MULTIPHYSICS ANALYSIS OF CRAB CAVITIES FOR HIGH LUMINOSITY LHC UPGRADE*

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Abstract

Development of the superconducting RF crab cavities is one of the major activities under the high luminosity LHC upgrade project that aims to increase the machine discovery potential. The crab cavities will be used for maximizing and leveling the LHC luminosity hence having tight tolerances for the operating voltage and phase. RF field stability in its turn is sensitive to Lorentz force and external loads, so an accurate modelling of these effects is very important. Using the massively parallel ACE3P simulation suite developed at SLAC, we perform a corresponding multiphysics analysis of the electro-mechanical interactions for the RFD crab cavity design in order to ensure the operational reliability of the LHC crabbing system.

INTRODUCTION

The high luminosity LHC upgrade project [1] aims to broaden the machine potential after 2025. To increase the accelerator luminosity beyond the design value the use of the superconducting RF crab cavities [2] is planned.

Two cavity designs, namely RFD and DQW [3], are now under development to demonstrate the beam crabbing scheme. One of the major operational concerns of this scheme is the RF field stability that is sensitive to Lorentz force and external loads. To ensure tight tolerances for the deflecting voltage and phase a good understanding of the complicated multiphysics interactions within the crab cavity is required. In particular, the electro-mechanical coupling parameters for the beam dynamics and performance analysis must be determined.

Table 1: Selected Parameters of the RFD Crab Cavity

Parameter	Value
Frequency [MHz]	400
Crabbing Voltage [MV]	3.34
Operating Temperature [K]	2

In this paper we study the RFD cavity design (see Table 1 for the list of selected relevant parameters) and use the parallel ACE3P simulation suite [4] to calculate the effect of the Lorentz force and tuner displacement on the RF frequency, determine mechanical eigenmodes as well as their coupling to electromagnetic fields.

SIMULATION MODEL

We consider the 3D mechanical model of the RFD crab cavity in a helium tank that was reconstructed based on the original drawings preserving the total mass and external dimensions, see Fig. 1 and Table 2 for more details.

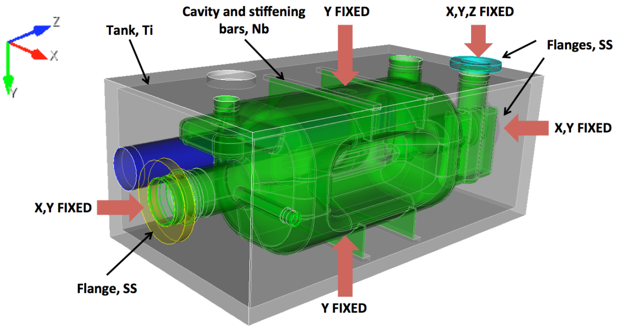

Figure 1: 3D structural model of the RFD crab cavity.

Table 2: Material Properties at 2 K

Material	Density [kg/m^3]	Poisson Ratio	Young's Modulus [GPa]
Nb	8700	0.38	118
Ti	4540	0.37	117
SS (316LN)	8000	0.29	193

The cavity mechanical interaction with the external world is a function of a complex supporting geometry, not fully designed at the time of the simulations. Same idea applies to the tuner and its frame. The boundary conditions are therefore a simplification, aimed at preserving the modes of the cavity inside the helium tank and are chosen as follows: the beam-pipe flanges are fixed in transversal plane and free longitudinally; the tuner (not shown in Fig. 1) is attached to the cavity constraining it vertically; the fundamental power coupler is fixed in all three directions.

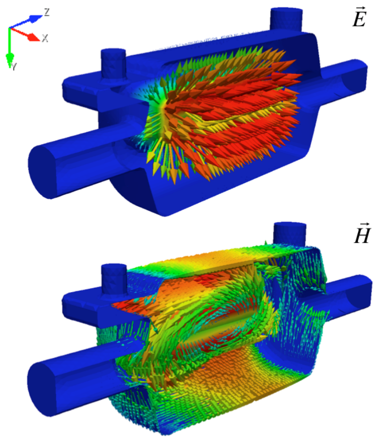

Figure 2: Electric (top) and magnetic (bottom) fields [a.u.] in the RFD cavity for the crabbing 400 MHz mode.

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For the corresponding RF calculations we use the vacuum model of the RFD crab cavity. The model and the electromagnetic fields for the crabbing 400 MHz mode are shown in Fig. 2.

LORENTZ FORCE DETUNING

Using the calculated deflecting fields, the pressure distribution on the cavity walls is determined – see Fig. 3.

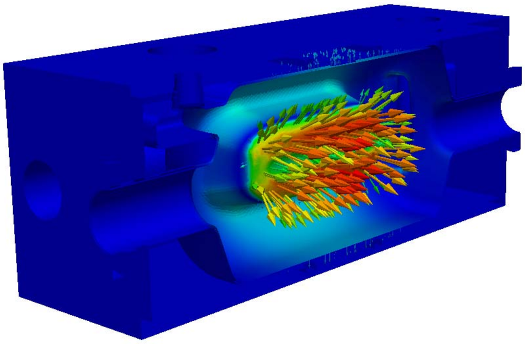

Figure 3: Electromagnetic pressure distribution [a.u.] on the RFD cavity walls for the 400 MHz crabbing mode.

To normalize this pressure to the crabbing voltage (V_x) of 3.34 MV we used two approaches both leading to the same results. First, Panofsky-Wenzel theorem [5], that relates the crabbing voltage V_x to the longitudinal voltage V_z for a given offset dx. Second, calculating V_x directly using the electromagnetic fields on the beam axis.

The normalized RF pressure served as a boundary condition on the cavity walls for the ACE3P multiphysics solver and the deformations due to the Lorentz force were simulated - see Fig. 4.

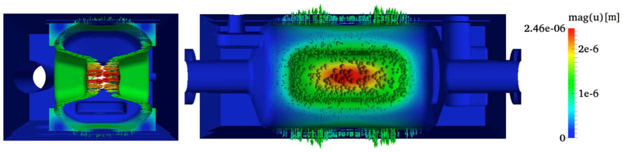

Figure 4: Displacements due to the Lorentz force shown on transverse (left) and longitudinal sections (right) of the dressed RFD cavity.

Performing the coupled RF study we determined the resulting RF frequency shift (Δf_L) and the Lorentz force detuning coefficient ($k_L = \Delta f_L / V_x^2$) to be -6639 Hz and -595.1 Hz/MV^2, respectively.

TUNER DISPLACEMENT

To compensate for the Lorentz force and other effects the tuning system is designed for the crab cavities [6]. To model the deformation caused by the tuner the top and bottom tuning surfaces (indicated in Fig. 1 as vertical red arrows) are 'pushed' towards the cavity center imposing the vertical displacement (dy) of 10 um on each of them. The resulting static deformations are shown in Fig. 5.

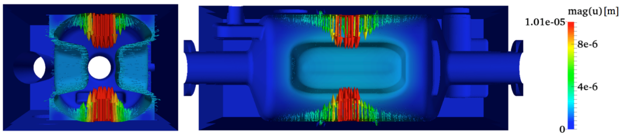

Figure 5: Displacements due to the tuning shown on transverse (left) and longitudinal sections (right) of the dressed RFD cavity.

Based on the structural deformations, we calculated the corresponding RF frequency shift (Δf_T) to be 10594 Hz. The RF frequency sensitivity with respect to the distance change between the tuning plates ($k_T = \Delta f_T / (2*dy)$) was determined to be 529.5 Hz/um. Since Δf_L and Δf_T have different signs, the tuner displacement $dy = \Delta f_L / (2*k_T) \approx 6.3$ um compensates for the frequency shift due to the Lorentz force.

In Fig. 6 the residual displacements of the cavity walls are shown in the case when the tuner compensates for the Lorentz force, essentially tuning the cavity to the nominal RF frequency of 400 MHz.

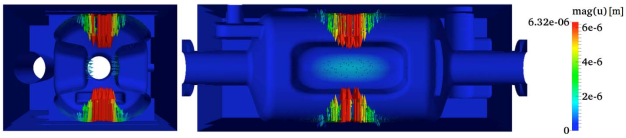

Figure 6: Residual displacements on the cavity walls due to the tuner compensating for the Lorentz force shown on transverse (left) and longitudinal sections (right).

MODAL ANALYSIS

Using the ACE3P mechanical eigenvalue solver [7] we simulate the natural modes of the dressed RFD cavity. In Table 3 the frequencies of the lowest 20 modes are presented. The values may be slightly overestimated since the mass of the liquid helium within the tank and other associated effects are not taken into account.

Table 3: Frequencies of the 20 Lowest Mechanical Modes for the Dressed RFD Cavity

Mode #	Frequency [Hz]	Mode #	Frequency [Hz]
1	175	11	454
2	220	12	496
3	274	13	526
4	289	14	570
5	365	15	575
6	375	16	587
7	382	17	590
8	388	18	620
9	435	19	624
10	450	20	625

If the gradient changes rapidly or external vibrations couple to the cavity some of the mechanical modes may be excited. To calculate their effect on RF we performed the spatial decomposition of the Lorentz force and tuner displacements in a way similar to [8]. On top of that we determined the contributing modes to the frequency shifts of the cavity, see Table 4. Some discrepancy between the static frequency shifts and the finite summations indicates that there are also contributions from the modes at higher frequencies.

Table 4: RF Frequency Shifts Due to the Contributing Mechanical Modes Identified by the Spatial Decomposition of the Lorentz Force and Tuner Displacements

Mode #	Frequency [Hz]	Δf_L [Hz]	Δf_T [Hz]
3	274	-1	3
4	289	-1	3
5	365	-4	9
7	382	-3	6
8	388	-9	17
9	435	-394	772
10	450	-2 505	4 752
11	454	-1 305	2 455
12	496	-17	29
13	526	-2	4
…	…	…	…
Sum over 20 modes		-4 235	8 039
Static frequency shift		**-6 639**	**10 594**

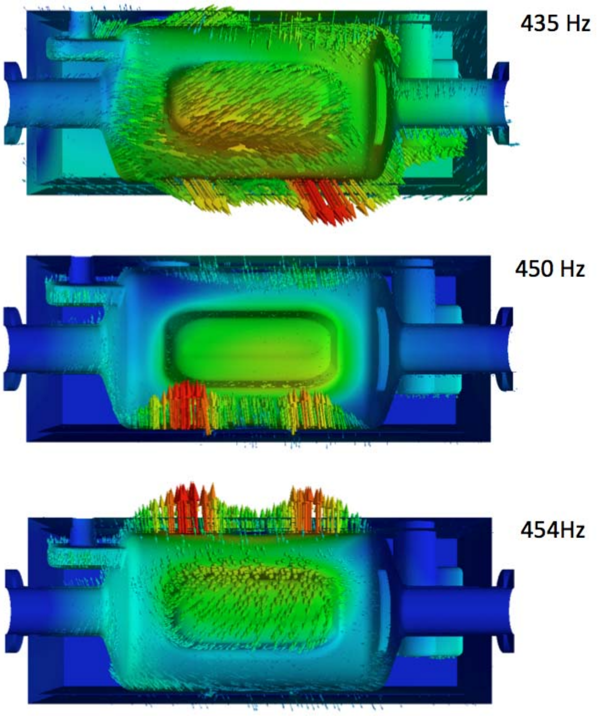

Figure 7: Displacement magnitudes [a.u.] of the mechanical modes at 435, 450 and 454 Hz (from top to bottom) having significant impact on RF frequency.

As demonstrated in Table 4, the modes number 9 (435 Hz), 10 (450 Hz) and 11 (454 Hz) significantly contribute to the RF frequency shift. Studying their spatial patterns (see Fig. 7) they appear to be nothing but the natural vibrations of the top and bottom cavity plates. These mechanical modes have rather high frequencies and are unlikely to be excited, however, if microphonics or gradient change couple to them it could have significant impact on the cavity performance.

CONCLUSION

Lorentz force detuning, tuner displacement and mechanical modes have been studied for the dressed RFD crab cavity using the ACE3P codes. It is demonstrated that the lower frequency modes (less than 400 Hz) have insignificant coupling to RF. However, if the top or bottom cavity plates hit the resonances at 435, 450 or 454 Hz this may have significant impact on detuning.

Further steps will include refinement of the RFD model with supports and tuner frame, analysis of the DQW design, calculation of the cavity response due to external vibrations as well as their effects on deflecting voltage and RF phase.

ACKNOWLEDGEMENT

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