Alignment of the Superconducting Cryostat for the Tesla Test Facility

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1. DESCRIPTION OF THE CRYOSTAT

The cryostat is the principal building block of the proposed TESLA - superconducting linac. It contains 8 superconducting RF cavities made from solid pure niobium and a quadrupole package. The cryostat includes two aluminum shields of 4.5 and 70 K with multilayer insulation on the outside.

The helium distribution system needed to operate the superconducting cavities at 2 K and the magnets at 4.5 K is also integrated into the cryostat. The two phase line transfers helium to the cavities, the gas return line transports gas from the cavities to the refrigeration plant. This line is connected to the cavity helium vessels via a helium bath at the end of the module. The 4.5 K forward and return lines cool the quadrupole package, the radiation shield and the 4.5 K intercept on the input coupler. The 70 K lines have the corresponding effect on the outer radiation shield and the 70 K intercept of the coupler.

The cryostat outer vacuum vessel is constructed of carbon steel and is evacuated to a pressure of less than 10^{-6} mbar during operation. In the Tesla Test Facility TTF it is connected by sliding sleeves to a feedcap which provides the link to the cryogenic supply at the upstream end of the prototype module. At the downstream end it is closed off by an endcap which seales off the vacuum space and turns around all the cryogenic flows [1]. Wires and cables are brought out at the module itself using flanges equipped with vacuum tight connectors. Figure 1 shows a cross section of the cryostat.

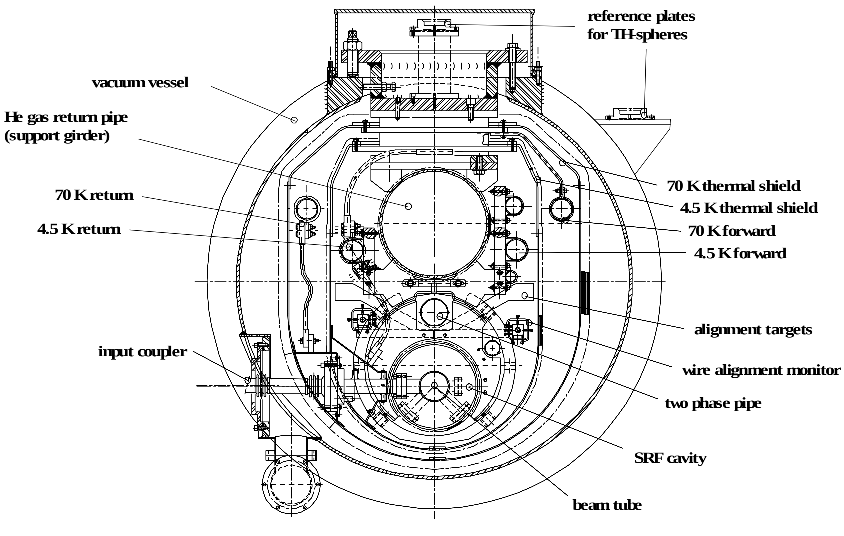

Figure 1: Cross section of the cryostat

Figure 2 gives a longitudinal view of the cryostat. The 300 mm diameter two phase helium return pipe acts as the structural backbone for the cryomodule. It is supported from above by three vertical posts that provide the necessary thermal insulation from room temperature. These posts are fastened to large flanges on the upper part of the vacuum vessel by adjustable brackets. They allow the alignment of the module axis independent of the absolute position of the vacuum flanges on which it rests.

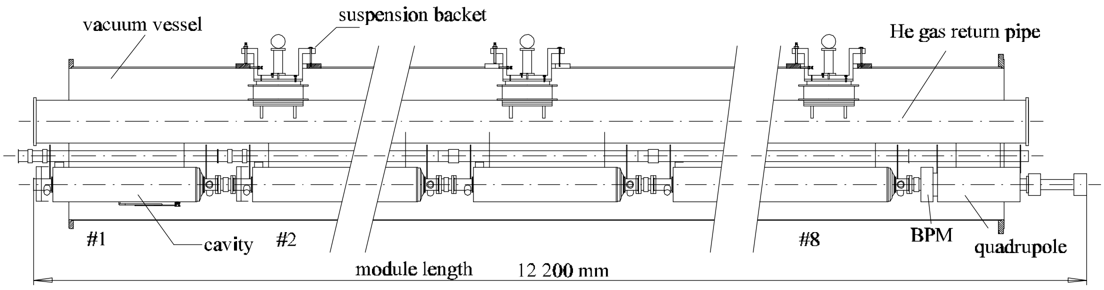

Figure 2: Longitudinal view of the cryostat

The posts consist of a fiberglass pipe terminated by two shrink - fit stainless steel flanges. At appropriate intermediate positions, optimized to minimize the heat leak, two additional shrink - fit flanges are provided to allow intermediate heat sink connections to 4.5 K and 70 K. The diameter of the posts has been chosen in such a way that resonant vibration modes near the 10 Hz operating frequency of the accelerator do not exist. In longitudinal direction the center post is fixed to the vacuum vessel while the two end brackets are free to move in the axial direction to accomodate differential shrinkage during thermal cycling.

The 8 cavities and the quadrupole package are attached to the helium return pipe by means of stainless steel brackets. They are equipped with adjusting screws which allow an independent alignment of the single components relative to the beam axis. For more details see [2].

2. INSTALLATION OF THE FIRST CRYOMODULE

2.1 Assembly of the cavity - string

The first prototype of these cryostats has been tested in the TTF linac since May 1997. Figure 3 shows the actual layout of this facility. The test module is placed immediately behind the injector system. Instead of the next two modules and the foreseen undulator a preliminary warm beam transport system is installed at present which allows to run the linac for the test measurements up to the diagnostic area.

The assembly of the prototype cryostat began in January 1997 . The first step was done in a class 100 cleanroom. Here the beam line components were connected together and filled with clean Argon gas at a pressure slightly above 1 bar. This procedure was carried out on top of support posts which are mounted on carts guided on a well aligned precision rail (Fig. 4). However, because of the length of the posts and the small base of the carts, the transverse alignment of the components with respect to the rail as reference axis was worse than 2 mm. On the other hand the roll of the cavities and of the magnet package had to be eliminated

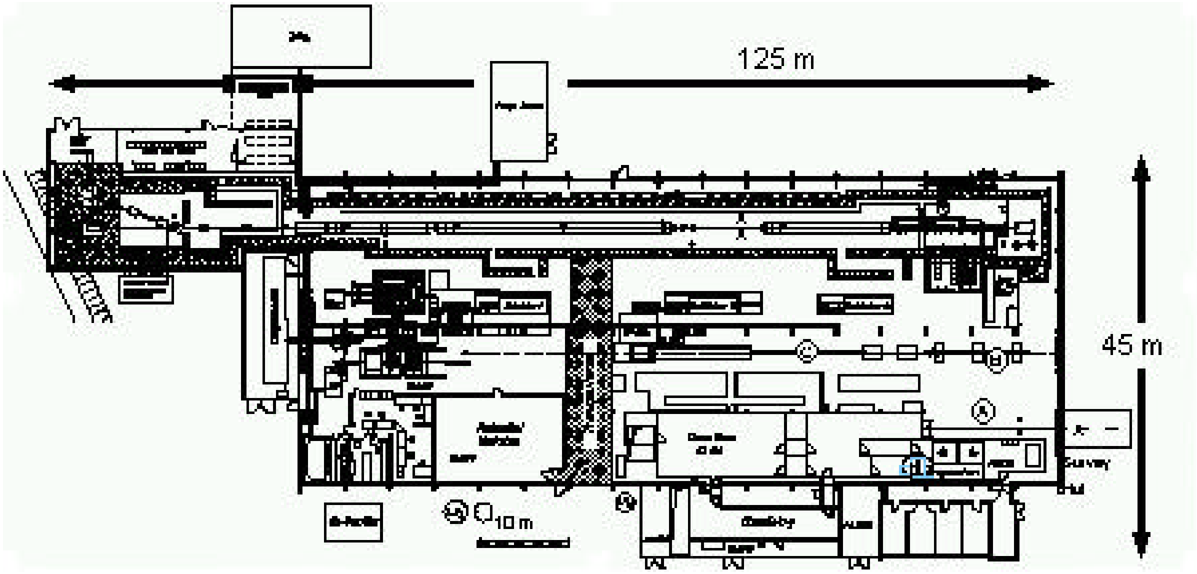

Figure 3: Layout of the Tesla Test Facility

already in the cleanroom, before the components were connected to each other by flanges. So, once the string was brought out of the cleanroom on its carts, a transverse prealignment to within at least 2 mm was carried out while the roll remained unchanged. Afterwards, still on top of the support carts, welding of the cryogenic two phase line connecting the cavity helium vessels and further necessary installations took place [3].

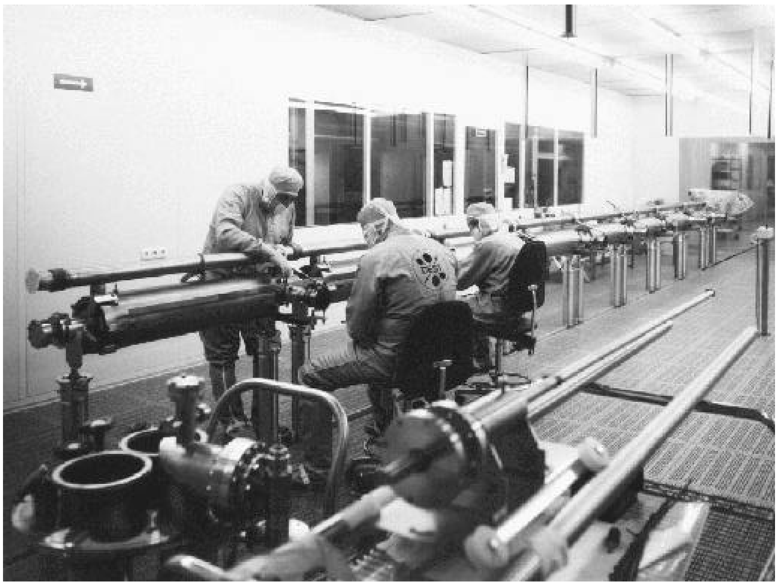

Figure 4: Connecting the cavity string in the cleanroom

2.2 Alignment of the cold mass

As the cross section (Fig. 1) shows the cavities and the magnet package are connected to the helium return pipe by ring shaped brackets which contain two alignment screws in their lower part and corresponding spring screws in the upper half. For the mounting phase the lower half can be removed so that the complete cold mass (helium return pipe with vertical posts and suspension brackets on top and ring brackets underneath , combined with the upper parts of thermal radiation shields, cryogenic pipes and cabling) can be lowered onto the cavity string.

On top of the cryostat support posts HERA - type centering plates for Taylor Hobson spheres are attached. These spheres, when aligned to a straight axis, define a parallel line to the ideal beam axis. Both lines are in the same vertical plane if the surface of the suspension brackets is kept horizontal. The nominal position of the axes of the return pipe and the ring brackets should be parallel and in the same vertical plane also.

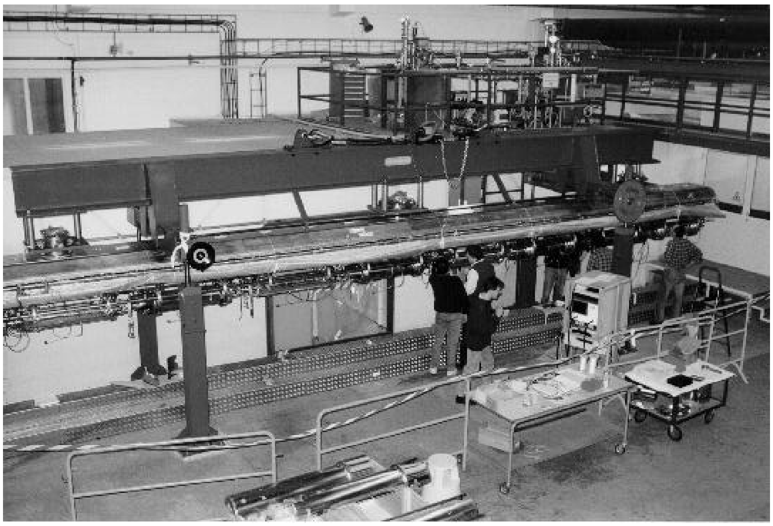

Figure 5: Assembly tooling

For the alignment of the three Taylor Hobson spheres an assembly tooling was necessary which supports the corresponding brackets as if they were mounted on top of the vacuum vessel of the cryostat. Figure 5 shows this tooling: a girder which carries the three suspension brackets with the cold mass and rests by means of two arms on four vertical posts , which are fixed to the concrete floor. A precision screw gear linkage system allows lifting of the girder, approximately 25 cm, with minimum motion in any other direction.

For the attachment of the cavity string to the cold mass the described assembly tooling was installed above the guiding rail in the remaining space between cleanroom and the south end of the hall, which was chosen for attachment and alignment of the cavities and quadrupole (installation area A). The cold mass was aligned with respect to the rail by using the three Taylor Hobson spheres on top and the alignment screws of the suspension brackets. The necessary measurements were carried out using a LEICA TC 2002 total station which was positioned on axis in a survey hut outside the hall (see Fig. 3).

A control measurement after aligning of the three cryostat support posts unfortunately showed that the return pipe and the ring brackets underneath had not their nominal position. It was necessary to define horizontal displacements for the three spheres on top, in order to bring return pipe and ring brackets exactly above the rail. Seen from the survey hut the first sphere had to be aligned +3.1 mm (to the right), the second +1.1 mm (to the right) and the third -0.4 mm (to the left). The zero roll and the same height of the spheres were kept as before.

Only then it was possible to lower the cold mass carefully onto the the cavity string. The cavities and quadrupole were attached to the cold mass using the foreseen supports. Then the assembled cold mass and cavity string was lifted off the string support carts. After some additional installations the system was now ready for the final alignment.

2.3 Alignment of the cavities

The axes of the 8 cavities should be aligned to the ideal beam axis to within ±0.5 mm, those of the quadrupoles to within ±0.2 mm. Additionally the midplane of the quadrupole package should be vertical to ±0.1 mrad.

The alignment procedure discussion is based on Figure 6. The alignment is performed with the cold mass and cavities still attached to the assembly tooling.

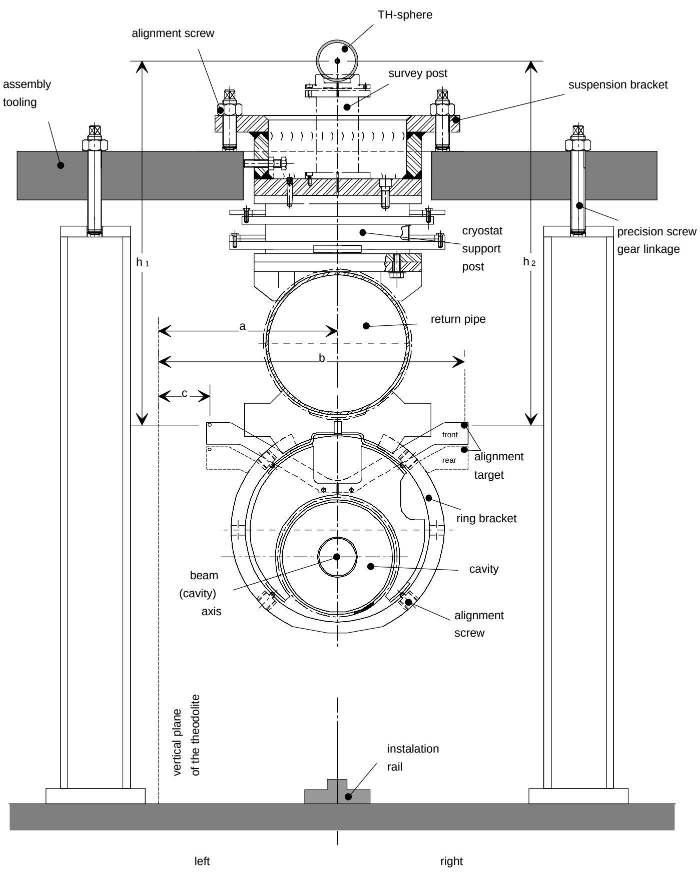

Figure 6: Front view of the alignment tooling

Cavities and quadrupole package are equipped with reference arms on both ends which carry two alignment targets each. The position of the ideal axes with respect to the corresponding alignment targets is defined by calibration measurements with CMM at the Lufthansa plant in Hamburg.

The targets are attached along the magnet and cavity string in such a way, that all targets of one side can be pointed at from a theodolite which is mounted nearly on axis in front of the module. By vertical and horizontal angular measurements their coordinates then can be derived, if the position of the theodolite with respect to the reference axis is known. Using two theodolites, one for each side, all the targets along the string can be determined and every axis point of the components be evaluated. Figure 7 shows the cavity string within the ring brackets and the leftside series of targets.

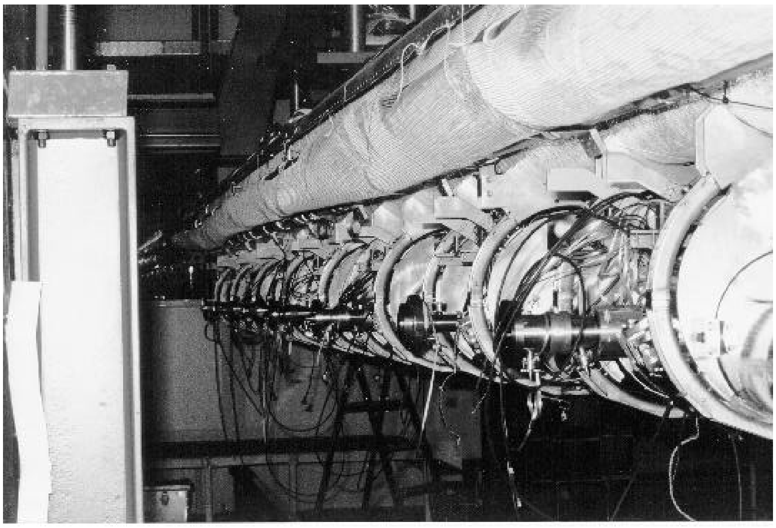

Figure 7: Cavity string with series of targets

The necessary measurements can be carried out only on the condition that the three Taylor Hobson spheres on top of the cryostat support posts are aligned with respect to the referencing installation rail as described before. Per definition all spheres have to have the same height and the roll of the suspension brackets has to be eliminated.

According to the results of the target survey cavities and magnet package can be moved in vertical and horizontal direction by the two screws in the lower half of the ring brackets, which are arranged under 45 degrees with counter spring screws in the upper half. Care must be taken that the roll of each component must not be influenced by the adjustment, as it has already been fixed during assembly in the cleanroom.

For the prototype module we used a slightly changed procedure to determine the target position. Since the succession of the cavities in the string was changed after they had been equipped with their reference arms, some of the targets were hidden behind those in front of them when they were pointed at from a theodolite on axis. So we chose a parallel vertical plane to that containing the reference axis on the installation rail with distance $\boldsymbol{a}$ and read the offsets of the alignment targets $\boldsymbol{b}$ and $\boldsymbol{c}$ using a ruler. The height differences $\boldsymbol{h_1}$ and $\boldsymbol{h_2}$ were determined by precision levelling.

Using the calibration values from Lufthansa one could reproduce the axis points from independent measurements within ±0.2 mm, which was good enough for the alignment of the components one by one. Unfortunately it turned out that tightening of the supports after the alignment sometimes alters the position so that several alignment steps became necessary to reach a stable position within the allowed tolerances. Because of the narrow time schedule we only performed two steps. Thereafter seven of the 18 reference arms still gave displacements between 0.5 and 1.0 mm. One even reached 1.9 mm due to a computation error. It was decided to leave the alignment as it was and proceed with the further installation of the module. Nevertheless, it was clear that while minor changes to the adjustment screws were needed, the Alignment Tolerances could be reached with this system.

The reference arms of the various components were changed next in such a way that the alignment targets were in their proper position according to their order in the string. That makes future measurements with theodolites on axis possible which is important especially for control measurements in the TTF. The coordinates of the new position of the alignment targets were determined twice in the same way as during the alignment procedure reading the offsets ***a, b, c*** and the height ***h***. All values were in accordance within 0.2 mm giving reliable reference together with the actual displacements of the cavity or magnet axes remaining after the alignment.

Last not least the monitors for the stretched wire measuring system, developed by INFN [4], were mounted and prealigned before the cold mass assembly was transported to another assembly position (installation area B in Fig. 3).

Here the wire system was installed and tested . It allows the measurement of alignment changes during operation of the cryomodule. Figure 8 shows the wire monitor which is fixed to a cantilever directly connected to the reference arms for the optical alignment. The monitors are connected by copper pipes with bellows which shield the wire from interfering signals. The picture also shows the illumination device for the optical targets, and, on the lefthand side, the upper half of the ring bracket holding the cavity with one of the spring screws.

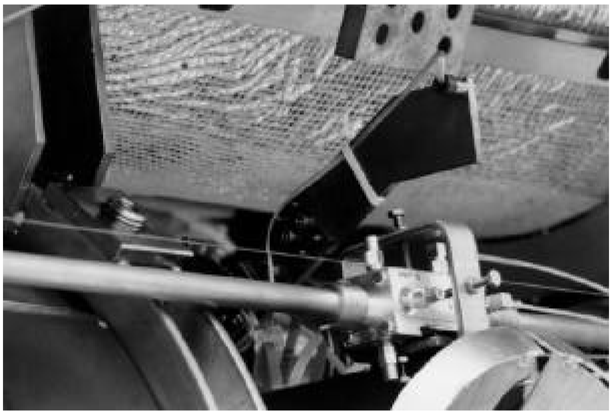

Figure 8: Target and wire monitor

2.4 Insertion into the vacuum vessel

After additional installation work at location B, especially for the quadrupole package, the whole system was moved to its final assembly position where the helium return pipe was suspended between two cantilevers (see C in Fig. 3). Here the last thermal shields and multilayer insulations were installed. Figure 9 shows the situation with the 4.5 K - shield just completed. This picture also shows that the cantilever in the foreground is movable on rails, while that in the background is fixed to the concrete floor of the hall and is long enough that the vacuum vessel on its carriage can be slid over behind the cold mass. After completion of the thermal shields this vessel in return was slid over the cold mass assembly.

Figure 9: Suspension of the cold mass between two cantilevers

Figure 10: Cold mass connected to the vacuum vessel

During this process the adjustable suspension brackets on top were removed. Appropriate pins ensured that they could be replaced to < ±0.1 mm of their original position after the vessel had reached its optimal position with respect to the cold mass. Figure 10 shows this situation seen from the opposite side than in Figure 9. The alignment screws of the suspension brackets were turned down to the surface of the three flanges on top of the vacuum vessel until the return pipe was lifted off the cantilevers, the cold mass then being connected to the vessel only by the three cryostat support posts again. To support this installation procedure some survey steps were necessary in advance:

1. We had to define a reference line given by the centerline of the guiding rails for the cantilever-and vacuum vessel carriages. It was marked by a Kern-centering plate for the total station on top of a stable post, built to support the cold mass in assembly location B, and a target on a shielding wall at the far end of the hall (see Fig. 3).
2. Two additional reference marks were set in the concrete floor of the hall parallel to the reference line and 1.5 m off to facilitate the alignment of the vacuum vessel.

The alignment procedure then was the following:

- After insertion of the cold mass the vacuum vessel was aligned such, that the two outer of the three flanges on top, which serve as base for the screws of the suspension brackets, were on the same height and had the roll = zero. The surface of the flange in the middle then proved to be 2.3 mm higher because of machining tolerances.
- The lateral position of the vacuum vessel was corrected by measuring the distance of the outer diameter of the endflanges from the parallel reference line on the floor. For the lateral as well as for the vertical alignment the appropriate adjusting screws of the vessel carriage were used.
- Only now the alignment of the cold mass was possible. The two outer Taylor Hobson spheres on top of the suspension brackets were moved to their nominal distance above the top flanges of the vacuum vessel. The sphere on top of the center post was adjusted to the same height with the endposts within measuring accuracy of the precision levelling, in order to bring the beam axis (cavity axes) to the foreseen height below the center line of the vessel. Simultaneously the roll of the upper surface of the suspension brackets was eliminated, as done already in assembly location A during the alignment of the cavities themselves.

- Finally the lateral alignment of the cold mass had to be carried out using the LEICA totalstation mounted on the Kern-centering plate. Once more the same displacements of the three support posts from the reference line had to be obtained as have been defined during the alignment of the cavities. The remaining offsets after the alignment from the nominal values were +0.1, +0.1 and +0.2 mm respectively .

As a final step the position of the three Taylor Hobson spheres on top had to be transferred to the two HERA-type centering plates mounted upon cantilevers on the side of the vacuum vessel. These plates later on are the only reference points which are accessable in the linac tunnel together with two ballscrews on either cantilever, which define the roll of the module. These ball screws were adjusted after the alignment of the vacuum vessel and the cold mass such, that inclinometers on top read roll zero.

The Taylor Hobson spheres on the side were referenced to those on the suspension posts by polar measurements once more with the LEICA total station from the Kern-centering plate and, additionally, by precision levelling. As result we had three dimensional coordinates for all five spheres in an internal Cartesian sytem of the module with sufficient accuracy for further alignments.

2.5 Installation of the module in the TTF linac

After finishing the alignment and transfer measurements, the remaining installation and instrumentation of the module was performed and checked by the cryostat crew. Then the module was ready to be moved to the test linac. Before that it was turned around by 180 degrees, so that the quadrupole package in the linac is located on the downsstream side.

The alignment of the module here was performed using angular- and distance measurements as well as precision levelling as it is usual for aligning beam transport systems. The reference points were brass bolts with crossmarks in the concrete floor ~ 1.25 m off the beam axis with their three dimensional coordinates determined with respect to the ideal beam line (see Fig. 3). With the roll measured upon the ballscrews of the cantilever plates and brought to zero the corresponding spheres of the module could be aligned within ±0.1 mm in lateral and vertical direction. Cavities and magnets should be expected to be on axis within at least ±0.2 mm, if their position with respect to the helium return pipe remained stable since the original alignment.

After the alignment the module was connected to the feedcap and the endcap. The necessary thermal shields and multilayer insulation was installed and the vacuum system completed. Furthermore, the main couplers were attached to the 300 K RF waveguide and the current leads from the quadrupole package connected to the power supplies. After a final instrumentation check the module was ready for the first cool down.

3. CONTROL MEASUREMENTS FOR THE CRYOSTAT

To be able to make geodetic control measurements for the position of the optical alignment targets during vacuum tests and cool down two optical windows have been integrated into the endcap of the module. They are mounted on an average axes with the series of corresponding targets such, that all can be pointed at from theodolites in front of the endcap. Figure 11 shows a mounted E2-theodolite and a window with an attached

Figure 11: Theodolite in front of observation window

autocollimation mirror during measurements which gave information about distortions while evacuating the cryostat from normal pressure to 0.9 mbar. Fortunately they were small and have no significant influence on angular measurements through the windows to the targets.

Assuming that the optical windows are plane and parallel and that the maximum angle of incidence is always smaller than 0.80 grades, using a TC 2002 instead an E2, the parallel shift of the line of sight by the window (thickness 10 mm) will not exceed 0.05 mm, if the pressure inside the tank is the same as outside. With vacuum inside the maximum additional correction is ±0.01 mm for the target farthest away from the theodolite. These values are of the size of the measuring accuracy and show that position controls through the windows are feasible.

The instruments were mounted on Kern-centering plates fixed to stable concrete blocks and referenced to the ideal beam line of the linac. Since the distance of the targets from the theodolites is known their coordinates can be determined by horizontal and vertical angular measurements.

The first of these measurements was carried out immediately after installation of the module without the windows on April 30. The second control survey took place on May 5 with the windows mounted. Three more followed under vacuum (May 7, 16 and 20). The results are shown in Figure 12 and 13 with the displacements of the cavity and magnet axes derived from the coordinates of either two alignment targets.

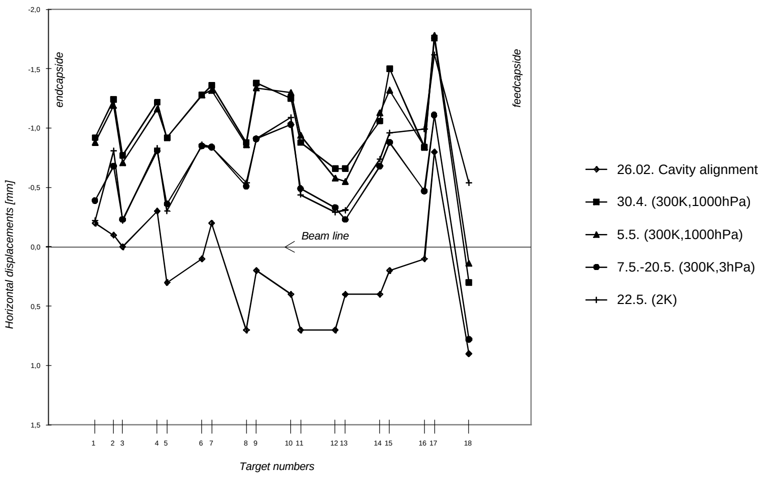

Figure 12: Horizontal displacements from beam line

Figure 12 gives the horizontal displacements from the ideal beamline. The first two measurements are matching very well (mean square value ±0.08 mm) which confirms the assumption that the windows have no significant influence. The differences with respect to the original cavity alignment however are surprising (mean value - 1.2 mm). The three measurements under vacuum move back to the beam line by ~ 0.5 mm and are corresponding with that after cooling down.

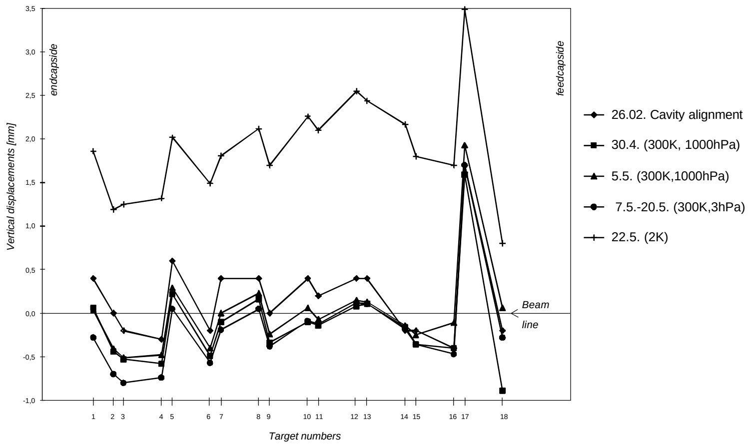

Figure 13: Vertical displacements from beam line

In Figure 13 the results of the height measurements are described. The first two measurements once more are matching with the exception of the targets 18 which, when warm, are difficult to aim at because of reflexions and weak illumination . The deviations from the original alignment here are on average about -0.2 mm. Obvious is the change in height due to thermal shrinkage after cooling down which has not been taken into account during alignment of the warm cavities.

After a good month of linac operation to set the RF system, accelerate the beam and measure the cryogenic performance of the module the system was warmed up and cooled down once more at the beginning of July. The procedure was accompanied by optical control measurements again. The results are shown in Figure 14 and 15. In contrast to Figure 12 and 13 the displacements here are referenced no more to the ideal beam line but to the axis of the cryomodule itself. A control measurement of the whole transportsystem of the TTF had shown in the mean time that the vacuum vessel had displacements from the beam axis of horizontally -0.5 mm and -0.7 mm and vertically -1.0 mm and -0.7 mm at the two survey plates on its side. The reason of this movements is not quite clear. The assumption may be realistic that the installation of the feedcap and endcap with the associated installation steps and, certainly, the additional concrete shielding to close the tunnel after installation are responsible for it. These displacements of course have to be removed as soon as possible by a alignment of the module and, for the time being, taken into account for all discussions on the behaviour of the string inside the tank.

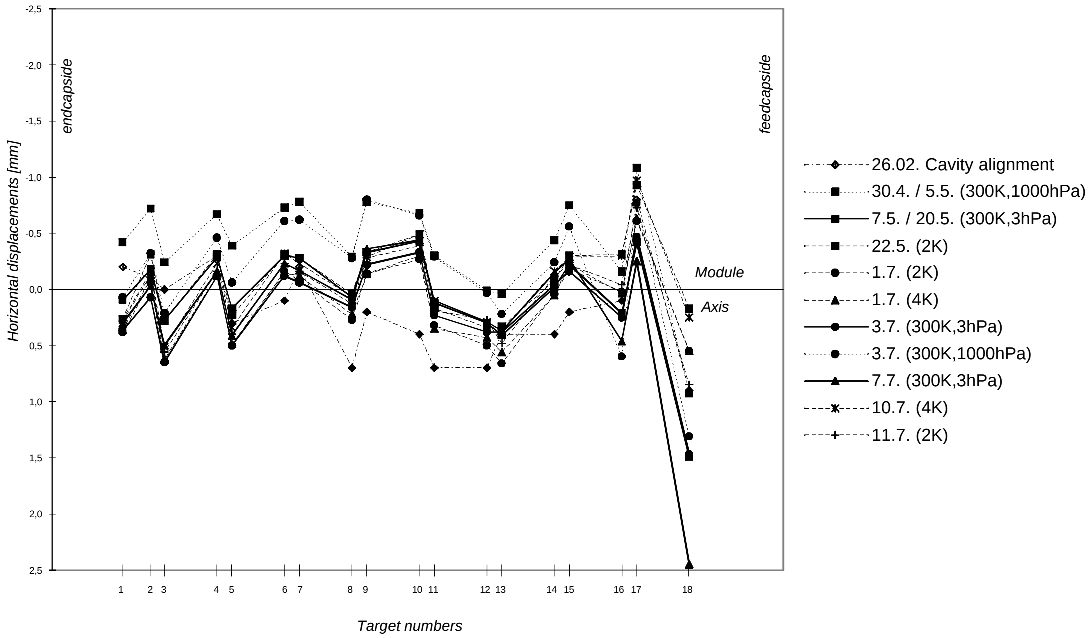

Figure 14: Horizontal displacements from Module Axis

Figure 14 also gives the horizontal displacements for the first series of measurements. The mean values from April 30 and May 5 are still on average -0.6 mm off from those of the fundamental alignment in February. Vacuum and cooling down moves the axes of the components back toward the module axis with astonishing repeatability. All displacements of the cold module can be reproduced within 0.3 mm, that under vacuum within 0.4 mm with the exception of number 18.

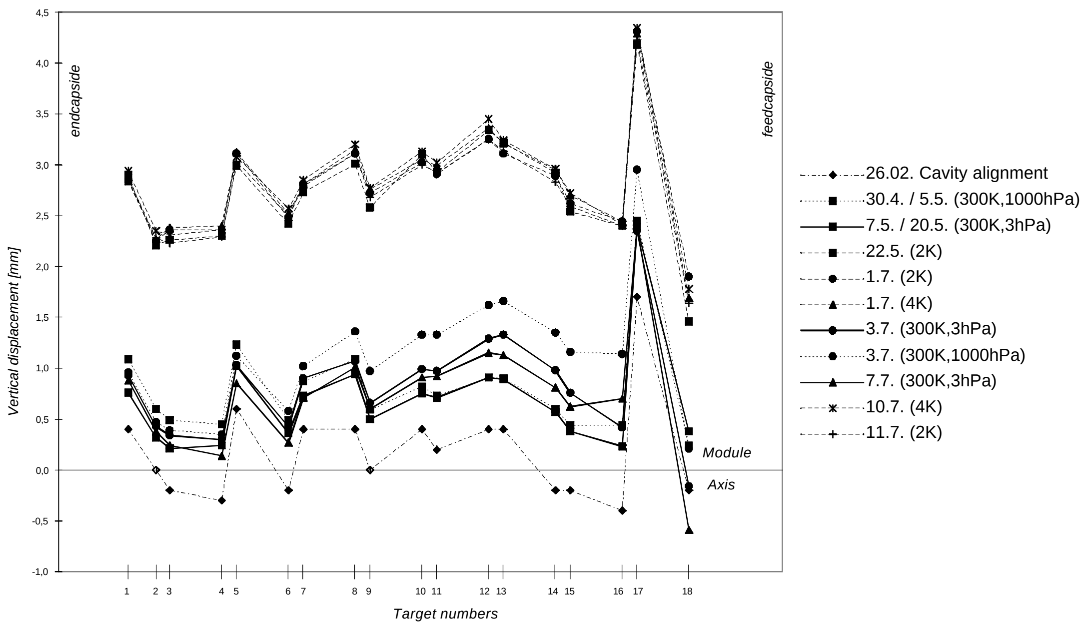

Figure 15: Vertical displacements from Module Axis

Similar effects can be seen in Figure 15 with the vertical displacements of the component axes. The cold measurements here can be reproduced even better within 0.2 mm, those under vacuum within 0.5 mm, once more with the exception of number 18. The mean values from

April 30 and May 5 here are on average 0.6 mm higher than that of the reference measurement before installation in the TTF. The comparable measurement on July 3 under room temperature and normal pressure however shows only for the first three elements (quadrupole, two cavities) a good matching within ±0.1 mm. The following cavities tend upwards to offsets up to 0.7 mm. Since the horizontal displacements also show a systematic effect (the values in the middle are comparable but the ends of the curve have an offset of about 0.5 mm) it can be assumed that the carrying helium return pipe at the time of our measurement had a deformation. Most probably it had not yet adapted to the new conditions during the four hours which had passed since the last measurement under vacuum on this day. Therefore this measurement is not comparable to the other ones.

4. CONCLUSIONS

The alignment philosophy for the module is based on the assumption that the helium return pipe keeps its position with respect to the vacuum vessel after it has been aligned using the Taylor Hobson spheres on top of the suspension posts. All connections between the return pipe and the cavity string including the quadrupole package have to be stable against movements and thermal cycles in order to keep the warm alignment of the string in the cold phase also. Furthermore the stability of the spheres on the suspension posts and the coordinate transfer to those attached to the outside of the vacuum vessel has to be reliable, because the suspension posts are not accessable any more after pumping the insulation vacuum.

For the test module mean discrepancies of 0.6 mm between the warm measurements immediately after aligning of the string underneath the cold mass and that after installation in the TTF were obvious. The standard deviations of each measurement were ±0.2 mm horizontally and ±0.1 mm respectively for the height, which can be explained by measuring inaccuracies or statistical movements of the components. The mean values however stand for a real movement of the string during installation and transportation which does not meet the TESLA - requirements, but is just acceptable for the TTF. For the following modules such movements have to be excluded. In any case test transports after alignment of the string should be performed under rough conditions with control surveys afterwards to discover instabilities of the supports. Only when the measurements are reproducable the further installation steps should be carried on. After the final alignment in the TTF using the two spheres on the side of the vessel an additional control measurement for the three spheres on top of the suspension posts is unavoidable. That´s the only way to detect eventual changes during transport into the tunnel before closing the vacuum flanges.

Such measurements were neglected for the test module because of lack of time under the narrow schedule for the assembly, so that the argument when and why the detected displacements took place could not be specified.

After pumping the insulation vacuum and also after cooling down we found a good reproducibility of the string axes. If we evaluate the mean values of the different results for every target position not only for the five cold but also for the five warm measurements under vacuum we get reliable information about the behaviour . Figure 16 gives these mean values for the horizontal, Figure 17 those for the vertical displacements. All these values have standard deviations of less than ±0.1 mm with the exception of number 18 under vacuum. These results confirm that the operation of the module, when cold, will be possible with stable alignment.

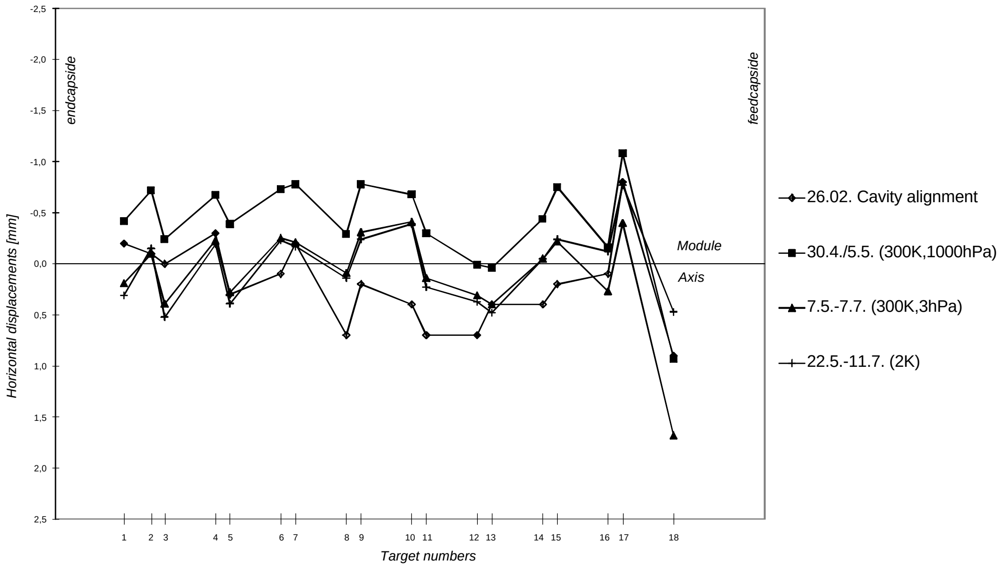

Figure 16: Horizontal displacements from Module Axis - Mean Values

In the horizontal plane the original warm displacements of the string are partially compensated and vacuum and cold position are matching pretty good. Only the last three points show a systematic, though stable, offset between warm vacuum and cold position which indicates a deformation of the helium return pipe by asymmetric forces in the feedcap region up to 1.2 mm.

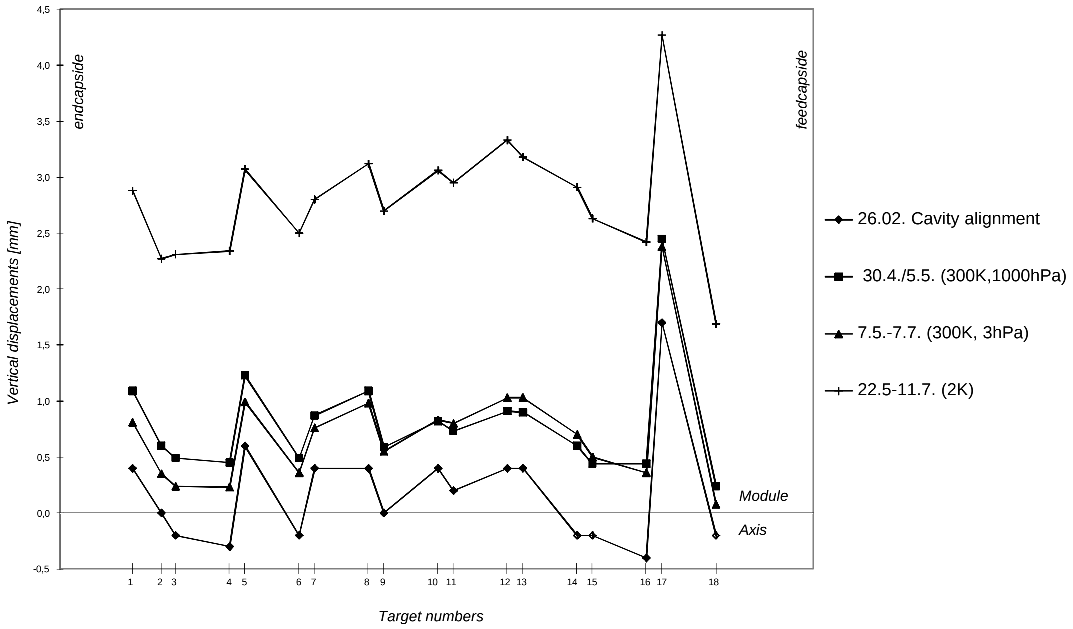

Figure 17: Vertical displacements from Module Axis - Mean Values

In the vertical plane warm and vacuum position are matching within some 0.1 mm. The cold positions show the predicted thermal shrinkage of about 2 mm related to the vacuum line. A deformation of the helium return pipe by cooling down can again be seen at the end of the last cavity with a downward movement of about 0.4 mm.

These effects on the return pipe were confirmed by measurements with the wire position monitors. The cryogenic connections at the feedcap therefore have to be improved for the future modules.

5. REFERENCES

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