650 MHz ELLIPTICAL SUPERCONDUCTING RF CAVITIES FOR PIP-II PROJECT *

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Abstract

Proton Improvement Plan-II at Fermilab is an 800 MeV superconducting pulsed linac which is also capable of running in CW mode. The high energy section operates from 185 MeV to 800 MeV instigated using 650 MHz elliptical cavities. The low-beta (LB) β_G =0.61 portion will accelerate protons from 185 MeV-500 MeV, while the high-beta (HB) β_G = 0.92 portion of the linac will accelerate from 500 to 800 MeV. The development of both LB and HB cavities is taking place under the umbrella of the Indian Institutions Fermilab Collaboration (IIFC). This paper presents the design methodology adopted for both low-beta and high-beta cavities starting from the RF design yielding mechanical dimensions of the cavity cells and, then moving to the workable dressed cavity design. Designs of end groups (main coupler side and field probe side), helium vessel, coupler, and tuner are the same for both cavities everywhere where it is possible. The design, analysis and integration of dressed cavity are presented in detail.

INTRODUCTION

Proton Improvement Plan-II (PIP-II) is Fermilab's project aimed for future development of the accelerator complex. In particular, it should provide LBNE (Long Baseline Neutrino Experiment) operations with beam power on target of at least 1 MW [1]. The central element of PIP-II is a new superconducting (SC) 800 MeV 2 mA CW linac initially operating in a pulsed regime to support beam injection into the 8 GeV Booster. PIP-II will use five types of SC cavities: 162.5 MHz half-wave resonators (HWR), two families of single-spoke resonator operating at 325 MHz (SSR1 and SSR2), and two families of elliptical cavities (LB650 and HB650) operating at 650 MHz. The layout of the PIP-II linac, (Fig. 1) shows the transition energies between accelerating structures, and their frequencies [2]. In this paper, the designs of the elliptical SC cavities for LB650 and HB650 are presented.

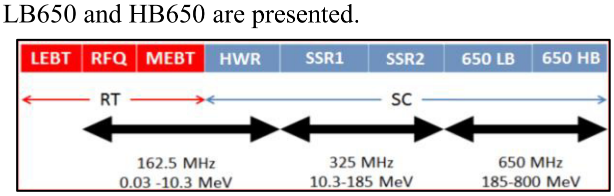

Figure 1: Layout of PIP-II injector linac.

DESIGN METHODOLOGY

Based on physics requirements for PIP-II, the functional requirement specifications (FRS) of the HB and LB elliptical cavities are defined [3,4]. Cavity shapes for end-cells and mid-cells are developed using RF simulations which satisfy the parameters of the FRSs as shown in Fig. 2. The cavity dimensions are computed for operating temperature of 2K. The cold RF shape is recomputed to the room temperature dimensions by using the coefficient of thermal expansion of the niobium. Additional thickness is added to this RF profile to account material removal during processing. The cavity dimensions after processing are used for mechanical simulations. However, for fabrication purposes only the warm inner profile without material removal is used. Fig. 2 illustrates general design practices for electromagnetic, RF and mechanical simulations and iterative process between them indicated by chain dotted lines. Mechanical design such as cavity/tuner stiffness and vessel design uses RF design input [5]. The coupler, tuner and magnetic shield designs are done separately, however they also contribute indirectly to cavity RF and mechanical designs.

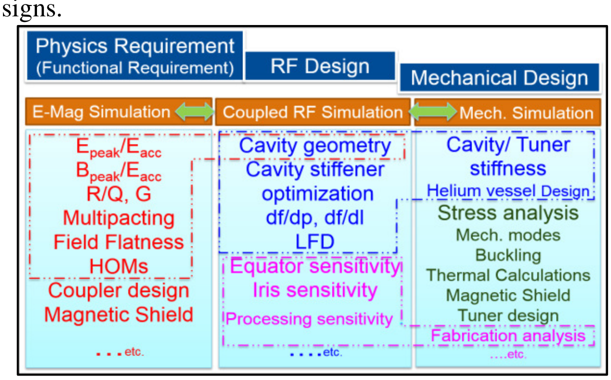

Figure 2: SC cavity design methodology.

650 MHz RF DESIGN

A requirement for both pulsed and CW operations significantly complicates the cavity design. The goal of the cavity shape optimization is to minimize both surface electric, E_{surf}, and magnetic, B_{surf}, fields.

Table 1: PIP-II Parameters of 650 MHz Cavities [3,4]

Cavity Parameters	LB650	HB650
β_G	0.61	0.92
β_{opt}	0.65	0.97
$R/Q(\beta_G)$, Ohms	327.4	576
$E_{surf}/E(\beta_G)$	2.43	2.1
$B_{surf}/E(\beta_G)$, mT/MV/m	4.6	3.94
G, Ohms	187	260
Energy gain per cavity MeV	11.7	19.9

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The RF design and optimization of the LB650 and HB650 has been done using CST and COMSOL [6,7]. More detailed description of RF design strategy for both cavities are explained in [8] and [9]. Table-1 shows the designed parameters for these cavities with the effective length is equal to $5\beta_G\lambda/2$.

COUPLED SIMULATIONS

The 650 MHz cavities have five elliptic cells for both LB and HB sections. For these cavities, it was decided to have similar mechanical structures for the end groups, helium vessel, and tuner. The common design of these components allows us to reduce complexity and risk, as well as the cost of development and production. Stiffening ring optimization is an important part of cavity design. It optimizes Lorentz Force Detuning (LFD), *df/dp*, and cavity stiffness per the FRS requirements. The final designs of the HB650 and LB650 cavities stiffness of 4 and 2.8 kN/mm, respectively, satisfies both LFD and *df/dp* requirements. Based on HOM studies and the main coupler (MC) position a beam tube diameter of 118 mm was chosen for both cavities. The beam tube at the MC end has a port for the RF power coupler, and the beam pipe at the tuner end has a port for RF field probe (FP) antenna. The helium vessel is made of titanium and has two inlets for helium filling at the bottom and has a two-phase helium return line at angle of 30° from the top of the vessel. Fig. 3 shows a 2D schematic of an axisymmetric section of the dressed cavity used for the coupled analysis [10].

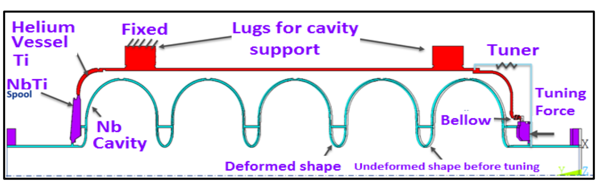

Figure 3: 2D axis-symmetric dressed cavity model.

Lorentz Force Detuning (LFD) and pressure fluctuations *df/dP* for the 650 MHz β=0.92 5-cell cavity dressed with the helium vessel (HV) is performed using COMSOL Multiphysics. For LFD, the resonance frequency of the π-mode is calculated before and after applying the EM radiation pressure load. Deformed shape is calculated using the solid mechanics module. This deformed mesh is used for checking frequency and we obtain the difference in the frequency. Tuner stiffness is also taken as variable parameter. Here we have taken cavity wall thickness of 3.75 mm for accounting the chemical treatments to the inner cavity surface. Further the model analysis (mechanical modes) of the dressed cavity is also performed. Table-2 shows the LFD, *df/dp* and 1st longitudinal mechanical mode dependence on the tuner stiffness for cavity stiffness of 4.0 kN/mm for HB650 cavity. This cavity stiffness values come for stiffener ring positions of 100 mm. The value of 1 Hz/(MV/m)^2 and 15 Hz/mbar are required by Functional Requirement Specification (FRS) for both LFD and *df/dp* respectively. The stiffness of current tuner design is greater than 60 kN/mm and it satisfies the LFD and *df/dp* values with some margin with respect to FRS requirement. Model analysis shows that 1st longitudinal mode will be above 100 Hz for more than 60 kN/mm tuner stiffness. Similar analysis is also being performed for LB650 cavity.

Table 2: LFD, *df/dp* and 1st longitudinal mechanical mode with respect to tuner stiffness for HB650.

Tuner Stiffness (kN/mm)	df/dp (Hz/mbar)	LFD Hz/(MV/m)^2	1st L. Mode (Hz)
0	14.5	-5.7	48.1
20	11.5	-1.152	98.2
40	11.1	-0.831	101.7
60	10.9	-0.713	102.8
80	10.8	-0.684	103.6

MECHANICAL DESIGN

3-D Elastic stress analysis for dressed cavity is performed with appropriate boundary conditions and loads as explained in Fig. 4 to ensure the structural stability of SRF cavity assembly using ANSYS [11]. Crucial stress locations in the cavity assembly are identified as shown in Fig. 5 termed as stress classification lines (SCL). Linearization of stresses has been performed at these locations to evaluate primary membrane, primary bending and secondary stresses. Assessment of linearized stresses has been carried out by comparing stresses with allowable stresses based on the ASME BPV Codes Section VIII Division 1 Subsection 5.2.2.4 and cavity protection against plastic collapse is ensured. A detailed mechanical design as per the requirement of ASME has been performed.

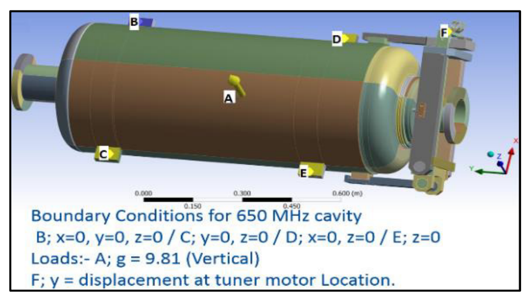

Figure 4: Loads and boundary conditions for simulations

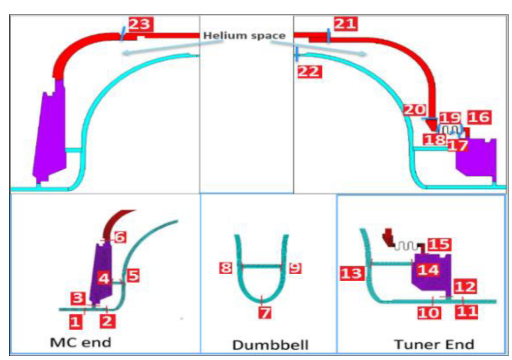

Figure 5: Stress classification lines on dressed cavity

Cavity is simulated for five load cases, which covers room temperature and cold (2K) fault loads, gravity, liquid helium pressure head, cool-down shrinkage, tuner extension and cavity vacuum failure loads. All applicable stress categories have been evaluated at the stress classification lines. It was found that in all cases the stresses are below the allowable values [12, 13]. Maximum shrinkage of cavity (Fig. 6) due to cool-down to 2K is 1.9 mm at tuner end and 0.455mm at coupler end.

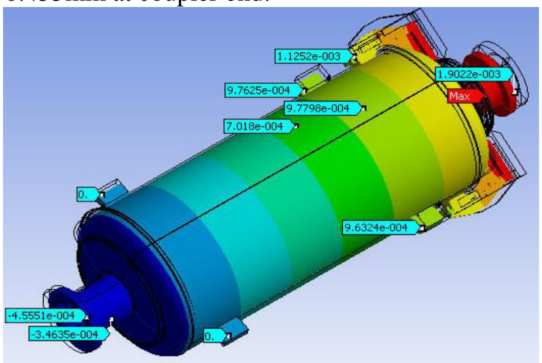

Figure 6: Cavity displacements due to cool-down to 2K.

COUPLER DESIGN

The RF coupler for LB650 and HB650 cavities is under design [14]. It is planned to use the same coupler for both cavity types. The coupler has waveguide input port. Through waveguide to coaxial transition a 3” (outer diameter) coaxial line transfers power to the cavity. The antenna tip is not axially symmetric. It makes coupling more efficient and allows one to adjust coupling by rotation of antenna tip. Coupler has a single room temperature coaxial ceramic window. The window diameter is 4”. Central conductor of the coupler is cooled by air. Possible multipactor will be supressed by HV bias. Appearance of coupler and its port is shown in Fig. 7.

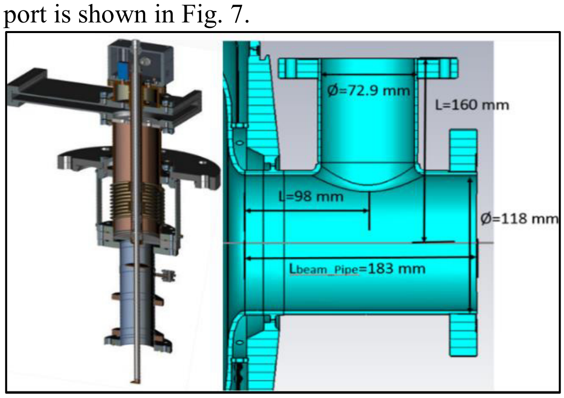

Figure 7: 650 MHz coupler and ports for LB650 and HB650 cavities.

TUNER DESIGN

The main tasks of the superconducting RF cavity tuner are to tune the cavity to the designed resonant frequency by compressing the cavity and to compensate Lorentz-force detuning (LFD) and microphonics. That requires both slow and fast tuners for compensating static errors and dynamic loadings, respectively. A double lever tuning system with electromechanical actuator has fairly good frequency resolution (~2Hz/step). In addition the fast actuation unit contains piezo-electric devices with limited stroke (~10um) but virtually infinite resolution. Coarse and fine tuning ranges and resolutions for these cavities are the same for both cavities and are 200 kHz and 600 Hz, respectively [15,16]. The design of the tuner is complete. It has a tuning ratio of 20:1 for slow tuner and 2:1 for fast tuner. Fig. 8 shows the 3D model of the tuner on a dressed cavity.

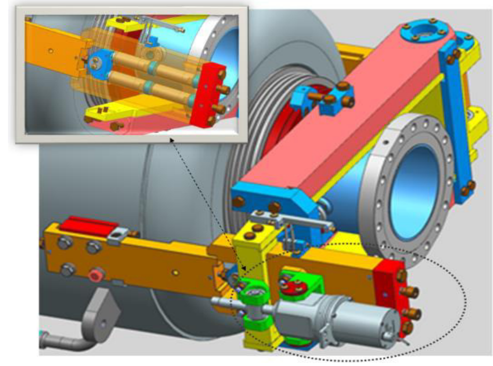

Figure 8: Double Lever tuner mechanism for 650 cavity.

DRESSED CAVITY FABRICATION

The development of bare cavity sequence is half-cell forming, half-cell to dumbbell welding, end group preparation, dumbbell to dumbbell welding, dumbbell stack to end group integration and welding. Once the bare cavity is welded its qualifications consists of leak tests, inspection, and RF QC tests. Now, it is processed for cleaning by BCP, EP, HPR etc. then the cavity is tested in VTS. Field flatness tuning is done after bulk EP and 800^{o} C heat treatment [17]. Other components such as helium vessel, bellow and end transition ring are further integrated to the bare cavity. The following tools/fixtures are used for cavity dressing:-

a. Insertion device (medium bertha) for preparing cavity for dressing. The bare cavity, helium vessel, bellow and end rings are tack welded in this fixture (Fig. 9).

b. Rotating fixture to revolve cavity during welding.

c. Globe box for welding 5-cell 650 cavities in inert atm.

During the entire fabrication process the dressed cavity RF frequency is monitored and kept within the specified limit.

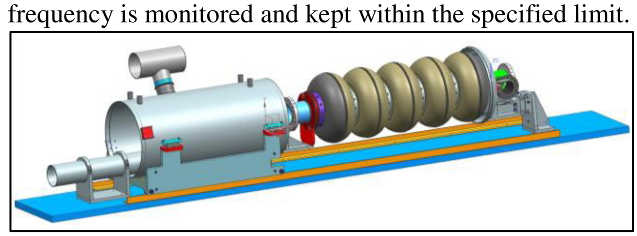

Figure 9: Insertion device for cavity dressing.

CONCLUSION

Development of 650 MHz elliptical cavities has been initiated for PIP-II project. Design and drawings of HB650 cavities are released by FNAL. Both FNAL and RRCAT are working for the development of these cavities [18]. It is expected to build HB650 bare cavity in next 6 months and first dressed cavity in a year. LB650 dressed cavity development has also been in progress with VECC [19].

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