Straightness Measurements for Accelerator Structures

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Abstract

The cavity structures of the S-Band Linear Collider have to be aligned better than 30 μm rms over their length of 6 m. In this paper relevant techniques for straightness measurements are described. Further the results of straightness measurements of the first test modules are discussed.

1 Introduction

In high energy research the intention is to have $e^+\bar{e}$–collisions by energy in the range up to TeV. This requires further developments of linear collider technology. For this purpose a linear collider should consist of two opposing linear accelerators with an active length of about 30 km. At present around the world different studies are under way to gain experience for the realisation of this. At DESY the S-Band Linear Collider (SBLC) project is pursued in the framework of an international collaboration to design a 500 GeV e^+e^-–collider *[Holtkamp, N. 1995].*

2 The S-Band Linear Collider Test Facility

Before developing the 500 GeV-collider a Test Facility is under construction at DESY. The S-Band Linear Collider Test Facility will serve as an unique test bed for the necessary technical developments of a large scale 2x250 GeV linear accelerator *[Holtkamp, N. 1995a].*

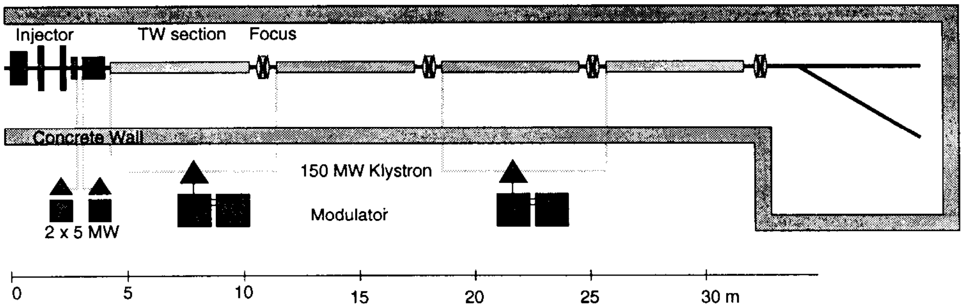

Figure 1. General Layout of the S–Band Test Facility at DESY

The general layout of the Test Facility is shown in Fig. 1. For the S-Band collider a "linear collider module" consists of one 150 MW klystron driven by one modulator and two 6 m long accelerating sections. Quadrupoles, beam position monitors and beam diagnostics also form part of the module. The test facility consists of two similar modules, with an injector in front in order to produce the full charge design bunch train and a beam diagnostics station down stream to analyse the beam energy, emittance and position *[Holtkamp, N. 1995a].*

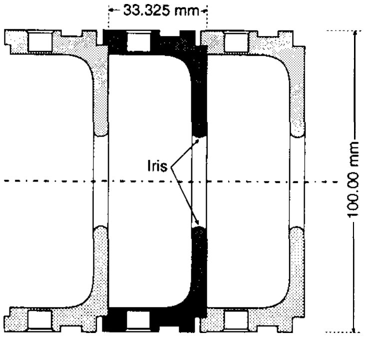

Figure 2. Cross Section of a Cup

A 6 m long module consists of 180 cups of copper. The cross section of a cup is shown in Fig. 2 and Fig. 3. The diameter is 100 mm and the height 33.325 mm. The required straightness of a module has to be better than 30 μm rms over the full 6 m length. In this paper relevant techniques for straightness measurements are described. In the test assembly each module is mounted on a set of micromovers, so the final adjustment of each module can be done by the Beam Based Alignment Techniques *[Boege, M. 1995].*

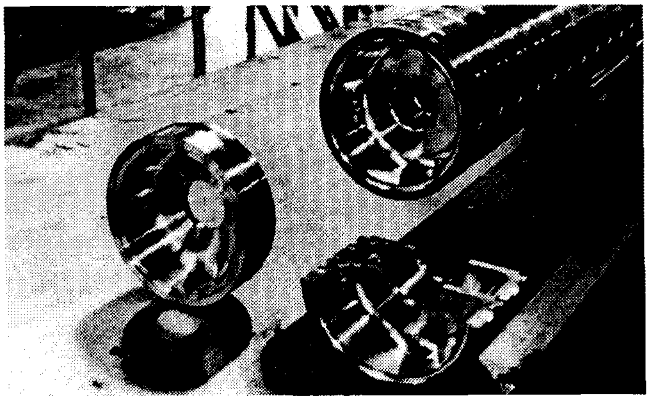

Figure 3. Cups of the Module

3 Straightness Measurement Techniques

In the following some alignment techniques are discussed which are suitable to control the straightness of a module. Certainly other techniques can be used besides (for example described in *[Schwarz, W. (Hrsg.) 1995]).* The advantages and disadvantages of the described techniques are discussed in respect of checking the straightness of a module to be better than 30 μm.

3.1 Straightness Measurement using Interferometer

For straightness measurements a normal laser interferometer will be used. In addition to the laser head and the measurement display unit for straightness measurements, a straightness interferometer (compensated wollaston prism) and a mirror (straightness reflector) are also required (Fig. 4). The mirror is mounted on a fixed support behind the module and the wollaston prism runs along the module (Fig. 10). The offset distance of the wollaston prism in horizontal or vertical direction with respect to a straight reference line will be measured, in that the reference line will be given by the mirror axis and not by the laser beam. The wollaston prism consists of two or three double refracted quartz prisms. In this prism the optical axes are perpendicular to each other.

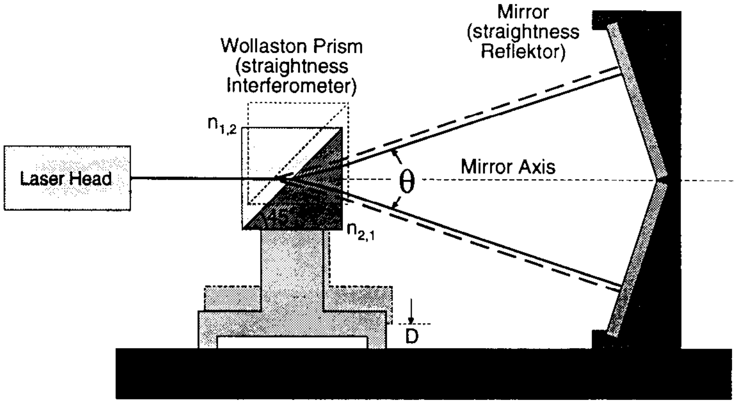

Figure 4. Straightness Measurements using Interferometer

Initially, the two paths from the interferometer to the reflector have some length relative to each other. If the straightness reflector is moved side-to-side (across the mirror axis), the relative lenghts of the two beams in the wollaston prism will change. The change in accumulated fringe counts N will be *[Hewlett-Packard 1982]*

$$N = 2\,D\cdot\sin(\Theta/2) \qquad (1)$$

where D : the distance of the offset and

Θ : the angle between the two beams leaving the interferometer.

To provide the correct readout of the offset distance, the electronic hardware automatically multiplies the fringe count by the reciprocal of $2\cdot\sin(\Theta/2)$. Small pitch, yaw, or roll motions of the interferometer do not create a path difference and therefore do not affect the measurement accuracy *[Hewlett-Packard 1982].*

At DESY the laser interferometer system HP 5528A is available. There are two straightness interferometers, one for the short range up to 3 m and another for the long range from 1 m to 30 m. In the first system the angle between the two beams Θ = 1.5916 degrees and in the second Θ = 0.1592 degrees. Notice that the difference of the two paths has to be measured with very high accuracy. For example, to determine the offset distance with a resolution of 1 μm one has to measure the path difference by the short range system with an accuracy of 28 nm and by the long range system of 3 nm. This requirement forces, among other things, extremely stable conditions of the atmosphere. If the wollaston prism is 10 m from the mirror a difference in the air temperature of the two paths of 0.01 K will change the measured offset by about 33 μm. In both systems the measurement range is ±1.5 mm and the resolution is better than 0.1 μm. The accuracy of the short range interferometer is between 3.5% and 1% and of the long range interferometer between 5% and 2.5% of the measured offset. With an interferometer, only one geometrical position can be measured either the vertical or the horizontal position. During the measurement care must be taken not to move the wollaston prism out of the laser beam or to interrupt the laser beam itself.

3.2 Straightness Measurement using the Intensity of two Laser Beams

In laser measurement system LMS 200 of the factory Feinmess in Dresden a special interferometer splits a laser beam into two separate beams (Fig. 5). The interferometer changes in direction of the original laser beam produce opposite changes in direction of the separated beams. Therefore the middle axis of the two beams is a reference line, which is independent of possible changes in direction of the laser beam.

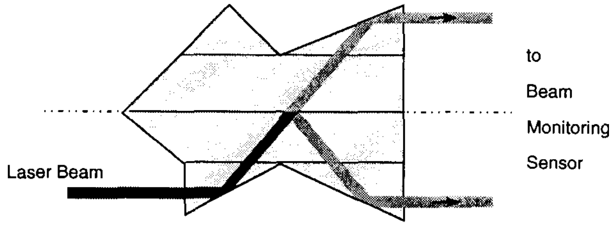

Figure 5. Interferometer of the LMS 200-System

The two beams enter into a beam monitoring sensor (Fig. 6). There each beam is splitted by two symmetrical arranged prisms. The intensity of the four laser beams depends on the position of the beam monitoring sensor relative to the middle axis of the incoming laser beams.

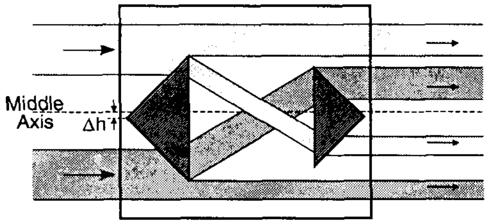

Figure 6. Beam Monitoring Sensor

To measure the intensity, the two upper and the two lower beams will go in each case to a receiving diode at the end of the alignment distance. The difference of the electrical signals of the two diodes corresponds to the distance of the offset of the beam monitoring sensor. Therefore the straightness measurement system consists of a laser interferometer with the special beam splitter, a beam monitoring sensor and the receiver (Fig. 7).

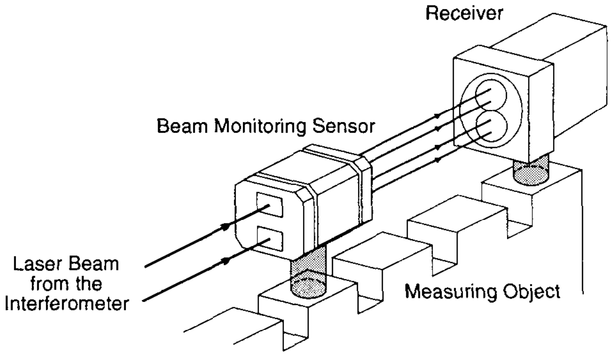

Figure 7. Components of the LMS 200-System

In the LMS 200-system it is acceptable to place the beam monitoring sensor out of the laser beam and also it is possible to interrupt the laser beam between single measurements. Therefore this system is more convenient for the user than the straightness measurement system described previously.

Usually the measurement range is ±500 μm over an alignment distance up to 20 m. After a special adjustment in factory the alignment distance can be extended up to 40 m. The resolution is 1 μm, in fine measuring range of ±50 μm 0.1 μm. The accuracy is given by

$$u = 2\,\mu m + 10^{-6} \cdot l_F + 0.1 \cdot |y| \qquad (2)$$

where u : accuracy,
l_F : distance between interferometer and beam monitoring sensor,
$|y|$: absolute value of distance of the offset.

The accuracy depends on the refraction condition of the air the laser beams pass through. With the LMS 200 system only one geometrical position can be measured either the vertical or the horizontal position comparable to the system described previously.

3.3 Straightness Measurement using Autocollimator

An autocollimator is qualified to measure the changes in direction of a surface mirror with very high accuracy. For straightness measurement using autocollimation a surface mirror is mounted in a sliding carriage running in defined steps along the module. In each position of the sliding carriage the vertical and the horizontal directions of the mirror axis will be measured by the autocollimator (Fig. 8).

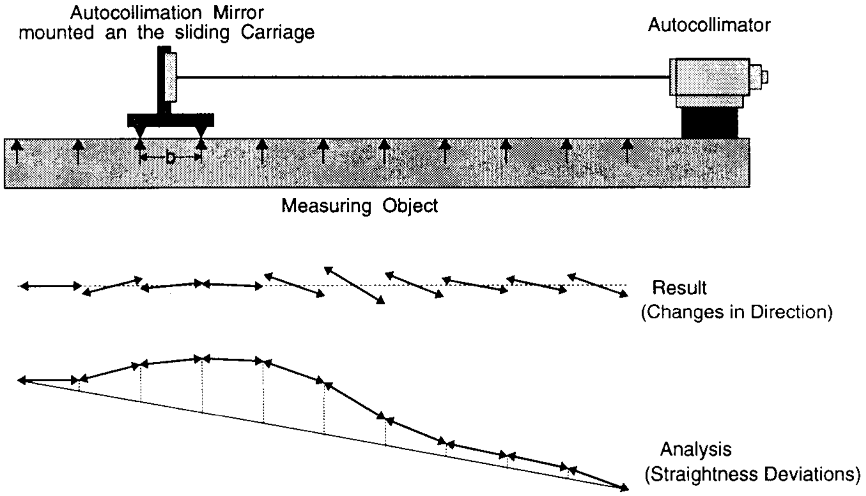

Figure 8. Straightness Measurement using Autocollimator

The changes in direction for each component in respect of the first mirror position multiplied by the distance *b* of the supporting points of the sliding carriage will be accumulated. Therefore the straightness curve of the module can be calculated. By the autocollimator technique in one process horizontal and vertical straightness deviations will be measured simultaneously. This is an important advantage compared to the two straightness measuring techniques described previously. Furthermore there is no laser beam to interrupt and it is possible to put the sliding carriage out of the field of vision of the autocollimator completely. When the changes in direction of the mirror are measured with an accuracy of 0.5”, the difference in position of neighbouring points (for example 100 mm apart) can be calculated to 0.2 μm. Certainly the accuracy will be negative influenced by the accumulation. The effects of refraction of air have also to be taken into account. Further it can be seen that the supporting points of the sliding carriage are pressed into the module by the weight irregularly. The weight of the carriage and the surface mirror must therefore be as low as possible.

At DESY the autocollimator Elcomat 2000 of the factory Möller-Wedel in Wedel is used. This electronic autocollimator has in the focal plane two CCD-line scan image sensors mounted perpendicular to each other to detect the crosshair reflecting from the surface mirror automatically. The measuring range is ±1000”. With increasing distance between autocollimator and surface mirror the measuring range will decrease. For a distance of 3 m the measuring range is now ±500” and for a distance of 7.5 m the measuring range is only ±100”. The accuracy of the Elcomat is between 0.15” and 0.50”.

4 Straightness Measurement of Test Modules

4.1 Interferometer and Autocollimation Technique in Comparison

In 1994 the first prototype of a module was made. For this module only 110 cups were soldered together. Therefore the length of this module is 3.7 m. The module is mounted on a massive bench of steel resting on four v-shaped supports (Fig. 9).

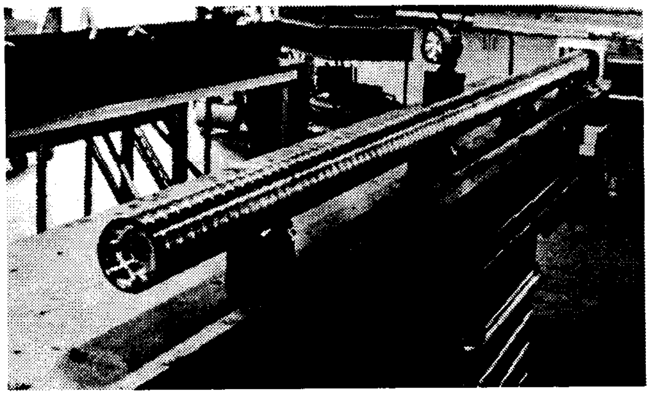

Figure 9. Test Module 3.7 m long mounted on a massive Bench of Steel

First the straightness of the module has to be measured using an interferometer. For this purpose at the end of the module the mirror is fixed on the bench (Fig. 10). With micrometric screws it is possible to align the mirror axis parallel to the axis of the module.

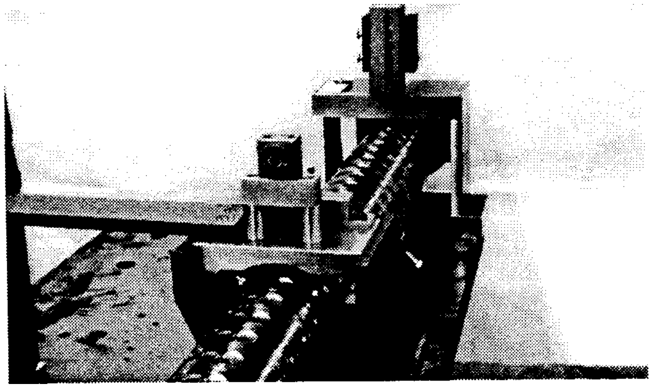

Figure 10. Straightness Reflektor and sliding Carriage with Wollaston Prism

To measure straightness deviations in a vertical plane the wollaston prism is mounted on a sliding carriage which is in contact with the module by two screws with spherical surfaces. The screws are set in under 45° to the line of gravity. A third screw at the end of the carriage above the module axis defines the pitch motion. The roll is defined by an arm supporting on the surface of the bench. Guide rails on both sides of the carriage define the yaw motion. By this it will be assumed that the surface of each cup is well enough machined to the iris. Now one has only to move the carriage from one cup to the other and to readout the straightness deviations on the measurement display (Fig. 11).

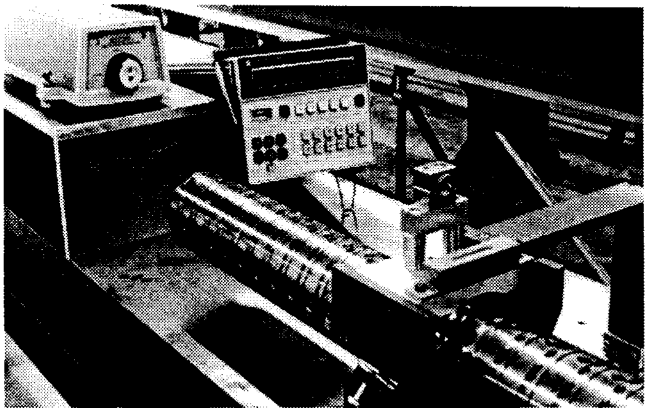

Figure 11. Laser Head with Measurement Display and sliding Carriage with Wollaston Prism

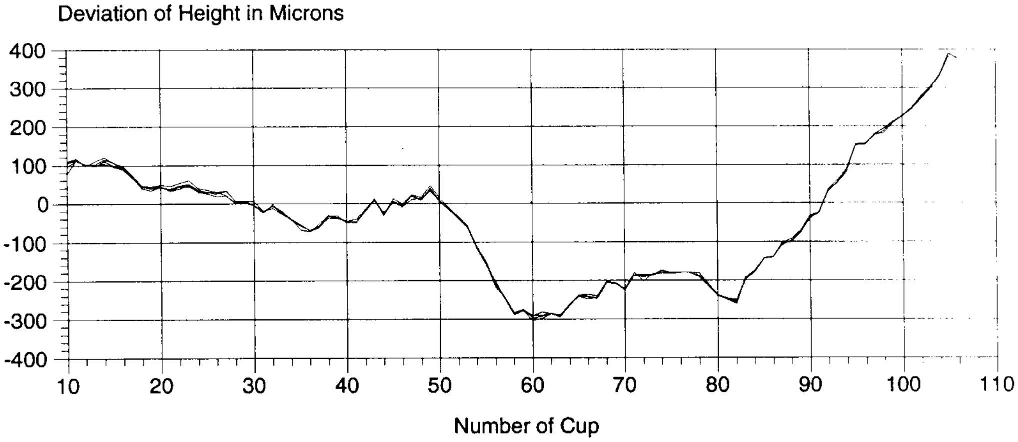

Figure 12. Vertical Straightness Deviations of the Test Module measured by Laserinterferometer

Fig. 12 shows straightness deviations of several measurements of the test module measured by the long range system. The deviations of straightness are from -300 μm to +400 μm. The differences between the individual measurements are as a rule only a few microns. Therefore straightness measurements using laser interferometer are suitable to obtain the required accuracy for the straightness control of the modules.

In the next step the straightness of the same module has to be measured by the autocollimation techniques. For that the sliding carriage with the autocollimator mirror is in contact with the surface of the module by four screws defining the three-dimensional position of the carriage clearly.

Only the roll motion of the carriage has to be fixed by an arm supporting on the surface of the bench (Fig. 13).

A pin in the carriage defines the longitudinal position by the groove of each cup. Therefore it is easy to set the sliding carriage on each cup one after another very quickly. The distance of the screws setting in at the beginning and at the end of the carriage corresponds with the height of the cups exactly.

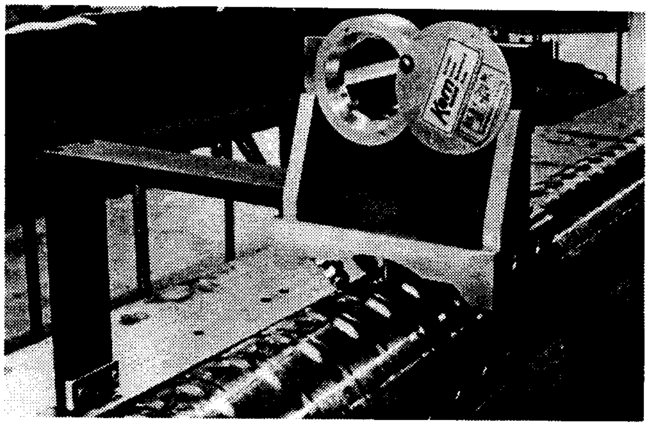

Figure 13. Sliding Carriage with Autocollimation Mirror

In 1994 the changes in directions of the mirror were measured by the electronic theodolite Kern E2 with an autocollimation accessory (Fig. 14) because the electronic autocollimator Elcomat 2000 was not yet provided. Here the coincidence of the crosshairs had to be done manually. The registration of the horizontal direction and the vertical angle were carried out automatically by a handheld computer. The measuring time is about 45 minutes.

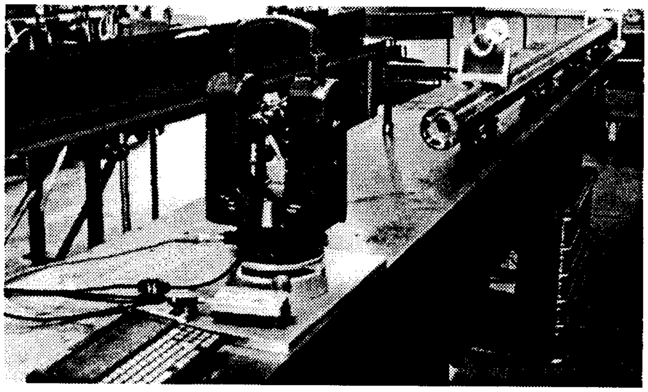

Figure 14. Electronic Theodolite Kern E2 and Autocollimation Mirror

In Fig. 15 the results of several measurements of the test module measured by the autocollimation techniques using the theodolite Kern E2 are printed out. The trend of the curves is identical with the results of the long range interferometer system (Fig. 12). Hereby both techniques are controlling themselves reciprocally. The deviations between the individual measurements are here a little bit larger than using interferometer technique, particularly at the end of the test modules, they are growing up to forty microns. This effect has to be explored by further investigations. Nevertheless

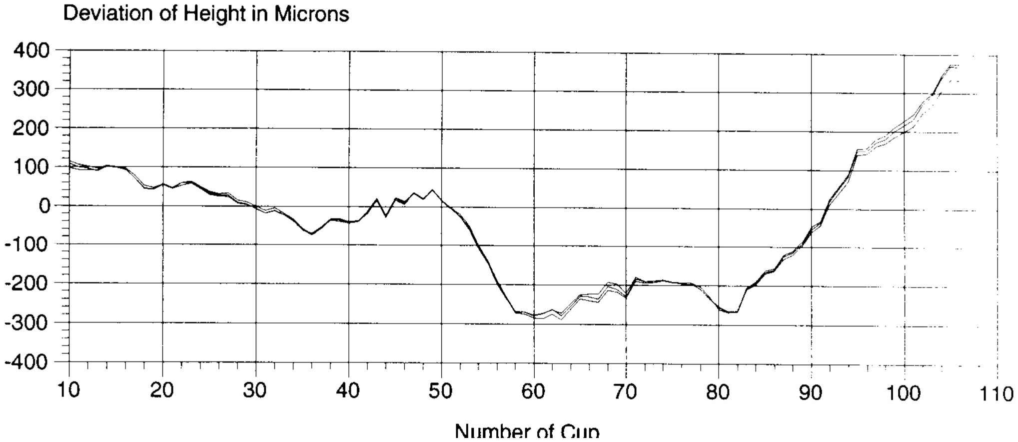

Figure 15. Vertical Straightness Deviations of the Test Module measured by Autocollimation Technique using the Theodolite Kern E2

the autocollimation technique is suitable to obtain the required accuracy for the straightness control of the modules. The advantages of the autocollimation technique were pointed out in section 3.3. To increase the accuracy in the autocollimator technique it is planned to use two sliding carriages. The distance *b* of the supporting screws of the first carriage corresponds with the height of the cups. However by the second carriage the distance *b* is a multiple of the height of the cups (for example the distance is four times of the height of the cups). Measurements carried out with the second carriage will give more stability in overlapped ranges and redundancy in the observations. A common adjustment of both measurements gives the position of each cup in respect to each other.

4.2 Straightness Tests with the second Module

For the measurements described in the section before the module rested on four supports. This gave rise to some problems. For example the module is so stiff that it does not rest on all four supports symmetrically. At least one support had not any contact to the module. Therefore the

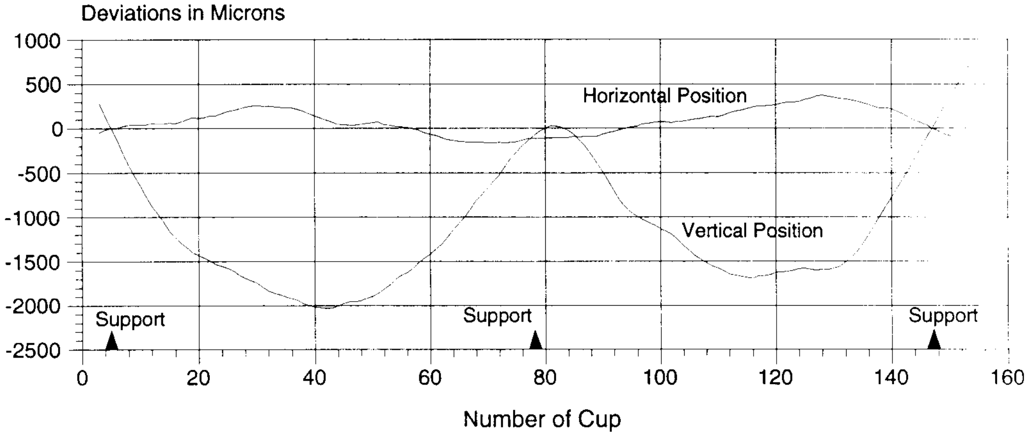

Figure 16. Straightness Deviations of the second Test Module measured by the Theodolite Kern E2

module was forced, under power, to all supports. Prior to that the supports were aligned by an alignment telescope. To avoid these problems the next module should be supported only on two supports, but then the calculated sag is too large to measure the straightness with the laser systems and with the autocollimator Elcomat 2000. To reduce the sag of the module at least three supports are chosen. With three supports the sag is calculated up to 100 μm. Immediately after the soldering process was finished the module (154 cups, 5.1 m in length) rested on three supports. The straightness measurements are carried out by the autocollimation technique using the theodolite Kern E2. The results are printed out in Fig. 16. It is noticed that the module has two systematic sag areas between the supports up to 2 mm. The real sag of the module is essentially larger than the calculated.

In the next test to try to reduce the sag the number of supports was increased. Now the module is resting on four supports. It is expected that the sag areas will be reduced permanently by the self-weight of the module. After the module has rested on four supports more than one day the straightness measurements are carried out by the theodolite Kern E2 and the autocollimator Elcomat 2000 (Fig. 17). With the autocollimator Elcomat 2000 the measuring time for one straightness measurement is about 10 minutes. The results are shown in Fig. 18.

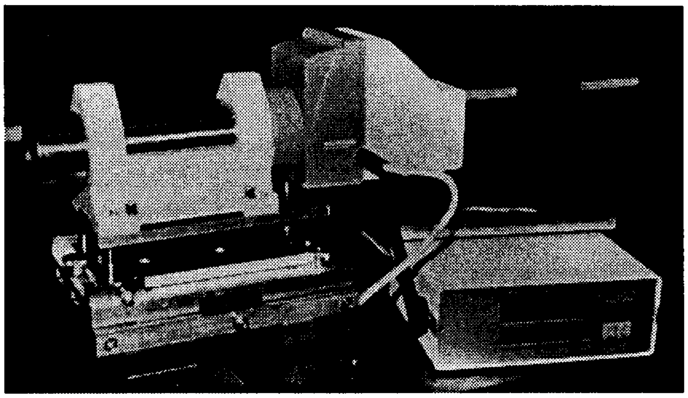

Figure 17. Autocollimator Elcomat 2000 in temporary Assembly

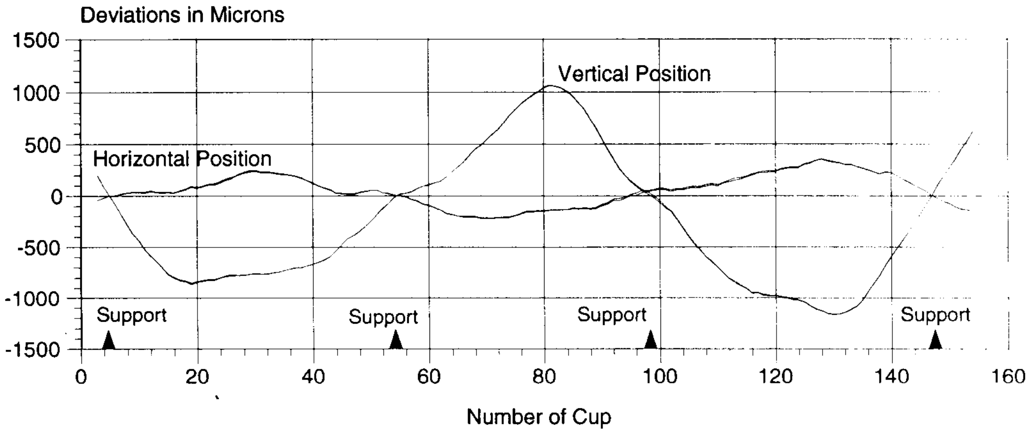

Figure 18. Straightness of the second Test Module measured by Theodolite Kern E2 and Autocollimator Elcomat 2000

The sag is not reduced by the new arrangement of the supports. The form of the curves has changed but the differences in the straightness are up to 2 mm as before. The reason for this is the module is very ductile after the soldering process. With time and under mechanical stress it will get more stiffness. In the meantime the module is now hardened. The differences between both measurements usually are only a few microns. The results of the autocollimation using theodolite Kern E2 are in principle identical with the results measured by the autocollimator Elcomat 2000.

In a further test the module is turned around its axis about 180° on the supports. Fig. 19 shows the results measured twice by the Elcomat 2000. At first sight the form of the module is in correspondence with the reciprocal curve of Fig. 18. The differences will be influenced by the force of gravity which causes the sag. The difference between both measurements is as a rule smaller than 10 μm. Only in the height there are systematic differences in the middle area of the module up to 35 μm.

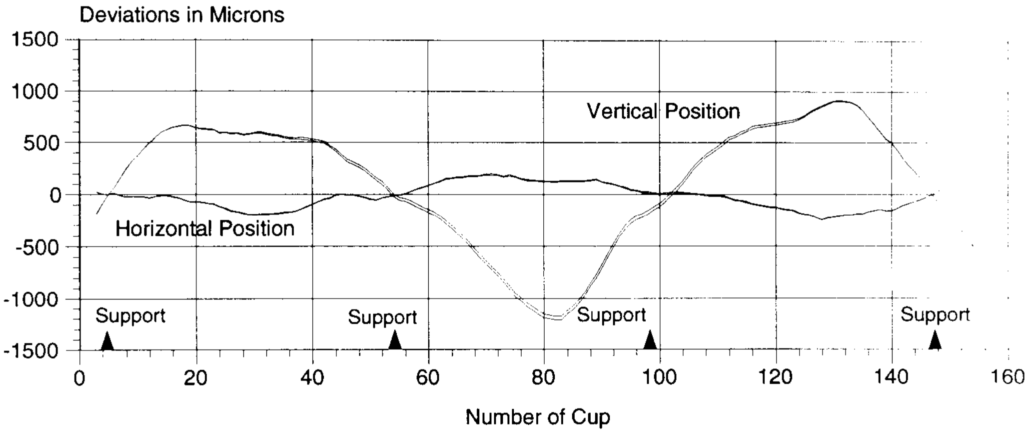

Figure 19. Straightness of the second Test Module turned around its Axis

4.3 Intensity and Autocollimation Techniques in Comparison

In October 1995 the third test module has to be controlled. It has a length of 5.1 m and consists of 154 cups as before. At first straightness measurements are carried out by the autocollimation technique using the theodolite Kern E2. The results of the measurements are shown in Fig. 20. The autocollimator Elcomat 2000 can not be used because for this modul the changes in direction are outside of the measuring range of the Elcomat.

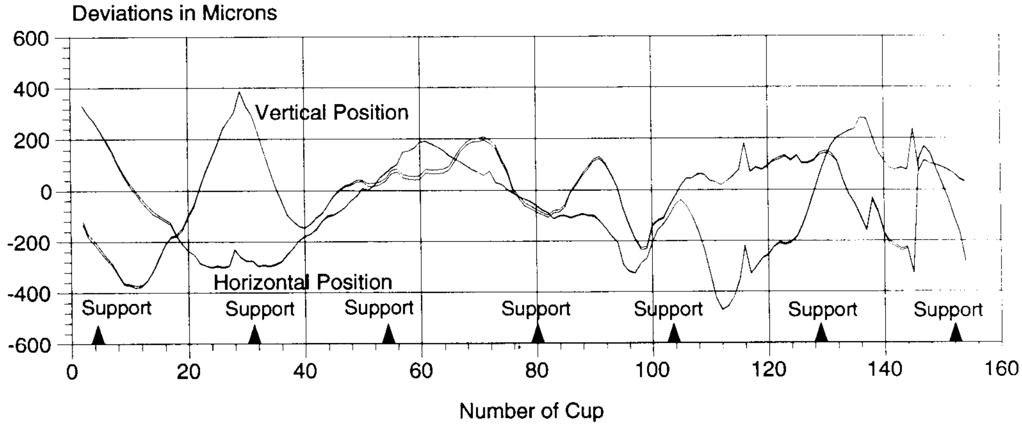

Figure 20. Straightness Deviations of the third Test Module measured twice using the Autocollimation Technique by the Theodolite Kern E2

To carry out horizontal straightness measurements by the LMS 200-System (see section 3.2; Fig. 21) the laser head is situated in the height of the axis of the module at the beginning of the module and the receiver at the other end. The laser beam is aligned as well as possible parallel to the axis of the module. The beam monitoring sensor is movable on a little table which in turn is movable on the bench. At one side of the sensor two pins are mounted. The sensor will be moved by hand until the two pins are in contact with the cups of the module. The pin in the middle of the sensor defines the offset and the other the yaw motion of the sensor (Fig. 22).

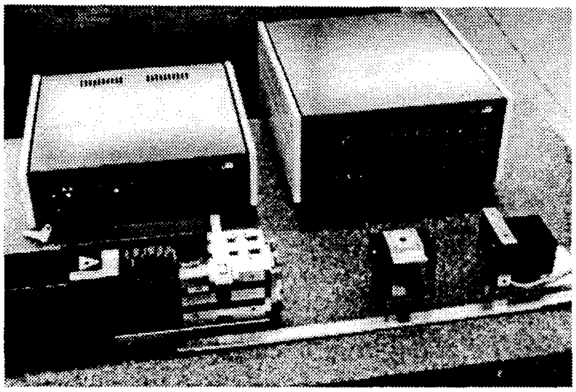

Figure 21. Components of the LMS 200-System

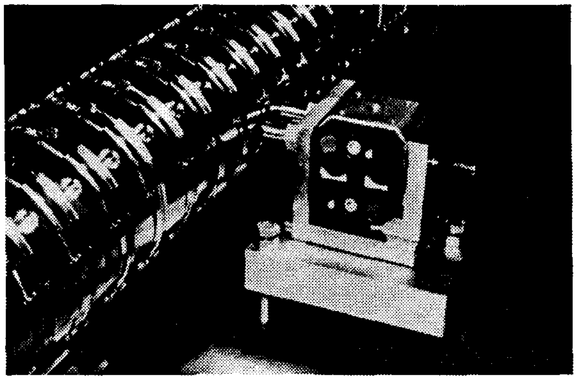

Figure 22. Beam Monitoring Sensor in Contact with the Module

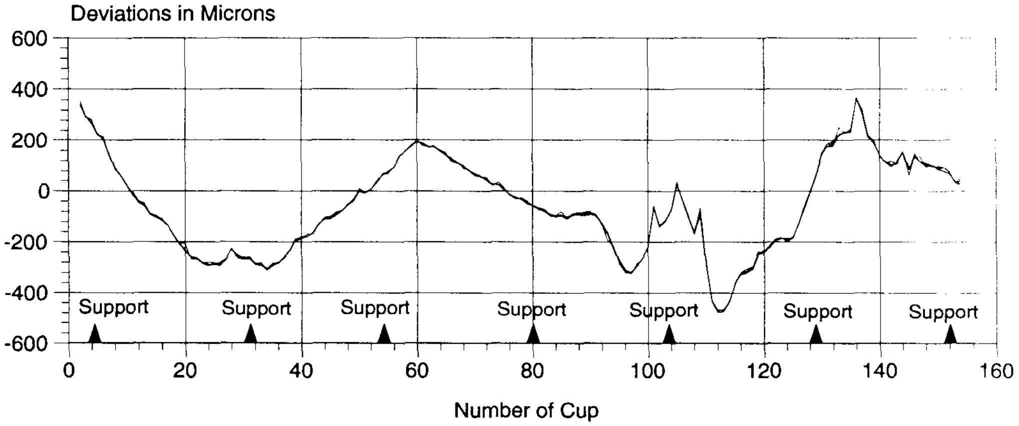

Figure 23. Horizontal Straightness Deviations measured four times using the LMS 200-System

The results of four measurements carried out by the LMS 200-System are shown in Fig. 23. The differences between the single rows are as a rule smaller than 15 μm. In Fig. 24 the means of the four LMS 200-measurements and of both measurements carried out by the theodolite Kern E2 are plotted out. The deviations between both curves usually are smaller than 15 μm. Only half a dozen of cups show differences up to 150 μm. Probable in those cases the cross sections are not exactly a circle, so it is possible that both measuring techniques show different results.

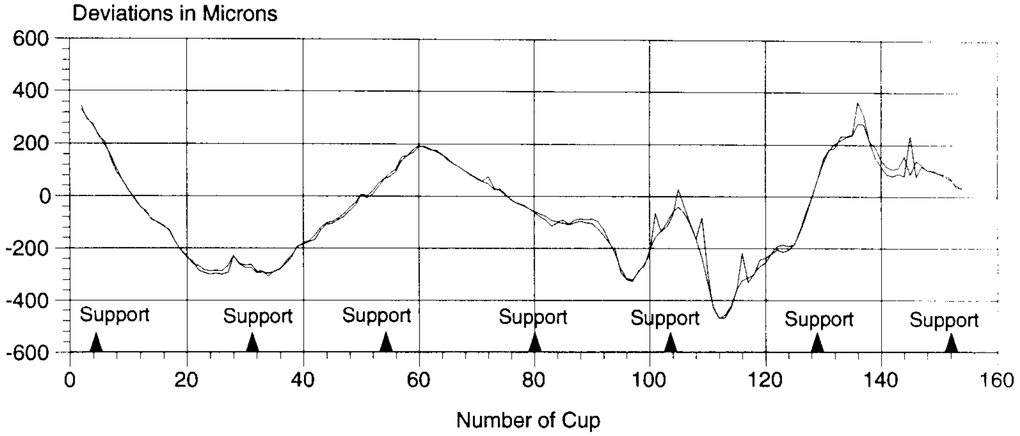

Figure 24. Autocollimation Technique and LMS 200-System in Comparison

The measuring time is about 25 minutes. Notice that only the horizontal and not the vertical deviations of straightness are obtained simultaneously and that the registration of the measured values will be done yet manually. Later a computer will be used to register the measured values. This LMS 200-System is suitable to obtain the required accuracy for the straightness control of the modules.

5 Conclusion

Summarized, three techniques are discussed to control the straightness of the modules. All techniques are able to obtain the required accuracy better than 30 μm about the length of a module of 6 m. Straightness measurements using laser interferometer and the intensity of two laser beams are able to measure only one position either the horizontal or the vertical one. Only straightness measurements using the autocollimation technique give by one measurement horizontal and vertical deviations simultaneously. The measuring time using an automatic autocollimator for example Elcomat 2000 is the shortest one of all tested techniques and for the user the process is more convenient than the other techniques. Therefore the final straightness control of the modules will be carried out by the autocollimation technique.

The straightness deviations of all tested modules are out of the allowable tolerances. Therefore a device is under construction to align the modules. The mobile device has two adjustable arms which can be fixed to the module at any position. Between both arms an adjustable plunger is able to press against the module. The plunger deforms the module in reference to the arm positions in a definable manner. Before the device can be used the straightness of the module has to be measured by autocollimation technique by Elcomat 2000. According to the graphics showing the straightness deviations the device will be put in position to deform the module in calculated manner. The device can make only horizontal deformations. Therefore the module has to be turned about its axis to remove vertical straightness deviations. After each deformation the straightness of the module has to be controlled again in a short time. For this purpose the straightness measurement system LMS 200 will be used.

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