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

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Abstract
The PIP-II 800 MeV linac employs 650 MHz elliptical 5-cell CW-capable cavities to accelerate up to 2 mA peak beam current of H^- in the energy range 185 – 800 MeV. The low beta (LB650) $\beta_G = 0.61$ portion should accelerate from 185 MeV to 500 MeV using 33 LB650 dressed cavities in 11 cryomodules. The high beta (HB650) $\beta_G = 0.92$ portion of the linac should accelerate from 500 to 800 MeV using 24 HB650 dressed cavities in 4 cryomodules [1]. The development of both type cavities is going on under IIFC collaboration. This paper presents design methodology. The discussion proceeds from RF design resulting in mechanical dimensions of RF cells to mechanical design and cavity dressing for both low- and high-beta cavities. Further the tuner design and its integration to the dressed cavity is discussed. The paper also explains the salient design features of these dressed cavities.

INTRODUCTION

Proton Improvement Plan II (PIP-II) is Fermilab's plan for future improvements to the accelerator complex, aimed at providing LBNF (Long Base Neutrino Facility) operations with a beam power of at least 1MW on the target. The central element of PIP-II is a new superconducting 800 MeV linac, injecting beam into the 8 GeV Booster.

The room temperature (RT) section includes a Low Energy Beam Transport (LEBT), RFQ and Medium Energy Beam Transport (MEBT). The RT section accelerates H^- to 2.1 MeV and creates the desired bunch structure for injection into the superconducting (SC) linac. The SC linac includes 162.5 MHz Half Wave Resonators, two types of 325 MHz Single Spoke Resonators and two types of 650 MHz 5-cell elliptical cavities [2]. In this article the status of development for last two cavity types (LB650 and HB650) is presented.

RF DESIGN

As mentioned above the PIP-II project employs 2 types of 650 MHz elliptical cavities. In the process of project development the serial iteration of RF design has been done. The shape of both cavities was modified to allow both pulsed and CW operation. Detailed RF optimization of HB650 cavity and RF design for LB650 cavity were presented at IPAC12 [3].

Below we summarize the main parameters of both LB650 and HB650 cavities in Table 1, where we assume that the effective length is equal to $5^*\beta G\ \lambda/2$.

Table 1: Main Parameters of 650 MHz Cavities

Cavity Parameters	LB650	HB650
β_G	0.61	0.92
β_{opt}	0.65	0.97
$R/Q(\beta_G)$, Ohms	327.4	576
$R/Q(\beta_{opt})$, Ohms	356.3	610
$E_{surf}/E(\beta_G)$	2.43	2.10
$E_{surf}/E(\beta_{opt})$	2.33	2.07
$B_{surf}/E(\beta_G)$, mT/MeV/m	4.6	3.94
$B_{surf}/E(\beta_{opt})$, mT/MeV/m	4.41	3.89
G, Ohms	187	260

DRESSING OF THE CAVITY AND MECHANICAL DESIGN

The LB650 & HB650 cavities consist of five elliptic cells. Although the cavity lengths are different for these cavities, it was decided to have similar mechanical designs of end-groups, helium vessel and tuner. This unification allows to reduce complexity and risk, as well as the cost of development and production. Stiffening rings between the cells and between the end-cell and end-group are important part of the design for both cavities. Optimization of stiffening ring's location and end group design controls the deformation of the cavity and is important part of mechanical design. It has to minimize LFD and *df/dp* without sacrificing the cavity tunability [4, 5]. The final designs of HB650 and LB650 cavities stiffness of 4 and 3 kN/mm, respectively. Based on HOM studies a beam tube diameter of 118 mm is chosen for both cavities [6]. The beam tube at the main coupler (MC) end has a port for the RF power coupler, and the beam pipe at tuner end has a port for RF field probe (FP) antenna. The helium vessel is welded to the end groups. The vessel has two ports for helium filling at the bottom and the two-phase helium return line is provided at 30° from the top of the vessel. At the sides of the helium vessel, four blocks are welded for supporting in the HTS cryostat or cryomodule. Lifting lugs are provided on the helium vessel for assembly and transport of the cavity. A bellows is provided at the tuner end between the helium vessel and the end group in order to provide frequency tuning. Figure 1 shows the various components on the cavity.

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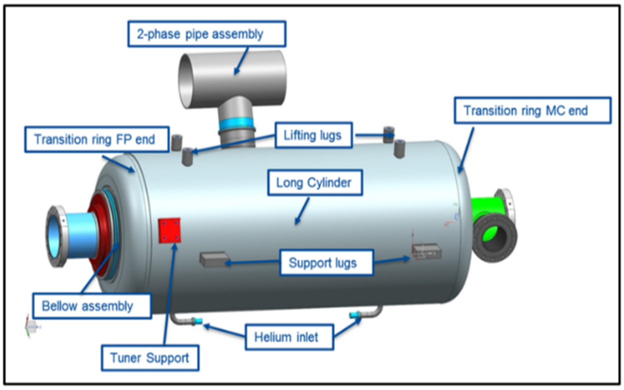

Figure 1: HB650 dressed cavity with various components.

We have studied both the Lorentz Force Detuning (LFD) and the frequency sensitivity to pressure fluctuations *df/dP* for the 650 MHz *β*=0.92 5-cell cavity dressed with the helium vessel (HV) using Comsol Multiphysics [7]. The resonance frequency of the π-mode is calculated before and after applying the pressure load. Deformation is calculated using the solid mechanics module. Then the mesh is deformed with the resultant displacement values to acquire the frequency change. Tuner stiffness is accounted. The studies have been done for a cavity wall thickness of 3.75 mm. Original niobium plate thickness is 4mm and removal of 250 µm is happening due to series of chemical treatments.

Figure 2 shows the LFD dependence on the tuner stiffness for stiffening ring positions of 90 mm and 100 mm. Red line shows the value of 1 Hz/(MV/m)^2 required by Functional Requirement Specification (FRS). The stiffness of current tuner design is greater than 60 kN/mm and one can see that even in the worst case the LFD value is below than the FRS requirement.

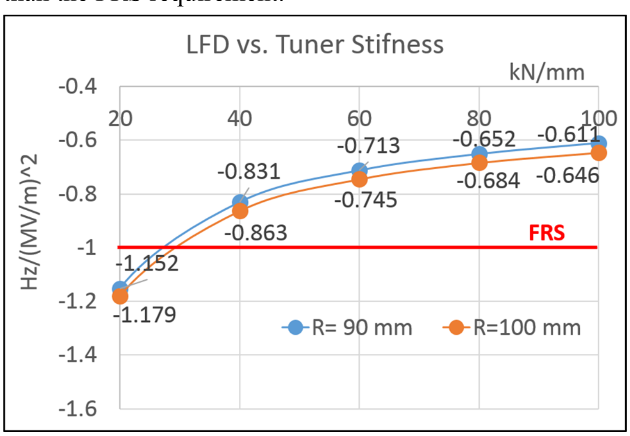

Figure 2: LFD coefficient vs. tuner stiffness.

Figure 3 presents the dependence of cavity frequency sensitivity to the He pressure, *df/dP*, on the tuner stiffness. The red line shows the FRS value. Similar to the case of LFD the value of *df/dP* is below the FRS requirement for the tuner stiffness of 60 kN/mm.

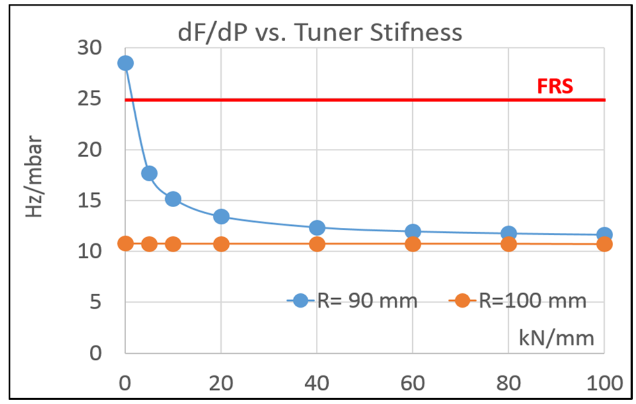

Figure 3: Dependence of *df/dP* vs tuner stiffness.

STRESS ANALYSIS

3-D Elastic stress analysis for dressed cavity was performed for various load cases to ensure the structural stability of SRF cavity assembly. Appropriate material properties, loads and constraints were applied and stress analysis of assembly was carried out. Stresses and displacements were evaluated for each load case. Crucial stress locations in the cavity assembly were identified. Linearization of stresses was performed at these locations to evaluate Primary Membrane, Primary Bending and Secondary stresses. Assessment of linearized stresses was 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 was ensured.

Finally, stress analysis of the dressed cavity in 5 different load conditions has been done. Figure 4 shows the solid model used in the simulations, Fig. 5 shows detailed description of loads conditions and Fig. 6 shows the stress classification lines used in analysis.

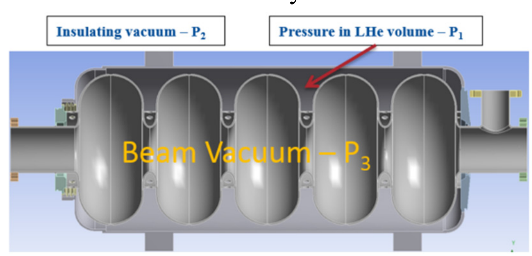

Figure 4: Solid model used in simulations.

Load Case	Loads	Condition Simulated	Applicable Temperature	Applicable Stress Categories
1	1. Gravity 2. $P_1 = 0.205$ MPa 3. $P_2 = P_3 = 0$	Warm Pressurization	293 K	Pm, P_L, Q, Pm + P_b, P_L + Q
2	1. Gravity 2. Liquid Helium head 3. $P_1 = 0.4$ MPa 4. $P_2 = P_3 = 0$	Cold operation, full LHe, maximum pressure – no thermal contraction	2 K	Pm, P_L, Q, Pm + P_b, P_L + Q
3	1. Cool down to 1.88 K 2. Tuner extension of 2 mm	Cool down and tuner extension, no primary loads	2 K	Q
4	1. Gravity 2. Liquid Helium head 3. Cool down to 1.88 K 4. Tuner extension of 2 mm 5. $P_1 = 0.4$ MPa 6. $P_2 = P_3 = 0$	Cold operation, full LHe inventory, maximum pressure – primary and secondary loads	2 K	Q
5	1. Gravity 2. $P_1 = 0$ 3. $P_2 = P_3 = 0.1$ MPa	Insulating and beam vacuum upset, helium volume evacuated	293 K	Pm, P_L, Q, Pm + P_b, P_L + Q

Figure 5: Five load conditions.

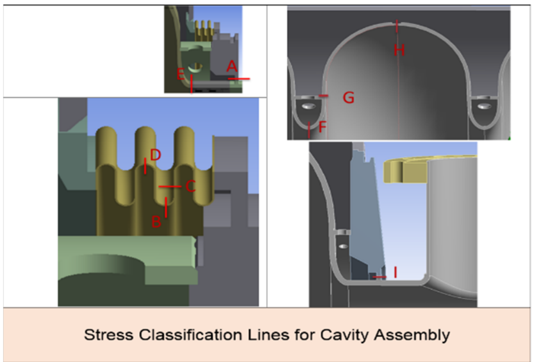

Figure 6: Stress classification line.

All 5 load cases were qualified. 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.

COUPLER DESIGN

The RF coupler for LB650 and HB650 cavities is under design. It is planned to use the same coupler for both cavity types. The coupler input is waveguide port. Internally, 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 coaxial ceramic window. The window diameter is 4''. The coupler is cooled by air. Possible multipactor will be supressed by HV bias. Appearance of coupler is shown in Fig. 7.

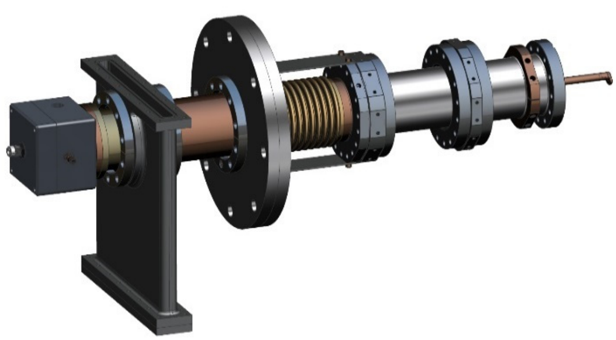

Figure 7: 650 MHz coupler for LB650 and HB650 cavities.

TUNER DESIGN

In order to obtain the required frequency range and resolution, the cavity tuning systems shall include course and fine tuning mechanism engaged in series. The former utilizes a double lever tuning system with electromechanical actuator (with stroke capability of 1-2mm) having fairly good frequency resolution, the latter contains piezo-electric actuators with limited stroke (2-10um) but virtually infinite resolution. The fine tuning system is required for compensation of microphonics and LFD. Table 2 defines both coarse and fine tuning range and resolution for HB650 cavity [4].

Table 2: Tuning Requirement of HB650 Cavity

Tuner parameter	For both LB650 and HB650 cavities
Coarse tuning range, kHz	200
Coarse tuner resolution, Hz/step	< 2
Fine tuner range, Hz	600
Accuracy of cavity resonance control (peak), Hz	20
Piezo tuner resolution, Hz	< 1

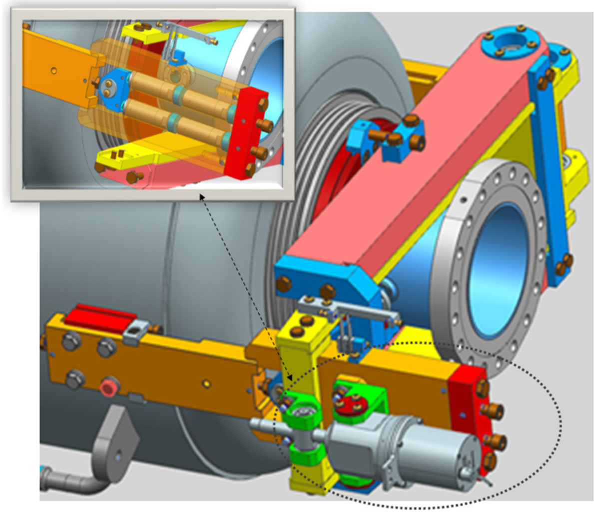

Figure 8: Double Lever tuner mechanism for HB650 cavity.

The design of the tuner is complete. It has a tuning ratio of 20:1 for slow tuner and piezo-tuner. Figure 8 shows the view of the tuner.

CONCLUSION

Development of 650 MHz cavities for PIP-II is progressing. The HB650 dressed cavity design is complete and drawings are released. LB650 dressed cavity design work is started in VECC in collaboration with FNAL.

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