ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAL035

DESIGN OF BETA=0.65, 5-CELL, 644 MHz ELLIPTICAL CAVITY FOR FRIB UPGRADE*

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Abstract

The superconducting (SC) linac of the Facility for Rare Isotope Beams (FRIB) under construction will deliver 200 MeV/u, 400 kW beam to the target for producing rare isotopes at Michigan State of University (MSU). For further beam energy upgrade, we are developing the beta = 0.65, 5 cells, 644 MHz elliptical cavity. The beam energy can be upgraded to 400 MeV/u by installing 11 cryomodules to the available space in the FRIB tunnel.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) currently being built at Michigan State University (MSU) is the next generation facility for rare isotope science. Rare isotopes, as the name implies, are not found on Earth since they have a short life time due to their instability. Production of such isotopes will enable discoveries in nuclear physics, nuclear astrophysics, as well as for societal needs.

The baseline design of FRIB linac will provide stable nuclei accelerated to 200 MeV/u for the heaviest uranium ions and 600 MeV for protons with 400 kW power on the target [1]. The optimal beam energy for production of rare isotopes is 400 MeV/u as was detailed in the early stages of a rare isotope accelerator design [2]. In addition, the same accelerator should provide higher energies for lighter ions. Particularly, the upgraded linac of FRIB should be able to accelerate protons up to 1 GeV for efficient production of rare isotopes using thick targets. The current design energy of the FRIB linac was selected due to cost considerations. Therefore, during the civil construction of the FRIB linac building, an 80-meter space in the tunnel was reserved for the future energy upgrade of the linac (Fig. 1).

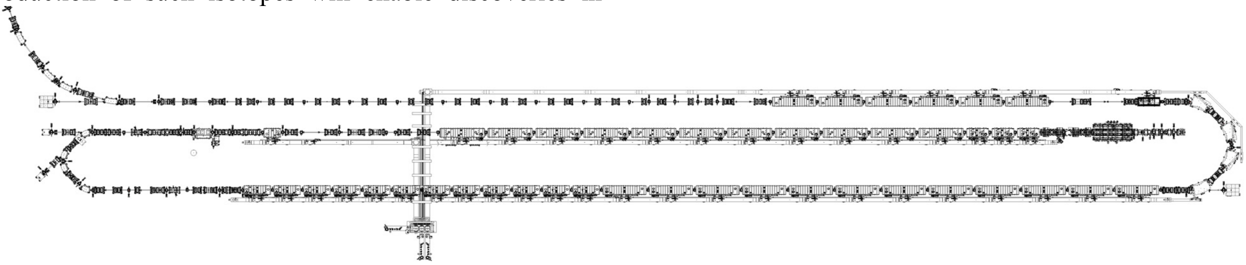

Figure 1: Layout of the FRIB Linac being constructed in Michigan State University.

In the earlier stage of the FRIB project we considered possibility for energy upgrade using the existing design of β_{opt}=0.53 half wave resonators (HWR) operating at 322 MHz. The production of these cavities for FRIB project is nearly complete. The available space in the FRIB tunnel can house 12 cryomodules of the existing design with a total of 96 HWRs and 12 superconducting (SC) solenoids. If we install 12 cryomodules with HWRs of the same performance as is specified for FRIB, the uranium beam energy can reach 300 MeV/u. In order to reach the required 400 MeV/u, all existing 144 HWRs and the new 96 HWRs must operate at 35% higher gradient than the current FRIB specification [3]. While achieving higher gradients with the new β_{opt}=0.53 HWRs is feasible after additional R&D, operation of the existing 18 cryomodules at higher gradients is not realistic. Since 2016, our focus is on elliptical SRF cavities at β_{opt} =0.65 operating at 644 MHz which can deliver the required real estate gradient to increase the uranium beam energy from 200 MeV/u to 400 MeV/u. In addition, the FRIB linac will be capable to deliver 1 GeV protons. A primary argument in favour of elliptical cavities is the substantial experience of multiple vendors worldwide in production of such cavities with high performance.

Therefore, research and development for a 5-cell 644 MHz elliptical upgrade cavity is under way. The initial design of the elliptical cavity has been developed in collaboration with Fermi National Accelerator Laboratory (FNAL). Two such cavities are being built by industry.

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*Work supported by the U.S. DOE Office of Science under Cooperative Agreement DE-SC0000661 and the NSF under Cooperative Agreement PHY-1102511, the State of Michigan and Michigan State University.
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BASIC CONSIDERATIONS

The FRIB cryoplant is able to liquefy helium at 2K to support 3.6 kW heat load. Total heat load in the baseline-FRIB is expected up to 2.4 kW at 2K. Therefore, it is highly desirable to develop very efficient SC cavities and cryomodules for the FRIB energy upgrade to stay within the limit of the existing cryoplant capacity. A cryomodule housing 5 elliptical cavities is planned. Each cryomodule is followed by a quadrupole doublet and a beam diagnostic box or dipole magnets for beam steering. The available 80-m space is sufficient to install 11 cryomodules, 22 quadrupoles, 6 diagnostic boxes and 5 steerer modules. Five-charge-states of uranium beam ($^{238}U^{76+}$ to $^{238}U^{80+}$) will be simultaneously accelerated along the upgraded section of the FRIB linac.

RF DESIGN

The electromagnetic design of the cavity includes geometry optimization to maximize shunt impedance and geometry factor while minimizing the magnetic B_{peak}/E_{acc} and electric E_{peak}/E_{acc} field enhancement factors which are the ratio of peak fields at the cavity wall to the accelerating gradient. These values must be minimized while also keeping a large voltage gain. A low E_{peak}/E_{acc} helps to reduce field emission while a low B_{peak}/E_{acc} helps to reduce the probability of cavity quench for given operational voltage. A smaller cavity aperture, decreases both the electric and magnetic field enhancement. A smaller aperture also gives a larger shunt impedance, which minimizes the heat losses. However, the aperture also affects the cell to cell coupling *k* which has an effect on the field flatness. The coupling for the 644 MHz cavity optimal dimensions is 0.71% calculated from $k = 2\frac{f_\pi - f_0}{f_\pi + f_0}$ where f_π and f_0 are the frequencies of π- and 0-mode correspondingly. Additionally, a larger aperture results in higher mechanical stability and is also more convenient for the cavity RF surface processing. The electric and magnetic field distributions for the optimized shape of the cavity are shown in Fig. 2. The simulation was performed using CST [4] software.

The required optimal beta of 0.65 is achieved by adjusting the cell length. The corresponding geometrical beta is 0.61. To obtain field flatness in 5-cell cavity the dimensions of the end cells are modified to accommodate transition to beam pipes. This requires slight modification of the end cells' shape. The cavity aperture is 83 mm which makes accelerator acceptance very large and helps to avoid beam losses in the upgraded section of the FRIB linac. In order to provide Q_{ext} down to 10^7 a large aperture, 100 mm, is designed for the end tubes to prevent penetration of the antenna into the cavity aperture. The basic cavity RF parameters are shown in Table 1.

The target value for the operational peak electric and magnetic fields are 40 MV/m and 78 mT respectively. These parameters are consistent with similar values in elliptical cavities used or projected in other large accelerator projects, for example in FNAL's PIP-II [4]. To achieve the proposed high quality of the surface processing of the elliptical cavities with significant practical margin an electropolishing system is being developed at FRIB.

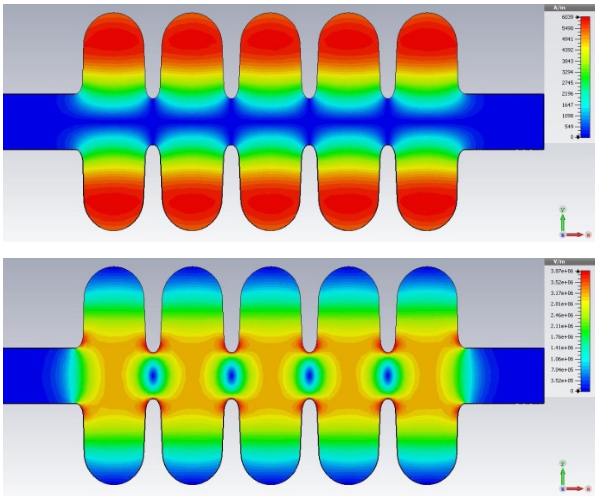

Figure 2: The magnetic (top) and electric (bottom) field distributions in the FRIB upgrade cavity.

Table 1: Basic Parameters of the Cavity

Parameter	Value	
Frequency (MHz)	644	
Beta	0.61 (G)	0.65 (O)
L_{eff}, 2.5βλ (m)	0.71 (G)	0.76 (O)
R/Q (Ω)	368	
G (Ω)	188	
Voltage (MV)	12.4	
E_{peak} (MV/m)	40	
B_{peak} (mT)	77.4	
E_{acc} (MV/m)	17.5	16.4
E_{peak}/E_{acc}	2.28	2.43
B_{peak}/E_{acc} (mT/ MV/m)	4.42	4.72

MECHANICAL DESIGN

The primary scope of the mechanical design of the cavity and its helium vessel is to minimize the sensitivity of the operational resonant frequency to fluctuations in helium pressure which are especially important for CW operation. The important step is the choice of niobium and titanium thickness. Like in many previously developed elliptical cavity designs, the helium vessel will be made of titanium. Niobium-titanium alloy disks will be welded to the niobium body for the installation of titanium vessel. The cavity 3D model is shown in Fig. 3. The cavity model shows lever type slow tuner which is being developed in collaboration with FNAL [5].

Extensive finite element analyses (FEA) were applied for the selection of cavity mechanical properties in order to withstand various steps during the cavity testing process, as well as failure modes during the operation. FEA of the cavity-tuner system was performed using COMSOL [6] software.

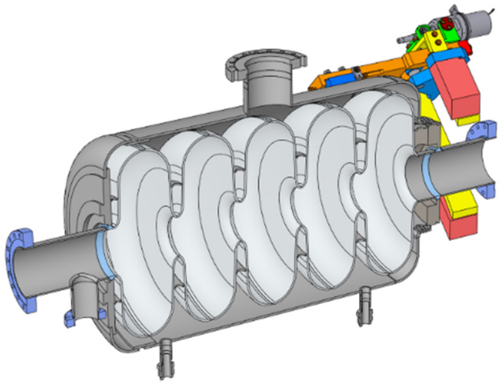

Figure 3: Proposed 644 MHz SC cavity in helium vessel with slow and fast tuners attached.

Stiffening rings have been widely used in elliptical cavity designs and are proven to decrease both sensitivity of the cavity frequency to helium pressure fluctuation and Lorentz detuning. The radial position of the stiffening rings of the 5-cell 644 MHz cavity was optimized using COMSOL. The df/dP was calculated with a varying tuner stiffness and a 4 mm niobium wall thickness. The results show that after a tuner stiffness of 40 kN/mm is applied the df/dP remains virtually constant for all the positions of the stiffening rings. The position from the axis was chosen to be 108 mm since this value gives a df/dP of zero at a tuner stiffness of 40 kN/mm which closely matches the calculated stiffness of the tuner.

Appling the force boundary condition to the tuning side, the cavity's tuning sensitivity is simulated, which is shown in Fig. 4. The tuning sensitivity is 258 kHz/mm.

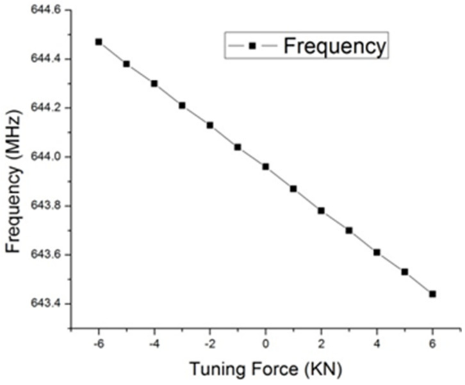

Figure 4: The tuning sensitivity of FRIB upgrade cavity.

Normally, the cryomodule's helium distribution contains a massive volume of liquid helium. The superconducting cavitiescan experience high gas pressure when liquid helium boils in abnormal conditions. To address the pressure vessel safety requirements, a simulation of the cavity and helium vessel was performed under application of high pressure. The pressure relief valve in the FRIB cryomodules is set at 2 bar. In the simulation, 4 bar pf pressure was assumed in the helium space of the cavity with factor of 2 safety margin. The displacement and von Mises stress distribution are shown in Fig. 5. The maximum von Mises stress is 59 MPa in niobium, which is lower than the 2K niobium's yield stress of 317 MPa [7]. The maximum von Mises stress in titanium is 660 MPa, which is lower than the 2K titanium's yield stress of 834 MPa [7]. Additional engineering analyses were performed to validate that the mechanical design of the cavity can safely withstand the most adverse conditions experienced during cavity production, testing and operational failure modes. These studies were conducted using ANSYS [8] and material properties at room temperature and 2K. Details of these studies are discussed elsewhere [9]. The thickness of the titanium vessel is selected to be 5 mm.

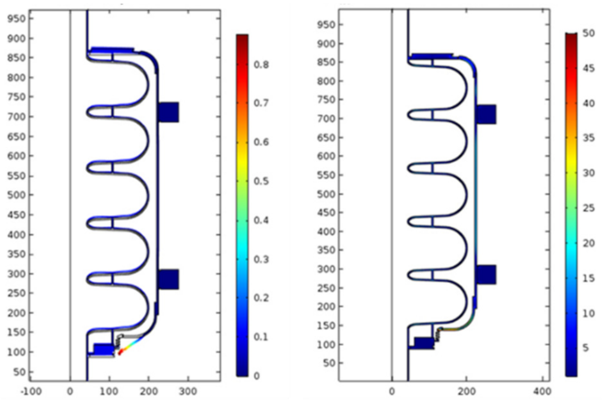

Figure 5: The displacement (mm, the left picture) and von Mises stress (MPa, the right picture) distribution in the cavity.

CONCLUSION AND OUTLOOK

The multi-physics design of β_{opt}=0.65 5-cell 644 MHz elliptical cavity for FRIB upgrade has completed. Two bare niobium cavities are being fabricated and will be ready for surface processing and tuning this summer. The development of multi-purpose handling fixture, bead-pull tests stand, cavity static tuning fixture and dunking test Dewar insert is under way. The cold testing of the first cavity is planned by the end of calendar year. In addition, the development of the slow and fast tuners, RF coupler and prototype cryomodule are being pursued too.

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