

3.9 GHz POWER COUPLER DESIGN AND TEST FOR LCLS-II PROJECT

N. Solyak, I. Gonin, C. Grimm, E. Harms, T. Khabiboulline, A. Lunin, O. Prokofiev, G. Wu, Fermilab, 60510 Batavia, IL, USA

Abstract

LCLS-II linac requires two 3.9 GHz cryomodules (eight cavities per CM), operating up to 16MV/m in cw regime. Fermilab has designed and built few prototypes of the cavity and auxiliaries and tested them at the vertical and horizontal cryostats. Fundamental power coupler, based on existing design (FLASH, XFEL) was redesign for 2kW average power. We built three prototypes and tested them at room temperature test stand. One coupler was assembled on the cavity and tested at horizontal cryostat as part of design verification program. Test results and comparison with simulations are discussed in this paper.

INTRODUCTION

In frame of 3.9 GHz prototyping and design verification program (DV) Fermilab built four bare cavities and modified three warm part of the FLASH/EuXFEL style couplers for measurements and testing. All cavities were chemically processed, tuned, cleaned, assembled and tested in the vertical cryostat (VTS). One prototype cavities was dressed to the helium vessel, assembled with coupler, magnetic shielding and tuner and tested in the horizontal cryostat as integrated unit to demonstrate the performance and define if any further modification required before starting serial LCLS-II production of three 3.9 GHz cryomodules.

Original design of the coupler has average power limitation <0.5 kW. For LCLS-II 3.9 GHz power coupler was modified to meet 2kW power requirements. For prototype we modified three existing warm sections of couplers left from FLASH 3rd harmonic production. The major modification done was replacing two long inner bellows with shorter bellows (15 convolutions instead of 20) and making a thicker copper plating on inner conductor, ~150 microns instead of 30 microns. In cold part of the coupler the only change was shortening the antenna length to reach QL ~1.5 · 10⁷ instead of 1.5 · 10⁶ before. Design of the 3.9 GHz coupler is discussed in more details in papers [1,2].

THERMAL ANALYSIS

Thermal regime of the coupler was analysed by using COMSOL software for simplified 2D-model and CTS software for 3D model to cross-check result. Thermal radiation was also included in the model. Results of 3D analysis is consistent with simplified 2D simulations.

The 2D model of the coupler and temperature distribution on inner and outer surfaces are shown in Fig. 1. In simulation we apply 1kW RF power on the coaxial port and put electrical boundary condition from cavity side. In plot the position of short corresponds cavity on-resonance case. This is the worst case scenario for coupler heating. Temperature distribution along inner conductor (shown in plot below) was simulated for two case: 1) stainless steel (SS)

antenna, plated by 30 micron of copper and 2) antenna made of pure copper. It is clearly seen that temperature of the copper antenna is much lower than stainless steel one.

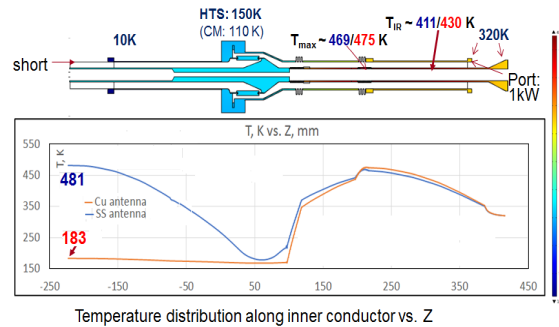


Figure 1: on top - 2D coupler geometry coloured by temperature. Below: temperature along inner conductor for stainless steel antenna (blue) and copper antenna (brown).

Cavity Q_{ext} changes after cooldown to 2K. On prototype Q_{ext} = 1.54 · 10⁷ at room temperature and 1.7 · 10⁷ measured at 2K. When we apply rf power to the coupler, heating also changes antenna length and Q_{ext}. To understand effect we simulated antenna deformation due to thermal stresses. Results are shown in Fig. 2 for the stainless steel antenna as a worst case. Black colour show coupler at room temperature before cooldown. After cooldown antenna shrink down by 123 μm in length. For 2kW rf power (or 1kW in SW regime) antenna elongates by 750 μm, so differential changes in length of antenna ~890 μm.

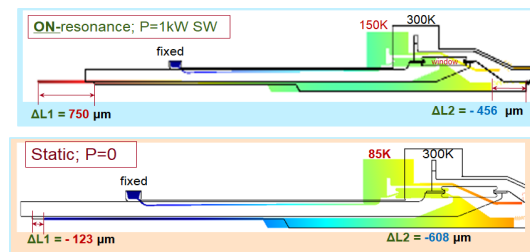


Figure 2: Antenna deformation due to thermal stresses.

Corresponding difference in antenna length and corresponding changes in Q_{ext} are shown in Table 1 for the cavity ON and OFF resonance and for different material of coupler antenna: copper and stainless steel.

Table 1: Antenna Elongation and Q_{ext} Changes for 1kW

Ant. Material	case	T, K max	T, K ant	dL μm	ΔQ/Q %
Copper	ON-res.	475	183	22	0.6
	Off-res.	428	174	15	0.4
SS+Cu 30μm	ON-res.	469	481	873	25
	Off-res.	447	386	591	16

COUPLER PROTOTYPING

Length of the coupler antenna defines the external Q_{ext} of the cavity. Q_{ext} sensitivity to the length is shown in Fig. 3 for LCLS-II cavity, approximately $\sim 30\%$ per mm. LCLS-II specify $Q_{ext} = 2.7 \cdot 10^7$ with acceptable spread $\pm 10\%$. Recent simulations shows that requirements on the spread can be relaxed.

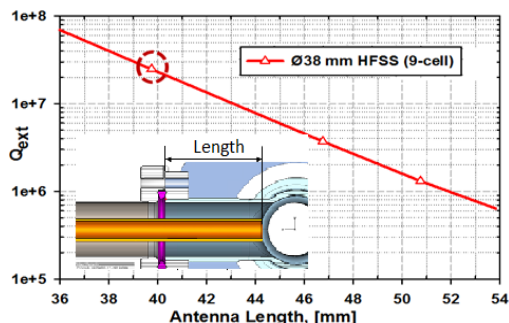


Figure 3: Q_{ext} of the 9-cell cavity as function of antenna length.

EuXFEL team reported Q_{ext} measurements on the first 3.9 GHz cryomodule (eight cavities), that show that external Q can be factor of 2 different from cavity to cavity. For prototype cavities at Fermilab it was found that coupler port position has deviation $\sim 1\text{mm}$, out of tolerance $\pm 0.2\text{mm}$. Antenna length in coupler machined more accurate $\pm 0.2\text{mm}$. Our measurements shows that cavity errors mostly contributed to the Q_{ext} deviation. Field flatness is another source of errors in Q_{ext} , degradation flatness to 90% may change Q_{ext} up to $\sim 20\%$.

COUPLER TESTING

Warm Coupler Test and High Power Conditioning

Two prototype couplers were assembled and installed on the test stand for high power test. Stand was modified for LCLS-II. After baking and pumping, rf power of 2kW in traveling wave regime applied and heat couplers. Temperature was measured on the coupler flanges and on antenna through view port on the waveguide cavity. Temperature of $\sim 200\text{C}$ was achieved in antenna and it still rising. During two shifts, 8 and 11 hours, couplers were conditioned at room temperature. Figure 4 illustrates test stand and plots showing rf power, vacuum in both couplers (white) and temperatures on the coupler.

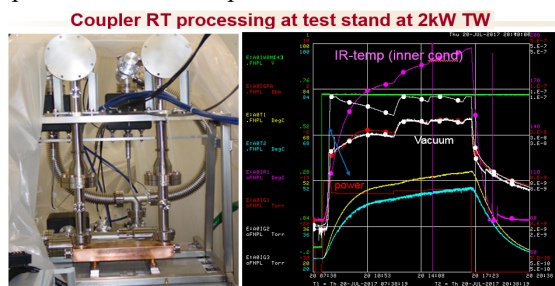


Figure 4: Test stand with two installed 3.9 GHz couplers (left) and plot, showing major control parameters.

Coupler Diagnostics in HTS

For horizontal test of the 3.9 GHz cavity [3,4], cavity and coupler was equipped with sufficient diagnostics to understand performance and cross-check measurements with simulations as much as possible. Coupler 5K and 70K intercept points were connected with copper straps to 5K and 70 K thermal shields in HTS. Knowing temperature dependent conductance of the straps allow to calculate heat power transferring from coupler to thermal shields. Schematic of the thermal diagnostics are illustrated in Fig. 5. Photos shows some details of connection.

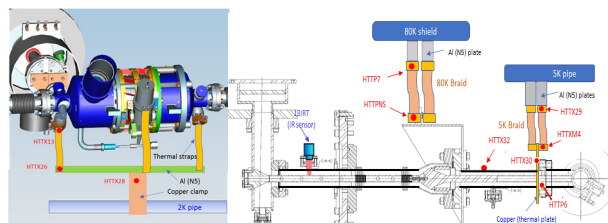


Figure 5: Thermal intercepts and temperature diagnostics in HTS tests.

Coupler Test Results

Coupler was tested up to 1 kW rf power in two regimes: with cavity ON and OFF-resonance. Each test requires 10 to 12 hours to reach equilibrium temperatures. The longest time constant has 80K intercept area, including 80K flange and thermal connection braids. Other areas: 5K intercept braids and room temperature end (waveguide with warm window) have faster temperature response. Figure 6 shows behavior of temperature sensors vacuum and power in 1kW/on-resonance test run to illustrate heating time constant for 80K intercept area of the coupler.

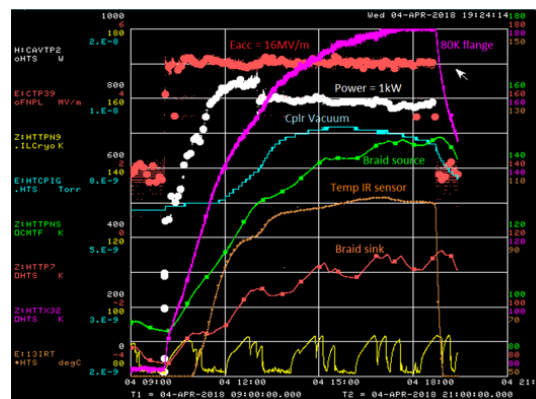


Figure 6: White-RF power (1kW), red circles-cavity gradient 16 MV/m, cyan – coupler vacuum, green and red temperature on braid source and sink.

Coupler 80K temperature is used for interlock and it should be $\sim 170\text{K}$ or less. Cryomodule shield temperature is $\sim 40\text{K}$ instead of 80-90K in HTS, it reduce temperature of flange to comfortable range. Figure 7 shows temperature of 80K flange summarized from several tests as a function of rf power (cavity on-resonance).

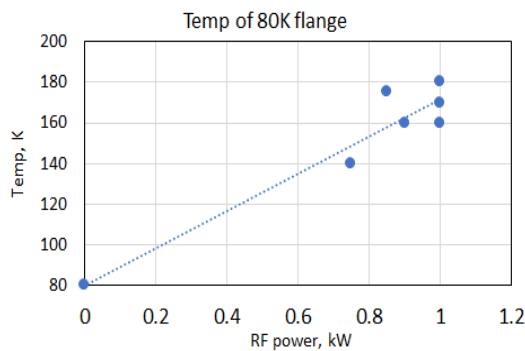


Figure 7: Temperature of the coupler 80K flange vs. rf power, measured in several tests.

Power flux from coupler to thermal shield at 80K intercept was calculated from temperature drop on one of the thermal strap with known conductivity (measured in wide temperature range) as shown in Fig. 8.

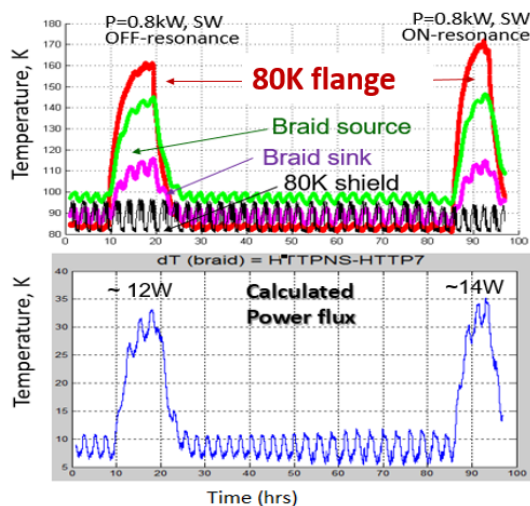


Figure 8: top-Temperature on the 50K coupler flange braid and 80K thermal shield. Below-differential temperature on the thermal braid and calculated power flux.

Similar plot for 5K intercept area is illustrated in Fig. 9, where flux power is estimated from temperature drop on thermal braid. Simulation results for power flux going to 80K and 5K temperature shield are shown in Table 2 for boundary conditions similar to what we had in HTS test.

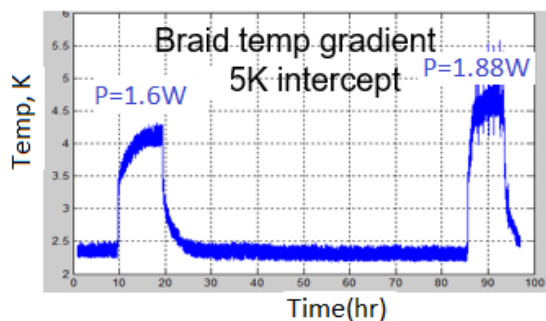


Figure 9: Temperature difference on the braid connected on 5K coupler intercept and calculated power flux.

Table 2: Power Flux to 5K and 80K Intercept, Simulated for 1kW SW RF Power

Ant. Material	case	$P_{flux@80K}$ W	$P_{flux@5K}$ W
Copper	ON-res.	13.4	0.87
	Off-res.	9.8	0.75
SS+Cu 30 μ m	ON-res.	15.3	1.05
	Off-res.	11.2	386

Coupler integration in the 3.9 GHz cryomodule is shown in Fig. 10, similar to 1.3 GHz design.

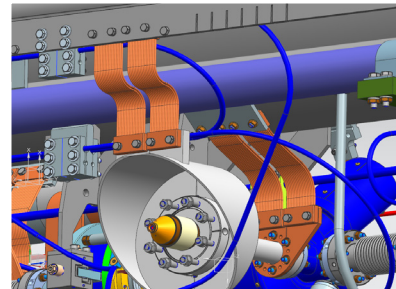


Figure 10: 3.9 GHz coupler thermal intercept design.

CONCLUSION

Design of all components of the 3.9GHz coupler is completed. We build prototypes and tested it on the dressed cavity in the horizontal cryostat. Test results demonstrated that coupler heating regime are close to prediction. Unwanted drift of the loaded Q during heating of the coupler should be significantly reduced for copper antenna instead of stainless steel antenna, tested in prototype version of coupler. This changes incorporated in the coupler design for production procurement. The first item from production will be assembled on the cavity and tested in HTS to confirm improvements in performance.

ACKNOWLEDGMENTS

We greatly appreciate the large contribution to this work from the entire Fermilab LCLS-II team, cryogenic engineers and technicians.

REFERENCES

- [1] I. Gonin *et al.*, "Thermal-mechanical study of 3.9GHz CW coupler and cavity for LCLS-II project", in *Proc. LINAC'16*, East Lansing, MI, USA, Sep 2016.
- [2] N.Solyak *et al.*, "Simulations and experimental studies of the third harmonic 3.9GHz coupler for LCLS-II SC project", in *Proc. IPAC'16*, Busan, Korea, May 2016.
- [2] T. Khabiboulline *et al.*, "Modification of 3rd harmonic cavity for cw operation in LCLS-II Accelerator", in *Proc. NAPAC'16*, Chicago, USA, Oct. 2016.
- [3] N.Solyak *et al.*, "Design and test results of the 3.9GHz cavity for LCLS-II", presented at IPAC'18, Vancouver, Canada, Apr.-May 2018, paper WEPML023, this conference.
- [4] S. Anderhold, "3.9GHz cw challenges and recent horizontal test result for 3.9GHz cavity", TTC meeting, Milan, Feb. 2018.