ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMK014

A NEW DESIGN FOR THE HILUMI RADIO-FREQUENCY DIPOLE BARE CAVITY*

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Abstract

Crabbing cavities are one of the technological landmark that will allow the LHC to optimize its performance and maximize its integrated luminosity by allowing a head-on collision between the bunches despite the non-zero crossing angle. A total of 8 crab cavities will be installed in the interaction region of each of the two experiments, ATLAS and CMS. In the last years, the two types of crab cavities were designed, built and tested under the US-LARP R&D program. Horizontal crabbing is obtained with a radio-frequency dipole cavity (RFD) designed by Old Dominion University (ODU), SLAC and Fermilab (FNAL). In this paper a new mechanical design, that uses passive stiffeners, is presented. This design leads to a decrease of the Lorentz Force Detuning frequency shift, satisfy the requirements on pressure sensitivity, validate the structural integrity and increase the tuner sensitivity and the maximum elastic tuning range. Furthermore, it will be possible to greatly simplify the shape of the magnetic shield and Helium vessel with respect to the current design.

INTRODUCTION

The requirements regarding the maximum allowable LFD, dF/dp and the maximum allowable working pressure for the RFD cavity are reported in Table 1 together with the nominal resonance frequency and the nominal deflecting voltage [1].

Table 1: RFD Main Parameters

Parameter	Value
Nominal Resonance frequency	400.790 MHz
Nominal Deflecting Voltage	3.4 MV
dF/dp	≤150 Hz/mbar
LFD coefficient at 3.4 MV	≤865 Hz/MV^2
Tuner sensitivity per side	~ 340 kHz/mm
Maximum elastic tuning range at 2K	644 kHz
Maximum allowable pressure at 293K	1.8 bar
Niobium shell thickness nominal	4 mm
Niobium shell thickness after BCP	3.85 mm
Pole stiffeners thickness after bulk and light BCP	6.2 mm

The yield stress σ_{ys} for the RRR 300 Niobium is set to 65 MPa from minimum acceptable yield stress reported in [2].

The conceptual design, shown in in Figure 1, satisfied the requirements of LFD coefficient (-851 Hz/MV^2 at 3.4 MV), dF/dp (-60 Hz/mbar) along with preserving the structural integrity at 1.8 bar [1].

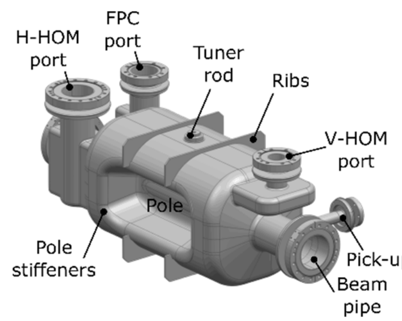

Figure 1: Conceptual design of the RFD.

These results are achieved because of the four ribs attached to the shell which minimize the displacements in the high magnetic field area, thus for the Slater perturbation theorem given in Eq. (1) [3]:

$$\frac{\omega_0-\omega}{\omega_0}=\frac{\int_{\Delta V}\left(\mu_0\left|\vec{H_0}\right|^2-\varepsilon_0\left|\vec{E_0}\right|^2\right)dV}{\int_V\left(\mu_0\left|\vec{H_0}\right|^2+\varepsilon_0\left|\vec{E_0}\right|^2\right)dV} \quad (1)$$

Despite the requirements being satisfied, the LFD coefficient is close to the upper limit of the requirement and unavoidable dimensional unconformities with respect to the nominal shape can lead to the non-satisfaction of this requirement. Furthermore, the four ribs complicate the shape, and thus the fabrication, of the magnetic shield. Additionally, the Helium jacket inner surface, for this conceptual design, is only two millimeters away from magnetic shield in the ribs area. In this paper a new design of the passive stiffeners for the RFD that improves the LFD coefficient and the tunability, satisfy the dF/dp requirement, simplify the design and fabrication of the magnetic shield and preserve the structural integrity, is presented.

NEW STIFFENERS DESIGN

Figure 2 shows the Lorentz pressure on the RF volume surface at the nominal field of 3.4 MV obtained from Comsol [4]. The surface integral of this pressure over the high electric field area (negative pressure values in Figure 2) is -125.4 N. The surface integral over all the remaining surfaces (positive pressure values in Figure 2) is 134.5 N. Since the high electric field region has a small surface compared to the high magnetic field region, its displacement will be much greater, thus for Eq. (1), the contribute of the high electric field regions to the frequency shift due to the Lorentz pressure is the most important.

* Work supported by Fermi Research Alliance, LLC under Contract No. DEAC02- 07CH11359 with the United States Department of Energy
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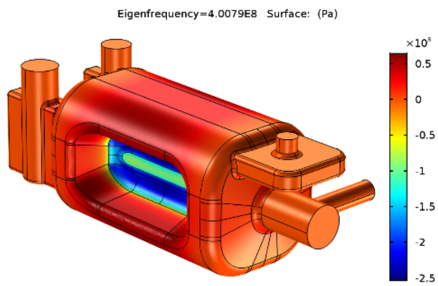

Figure 2: Lorentz pressure on the RF volume surface.

For the design of the stiffeners to be used to minimize the displacement due to the Lorentz pressure, Ansys Topology Optimization [5] is used. This tool allows to specify supports and loads located on the mechanical structure and to find the best shape that minimizes a user defined objective. For this analysis the compliance of the stiffeners is minimized, starting from a bulk volume of material attached to the central section of the cavity shell. The toolbox allows to specify which percentage of mass to retain and the minimum thickness of the optimized shape. For this simulation a 20% retain on the mass has been selected and a minimum of 4 mm is set as minimum thickness, which is the commonly used thickness of Niobium sheets for SRF cavity fabrication. Only a quarter of the central section is used for the optimization, taking advantage of the symmetry planes and of the fact that the end faces displace by less than an order of magnitude with respect to the pole when the Lorentz pressure is applied to the shell. As boundary conditions the end faces are fixed and the Lorentz pressure extracted from Comsol is applied on the inner surface of the shell. Figure 3 shows the geometry to be optimized (the quarter of the central section of the shell is colored in green and the stiffening volume is light-brown) and the result from the optimization are shown in Figure 4.

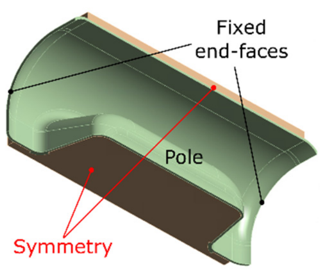

Figure 3 Geometry to be optimized

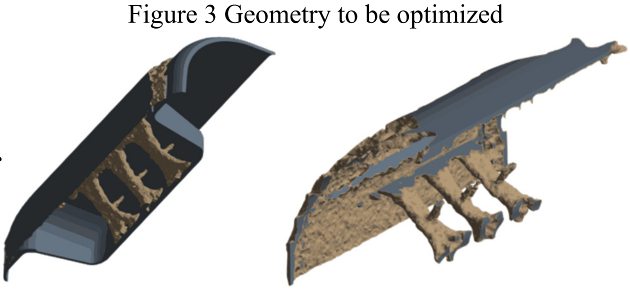

Figure 4: Optimized geometry.

The optimization results suggest a set of stiffening elements inter-connecting the center of the pole to the outer shell. Two simple 4 mm thick Niobium plates and a central strip are designed based on this result and shown in Figure 5. The elliptical hole at the center of the plates facilitate the inspection after welding and its dimension and position are based on a stress analysis that shows how this portion of the plates is unloaded when the Lorentz pressure is applied to the inner surfaces of the shell (Figure 6).

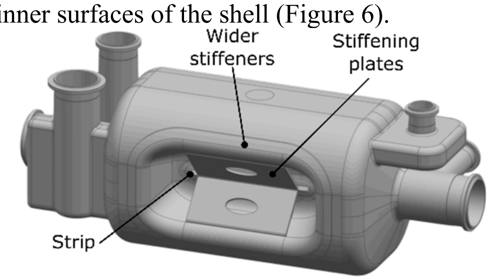

Figure 5: High electric region plates attached to the centre of the cavity pole help to reduce the displacements due to the Lorentz pressure.

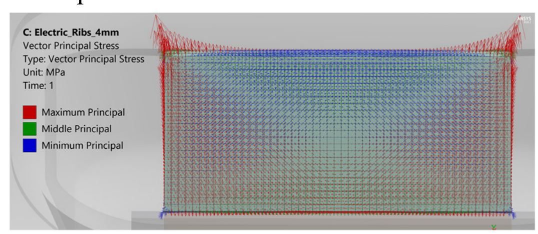

Figure 6: Principal stresses in the stiffening plates when the Lorentz pressure is applied to the inner surface of the cavity shell.

Figure 5 shows that the stiffeners around the cavity pole are wider with respect to the conceptual design. As it is shown in the final section of this paper, the region where these stiffeners are placed, is an area of high mechanical stress and the pole displacements, due to the Lorentz pressure and external pressure, are strongly affected by its rigidity. The stiffening plates and wider stiffeners do not extend out of the bounding volume of the central area, simplifying the design of the magnetic shield and maximizing the gap between the Helium jacket and the bare cavity.

Table 2 reports the results from the multiphysic simulations [4] for the cavity shown in Figure 5. The LFD coefficient has almost halved with respect to the conceptual design while dF/dp still satisfy the requirements.

Table 2: Parameters for the RFD with Stiffening Plates and Wider Stiffeners

Parameter	**Value**
dF/dp	-94.3 Hz/mbar
LFD coefficient at 3.4 MV	-477 Hz/MV^2

However, the stresses near the tuner rod for the working pressure of 1.8 bar are not acceptable for this new geometry. The linearized membrane plus bending stress equals to 118 MPa with an allowable of 52 MPa [6-7] (Figure 7). To strengthen this area, without adding new ribs that may create interference with the Helium vessel and will increase the number of welds to the shell, a simpler solution is adopted.

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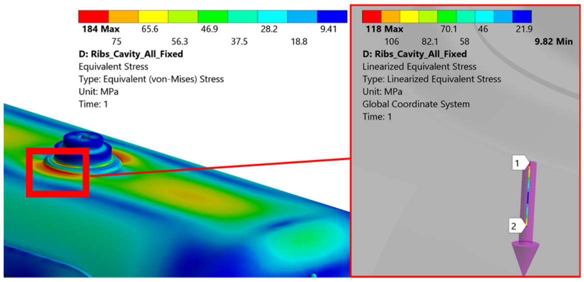


Figure 7: Von Mises and linearized stresses in the tuner rod area.

A racetrack with a nominal thickness of 6.35 mm is added to the tuning area as shown Figure 8. This racetrack increases the strength of the tuning area and greatly improve the tuning sensitivity as well as further reducing the LFD coefficient at the cost of slightly worse dF/dp.

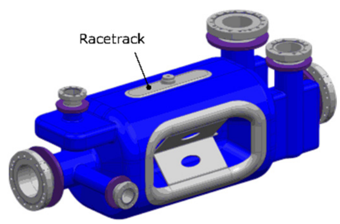
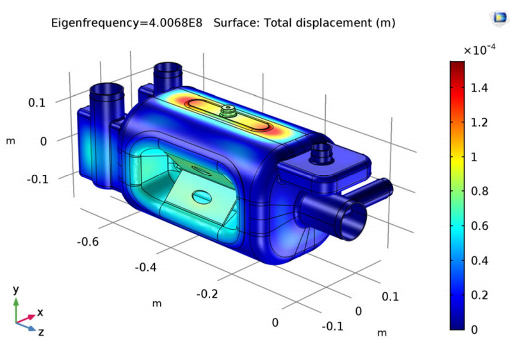
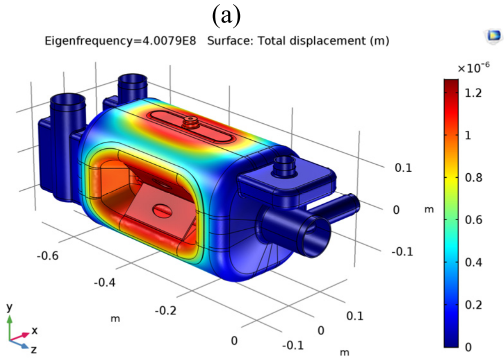


Figure 8: Final design for the RFD cavity.



(a)



(b)

Figure 9: Total displacement for 1 bar applied to the cavity shell surfaces (a), total displacement when the Lorentz pressure is applied to the cavity shell surfaces.

Figure 9 (a) shows the displacement when 1 bar of external pressure is applied to calculate dF/dp and Figure 9 (b) shows the displacement when the Lorentz pressure at nominal field (3.4 MV) is applied to the cavity shell surfaces.

Table 3 shows the final parameters for the final cavity design of Figure 8. The LFD coefficient has been amply reduced with respect to the conceptual design while dF/dp remain below the specified requirement. Furthermore, the tuner sensitivity per side is increased to a final value of 530 kHz/mm as well as the elastic tuning range to 1160 kHz.

Table 3 Parameters of the final design for the RFD

Parameter	**Value**
dF/dp	-113 Hz/mbar
LFD coefficient at 3.4 MV	-449 Hz/MV^2
Tuner sensitivity per side	~ 530 kHz/mm
Maximum elastic tuning range at 2K	1160 kHz

For the structural integrity analysis, the Limit-Load analysis method [6] is adopted as an alternative to the elastic analysis and stress linearization. The ASME code define the allowable stress for this analysis as $1.5S$, where $S = \frac{2}{3}\sigma_{ys}$. After Fermilab de-rating factor is applied [7] the allowable becomes 52 MPa and an elastic-perfectly plastic material model is used. Since convergence is achieved the component is stable under the applied load (Figure 10).

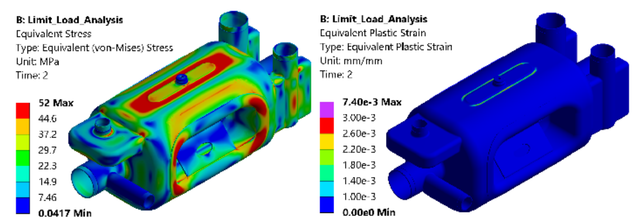


Figure 10: Limit-load analysis results: von-Mises stress and equivalent plastic strain.

CONCLUSION

The new design of stiffeners for the bare RFD cavity adequately satisfy the requirements of LFD coefficient at nominal field and dF/dp. Furthermore. the tuning sensitivity and the maximum elastic tuning range have been almost doubled with respect to the conceptual design and the region near the tuning rod is free from ribs, which will allow to greatly simplify the design of the magnetic shield and obtain the maximum gap between the Helium jacket and the bare cavity shell.

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