MODIFICATION OF 3RD HARMONIC CAVITY FOR CW OPERATION IN LCLS-II ACCELERATOR*

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Abstract

A 3.9 GHz 3rd harmonic cavity was developed at FNAL and it is currently used in the FLASH accelerator at DESY in order to improve FEL operation. The European XFEL accelerator in Hamburg also adapted the same cavity design for a pulsed linac operation. The 3rd harmonic cavity for the LCLS-II accelerator at SLAC will operate in a continuous wave (CW) regime. A CW operation and a high average current in the LCLS-II linac result in increased heat loads to main and HOM couplers of the cavity. Several cavity design modifications were proposed and investigated for improving a cavity performance in the CW regime. In this paper we present results of the design review for proposed modifications.

INTRODUCTION

The LCLS-II superconducting linac consists of thirty five 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 linearizing 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	-
Average 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	-	-

A continuous wave (CW) operation of the 3.9 GHz cavity in LCSL-II linac at gradient of 14.9 MV/m sets an extra requirement on possible overheating of the HOM coupler feedthrough [2]. We revised the design of the 3.9 GHz cavity and proposed minimal improvements in order to keep the geometry of cavity cells unchanged.

In the original design of the 3.9 GHz cavity we observed a trapped dipole mode in the power coupler of the cavity, where the cut-off frequency for the dipole TE_{11} mode is close to the frequency of the operating mode. This trapped dipole mode affects on RF fields in the HOM coupler at the operating frequency as well. Therefore we proposed a reduction of the beam pipe diameter from 40 mm to 38 mm. This modification allowed to move the frequency of the trapped dipole mode away from the operating frequency, which simplifies HOM coupler notch frequency tuning and reduces the leakage of RF power at operating frequency.

Another concern was a thermal quench of HOM antenna at about 20 MV/m observed during a vertical test (VT) in the CW regime. In the VT setup all components are submerged into a superfluid helium and therefore cooling of the HOM feedthrough is significantly better than in the cryomodule. The HOM feedthrough antenna is made of a solid Niobium, which does not produce significant amount of RF losses until its temperature is below critical. Operating mode RF fields may initiate a thermal runaway process and cause a quench in HOM feedthrough antenna is case of pure cooling [3]. In order to avoid such a scenario and reduce the antenna RF heating we proposed to move the antenna away from the f-part and use a shorter antenna tip by increasing the height of the f-part snag. As a result, the length of antenna tip is decreased from 5 mm to 1 mm and the height of the f-part snag is increased to 7.8 mm.

Previously few cavities developed a vacuum leak on the HOM coupler can after a bulk BCP processing. Concequently the original thickness of the can was increased from 1 mm to 1.15 mm for XFEL cavities. For ensuring a good safety margine we decided on a futher increase of the HOM can thickness. Mechanical stress analysis demonstrates a feasibility of 1.3 mm thickness.

The 3.9 GHz cavity in LCLS-II linac can emit on HOM coupler up to 5 W of average RF HOM power. Additionally up to 1 W of RF power can leak by the operating mode. In order to make a correct choise of RF cables for HOM coupler a thermal analysis was performed.

BEAM PIPE MODIFICATION

A conical tapering of the NbTi transition ring was accepted for the beam pipe aperture reduction from 40 mm to 38 mm (see Fig. 1).

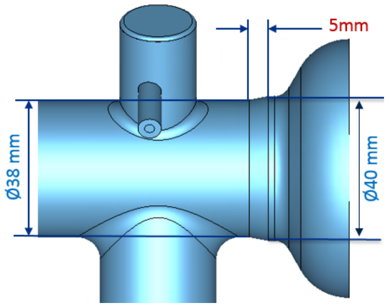

Figure 1: New beam pipe and transition ring.

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Reduction of coupling between power coupler and the cavity was compensated by increasing of the power coupler antenna by 2.5 mm. The frequency of a nearby trapped dipole mode is increased by 100 MHz (see Fig. 2).

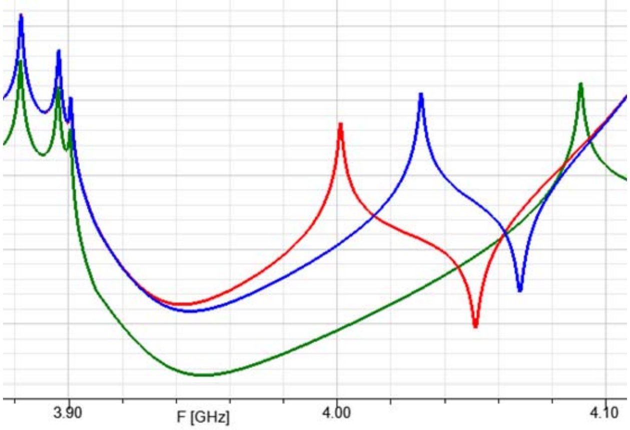

Figure 2: S_{21} signal for 40 mm (red) and 38 mm (green).

Design of cavity cells, cavity length, shape and position of conical flanges were not changed. Outer diameter of the interconnecting bellows is also reduced from 42 mm to 38 mm.

HOM F-PART MODIFICATION

The height of the f-part snag is increased by 2 mm limited by a clearance space during HOM coupler production, as shown in Fig. 3. The length of antenna tip is shortened by 2 mm and the shape of the tip was modified accordingly.

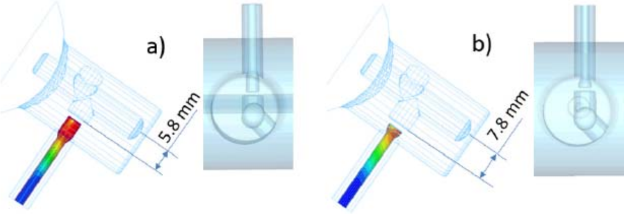

Figure 3: Modifications of the HOM coupler for the 3.9 GHz cavity: a) XFEL design and b) LCLS-II design.

RF heating of the HOM antenna is reduced by about 5 times. HOM coupling not reduced significantly. The distance from beam line to the F-part was kept 15 mm as in the initial design.

HOM SIMULATIONS

Detailed analysis of the HOM spectrum up to 10 GHz in initial designs of the 3rd harmonic cavity are presented in [4, 5] for a single resonator with perfect electric or magnetic boundary conditions at both ends. While such an approach allows simplifying calculations, it might result in a significant uncertainty of HOM resonant frequency, shunt impedance and quality factor. As a remedy we use a chain of three connected cavities with matched impedance boundaries set for all couplers ports and both ends of a beam line. Fig. 4 shows maps of electric fields for first two modes in the 2nd monopole passband.

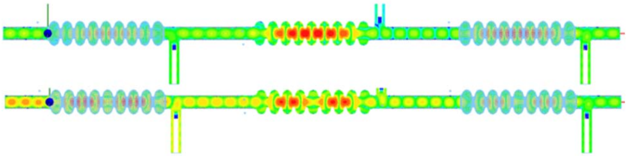

Figure 4: Electric field map of HOMs in the 2nd monopole band of the 3.9 GHz LCLS-II cavity.

In spite of the operating mode, which is tuned separately, the parameters of HOMs vary from one cavity to another due to finite mechanical tolerances of cavities fabrication. For that we generated random cavity geometries with imperfections while preserving operating mode frequency and field flatness [6]. Next we compared HOMs parameters of both XFEL and LCLS-II designs of the 3.9 GHz cavity. The result is presented in Fig. 5 for frequency passbands containing HOMs with the largest shunt impedances or quality factors.

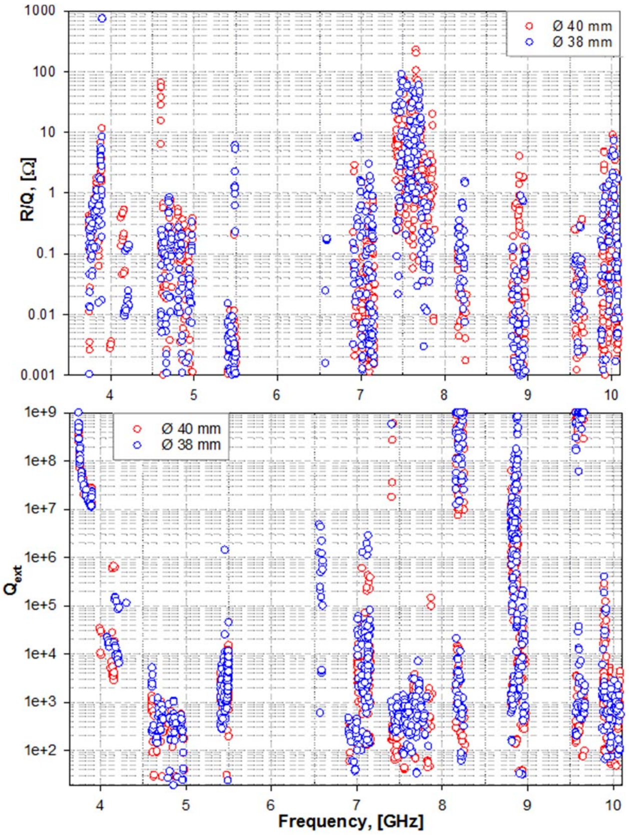

Figure 5: Longitudinal HOMs R/Q (up) and loaded quality factors (down) in the XFEL (red) and LCLS-II (blue) 3rd harmonic cavities.

Finally we conclude that the new design of the HOM coupler demonstrates about the same efficiency in HOMs damping as the original version developed for the XFEL 3rd harmonic cavity.

HOM COUPLER CAN MODIFICATION

In the initial FLASH design the top wall thickness of the HOM can was 1 mm, machined from a solid piece. According to Fermilab experience there are two cases, when

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cracks were developed after series of chemical treatment. In the XFEL design a thickness was increased to 1.15 mm, nevertheless one prototype cavity had the similar problem. Therefore, we decided to increase a thickness to 1.3 mm.

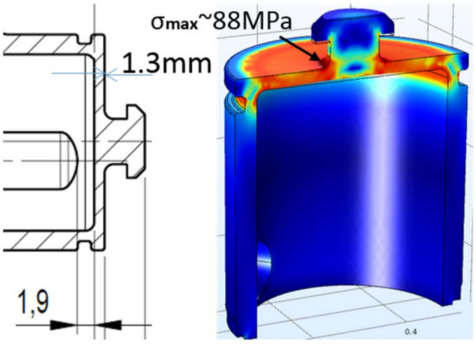

Figure 6: Mechanical analysis of the HOM can thickness

COMSOL analysis of mechanical stresses has been done. Nonlinear behaviour of the stress-strain characteristic is taken into account. The yield stress is about 80MPa. Analysis demonstrated that von Misses stresses for 1.3 mm thickness of the top plate in tuning range of +/- 200 µm is 88 MPa. Figure 6 shows the top part of the HOM coupler can and von Misses stresses distribution.

HOM CABLE THERMAL SIMULATIONS

An RF signal is transmitted through the HOM feedthrough and the coaxial cable to the connector on the CM outer flange where it is terminated with a matched load. RF power traveling in cable consists of the 3.9 GHz fundamental frequency power leaking from the cavity and HOMs harmonics generated by a beam.

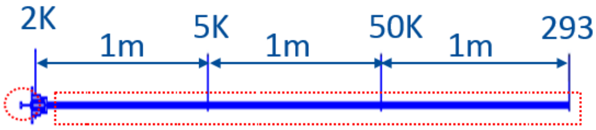

Figure 7: HOM cable cooling layout.

In order to make a correct choice of the coaxial cable, RF simulations were carried out using COMSOL [7]. HOM feedthrough is thermally anchored to 2 K two-phase pipe by copper straps. Additionally, the cable is clamped to heat sinks attached to 5 K cooling pipe and 50 K cooling shield of CM, as shown in Fig. 7.

Thermal simulations were performed to find the quench limit on both the cavity and antenna tip for various accelerating gradients. Clearly, the temperature nonlinearly increases upon increasing the cavity's gradient. Cavity will eventually quench around the 140 mT peak surface magnetic field. It is worth mention that the antenna tip is actually relatively cooler than the cavity surface, which means that the antenna is not limiting the performance of the cavity. In this particular simulation, no RF power loss was included coming from the cable.

On the other hand, Figure 8 shows the temperature along the RF cable axis, assuming the cooling configuration illustrated in Figure 7, for various level of RF power flowing along the cable. We have also included the effect of fundamental mode heating on the antenna tip through a heat flux boundary condition on the antenna's tip. In this analysis, the loss of the cable and the cooling scheme play a critical role in determining the maximum temperature the cable would reach. We have assumed a cable loss of 0.6 dB/m at 3 GHz, which we find to be feasible for cables with PTFE dielectric. Copper was also assumed for both inner and outer conductor, in order to secure good thermal conductivity to handle the several watts of heating. From the analysis we conclude that the cable should be able to handle up to 8 W of average RF power.

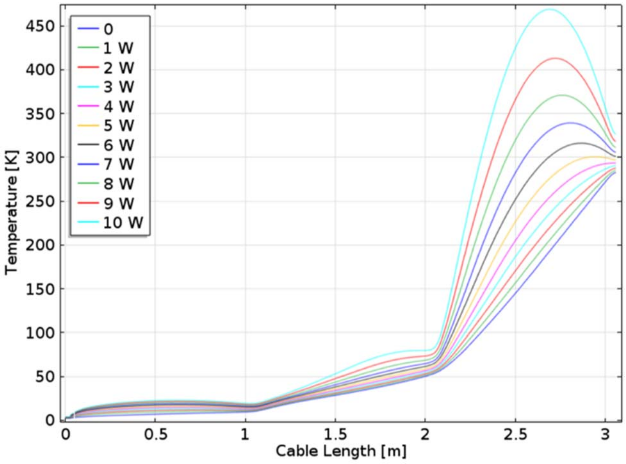

Figure 8: Temperature profile along the RF cable axis for various level of power.

CONCLUSION

Modification of the 3.9 GHz cavity for CW operation in the LCLS-II linac is completed. The beam pipe with reduced aperture increases the frequency of lowest HOM mode and, thus, resolves the HOM coupler notch filter tuning. Simple modifications of the HOM coupler f-part and the antenna reduce RF losses in the HOM feedthrough. HOM simulations demonstrated that the new design is satisfied to nominal operation requirements. Increased thickness of the HOM can reduces a vacuum leak possibility. Proper RF cable for CM is proposed based on RF and thermal simulations.

ACKNOWLEDGMENT

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