

Fiducialization of Superconducting Radio Frequency Cryomodules at Jefferson Lab

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1. INTRODUCTION

During the early 1990's the Continuous Electron Beam Accelerator Facility (CEBAF), was under construction in Newport News, Virginia. The facility was to be the first of its kind in that it was to provide a continuous beam of electrons for experimental physics at energies of several GeV. One of the key elements of this unique machine was the 338 superconducting radio frequency (SRF) cavities built into 42 cryomodules and arranged in two linacs. These were linked by arcs of conventional magnets which allowed recirculation through the linacs up to five times, in order to achieve the design energy of 4GeV. Within each cryomodule the cavities were aligned and referenced to external fiducials allowing alignment on the design beampath. This paper describes the process developed to achieve this, how it evolved with improving instrumentation, and the results obtained. Suggestions for alternative methods which may prove useful for future projects are also discussed.

1.1. Alignment Specifications

The original specifications for cavity alignment were developed in the late 1980's and were limited to the mechanical structure. These were expanded during several studies to consider the accelerating fields. From these, a specification for mechanical alignment was agreed which stated:

The accelerating structure should be supported in such a way that the accelerating field in any cavity will be aligned relative to the nominal beam trajectory with a root-mean-square angular precision of $\sigma_{\text{pitch or yaw}} = 2$ mrad, with a 2σ cut-off. [1]

This 2 mrad r.m.s. error was distributed amongst three error sources, namely individual cavity alignment, cavity pair alignment, and cryomodule alignment. The errors assigned to each category were 0.5 mrad, 1.25 mrad and 0.1 mrad respectively. Combined in quadrature these fall below the 2 mrad specification mentioned above.

Although specifications for the alignment were well defined, the means of achieving these was not so clear. Early designs of the cavities did not provide datums which could be used throughout the assembly process. The center-line datums used in the manufacturing drawings had to be defined by end flanges. Some of these were covered up during the cavity pair assembly and the physical datum then had to be transferred to beamline valve flanges which could then be used in the remaining assembly steps. Measurements were made to check the integrity of these transfers, and were considered acceptable.

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1.2. Cryomodule Assembly

A SRF cavity is made up of 5 niobium cells. Two of these are arranged as cavity pairs inside a cryounit. A cryomodule contains four cryounits, hence eight cavities. Alignment is controlled at each stage of the assembly process. For the initial phase, a special fixture was made to ensure that the alignment of each cavity, which is defined by the end flanges, is maintained in the cavity pair assembly (Fig. 1). The fixture also enables the end flange datum to be transferred to the beamline valve flanges which are positioned on the same rails.

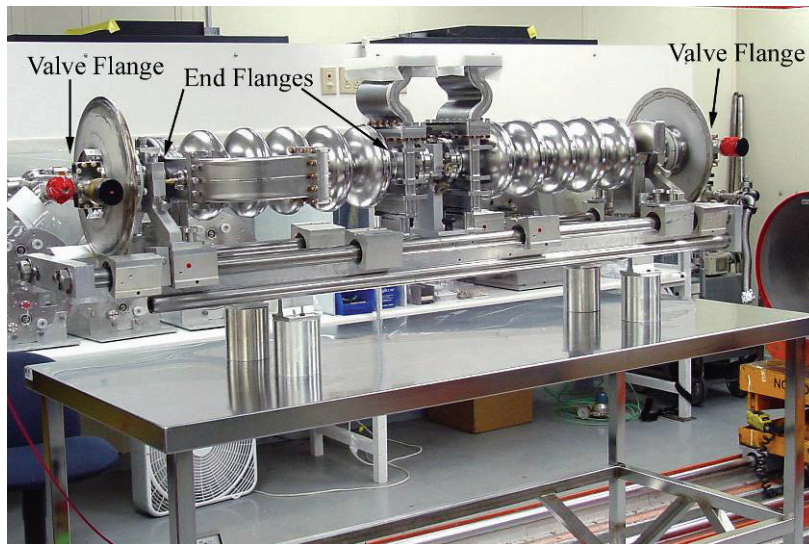


Fig. 1. Cavity Pair on Alignment Fixture

After sealing and testing, the cavity pairs are inserted into a helium vessel using Thompson rods (Fig. 2). The cavity pairs are attached to the helium vessel at the two flanges located at the center of the pair. Two additional titanium supports are added to brace the ends of the cavities, and to maintain the alignment after the rods of the fixture are removed.

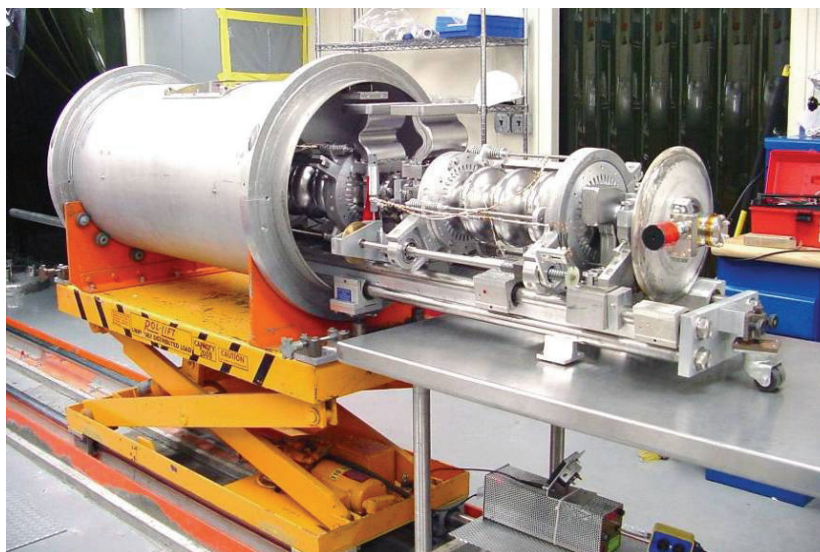


Fig. 2. Cavity Pair inserted into Helium Vessel

Following the addition of insulation and electrical connections, special tooling mounted on Thompson rods is used to insert the helium vessel into the outer vacuum vessel, and to form a cryounit (Fig. 3). The helium vessel is at this point supported and axially restrained by nitronic rods. The geometric arrangement and thermal properties of cavity and helium vessel supports were designed to minimize movement during thermal cycles.



Fig. 3. Helium Vessel inserted into Vacuum Vessel

The final stage in the assembly process is to connect the four cryounits and end cans to form a cryomodule. This process takes place on fixed Thompson rails. Four granite piers (Fig. 4) form two external baselines parallel to the rails. Linescopes are set up on the piers and sight a Taylor Hobson target at the opposite end. Target arm fixtures (Fig. 5) are attached to the beamline valve flanges between cryounits. A rough alignment is carried out by sighting these from the reference line and bringing the flange into horizontal and vertical alignment using adjustment on the nitronic rods supporting the helium vessels.



Fig. 4. Granite Pier



Fig. 5. Target Arm Fixtures

Before the final alignment and fiducialization of the cryomodule, welding is completed, and the end cans are attached. Up to this point, each cryounit has been supported on the Thompson rails. Now, with the cryomodule connected as a single component, all but two of the supports are removed. The remaining supports replicate those that will be used when the cryomodule is aligned in the linac tunnel.

Linescopes and reference targets are again set up on the granite piers, and the target arm fixtures attached to the beamline valve flanges. The flanges are then brought into a final alignment tolerance of 0.50mm by adjusting the nitronic rods. This is an iterative process, adjusting and re-adjusting the flanges until they are all within tolerance. After this, the lines between the granite piers serve as the reference for the center-line of the cryomodule.

1.3 Cryomodule Fiducialization

Fiducialization is then carried out. Eight tooling ball blocks (Fig. 6, points A-J) welded onto the external vacuum vessel serve as permanent references. Four or five others (points TP1-5) are glued into place to act as temporary transfer points. These are used to tie in both sides of the fiducialization survey, and were originally intended for use in smoothing surveys in the linacs.

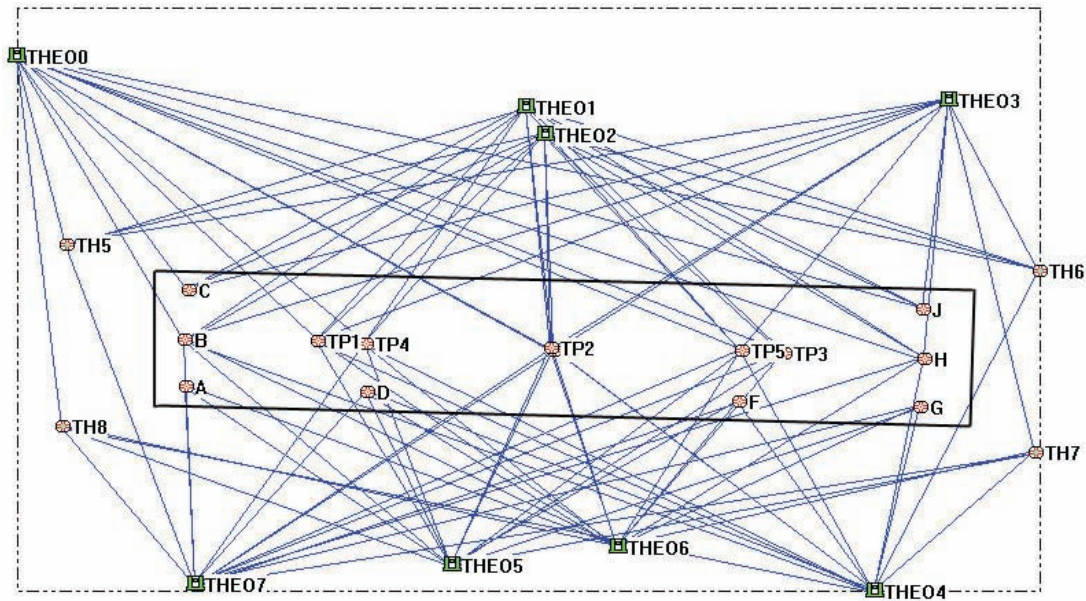


Fig. 6. Theodolite scheme for Cryomodule Fiducialization

A multi-theodolite survey is used to tie these references to the four granite piers (points TH5-8). Eight theodolite stations are used on a typical survey, with four on each side of the cryomodule. Alternating high and low stations ensured strong vertical geometry (Fig. 7). An object oriented 3D bundling solution is used to adjust the observations and obtain coordinates in an arbitrary system.



Fig. 7. Cryomodule Fiducialization

Two scale bars are used in order to define the scale of the survey. Initially, commercially available invar tubes were used, but these proved awkward due to the flat target style which restricted sightings. There was also the possibility of incorrect assembly of the tubes. Custom made one-piece carbon fiber rods were chosen as an alternative. These allowed for rotatable slant view targets, and meant that the bars could be placed and viewed from anywhere within the survey area. The carbon rods were calibrated using an interferometer and a coordinate measuring machine. Initial doubts on the accuracy of the scale bars meant that sample distances were measured between cryomodule fiducials in each survey. These were measured using a stick-micrometer, and provided a consistency check with the theodolite survey values.

To obtain meaningful coordinates, the results of this survey are transformed onto the granite piers using a 6 parameter transformation. The piers are defined as equidistant from the cryomodule center-line in X (horizontal), and at zero elevation (Y). Distance along the beamline (Z) is referenced to the upstream end-flange of the cryomodule.

The final location coordinates are obtained using a further transformation of these fiducials onto ideal reference coordinates in the linac tunnels. For the CEBAF accelerator, alignment in the linac was carried out using optical tooling techniques.

1.4 Accuracy

Concentrating only on the assembled cryomodule, there are three major sources of error. These are the alignment of the helium vessel with respect to the granite piers, the fiducialization survey, and the final alignment in the linac. The tolerance for the alignment with respect to the piers is $\pm 0.50\text{mm}$. To this should be added approx. 0.07mm for the mechanical errors of the arms with respect to the flanges. The fiducialization survey typically returns one sigma standard errors of 0.05mm in X and Y, and 0.08mm in Z. Again, an additional 0.05mm for mechanical errors of targets and fixtures should be added. The linac alignment with optical tooling yielded errors of 0.15mm and again 0.05mm for fixturing.

$$\begin{aligned}\text{This gives: } \sigma &= \sqrt{(0.50^2 + 0.07^2 + 0.05^2 + 0.05^2 + 0.15^2 + 0.05^2)} \\ \sigma &= 0.53\text{mm}\end{aligned}$$

With a cryomodule length of 10 meters, it can be seen that this falls well within the 0.1 mrad tolerance outlined earlier in this paper.

Over a period of 3 years, more than forty cryomodules were assembled, fiducialized, and aligned in this manner. The techniques developed appear to have been an effective way of using the available technology at that time.

2. SECOND GENERATION CRYOMODULES

For the SNS and 12 GeV cryomodules there were significant modifications in the design. A spaceframe was employed to support the cavity/helium vessel string, instead of supporting it directly on the vacuum vessel (Figs. 8 and 9). Also a new cavity assembly carriage enabled the entire cavity string to be inserted into the spaceframe at the same time rather than assembling in stages, first into cryounits, then into the cryomodule. One advantage of the new system is that it allowed the vacuum vessel to be manufactured as one unit. This could then be carried out by outside vendors, thus reducing welding and assembly time on site, and resulting in a more standardized end product.

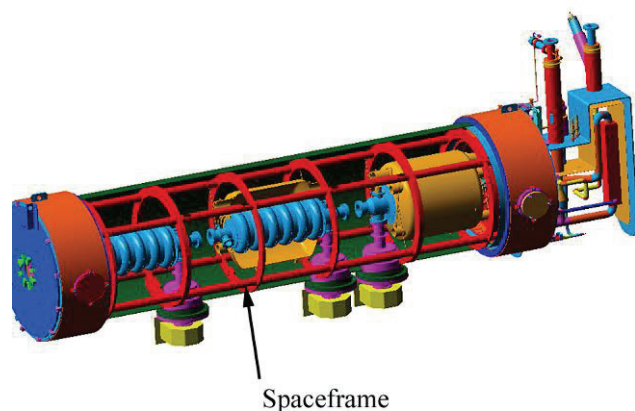


Fig. 8. SNS cryomodule showing spaceframe

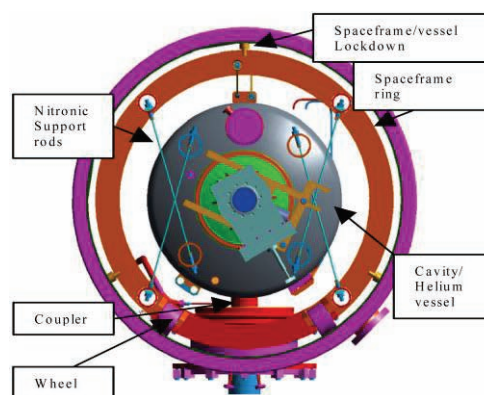


Fig. 9. SNS cryomodule end view

Between 2003 and 2005 twenty-four new style cryomodules were built and shipped to the Spallation Neutron Source project in Oakridge, Tennessee. At this time the Jefferson Lab alignment group had started using the Faro Gold Arm portable coordinate measuring machine (PCMM) in much of its work around the lab. It was natural, therefore, to consider if this device could be applied to the task of cryomodule fiducialization. The results of tests carried out into the accuracy of “leap-frog” surveys using the arm indicated that this technique had too rapid a build up of error to be useful in the fiducialization process. After six “leaps” coordinate differences of over 0.5mm in the Y direction were noted, although horizontally these were closer to the 0.1mm range. On other tasks the PCMM arm had been used within a local control network to eliminate leap-frog errors. For this task, however, the use of a local network was pointless since the theodolites used to measure the network may just as well fiducialize the cryomodule. The Faro PCMM arm did prove valuable, however, for quality control measurements of cryomodule components within its measuring envelope (2.4 meters).

The design changes and the new technology available, therefore, had little effect on the fiducialization of SNS cryomodule. It was decided that the same theodolite based system that was used for CEBAF would be the most effective approach for the SNS components. During initial fiducializations, consistency measurements were made on the new style target arm fixtures. Unlike the previous target arms which extended on both sides of the cryomodule, the arms for the SNS cryomodules could only be measured on one side. For the consistency checks, the arms were attached to the beamline valve flanges and surveyed in place, together with the granite piers. Initially, these checks highlighted discrepancies of over 0.5mm in the vertical position of the arms, and an average of about 0.3mm in the horizontal. This was resolved by reviewing the procedures on the arm placement (especially with levelling), and re-measuring the arm lengths on the CMM. A final check survey yielded an average agreement of less than 0.10mm horizontally, and 0.15mm vertically [4].

For the new style 12 GeV CEBAF cryomodule, design changes required that the space frame was rolled out of the vacuum vessel after final alignment. This meant that the transfer from the granite piers to the vacuum vessel fiducials could not be completed directly. Instead, the center line defined by the granite piers was transferred to four extension rods located on the spaceframe. These extension rods were visible through ports in the vacuum vessel and were subsequently used to define fiducials on its surface.

For the later fiducialization surveys of the 12 GeV and SNS cryomodules, the alignment group was able to test out the recently acquired Faro laser tracker. The observation pattern was similar to that used in the theodolite survey. The results, however, were significantly better. Coordinate standard errors improved by up to a factor of 2 in X and Y, and by more than a factor of 3 in Z (Table I). Given the necessity of carrying out two surveys for the fiducialization of the 12 GeV cryomodules, this has helped to maintain overall errors within tolerance.

Table I: Sample Standard errors (mm) from Cryomodule Surveys

	Tracker			Theod.		
	z	x	y	z	x	y
TH1	0.018	0.014	0.017	0.072	0.035	0.032
TH2	0.015	0.011	0.010	0.032	0.016	0.017
Pt6	0.009	0.009	0.006	0.026	0.020	0.012
Pt7	0.009	0.009	0.006	0.032	0.020	0.013
Pt8	0.010	0.009	0.007	0.041	0.021	0.015
Pt9	0.010	0.009	0.008	0.047	0.022	0.016
Pt10	0.012	0.010	0.009	0.052	0.024	0.018

3. FUTURE DEVELOPMENTS

Improvements to the Jefferson Lab cryomodule fiducialization scheme are unlikely to result from improvements in the instrumentation used in the final fiducialization survey. The use of the PCMM, as has been discussed, is not well suited for such a task, although it will continue to be used in the QC of smaller components. Using the laser tracker in

the fiducialization survey has already shown improvements in accuracy. It should be possible to optimize its use in future surveys in order to balance accuracy with efficiency.

The mechanical fixturing must be considered as a good candidate for improvement. Experience with the target arm fixtures demonstrated that great care must be employed in order to achieve accurate results. It may be possible to improve their accuracy and ease of use, or even, perhaps, to eliminate them entirely. Future spaceframe designs may allow access directly to the beamline valve flanges. These could then be included in the fiducialization survey rather than piers.

It is more likely that improvements can be made during the assembly phase through strict control of stack-up tolerances. This should be a particular concern in future machines such as the ILC. The entire assembly process from cavity fabrication, string assembly and internal alignment through to final fiducialization, needs to be carefully considered. The identification of a single datum which is accessible throughout the job from start to finish would eliminate the several transfers required in the technique described here. This would also assist in the control of dimensional elements. For large scale projects, where commercial partners are an indispensable part of the undertaking, the assembly and fiducialization process needs to be standardized so that it is suitable for industry. The simplification of datum definition and transfer techniques would prove to be an essential element in the standardization of such a process.

References

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