# DESIGN OF A BETA = 0.29 HALF-WAVE RESONATOR FOR THE FRIB DRIVER LINAC*

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*Abstract*

The driver linac for the Facility for Rare Isotope Beams (FRIB) will produce primary beams of ions at 200 MeV per nucleon for nuclear physics research. The driver linac will require 344 superconducting cavities, consisting of two types of Quarter-Wave Resonators (QWRs, $\beta$ = 0.041 and 0.085) and two types of Half-Wave Resonators (HWRs, $\beta$ = 0.29 and 0.53). A first-generation $\beta$ = 0.29 HWR has been designed, prototyped, and tested. Second-generation versions of the other cavities are being developed, with multiple resonators of each type having been tested. A second-generation $\beta$ = 0.29 HWR design has been developed, making use of the experience with the first-generation $\beta$ = 0.29 HWR and second-generation $\beta$ = 0.53 HWR. In the second-generation design, the inner conductor is tapered to reduce the peak surface magnetic field. The outer conductor is a straight tube to increase the mechanical stiffness and reduce the sensitivity of the resonant frequency to bath pressure fluctuations. Optimization was employed to minimize the peak surface electric field. The second-generation $\beta$ = 0.29 HWR design will be presented, including the RF design and mechanical analysis.

## INTRODUCTION

The FRIB driver linac will deliver stable beams to a production target at 200 MeV/u or greater energy. For heavier ions, as many as five charge states will be accelerated to the target to deliver beam power of up to 400 kW [1]. To efficiently provide the flexibility required, a CW superconducting linac [2, 3] was chosen. Half-Wave Resonators (HWRs) were chosen for the high energy section because they are the most effective geometry at the frequency and velocities (322 MHz, $\beta$ = 0.29 and 0.53) required. Although several groups have designed and prototyped HWRs or spoke cavities, the only HWR operational experience so far is at the SARAF linac, which uses $\beta$ = 0.09 HWRs [4].

### *Design Overview*

The 322 MHz $\beta$ = 0.29 half wave resonator (HWR) has a 30 mm aperture in the drift tube, and a 32 mm beam port inner diameter. Beam dynamics suggest that an increased aperture may be required in this section of the linac, so a design with a 40 mm aperture (42 mm beam port inner diameter) has been studied. It will operate at 2 K with a goal of 2.9 watts helium load (dynamic). Frequency control will be provided by means of a mechanical tuner attached to the helium vessel. This tuner will perturb the cavity near the beam ports by means of a stepper motor and piezoelectric actuator in series. Both the stepper motor and piezo actuator will be outside the cryomodule. Ports perpendicular to the beam axis on the mid-plane will be used for RF coupling (see Fig. 1). Four ports have been added to the top shorting plate to facilitate etching and provide better access during the high-pressure rinsing step which precedes clean room assembly.

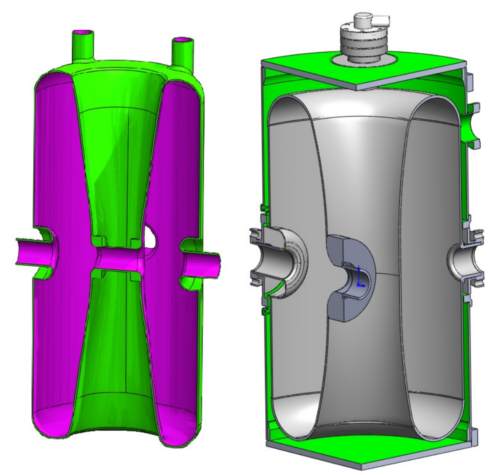

Figure 1: Left: sectional view of half the cavity before helium vessel installation. Right: sectional view of one quarter of the cavity with helium vessel, with beam port on the left and RF port on the right.

## ELECTROMAGNETIC DESIGN

RF parameters of this cavity were simulated and optimized using the 3D field solver ANSYS-APDL [6]. Additional simulations were done using ANALYST [7] to verify EM performance.

### *Figures of Merit*

The cavity figures of merit are shown in Table 1. During development of the half wave geometry, special attention was paid to minimizing surface fields, especially the peak surface electric field. Also taken into consideration was the need for the design to be compatible with established

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techniques for cavity fabrication and surface preparation, to maximize the probability of reliable performance.

Table 1: Electromagnetic Figures of Merit.

| Parameter | Value |
|---|---|
| $\beta_{opt}$ | 0.29 |
| Accelerating Voltage | 1.9 MV |
| Peak Surface Electric Field | 31.5 MV/m |
| Peak Surface Magnetic Field | 75 mT |
| Stored Energy | 8.9 J |
| Geometry Factor | 61.5 Ω |
| $R_{eff}/Q$ | 204.3 Ω |

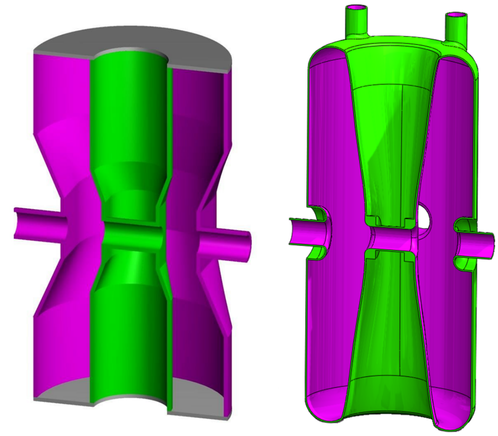

Figure 2: Section view of First (left) and Second (right) generation HWRs.

### *Further Work*

During development, the reduction of the peak magnetic field was limited by the use of a straight cylinder for the outer conductor. Further reduction in peak surface magnetic fields could be achieved with a tapering of the outer conductor or an increase in diameter of the outer conductor. Testing of the need for rinse ports is ongoing with the 0.53 HWR prototypes. If the cavity would be rinsed reliably without use of the rinse ports, they could be removed, simplifying fabrication of both the 0.29 and 0.53 HWRs. In addition, further work is required to study the effects of increasing the aperture from 30 mm to 40 mm. Initial simulations indicate a worsening of cavity performance (e.g. increase in peak surface fields, decrease in $R_{eff}/Q$, etc.) of between 2% and 5%.

## MECHANICAL DESIGN

Variations in the bath pressure produced large frequency shifts for the first generation $\beta = 0.29$ HWR [5]. This would present a challenge for amplitude and phase control, which was a major motivation for the cavity redesign. The second generation $\beta = 0.29$ HWR has a straight, cylindrical outer conductor and a tapered inner conductor (both 2 mm thick), replacing the squeezed tube designs from the first generation (see Fig. 2). In addition, rounded short plates (3 mm thick) have replaced the flat short plates of the first generation. These changes provide for a significant increase in stiffness over the first generation. The beam ports were also redesigned for both optimum $\beta$ and ease of mechanical tuning without sacrificing overall cavity stiffness.

### *Mechanical Stiffness*

Mechanical simulations were done in ANSYS-APDL [6] to quantify the displacements and resulting frequency detuning of the cavity due to fluctuations in the liquid helium bath pressure. The simulation procedure used was similar to the one used by E. Zaplatin for similar simulations for the FRIB quarter-wave resonators [8]. Fig. 3 shows a contour plot of the deformation expected in the cavity due to a pressure differential. Using this modeling technique, the shift in the resonant frequency ($f$) due to a change in ambient pressure ($P$) was estimated. The majority of the displacement occurs on the inner conductor on either side of the drift tube. There are both magnetic and electric fields in this region, and they have opposite contributions to the frequency shift. This leads to a predicted value of $|df/dP| \leq 2$ Hz/mbar (compared to 200 Hz/mbar for the first generation $\beta = 0.29$ HWR). This is achieved without any additional manufacturing steps to add stiffening. Additional simulations have determined that this coefficient is insensitive to manufacturing errors. Lorentz force detuning was also simulated and found to be small enough to be unimportant for cavity operation.

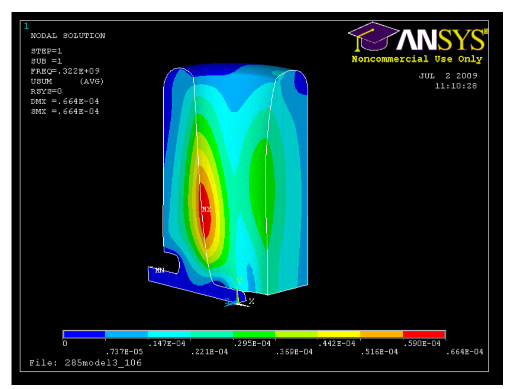


Figure 3: Displacement contours from a mechanical model with one bar of applied pressure in ANSYS.

### *Cavity Tuning*

The change in design to straight cylindrical outer conductor and tapered inner conductor has resulted in a cavity geometry that is very stiff. The use of beam port cups provides a location that is less mechanically rigid with high enough fields to give a good tuning range without the need for excessive force. A tuning mechanism has been designed and prototyped for the $\beta = 0.53$ HWR. The design provides fine and coarse tuning through a single mechanical linkage, with the actuator outside the cryomodule. This tuning mechanism is designed to provide a 20 to 1 mechanical advantage (the force applied to the beam ports is 20 times the actuator force). We plan to modify this design for the $\beta = 0.29$ HWR after testing it with the $\beta = 0.29$ HWR.

### *Cavity Fabrication*

The cavity fabrication procedure is similar to the $\beta$ = 0.53 HWR. Aluminum dies will be used to form the two beam port cups, the two short plates, and the inner conductor in two pieces. The outer conductor will be rolled. The drift tube and rinse ports will be machined out of a solid niobium billet. All subassemblies will be electron beam welded together, with the final step being the beam port cups, which will be positioned to achieve final frequency. Fig. 4 shows the fabrication of a $\beta = 0.53$ HWR cavity.

Figure 4: $\beta = 0.53$ HWR subassemblies (left) and a completed bare cavity (right)

Prototyping of the $\beta = 0.53$ HWR has shown that the final weld of the tapered inner conductor to the short plate can pose significant challenges. It was difficult to fabricate the parts to the tolerances needed to produce a smooth inner surface at the weld joint. Adding a small straight section at either end of the inner conductor (see Fig. 5) would allow a stacking and trimming step before welding. This would significantly ease subassembly tolerances as well as allowing an additional frequency adjustment step. Electromagnetic simulations show that this modification does not significantly impact cavity performance.

## CONCLUSIONS

A mature design for a second generation 322 MHz, $\beta$ = 0.29 HWR is complete. Major flaws encountered in prototyping of the first generation $\beta = 0.29$ HWR have been corrected. Electromagnetic and mechanical simulations have been done to validate these improvements, and indicate good performance similar to the $\beta = 0.53$ HWR. Difficulties encountered in the prototyping of the $\beta = 0.53$ HWR have motivated design modifications which have been validated with simulation. Prototyping and testing of five $\beta$ = 0.53 HWRs (1 fabricated at MSU and 4 fabricated with

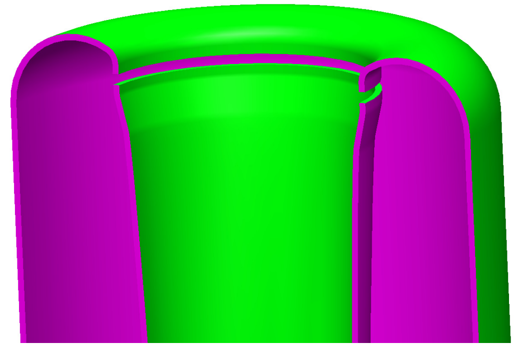

Figure 5: CAD drawing of straight section on HWR inner conductor in section view. The weld joint between inner conductor and shorting plate at the straight section has been expanded for emphasis.

industrial partners) is ongoing. The goal is to validate the major design features of the cavity, helium vessel, tuning mechanism, and RF input coupler, which are similar or identical for the two HWRs. A prototype $\beta = 0.29$ HWR is expected by the end of 2012.

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