New Helium Vessel and Lever Tuner for the 650 Mhz Cavities for Project X*

I. Gonin#, M. Awida, E. Borissov, M. Foley, C. Grimm, T. Khabiboulline, M. Merio, Y. Pischalnikov, L.Ristori, V. Yakovlev, FNAL, Batavia, IL 60510, USA

Abstract

The proposed design of the 3 GeV Project X Superconducting Linac employs two families of 650 MHz 5-cell elliptical cavities with different β. The β_G =0.61 will cover the 177-467 MeV range. To cover the range between 467-3000 MeV two versions of 650 MHz 5-cell elliptical cavities with β_G =0.9 and β_G =0.92 has been proposed. The low beam current for CW operation of the Project X requires cavities to operate at a high loaded Q and thus, narrow bandwidth. Therefore it requires the optimal mechanical design of cavities to minimize the sensitivity to microphonics.

INTRODUCTION

Fermilab is currently developing a multi-MW proton source, Project-X (PX) [1], which will provide intense muon, kaon, neutrino and nuclei beams for broad and diverse program at the intensity frontier of particle physics. Possible future upgrades of Project-X may require operating linac in a regime of a high beam current, when an average beam current is 5 mA or even 10 mA. The design of 5-cell elliptical 650 MHz β_G =0.9 is under development at Fermilab. An alternative design of elliptical cavity with a larger aperture (59 mm) and β_G=0.92 is suggested for HE 650 MHz section in order to comply with various upgrade scenarios of the Project X linac [2]. The design of a dressed cavity (both β_G =0.9 and β_G =0.92) has been mechanically optimized by minimizing df/dP, the sensitivity to microphonics detuning due to fluctuations in helium pressure. The results for β_G =0.9 version has been presented at IPAC 2013 [3]. In this paper we will present the results of COMSOL simulations of df/dP, mechanical resonances and cavity tunability of an alternative β_G =0.92 cavity. We will also present the mechanical design of tuners and ANSYS analysis of their properties. The tuner system will be identical for both versions of cavities design.

HELIUM VESSEL DESIGN

The helium vessel assembly is constructed from a single 5 mm thick sheet of grade 2 titanium that is rolled and seam welded into a tube with an inside diameter of 441 mm and a length of 930 mm. Two helium fill ports are featured to allow for an even cool-down of the cavity. The helium vessel assembly is shown in Figure 1. The weld joint designs on the helium vessel satisfy the ASME Boiler & Pressure Vessel Code Section VIII Division 2. It is important to note that the 5 mm wall thickness for the helium vessel specification was not because of the ASME code, but rather to help in reducing *df/dP* by using the helium vessel to help stiffen the cavity.

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# gonin@fnal.gov

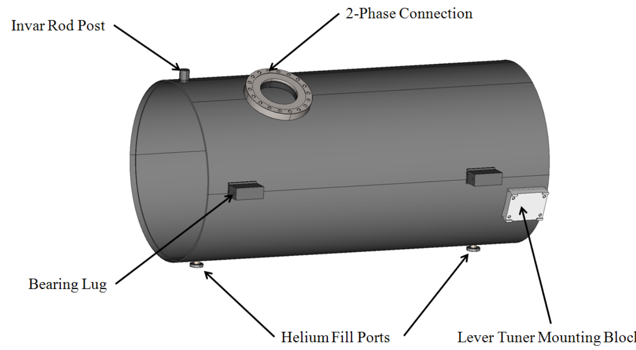

Figure 1: He vessel assembly.

The main coupler end and the field probe end of the helium vessel have slightly different joint designs due to the cavity installation sequence and variations in cavity lengths. The main coupler end of the vessel is considered a fixed position relative to the main coupler port of the cavity, and consistency between these key features for dressed cavities is maintained. Figure 2 shows the titanium-to-titanium TIG weld connection between the cavity and the helium vessel at the main coupler end. This joint design utilizes a backing ring and satisfies the ASME code.

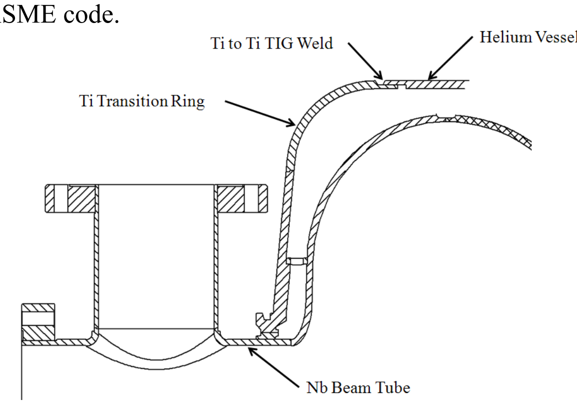

Figure 2: He vessel to cavity fixed joint design.

To allow for variations in the lengths of the manufactured cavities, the field probe end required a sliding joint design that would allow for cavity insertion from the field probe end to the main coupler end. As shown in Figure 3, cavities that vary by ±10 mm in length will not have any effect on the vessel design. This joint also satisfies the ASME code.

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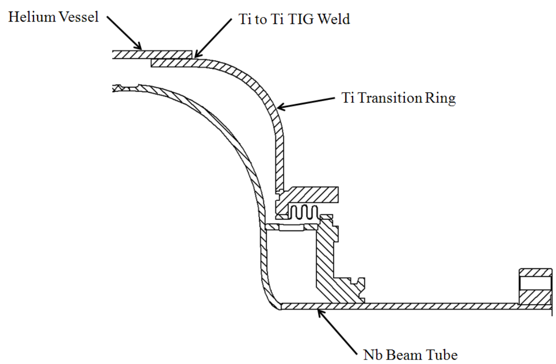

Figure 3: He vessel to cavity sliding joint design.

Dressed Cavity Pressure Boundary

Where practical, the overall cavity design must adhere to the ASME Boiler and Pressure Vessel Code. The pressure boundary will consist of the cavity walls, the connecting flanges, conical disks, and the helium vessel shell. This is outlined in Figure 4.

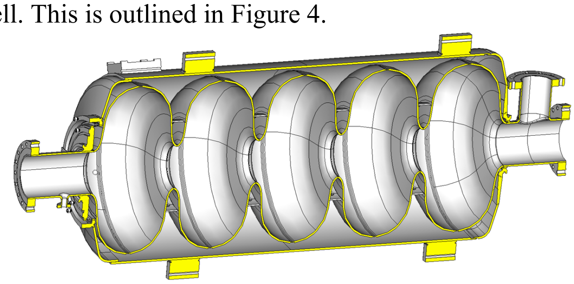

Figure 4: Pressure boundary of dressed cavity shown in yellow.

All electron-beam (EB) welds within the pressure boundary defined above are required to have a fully consumed joint: i.e. duel pass with full overlap or full penetration.

TUNER SYSTEM DESIGN

A compact fast/slow tuner for both versions of cavities has been developed for final tuning of the resonance frequency of the cavity after cooling down and to compensate frequency detuning due to the microphonics.

As shown in Figure 5, one end of the cavity is equipped with a lever tuner. The lever tuner was designed

- to tune cavity in the range of 200kHz.
- able to deliver up to 20kN forces on the cavity.
- fast tuning range up to 1kHz.

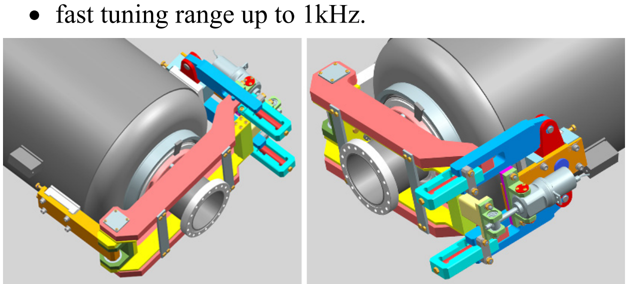

Figure 5: Lever tuner installed on dressed 5 cell cavity.

MECHANICAL ANALYSIS

The mechanical analysis of the β_G =0.92 650 MHz 5-cell elliptical cavity has been performed using the COMSOL and ANSYS FEA software. Figure 6 details a cross-section of the mechanical assembly including the niobium cavity shell and HV. Table 1 lists the material properties for 2K operating temperature used in the simulations. This assembly has different end groups – the left end group incorporates the slow and fast tuning systems and the right end group incorporates the main coupler.

The mechanical design of the cavity includes the following:

- Optimization of the df/dP, the sensitivity to microphonics detuning from fluctuations in helium pressure.
- Cavity tunability analysis.
- Incorporate the slow (stepper motor) and fast (piezo actuator) tuner designs. The slow tuner should be compact, reliable and provide the required tuning range, (about 200 kHz) keeping the cavity deformation below the yield limit.
- Simulations of cavity sensitivity to microphonics due to mechanical resonances and LFD.

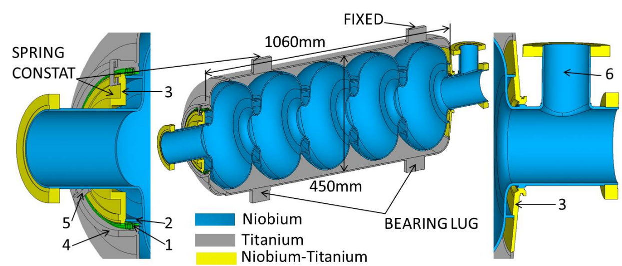

Figure 6: COMSOL model of mechanical assembly used in simulations. 1–bellows, 2–stiffening ring between end half-cell and conical flange, 3–conical flange, 4–bellows ring, 5–support brackets, 6–main coupler. Left – tuner end group. Right – main coupler end group.

Table 1: Mechanical Properties of Materials at 2K

	Young's modulus, GPa	Poisson's ratio	Density kg/m^3
Niobium	118	0.38	8700
Titanium	117	0.37	4540
Niobium-Titanium	68	0.33	5700

Optimization of df/dP

Initially the goal was to minimize df/dP as much as possible so we chose a middle stiffening ring radius of 134 mm (A) that resulted in df/dP < 5 Hz/mbar, however the cavity becomes quite stiff ~18 kN/mm at this ring radius. Room temperature RF tuning of the cavity was questionable. Afterwards, for an alternative β_G =0.92 cavity design we made a decision to sacrifice df/dP for the sake of making the cavity more tuneable and less stiff in order to avoid complicating the tuner design. A smaller

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diameter of bellows was proposed in order to help reduce df/dP of the dressed cavity.

COMSOL multiphysics 3D simulations of df/dP in the model presented in Fig. 6 has been done**.** The RF volume deformation induced by internal pressure determines the frequency shift. Boundary conditions used in calculations are:

- fixed displacement one of the bearing lug of Vessel.
- tuner stiffness is simulated by applying the spring constant K_{tuner}.

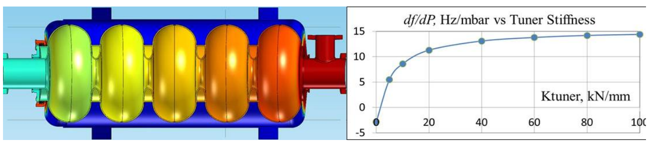

Figure 7: Total displacement for 1 bar internal pressure (K_{tuner} =20 kN/mm) and df/dP vs. stiffness of the tuner.

Fig. 7 shows the total displacements for an internal pressure of 1 bar with a 20 kN/mm tuner stiffness and dependence of df/dP vs. tuner stiffness. Modern cryogenic systems achieve rms pressure stabilities of ~0.2 mbar. It means, that even in case of infinite tuner stiffness, one can expect the maximum frequency deviation due to pressure fluctuation will be <4 Hz.

Mechanical Resonances

Mechanical resonances of cavities in a cryomodule can be excited by external vibrations. Fig. 8 represents the displacement plots of 10 lowest mechanical modes (7 of them are transverse T#1-T#7 and 3 longitudinal L#1-L#3). Boundary conditions used in the calculations are similar to the calculations described in the previous section. Fig. 8 shows the dependencies of the 3 lowest longitudinal modes vs. tuner stiffness.

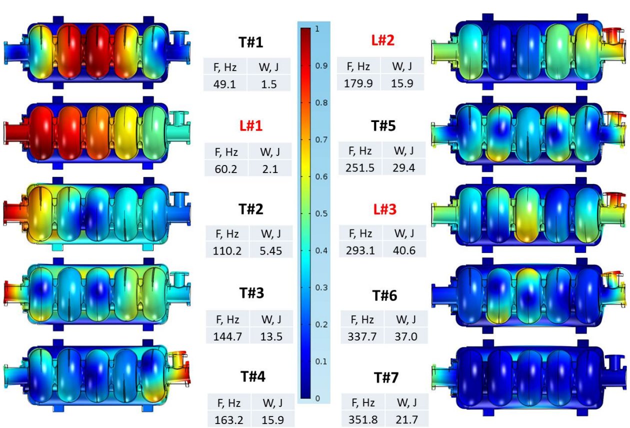

Figure 8: Frequencies, total energy, and COMSOL plots of normalized displacements of 10 lowest mechanical modes. Normalization is 1 mm maximum displacement.

ALLOWABLE WORKING PRESSURE

The dressed cavity has to be rated for a Maximum Allowable Working Pressure (MAWP) of 2 bar at Room Temperature (RT) and 4 bar at Cryogenic Temperature (CT). Preliminary structural analyses have been performed to verify that this requirement can be met. Different loading conditions have been studied; these are a combination of He pressure, dead weight, cooldown and tuner displacement. For each analysis, the Equivalent Stress is computed with finite element code and compared to the yield limit of the materials used (see Table 2). The results show that the MAWP required can be achieved under all the loading conditions.

Table 2: Yield Limit of the Materials Used for the Dressed Cavity

	Niobium	Nb-45Ti	Titanium, grade 2
RT (300 K)	38 MPa	475 MPa	275 MPa
CT (2 K)	317 MPa	544 MPa	834 MPa

Figure 9 shows the Von Mises Stress distribution for the cavity cooled down at 2 K and with a He pressure of 4 bar. The Equivalent Stress is below the yield of each material.

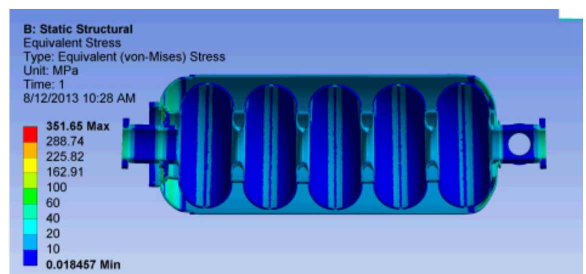

Figure 9: Equivalent Stress distribution at 2 K with 4 bar pressure applied.

Preliminary linear mechanical analyses have been done and show that the MAWP of 2 bar at RT and 4 bar at CT can be achieved. In the future, a set of linear, elastic plastic and local analyses will be performed to ensure that the dressed cavity complies with ASME Boiler and Pressure Vessel Code requirements.

REFERENCES

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