LCLS-II Technical Note

FEA Analysis of the LCLS-II 3.9 GHz cavity full assembly (HV+Cavity+Tuner)

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Abstract

COMSOL simulations of LCLS-II 3.9 GHz dressed cavity Lorentz force detuning (LFD), frequency shift due to Helium Vessel pressure fluctuation dF/dP and mechanical modal analysis has been done. All this parameters were calculated for the tuner with stiffness in the range from 0 to 100 kN/mm. Two different wall thicknesses were taken into account 2.8 mm and 2.5 mm (smaller thickness due to chemical polishing with maximum 300 μm material uniform removal).

1. CAD model

Fig. 1 show the CAD solid dressed cavity model used in simulations. Materials and boundary conditions are presented. In model tuner stiffness was applied to the right face of the bellow as shown in figure 1. Model has vertical plane (YZ) of symmetry (no coupler port, no HOM couplers, no field probe).

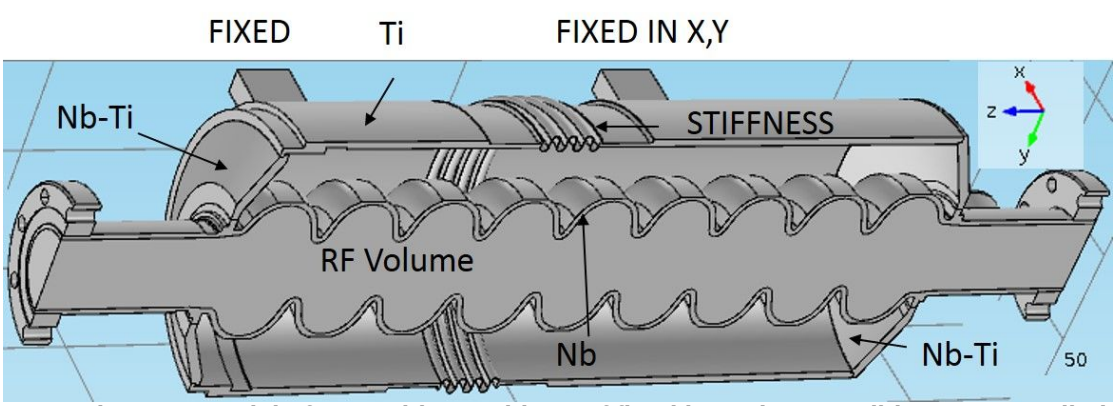

Figure 1: The CAD model of assembly. Positions of fixed boundary conditions was applied are shown. Advantages of symmetry are taken into account.

2. Material properties

The assembly consists from a different materials: cavity – Niobium, Titanium HV, Niobium-Titanium conical flanges. Material properties for room temperature and for 2K cases used in simulations are shown in Table 1.

Table 1 Material properties used in simulations*

	Young's modulus 293K/2K	Poisson ratio 293K/2K
Niobium	105/118	0.38
Titanium	106/117	0.37
Niobium-Titanium	62/68	0.33
SS 316LN	195/208	0.33

*TD ER-10163, M.Merio, October 2011

3. FE Mesh

The typical FE mesh used in COMSOL analysis is shown in Figure 2. About one million of 2nd order 10-nods tetrahedral elements were used in simulations. To increase simulation accuracy, mesh has been densened in critical areas (bellows, irises etc).

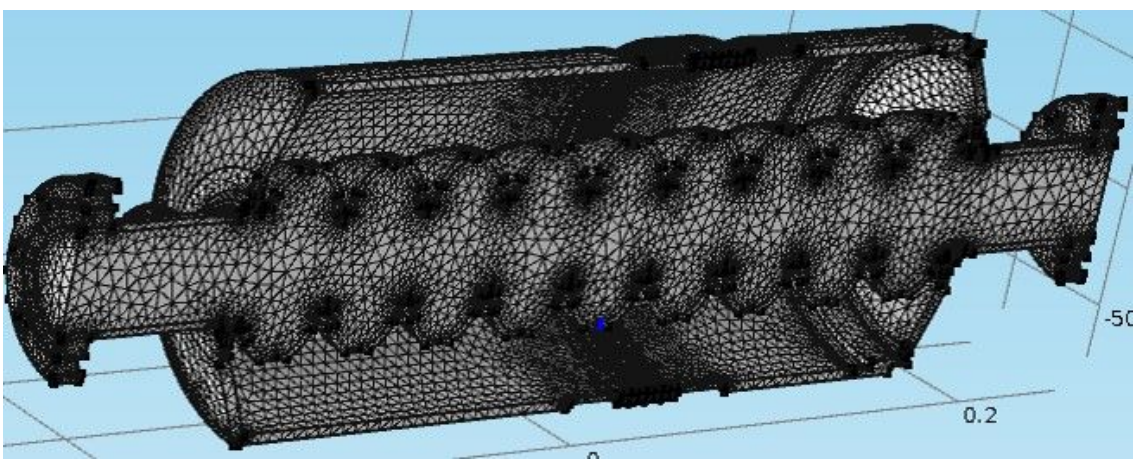

Figure 2: FE mesh used in COMSOL analysis. To increase accuracy mesh has been densened in critical areas.

4. Results

We ran 3 COMSOL analyses:

1. LFD simulations vs. tuner stiffness for 2 different cavity wall thickness
2. dF/dP simulations vs. tuner stiffness for 2 different cavity wall thickness
3. Modal analysis vs. tuner stiffness of 10 lowest natural modes

4.1 LFD simulations

COMSOL Multiphysics algorithm to evaluate LFD consists from following steps.

1. Running RF analysis of CAD model (Fig.1) in RF domain to calculate initial fundamental frequency
2. Running Solid Model analysis with boundary conditions showing on Fig. 1, normalized Lorentz forces applied to cavity surface according to EM field from step 1 and applied tuner stiffness.
3. Running Moving mesh COMSOL module to modify initial mesh according to wall displacements from step 2.
4. Running again RF analysis of CAD model with modified mesh in RF domain to calculate a new fundamental frequency.
5. Calculate LFD coefficient based on the difference of frequencies from steps 1 and 4

Fig. 3 presents the LFD coefficient in Hz/(MV/m)^2 vs tuner stiffness for 2 different wall thicknesses.

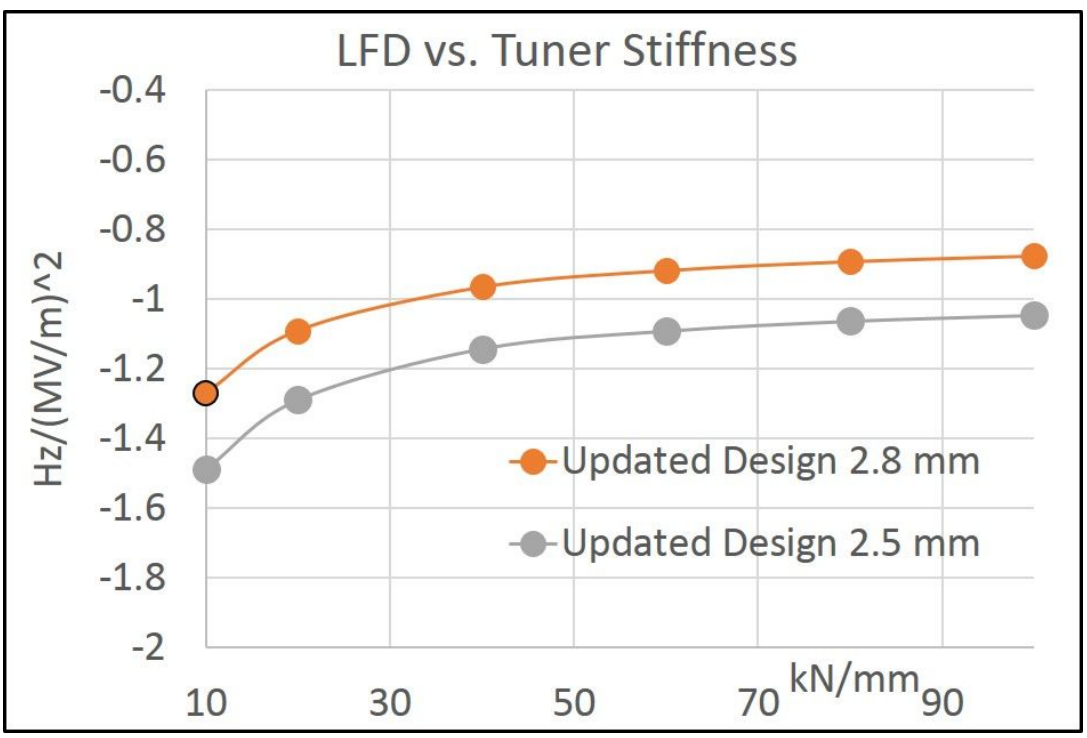

Figure 3: Dependence of LFD vs. cavity stiffness for 2.8 and 2.5 cavity wall thickness.

LFD analysis shows that for the maximum designed gradient E_{acc}=14.9 MV/m and for predicted tuner stiffness 40 kN/mm the frequency shift due to Lorentz forces will be between 200 Hz and 255 Hz depending on the cavity wall thickness.

4.2 dF/dP simulations

COMSOL Multiphysics algorithm to evaluate dF/dP consists from following steps.

1. Running RF analysis of CAD model (Figure 1) in RF domain to calculate initial fundamental frequency.
2. Running Solid Model analysis with boundary conditions showing on Fig. 1. -1 bar pressure applied to helium circuit surface and applied tuner stiffness.
3. Running Moving mesh COMSOL module to modify initial mesh according to wall displacements from step 2.
4. Running again RF analysis of CAD model with modified mesh in RF domain to calculate a new fundamental frequency.
5. Calculate dF/dP coefficient based on the difference of frequencies from steps 1 and step 4.

Fig. 4 presents the dF/dP coefficient in Hz/mbar vs tuner stiffness for 2 different wall thicknesses.

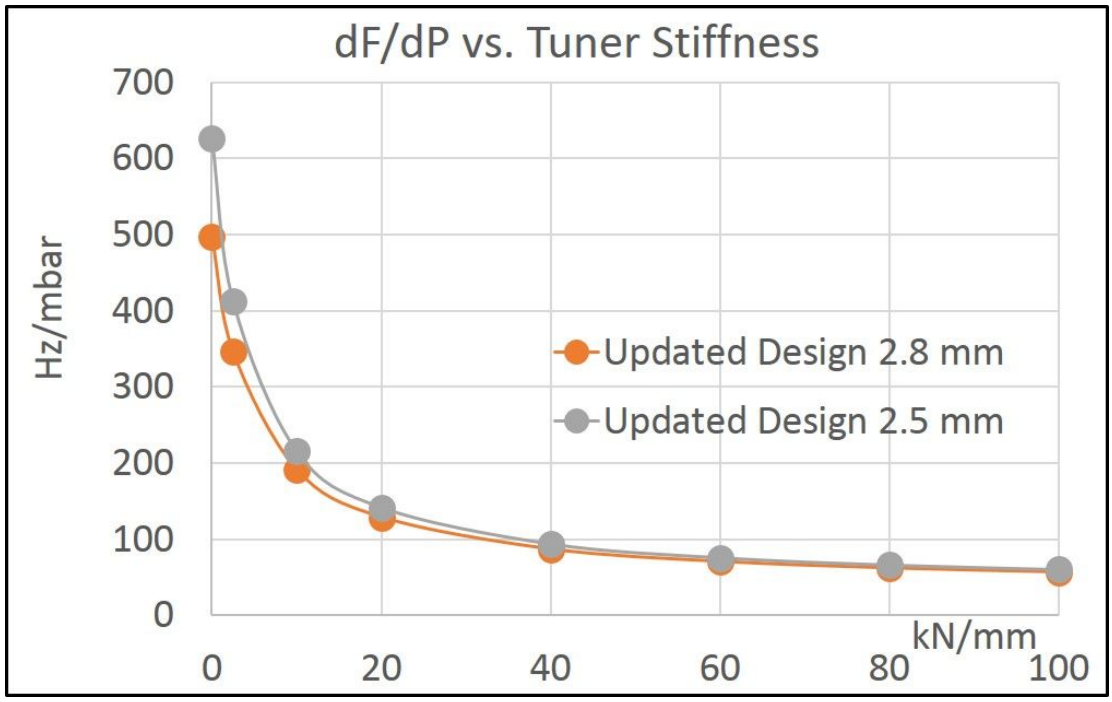

Figure 4: Dependence of dF/dP vs. cavity stiffness for 2.8 and 2.5 cavity wall thickness.

Maximum FRS peak cavity detune with piezo tuner control is 30Hz. Expected pressure stabilities of ~0.2 mbar rms, achieved in modern cryogenic systems rms. It means, that in case of tuner stiffness 40 kN/mm or greater one can expect the maximum frequency deviation due to pressure fluctuation <20 Hz, which is below the FRS value.

Measurements of dF/dP coefficient done for 3.9GHz cavities built for FLASH cryomodule are consistent with simulation results. All measurements shows dF/dP ~ 80-90 Hz/mbar for large stiffness case, see Table 1.

Table 1. Measured dF/dP during pressure test of 3.9 GHz dressed cavities

Cavity	dF, MHz	P, psi	kHz/bar	Comments
F3A3	0.163	33.5	71	With rods
F3A4	0.156	32	71	With rods
F3A5	0.127	29	64	With rods
F3A7	0.213	32	97	with Tuner
F3A8	0.182	32	83	with Tuner

4.3 Modal Analysis

COMSOL Multiphysics has been done to evaluate 10 lowest natural mechanical modes in 3.9 GHz LCLS-II dressed cavity. Fig. 5 shows the amplitude of displacement and natural frequencies of these modes for the predicted 40 kN/mm stiffness of the tuner. 7 transvers (**T#1-T#**7) and 3 longitudinal **(L#1-L#3)** modes was found. RF frequency shift for transverse mode vs. amplitude or mechanical mode has second order instead of linear behavior of longitudinal mode and therefore much less sensitive. For the same amplitude of mechanical mode, all transverse modes have much smaller contribution to the RF frequency shift compared to with longitudinal modes.

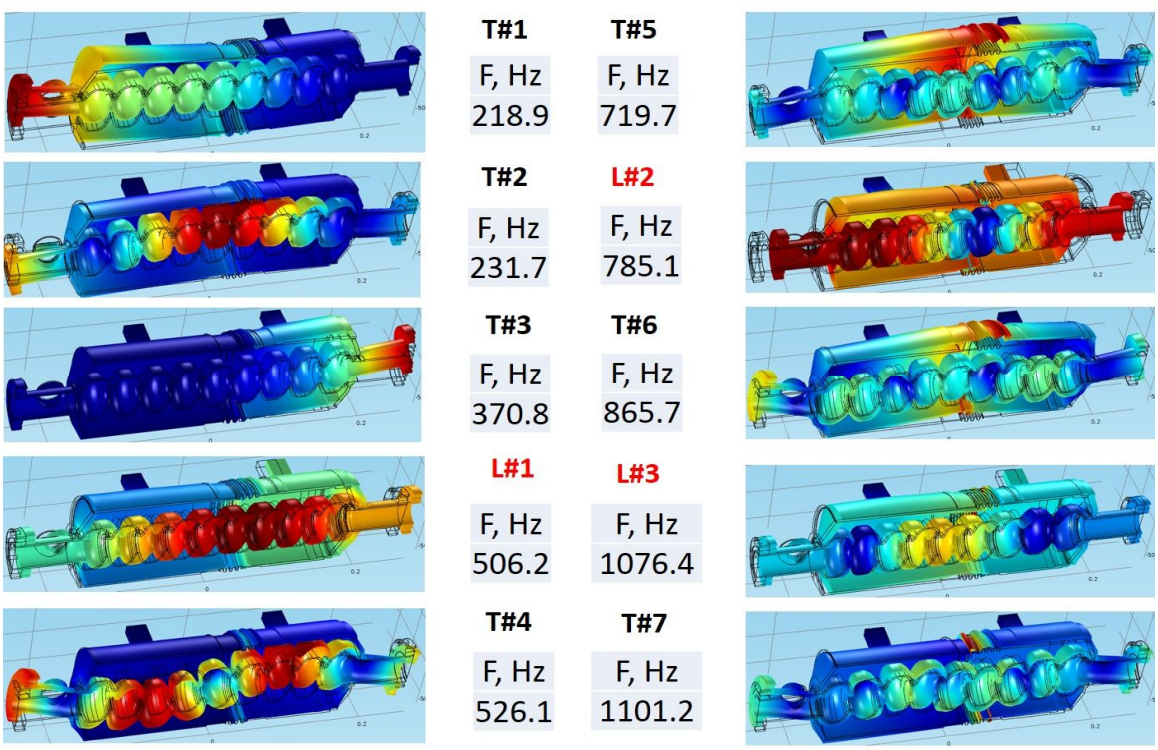

Figure 5: Displacement pictures and frequencies of 10 lowest natural modes

Fig.6a and 6b shows the amplitude of transverse mode **T#2** and three lowest longitudinal modes (**L#1-L#3**) and RF frequencies dependencies vs. amplitude of mechanical modes for the predicted 40 kN/mm stiffness of the tuner. As expected RF frequency has second order for transvers modes and

linear dependence on amplitude of longitudinal modes. The lowest longitudinal mode has frequency F=506.2 Hz.

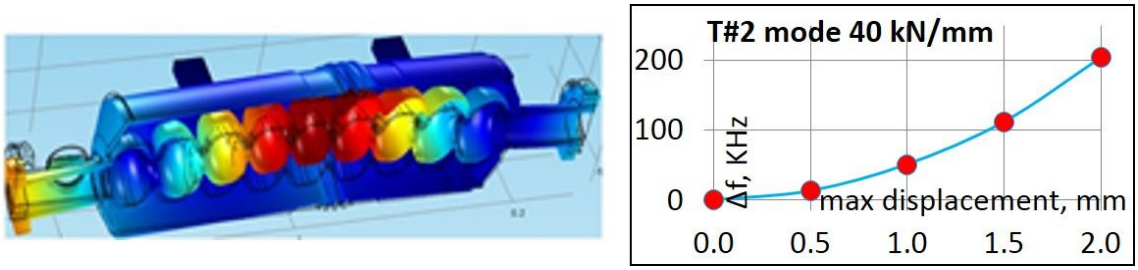

Figure 6a: Map of displacement for transverse T#2 mode and RF frequencies vs. amplitude.

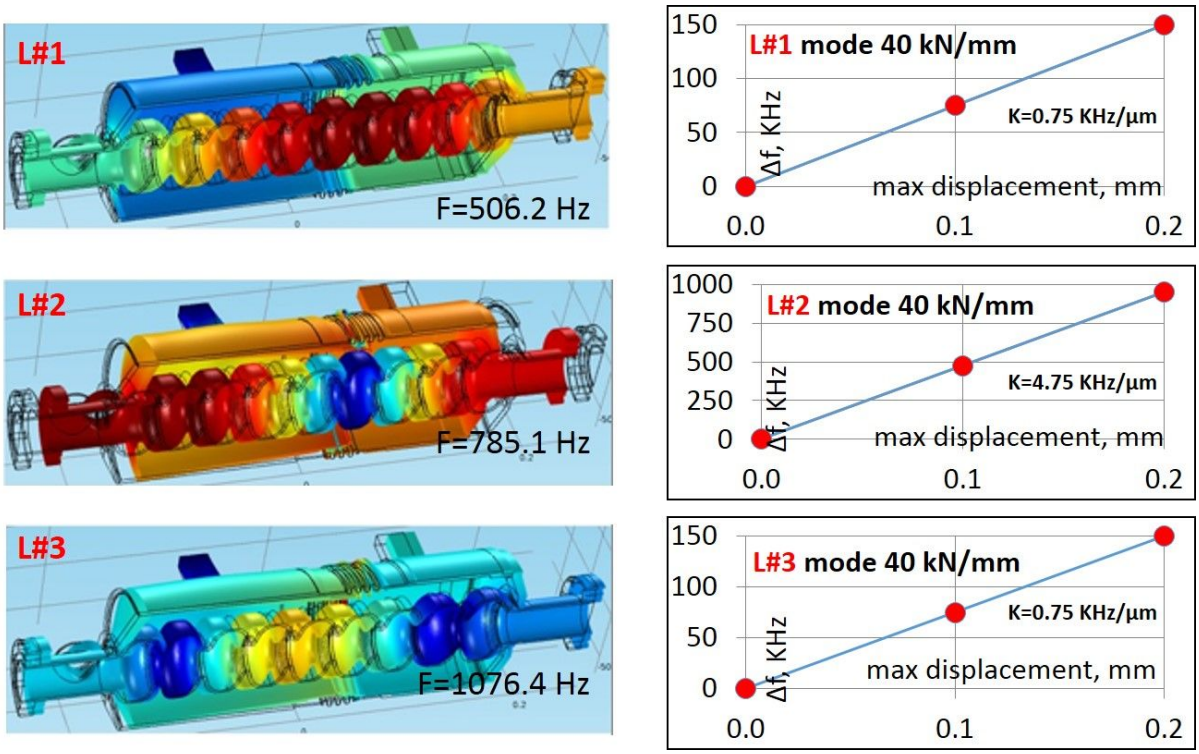

Figure 6b: Map of displacement of longitudinal L#1-L#3 modes (left) and RF frequencies vs. amplitude of mechanical displacement.

Table 2 shows the sensitivity of frequencies of **L#1-L#3** modes vs. total cavity deformation dF/dL and changes the distances between lags dF/dLag.

Frequency of mechanical mode of dressed cavity is sensitive to the stiffness of the blade-tuner. Figure 7 shows the frequencies of **L#1-L#3** modes vs. stiffness of the tuner.

Table 2: Sensitivity of Longitudinal modes.

Mode number	dF/dL, kHz/µm	dF/dLag, kHz/µm
L#1	2.77	1.55
L#2	2.5	6.1

L#3	6.6	1.28

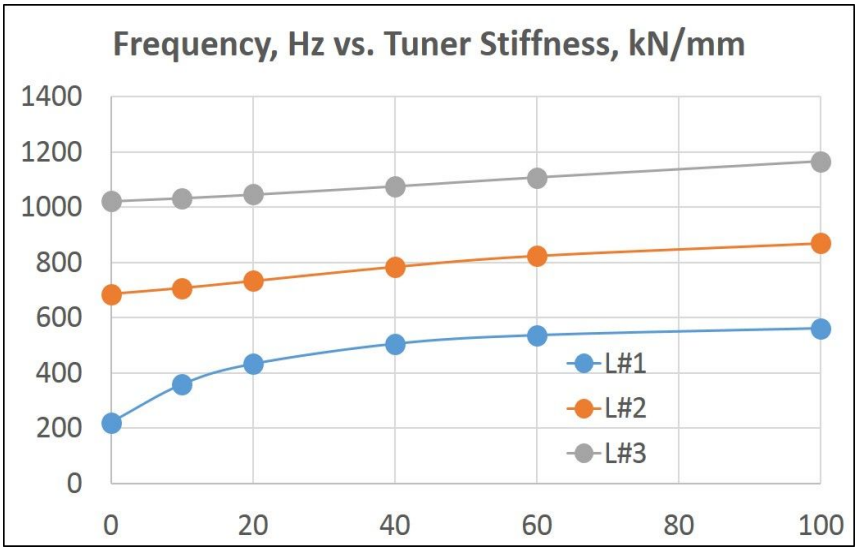

Figure 6: Frequencies of L#1-L#3 modes vs. stiffness of the blade-tuner.

5. Conclusion

COMSOL simulations of LCLS-II 3.9 GHz dressed cavity Lorentz force detuning (LFD), frequency shift due to Helium Vessel pressure fluctuation dF/dP and modal analysis has been done. All calculated parameters are sensitive to the stiffness of blade-tuner.

Lorentz Force Detuning coefficient for typical stiffness of tuner 40kN/mm is in range -0.95… – 1.15 [Hz/(MV/m)2] depending on cavity wall thickness (2.8…2.5mm). These values are close to FRS values specified in document [1].

Frequency sensitivity to the Helium pressure fluctuation is in range ~90-100 Hz/mbar for typical stiffness of tuner and cavity wall variation. Expected frequency variation is <20Hz if pressure is stabilized better than 0.2mbar. Piezo-tuner will be able to control these variations.

Mechanical vibration is source of microphonics which causes cavity detuning. Simulations shows that cavity frequency is most sensitive to longitudinal modes. It was found three lowest mechanical longitudinal modes at frequencies: 506, 785 and 1076 Hz for tuner with stiffness 40 kN/mm. Sensitivities of these modes to the amplitude of displacement are: +0.75; -5.0; -0.75 kHz/µm correspondingly.