DEVELOPMENT OF A PROTOTYPE 197 MHz CRAB CAVITY FOR THE ELECTRON-ION COLLIDER AT JLab

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Abstract

Thomas Jefferson National Accelerator Facility (JLab) is currently developing a prototype 197 MHz Radio-Frequency Dipole (RFD) crab cavity as part of the Electron-Ion Collider (EIC) to be built at Brookhaven National Laboratory (BNL). Cryomodules containing these cavities will be part of the Hadron Storage Ring (HSR) of the EIC. The prototype cavity is constructed primarily of formed niobium sheets of thickness 4.17 mm, with machined niobium parts used as interfaces where tight tolerancing is required. The cavity's large size and complex features present several challenges in fabrication, tuning, and RF testing. Structural and forming analyses have been carried out to optimize the design and fabrication processes. An overview of the design phase and the current state of fabrication are presented in this paper.

INTRODUCTION

The EIC will be built at BNL and will be the newest accelerator under the US Department of Energy's Nuclear Physics program. The construction will be split between several US national labs, with the bulk of the scope under JLab and BNL; JLab's scope includes the design and fabrication of the superconducting Radio-Frequency (RF) systems for the collider.

Collisions between ions and electrons will occur in the Interaction Regions (IR) between the Hadron Storage Ring (HSR) and the Electron Storage Ring (ESR). The luminosity requirements (10^{34} cm^{-2}s^{-1}) require that crabbing systems be used in the interaction region [1]. The RF-dipole design was chosen for the crab cavities in these regions. The HSR will have cryomodules containing 197 MHz crab cavities and second-harmonic 394 MHz cavities to linearize the kicks [2]. The shorter bunch lengths in the ESR mean that only 394 MHz cavities will be sufficient.

Eight 197 MHz cavities will be installed in four cryomodules in the HSR. Table 1 shows the deflecting voltage requirements for the HSR and ESR. As the 197 MHz crab cavity system is considered one of the critical components in the RF systems scope, a prototype will be fabricated at JLab.

Table 1: Crabbing Systems of EIC [1]

	V_t [MV]		No. of cavities	
System	**HSR**	**ESR**	**HSR**	**ESR**
197 MHz	33.83	–	8	–
394 MHz	4.75	2.90	4	2

RF DESIGN

The RF performance requirements for the cavity are listed below [3]:

- Nominal transverse voltage per cavity = 8.5 MV
- Maximum transverse voltage per cavity = 11.5 MV
- Peak fields at 11.5 MV: Ep < 45 MV/m and Bp < 80 mT

Figure 1 shows the distribution of the surface electric and magnetic fields. Figure 2 shows the baseline crab cavity design, showing coaxial Higher-Order Mode (HOM) dampers.

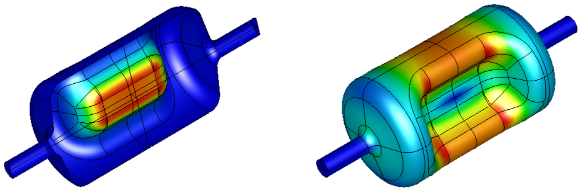

Figure 1: 197 MHz RFD cavity surface electric fields (left) and surface magnetic fields (right) [1]. The color scale from blue to red represents low to high amplitude, respectively.

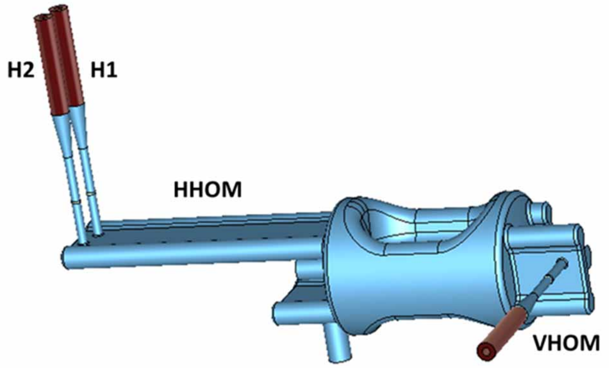

Figure 2: Coaxial HOM dampers and waveguides on the baseline 197 MHz cavity design [2].

In addition to the RF requirements, the already-built accelerator tunnel and other existing systems impart physical constraints on the cavities and cryomodules [3]:

- Beampipe aperture: 100 mm
- Cavity length (flange-to-flange): <1.5 m
- Cryomodule Length: <12.5 m

The waveguides for the horizontal and vertical HOM dampers have a novel 'dogbone' shape. The waveguides on

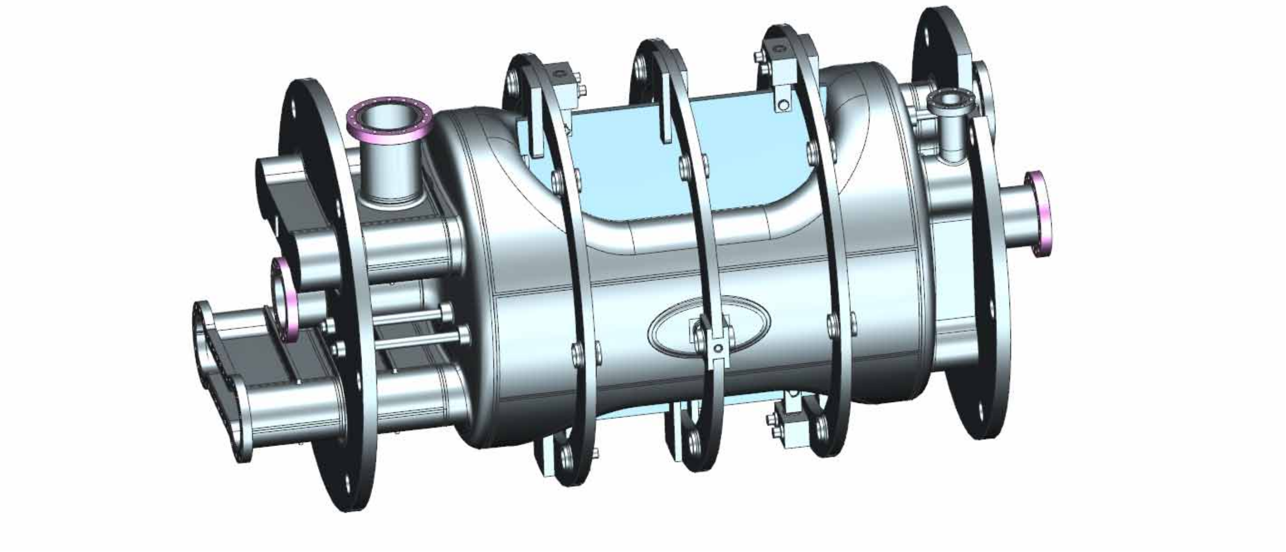

Figure 3: The 197 MHz crab cavity shown without the longitudinal stiffening tubes.

the two end groups are oriented perpendicular to one another. The horizontally oriented waveguide propagates the fundamental mode (hence one has the FPC port), while the waveguides in the vertical orientation do not; the pick-up port is located on one of these vertical waveguides [2].

The dogbone waveguide stubs on the cavity are designed to provide a low cut-off frequency; the first HOM of this cavity is 350 MHz, while the dogbone waveguide's cut-off frequency is 348 MHz [1]. The HOM dampers themselves are not within the scope of the cavity's prototyping effort.

The most critical dimension of the cavity is the gap between the two poles (100 mm).

PROTOTYPE CAVITY

The prototyping process for the crab cavity is designed to test both the fabrication processes required and the RF design of the cavity (Fig. 3). A copper cavity will be fabricated before the niobium version to conduct warm RF measurements. The end goal for the prototype cavity is to be tested at 2 K in the JLab Vertical Test Area (VTA). The external dimensions of the cavity are thus restricted to the largest available dewar at JLab, which has a usable diameter of 33 inches. Due to the long lead times for niobium sheets, the formed sections of the crab cavity will be made from the 4.17 mm thick sheets which are available; this thickness is designed to reach a nominal 4.00 mm after electropolishing (EP) and/or buffered chemical polishing (BCP).

The majority of the cavity will be constructed from high-RRR niobium, apart from the dogbone waveguide flanges that will be reactor grade niobium.

FABRICATION STRATEGY

The 197 MHz crab cavity is one of the largest to ever be put into production. The internal RF space has a diameter of 598 mm and a length of 950 mm. The presence of the stiffening components and waveguides increases the diameter to 762 mm with a length of 1475 mm.

The large sections of formed niobium parts are difficult to manufacture within the tight tolerances generally required of a cavity. Where possible, interfaces have been machined from solid, bulk niobium instead of forming weld preps.

In addition to the challenges of physically manufacturing and handling the components, the cavity is also weak in pressure resistance. The 4 mm thick walls cannot withstand vacuum loads, so a stiffening exoskeleton is required.

Stress Analysis

The design pressure was established from the VTA dewar with the lowest relief pressure. Dewar-5 contains the lowest set point relief valve, set at 22 psid. The interior of the cavity is evacuated for VTA testing, which drives the 22 psi external design pressure condition [4].

Some of the cavity features are inherently weak in resisting external design pressure. Each pole, which extends deep into the cavity volume, is a flat region of 174 in^2 resulting in a thrust force of ~ 2,500 lb (Fig. 4). The end dishes are only slightly convex, and have Horizontal HOM/Vertical HOM penetrations and each has an area of ~ 430 in^2 resulting in a thrust force of ~ 6,300 lb [4].

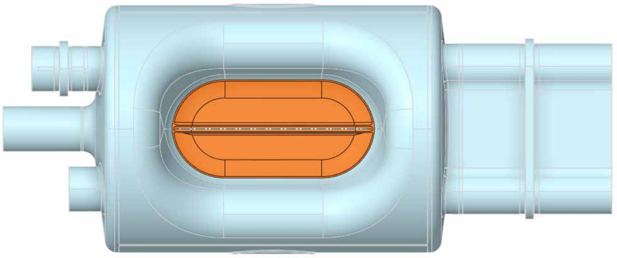

Figure 4: Pole region of the crab cavity.

The bare cavity weldment is unable to be evacuated as the 1 atm differential would over-stress the cavity. Several different stiffener configurations were considered and analyzed to strengthen the cavity. The current design was favored as it reduced complexity and the number of welds on the cavity's outer surface.

A finite element analysis was performed in ANSYS Mechanical to simulate the 22 psi external design pressure on the cavity while suspended in the VTA dewar. Room temperature material properties were used. The tops of the cage support rods were fixed and a gravity boundary condition was added.

The allowable stress for high-purity Nb is 6.3 ksi (9.3 x 2/3 ksi). Stress Classification Lines (SCL) were implemented at the highest stress region per the requirements of ASME BPVC VIII-2 to ensure the 6.3 ksi membrane and 9.5 ksi membrane + bending allowable stresses are not exceeded [4].

Stiffening Structure

The niobium walls of the bare 197 MHz cavity cannot withstand a 1 atm pressure difference without additional stiffening components. The system designed to allow the prototype cavity to be tested in the VTA is shown in Fig. 5.

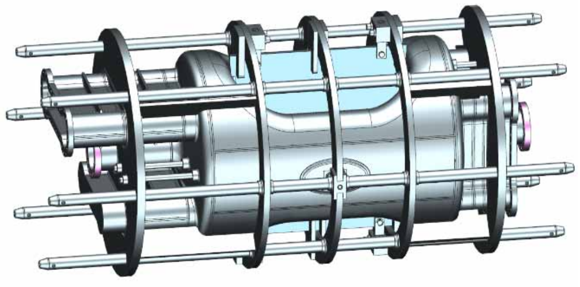

Figure 5: Stiffening scheme for the 197 MHz crab cavity.

The vacuum forces pull the end groups toward the center of the cavity and attempt to collapse the central poles. Each of the end groups has a Nb55Ti end plate welded to the waveguides (Fig. 6). This dish simulates the additional strength that would be added by the presence of the helium vessel in a production cavity. The dishes also serve as stiff features to align the waveguides and beampipes on the end groups.

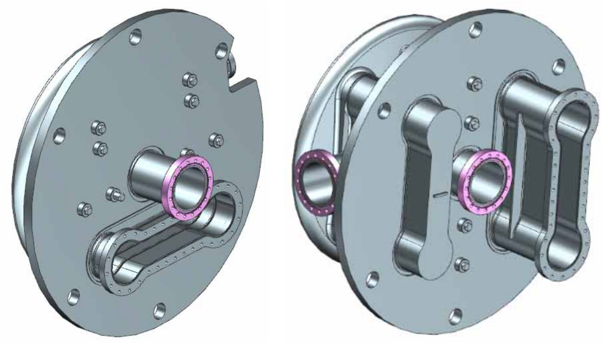

Figure 6: NbTi end plate on the two end groups.

The central section of the cavity has three Grade-2 titanium rings that attach to stiffening ribs in the pole region (Fig. 7). Titanium is used on the stiffening components where possible due to similar thermal expansion coefficients with niobium. Figure 8 shows the different materials that make up the pole stiffening components. In addition to keeping the pole region from collapsing, the rings also have features that can be used as weld fixtures and tuning mechanisms. Gussets connect the end dishes and outer titanium rings to provide longitudinal support.

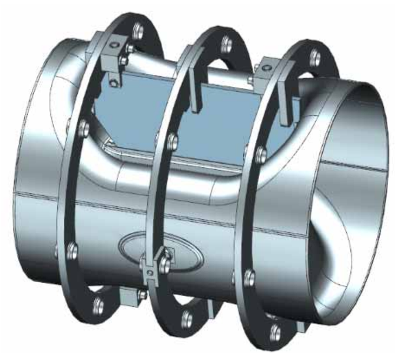

Figure 7: Central body assembly showing titanium stiffening rings.

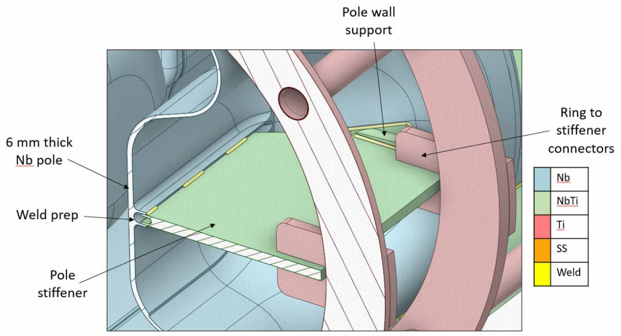

Figure 8: Materials and components of the pole stiffeners.

Six titanium tubes run along the length of the cavity, and are welded to the end dishes and central rings. These are designed to withstand the vacuum forces pulling the end groups toward the center of the cavity.

Development of Forming Processes

Forming dies for the crab cavity were designed with preliminary analysis carried out using LS-DYNA. Though the dies and components varied greatly in terms of complexity, they followed the same general development process.

Conceptual Design A preliminary model is first created to test the basics of the design. This step could be simple or complex depending on the component being built. These preliminary simulations are used to predict material flow and damage (e.g. wrinkling and cracking). Some of the crab cavity's more complex components have taken multiple iterations to develop a rough model.

Parameter Studies The models were analyzed to fine-tune the forming process. Parameters including the blank shape, thickness, and material type were adjusted and verified. A failure analysis was also performed at this stage. Certain shapes are more prone to excessive thinning that could lead to cracks or unusable parts. Other shapes could wrinkle or buckle. LS-DYNA outputs a thickness profile for the entire part that can be compared to stress analysis requirements.

Cracking in the formed material is a more complex behavior that is harder to predict. Forming Limit Diagrams (FLDs) were used to study cracking in blanks. FLDs are normally developed for a material through a series of mechanical tests. For these studies, the high-purity Niobium FLD developed by Croteau et al. [5] was used in the LS-DYNA models to determine regions in the blanks that were susceptible to cracking.

Springback was another area of concern for the forming process. LS-DYNA provided graphical results showing the expected deformation of the metal immediately after being released from the stamping. This allowed for the construction of springback-compensated dies, where the shape is not built to nominal dimensions, but rather shifted by the predicted springback amount. This allows the part to 'spring back' into the desired nominal position after the die is removed.

Optimization The final steps interface the LS-DYNA models with the mechanically designed die and blank components. Factors such as additional trimming material on the blanks and the sequence of forming steps are finalized at this stage. More complex parts, like the top 'saddle' section where the pole curves into the outer wall of the crab cavity, required the use of multiple stamping steps. Features were introduced to some dies to keep options available in case one of the forming steps did not function as planned.

Assembly Strategy

The crab cavity's complex geometry makes it difficult to meet the required tolerances during the EBW and forming processes. In particular, the assemblies involving the pole assembly and dogbone waveguides present difficulties in meeting the tight profiles required for the EBW. Where possible, the interfaces between the formed parts and other components (e.g. waveguide to NbTi end dish) will be machined from niobium billet [6].

As shown in Fig. 9, the waveguide (the HHOM waveguide is used as an example) has a machined central section that is tightly tolerance to fit in the hole in the end dish. The waveguide sub-assembly uses the flats on these central sections as datums to machine the dogbone flange parallel and as a reference to machine to complex interface to the end dish. The NbTi plate then acts as a built-in welding fixture to correctly position and align the waveguide and beampipe in relation to the end dish (Fig. 10).

The most critical part of the crab cavity is the pole and its adjoining regions. The pole itself is machined from solid niobium to reduce deviations in profile that may occur in the forming process. The two pole sub-assemblies will be fixtured with the nominal pole gap. The body strip components on the side of the cavity will be trimmed (if required) to target the correct outer diameter and roundness (Fig. 11). Once welded, the titanium stiffening rings will be installed to hold the pole positions. A metrology step will be performed to determine whether tuning adjustments are required (see next section) [6].

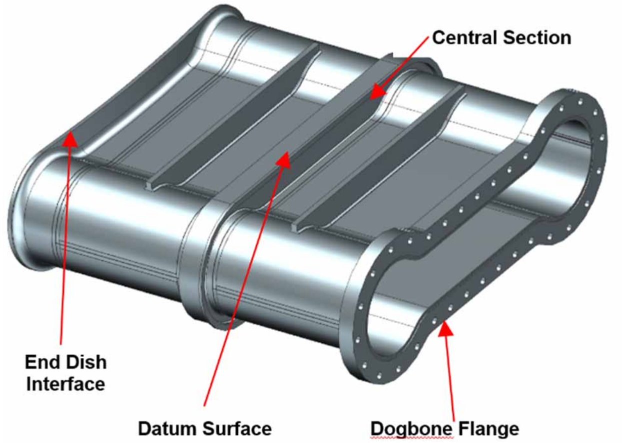

Figure 9: Interfaces on HHOM waveguide.

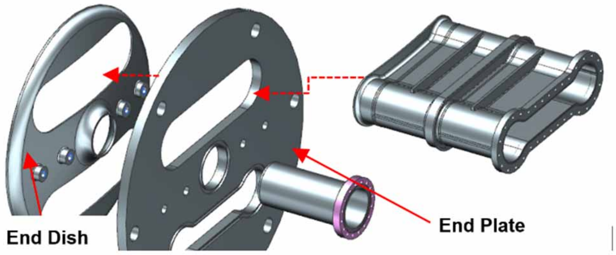

Figure 10: Waveguide assembly scheme.

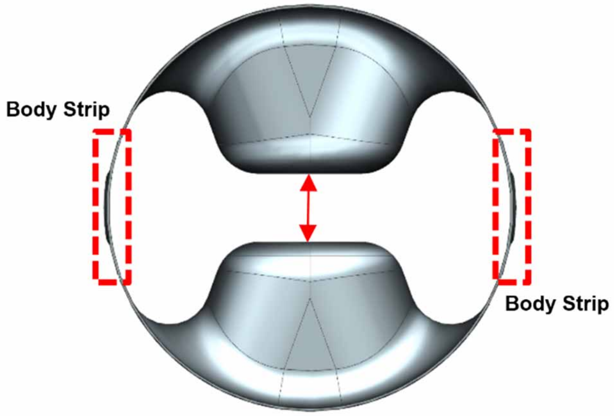

Figure 11: Central body of the cavity with pole gap shown by the red arrow.

Tuning

The majority of the cavity's outer shell is made from formed niobium, with large welds joining the pole assemblies. The nature of the forming and welding processes makes it difficult to maintain the nominal dimensions found in the RF model. In particular, the final diameter of the cavity is difficult to predict due to the locations of the EBWs. Simulations were carried out to determine whether adjusting the pole gap or cavity length could be used to account for manufacturing errors and bring the cavity back to within the target frequency and impedance budget (10 kΩ longitudinal, 0.132 MΩ/m horizontal, and 0.66 MΩ/m vertical).

A first set of calculations showed that an increase in cavity radius of 0.5 mm could be offset by an increase in pole gap of 0.71 mm to keep the fundamental frequency unchanged. The cavity radius decreasing by 1.3 mm would need the pole gap to decrease by 1.85 mm to maintain the fundamental frequency; both these cases adhere to the impedance limits [7].

A second study looked at the prospect of compensating for deviation in radius by trimming the length of the cavity. It was found that a deviation in the radius of just +/- 0.06 mm would require a change in cavity length of +/- 1.27 mm respectively. Trimming beyond 1.27 mm would raise the HOM impedance beyond specification, so compensating for any larger deviations in radius is not possible [7].

The cavity will undergo a tuning step in an intermediate fabrication step to make up for any deviations in the outer shell radius; the tuning step will be carried out in the configuration shown in Fig. 5. Two pole adjustment mechanisms will be installed on the titanium rings to push or pull the pole assembly (Fig. 12). This action will change the pole gap to the desired value. The process is iterative as changing the pole gap will also affect the outer radius of the cavity. A tuning stroke of -0.5 mm and +2.0 mm is predicted. The length of this assembly will also be oversized to ensure enough length remains for final trim tuning to achieve the target operating frequency before the final welding of end groups to the center body. This tuning step will be carried out with respect to metrology conducted on this assembly [6].

The pole gap will remain tunable until the end groups are welded to the central body. Warm RF measurements at this point will be used to determine whether any additional adjustment is required. In the final configuration, the rib supports (Fig. 12) will be welded to lock the poles into place [6].

Chemistry and Processing

The 197 MHz crab cavity has a vacuum volume of ~48 gal., and an estimated weight of over 1000 lbs when filled at 60 % with acid. This makes the handling and processing of this cavity particularly difficult. These constraints render some of JLab's facilities, in their current state, unsuitable for the processing of this cavity. Updates have been proposed and are under revision to accommodate this and other types of cavities needed for the EIC.

For the prototype, a scope of work has been put in place with Argonne National Lab (ANL) where minor updates to their facilities will enable them to process the cavity. JLab will provide ANL with a fully welded cavity, and a total of ~150 µm will be removed from the inner niobium surface using ANL's rotational BCP stand. Intermediate wall thickness measurements will indicate uniform removal.

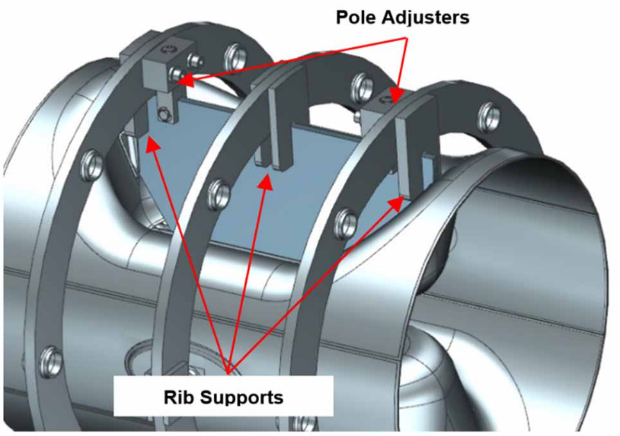

Figure 12: Pole adjustment mechanism.

The 600 ºC heat treatment, high-pressure rinsing, as well as cleanroom assembly will be performed by ANL, delivering a ready-to-test cavity to JLab.

CURRENT STATUS

A number of the forming dies have been fabricated and received at JLab. Testing is currently underway using 6061-0 aluminum blanks (Fig. 13), which will be followed by softened OFE copper blanks. Though the aluminum will behave differently than niobium, the testing will allow any major flaws in the forming dies to be identified.

Figure 13: A forming die after stamping an aluminum test part.

CONCLUSION

The 197 MHz crab cavity is one of the most critical components in the EIC. A prototype cavity is currently being fabricated at JLab, to be tested at 2 K in the VTA. The size and complex geometry of the cavity provide challenges in manufacturing, welding, tuning, assembly, and processing. A fabrication plan has been put in place and tooling procurement has started.

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