THERMAL-MECHANICAL STUDY OF 3.9 GH CW COUPLER AND CAVITY FOR LCLS-II PROJECT*

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Abstract

Third harmonic system was originally developed by Fermilab for FLASH facility at DESY and then was adopted and modified by INFN for the XFEL project [1-3]. In contrast to XFEL project, all cryomodules in LCLS-II project will operate in CW regime with higher RF average power for 1.3 GHz and 3.9 GHz cavities and couplers. Design of the cavity and fundamental power coupler has been modified to satisfy LCLS-II requirements. In this paper we discuss the results of COMSOL thermal and mechanical analysis of the 3.9 GHz coupler and cavity to verify proposed modification of the design. For the dressed cavity we present simulations of Lorentz force detuning, helium pressure sensitivity df/dP and major mechanical resonances.

INTRODUCTION

The LCLS-II SCRF baseline linac consists of 35 1.3 GHz, 8-cavity Cryomodules (CM), and two 3.9 GHz, 8-cavity CMs. 3.9 GHz third harmonic superconducting cavities are used to increase the peak bunch current and to compensate nonlinear distortions in the beam longitudinal phase space due to sinusoidal 1.3 GHz accelerating cavity voltage [1]. The fundamental power coupler (FPC) is one of critical component of the third harmonic system developed for the LCLS-II project.

For a 300 uA beam current, a 15.5 MV/m nominal accelerating gradient and a 180 deg beam-to-rf phase, the RF power induced by a beam and radiated to the power coupler is about 1700 W per cavity. If the cavity is detuned by 30 Hz due to microphonics , the required input power from the rf source to maintain the operating gradient would be about 80 W. In whole range of beam parameters, the coupler needs to be rated for at least 1.9 kW of average RF power (in particular, it needs to operate below the peak surface temperature noted below). Therefore in simulations we apply 2 kW of the input RF power in the TW regime.

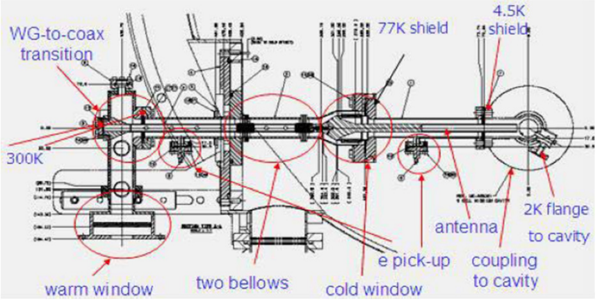

Figure 1: The 3.9 GHz power coupler developed at FNAL.

COUPLER THERMAL ANALYSIS

The final design of the 3.9 GHz power coupler is shown in Figure 1. It consists of a 50 Ohm coaxial line with a 30 mm diameter of the outer conductor. Two ceramic windows provide double protection of the cavity from potential damage of the ceramics. The design of the cold (50K) cylindrical window is almost identical to window used in 1.3 GHz XFEL coupler design. Warm pill-box window is installed in waveguide assembly.

Thermally, the power coupler represents a connector from the room temperature (300K) to the superconducting cryogenic environment (2K). Figure 2 shows the thermal model and boundary conditions used in COMSOL simulations [4]. Power dissipation and heat loads were calculated by using temperature dependences (electrical resistance and thermal conductivity) of materials used in coupler.

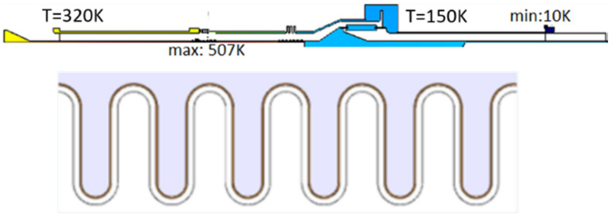

Figure 2: COMSOL thermal analysis model.

Originally, 3.9 GHz power coupler for the FLASH project was designed for pulsed operation (power 50 kW, duration is ~2ms, maximum repetition rate is 10 Hz; average power ~ 1kW). The LCLS-II requirements are CW operation at ~2 kW in quasi - traveling wave regime. At first, we performed COMSOL thermal simulations using LCLS-II parameters without any modifications of the 3.9 GHz coupler. It is resulted in an overheating of the inner conductor of the warm part of the coupler up to 670 K. Thus, we propose the following modifications of the current design:

- Reducing the length of two inner bellows from 20 convolutions to 15 convolutions.
- Increase the thickness of a copper plating in the inner conductor.
- Increase the thickness of ceramics in cold window to move parasitic mode away.

In original design our measurements show that one of the parasitic mode in cold ceramic is pretty close to fundamental mode, which can introduce extra heating of window in CW regime. Last modification is proposed to move nearest parasitic mode off working frequency 3.9GHz.

Figure 3 shows the results of COMSOL thermal simulations for 2kW traveling wave power in coupler and 20, 15 and 10 convolutions of inner bellow vs. copper plating

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thickness. Dotted line shows the acceptable level of temperature 450 K. To stay below acceptable level one need to plate bellows with 130, 120 and 100 microns for 20, 15 and 10 convolutions.

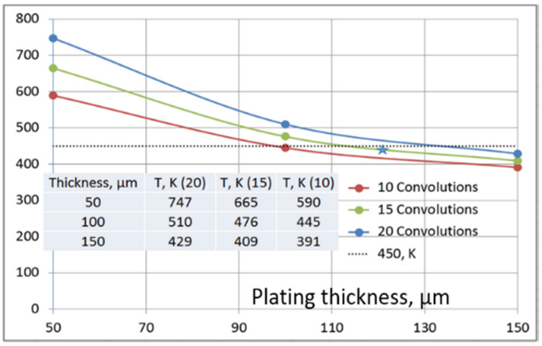

Figure 3: Maximum coupler surface temperature versus copper plating thickness and number of convolutions.

Finally we conclude that the optimal modification is a reduction of the convolution number in bellow to 15 and increasing the copper plating thickness of the inner conductor up to 120 microns. Static and dynamic heat loads in the modified coupler are listed in the Table 1.

Table 1: Static and Dynamic Heat Loads in the Modified 3.9 GHz Power Coupler

Parameter	**5K**	**50K**
Static, W	0.84	1.45
Dynamic, W	2.1	5.9

COUPLER MECHANICAL DESIGN

COMSOL simulations has been performed to study stresses in inner and outer conductor. Figure 4 shows the solid model and boundary conditions used in simulations. Fixed faces are shown, tip of the antenna moved in transverse and longitudinal directions.

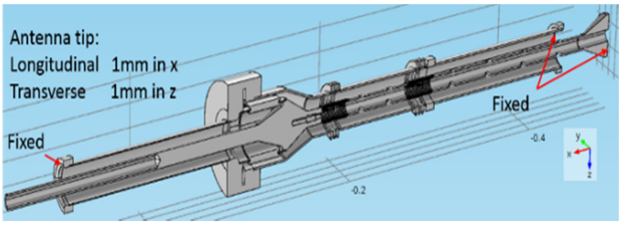

Figure 4: COMSOL solid model and mechanical boundary conditions.

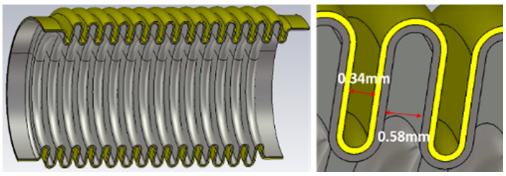

Figure 5: COMSOL solid model of inner bellows.

Figure 5 presents the solid model of 15 convolutions of stainless steel bellows with 120 microns of copper plating.

Figure 6 shows Von Misses stresses for 0.5 mm longitudinal deformations of each inner bellows.

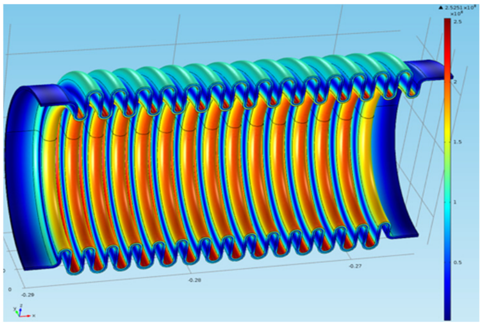

Figure 6: Von Misses stresses in inner bellows.

Table 2 summarized the maximal stresses in MPa/mm for 15 convolutions inner bellow and 3 convolutions of outer bellow.

Table 2: Summary of Stresses

Parameter	**MPa/mm**
Inner conductor, transverse	38
Outer conductor, transverse	45
Inner conductor, longitudinal	253
Outer conductor, longitudinal	98

Typically bellow endurance limit for infinite cycles is from 83 to 166 MPa or 300 MPa for a low cycle fatigue strength.

Two prototypes of the 3.9 GHz power couplers will be built by the end of September for testing properties at 2kW power level. For prototype we are modifying warm sections of two existing FLASH type couplers.

CAVITY MECHANICAL PROPERTIES: LFD AND DF/DP ANALYSIS

We have studied both Lorentz Force Detuning LFD and the frequency sensitivity to the helium pressure fluctuation df/dP in the 3.9 GHz 9-cell dressed cavity using Comsol Multiphysics package [4]. Design of the cavity and helium vessel was modified to accommodate larger cryogenic heating in CW regime and improve RF properties of the cavity [5]. The resonance frequency of the π- mode was calculated before and after applying the pressure load. Deformation is calculated using the solid mechanics module then the mesh is deformed with the resultant displacement values to acquire the frequency change. Tuner stiffness in wide range value is taken into account.

Both studies has been done for cavity wall 2.8 and 2.5 mm. Original niobium shell thickness is 2.8 mm thickness and removal of 200 μm is an attempt to predict the maximal thickness change after a series of chemical treatments.

Figure 7 shows the LFD distribution vs. tuner stiffness. The stiffness of current tuner design is greater than 60 kN/mm. Figure 8 presents the frequency sensitivity to helium pressure fluctuation df/dP as a function of tuner stiffness in dressed cavity for two different thicknesses of the cavity wall.

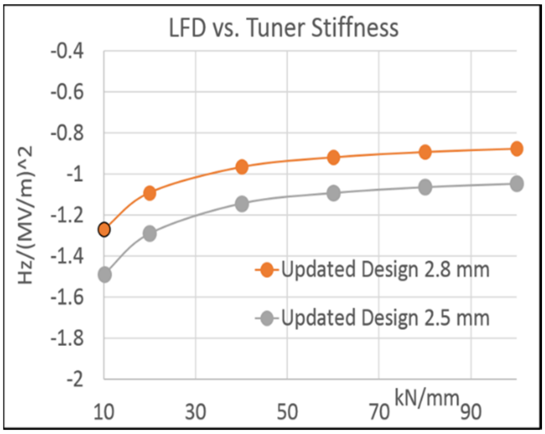

Figure 7: LFD vs. tuner stiffness.

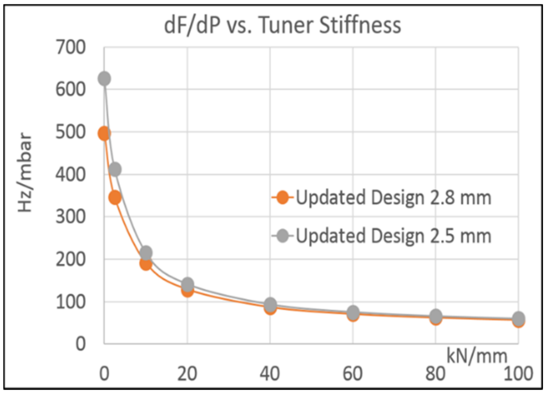

Figure 8: dF/dP vs. tuner stiffness.

MECHANICAL MODES ANALYSYS

COMSOL software has been used to calculate the mechanical resonances in the complete cavity assembly. Figure 9 shows the COMSOL plots of displacement of the first 3 lowest longitudinal mechanical modes.

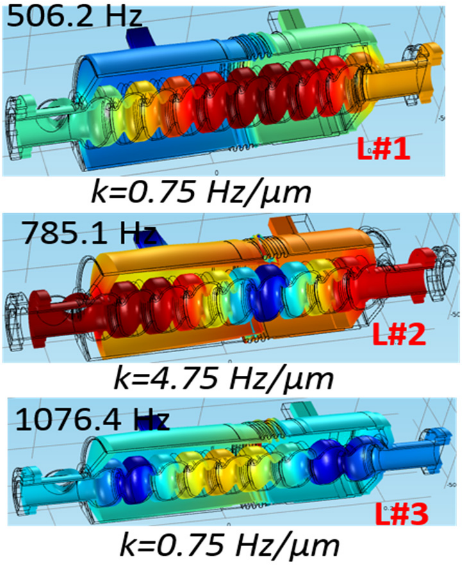

Figure 9: Deformations of longitudinal modes.

Longitudinal modes typically have higher contribution to the RF frequency shift, than transverse one for the same excited amplitude. The frequency shift for the longitudinal modes is proportional to the mode amplitude.

Blade-tuner stiffness varies from cavity to cavity. Frequency of mechanical resonance depends on tuner stiffness. Figure 10 shows the dependence of frequencies as a function of tuner stiffness for three lowest longitudinal modes.

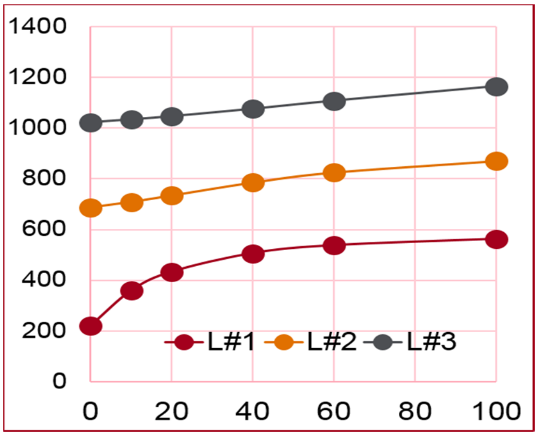

Figure 10: Frequencies (Hz) vs. tuner stiffness (kN/mm).

CONCLUSION

FNAL/FLASH designs of the 3.9 GHz fundamental power coupler and the cavity were modified to meet LCS-II requirement. Simulations of mechanical and thermal properties of the coupler and cavity was performed to verify effect of modifications. Simulated performances of the cavity and couplers are satisfy LCLS-II requirements. Prototypes are ordered and expected to be ready for testing in October 2016.

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