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FABRICATION EFFORTS TOWARD A SUPERCONDUCTING RF PHOTO-INFECTOR QUARTER-WAVE CAVITY FOR USE IN LOW EMITTANCE INJECTOR APPLICATIONS*

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Abstract

The Facility for Rare Isotope Beams (FRIB), in collaboration with Argonne National Laboratory and Helmholtz-Zentrum Dresden-Rossendorf, is working on the design and fabrication of a photo-injector cryomodule; suitable for operation as part of the Linac Coherent Light Source II High Energy accelerator systems at SLAC National Accelerator Laboratory. Project scope requires the fabrication of two 185.7 MHz superconducting, quarter-wave resonators-based injector cavities. Cavity fabrication will be completed at FRIB with contracted vendors supporting subcomponent fabrication and electron-beam welding. Fabrication will use poly-crystal and large grain RRR niobium materials. The current status of cavity fabrication will be presented including material procurement, prototype forming, and electron-beam welding development.

INTRODUCTION

A research collaboration was formed in 2022 with the goal to design and fabricate a low-emittance superconducting injector cryomodule for potential use as part of the Linac Coherent Light Source II High Energy (LCLS-II-HE) project. The collaboration group is made up of research teams from The Facility for Rare Isotope Beams (FRIB), Argonne National Accelerator Laboratory (ANL), and The Helmholtz-Zentrum Dresden-Rossendorf (HZDR). The research is in support of the LCLS-II project at SLAC [1].

The project will conclude with the demonstration of a fully operational cryomodule; housing one 185.7 MHz quarter-wave superconducting radio frequency (SRF) gun cavity, shown in Figure 1, an emittance compensation solenoid [2], cathode stalk and plug system, power coupler, and cavity tuning system. The cryomodule is designed for 4 K operation and complete integration into the SLAC accelerator facility.

For the cavity construction phase of the project, a decision was made to fabricate two gun cavities. The first cavity will be used to prove out manufacturing methods, such as component forming and electron-beam (EB) welding, and document frequency change for each fabrication step. This information is critical in predicting the final frequency of the second cavity; built into the cryomodule for operational use. The only mechanical difference between the two cavities is the first cavity will not have the beam aperture in the Nose component to easy processing. This feature will be added to the second cavity for injector operation. The fabrication steps, and related development, in the construction of the first SRF gun cavity will be presented.

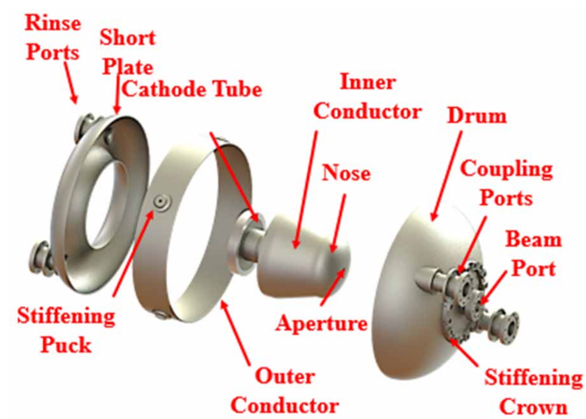

Figure 1: SRF gun cavity with key components.

CAVITY DESIGN

The cavity design is a collaborative effort among the three institutes; FRIB, ANL, HZDR. The design parameters and space envelope were directed by SLAC's Accelerator team. A mechanical drawing was established and used as the basis to begin optimizing the cavity shape using electro-magnetic simulation modelling.

Electro-Magnetic Design

The electro-magnetic modelling was a combined effort of FRIB, ANL, and SLAC. Superfish and CST Microwave Studio were used to model and optimize the cavity shape [3].

Mechanical Design

Upon completion of the electro-magnetic model, a full mechanical analysis was performed on the cavity structure using ANSYS WB for FEA [4]. ASME BPVC section VIII, Division-2 [5] was used as a basis for evaluation; looking closely at material thickness, weld joint design, and strategically placed stiffening elements.

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CAVITY MATERIALS

The SRF gun cavity will be fabricated using high RRR (Residual Resistivity Ratio) niobium (RRR>300) and with mechanical properties suitable for use in SRF cavity applications [6]. High RRR poly-crystal niobium was used to fabricate most of the cavity components. A decision was made to fabricate the Nose (top of Inner Conductor), shown in Figure 2, by machining the component directly from a thick piece of niobium, eliminating the need to form the Nose from sheet. Large-grain niobium (Ingot slice) was chosen as the stock material for fabrication. The large-grain niobium offered a significate cost advantage, as well as, the potential to improve performance with the reduction of grain boundaries. Several stiffening elements are welded directly to the cavity structure and are fabricated from high RRR niobium to eliminate alloying concerns during EB welding.

A niobium-titanium alloy (Nb-Ti) is used as a transition material between the niobium cavity and titanium (Grade 2) helium vessel [7]. The Nb-Ti (55% titanium) alloy can be easily electron-beam (EB) welded to the niobium of the cavity and welded to the titanium vessel using Tungsten Inert Gas (TIG) welding. The Nb-Ti alloy is also a harder material that allows for the cutting of the vacuum sealing features. A Conflate vacuum seal design (European dimensions) is used for all vacuum connections [8].

Material thickness was a critical parameter in material specification and was heavily evaluated during the cavity design review. Material thickness tolerances was specified to ensure the niobium maintained a minimum thickness at the completion of cavity fabrication. The thickness tolerance must account for potential thinning during component forming and material removal during cavity processing, as shown in Table 1. The final niobium thickness is critical in evaluating the mechanical response of the cavity and meeting criteria relating to pressure codes. Material thickness was monitored during fabrication using an ultrasonic thickness measuring probe.

All niobium materials received are inspected against an Acceptance List Criteria (ACL). Mechanical and electrical properties are measured to confirm material specifications were met (i.e. tensile test, RRR measurement). In addition, a parallel study on as-received niobium was completed to measure material Yield Strength values before and after heat treatment; verifying no change in value [9].

Table 1: Cavity Component Niobium Thickness Management

Component	Nominal (mm)	Forming (mm)	2 Etches (mm)	Final (mm)	Justification
Nose	4.0	4.0	0.5	3.5	Machined to match Inner conductor
Cathode Tube	4.0	4.0	0.5	3.5	Machined Component
Inner Conductor	4.5*	4	0.5	3.5	Worst Case Expected
Cathode Short	4.5	4.0 (Local)	0.5	3.5	Beta=0.53 Short Plate Measurements
Outer Conductor	4.5	4.5	0.5	4.0	Little thinning expected in rolling operation
Anode Short	4.7	3.5	0.5	3.0	Projection

Figure 2: Cavity nose fabricated from large grain ingot slice.

CAVITY FORMING

The main cavity components are fabricated using industrial forming practices such as hydro-forming, spinning, and deep-drawing. Forming and tooling designs were evaluated to ensure SRF design capability and dimensional tolerance.

Hydro-Forming

In an attempt to reduce fabrication costs, hydro-forming was evaluated as a method to produce the cavity's Inner Conductor. Hydro-forming from a single sheet would eliminate the need for any electron-beam seam welds and reduce tooling costs. Hydro-forming attempts were made with an industrial vendor using copper and aluminium materials; all resulting in failure (tearing). A progressive die concept was investigated before the decision was made to change to a different forming method.

Deep Drawing

Deep-drawing of niobium components has been widely used in the fabrication of SRF cavities; including many components of the FRIB production cavities. Deep-draw was used to form the gun cavity's Short Plate; following a forming die design similar to what was used in FRIB cavity design. A single stamp die set was fabricated from 7075 aluminium and designed to interfaces with a 1000 ton hydraulic press, shown in Figure 3. Copper and Aluminium prototype stampings were visual inspected and measured. CMM data from the prototype stampings showed a secondary "re-stamp", using the same die set, was required to meet dimensional tolerance; first stamp at 600 tons, followed by re-stamp at 400 tons.

Spinning

Spinning was selected to fabricate both the Drum and Inner Conductor components and was contracted to an outside vendor. The Drum was spun from a flat sheet against an internal mandrel; as shown in Figure 4 (left). The Inner Conductor was first rolled from a flat sheet to a tapered tube. The tube's seam was EB welded and then spun against an internal die, shown in Figure 4 (right).

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Figure 3: Deep-drawing of short plate ~600 tons.

Figure 4: (Left) spinning of drum, (right) spinning of Inner conductor.

CAVITY ELECTRON-BEAM WELDING

All required EB welds are completed using a Sciaky low-voltage (50 kV), 5-axis EB welding system. All weld joints were first developed using coupons to verify weld programs and measure weld joint penetrations and shrinkage. Several types of EB welds were developed; keyhole, conduction, cosmetic, and welding of differential materials (niobium to Nb-Ti and Nb-Ti to titanium). In addition, multiple "gun-to-work" distances were required and the development of 3-point weld programs (using X, Y, and Z movements).

Weld coupons are sectioned and polished to measure/verify weld penetration depth, shown in Figure 5. Weld shrinkage measurements were also recorded. Quantifying weld shrinkage of the final EB welds is critical in predicting the as-welded cavity frequency.

In parallel to weld program development, a complete set of EB weld tooling was designed and fabricated to able cavity components to be orientated in positions to access EB weld joints while fitting in the operating envelope of the welding chamber.

NOTE: final conduction (full-penetration) weld was made at a diameter of 23.9 inches; ~75 inches of continuous EB welding at 6 inches-per-minute.

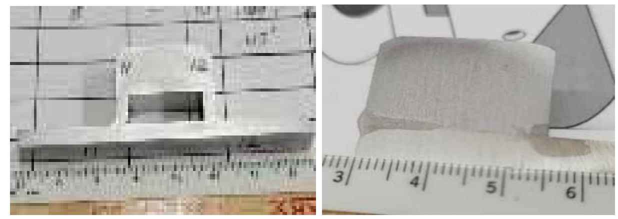

Figure 5: Keyhole weld development for stiffening elements; verifying penetration depth.

Final Stack-Up/Trim

Prior to the final welding sequence, the three main cavity components are stacked-up, using tooling to compress unwelded joints, and frequency measured, shown in Figure 6. Q values are monitored with a network analyzer to ensure a good fit-up of parts (tight joints). After establishing a baseline frequency, the Short Plate is trimmed to adjust and predict the final frequency of the cavity. By trimming the cavity's Short Plate for frequency adjustment, the accelerating gap between the cavity's Beam port and Nose/Aperture is maintained. Multiple trim steps are used to slowly walk toward the design frequency, while also establishing a ratio of material removed to frequency shift (~400 kHz/mm). Final weld shrinkage must also be accounted for in predicting the as-welded frequency. The final EB weld is a conduction mode, full penetration weld between the Outer Conductor and Short Plate, shown in Figure 7.

Figure 6: Stack-up/frequency measurement tooling.

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Figure 7: Final conduction mode (full-penetration) weld.

EB Welded Repair

Upon inspection of the cavity's final weld, a small area at the weld overlap was observed with a lack of penetration, shown in Figure 8 (left). Lack of penetration means there was no visible under-bead on the weld joint (internal cavity surface). This is the result of power reduction in the overlap region during EB welding. When completing components with radial welds, power must be adjusted to avoid a build-up of heat in the overlap region; resulting in a potential weld blow-out. A small repair to the underpenetrated area was successfully completed, shown in Figure 8 (right).

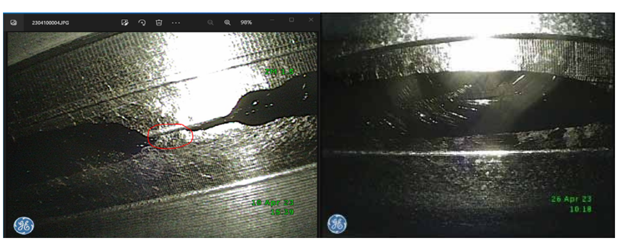

Figure 8: (Left) weld area with non-pentrated weld (break in underbead), (right) weld underbead after repair.

Virtual Welding/Frequency Tuning

Before the cavity was jacketed with an external helium vessel, a "virtual" weld was applied to the niobium cavity; along the circumference of the Outer Conductor. A virtual weld is a non-structural weld that is used to shift the cavity's frequency by causing some controlled shrinkage to the material/cavity volume. During FRIB production, virtual welding was used as a tool to control the final frequency of several cavities [10]. The virtual weld applied shifted the cavity frequency ~ 70 kHz (~0.08 inch dimensional shrinkage). By scaling the shrinkage with power, frequency adjustment has been shown useful in tuning cavities from 20-200 kHz.

HELIUM VESSEL ASSEMBLY

After completion of the niobium resonator structure, the cavity is jacketed with a Grade 2 Titanium Helium Vessel. Titanium is chosen because of its closely matched thermal contraction properties to niobium. The cavity's Helium Supply and Helium Return are commercial stainless steel vacuum flanges (Conflate) that are joined to the titanium helium vessel using an explosion bonded bi-metal (stainless steel to titanium) transition. Welding was completed using conventional TIG welding with the use of a MegaFlo torch nozzle to ensure argon gas coverage on the top side weld area, shown in Figure 9. An argon purge was maintained inside the cavity helium space to <20 ppm of Oxygen during all welding. Titanium welding rod (Royal ER Ti-2) was used for all welds. Niobium to titanium transitions were completed using an intermediate niobium-titanium alloy, as discussed in the Cavity Material section. All helium vessel joints are designed as full penetration welds. Weld Maps are completed for all welding tasks, including welding rod certifications. All welds are completed by certified welders in titanium with full inspection from a Certified Weld Inspector (CWI).

In addition to the cavity's helium supply and helium return, several interface points are designed to the outside of the cavity's helium vessel. These interface points serve as connections to cavity process tooling, cavity tuner system, and cavity-to-cryomodule rail interface, as shown in Figure 10. Interface features are positioned using tooling to ensure dimensional tolerance.

Figure 9: Tungsten Inert Gas (TIG) welding of cavity helium vessel.

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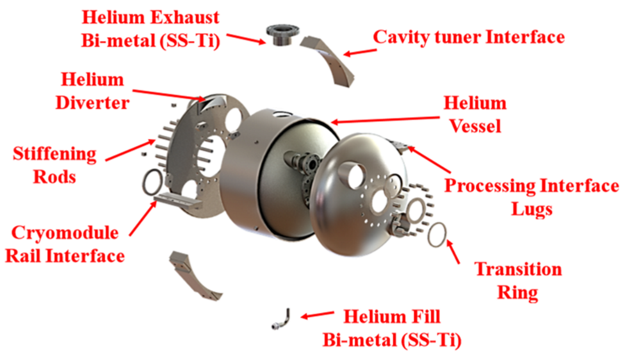

Figure 10: Helium Vessel with key components.

CRYOMODULE INTEGRATION

The jacketed cavity will be cold tested in three stages; first in a vertical test Dewar. The second stage will be a horizontal configuration with the cavity axillary systems included; power coupler and cavity tuner. The third test stage will follow the assembly of the cavity into an operational cryomodule, shown in Figure 11. After certification testing is complete, the cryomodule is designed to integrate into the SLAC accelerator facility [11].


Figure 11: Cryomodule Integration.

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