

MECHANICAL OPTIMIZATION OF HIGH BETA 650 MHZ CAVITY FOR PULSE AND CW OPERATION OF PIP-II PROJECT*

Timergali N. Khabiboulline[#], Ivan V. Gonin, Chuck Grimm, Andrei Lunin, Thomas H. Nicol, Vyacheslav P. Yakovlev, Fermilab, Batavia, IL 60510, USA
 Pankaj Kumar, RRCAT, Indore, India

Abstract

The proposed design of the 0.8 GeV PIP-II SC Linac employs two families of 650 MHz 5-cell elliptical cavities with 2 different beta. The $\beta=0.61$ will cover the 185-500 MeV range and the $\beta=0.92$ will cover the 500-800 MeV range. In this paper we will present update of RF and mechanical design of dressed high beta cavity ($\beta=0.92$) HB650 optimized for pulse regime of operation at 2 mA beam current. In previous CW version of PIP-II project the mechanical design was concentrated on minimization of frequency shift due to helium pressure fluctuation. In current case of pulse regime operation the main goal is Lorentz force detuning minimization. We present the scope of coupled RF-Mechanical issues and their resolution. Also detailed stress analysis of dresses cavity will be presented.

INTRODUCTION

HB650 cavity originally was developed for CW operation. Current cryogenic power deficiency forced to consider switching of operation regime from CW to pulse mode in order to reduce cryogenic losses. During pulsed operation electromagnetic field energy stored in the cavity change with time and RF filed pressure to cavity walls also change causing resonance frequency modulation. Low beam current of 2 mA require relatively low RF power, therefore operating loaded Q of the cavity is high and operating frequency bandwidth 60 Hz is very narrow. Requirements for accelerating field amplitude 0.1% and phase 0.1° are very tight [1]. Lorenz force detuning (LFD) factor became a critical factor for cavity design optimization [2]. We introduce some modifications to dressed cavity design in order to reduce LFD coefficient. Also we need to keep very low sensitivity of operating mode resonance frequency to Helium pressure variations. Some modifications were added to simplify cavity tuner installation.

Cavity Mechanical Design Optimization

As mentioned above, the original design of the cavity and Helium vessel has been done for CW version of PIP-II project. For original design “as is” $LFD \sim 1.33 \text{ Hz}/(\text{MV}/\text{m})^2$ [3] i.e. 530 Hz of detuning for $E_{acc}=20 \text{ MV}/\text{m}$. Fig. 1 shows the cavity wall deformation corresponded to $E_{acc}=20 \text{ MV}/\text{m}$.

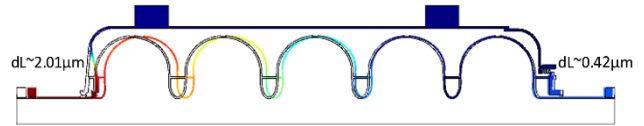


Figure 1: Wall deformation in original design.

On Fig. 1 are shown also 2 μm deformation of “coupler end” (left) and 0.42 μm of “tuner end” (right). Cavity sensitivity is $\sim 160 \text{ Hz}/\mu\text{m}$. It means that Helium vessel walls deformations have 70% impact on the LFD value. Having the goal to minimize the Helium vessel modifications, the obvious way to significantly reduce the LFD value is to strengthen its walls. Also to reduce LFD coefficient, reducing process included optimization of position and number for stiffening rings of the cavity. One and two rings were considered with radius of rings as a parameter for optimization. Low sensitivity to helium pressure variations and external vibrations is still necessary parameter during optimization.

One of the possible solution to reduce the LFD is adding the second stiffening ring in the cavity. Figure 2 shows the 3D view of COMSOL solid model. Two rings with radiuses R1 and R2 used in optimization process. Radius of stiffening ring in the end groups are the same as in original design. In these simulations we keep beam pipe flanges fixed.

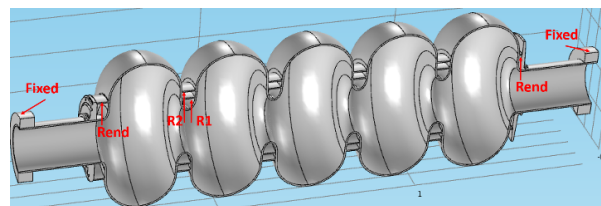


Figure 2: 3D view of COMSOL model with 2 rings.

In 2 rings option the cavity stiffness only depend on the position of the ring R2. Figure 3 shows the dependence of the stiffness vs. R2 radius. We decided to keep radius R2 not higher than 120mm to avoid the cavity over stiffening.

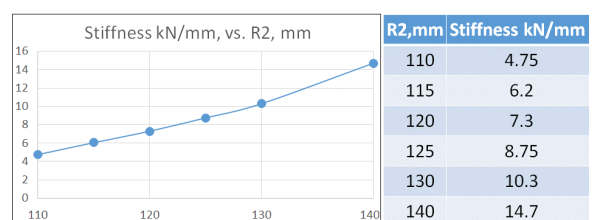


Figure 3: Cavity stiffness vs. position if the ring R2.

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[#]khabibul@fnal.gov

Figure 4 shows the results of 2 rings version simulations which has been done for R2=110 mm and 120 mm. One can see that the minimal LFD value reached for R2=120mm R1=87mm.

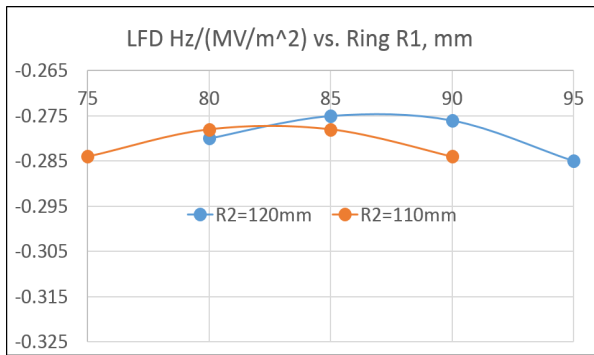


Figure 4: LFD vs. R1 for R2=110mm and 120mm.

Figure 5 shows the cavity wall deformations for optimal stiffening ring position in case of one and two rings with fixed beam pipe. For 2 rings LFD~0.275 Hz/(MV/m)² for 1 ring LFD~0.38 Hz/(MV/m)². Because the difference in LFD value for one and two rings options is not essential and the complexity of production of the cavity with two rings is high enough, we decided to use one ring option and redesign the end groups of original Helium vessel.

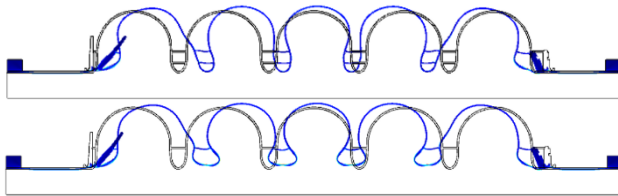


Figure 5: Cavity walls deformation in case of two rings (up) and one ring (down) for minimal LFD values.

HELIUM VESSEL DESIGN CHANGE

Stiffness of the helium vessel was not essential during dressed cavity optimization for CW operation. For pulsed operation only cavity design modifications still not enough to satisfy dressed cavity functional requirements and optimization of the helium vessel design started. Increasing stiffness of the helium vessel ends allowed to reduce LFD coefficient ~ 2 times.

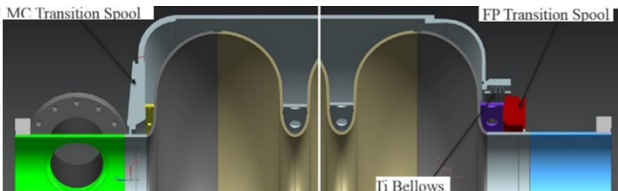


Figure 6: Optimized dressed cavity end.

The helium vessel is constructed using 5mm thick titanium sheets that are either rolled and seam welded or spun formed in sections, and circumferentially welded to the desired length. The vessel becomes an integral part of the analysis of the dressed cavity to achieve the functional requirements by welding it to the thick Nb55Ti transition

spool part shown in Fig. 6. Additional features include a 4” bi-metal transition that allows the cryomodule to transition to a stainless steel 2-phase line. There are also dual bi-metal transitions on the helium fill lines to allow the transition to a stainless steel line in the cryomodule, these are shown in Fig. 7. During the dressing stage, the helium vessel is slid over the field probe end of the cavity and welded to the main coupler end which is fixed. The field probe end features a sliding joint to allow for the differential lengths of the cavity due to processing and tuning.

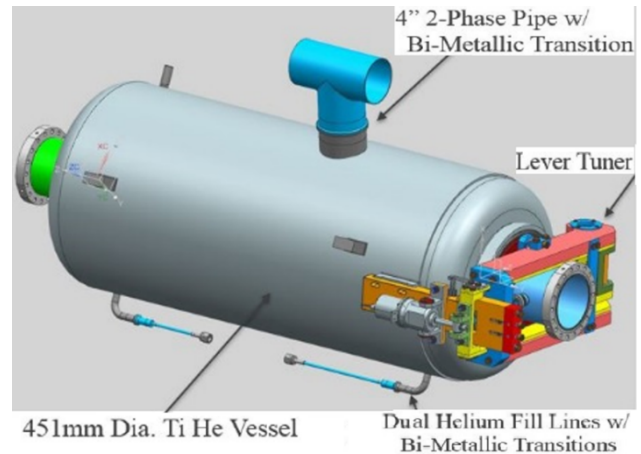


Figure 7: Dressed cavity.

STRESS ANALYSIS

The mechanical design of cavity – Helium vessel system have a scope of issues besides of LFD minimization. Cavity stiffness should have a suitable level to allow for cavity tuning. Sensitivity to microphonics due to helium pressure fluctuation (df/dP) and mechanical vibrations should be minimized. A cavity has to withstand mechanical stresses induced by a differential pressure between beam pipe vacuum and atmospheric pressure in the helium vessel, cool-down from room temperature to cryogenic temperatures, tuner mechanism operation etc.

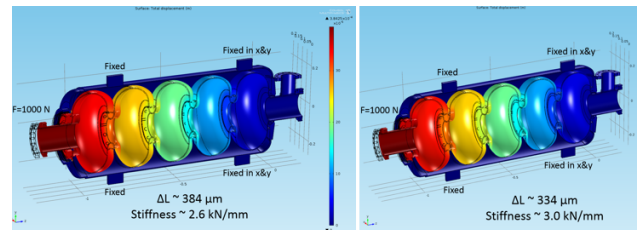


Figure 8: Cavity stiffness simulations. R=90mm (left) R=100mm (right).

Also dressed cavity has to be qualified in 5 different load conditions by stress analysis:

- Warm pressurization
- Cold operation at maximum pressure
- Cool down an tuner extension
- Cold operation at maximum pressure
- Upset conditions – insulating and beam vacuum failure.

After redesign of end groups of helium vessel, as described in previous section, COMSOL simulations for 2 different ring positions $R=90$ mm and $R=100$ mm has been done to address all issues mentioned above.

Figure 8 show the cavity stiffness simulations. For $R=90$ mm stiffness is 2.6 kN/mm for $R=100$ mm 3.0 kN/mm. This number are acceptable.

Figure 9 shows the values of LFD vs. stiffness of the tuner for two ring positions. Simulated tuner stiffness is higher than 60 kN/mm and we can expect that $|LFD|$ will be less than $0.75 \text{ Hz}/(\text{MV}/\text{m})^2$.

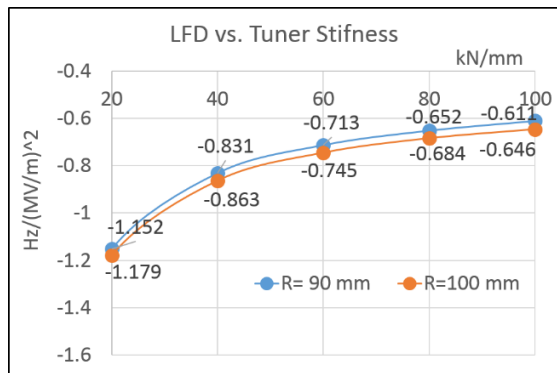


Figure 9: LFD vs. tuner stiffness for 2 ring positions.

Figure 10 shows the dependence vs. tuner stiffness of lowest transverse and 3 lowest longitudinal mechanical resonances for two ring positions.

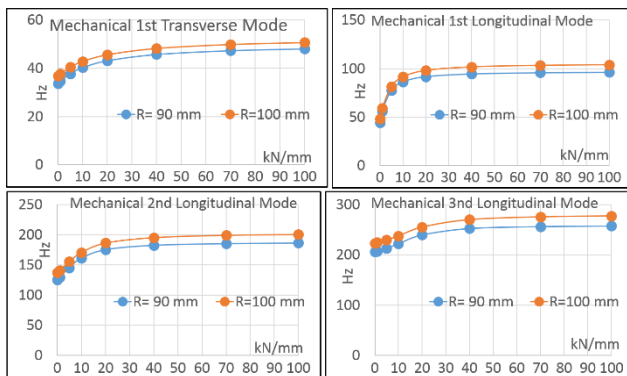


Figure 10: Mechanical resonances vs. tuner stiffness.

Figure 11 shows the dependence of df/dP vs. tuner stiffness for two ring positions. In case of tuner stiffness is higher than 60 kN/mm for both ring positions df/dP is less than 12 Hz/mbar.

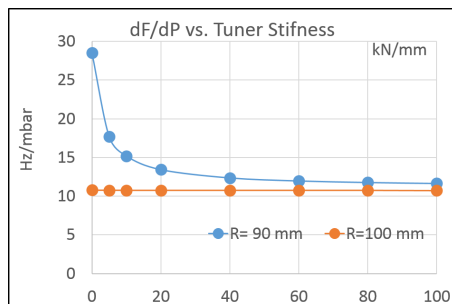


Figure 11: df/dP vs. tuner stiffness.

Finally, stress analysis of dressed cavity in 5 different load conditions mentioned above has been done. Figure 12 shows the solid model, Fig.13 shows detailed description of loads conditions and Fig. 14 shows the stress classification lines used in analysis.

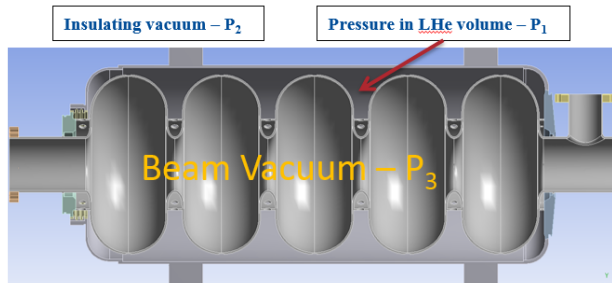


Figure 12: Solid model used in loads qualification.

Load Case	Loads	Condition Simulated	Applicable Temperature	Applicable Stress Categories
1	1. Gravity 2. $P_1 = 0.2 \text{ MPa}$ 3. $P_2 = P_3 = 0$	Warm Pressurization	293 K	$P_m, P_L, Q, P_m + P_b, P_L + Q$
2	1. Gravity 2. Liquid Helium head 3. $P_1 = 0.4 \text{ MPa}$ 4. $P_2 = P_3 = 0$	Cold operation, full LHe, maximum pressure – no thermal contraction	2 K	$P_m, P_L, Q, P_m + P_b, P_L + Q$
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. $P_1 = 0.4 \text{ MPa}$ 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. $P_2 = P_3 = 0.1 \text{ MPa}$	Insulating and beam vacuum upset, helium volume evacuated	293 K	$P_m, P_L, Q, P_m + P_b, P_L + Q$

Figure 13: Five loads conditions description.

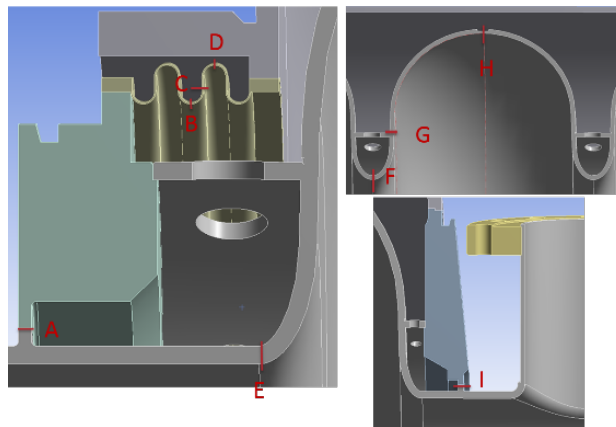


Figure 14: Stress classification lines.

All 5 load cases were qualified. All applicable stress categories has been evaluated at the stress classification lines (see Fig. 14) and are below allowable stresses.

POWER COUPLER UPDATE

Helium vessel modifications lead to moving power coupler port by 11 mm away from the cavity. RF simulations were provided in order to keep necessary coupling with the cavity and minor change were

introduced to power coupler design, Fig 15. Particularly antenna length and penetration to beam pipe increased by 6 mm.

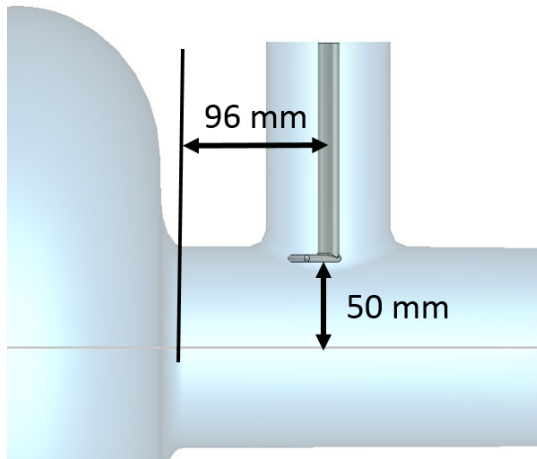


Figure 15: Coupler tip 50 mm from beam line.

CONCLUSION

Dressed HB650 cavity design was modified to satisfy new requirements for pulsed operation. Mechanical analysis of the 3D model done and drawings release process started. We planning to build several cavities next year and integrate to 1st HB650 cryomodule in 2017. Some of these cavities will be manufactured, processed and tested in India within scope of IIFC collaboration [4].

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