MECHANICAL DESIGN AND ENGINEERING OF THE 3.9 GHZ, 3RD HARMONIC SRF SYSTEM AT FERMILAB

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Abstract

The mechanical development of the 3.9 GHz, 3rd Harmonic SRF System is summarized to include: the development of a full scale copper prototype cavity structure; the design of the niobium 3 cell and niobium 9 cell structures; the design of the helium vessel and cryostat; the HOM coupler design; and a preliminary look at the main coupler design. The manufacturing processes for forming, rolling, and e-beam welding the HOM coupler, cavity cells, and end tubes are also described. Due to the exotic materials and manufacturing processes used in this type of device, a cost estimate for the material and fabrication is provided. The 3rd harmonic design is organized via a web-based data management approach.

WEB BASED DATA MANAGEMENT

Throughout the entire design and engineering process, the project data is organized and tracked within Microsoft Excel and can be viewed via the internet [1]. The constantly current and easily viewed design intent is shared and discussed between collaborators from around the world. Within this database are CGM, JPEG, ASCII, PDF, DOC and VRML files as well as complete bill of materials for all assemblies. Material cost quotations, FEA reports, and general layouts are also viewable.

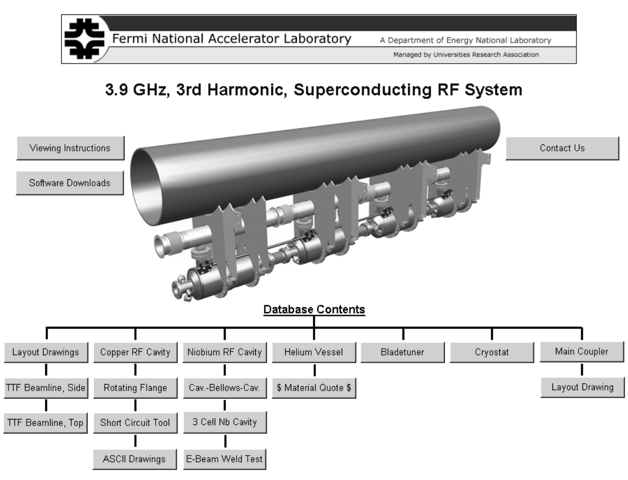

Figure 1: Internet based MS Excel database.

COPPER CAVITY PROTOTYPE

To verify the design parameters and to reduce costs, a nine cell, adjustable, copper cavity prototype was fabricated and tested [2].

Cell Forming

Cells were fabricated from 2.8mm thick, oxygen-free, copper disks using a stamping and coining process (see Fig. 2). The shapes were accurately measured and compared to the theoretical profile. Small changes in the die were made and with an additional stamping and coining process, the final cell shape was a near perfect match to the theoretical profile.

Figure 2: Cell die.

Brazing

After forming, the cells are machined and intentionally left 0.64mm longer than theoretical so that individual cell tuning can be achieved. Once the cells are tuned, two cells are mated together using a 65% copper, 35% silver slurry braze to form a “dumbbell” (see Fig. 3).

Figure 3: Brazed, copper “dumbbells”.

HOM Prototype

The HOM (Higher Order Mode) Coupler prototype is designed to be adjustable so that sufficient testing can be preformed to accurately define the position of the internal antenna and formteil (see Fig. 4). The tuning disk is fabricated from annealed copper and is adjustable to permit varying the capacitance gap (see Fig. 5). Once the operating parameters are defined by the copper model study, the niobium design is set and fabricated. Although seemingly rigid, the niobium HOM body and antenna are designed to allow for a small adjustment to tune the capacitance.

Figure 4: HOM Couplers without tuning disks.

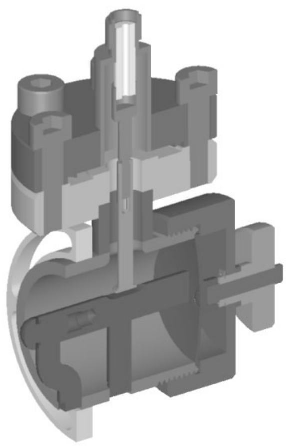

Figure 5: Section view of HOM Coupler.

Adjustable Prototype

Similar to the HOM Coupler prototype, the copper cavity assembly is designed to allow for end tube rotation. The position of the HOM couplers relative to each other (one at each end) are defined by realistic field measurements rather than determined only by analysis. The end-tubes are tightly connected to the brazed, copper, nine-cell cavity with clamps to allow for rotation and yet still provide a good RF connection (see Fig. 6).

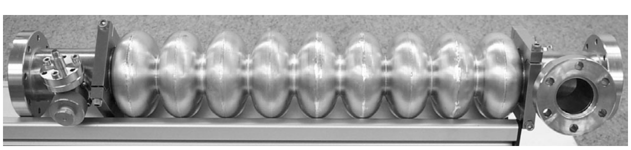

Figure 6: Copper cavity prototype.

Cell Testing

Frequency and capacitance measurements are collected as the cavity assembly is manipulated in the following manner:

- HOM Couplers and end-tubes are rotated.
- Tuning disk position in HOM Coupler is varied.
- HOM Coupler antenna gap is varied.
- HOM Coupler formteil tip is varied in length.
- RF cells are squeezed (see Fig. 7).

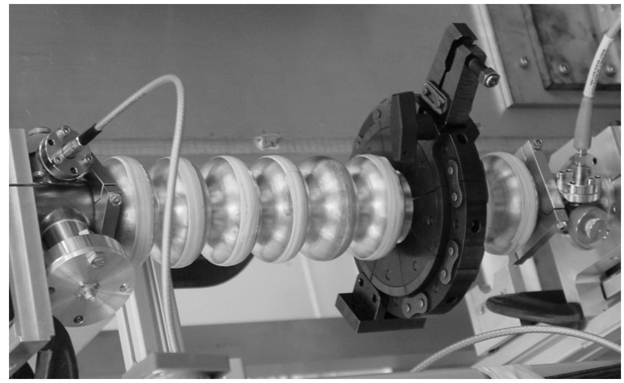

Figure 7: Copper cavity during testing.

NIOBIUM RF CAVITIES

The design of the niobium cavity is greatly simplified by eliminating the rotation and alignment capabilities. By studying the copper model, the operating parameters are determined and implemented in the niobium design. Although simplified in design, there are complications that arise when working with niobium and e-beam (electron-beam) welding.

3 Cell RF Cavity

To verify that the niobium cavity design will perform as expected at cryogenic temperatures, a three-cell cavity was built (see Fig. 8). The cavity must be chemically etched and then tested in a vertical test apparatus. The fixture to mount and test this three-cell cavity was not complete at the time of this publication (see Fig. 9).

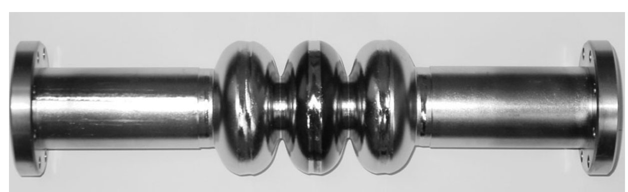

Figure 8: Niobium 3-cell cavity.

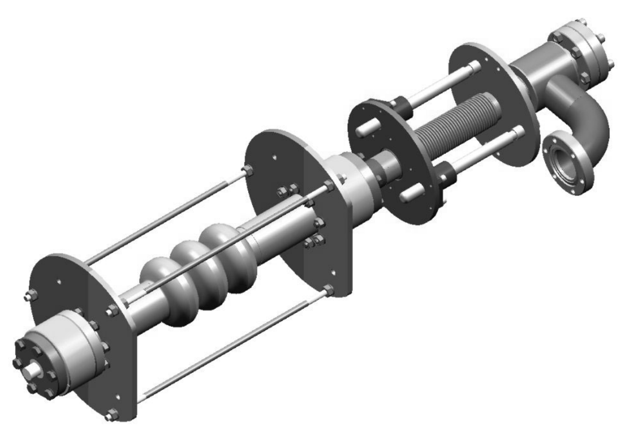

Figure 9: Niobium 3-cell test fixture.

9 Cell RF Cavity

The design of the nine-cell cavity is near completion. However, the design may go through another iteration based upon the results of the copper cavity model testing. Finite element analyses helped to optimize the shape of the niobium-titanium end flanges. The e-beam welding procedure is critical to insure strong joints that are vacuum tight and resistant to problems associated with chemical acid etching. Due to welding parameters, a detailed e-beam welding plan was developed to insure a proper and sequential fabrication order (see Fig. 10).

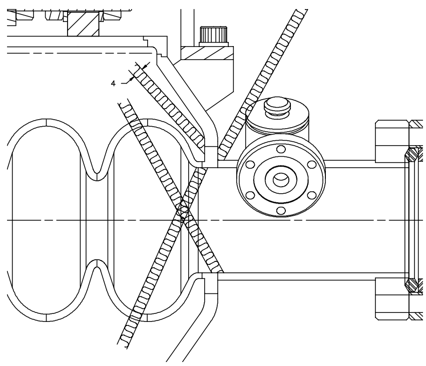

Figure 10: E-beam welding angles.

The RF cavity cells and end-tubes are niobium while the end-cell conical flanges and standard flanges are niobium-titanium (Nb-Ti). The outer helium vessel is fabricated from titanium. The Nb-Ti parts are used as a transition for welding from niobium to Nb-Ti to titanium. Niobium is far too expensive to be used for the entire cavity and vessel assembly. Also, niobium cannot be welded directly to 316L stainless steel, hence the use of titanium and Nb-Ti (see Fig. 11).

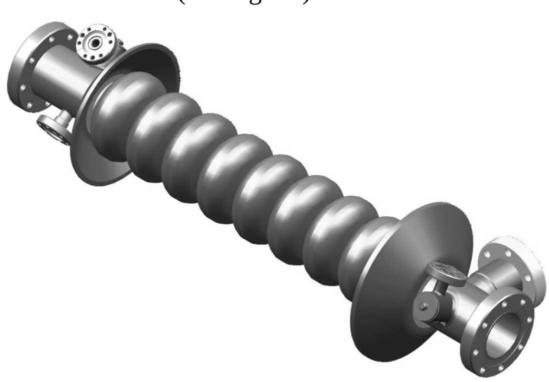

Figure 11: Niobium RF cavity structure.

Niobium HOM Coupler

An effort was made to simplify the construction of the HOM coupler body by machining the HOM coupler body from one piece of niobium. The formed insert (formteil) inside of the HOM body is machined as a solid part and is e-beam welded into the HOM body (see Fig. 12). This welded assembly is then e-beam welded into the niobium end-tube (see Fig. 13). Testing of this concept is in process. End-tube distortion during the welding process is a major concern.

Figure 12: Niobium HOM body with formteil.

Figure 13: Nb HOM coupler and end-tube.

The HOM coupler serves two purposes. The tuning disk gap can be varied to tune for a rejection frequency of 3.9 GHz while the HOM antenna adjusts the coupling of the higher frequency modes. Due to manufacturing tolerances, this gap must be adjustable. By mounting the antenna on a slightly flexible metal diaphragm, the gap can be measured and then set with the use of shims and a locking clamp (see Fig. 14). The gap is only adjustable in one direction so the initial gap is deliberately set to 1.3mm and is then adjusted accordingly to 0.8mm with the shims.

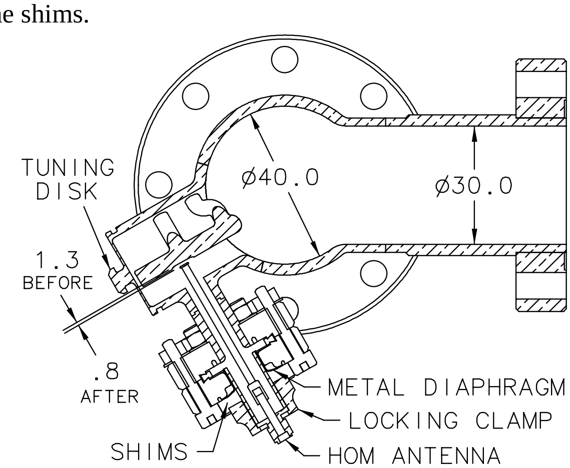

Figure 14: HOM coupler with adjustable antenna.

The capacitance can be measured and altered by removing the locking clamp, resizing the shims, and reassembling. This simple design permits adjustment without compromising the vacuum seal or the interior cleanliness (see Fig. 15).

Figure 15: HOM coupler external view.

SRF COLDMASS SYSTEM

In order to develop the individual RF components, the overall system parameters were needed. These working parameters were identified early on in the development process with the general space parameters driven by the scientists at DESY. After applying realistic engineering and manufacturing constraints, a final coldmass design has been established (see Fig. 16).

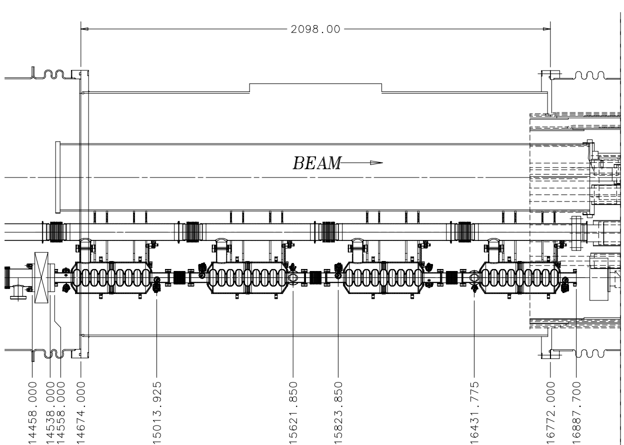

Figure 16: 3rd harmonic layout at DESY.

Helium Vessel

A titanium vessel surrounds the SRF cavity structure. Titanium was selected for the vessel shell for its ability to be welded to the Nb-Ti conical end flanges found at each end of the SRF cavity. The vessel has a helium supply port for two phase helium flow. The liquid helium temperature surrounding the SRF cavity is 1.8K.

Although there is only one SRF cavity design, due to the mounting locations of the main couplers, the helium vessel must have four different designs. Even with four unique vessel weldments, the individual vessel components are the same regardless of the configuration used. In fact, most of the vessel weldment can be fabricated prior to final welding which helps expedite the fabrication of a spare vessel assembly. To reduce costs, four spare units are not needed. However, a penalty is paid due to the time needed to complete the fabrication of a new vessel.

A titanium bellows is used at the center of the vessel to allow for expansion and contraction while tuning the cavity with a DESY style "bladetuner" (see Fig. 17). A large flange is located on each half of the vessel for mounting the bladetuner. Each flange also has two welded lugs used for mounting and aligning the vessel into the coldmass (see Fig. 18).

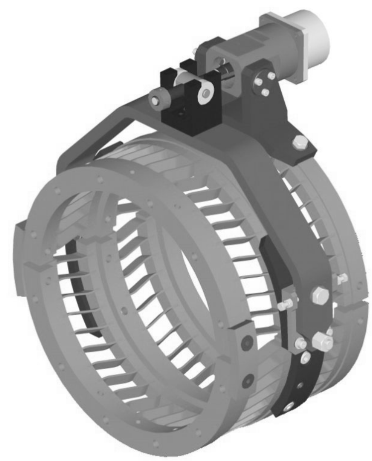

Figure 17: DESY style "Bladetuner".

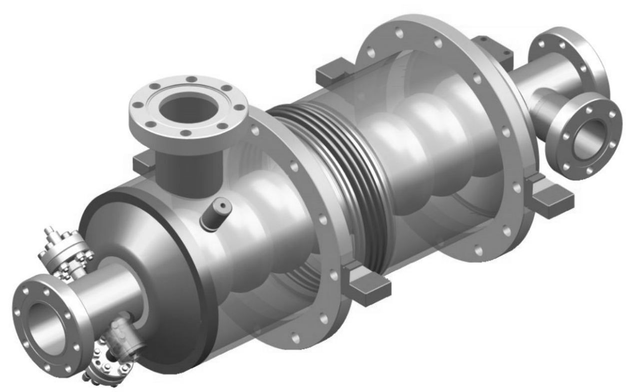

Figure 18: Helium vessel assembly.

Material Costs

Material to produce seven helium vessels, as shown in figure 17, has been purchased at an approximate cost of $40,000US. This price does not include the niobium to produce the mid-cells and end-cells. Currently, $200US per pound to procure niobium (RRR 300) sheet used to fabricate these cells is a good estimate. As with most projects, the material is inexpensive compared to the cost of fabrication. As an example, the e-beam welding of the 9-cell cavity shown in figure 11 is estimated at $21,000US and that does not include any machining costs! E-beam welding for this project has been priced at $200US per hour. Also, welding fixtures alone can cost in the range of $10,000US - $12,000US; a hidden cost sometimes forgotten.

Coldmass

A 300mm diameter stainless steel pipe is used as a mounting point for the four helium vessel assemblies, the cryogenic plumbing, and the heat shields. The support pipe also houses the return cryogenic pipes. The basic coldmass components have been established to insure that the design of the individual helium vessels is compatible with the overall design. More work is needed to complete the coldmass assembly design. Because this system will be installed in Germany, great attention is given to the interface between this system and the connecting cryostats at DESY (see Fig. 19).

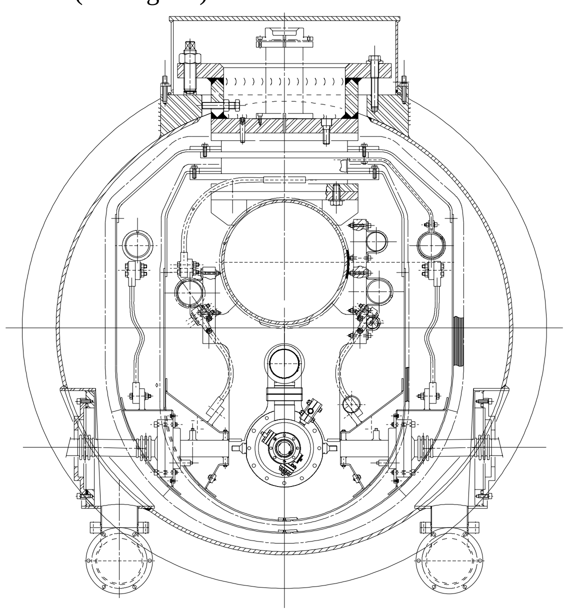

Figure 19: Cryostat/Coldmass cross-section.

A long invar rod is used to minimize the thermal contraction between each vessel. One of the center vessels is locked into position while the remaining three vessels are free to shift longitudinally during cool-down. The helium supply piping is fabricated from 316L stainless steel and connects into the titanium helium vessels through a standard conflat flange (see Fig. 20). This was done to reduce the material costs associated with procuring titanium bellows.

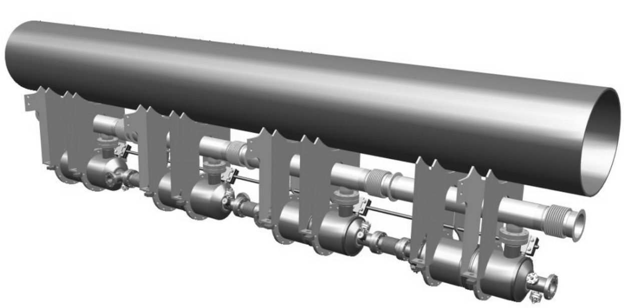

Figure 20: Partial coldmass.

CRYOSTAT ASSEMBLY

A DESY style cryostat is being designed to ease the interconnection between the two systems. Due to the short length of this cryostat, ~2m, the design will rely upon the adjacent cryostats providing the cryogenic fluids needed for cool-down. The support structure for the coldmass and the cryostat will be as close to the DESY design as possible for practical reasons.

One notable difference in this system design is the placement of the main couplers. At DESY, all main couplers are positioned on only one side of the beamline. However, in this design, there is not enough room to mount the main couplers on only one side. Therefore, the main couplers alternate from one side of the cryostat to the other. This actually provides a more balanced SRF design and works well for our geometry and available space (see Fig 21). The main coupler ports are also positioned 2.5mm higher than their mounting point on the helium vessels. This is very intentional so that the main coupler and the helium vessel will be aligned at cool-down.

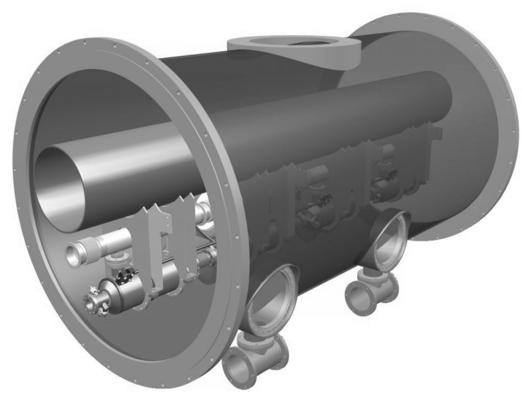

Figure 21: Cryostat with partial coldmass.

MAIN COUPLER ASSEMBLY

The physics behind the main coupler are well understood [2]. However, the design is in transition from an adjustable antenna to a fixed antenna (see Fig. 22).

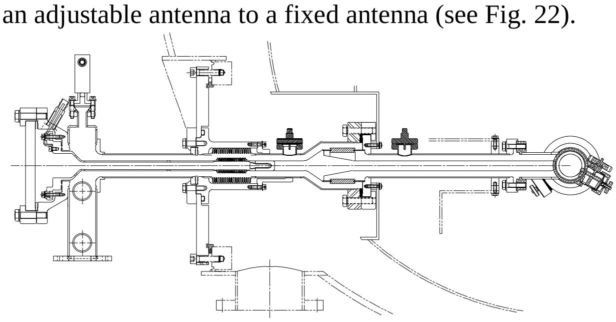

Figure 22: Main Coupler preliminary, stationary design.

REFERENCES

[1] http://www-td.fnal.gov/lc/sc/lc.html.

[2] N. Solyak, "Development of the 3RD Harmonic Cavity at FNAL. Status and First Results," SRF Workshop 2003.