

## $\beta=0.285$ HALF-WAVE RESONATOR FOR FRIB\*

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### Abstract

We have developed an optimized electromagnetic and mechanical design of a 322 MHz half-wave resonator (HWR) suitable for acceleration of ions in the post-stripper section of the Facility for Rare Isotope Beams (FRIB). The cavity design is based on recent advances in SRF technology for TEM-class structures being developed at ANL. Highly optimized EM parameters were achieved using an "hourglass" cavity shape for the HWR. This new design will be processed with a new HWR horizontal electropolishing system after all mechanical work on the cavity including the welding of the helium jacket is complete. Recently, this procedure was successfully tested on a quarter wave resonator developed for the ATLAS upgrade which achieved peak surface fields of 70 MV/m and 105 mT. Following these results we propose to operate the HWR with a 2.5 MV accelerating voltage per cavity at the optimal ion velocity of  $\beta_{OPT} = 0.285$ . Fabrication of the cavity can be started immediately as soon as funding is available.

### INTRODUCTION

In the early stages of the FRIB driver linac design it was decided to use HWRs in the post-stripper section for the energy range from 16 to 55 MeV/u. The original design uses 72 HWRs with  $\beta_{OPT} = 0.285$  [1]. This paper reports on an advanced HWR design developed for this energy range. To improve accelerator performance and decrease cost, the following main design goals were pursued in the cavity development [2]:

- 40-mm aperture diameter to avoid beam losses and facilitate beam centroid tuning;
- Higher accelerating gradients (voltages per cavity) to reduce the cavity count and, consequently, the cost;
- Reduced cryogenic load by applying advanced RF design and surface processing techniques.

### OPTIMIZED EM DESIGN

The electromagnetic (EM) design of the cavity was performed using MWS software and detailed results are reported elsewhere [3]. The EM design of the HWR is primarily based on a successful 72.75 MHz  $\beta_{OPT} = 0.077$  quarter-wave resonator (QWR) recently tested to 4.4 MV of accelerating voltage [4,5]. To increase the available accelerating voltage, the cavity shape is highly optimized reducing both  $B_{PEAK}/E_{ACC}$  and  $E_{PEAK}/E_{ACC}$  [3]. The final cavity shape looks like an hourglass as shown in Fig. 1. A cavity shape with tapered central and outer conductors

was proposed and studied in earlier publications [6,7]. Only recently, the fabrication technology became available to build such cavities [8,9]. The confidence in the proposed HWR design and predicted performance is based on the very successful design, construction and testing of a conical QWR for the ATLAS upgrade [4,8]. Optimization of the cavity shape was performed taking into account die-forming fabrication technology available from industry. For example, the same toroid die as for 72 MHz QWRs [8] will be used. This allows us to reuse the fixturing hardware developed earlier. The results of the EM optimization are summarized in Table 1. We have noticed an appreciable effect of the coupling ports (pos. 2 in Fig. 1) on the peak magnetic field as is shown in Table

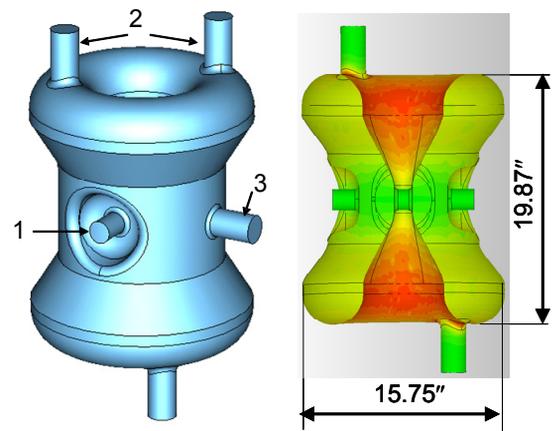


Figure 1: 3D view (on the left) and cross-section (on the right) of the cavity. 1-beam port, 2- coupling ports, 3- RF coupler port.

Table 1: Cavity RF parameters

Port's blending radius	No ports	0.25"	0.5"
Frequency, MHz	322		
Optimal beta, $\beta_{opt}$	0.285		
$L_{EEF} = \beta_{opt}\lambda$ , cm	26.6		
$G = Q_0 R_s$ , $\Omega$	97	97	97
$R/Q_0$ , $\Omega$	194	194	194
$E_{pk}/E_{acc}$	4.38	4.49	4.49
$B_{pk}/E_{acc}$ , G/(MV/m)	71.2	104	79.5
$U_0/E_{acc}^2$ , J/(MV/m) <sup>2</sup>	0.175	0.175	0.175

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1. These ports are required to provide an access for electropolishing cathodes. Table 1 compares main cavity parameters with and without the ports. The 0.5" blending radius of the ports is implemented in the design.

## MECHANICAL DESIGN AND ENGINEERING ANALYSIS

The primary scope of the mechanical design of the cavity and its helium jacket is to:

- Provide an overall compact mechanical design to maintain a high real estate accelerating gradient;
- Provide coupling ports enabling advanced RF surface processing techniques (electropolishing and high pressure water rinsing);
- Integrate a coupling port for a 4-kW capacitive RF coupler;
- Facilitate the integration of several cavities and their sub-systems (RF coupler and tuners) into the cryomodule;
- Provide a means for cavity alignment in the cryomodule;
- Ensure that the stresses in the niobium and the stainless steel parts are below the maximum allowable limits;
- Minimize the sensitivity of the resonant frequency to fluctuations in helium pressure;
- Ensure that the slow tuner operation provides a tuning range of ~100 kHz and that the correlated cavity deformations remain well below the plastic limit;
- Integrate a compact piezoelectric mechanical fast tuner with a ~200 Hz tuning window;
- Create a complete set of fabrication drawings.

To ensure an accurate representation of the optimized electromagnetic model in the mechanical assembly created with Autodesk Inventor, several iterations of engineering analysis have been performed. To validate the correctness of the mechanical design, the cavity RF volume was extracted from Inventor as a step file and simulated in CST MWS to compare against the original optimized design. This procedure was repeated several times to achieve complete replication of the RF volume in the Inventor model. In the final model, the variation of the RF parameters between the original MWS model and the model derived from the Inventor Shell is less than 3%. Engineering analysis was performed using the ANSYS multiphysics Finite Elemental Analysis (FEA) software. The cavity model in ANSYS is shown in Fig. 2.

For the application of the HWR in the FRIB driver linac, three major sub-systems are required: a 4-kW RF coupler, a slow and a fast tuner. A capacitive RF coupler was developed for a 72 MHz QWR [10] and will provide RF power through the port which is perpendicular to the beam axis (pos. 1 in Fig. 2). A pneumatically actuated mechanical slow tuner which compresses the cavity along the beam axis is located outside of the helium vessel and will be attached to the SS flanges shown in Fig. 2 (item 7). The design of the slow tuner is based upon the slow

tuners used since 2009 in the Argonne ATLAS energy upgrade cryomodule [9]. A new piezoelectric fast tuner was developed for 72 MHz QWRs [10]. The tuner has shown excellent performance and will be used in the proposed HWR. The piezoelectric tuner assembly will be attached to the 3" niobium ring (pos.5 in Fig. 2) welded to the cavity wall as is shown in Fig. 2. The piezo actuator presses on a small niobium button electron-beam welded directly to the cavity wall and reacts against the niobium ring. In this way the cavity helium jacket is mechanically decoupled from the tuner actuation.

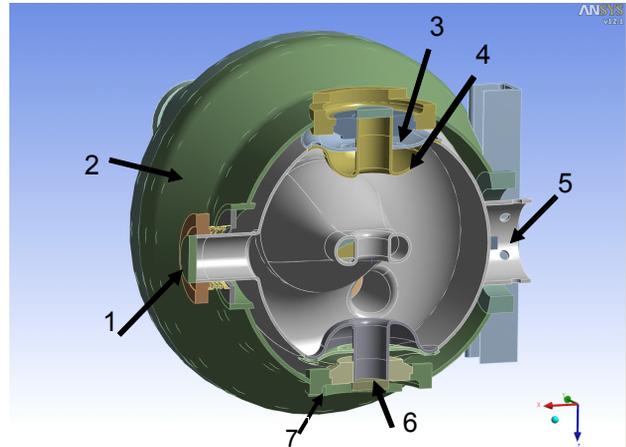


Figure 2: A half cavity model in ANSYS. 1- RF coupler port, 2- stainless steel jacket, 3- re-entrant nose doubler, 4- re-entrant nose, 5 – niobium ring for installation of the piezotuner, 6- beam port, 7 – stainless steel flange.

Engineering analysis included the stress analysis of the cavity and its helium vessel to ensure the operating stresses are below the maximum allowable limits. The design pressure is set by the operation of the cryogenic system and the pressure relief valve. Stresses were determined in the helium vessel and the niobium assuming a helium pressure of 40 psi. In general the conditions of over pressure could occur during cryogenic cooling with the structure at or near room temperature, and since room temperature strength limits (i.e., yield and ultimate), are lower than cryogenic limits the room temperature limits were used. The stress analysis has been performed in the presence of both fast and slow tuners. In the finalized design the stresses do not exceed 7,000 psi and 12,000 psi in the niobium and the stainless steel (SS) parts respectively. Both Nb and SS stresses are highly localized and are below the yield strength of the corresponding material.

Two methods have been studied for minimization of the cavity frequency sensitivity to fluctuations of the helium pressure,  $\partial f / \partial P$ : (1) adding gusseting to reduce the cavity deflections in the high electric field region and (2) varying the depth of the re-entrant nose doublers (pos. 3 in Fig. 2). The results of these studies showed that no gusseting is required; minimal value of  $\partial f / \partial P = -3.8$

kHz/atm was achieved by optimal choice of the doubler location.

Simulations of the slow tuner were performed by applying a force to the SS flanges of the helium jacket (pos. 7 in Fig. 2). For example, a 1500 N force results in an inward deflection of the drift tubes by 0.6 mm and a frequency shift of 90 kHz. ANSYS simulations of the piezoelectric tuner find an  $\sim 10$  Hz/micron sensitivity which can provide an  $\sim 300$  Hz tuning window with piezo stacks similar to those used for the 72 MHz QWR [10].

## RESONATOR ELECTROPOLISHING

Recently, we have successfully applied electropolishing to a completed cavity with the integral helium jacket installed. Excellent performance of the QWR [4,5] validates the state-of-the-art of the design approach, fabrication and RF-surface processing techniques. The mechanics of electropolishing low-beta resonators where the centre conductor and outer conductor are coaxial is very similar to the highly optimized procedure for polishing elliptical cell cavities for the ILC. This is the case for HWRs too. Fig. 3 schematically shows the planned location of 4 cathodes for electropolishing the proposed HWR once completed.

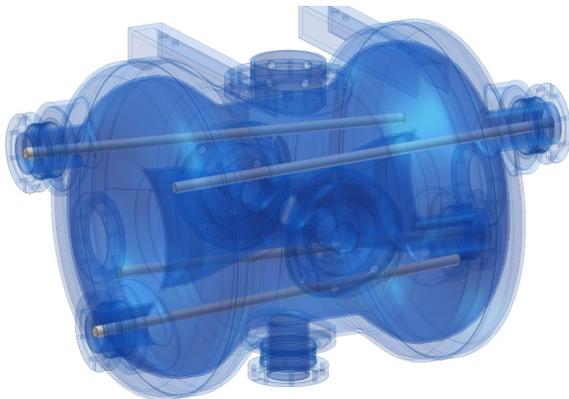


Figure 3: 3D model of the cavity with electropolishing cathodes inserted through two ports at each end.

## HWR OPERATIONAL PARAMETERS

The proposed operational parameters for the new HWR are listed in Table 2 and based on our recent experience with the ATLAS energy upgrade cryomodule and new 72 MHz cavity tests. The peak fields shown in Table 2 were taken directly from the CST MWS screen in a simulation with  $\sim 4M$  mesh cells. It is well known that the peak fields are usually lower by 10%-15% if correct interpolation procedures are applied. Cavity peak fields shown in Table 2 were exceeded by more than 50% in the recent tests of the 72 MHz QWR.

If the proposed HWR is applied to the post-stripper section of the FRIB driver linac, the following advantages will be realized as compared to the baseline design:

- Reduced number of cavities, cryomodules;
- Reduced real-estate length;
- Reduced cryogenic load.

Table 2: HWR operational parameters

Parameter	Value	Unit
Operating temperature	2	K
Accelerating voltage	2.5	MV
Peak electric field	41.5	MV/m
Peak magnetic field	73.6	mT
Residual resistance	<5	n $\Omega$
Stored energy	15.3	Joule

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