ELECTRO-MECHANICAL MODELING OF THE LCLS-II SUPERCONDUCTING CAVITIES*

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Abstract

The 4 GeV LCLS-II superconducting linac will contain 280, 1.3 GHz TESLA-style cavities operated CW at 16 MV/m. Because of the low beam current, the cavity bandwidth will be fairly small, about 32 Hz, which makes the field stability sensitive to detuning from external vibrations and He pressure fluctuations. Piezo-electric actuators will be used to compensate for the detuning, which historically has been difficult at frequencies above a few Hz due to excitation of cavity mechanical resonances. To understand this interaction better, we have been doing extensive modeling of the cavities including mapping out the mechanical modes and computing their coupling to Lorentz forces, external vibration and piezo actuator motion. One goal is to reproduce the measured detuning response of the piezo actuators up to 1 kHz, which is sensitive to how the cavities are constrained within a cryomodule. In this paper, we summarize some of findings.

INTRODUCTION

The LCLS-II project [1] has adopted TESLA-style superconducting cavities [2] for the 4 GeV CW linac being built at the SLAC National Accelerator Laboratory. It will deliver high-brightness, high-repetition-rate electron beams that will drive an X-ray FEL. When operating the narrow bandwidth (BW) TESLA cavities at 16 MV/m, feedback systems [3] will be used to stabilize the cavity fields and frequencies. The BW of the latter is limited by the response of the cavity mechanical resonances.

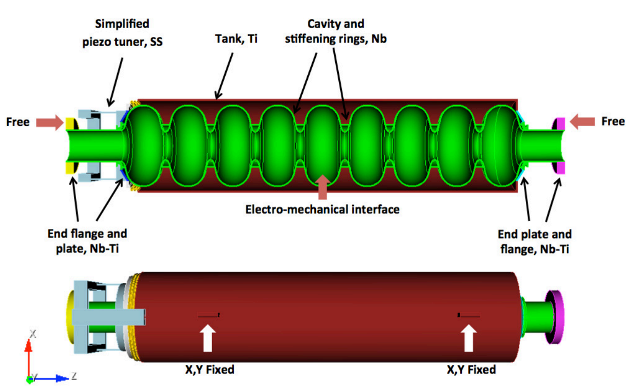

Figure 1: 3D mechanical model of the TESLA cavity.

To understand this effect better, we performed extensive analysis of the coupled electro-mechanical interaction between the RF fields, cavity motion and deformations. The massively-parallel ACE3P simulation suite [4] was used to determine mechanical eigenmodes of the cavity, their coupling to Lorentz and piezo tuner [5] forces as well as to calculate the corresponding RF responses.

In this paper the 3D cold mechanical model of the superconducting TESLA cavity in a helium vessel is considered, where the piezo-electric tuner is replaced by the spring of equivalent stiffness, i.e. 30 N/um [5]. The model, material details and boundary conditions are shown in Fig. 1.

We also study the corresponding vacuum model of the cavity, which is used to calculate RF detuning due to mechanical deformations - see Fig. 2.

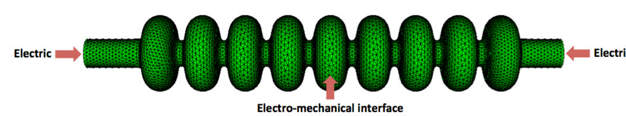

Figure 2: Meshed vacuum model of the TESLA cavity.

The electro-mechanical interface, essentially the cavity internal surface shown in Fig. 1 and Fig. 2, serves as the boundary between the RF and mechanical simulations.

MECHANICAL EIGENMODES

Using the mechanical model we have simulated eigenmodes of the TESLA cavity. The frequencies of the first 20 modes are shown in the Table 1.

Table 1: Eigenmodes of the cavity, longitudinal modes are listed in red.

Mode #	Frequency [Hz]	Mode #	Frequency [Hz]
1	51	11	260
2	57	12	265
3	103	13	299
4	133	14	350
5	145	15	351
6	179	16	386
7	185	17	395
8	221	18	438
9	239	19	441
10	254	20	463

In Fig. 3 we show the surface displacements, indicated in magnitude and direction by the color scale and arrows, for the transverse mode at 57 Hz as well as for two longitudinal modes at 239 Hz and 299 Hz.

It should be noted here that this simulation doesn't take into account any damping or friction nor the effect of the liquid helium within the tank.

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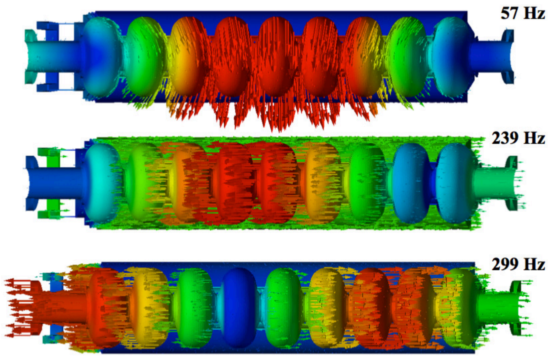

Figure 3: Displacements of mechanical modes at 57, 239 and 299 Hz.

LORENTZ FORCE DETUNING

Using the vacuum model of the TESLA cavity we simulate the RF field distribution at 1.3 GHz for the accelerating mode - see Fig. 4.

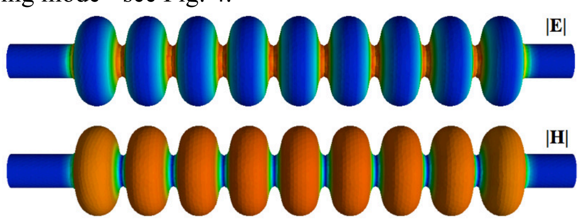

Figure 4: Complex magnitudes of electric (top) and magnetic (bottom) fields for the 1.3 GHz acceleration mode.

RF pressure on the cavity walls (Lorentz force) is calculated based on the following standard formula:

$$\vec{P} = \frac{1}{4}\left(\mu\left|H(x,y,z)\right|^2 - \varepsilon\left|E(x,y,z)\right|^2\right)\vec{n},$$

and used as the boundary condition on the electromechanical interface for the ACE3P structural solver.

Normalizing the electromagnetic fields to an acceleration gradient (G) of 16 MV/m, we computed the mechanical deformation due to the static Lorentz force - see Fig. 5. These displacements were used to compute the resulting RF frequency shift, Δf = -276 Hz, and the Lorentz force detuning coefficient, $k_L = \Delta f / G^2$ = -1.08.

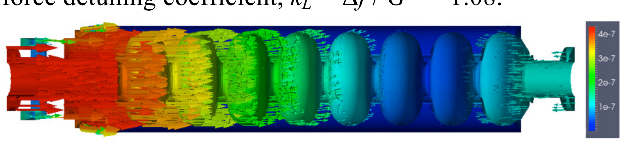

Figure 5: Displacements due to the static Lorentz force.

CAVITY RESPONSE TO STATIC PIEZO LOAD AND MODE DECOMPOSITION

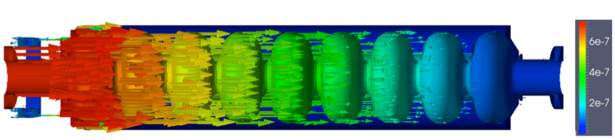

Figure 6: Displacements due to a static piezo load.

The static piezo load was modeled by ‘pushing’ the ends of the simplified piezo tuner in the opposite directions, i.e. ‘pushing’ the cavity against the tank. The displacements caused by the static pressure of 1 MPa are illustrated in Fig. 6.

According to [6], the displacements and the corresponding RF frequency shift due to the external loads can be expanded in terms of the mechanical modes. Using the decomposition tool recently developed in the ACE3P simulation suite, we computed the overlap of the mode spatial patterns with the static Lorentz force (LF) and static piezo tuner (PZT) induced displacements. The results of this decomposition are presented in the Table 2.

Table 2: Spatial decomposition of displacements from the Lorentz and piezo tuner forces for the contributing modes, longitudinal cavity modes are shown in red.

Mode #	Frequency [Hz]	Δf_{LF} [Hz]	Δf_{PZT} [Hz]
9	239	-21	-42
13	299	-135	-156
21	480	-9	-22
26	598	-27	-7
30	687	-1	-3
35	768	1	12
45	931	-9	-9
…	…	…	…
Sum over 50 modes		-200	-227
Static frequency shift		-276	-219

It can be seen that displacements for the static Lorentz force mostly couple to the longitudinal modes, meaning that only these modes would be excited if the RF gradient changes. The 28% discrepancy between the static frequency shift and the finite summation over the first 50 modes (up to ~1.1 kHz) indicates that there are also contributions from modes at higher frequencies.

Displacements for the piezo actuator force couple to the same modes as for the Lorentz force, although with somewhat different strengths, providing a way to compensate its effect. A smaller discrepancy exists between the static frequency shift and the finite summation for Δf_{PZT}. This is due to the fact that the piezo force results in a more 1-D like displacement than the essentially 2D Lorentz force - this is clearly seen by comparing displacements in Fig. 5 and Fig. 6.

CAVITY RESPONSE TO PIEZO MOTION

The piezo-actuator motion was simulated in the frequency domain by using the ACE3P harmonic response solver [7]. The ends of the simplified piezo tuner were ‘pushed’ in the opposite direction with a sinusoidal amplitude of 1 MPa and the effect on RF frequency was recorded for mechanical frequencies from 0 to 1 kHz.

In this simulation we took into account mechanical damping by employing the Rayleigh proportional model described in [8]. Having no reliable measurements for the LCLS-II TESLA-like cavities, the amount of damping was assumed to be 0.3%, the value experimentally deter-

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mined during the development of similar accelerating structures [9].

To bound the problem, RF detuning was calculated for two piezo tuner stiffnesses, k_{PZT} = 30 N/um and k_{PZT} = 220 N/um - see Fig. 7.

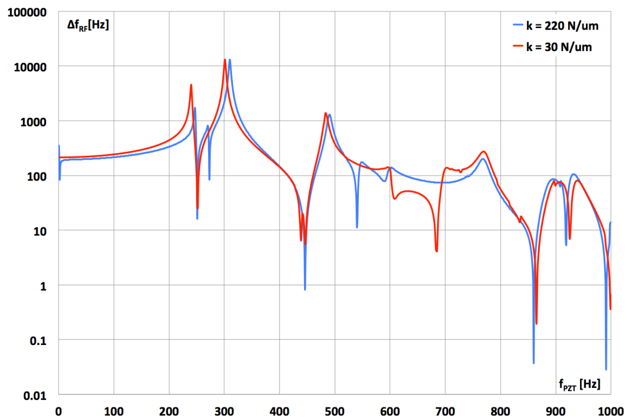

Figure 7: RF detuning response as a function of the piezo force frequency for tuner stiffnesses of k_{PZT} = 30 N/um (red) and k_{PZT} = 220 N/um (blue).

The RF detuning response was measured at Fermi National Accelerator Laboratory for a cavity at room temperature [5], and at Cornell University as part of a horizontal test of an LCLS-II cavity [10] - see Fig. 8. The bottom plot in Fig. 8 is generated at SLAC [11] from the Cornell data.

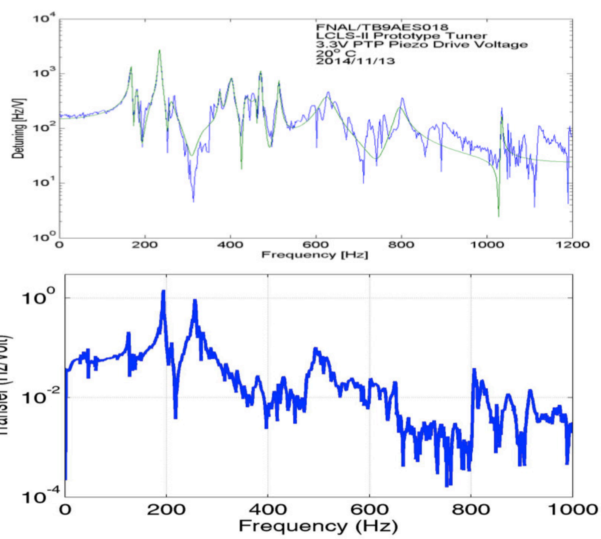

Figure 8: RF detuning response as a function of the piezo actuator frequency measured at FNAL (top) and Cornell (bottom).

As expected, the dominant axial modes identified by the modal decomposition appear in both simulation and measurements. We believe that the difference between the measured and simulated responses is mainly caused by uncertainties and simplifications in the model (tuner stiffness, damping coefficients and the frictional motion in the axial direction that is allowed by He vessel support mechanism). Also, the noisy environment during the measurements (vacuum pumps near to the cavity, etc.) contributed some. Finally, the mechanical model we use does not include the liquid He in the tank, the power coupler and some other minor components. As a result, the effective mass that moves is larger than modeled and the eigenfrequencies we computed are overestimated to some extent.

CONCLUSION

As demonstrated, the Lorentz force and the piezo-actuator motion mainly couple to the same longitudinal cavity modes providing a way to compensate higher frequency detuning if required. More work on matching the simulated RF responses with the measurements will be done once new experimental data become available. Meanwhile we are studying the effect of external forces on the detuning to complete a comprehensive understanding of the electro-mechanical cavity model.

ACKNOWLEDGEMENT

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