3D Simulations of 3.9 GHz Coupler for LCLS-II Project

V. Balakin, I. Gonin, A. Lunin, N. Solyak

Abstract
The input coupler of the 3rd harmonic LCLS-II cavity must operate up to 1.8 kW average RF power [1]. The coupler geometry is based on the design developed for the 3.9 GHz XFEL cavity with few modifications. For mitigating the risk of coupler overheating the shorter bellows are used and the copper plating thickness of the inner conductor is increased from 50 μm to 150 μm. During a recent high-power RF testing of the modified coupler at room temperature a strong heating of the coupler antenna was observed. We performed detailed multiphysics simulations in order to explain the coupler test results and to modify the design for further reducing of antenna heating. The CST Multiphysics suite was used for the coupler analysis with various temperature boundaries [2]. The coupler model was updated to the 3D version including coaxial-to-waveguide transition, while previously we ran coupler simulations in the 2D domain for the simplification [3].

Power Coupler Thermal Boundaries

The 3.9 GHz coupler is transferring RF power through the warm (@300 K) input section to a superconducting cavity (@2 K) [see Figure 1]. The 3.9 GHz cavities are used for linearizing the longitudinal beam profile. The cavity operates close to 180° beam-to-RF phase, where the beam induced RF power is radiating from the cavity into the coupler. The maximum estimated coupler RF load including margins for microphonics and a cavity voltage regulation is about 1.8 kW of average power in the traveling wave regime. There are two main issues that have to be taken into account to prevent possible coupler overheating:

- Decreasing the antenna tip temperature, since the thermal radiation power flux is proportional to $T^4$ and a significant amount of the heat load might be deposited directly to a superconducting cavity. Cooling the cavity at 2 K is costly, thus, it is quite important to decrease the amount of radiating power from the antenna tip.
- The coupler temperature in each point should not exceed 450 K for preventing extensive surface degassing.
**Material Properties Overview**

The coupler coaxial parts are made from the 316LN stainless steel with a copper plating of coaxial inner surfaces (10 µm for the outer conductor, 150 µm for the warm part of inner conductor). We used the copper electrical conductivity $\sigma = 5.3E7$ S/m, including 10% surface roughness, in our RF simulation. The emissivity properties of both stainless steel and copper surfaces were taken 0.5 as a conservative approach. Figure 2 shows plots of the OFC copper and the 316LN steel thermal conductivity temperature dependences.

![Thermal conductivity](image)

**Figure 2. Thermal conductivity.**

Important parameters of a coupler ceramic window are the permittivity and the loss tangent, because they define the RF volume loses in the ceramic material. We used 94% Al2O3 ceramic with $\varepsilon = 9.4$ and $\Delta = 0.003$.

**CST Multiphysics simulations**

The nonlinear multiphysics analysis is a self-consistent process of solving coupled electromagnetic and thermal problems. At first o, the EM simulations were made and the results of RF heat loads were used for calculation of a temperature distribution along the coupler [see Figure 3].
Coupler simulations were made for various options of antenna copper plating and cooling of the 50 K thermal shield flange. We investigated three versions of the antenna design: stainless steel 316LN antenna with 50 µm and 150 µm thicknesses of the copper plating, and solid OFC copper antenna. Also, we varied the temperature of the 50 K flange in the 50...150 K range. The calculated temperature distributions along the coupler are shown on Figure 4 for all three versions of the antenna and the fixed 150 K temperature of the 50 K flange. Evidently, the thicker copper plating or the solid OFC copper antenna provide a better thermal conductivity and thus minimize RF heating of the antenna tip. Figure 5 illustrates the temperature distributions along the inner coaxial conductor. The far-right point on the plots corresponds to the temperature of the antenna tip. The strong dependence of antenna heating versus a copper plating thickness is clearly visible.
For the next step, we added the input waveguide port to the CST model. Consequently, as the coupler antenna temperature has increased by about 10% compared to the coaxial coupler geometry without the input waveguide (see Figure 6). Based on the simulating results we decided to change the antenna material from the 316LN stainless steel to the OFC copper and, therefore secure the maximum temperature of the antenna tip bellow 200K.

**Figure 5. Temperature distribution along the coupler inner conductor.**

**Figure 6. Temperature distribution along inner conductor and general temperature distribution (with waveguide port).**
Thermal flux distribution along the coupler

Figure 7 illustrates calculated heat loads along the coupler and through the coupler flanges thermally anchored to the 50 K and 5 K cooling circuits. The total calculated heat load is about 17 W, which is close to the analytical estimation of 16 W, with surface RF loses in the coupler assuming its operation in the travelling wave regime. The ceramic windows volume loses are about 1.3 W, heat fluxes coming from the antenna tip and from the inner warm conductor are 4 W and 4.75 W respectively. Resulted heat loads to the 50K and 5 K flanges are 14.8 W and 0.95 W. Finally, we found the integrated thermal radiation from the outer coaxial surfaces are below 1 W for the worst case scenario, when the 50 K flange temperature rises to 150 K.

Conclusion

The 3D multiphysics simulation of the 3.9 GHz coupler was made by the CST Studio and results are in good agreement with previous 2D analysis done using COMSOL software. The temperature distributions along the coupler and resulting heat loads to the 50K and 5K cooling circuits were simulated for three versions of the coupler antenna:

- Antenna made of the 316LN with 50 µm of copper plating
- Antenna made of the 316LN with 150 µm of copper plating
- Antenna made of the pure OFC copper

Based on simulating results it was decided to change the antenna design from the copper plated 316LN stainless steel to the solid OFC copper. The proposed solution simplifies the coupler manufacturing and lowers the maximum antenna temperature, while keeping the sufficient antenna mechanical rigidity.

[1] Physical Requirements Documents LCLSII-4.1-PR-0097-R2