NUMERICAL CALCULATION OF THE LORENTZ FORCE DETUNING AND THE PRESSURE SENSITIVITY FOR THE HL-LHC CRAB CAVITY *

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Abstract

Crab cavities are fundamental components of the HL-LHC upgrade project. These Radio Frequency cavities, operated at the appropriate frequency, 'tilt' the proton bunches to increase the luminosity at the collision points IP1 (ATLAS) and IP5 (CMS). Two different superconducting crab cavities were developed: RF Dipole (RFD) for horizontal deflection and Double Quarter Wave (DQW) for vertical deflection. During operation, the cavity walls are deformed due to the loading conditions. This deformation changes the electro-magnetic field inside the cavity and consequently its RF frequency. In the present study, the numerical evaluation of the Lorentz Force Detuning (LFD) and the Pressure Sensitivity (PS) of the DQW cavity, using COMSOL Multiphysics, is presented. The LFD is the fundamental frequency change of the cavity due to the electromagnetic forces acting on its walls, while the PS is the frequency shift when the cavity is subjected to pressure fluctuations of the helium bath. Finally, a comparison with the results measured during the cold test of the manufactured cavities, and with the previous simulations results obtained for the RFD cavity is done.

INTRODUCTION

During the operation of the crab cavities on a particle beam, the RF frequency of the EM fields in the cavity must correspond to the energy of the traversing particles [1]. To have the resonant RF frequency of the cavity as close as possible to this frequency, a mechanical tuner [2] is used to deform the cavity walls which is a relatively slow action. It is important to assess and mitigate the dynamic frequency variations due to LFD and PS. The present contribution evaluates LFD and PS of the DQW cavity using COMSOL Multiphysics 6.0. For this purpose, RF-structural coupled calculations were performed following the procedure described in [3]. To confirm the numerical model used in the present work, simulations of the bare and the cavity with the Helium tank (jacketed cavity) were done in the test conditions at 2 K in a liquid helium bath. The results are compared with the measurements during the cold tests of the manufactured bare and jacketed cavities. Finally, the LFD and PS of the jacketed cavity in nominal operating conditions are determined and compared with previous simulation results obtained for the RFD cavity.

NUMERICAL MODEL

The numerical model includes two different domains (Fig. 1): one for structural purposes (cavity body, four pre-tuner- and two tuner connectors), and a domain for the RF calculations (the vacuum volume inside the cavity body). The calculations are carried out with the nominal geometry and wall thickness of the cavity after chemical polishing. Its thermal contraction to 2 K is also considered.

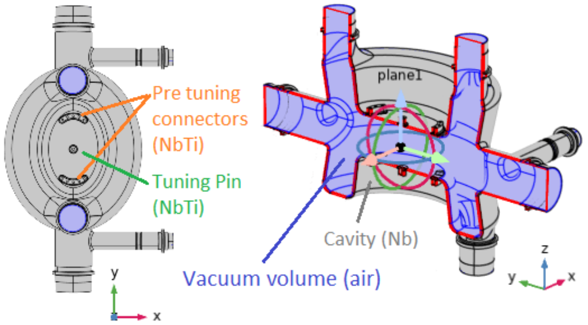

Figure 1: Model section.

SIMULATION CASES

Simulations were performed for the following three conditions.

Cold Test of the Bare Cavity

The Bare Cavity (BC) is connected to a stiffening frame (Fig. 2) to protect it, during tests in liquid helium, against pressure variations in the cryostat. This is needed in the absence of the Helium tank to avoid plastic deformations. The cavity is supported on one beam port flange and guided in the beam axis direction. The High Order Mode filter (HOM) and Fundamental Power Coupler (FPC) ports are all closed with flanges and connected to the stiffening frame, while the pick-up ports and tuning connectors are not constrained. Finally, the pre-tuning connectors (Fig. 1) on the poles of the cavity are also connected to the stiffening frame. To reduce the model size for both LFD and PS calculations, springs representing the calculated stiffness of the stiffening frame are placed at the appropriate interfaces.

Cold Test of the Jacketed Cavity

The "Jacketed Cavity" (JC) is the bare cavity assembled inside six Titanium grade 2 walls, bolted and welded together forming the helium vessel (*viz.* He-tank). All the cavity ports are bolted and welded to the He-tank walls. HOM filters or FPC are not present, and all ports are closed

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by flanges. Parts of a mechanical pre-tuner are connecting rigidly the pre-tuning connectors (Fig. 1) on the poles to the He-tank. The tuning rods connected to the centre of the cavity poles and the pick-up ports remain free in the numerical model, given that they are connected through bellows to the tank. To test the JC in a liquid helium bath, the cavity is supported on one beam port flange in the same way as the BC (Fig. 3). In the numerical model the tank walls are replaced by fixed boundary conditions on the cavity ports, considering a high stiffness of the He-tank. The cavity pre-tuner is represented by a spring with separately calculated stiffness between the pre-tuner connectors on the two poles.

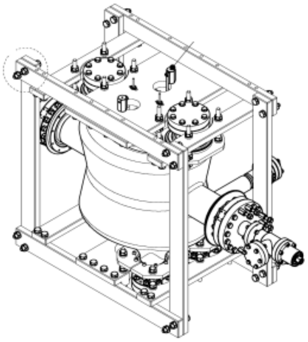

Figure 2: Cold test set-up of the bare cavity.

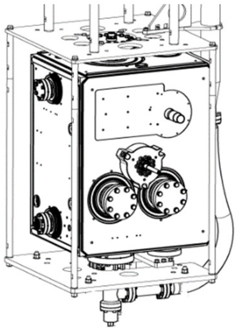

Figure 3: Cold test set-up of the jacketed cavity.

Jacketed Cavity in Operation

An active tuner system is used to change the fundamental frequency of the cavities during operation inside the cryomodule [2]. It applies a symmetric vertical deformation on the two cavity poles, through the tuning rods connected to the tuning pins (Fig. 1). The boundaries in the numerical model are identical to the cold test of the JC, with, additionally, a spring of 6.9 kN/mm between the two tuning connectors, representing the current tuner system stiffness.

PS AND LFD LOADS

For the PS value calculation, a pressure of -1 bar is applied on the internal surface of the cavity. However, the typical variation of the helium bath pressure in the test cryostat is of the order of one mbar, a value that is used to calculate the maximum deformation (Fig. 4).

For the LFD calculation, an electro-magnetic pressure is applied instead, which depends on the electric and magnetic fields in the cavity at the nominal field. COMSOL scales the electromagnetic fields to some value of the stored energy inside the cavity (U_{COMSOL}). Therefore, to calculate the electromagnetic fields at the nominal deflecting voltage ($V_{nominal} = 3.4$ MV), the stored energy is scaled to the energy present at the nominal deflecting voltage ($U_{V_{nominal}}$) [3].

$$U_{V_{nominal}} = U_{COMSOL}\ x\ \left({}^{V_{nominal}}/_{V_{COMSOL}}\right)^2$$

RESULTS

The maximum calculated deformations of the jacketed cavity, induced by a 1 mbar He pressure fluctuation (Fig. 4), is observed at the poles, with a higher and broader displacement on the less stiff bottom pole, at the side without HOM. The maximum deformations due to Lorentz forces at nominal field (Fig. 5) are more centred on the cavity poles, symmetric and a factor of ten larger than the deformation due to a 1 mbar pressure fluctuation.

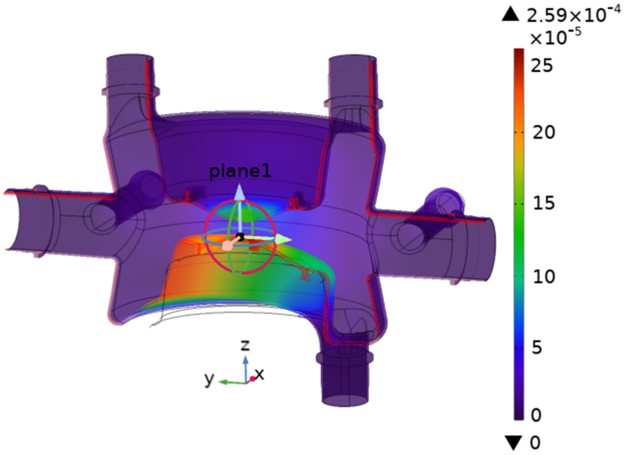

Figure 4: PS jacketed cavity. Total displacement of the cavity walls (mm) for 1 mbar.

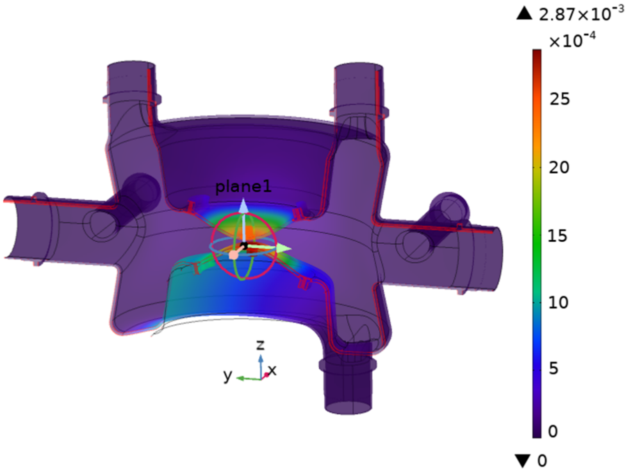

Figure 5: LFD jacketed cavity. Total displacement of the cavity walls (mm) at nominal field.

The calculated deformations induced by pressure and Lorentz forces in the bare cavity walls during the cold test, have the same shape as for the jacketed cavity, but are more significant in magnitude. This is also reflected in the higher PS and LFD of the BC compared to the JC, both for the calculations and experimental measurements [4], as shown in Table 1. The stiffening frame connecting the HOM and FPC ports and the pre-tuner parts of the bare cavity during the cold tests, is significantly less stiff than the He tank of the jacketed cavity. This implies that the LFD and PS values of the jacketed cavity are more significant for operation than the values of the bare cavity.

There is a very good agreement between calculated and measured results, with a maximum difference of 17%. Differences are likely to be explained by the simplified boundary condition in the models, geometry and wall thickness differences, and material parameters. More complete (and time consuming) models are for the moment not required.

Table 1: LFD and PS values calculated and measured for jacketed (JC) and bare cavity (BC)

	LFD [Hz/MV^2]	**PS [Hz/mbar]**
JC calculated	-256	-215
BC calculated	-418	-494
JC measured	-218	-244
BC measured	-358	-422

With the validated DQW JC model and an additional spring for the tuner stiffness, the values of the PS and LFD during operation were computed (Table 2) and compared to the RFD calculated values [3].

Table 2: LFD and PS values calculated operation values for DQW and RFD

	LFD [Hz/MV^2]	**PS [Hz/mbar]**
DQW	-126	-110
RFD	-659	-244

The stiffness of the tuning system of the DQW cavity decreases the jacketed cavity LFD and PS values almost by a factor of two. To further evaluate and possibly optimise the influence of the tuning system stiffness, a parametric study of the tuning system stiffness was performed (Fig. 6). As expected, the absolute values of PS and LFD of the cavity decrease with the stiffness of the tuning system. The decrease is however non-linear. Further increase in the tuner stiffness beyond the current 6.9 kN/mm will not create a sufficient gain against dynamic perturbations.

Table 2 indicates that the RFD cavity is significantly more sensitive than the DQW cavity to pressure variations and electromagnetic forces. This can be in the first place explained by the stiffer geometry of the DQW cavity. In addition, the DQW has the pre-tuner, which constraints the deformation of the cavity poles making this cavity even stiffer than the RFD. This is especially noticeable in the case of the LFD where the main part of the deformation occurs at the poles for both cavities. Finally, as reported in [3], the tuner has an adverse effect on the pressure sensitivity in the RFD cavity where the tuner is connected to a different magnetic field part of the cavity, reducing the effect where two parts of the RFD cavity have a PS with opposite signs.

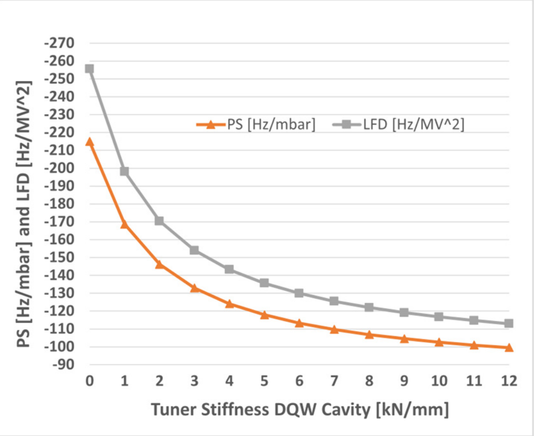

Figure 6: DQW PS and LFD as a function of the tuning system stiffness.

CONCLUSION

Coupled RF-structural simulations to compute the PS and the LFD of the DQW cavity were made. First, simulations of the cold tests of the bare and jacketed DQW cavity have been performed with COMSOL Multiphysics. The simulation results have been compared with the values measured during cold tests of the manufactured cavities at CERN. A very good agreement has been found between the numerical and the experimental results, with the maximum difference of 17%. Finally, the calculated PS and LFD of the DQW cavity in nominal operating conditions (with tuner attached), are determined and compared with the values of the RFD previously calculated. It can be stated that the DQW cavity is stiffer than the RFD cavity due to its shape, the presence of the pre-tuning system, and the tuning system used. A parametric analysis shows that the current DQW tuner stiffness is optimal for reducing LFD and PS.

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