MULTI-PHYSICS ANALYSIS OF CW SUPERCONDUCTING CAVITY FOR THE LCLS-II USING ACE3P*

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Abstract

The LCLS-II linac utilizes superconducting technology operating at continuous wave to accelerate the 1-MHz electron beams to 4 GeV to produce tunable FELs. The TESLA 9-cell superconducting cavity is adopted as the baseline design for the linac. The design gradient is approximately 16 MV/m. The highest operating current is 300 µA. Assuming that the RF power is matched at the highest current, the optimal loaded QL of the cavity is found to be around $4 \times 10^7$. Because of the high QL, the cavity bandwidth approaches the background microphonic detuning, and the performance of the cavity is tightly coupled to the mechanical perturbations of the cavity/cryomodule system. The resulting large phase and amplitude variations in the cavity require active feedback to achieve the 0.01% amplitude and phase stability requirements. To understand the cavity RF response and feedback requirements to the microphonics and Lorentz Force detuning, we have developed a simulation model of the RF-mechanical coupled system using parameters obtained with the multi-physics solver ACE3P. We will present the simulation results of the preliminary study of the mechanical resonance of the LCLS-II RF cavity and the reduced model to be used in the analysis of RF station topologies and feedback schemes.

INTRODUCTION

LCLS-II [1,2] will use a CW SRF linac to deliver high-brightness and high-repetition-rate electron beams for the FELs. The machine is design for 1-MHz reprate with a max current of 300 µA. The nominal beam energy is 4 GeV. The linac will be based on the TESLA 9-cell cavity design [3] with an unloaded Q0 of $2.7 \times 10^{10}$ and a Qext of $4 \times 10^7$. The nominal gradient is 16 MV/m. Lorentz Force detuning (LFD) remains important in CW operation for RF turn-on, and trips caused on/off cycles. The frequency sensitivity to pressure variations, dF/dP, is important to minimize the coupling between the RF to the Helium pressure fluctuations. An end-lever tuner is proposed for the LCLS-II cavities. The frequency sensitivity to pressure variations and LFD depends on the design of the stiffening of the cavity and end-plates as well as the tuner strength, which can be optimized. To be able to operate the CW machine reliably, the resonance frequency change due to mechanical vibrations caused by external vibration sources and LFD need to be compensated. A simulation model for the RF-mechanical coupled system is being developed to understand the cavity RF response and feedback requirements to the microphonics and LFD. The parameters of this model were obtained using the parallel multi-physics (RF, thermal, mechanical) solvers of ACE3P [4,5].

The cavity models being studied are shown in Fig. 1. The model for the mechanical analysis includes the 2.8-mm thick cavity shell, the stiffness rings, Helium vessel and bellows, and a simplified tuner. The properties of the materials used in the simulation are shown in Table 1. The domain for the RF analysis is the inside vacuum volume of the cavity. The bound surface of the vacuum volume is the interface surface for mapping the RF solutions to the mechanical solver and vise versa. In this paper, we present the preliminary results of the ongoing study of the mechanical resonance of the LCLS-II SRF cavity and the reduced model to be used in the analysis of RF station topologies and feedback schemes.

Figure 1: LCLS 9-cell cavity with Helium tank.

Table 1: Material Properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Nb</th>
<th>Nb-Ti</th>
<th>Ti</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$  [kg/m$^3$]</td>
<td>8700</td>
<td>5700</td>
<td>4540</td>
<td>8000</td>
</tr>
<tr>
<td>Poisson Ratio, $\nu$</td>
<td>0.38</td>
<td>0.33</td>
<td>0.37</td>
<td>0.29</td>
</tr>
<tr>
<td>Lowest acc HOM</td>
<td>118</td>
<td>68</td>
<td>117</td>
<td>193</td>
</tr>
</tbody>
</table>

LORENTZ FORCE DETUNING AND DF/DP

The Helium vessel is welded to the cavity end-plate on one end and is connected to the cavity by a bellows on the other end so it does not assert significant resistance to the frequency tuner. The beam pipe flange on the welded side of the Helium vessel is fixed in position while the flange on the other end is connected to the beam pipe which has a bellows. These set of bellows allow one side of the cavity to move “freely” to accommodate the geometry change during the cool down and warm up and the frequency tuning by the tuner. These bellows contribute relatively weak constraints to the cavity length change. The frequency tuner on the other hand holds the cavity tight to maintain the cavity frequency. The cavity length change due the Lorentz force and Helium pressure and etc work against the tuner and could elastically deform it so the tuner asserts an elastic constraint to such cavity geometry changes. The effect of the tuner elastic strength on the LFD and dF/dP is evaluated for different

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stiffness ring radii. In the simulation model, the tuner is simplified to a pair of stainless steel rods of equivalent spring constant \( K = \frac{YA}{L}, \) \( Y= \) Young’s Modulus, \( A= \) area, \( L= \) length.

Lorentz Force Detuning (LFD)

The LFD is the frequency change due to the cavity shape deformation by the electromagnetic pressure on the cavity surface. The LFD coefficient was calculated in three simulation steps: calculate the RF modes on the vacuum mesh, Fig. 2 right, using the RF eigenmode solver, calculate the cavity shape deformation on the mechanical mesh, Fig. 2 left, under the RF pressure, \( P = \frac{\mu_0 f^2 E^2}{4}, \) using the mechanical analysis solver, then map the deformed mechanical cavity shape onto the vacuum mesh and calculate the RF frequency change due to the deformation. The LFD coefficient is then calculated as \( K = \frac{\Delta f}{E_{acc}}. \)

Figure 6: Cavity deformation due to helium pressure.

The stiffness ring radius has opposite effects on the \( dF/dP \) and LFD. A larger stiffness ring radius reduces the \( dF/dP \) while increases the LFD. The LFD is minimal at a stiffness ring radius of around 50 mm while the \( dF/dP \) is close to its maximum. A stiffer tuner can effectively minimize both sensitivities.

MECHANICAL MODES

The geometry used for the mechanical mode calculation is as shown in Fig. 1. The rod representation of the tuner used in the LFD and \( dF/dP \) calculations won’t be suitable as both the normal and sheer elasticity strengths need to be included for the longitudinal and transverse mechanical modes. In this preliminary study, we used a cylindrical disk to model the tuner. We plan in the future to include more details of the tuner geometry that can represent the elastic properties. Mechanical modes were calculated for cavity with different stiffness ring radii. The table in Fig. 7 listed the first 21 mechanical modes. The mode in blue text are the longitudinal modes and the other modes are either cavity transverse modes or the modes of the Helium vessel. It worthwhile to mention that each transverse mode frequency listed in Table 1 represents a pair of orthogonal modes in x and y planes due to symmetry. The pictures in Fig. 7 are the mechanical mode patterns.

Figure 7: Mechanical modes.
REDUCED CA VITY MODEL

In this section, we present a reduced cavity model to be used to simulate the RF-mechanical coupled system. Following [6], a mechanical displacement in the cavity structure can be decomposed in a complete infinite set of orthonormal mechanical modes. The amplitude of each mechanical mode can be represented by

\[ q_i = \frac{1}{2} \left( q_i + \omega_i q_i \right) + \frac{\Omega_i}{c} F_i \]

where \( q_i \) is the amplitude, \( F_i \) the mechanical force, \( c \) the elastic constant, \( \omega_i \) the frequency and \( r_i \) the decay time of mechanical mode \( u \). The frequency shift \( \delta \omega_i \) caused by the mechanical mode \( u \) is proportional to \( q_i \) and the force \( F_i \) due to radiation pressure which is proportional to the square of the field amplitude. The equation for \( \delta \omega_i \) is

\[ \delta \omega_i = \frac{2}{\tau_i} \omega_i + \frac{\Omega_i}{c} \delta \omega_i = -k_i \Omega_i \psi_i(t) \tag{1} \]

where \( k_i \) represents the coupling between the RF and the mechanical mode \( u \). This equation describes how the cavity frequency is affected by the field amplitude.

On the other hand, the field amplitude depends on the frequency detuning between the cavity and the RF source. This relationship can be analyzed by solving the differential equation representing the field in the cavity, assuming it is driven by a generator where the amplitude and phase of this signal are considered as independent variables. Using in-phase/quadrature formalism to represent the resulting differential equation,

\[ \begin{pmatrix} v_{\text{ch}}(t) \\ v_{\text{Q}}(t) \end{pmatrix} = \begin{pmatrix} -\omega_{\text{ch}} & -\omega_{\text{Q}} \\ \omega_{\text{ch}} & -\omega_{\text{Q}} \end{pmatrix} \begin{pmatrix} \delta \omega_{\text{ch}}(t) \\ \delta \omega_{\text{Q}}(t) \end{pmatrix} + \begin{pmatrix} R \omega_{\text{ch}} \\ R \omega_{\text{Q}} \end{pmatrix} \begin{pmatrix} 1 \omega_{\text{ch}}(t) \\ 1 \omega_{\text{Q}}(t) \end{pmatrix} \tag{2} \]

where \( v_{\text{ch}}(t), v_{\text{Q}}(t) \) are the in-phase/quadrature voltages of the cavity, \( i_c \) and \( i_b \) are the driving current and beam current, respectively and \( \Delta \omega(t) = -\omega_{\text{ch}} + \omega_{\text{Q}} + \delta \omega(t) \). It is important to observe in eqns. (1) and (2), there are two coupling terms between the field amplitude and the detuning. The mechanical modes are forced by the EM fields through the term \(-k_i \Omega_i \psi_i(t)\) and the field is affected by the cavity detuning by \( \Delta \omega(t) v_{\text{ch}}(t), v_{\text{Q}}(t) \).

This reduced model allows analyzing the stability and performance of the RF station for different topologies, e.g. single cavity, multiple cavities, etc. and different operation conditions in closed loop. From the multiple configurations, let us pick the simplest case that is when the cavity is driven by a generator in open loop. The reduced model is \( \dot{x} = f(x) + g(x)u \), with \( x = [\text{in} \text{ch}(t) \text{ inQ}(t) \delta \omega_{\text{ch}} \delta \omega_{\text{ch}} ... \delta \omega_{\text{ch}} \delta \omega_{\text{Q}}]^T \), then \( \dot{x} = 0 = f(x) + g(x)u \) defines the operation point. Linearizing \( \dot{x} = f(x) + g(x)u \) around the operation point one obtains \( \delta \dot{x} = A \delta x + Bu \), with \( \delta x = x - x_0 \).

The eigenvalues of \( A \) define the stability of the operation point. It is possible to analyze the stability for changes in multiple parameters. Let us analyze the case of the LCLS-II cavity where the field is set at 16MV/m and the detuning \( \omega_{\text{chN}} \) is changed and used as parameter to analyze the stability of the system in different conditions.

![System eigenvalue and time domain simulation](image)

Figure 8 (a) shows the system eigenvalues assuming one mechanical mode for detuning \( \Delta \omega = -35\text{Hz}, -10\text{Hz}, 5\text{Hz}, 0\text{Hz}, 2.5\text{Hz}, 5\text{Hz}, 15\text{Hz}, 35\text{Hz}. \) The mechanical modes become unstable, for \( \Delta \omega < -0.88\text{Hz}. \) The RF eigenvalues are unstable if \( \Delta \omega > 5.5\text{Hz}. \) Figure 8 (b) shows the \( v_{\text{in}}, v_{\text{Q}} \) voltages when the mechanical mode is unstable and Fig. 8 (c) shows the \( v_{\text{in}}, v_{\text{Q}} \) voltages when the EM mode is unstable.

**SUMMARY**

The multiphysics solver ACE3P was used to calculate the dF/dP, Lorentz Force detuning and mechanical eigenmodes of the LCLS-II cavity. The impact of stiffness ring radius and the tuner elastic strength on the dF/dP and Lorentz Force detuning was compared. Changing the stiffness ring radius has opposite effects on the dF/dP and LFD. The tuner stiffness can effectively minimize both sensitivities. The mechanical mode frequencies also increases as the stiffness ring moved outward. The coupling of these modes to the RF are being calculated. A reduced cavity model is being developed to analyze the coupled RF-mechanical system. Parameters for coupled system will be extracted from the results of the ACE3P multiphysics solvers.

**REFERENCES**