SIMULATIONS AND EXPERIMENTAL STUDIES OF THIRD HARMONIC 3.9 GHz CW COUPLER LCLS-II SC PROJECT*

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Abstract

LCLS-II linac is based on SRF technology developed for the XFEL project. The XFEL 3rd harmonic system built by INFN is based on the original designs of cavity and power coupler developed and built by Fermilab for the FLASH facility at DESY. For LCLS-II application both designs of the 3.9 GHz cavity and the power coupler have been modified for an operation in the continuous wave regime up to 2 kW average RF power. In this paper we discuss coupler modifications and the result multiphysics analysis for various operating regimes. For the initial test of a proposed design, we decided to modify two spare warm sections of power couplers, built for the FLASH facility, by shortening both of two inner bellows and making a thicker copper plating. Modification of the existing coupler test stand and the test program are briefly discussed in this paper.

INTRODUCTION

The LCLS-II SRF linac consists of 35 1.3 GHz, 8-cavity Cryomodules (CM), and two 3.9 GHz, 8-cavity cryomodules. Third harmonic superconducting cavities are used for increasing a peak bunch current and for a linearizing of the longitudinal beam profile. Table 1 shows main parameters of the 3.9 GHz cavity and cryomodule developed for the LCLS-II linac [1].

Table 1: Main parameters of the 3.9 GHz CM and cavity.

	Nominal	Min	Max
Average Q0 at 2K	2.0×10^9	1.5×10^9	
Avrg gradient, MV/m	13.4	-	14.9
Beam to rf phase, deg.	-150	-90	-180
Cavity R/Q	750 Ω	-	-
G factor	273 Ω	-	-
FPC, Q_{ext}	2.7×10^7	-	-

The fundamental power coupler (FPC) is one of the critical components of the 3.9 GHz cryomodule. For the 300 uA beam current, the RF power induced by a beam and radiated to the power coupler is about 1.5k W per cavity. Required power from klystron is ~ 0.5 kW to cover all range of possible parameters, including cavity microphonics. Thus, the coupler needs to be rated for at least 2kW of average RF power (mostly travelling wave regime).

POWER COUPLER DESIGN

Fermilab has developed and built the 3.9 GHz cryomodule with four cavities for the FLASH facility at DESY [2]. Design of the fundamental power coupler (FPC) was optimized for the pulse operation to accommodate up to 50 kW pulsed RF power and about 600 W of average RF power. The mechanical design of the 3.9 GHz power coupler developed at Fermilab is shown in Figure 1. It is based on the 50 Ohm coaxial line with a 30 mm diameter of the outer conductor. Coupler has a fixed coupling, the antenna length was chosen to provide Qext~1.e6 for FLASH beam parameters. This design is also accepted with small modifications for the 3rd harmonic system in the XFEL project.

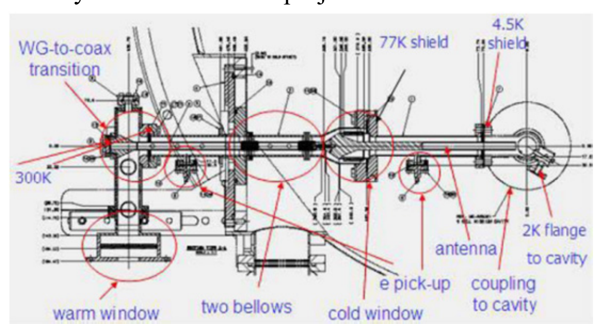

Figure 1: 3.9 GHz power coupler developed at Fermilab.

One of the LCLS-II requirements for the 3.9 GHz power coupler is a CW operation at 2 kW in the traveling wave regime. Initial thermal simulations performed by the COMSOL software shown that using the original coupler design as is (no modifications, except the length of antenna) will result in an overheating of the inner conductor in the warm section of the coupler up to 670 K at the 2 kW of CW input RF power. For reducing the maximum temperature to the level of < 450 K, determined as a comfortable and safe for the CW coupler operation, we propose the following modifications of the current design:

- Reducing the length of two inner bellows (use 15 convolutions instead of 20 convolutions).
- Increasing thickness of a copper plating of the inner conductor from 30 to 120 microns.

THERMAL ANALYSIS

The COMSOL 3D-model for thermal and mechanical simulations of the 3.9 GHz power coupler is shown in Figure 2. Two flanges of the coupler are thermally anchored to the cryomodule 5 K and 70 K thermal shields respectively with thermal straps. Temperature boundary

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conditions shown in the Figure 2 are estimated including temperature drops in thermal straps for the steady-state condition at 2 kW average RF power. We use copper thermal and electrical conductivities corresponding to the RRR=50 and take into account anomalous skin effect for RF loss calculations [3]. The relative permittivity of ceramic is chosen equal to 9.8 and the loss tangent is 3e-4.

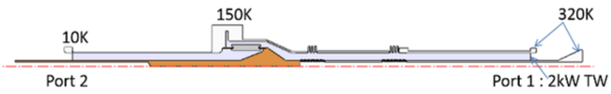

Figure 2: COMSOL thermal analysis model.

The original 3.9 GHz FLASH power coupler has two bellows with 20 convolutions on the inner conductor and two bellows with 3 convolutions on the outer conductor. Results of COMSOL Multiphysics simulations performed for 10, 15 and 20 convolutions of inner conductor bellows and for 50, 100 and 150 microns of copper plating thickness are summarized in Figure 3. Black star in Figure 3 corresponds to the 443 K maximal temperature rise, which is below the 450 K threshold of maximal acceptable coupler temperature. Thus, for solving the inner conductor overheating problem we propose to reduce the length of two inner bellows from 20 to 15 convolutions and to increase the thickness of a copper plating on the inner conductor from 30 to 120 microns

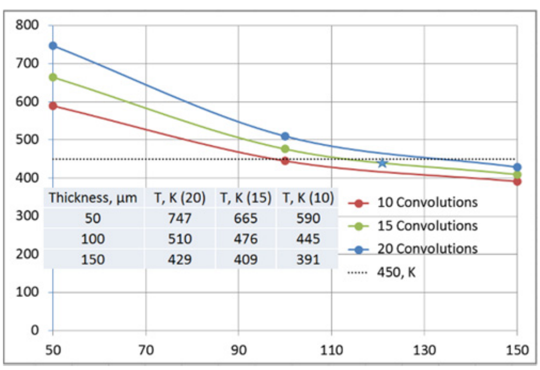

Figure 3: Maximum temperatures of inner conductor vs. number of convolutions and copper plating thickness.

A calculated temperature map in the coupler and a temperature distribution along the surface of the inner conductor for the bellows with 15 convolutions and 120 microns thickness of a copper plating are illustrated in Figure 4.

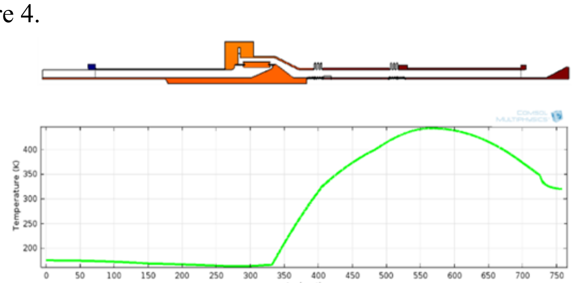

Figure 4: Temperatures distribution in coupler and along inner conductor surface.

MECHANICAL DESIGN

Analysis of mechanical stresses in coupler components was performed by the COMSOL code. The 3D solid model of the 3.9 GHz coupler is illustrated in Figure 5. As a result, transverse and longitudinal displacements and stresses of the coupler inner and outer conductors have been evaluated. The coupler antenna is deformed in both transverse and longitudinal directions as shown in Fig.5.

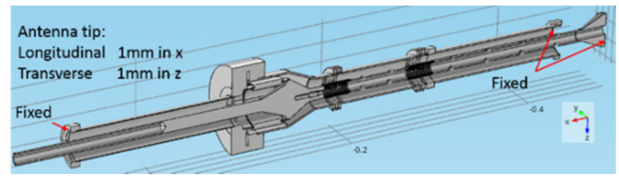

Figure 5: COMSOL solid model of the 3.9 GHz power coupler with mechanical boundary conditions.

The solid model of a copper plated (120 µm) stainless steel inner bellows is shown in Figure 6. The calculated distribution of von Misses stresses for the longitudinal coupler deformation of 1mm (0.5mm per bellows) is presented in Figure 7.

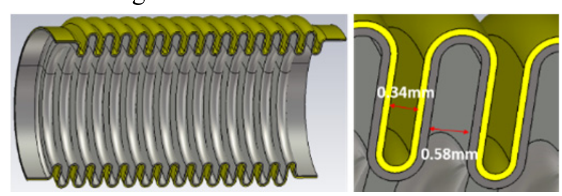

Figure 6. Solid model of the stainless steel bellows with 15 convolutions and 120 µm copper plating.

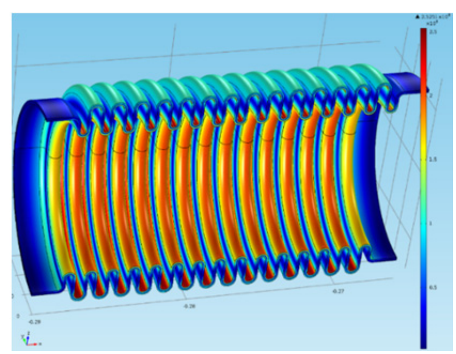

Figure 7: Von Misses stresses for 0.5 mm longitudinal deformations of each bellows.

The results of von Misses stress analysis are summarized in Table 2. Stresses are shown for 1mm displacement of antenna, consequently the yield stress of bellows material can be as high as 253 MPa. Typically copper bellow endurance limit for infinite cycles is from 83 to 166 MPa or 300 MPa for a low cycle fatigue strength.

Table 2: Summary of stresses in bellows (1mm total).

Source	Amplitude	Units
Inner conductor, transverse	38	MPa/mm
Outer conductor, transverse	45	MPa/mm
Inner conductor, longitudinal	283	MPa/mm
Outer conductor, transverse	98	MPa/mm

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COLD WINDOW MODIFICATION

In the original version of 3.9 GHz coupler the design of the cylindrical cold window is nearly identical to the 1.3 GHz coupler. This window is incorporated in the 3.9 GHz coupler as well and matched carefully for eliminating reflections at the operating frequency. Typical plot of the S11 parameter is shown in Figure 8 for the nominal dimensions of the ceramic window.

Due to a large size of the alumina ceramic window, the parasitic modes can be trapped inside the ceramics itself. In the nominal design we tried to have large enough frequency separation between parasitic and operating modes. Nevertheless, manufacturing errors and variation in properties of ceramics might shift frequency of parasitic mode close to the operating mode, which can be dangerous, especially for CW operation at high RF power.

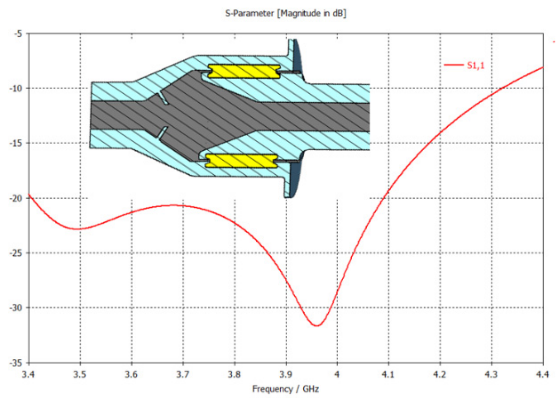

Figure 8: S11 parameter of the ceramic window.

Simulations for ceramics with ε=9.8 predicts frequencies of nearest trapped modes 3.9106; and 3.912 GHz, which is a function of permittivity. Structure of modes is shown in Figure 9.

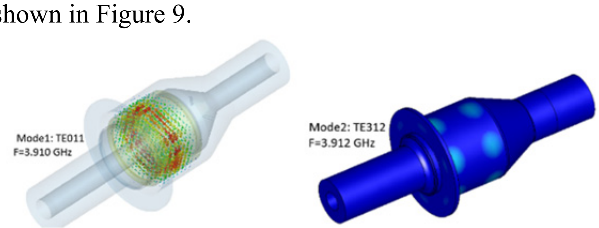

Figure 9: Two nearest trapped modes in the coupler ceramic window.

One of this parasitic mode with the frequency of ~20 MHz below the 3.9 GHz is observed during measurements of a few power couplers built for the FLASH project. A presence of parasitic resonance close enough to the operating frequency can cause an overheating of the ceramics and possibly a window damage in the CW regime. For a safe operation it was decided to move the frequency of nearest parasitic mode down by ~30 MHz. Taking into account the calculated sensitivity of parasitic mode frequencies from inner and outer diameters of the ceramic window of ±65.6 MHz/mm, we decided to increase the overall thickness of ceramics by 0.5 mm. For that purpose both the inner and outer diameters were changed symmetrically by 0.25 mm each, which shifts down by 33 MHz the frequency of nearest parasitic mode and, thus, secures of about 50 MHz isolation from the operating mode.

Properties of alumina ceramics (ε, tanδ) used for coupler production was measured at frequencies around 4GHz in a special set-up. Configuration of the test setup and dimensions are shown in Figure 10. The sample of cylindrical ceramic (cut out of one of the cold window) is installed in the copper cavity by using tiny plastic rods for support. Frequencies and Q-factors of resonance modes of empty cavity and cavity with ceramics were measured for 5 lowest modes in the frequency range from 3.53 GHz to 4.99 GHz. From these measurements we found ceramic properties (ε, tanδ) using the best fit approximation and taking into account losses in cavity walls.

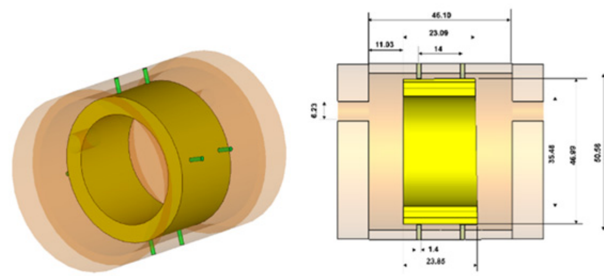

Figure 10: Set-up for ceramic measurement.

Measured values of ceramic permittivity and loss tangent coefficient (averaged over first 5 modes) are ε=9.71 and tanδ=3.6E-4 respectively.

CONCLUSION

The following modifications of the 3.9 GHz fundamental power coupler developed for the XFEL 3rd harmonic system are proposed to satisfy to the LCLS-II requirements: a) a redesign of the coupler antenna, b) increasing the thickness of a copper plating up to 120 microns on the inner coaxial conductor and bellows, c) a reduction of the inner conductor bellows convolutions from 20 to 15 and d) increasing the thickness of ceramic window by 0.5 mm. COMSOL multiphysics analysis confirm that proposed modifications provide a safe operation of the 3.9 GHz coupler at 2 kW average RF power with the maximum temperature rise below the 450 K threshold.

REFERENCES

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