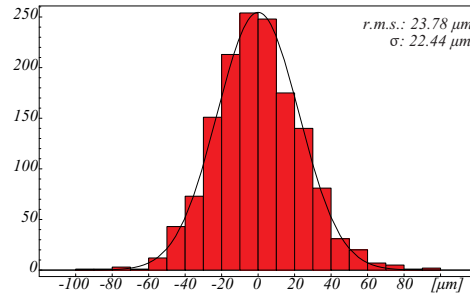
#### Spread of BCAM measurements

The spread of the data which were averaged over the measurements shown in Figure refsagitta-2 is mainly induced by thermal fluctuations along the light path and hence increases with the length of the optical path. In this case the measure of the separation of the two light sources integrated in each BCAM provides a measure of the thermal fluctuations, which are superimposed to the intrinsic BCAM resolution. Figure 8.13 shows the spread of the data for the different optical path lengths, normalized to movements on the CCD.



**Figure 8.13:** Spread of the measured distance between the two light sources seen from the simulator BCAM and normalized to movements on the CCD. The spread increases with the length of the optical path; *left*: 6280 mm ( $\sigma = 1.1 \mu\text{rad}$ ); *middle*: 12980 mm ( $\sigma = 1.7 \mu\text{rad}$ ); *right*: 20790 mm ( $\sigma = 2.3 \mu\text{rad}$ ).

The so obtained total sensor resolution can be expressed as the resolution to which the muon simulator can measure the sagitta error due to the chamber movements. Figure 8.14 shows the resolution calculated from the individual distributions in Figure 8.13 and expressed as the contribution to the measurement of the sagitta.



**Figure 8.14:** Resolution of the muon simulator expressed as the contribution to the measured sagitta error.

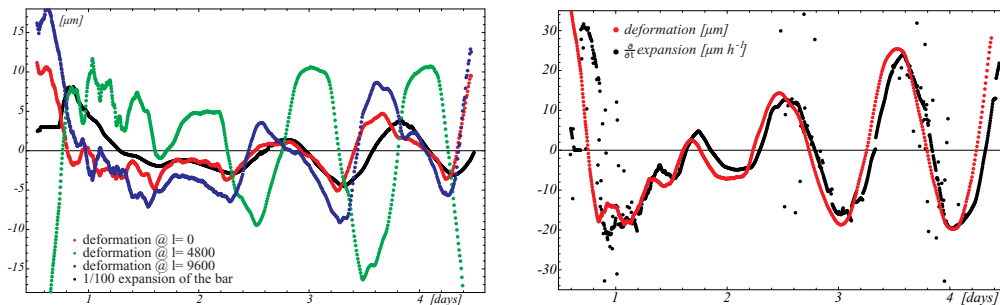
### Motion of alignment bars

The alignment bars mounted in H8 mainly change their shape due to temperature variations. The deformations are of the order of  $10\ \mu\text{m}$  for a temperature ranging from  $18^\circ\text{C}$  to  $22.7^\circ\text{C}$ . The deformation over time shows the influence of the bar supports used. Thus, when the bar expands or contracts, the torque induced from the constraining forces of the bar supports, leads to first mode deformations. Figure 8.16-left, shows the movements of points at the ends each and in the middle of the bar. The ends move antiparallel to points in the middle. This movements can be expressed as the deformation as defined in Figure 8.15.



**Figure 8.15:** First mode deformation of a bar expressed in one value.

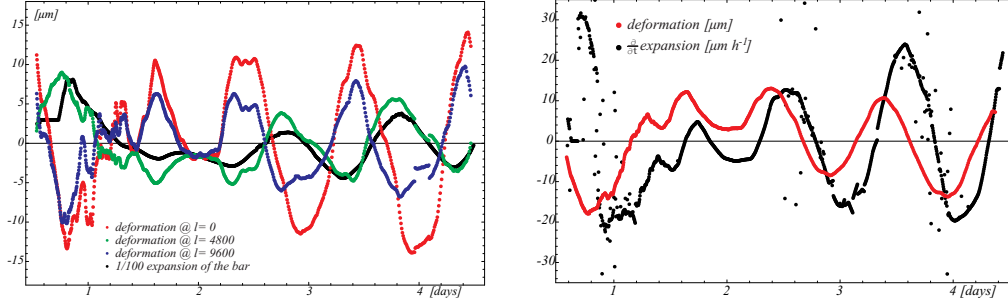
Figure 8.16-right shows that this deformation correlates with the expansion of the bar, (which is proportional to the temperature trend).



**Figure 8.16:** *left:* movement of the upper EO-bar in horizontal direction during 4 days, compared to the thermal expansion of the bar; *right:* deformation compared to expansion.



In horizontal direction the bar shows the same behavior in a reversed manner. Here the middle of the bar moves parallel to the temperature trend, which gives only evidence about the choice of the bar coordinate system.

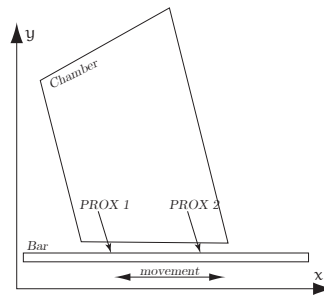


**Figure 8.17:** *left:* movement of the upper EO-bar in vertical direction during 4 days, compared to the thermal expansion; *right:* deformation of the bar compared to the expansion of the bar.

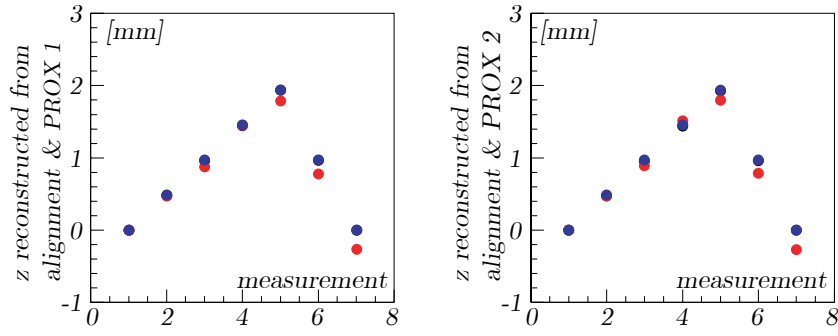
### 8.3.6 Controlled Displacement of an Alignment Bar

To test the capability of the alignment system to correctly reconstruct movements of components, one alignment bar (EO low) was mounted on a micrometer stage, to allow for controlled movements along the bar axis, with a precision of better than  $10\text{ }\mu\text{m}$ . Movements of the bar in steps of  $0.5\text{ mm}$  have been performed. After each movement the position of this bar was reconstructed from the alignment data.

The reconstruction demands to fix the global coordinate system to any of the devices involved. For this test the lower EM bar was chosen. During the measurements the temperature changed by about  $0.5^\circ\text{C}$  and hence the origin of the coordinate system moved. Figure 8.19 is showing the movement of the lower EO bar reconstructed from the measurement of the proximity sensors, which are almost directly measuring the movement of the alignment bar and hence overlap with the values from the micrometer stage. The second set of points shows the bar position reconstructed from the remaining alignment sensors, which are mainly two azimuthal and two polar BCAMs.

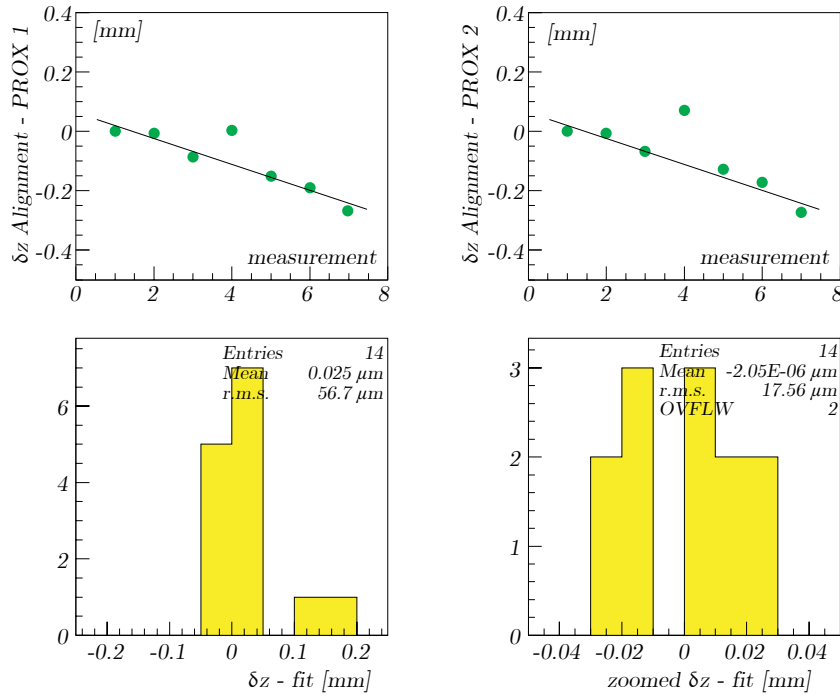


**Figure 8.18:** Sketch of the performed movement of the lower EO bar.



**Figure 8.19:** Movement of the lower EO bar; *blue*: measured with the micrometer stage and the proximity monitors (points are overlapping); *red*: reconstructed from the remaining alignment sensors.

The difference between the prediction and the measurement is shown in Figure 8.20. Here the deviation from horizontal indicates the movement of the global coordinate system, where else the deviation from the straight line indicates the error in reconstructing the bar position.

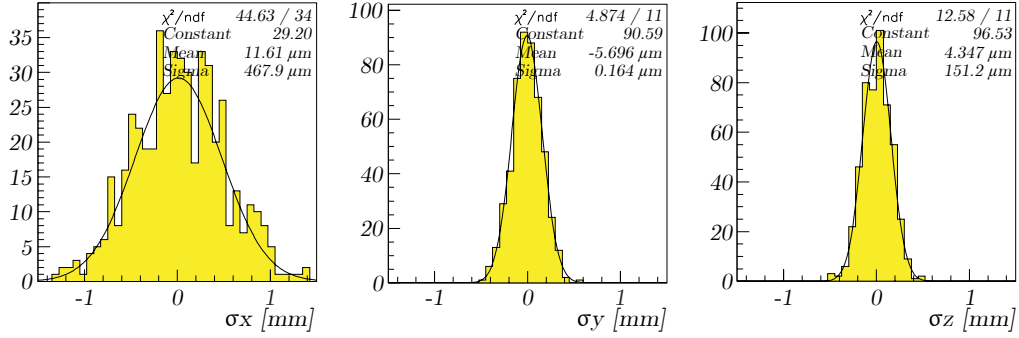


**Figure 8.20:** Reconstructed position of the lower EO bar, subtracted from the measurement with the micrometer stage, or the measurements of the proximity monitors, which are directly related to this bar; *left top*: reconstruction compared to the measurement of the proximity monitor mounted at higher  $\eta$ ; *right top*: reconstruction compared to the measurement of the proximity monitor mounted at lower  $\eta$ ; *left bottom*: residual error for all measured points; *right bottom*: residual error when rejecting the one outlier.

The positioning accuracy of the lower EO bar measured with the alignment system is  $57\text{ }\mu\text{m}$ . The reason for the one outlier is unclear, when rejecting this measurement, the positioning accuracy is  $17.6\text{ }\mu\text{m}$ .

### Simulated positioning accuracy

To obtain information about the accuracy one can expect for such movements, the absolute positioning accuracy of this bar has been simulated. To retrieve the relative positioning accuracy, the simulated values have to be scaled with the difference in accuracy between absolute and relative measurements. The sensors which are directly involved to provide the position of this bar are BCAMs, for which the absolute to the relative accuracy scales 10:1. Figure 8.21 shows the simulation results of the absolute positioning accuracy for movements of the lower EO bar in H8 coordinates.



**Figure 8.21:** Simulation of the absolute position accuracy of the lower EO bar, reconstructed from the alignment sensors. The positions are displayed in the H8 coordinate system.

In the H8 coordinate system the bar is rotated in the horizontal x-z plane by  $15^\circ$ . Thus when transforming the H8 coordinate system into the bar coordinate system ( $\sigma_{z,\text{bar}} = \sigma_x \sin 15 + \sigma_z \cos 15$ ) one obtains  $199\text{ }\mu\text{m}$  for the absolute positioning accuracy and  $20\text{ }\mu\text{m}$  for the relative positioning accuracy in the direction along the bar. This  $20\text{ }\mu\text{m}$  are in reasonable agreement to the measurement above. The difference of about 10% between the simulation and the measurement can be explained by the fact that the  $5\text{ }\mu\text{rad}$  resolution for the BCAMs, which have been used in the simulation, are a design value.

As a rough estimate for the expected accuracy, one can calculate the combined error of the four BCAMs that are mainly involved in this position measurement. Here the actual distance to the bar multiplied with the relative accuracy of  $5\text{ }\mu\text{rad}$  delivers:  $16.3\text{ }\mu\text{m}$  ( $= 1/4 \sqrt{3960.5 \cdot 10^{-6} \oplus 5260.5 \cdot 10^{-6} \oplus 7650.5 \cdot 10^{-6} \oplus 8300.5 \cdot 10^{-6}}$ ). Since the viewing direction of the four BCAMs is not perpendicular to the bar, this rough estimate leads to a smaller number than the simulation.

The simulated positioning accuracy for movements of the lower EO bar along its axis is 20  $\mu\text{m}$ , and in reasonable agreement to the measurements.

### 8.3.7 Consistency of Alignment Reconstruction

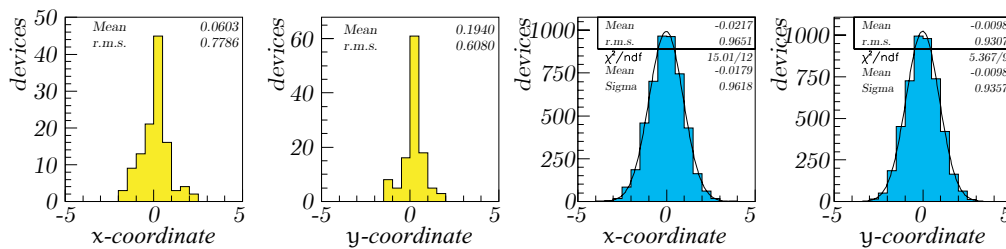
All alignment bars are equipped with two survey rings which are located close to the position of the support points. These rings provide holes for survey targets and thus allow to measure the position with optical survey techniques, which are accurate to about 0.3 mm. The so obtained bar positions can be used to calculate the readout values of each individual sensor, and compared to the actual alignment sensor values.

The comparison of these two different techniques provides information about the absolute positioning accuracy of the alignment system, which is dominated by the calibration of the BCAMs.

At the time of writing only uncalibrated sensors have been available. The accuracy of an uncalibrated BCAM is mainly affected by the precision of mounting the CCD relative to the lens and relative to the grooves on which the BCAMs are mounted to the three-ball patterns of their corresponding platforms. (The positioning accuracy of a CCD is expected to be of the order of 100 - 200  $\mu\text{m}$  [JB:02].)

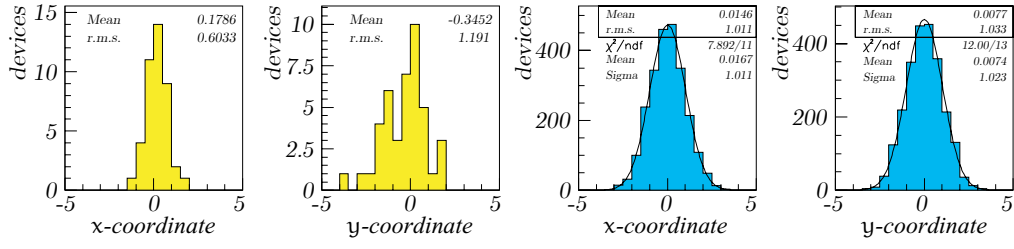
To account for the decreased accuracy of the sensors used, the following plots are showing the distributions of pull values, which are the predicted sensor values subtracted from the measured sensor values divided by the expected sensor accuracy. These pull values should be one or less than one.

Three types of measurements can be performed with BCAMs. One measurement concerns the determination of the absolute position of the partner BCAM, for which the pull values are shown in Figure 8.22.



**Figure 8.22:** Distribution of pull values for absolute position measurements; *left*: measured sensor values; *right*: simulated sensor values.

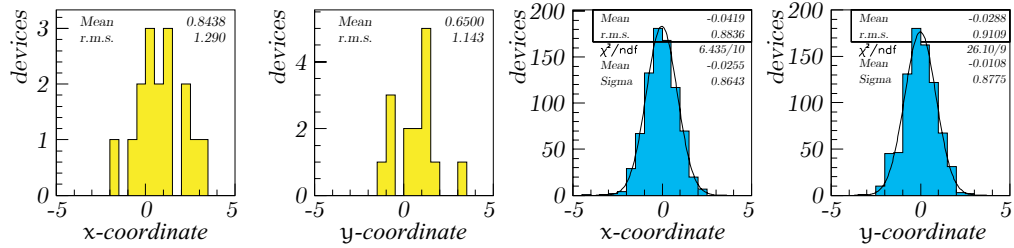
Another check can be performed by measuring the distance of the two light sources that are integrated into the BCAM. The pull values for this measurement are shown in Figure 8.23.



**Figure 8.23:** Distribution of pull values for the distance between the two light sources integrated in each BCAM; *left*: measured; *right*: simulated.

The fact that the deviation in the  $y$  coordinate is larger than the deviation for the  $x$  coordinate is related to the geometric position of the light sources, which are separated in  $x$  but not in  $y$  direction, thus a rotation of the CCD (which is also included in the BCAM calibration) contributes mainly to the error in the  $y$  coordinate.

The third type of measurement is shown in Figure 8.24. Here the pull values for the distance measurement of light sources on different BCAMs along the same alignment corridors are shown.



**Figure 8.24:** distribution of pull values for the distance between the two light sources on different BCAMs; *left*: measured; *right*: simulated.

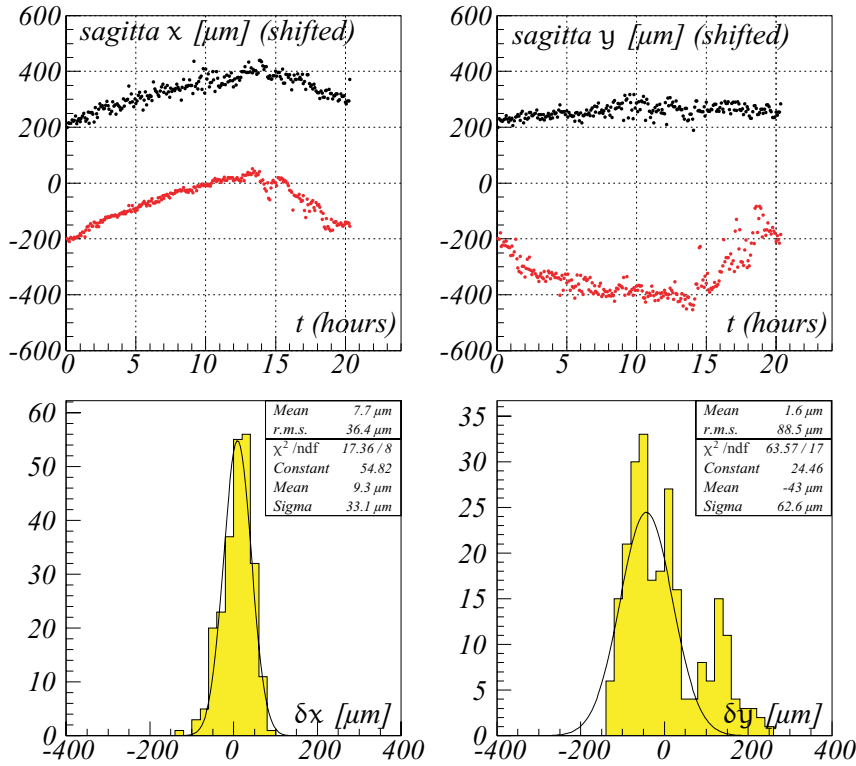
Assuming the accuracy of the uncalibrated sensors is the only limiting factor in reconstructing absolute positions, one can conclude from the fact that all pull values are close to one, and therefore using calibrated devices the reconstruction is expected to meet the specifications.

### 8.3.8 Reconstruction of Chamber Positions

The task of the alignment system is to provide the chamber positions with a precision, such that the contribution of the alignment system to the overall sagitta error in the main bending direction is  $\leq 30 \mu\text{m}$  r.m.s. One of the aims of the H8 test beam stand is to prove the precision with which this sagitta correction can be measured. To compare

the reconstructed chamber positions to a measurement, the phantom chambers used in the first stage of the H8 test stand, have been equipped with a muon simulator (Figure 8.3). The relative chamber movements measured with this additional straight line reference, can thus be compared to the chamber positions, reconstructed with the alignment system. The reconstruction first determines the global bar positions from the BCAM measurements and afterwards relates the chambers to the bars by using the proximity part of the alignment system.

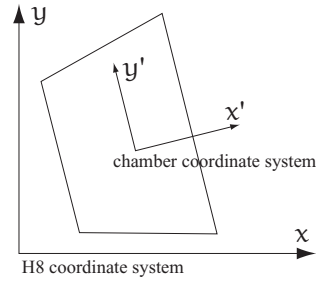
Figure 8.25-top shows the sagitta correction, reconstructed from the alignment system, in comparison to the sagitta error, measured with the muon simulator. The difference between the reconstructed sagitta correction and the measured sagitta error (Figure 8.25-bottom) leads to  $33.1 \mu\text{m}$  in horizontal direction and to  $62.6 \mu\text{m}$  in vertical direction.



**Figure 8.25:** Sagitta correction reconstructed from the alignment system relative to the sagitta measured with the straight line reference of the muon simulator; the plots are shown in the H8 coordinates system (x-coordinate horizontal, y-coordinate vertical); for reasons of illustration, the two sets of datapoints have been shifted by  $\pm 200 \mu\text{m}$ . *top*: black: measurement of the muon simulator; red: reconstructed with the alignment system; *bottom*: difference between measurement and reconstruction.

After correcting this values with the resolution of the muon simulator ( $23.8 \mu\text{m}$ ; derived in Section 8.14), the remaining contribution of the alignment to the sagitta error is  $23 \mu\text{m}$  in horizontal direction and  $58 \mu\text{m}$  in vertical direction. The main bending direction of the corresponding chamber triplet is rotated by  $14^\circ$  relative to the H8 coordinate system, in which the chamber positions have been reconstructed (illustrated in 8.26). Thus the

obtained error in sagitta correction in the  $x$ -coordinate is slightly larger than in the main bending direction. The precision in reconstructing the chamber positions is affected by the thermal expansion of the phantom chambers. These chambers are not equipped with temperature sensors. Due to the chamber dimensions, this thermal effect is larger in the vertical direction.



**Figure 8.26:** *left:* orientation of the reconstructed chambers, relative to the coordinate system used for the reconstruction. (The main bending direction is parallel to the  $x$ -coordinate of the chamber coordinate system.)

The first measurement performed to prove the capability of the alignment system to follow relative chamber motions, shows that the contribution of the alignment system to the overall sagitta error is less than  $30\text{ }\mu\text{m}$  r.m.s. in the main bending direction. This result is in agreement to the simulation discussed in Section 8.5.





## Chapter 9

# Proposed Design for the ATLAS Alignment Bar

### 9.1 Introduction

The six alignment bar prototypes built for the H8 setup are functioning and show in combination with the measurement and reconstruction techniques that these bars fulfill the precision requirements. In addition the experience gained during this R&D phase permitted to improve the bar design. This chapter will discuss the design proposed for the ATLAS alignment bars and explain the improvements. Also a manual that explains the steps from assembling a bar to its installation in ATLAS is presented.

### 9.2 Key Features of the Proposed Design

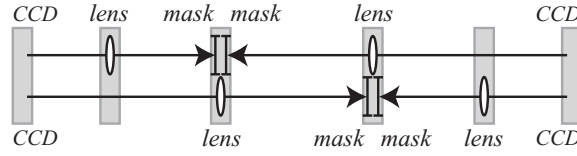
At the time I designed the first prototype, details of the concept of the end-cap alignment had not been settled. The prototype was meant to demonstrate that the precision requirements can be reached, but the in-bar instrumentation of these bars is providing a dynamic range in terms of allowed deformation that is not sufficient for the load ATLAS bars have to carry<sup>1</sup>. The dynamic range of the prototype is mainly limited by the RASNIK reaching from one bar end to the other. The dynamic range can be increased when using a different layout for the optical in-bar instrumentation.

#### 9.2.1 Layout

Figure 9.1 illustrates the proposed layout, which consists of 4 overlapping RASNIKS.

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<sup>1</sup>In fact also the positions of the support points of the bars used in H8 had to adapted individually, to maintain the limited dynamic range at least in the orientation the bar was meant to be installed.



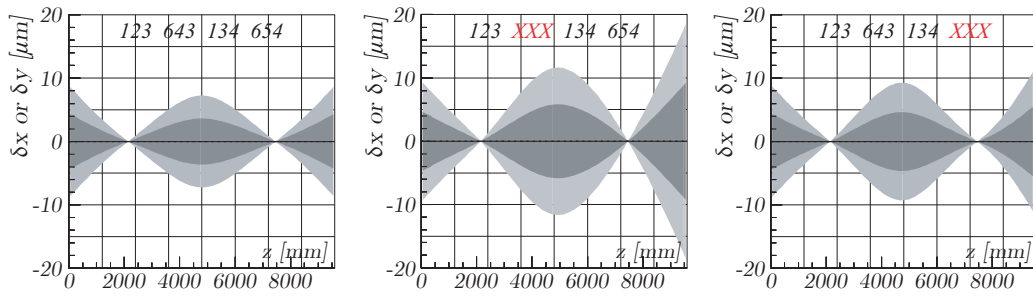
**Figure 9.1:** In-bar instrumentation consisting of four RASNIKs.

In view of the CMM measurements this new layout has the advantage, that compared to the prototype the number of measurements necessary to calibrate the in-bar RASNIKs can be reduced by  $1/3$ , since the extra measurement of the mid part of the bar is no longer necessary. The fact that no RASNIK is longer than the range of the machine also allows to directly measure all components involved, which also increases the precision of the calibration.

The operating principle of RASNIKs demands that the mask image is properly focussed onto the CCDs. The RASNIKs of the prototype bar had to be built from custom made lenses, which are much more expensive than commercial lenses. The new design allows for enough flexibility to use commercial lenses. The focal length of one lens is appropriate for the 6.2 m long RASNIKs, while doublets of the same lens are used to focus correctly for the 2.8 m long RASNIKs. The choice of using 6 lenses of equal focal length also allows to sort the lenses appropriately (i.e. using a minimum spread in focal length for the long RASNIKs, and build the lens doublets for the short RASNIKs from the left and the right tail of the distribution in focal length).

### 9.2.2 Redundancy

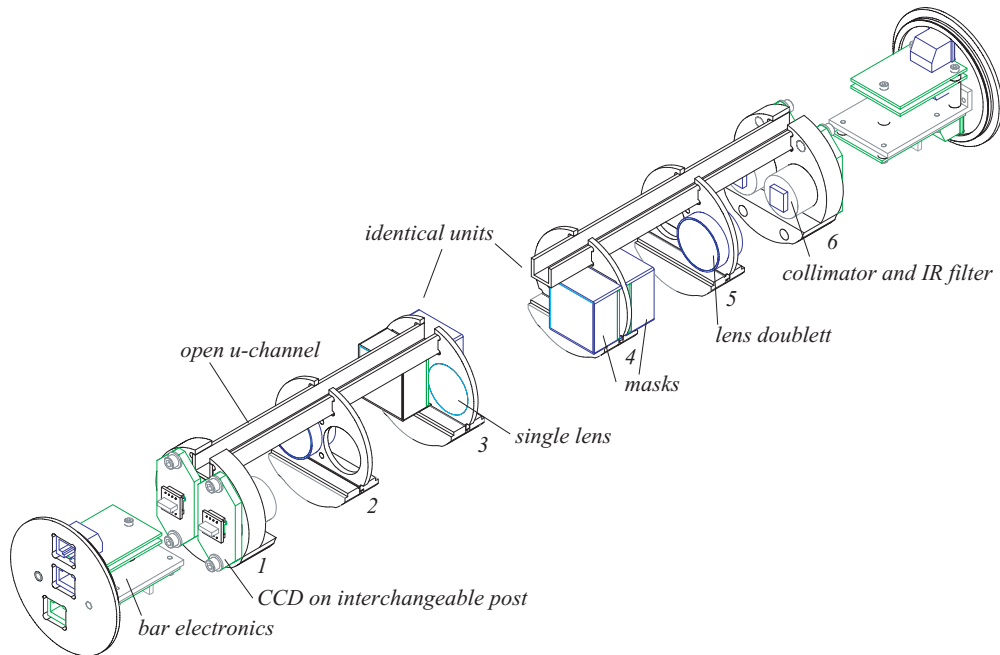
The layout in Figure 9.1 shows 4 RASNIKs, while for the reconstruction of the bar shape only three RASNIKs are needed. Thus the four-RASNIK layout is redundant in the sense, that one RASNIK can fail, and the shape of the bar can still be reconstructed from the remaining three RASNIKs without significant loss in precision. Figure 9.2 shows the envelopes of false shapes calculated with the calibration accuracies obtained from the calibration of the H8 bars, as well as the precision calculated for a loss of one short or one long RASNIK.



**Figure 9.2:** Precision in measuring the bar shape with the in-bar instrumentation when using 4 RASNIKS (bright, worst calibration obtained from the H8 prototypes: 10  $\mu\text{m}$ ; dark, average calibration: 6  $\mu\text{m}$ ; *left*: all 4 RASNIKS used; *middle*: one long RASNIK is not used; *right*: one short RASNIK is not used.

### 9.2.3 Design

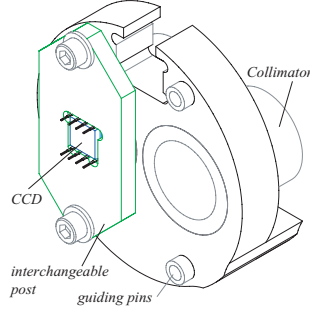
The 9.6 m long skeleton as used for the prototype has been replaced by two 4.5 m long units which are identical. The individual discs are connected with a u-channel, which has the advantage, that all the cables for the in-bar instrumentation can be guided inside this channel. The use of such an open channel reduces the assembly time.



**Figure 9.3:** Drawing of the proposed in-bar instrumentation.

The new layout foresees the possibility of replacing the CCD heads. Thus the CCD heads are glued to a post which can individually be calibrated on a small calibration stand.

This calibration stand will consist of a mask and a lens of short focal length, where the post can be placed on guiding pins. The calibration values are then the position of the CCD relative to the pins and the orientation of the CCD relative to the mask.

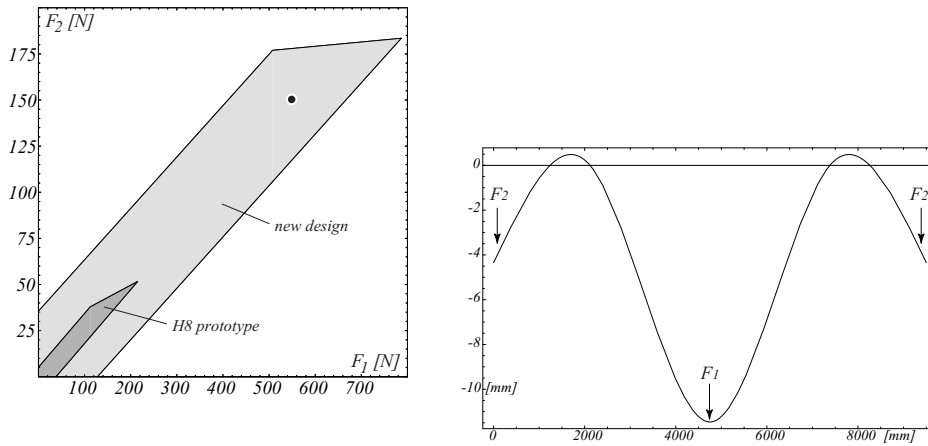


**Figure 9.4:** Illustration of the end-station with one CCD removed.

The layout of the masks that are implemented is identical to the layout used for the masks of the proximity monitors. These masks are with  $30 \times 30 \text{ mm}^2$  larger than the ones used for the prototype.

#### 9.2.4 Dynamic Range

One of the main issues when designing the new in-bar instrumentation was to overcome the limited dynamic range of the prototype. The layout shown in Figure 9.1 in combination with the larger masks provides a dynamic range that allows for loads twice as high as expected for a final ATLAS bar. Figure 9.5 shows the dynamic range expressed as forces that can act in the middle and the bar ends each.



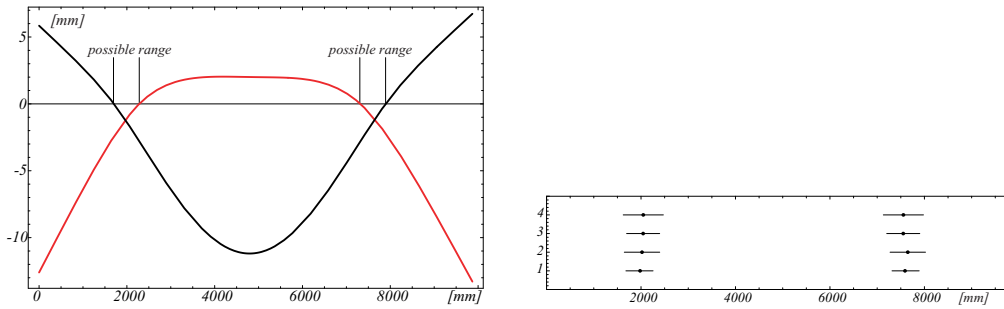
**Figure 9.5:** Dynamic range of the proposed alignment bar compared to the dynamic range of the prototype built for H8.

The tubes delivered from the manufacturer show a bow with a sagitta of up to 5 mm,

as well as the lenses available show a non negligible centricity error. Both effects can be compensated at the time of assembling the bar. In the new design it is foreseen to measure the centricity of the lenses and drill the holes which are defining the orientation of the discs (and the lenses) inside the bar with respect to the bow of the bar.

### Possible shifts of support points

As mentioned earlier, the range of the in-bar instrumentation must also allow for enough freedom to position the two support points. The allowed range has been calculated for the loads an ATLAS like EM-bar has to carry. Figure 9.6 shows the deformations for a displacement of the support points by  $\pm 280$  mm relative to the ideal support points (Bessel points). Figure 9.6-left shows different Bessel point and maximum allowed displacements for different load scenarios.



**Figure 9.6:** *left:* possible bar deformation, due to the displacement of the support points relative to the Bessel points by  $\pm 280$  mm each; *right:* Bessel points and maximum range of displacement for different load scenarios of an ATLAS like bar foreseen for the EM layer. The global minimum for these 4 cases leads to  $\pm 280$  mm.

The new design offers a dynamic range of the deformation measurement which is twice as high as expected for the ATLAS bars. The range of displacing each of the support positions relative to the Bessel points is  $\pm 280$  mm.

The 4-RASNIK layout is symmetric and built with commercial lenses of equal focal length. The distribution of the RASNIK elements has been optimized in view of the range of the coordinate measuring machine, which thus allows direct access to all elements involved and reduces the calibration time by 1/3 compared to the prototype.

Redundancy and the interchangeability of the RASNIK CCDs are additional features of this design.

### 9.3 Assembly Steps in the ATLAS Alignment Bar

This section is intended to provide a step by step assembly guide with the aims: to document lessons learned from the prototype to allow groups to evaluate the work needed to realize this alignment bars, and to provide a list of all steps from producing the bar, calibrating its instrumentation until it is mounted in its final position.

#### 9.3.1 Manual

##### 1. Bar assembly

- Preparation of the tube:

The tube for the alignment bar has to be cut in length, and holes have to be drilled to attach the in-bar instrumentation. Since the tubes show a non negligible deviation from straight (bow), the holes have to be drilled with respect to the inner curvature of the bow. Thus, the bar has to be held at the ends to allow the tube to rotate such that the bow is aligned in the direction of gravity. In this orientation a ruler can be fixed to the tube to mark the length and the positions for the holes. The circular position of the holes defines the orientation of the discs inside the bar and hence the orientation of the RASNIK mask relative to the CCD.

- Preparation of the discs:

To compensate for the bow of the tube, the centration of the lenses used for the in-bar RASNIKS has to be measured. The lenses should be glued into the corresponding disc, such that the offset from the optical axis points into the direction of the threaded hole used to mount the disc inside the bar. To minimize the spread in focal length, the singlets used for the long RASNIKS should be sorted from the center of the distribution in focal length, and the doublets used for the short RASNIKS should be assembled from samples of the left and the right tail of the focal length distribution.

The temperature sensors and the masks have to be glued to the disks. The CCDs are glued to their post, and need to be calibrated relative to the mounting grooves. The calibration is obtained by placing the post on a little calibration stand, which consists of a masks and a lens of short focal length. The calibration values are the coordinates perpendicular to the optical axis and the rotation obtained from the image analysis. After that the CCDs can be mounted to the corresponding discs.

- Assembly of the discs:

The discs have to be combined to units and need to be aligned relative to the mounting holes that have been drilled into the tube. Thus the discs for one unit have to be pushed onto the u-channel. A set-screw screwed into each disc can be used to place the units on the outside of the bar, and thus align the discs with respect to the holes of the bar. After that the positions for the pins that are pushed into the connecting u-channel, to constrain the discs in the lateral position can be marked. The accuracy for this pins is moderate of

the order of a few mm and should allow the discs to slide by 3-5 mm, in order not to wedge the discs when the bar is deformed.

At the time of pushing the pins into the u-channel, the cabling of the temperature sensors and the RASNIK masks has to be performed, since the pins are also used to force the cables into the u-channel and hence serve as stress relief for the cables.

After that the set screws can be removed, and the units can be pushed into the tube. The end-stations containing the bar-electronics have to be connected to the cables and mounted to the bar-ends.

A functionality check of the in-bar instrumentation finishes the assembly of the in-bar instrumentation of the alignment bar. When reading the RASNIKS, the range of the image analysis have to be set corresponding to the magnification and the mask-pitch, such that at least 2 code squares are visible in each coordinate.

- Mounting of sensor platforms and kinematic mounts:

The positions of the individual components mounted onto the bar can again be determined with a ruler that is fixed to the bar. After that the kinematic mounts have to be attached such that the screws keeping the in-bar instrumentation point upwards in the final position in ATLAS. This rotational alignment is moderate of the order of a few degrees. The weight of each individual sensor platform has to be measured, since it is needed for the reconstruction. The accuracy is moderate of the order of a few grams. The sensor platforms can then be mounted and aligned relative to the orientation of the kinematic mounts. The sensor platforms have to be adjusted within  $\pm 0.5$  mrad relative to each other.

## 2. Bar Calibration

- The expansion coefficient of the alignment bar has to be measured. This is best done with a laser interferometer, mounted to the bar to measure the bar length as a function of temperature, which is measured by the in-bar instrumentation. (Day-night temperature variations are normally sufficient.)
- In preparation of the CMM measurement, additional steel balls have to be glued to the outside of the bar, close to the locations of the individual RASNIK elements. To define the bar coordinate system three steel balls need to be attached to the bar in the region where the CMM measurements of the two parts of the bar overlap. (Minimum influence on the change in position along the bar is obtained when positioning all balls on the side of the bar which is perpendicular to the main direction of deformation; see Figure 6.9, p.6.9)
- The bars have to be mounted and adjusted on the table of the CMM. The bar should be mounted such that the orientation of the bar is closest to the final orientation in ATLAS. (i.e. 4 bars in 0° orientation and 4 bars in 180° orientation.). As the long bars have to be measured in two parts, the change in orientation relative to gravity when measuring the second part of the bar has to be minimized. This can be realized by using one sensor

platform for both CMM measurements to align the bar relative to gravity. (With a bubble level 0.1 mrad can be achieved)

- To calibrate the RASNIKS the centers of the corresponding balls have to be measured. At least two different measurements have to be performed (preferably more to allow for cross checks). Different RASNIK values are obtained by deforming the bar. One deformation can in parallel be used to retrieve Young's modulus, when using a known weight at a discrete point (see Section 7.3.1, p.78).
- Before measuring, the bar has to be blocked in the middle and at the ends. For the initial shape measurement all balls mechanically connected to the bar have to be measured. When blocking the bar for this measurement, the RASNIK values should not change by more than 10-15  $\mu\text{m}$  during the fixation. To measure the second part of the bar, the bar has to be shifted relative to the CMM, and aligned relative to gravity with respect to the prior used platform. When measuring the individual three-ball patterns on a sensor platform, the probe head orientation has to remain unchanged. (The local accuracy for the individual three-ball patterns is 3.4  $\mu\text{m}$ , the global accuracy is of the order of 20  $\mu\text{m}$ .)
- The same procedure as applied for the calibration of the first half of the bar has to be performed for the second half of the bar.

### 3. Initial shape

- The calibration constants for all RASNIKS are retrieved from the CMM measurements (see Section 5.3.1, p.51; a calibration program is available).
- To combine the two measured parts of the bar to one "bar shape", the difference in deformation between the two part measurements has to be corrected. Therefore the CMM measurements of one part of the bar have to be adapted such that the RASNIK and the temperature values obtained during the CMM measurement are equal for both parts of the bar. Afterwards the measured points in the overlap region (i.e. the balls defining the bar coordinate system) serve to combine the two bar parts.
- The set of RASNIK values in combination with the bar shape represent the initial bar shape.

### 4. Shipping of the bar

- To avoid to damage the measured balls of the platforms, protective covers have to be mounted to the platforms. The balls that have additionally been glued directly to the bar are in principle no longer needed. (They could only serve a re-calibration of the bar.)
- Before packing the bar into the transport box the bar ends have to be covered to avoid dust entering the bar.



- At the time of installation the bar should be placed horizontal, to check whether the RASNIK values changed, which could indicate that some RASNIK elements moved during the transport. (This test is accurate to  $\sim 30\text{ }\mu\text{m}$ ; see Section 8.3.2, p.98)

## 5. Installation

- After removing the protective covers and cleaning the three-ball mounts, the sensors can be mounted to their corresponding platform. (The fixation of the sensors has to be performed either with a torque wrench, or by tightening the fixation screw finger tight +  $\frac{1}{2}$  a turn)
- The sensors have to be connected such, that the cables run to the closest bar support, where they are connected to a multiplexer.  
At this time it is essential to note the serial number of each sensor, since the individual sensor calibration is referred to this number and is unambiguously needed for the alignment reconstruction. The readout system identifies the sensors by the channel number they are connected to the multiplexer. Thus the channel number must also be provided.
- When mounting the bar to the structure, the orientation of the guiding ring of the lower mount has to be corrected such that this ring is in the final bar position perpendicular to the bar (see Section 4.4.3, p.47). After that, survey targets are attached to the survey rings, and an optical survey is performed. The so obtained bar positions are used as special sensor inputs for the first global positioning in the reconstruction software ARAMYS.

## 6. Shape reconstruction

- The first estimate of the change in bar deformation is calculated. Here the weight of the individual sensors and sensor platforms that are mounted to the bar is needed, and has to be scaled with the inclination of the bar relative to the orientation it was measured on the CMM. The same numbers are needed for the calculation of the bar expansion.  
This calculations have to be performed once and are part of the reconstruction routine.
- During operation the readout values provided from the in-bar instrumentation are used to continuously refine the estimated shape with the virtual load model. The shape reconstruction is implemented in ARAMYS.



# Chapter 10

## Conclusions

The design and measurements of an alignment bar prototype have been presented as well as first measurements on the end-cap alignment system.

The design of the bar which is based on overlapping straightness monitors (RASNIKS) allows to mount the sensors needed to measure the bar shape, inside the bar. It has been shown under which conditions the kinematic mounts, supporting the bar, can be used for ATLAS. Based on the presented design six alignment bars have been built.

A strategy to calibrate the in-bar instrumentation and to measure the initial shape of the bar has been developed. It allows to follow any change in shape, by referring the measurements of the in-bar instrumentation to the initial measured shape.

An algorithm to calibrate the optical in-bar instrumentation and to measure the initial shape of the bar with a large coordinate measuring machine has been worked out and successfully tested.

A model to interpolate the complete bar shape measured from the optical in-bar instrumentation, has been derived. It has been shown that the implementation of the mechanical properties of the bar into the analytic shape model is inevitable to predict the shape at the required level of accuracy. This model iterates the bar shape in three steps:

- A first estimate of the change in deformation is based on the knowledge of the discrete loads introduced from sensors and sensor platforms mounted onto the bar, and its orientation relative to the direction of gravity.
- The measurements of the in-bar instrumentation are used to refine the first estimate. *Virtual loads* have been introduced, to absorb all the loads that have not been accounted for in the first estimate, into a discrete number of parameters. This number of parameters is only dependent on the number of points measured with the in-bar instrumentation. It has been shown, that the knowledge of the relative position of five points (three virtual loads) along the bar is sufficient to achieve a satisfactory bar shape prediction.
- The behavior of the platforms mounted to an alignment bar is accomplished by

locally modifying the refined deformation. This modified and refined deformation is then finally superimposed to the initial measured shape and thus provides the actual bar shape.

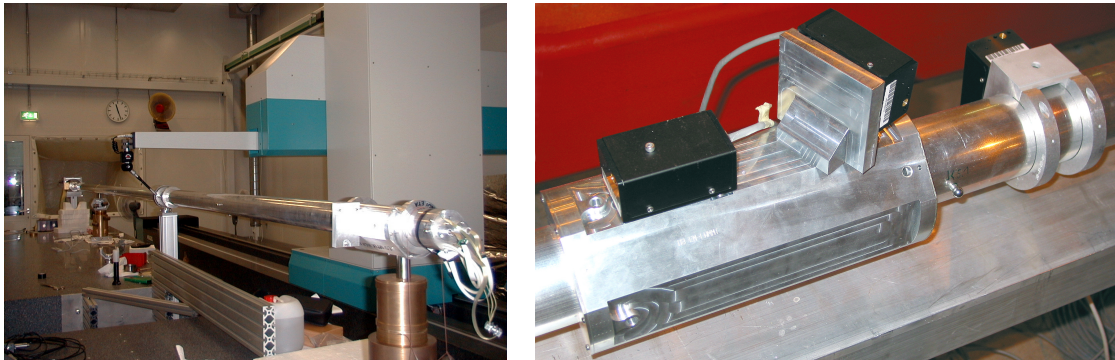
Extensive measurements on all six alignment bars have shown that a prediction of the bar shape to  $\sim 10\text{ }\mu\text{m}$  r.m.s. perpendicular to the bar and to  $\sim 20\text{ }\mu\text{m}$  r.m.s. along the bar can be reached under laboratory conditions. These measurements have also shown, that in order to reach the required precision in knowing the viewing direction of the sensors (BCAMs) mounted onto the bars, stringent requirements are imposed on the coordinate measuring machine. Results show that  $58\text{ }\mu\text{rad}$  r.m.s. can be reached, which is in reasonable agreement with the required precision of  $50\text{ }\mu\text{rad}$  r.m.s.

One independent cell of the end-cap alignment (one octant) has been set up in the H8 test beam area to test the performance of the end-cap alignment system. The intrinsic resolution of alignment sensors, the behavior of the alignment bars in an vibrational environment, long term stability measurements, the reconstruction of a bar position with the global alignment, and the consistency of the alignment reconstruction has successfully been tested. We could demonstrate that in this test the precision requirements on the ATLAS alignment system could be achieved.

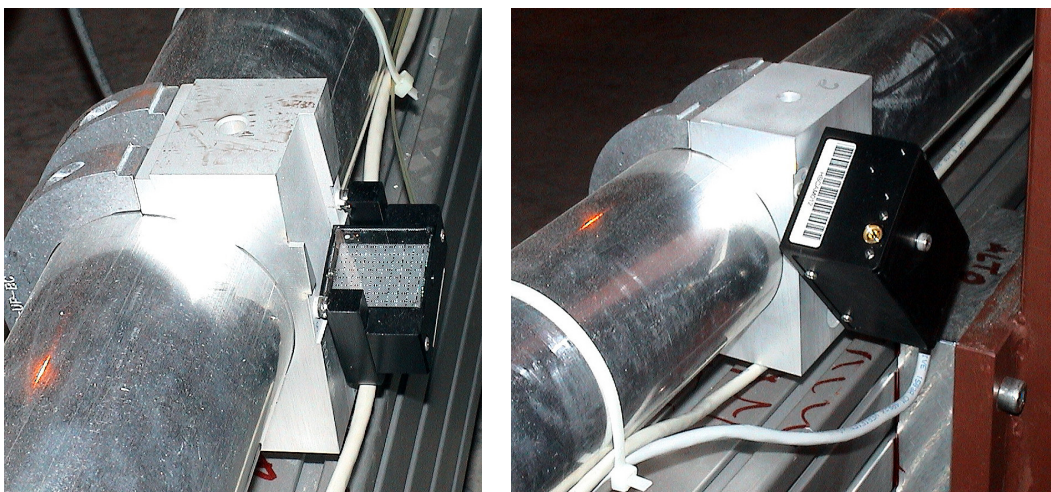
Based on the knowledge gained, a design for the ATLAS alignment bar has been proposed, designed and assembled. A manual describing all the steps from assembling the bars until installing them has been provided.

# Appendix A

## Pictures

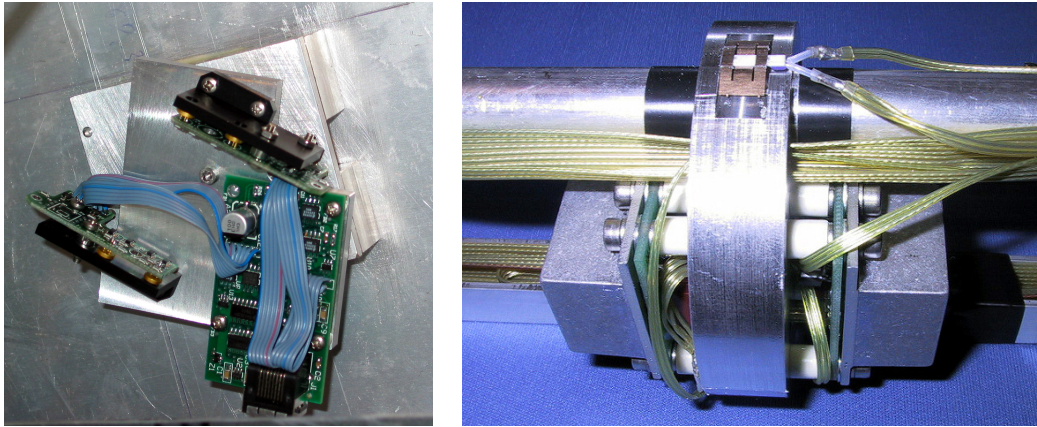


**Figure A.1:** *left:* coordinate measuring machine in Freiburg (Germany). The first tested bar is mounted on the table, the probe head is touching the bar approx. in the middle. At the end of the bar one polar/radial platform is mounted. *right:* polar/radial platform, a steel ball used for the CMM measurements glued to the bar, an azimuthal platform and a BCAM mounted to it.

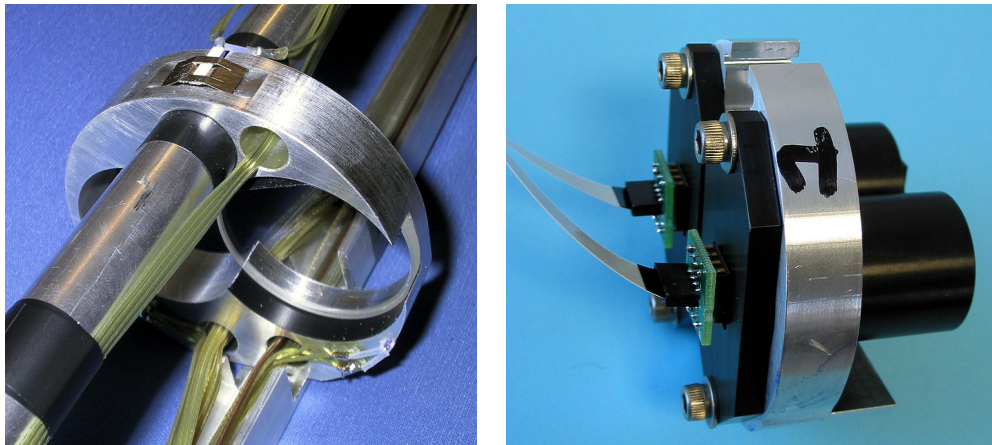


**Figure A.2:** *left:* proximity mask and corresponding platform; *right:* azimuthal BCAM and corresponding platform.

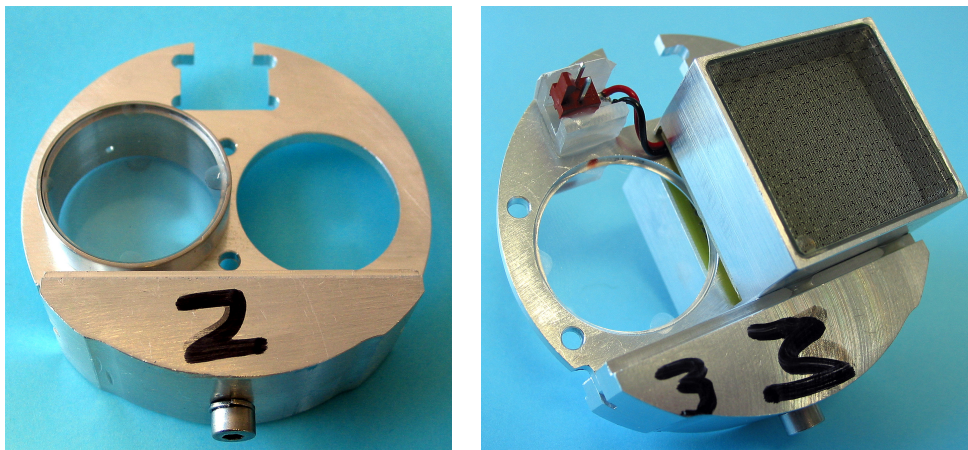




**Figure A.3:** *left:* light source, mounted to a phantom chamber. (A sketch of the corresponding alignment line which is needed to measure the out of plane movement is illustrated in Section 2.8, p.29); *right:* disc of the skeleton from an H8 prototype alignment bar. The picture shows two RASNIK masks and one temperature sensor.



**Figure A.4:** *right:* disc of the skeleton from an H8 prototype alignment bar. The picture shows one disc carrying one lens and three temperature sensors. *right:* picture of the first discs built according to the design proposal; disc containing two CCDs and the corresponding collimators.



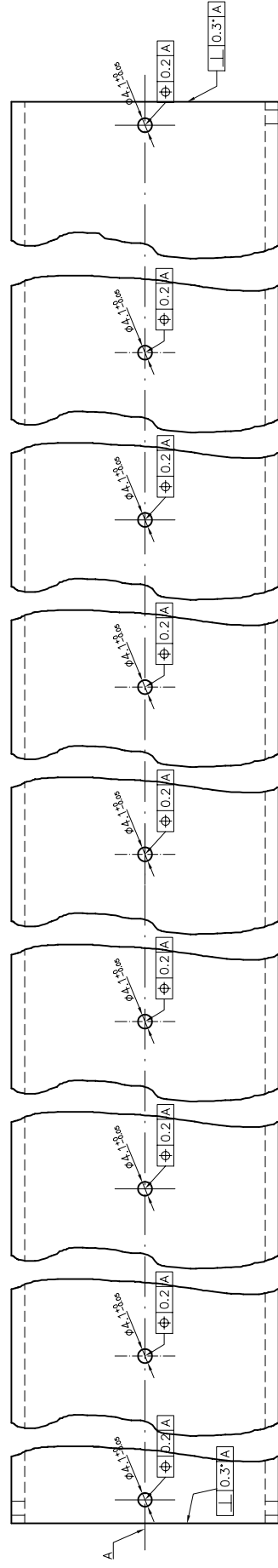
**Figure A.5:** Picture of the first discs built according to the design proposal; *left:* disc containing the lens doublet; *right:* disc containing one lens and the RASNIK masks.

## **Appendix B**

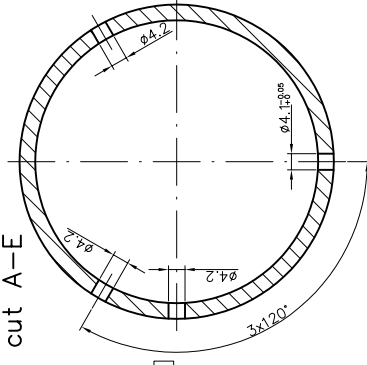
### **Design Drawings of the Alignment Bar Prototype**



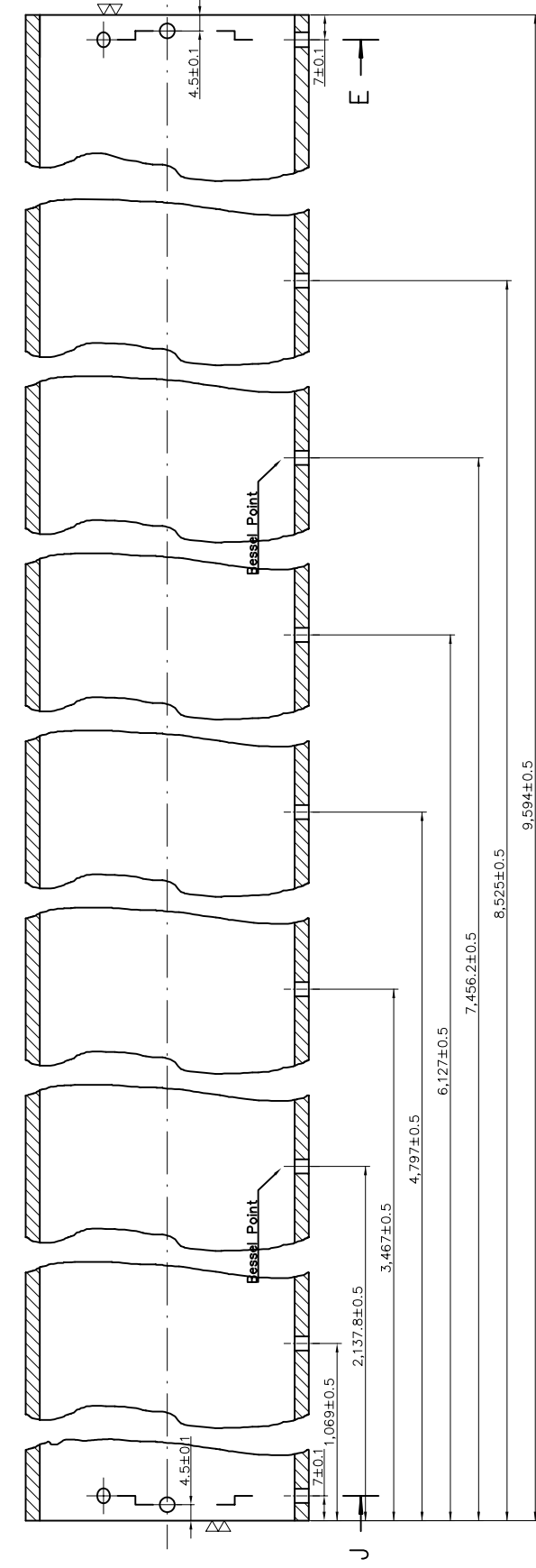




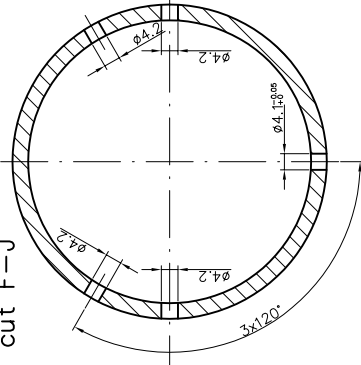
cut A-E



A



cut F-J

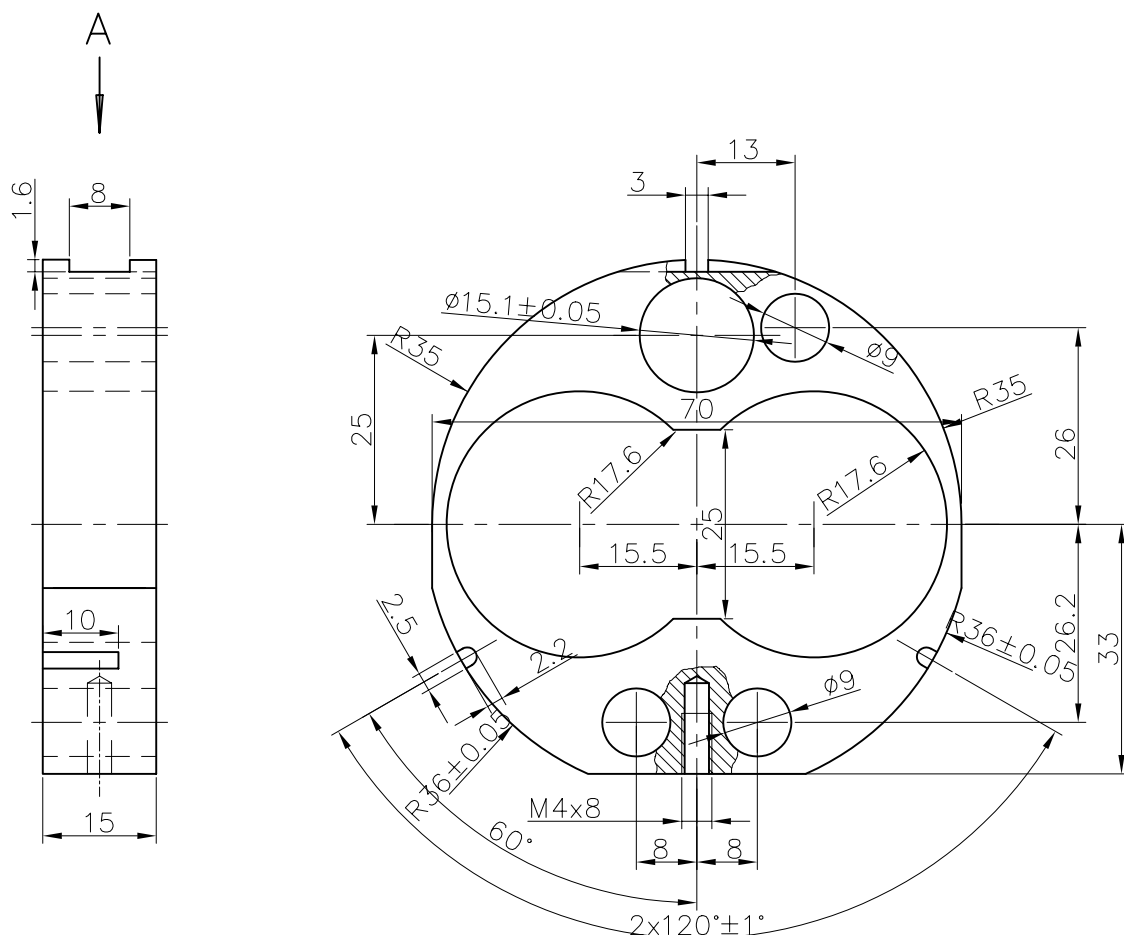


|       |         |                                    |                                                                 |              |
|-------|---------|------------------------------------|-----------------------------------------------------------------|--------------|
| Scale | Al Tube | Anticorodal<br>drawing units<br>mm | Permissible variation<br>in mm dimensions<br>without tolerances |              |
|       |         |                                    | 0.5-3                                                           | ±0.05        |
|       |         |                                    | 3-6                                                             | ±0.05        |
|       |         |                                    | 6-30                                                            | ±0.1         |
|       |         |                                    | 30-120                                                          | ±0.15        |
|       |         |                                    | 120-315                                                         | ±0.2         |
|       |         |                                    | 20.05.00                                                        | A. Schricker |

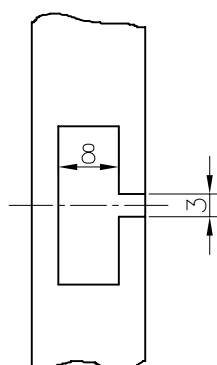








Detail A



Permissible variation  
in mm dimensions  
without tolerances

|         |       |
|---------|-------|
| 0.5–3   | ±0.05 |
| 3–6     | ±0.05 |
| 6–30    | ±0.1  |
| 30–120  | ±0.15 |
| 120–315 | ±0.2  |

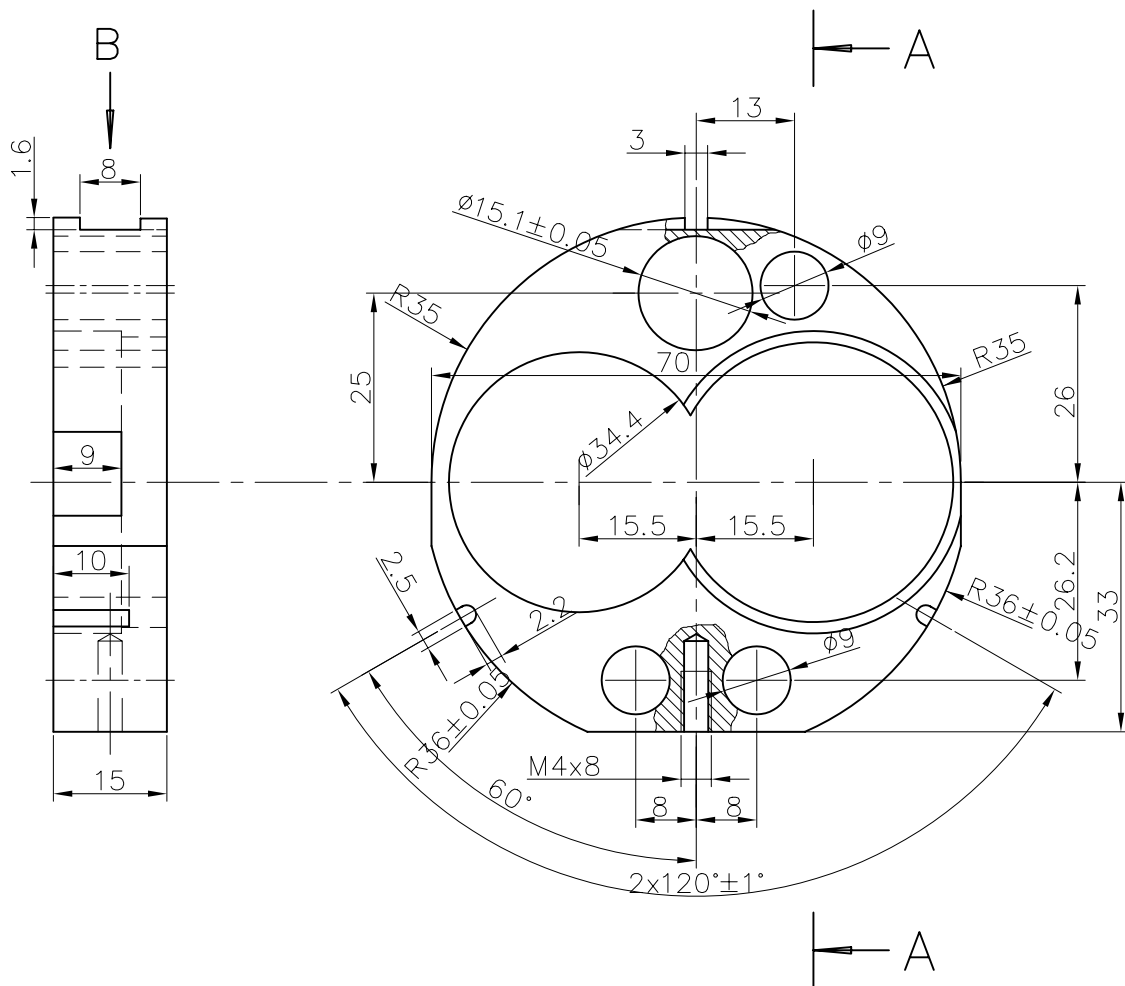
Scale  
1:1

Support 2, 4, 6, 8

Anticorodal  
drawing units  
mm

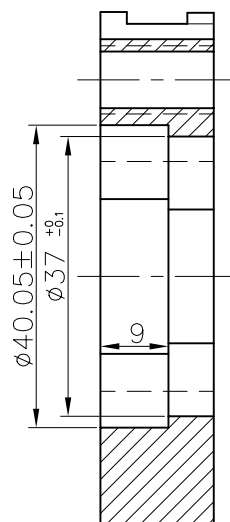
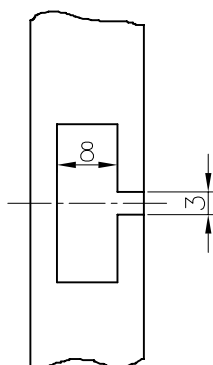
19.05.00

A. Schricker



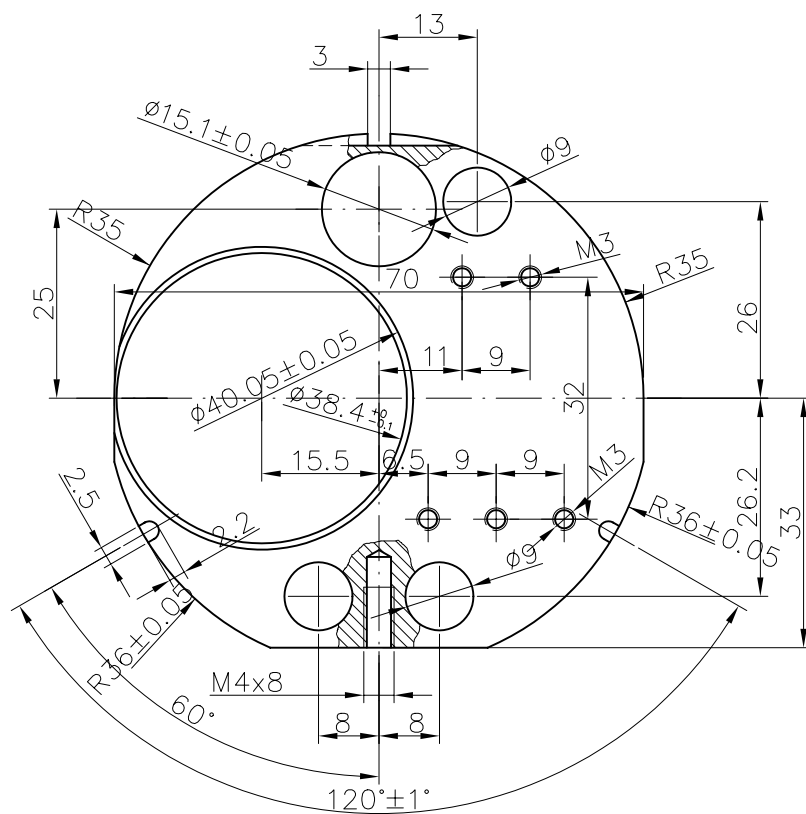
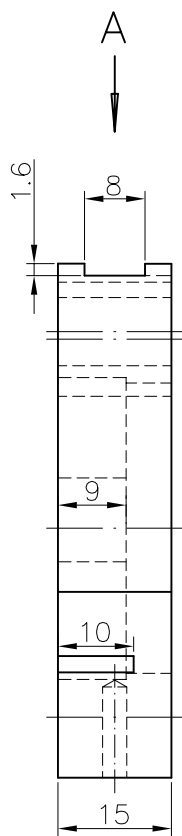
Detail B

Cut A—A

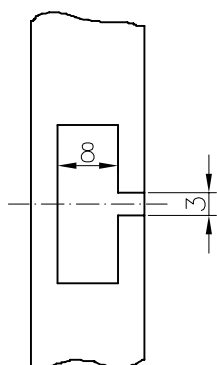


| Permissible variation<br>in mm dimensions<br>without tolerances |       |
|-----------------------------------------------------------------|-------|
| 0.5–3                                                           | ±0.05 |
| 3–6                                                             | ±0.05 |
| 6–30                                                            | ±0.1  |
| 30–120                                                          | ±0.15 |
| 120–315                                                         | ±0.2  |

|              |              |                     |              |
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|              |              | drawing units<br>mm | A. Schricker |

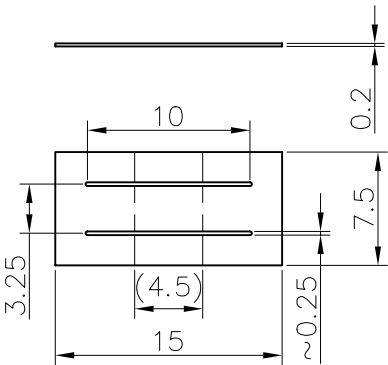


Detail A

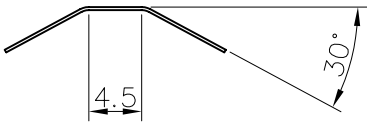


|                                                                 |       |
|-----------------------------------------------------------------|-------|
| Permissible variation<br>in mm dimensions<br>without tolerances |       |
| 0.5–3                                                           | ±0.05 |
| 3–6                                                             | ±0.05 |
| 6–30                                                            | ±0.1  |
| 30–120                                                          | ±0.15 |
| 120–315                                                         | ±0.2  |

|              |           |                     |              |
|--------------|-----------|---------------------|--------------|
| Scale<br>1:1 | Support 5 | Anticorodal         | 16.05.00     |
|              |           | drawing units<br>mm | A. Schricker |



Bending



Scale 1:1



|                                                                 |       |
|-----------------------------------------------------------------|-------|
| Permissible variation<br>in mm dimensions<br>without tolerances |       |
| 0.5–3                                                           | ±0.05 |
| 3–6                                                             | ±0.05 |
| 6–30                                                            | ±0.1  |
| 30–120                                                          | ±0.15 |
| 120–315                                                         | ±0.2  |

|              |               |                     |              |
|--------------|---------------|---------------------|--------------|
| Scale<br>2:1 | Sensor spring | Anticorodal         | 20.05.00     |
|              |               | drawing units<br>mm | A. Schricker |



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# Curriculum Vitae

Born in Vienna on November 13<sup>th</sup> 1970

Married, one child

*09/77 – 06/81* Primary School in Vienna

*09/81 – 06/85* High School (“Bundesrealgymnasium Wien XV”)

*09/85 – 04/90* Technical school for precision engineering, 2340 Mödling, final exam with distinction.

*Aug. 86 – 89* Yearly internship at Reichert-Jung Optische Werke, miscellaneous work on grinding optical prisms, preparing tools, construction design.

*Sept. 90* Internship at Leica, construction of parts for microscopes and microtomes.

*10/90 – 09/91* Military service at the Austrian Army (officers course)

*09/91 – 10/99* Study of Physics at the “Technische Universität Wien”. Diploma thesis: “Cryogenic Positioning System for Investigation of Magnetic Textures by means of 3D Neutron Depolarisation”.

*July 92 – 94* Yearly internship at AUER Süßwarenfabrik, machine rebuilding and maintenance, setup and programming of an electronic inventory system.

*July 96* Internship at TUG (an Environmental technology firm), coordination of cooperation of various companies for building parts of a diesel catalyst.

*Sept. 93 – 97* Yearly field exercises as a commander at the Austrian Army.

*10/00 – 09/02* Selected for the “Austrian Doctoral Student Programme” at CERN (Geneva): Doctoral thesis within the ATLAS Muon Collaboration about “The Alignment System of the ATLAS Muon End-Cap Spectrometer”.

*04/00 – 04/01* Learned French in courses at CERN (Geneva)

## List of Publications

1. H.Leeb, M.Hochhold, G.Badurek, R.J.Buchelt, A.Schricker: *Neutron Magnetic Tomography: A Feasibility Study*, Australian J. Phys. 51, 401-13 (1998)
2. A.Schricker: *Tieftemperatur-Positioniersystem zur Untersuchung magnetischer Texturen mittels 3D-Neutronen Depolarisation*, diploma thesis (1999)
3. G.Badurek, R.J.Buchelt, A.Schricker, A.G.Wagh, V.K.Rakhecha: *Neutron Polarimetric Separation of Geometric and Dynamical Phases*, Physics Letters A, 268 209-216 (2000)
4. A.Schricker, G.Badurek, R.Buchelt, R.Grössinger: *A Low-Temperature Neutron Polarimeter for Magnetic Texture Analysis*, Physica B 276-278, 110-111 (2000)
5. R.J. Buchelt, G.Badurek, A.Schricker, Z.Hradil: *Semi-step tuning and spin state estimation in neutron polarimetry*, Physica B, 276-278 108-109 (2000)
6. A.Schricker: *Refractive Bending of Light due to Thermal Gradients in Air*, ATLAS Muon Note, (2002)
7. C.Amelung, A.Schricker: *Calibration of Alignment Bars for the ATLAS Muon Spectrometer Endcap*, ATLAS Muon Note, (2002)

I only quoted those publications to which I made a major contribution