COUPLED ELECTROMAGNETIC AND MECHANICAL SIMULATIONS FOR HALF-WAVE RESONATOR DESIGN*

J. P. Holzbauer†, J. Binkowski, M. J. Johnson, S. J. Miller, J. Popielarski, Y. Xu
Facility for Rare Isotope Beams (FRIB), Michigan State University, East Lansing, MI 48824 USA

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, β = 0.041 and 0.085) and two types of Half-Wave Resonators (HWRs, β = 0.29 and 0.53). A first-generation β = 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. Second-generation β = 0.29 and 0.53 HWR designs are nearing completion, making use of the experience with the first-generation HWRs. In the second-generation design, the inner conductor is tapered to reduce the peak surface magnetic field. The outer conductor is a straight cylinder to increase the mechanical stiffness. Mechanical simulations of the β = 0.53 HWR at 322 MHz have been performed, this work will be repeated for the β = 0.29 HWR design by the end of the year. Part of this work has been the optimization of the mechanical properties to minimize Lorentz Force Detuning and Helium bath pressure sensitivity while providing adequate tuning range. The simulation techniques used for this work and the resulting proposed cavity stiffening will be presented.

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 among the most effective geometry at the frequency and velocities (322 MHz, β = 0.29 and 0.53) required. Although several groups have designed and prototyped HWRs or spoke cavities [4], the only HWR operational experience so far is at the SARAF linac, which uses β = 0.09 HWRs [5]. A significant problem discovered in the SARAF HWR design was mechanical instability and pressure sensitivity. This instability made the low-level RF control of these cavities far more complex than expected. Learning from their experience and avoiding similar problems is a significant focus of our mechanical simulation work.

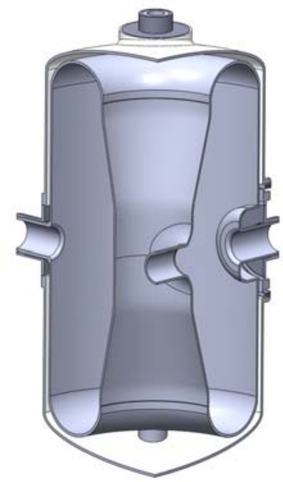

Figure 1: A sectional view of the cavities with helium vessel. Note the beam port on the right, RF port on the left, and rinse port at the top.

Design Overview

The 322 MHz β = 0.29 and 0.53 half wave resonators (HWRs) have a 40 [mm] aperture in the drift tube, and a 42 [mm] beam port inner diameter. All FRIB cavities will operate at 2 K with the HWRs having dynamic heat load goals of 2.9 and 6.3 [Watts], respectively. Frequency control will be provided by means of a mechanical tuner attached to the helium vessel. This tuner will move 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 Figure 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.

Cavity Features

The cavity figures of merit are shown in Table 1. During development of these half wave geometries, special attention was paid to the need for the design to be compatible with established techniques for cavity fabrication and surface preparation, maximizing the probability of reliable performance. The most notable examples of this were the

* This material is based upon work supported by MSU and by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661
† holzbaue@nscl.msu.edu

simplification of the inner conductor. The inner conductor was modified from a curved to a straight taper and a small straight section was added near the short plate. These ease fabrication and allow an additional trimming step before electron-beam welding. Further details on this work can be read here [6,7].

Table 1: Electromagnetic figures of merit of the Current Generation HWRs

Parameter	**0.29**	**0.53**	Units
Accelerating Voltage	1.90	3.70	MV
Accelerating Electric Field	7.0	7.4	MV/m
Peak Surface Electric Field	30.6	29.7	MV/m
Peak Surface Magnetic Field	54.4	77.4	mT
Stored Energy	8.0	31.6	J
Geometry Factor	77.9	96.3	Ω
R_{eff}/Q	224.4	214.3	Ω

MECHANICAL SIMULATION

After the electromagnetic design had been completed, the cavities and helium vessels were mechanically designed. It was desired to verify the mechanical performance of these designs for a range of important operational situations. These simulations include verifying the tuning range of the cavity, achieving an acceptably low pressure sensitivity, and verifying that Lorentz Force Detuning will not be a problem in operation. These parameters were simulated and optimized using the 3D Multiphysics solver ANSYS-APDL [8].

Simulation Procedure

Mechanical simulations of cavity parameters begin with models of the high-purity Niobium cavity, the 304 Stainless Steel helium vessel, and the Niobium-Titanium transition pieces. For simplicity, all bolt holes and flanges that will not affect the results are removed. An example of the geometry, assembled and ready for simulation can be seen in Figure 1. From this geometry, the cavity vacuum is created and all components meshed using tetrahedral elements. First the cavity vacuum is used to solve for the cavity figures of merit including frequency. Then, pressure is applied to the cavity components, and the resulting deformation is simulated. The nature of the applied pressure is dependant on the process being simulated, which will be discussed in more detail below. It is important to note that the mesh in the cavity vacuum is retained during the simulation of the mechanical deformation. These elements are assigned extremely weak mechanical properties as to not affect the mechanical displacement. Finally, the cavity figures of merit are recalculated using the perturbed mesh. The calculated shift in frequency is highly accurate due preserving the mesh through the mechanical deformation simulation. This simulation procedure is similar to the one used by E. Zaplatin for simulations of the FRIB quarter-wave resonators [9].

Mechanical Pressure Sensitivity Simulations

Mechanical simulations were done to quantify the displacements and resulting frequency detuning of the cavities due to a pressure differential across the cavity wall. This was modeled with a constant pressure on the outside of the cavity wall and inside of the helium vessel. Using this modeling technique, the shift in the resonant frequency (f) due to a change in ambient pressure (P) was estimated. This shift is dominantly linear, and is thus quantified by the coefficient df/dP. In operation, the cavity will be pumped down to high vacuum (<1E-8 [torr]) while bathed in liquid Helium at ˜23 [torr] for operation at 2 K. The FRIB cryoplant has been specified to have a fast pressure variation of $<$ 1 [torr] peak-to-peak. This variation in pressure can have significant cavity controls implication if the pressure sensitivity of the cavity is too high. From control bandwidth specifications and prior experience, the required specification for cavity pressure sensitivity is $|df/dP| \leq 2$ [Hz/torr]. The second generation β = 0.53 HWR an outer conductor and inner conductor made from 3 [mm] Niobium sheet with a rounded short plate formed from 4 [mm] Niobium sheet. The beam ports were designed for optimum β and ease of mechanical tuning without sacrificing overall cavity stiffness. The unstiffened β = 0.53 HWR design was simulated, and its df/dP was found to be 8.11 [Hz/Torr], requiring additional stiffening. Varying the thickness of the inner and outer conductors was the first solution studied. It was found that using thicker material increased df/dP by shifting the deformation and decreasing the benefits of compensation, and thinner material would not provide enough mechanical robustness. This meant that more specialized and targeted stiffening would need to be designed. After considerable study, two modifications were chosen and optimized. First, the cavity needed to be more symmetrically attached to the helium vessel. The current design has four rinse ports on one short plate that penetrate the ends of the helium vessel. This connection will be mirrored on the other short plate without penetrating the cavity or helium vessel. Additionally, a pair of stiffening rings were designed for the inner conductor. These would be welded into the inner conductor symmetrically at a specific distance from the beam plane, determined to be $\pm$180 [mm]. The exact design of the symmetric attachment on the short plate and the thickness of the stiffening rings gives a sufficient range to reduce $|df/dP|$ to $<$ 2[Hz/torr]. A typical example of this stiffening scheme can be see in Figure 2.

Lorentz Force Detuning

The interaction of the surface electromagnetic fields in a cavity with the induced surface currents and charges results in a Lorentz force on the cavity walls. This pressure results in a deformation of the cavity walls, changing the cavity

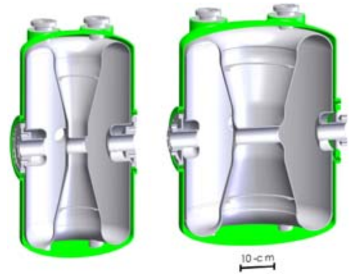

Figure 2: A sectional view of a quarter of the cavity with helium vessel. Note the placement of the symmetric stiffening and the planar disks for stiffening of the inner conductor.

volume by ΔV. This shifts the resonant frequency of the cavity, which can be approximated well as a perturbation using Slater's Theorem. The resulting frequency shift is

$$\frac{\Delta f}{f_0} = \frac{1}{4U}\int_{\Delta V}(\epsilon_0 E^2 - \mu_0 H^2)dV = -\frac{1}{U}\int_{\Delta V}(P)dV \quad (1)$$

where U is the stored energy in the cavity and f_0 is the resonant frequency of the cavity before perturbation. It is worthwhile to note that the quantity PdV is always positive. This results in a non-zero frequency shift that is always negative and varies linearly with the stored energy. Thus, this shift is often quantified by K_L which is defined as

$$K_L = \frac{\Delta f}{(\Delta E_{acc})^2}; E_{acc} = \frac{V_{acc,\beta_{opt}}}{\beta_{opt}\lambda} \quad (2)$$

From experience at other accelerators and the requirements of the Low-Level RF controls systems, the requirement for this process has been set at $K_L \leq -3[\frac{Hz}{(MV/m)^2}]$. To simulate this process, the pressure is calculated for every element face on a cavity surface, then applied to the mechanical model. The majority of the deformation from this force is in the most mechanically weak region of the cavity, the beam ports. The beam port will be connected directly to the cavity tuner, and this connection complicates this simulation. Simulations have been performed with the beam ports unrestricted ($K_L = -4.1[\frac{Hz}{(MV/m)^2}]$) and with the beam ports artificially fixed ($K_L = -2.1[\frac{Hz}{(MV/m)^2}]$). It is expected that this second condition will more accurately reflect the influence of the tuner, and further simulations are underway to validate this assumption.

Cavity Tuning Figures of Merit

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 β = 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 an 8 to 1 mechanical advantage. The force applied to the beam port is 8 times the actuator force. Simulations with the current cavity and helium vessel design show that for the full 150 [kHz] tuning range, a force of 2124 [N] is required on each beam port. This force results in a displacement of 1.24 [mm]. These figures will be verified in the HWR test cryomodule currently being assembled at MSU.

CONCLUSIONS

A mature design for a second generation 322 MHz, β = 0.53 HWR is complete. Major flaws encountered in prototyping of the first generation β = 0.29 and 0.53 HWRs have been corrected. Electromagnetic and mechanical simulations have been done to validate these improvements, and indicate good performance. Prototyping and testing of five first generation β = 0.53 HWRs (1 fabricated at MSU and 4 fabricated with industrial partners) are ongoing. Design of a β = 0.29 HWR is nearing completion; many features are similar or identical to the second generation β = 0.53 HWR. Prototype second generation β = 0.29 and 0.53 HWRs are expected by early 2012. It is expected these prototypes will demonstrate final, mature cavity designs to be used for the FRIB driver linac.

REFERENCES

[1] R.C. York, "FRIB: A New Accelerator Facility for the Production of and Experiments with Rare Isotope Beams", presented at the 2009 Particle Accelerator Conference, Vancouver, BC, Canada, May 2009, MO3GRI03

[2] W. Hartung, et. al., "Production Cavities and Cryomodules for a Heavy Ion Re-Accelerator at Michigan State University", in Proceedings SRF 2009: 14th International Conference on RF Superconductivity: Berlin, Germany, Helmholz-Zentrum Berlin, Berlin, Germany, 2009, p. 201-204

[3] J. Popielarski, et. al., "Development of a Superconducting Half Wave Resonator for Beta 0.53", presented at the 2009 Particle Accelerator Conference, Vancouver, BC, Canada, May 2009, WE5PFP039

[4] T. L. Grimm, et. al., "Experimental Study of a 322 MHz v/c = 0.28 Niobium Spoke Cavity", in Proceedings of the 2003 Particle Accelerator Conference, IEEE Publishing, Piscataway, New Jersey, 2003, p. 1353-1355

[5] L. Weissman, et. al., "The Status of the SARAF Linac Project", presented at LINAC10: XXV Linear Accelerator Conference, Tsukuba, Japan, September 2010, WE102

[6] S. Miller, et. al., "Design for Manufacture of Superconducting Half Wave Cavities", To be be preseneted at this conference. ID: MOPO052

[7] Y. Xu, et. al.,"Design of a 322 MHz Beta=0.29 Half Wave Resonator," To be presented at this conference. ID: MOPO0046

[8] ANSYS-APDL, ANSYS Inc., Canonsburg PA, www.ansys.com

[9] E. Zaplatin, et. al., "Structural Analyses of MSU Quarter-Wave Resonators", in Proceedings SRF 2009: 14th International Conference on RF Superconductivity: Berlin, Germany, Helmholz-Zentrum Berlin, Berlin, Germany, 2009, p. 560-563.