HOM COUPLER PERFORMANCE IN CW REGIME IN HORIZONTAL AND VERTICAL TESTS

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Abstract

Power dissipation in HOM coupler antenna can limit cavity gradient in cw operation. XFEL design of HOM coupler, feedthrough and thermal connection to 2K pipe was accepted for LCLS-II cavity based on simulation results. Recently a series of vertical and horizontal tests was done to prove design for cw operation. In vertical test was found no effect of HOM coupler heating on high-Q cavity performance. In horizontal cryostat HOM coupler was tested up-to 23MV/m in continuous wave mode. Result proves that XFEL HOM coupler meets LCLS-II specifications.

INTRODUCTION

Higher order modes (HOM) are excited in the particle accelerator's superconducting cavities by the particle beam causing instabilities and affecting the particle accelerator performance. In this perspective it is essential to couple them away from the cavity through specially designed HOM antennas [1]. However, the RF losses accumulated on the HOM antenna surface will induce heating and might cause the antenna surface to heat up and eventually quench if the temperature exceeds 9.2 K, the critical temperature for niobium. The problem is rather more critical for continuous wave (CW) machines compared to pulsed machines [2-3].

LCLS-II, a proposed coherent light source to be built at SLAC, is a continuous wave linear accelerator that would utilize state of the art superconducting cavities. Heating of HOM couplers is one of the technical challenges. Our simulation shows that antenna overheating for the ILC style of HOM couplers and feedthroughs will limit cavity gradient to ~10 MV/m in CW operation.

Given that we would like to utilize several existing ILC cavities in the LCLS II project, we investigate in this paper the possible shape modifications of the current ILC HOM antenna that could lower the RF losses (the goal is to reduce the losses by a factor of 4), while relatively preserving the current coupling (LCLS-II requirements for HOM damping is $Q_{ext} < 1.e6$ for the most dangerous modes, so our goal is to avoid reducing the coupling more than 10 times [4-5]). Another option is to use a better design for the feedthrough with improved thermal conductance to remove power dissipated in the antenna. In both options we assume that the design of the HOM coupler itself (f-part and can, see Figure 1) remains untouched from the original one used in XFEL and ILC cavities. A recent proposal [2] aimed at reducing heating of the HOM antenna requires a modification of the f-parts. We don't consider this option here, since it is not a viable solution for existing ILC cavities; moreover, it would require prototyping.

HOM COUPLER

The LCLS-II project is based on ILC/XFEL technology. However some modifications are required to accommodate a much higher heat load in CW operations (gradient 16 MV/m; beam: 300pC, 1MHz; σ_z=25µm at the end of the linac).One of the constraints on the LCLS-II project is that the first two cryo-modules will use existing ILC cavities provided by Fermilab with "short-short beam pipe" configuration, as shown in Figure 1(a). Therefore no modification of the HOM coupler design (except the feedthrough) is possible.

Figure 1(a) shows the geometry of the conventional ILC 9-cell elliptical cavity. The cavity has a power coupler and a HOM antenna (HOMc) on one side and a pick-up and a HOM antenna (HOMpu) on the other side. Figure 1 also shows the front projection of the cavity showing the details of both HOM antennas, and the f-parts. Possible modifications to the current ILC design of the HOM antenna are either changing the gap size or changing the tip size.

More than a hundred TESLA HOM couplers have operated for many years in TTF and around the world in short pulse regimes (few % duty factor) with a beam current up to 9 mA. In acceptance tests of these couplers and in multi-year operation in facilities, it was found that this design is robust (no overheating, no multipactoring), and cavities can operate up to 35 MV/m gradient if the couplers are properly cleaned. However, at long pulse regimes in some cavities with attached HOM feedthroughs, DESY [2] and JLAB [3] observed heating of the HOM couplers, which might be a serious limitation for CW operation. To improve heat removal performance new designs of the feedthrough were developed by JLAB and DESY to reduce heating. For XFEL applications the configuration of antenna was modified (tip diameter was reduced from 11mm to 7.8mm). For 3.9 GHz cavities, FNAL modified the JLAB feedthrough design to prevent internal resonances up to 10 GHz .

All feedthrough designs have these common features:

- Sapphire window instead of Alumina (x3 higher thermal conductivity at 2K)
- Molybdenum internal pin connector instead of SS (x200 higher thermal conductivity at 2K)
- Use copper socket for better cooling

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Figure 2 illustrates the different constituent parts of the HOM feedthrough in (a) and shows a picture of the XFEL feedthrough(b).

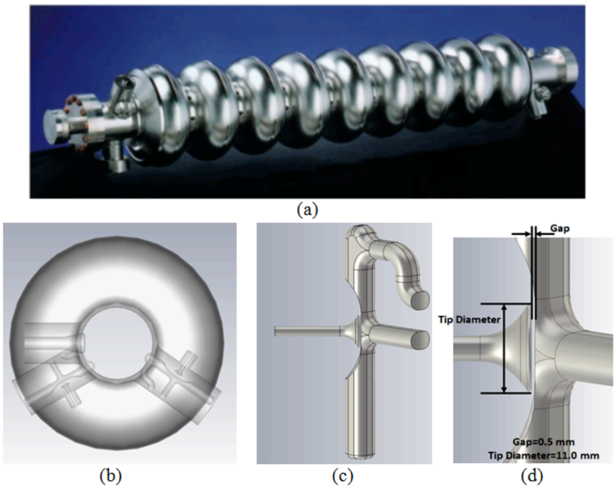

Figure 1: The geometry of the HOM coupler and antenna (a) ILC cavity. (b) Transparent front view of the cavity showing HOM couplers. (c,d) HOM antenna and f-part.

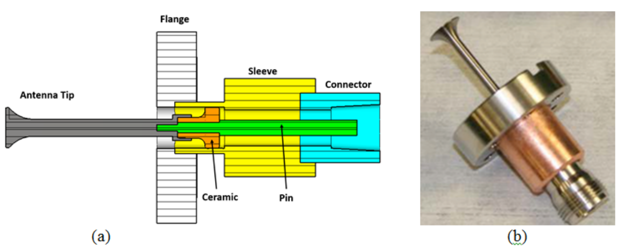

Figure 2: HOM coupler feedthrough. (a) Sketch showing the cross-section and highlighting the different feedthrough parts. (b) DESY feedthrough.

ANALYSIS OF FEEDTHROUGH HEATING

In this section the electromagnetic performance of possible modified designs is reported. In this perspective, we will take the conventional ILC style antenna as a reference design and the modified versions will be evaluated based on their performance relative to this reference design with respect to losses and external quality factor (Q_{ext}) of the antenna. Ratios of both losses and Q_{ext} will be used as criteria of comparison.

Electromagnetic Analysis

a) Modified Design of Trimmed Antenna

Trimming the antenna should reduce the losses but will considerably change the coupling (Q_{ext}). To investigate this modification option, the geometry was simulated with a trimmed antenna. Two trimmed versions were simulated with 2.5 mm and 3.5 mm gap sizes. Figure 3(a) shows the effect of trimming the antenna on Q_{ext} for all higher order modes up to 2.5 GHz. Magnetic-magnetic (MM) boundary conditions were enforced on the pipe boundaries in all simulations. Clearly, the gap size significantly affects the coupling. Ignoring the fundamental band around 1.3 GHz, the maximum ratios of Q_{ext} are shown in Table 1.

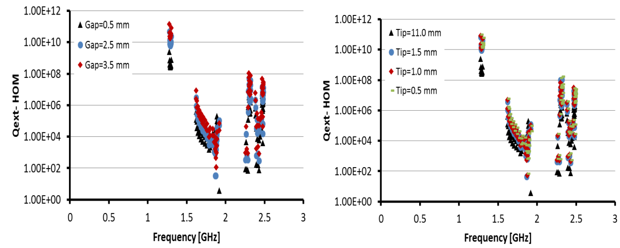

Figure 3: Effect of modifying the HOM antenna on external quality factor. (a) Effect of gap size. (b) Effect of tip size.

b) Modified Version of Reduced Tip Size

The second option to modify the ILC antenna is to reduce the tip size while keeping the gap size as is, in order to relatively preserve the coupling. Figure 4(b) shows the geometry of the antenna and its tip after reduction. The tip size is to be reduced from 11 mm diameter in the case of the ILC to pen-like shapes with tip sizes of 1.5 mm, 1.0 mm and 0.5 mm, respectively.

Table 1 summarizes the results of the different trimmed versions, indicating also the ratio of the RF losses. On average (between HOMc and HOMpu) the losses are projected to be reduced by a factor of 0.32, 0.21 for the trimmed version of 3.5 mm, and 2.5 mm in gap size, respectively. Table 1 indicates that antennas with gap size larger than approximately 2.7 mm would have a ratio of Q_{ext} higher than 10. Table 2 summarizes the results of the different tip size versions, indicating also the ratio of the RF losses (with respect to the ILC reference design). On average (between HOMc and HOMpu) the losses are projected to be reduced by a factor of 0.25, 0.24, and 0.23 for a tip size of 1.5 mm, 1.0 mm and 0.5 mm, respectively. It is clear from Table 2 that antennas with tip sizes smaller than 1.5 mm in diameter would have a ratio of Q_{ext} higher than 10.

Table 1: Effect of Trimming the HOM Antenna

Trim by	Gap [mm]	Ratio HOMc Losses	Ratio HOMpu Losses	Average Loss	Ratio of Q_{ext}
0.0 mm	0.50	1.00	1.00	1.00	1.00
2.0 mm	2.50	0.32	0.33	0.32	7.43
3.0 mm	3.50	0.21	0.21	0.21	21.06

Table 2: Effect of Reducing the Tip Size of the HOM Antenna

Tip Diameter [mm]	Gap [mm]	Ratio HOMc Losses	Ratio HOMpu Losses	Average Loss	Ratio of Q_{ext}
11	0.50	1.00	1.00	1.00	1.00
1.5	0.50	0.25	0.25	0.25	9.30
1.0	0.50	0.24	0.24	0.24	11.60
0.5	0.50	0.22	0.23	0.23	14.34

Despite the high overall ratio of HOM couplings for larger gap sizes, the detailed EM analysis performed in [4] for monopole HOMs with the highest R/Q values demonstrates a moderate rise of their Q-factors, while the effect from dipole HOMs is almost negligible for the parameters of the LCLS-II linac [5]. Thus, we conclude that having a larger gap size around 2 mm is favourable for avoiding HOM antenna overheating and simplifying the HOM feedthrough assembly.

Thermal Analysis

We carried out a thorough thermal quench study of the proposed design in comparison with the conventional ILC design to fully examine the thermal properties of the structure in both cases and demonstrate the potential of the modified structure [6]. In order to run an accurate thermal analysis it was necessary to represent the thermal conductivity of each material in the model as a function of temperature [7-8].

Figure 4(a) and (b) show the assembly model of both the ILC conventional antenna and the proposed modified version with a pen-like antenna of 1.5 mm tip size and 0.5 mm gap size. Dimensions were chosen based on the earlier electromagnetic analysis to secure both lower losses (RF losses are less by a factor of 4) and relatively preserve the coupling (Q_{ext} is higher by a factor of 9.3).

The plot in Figure 4(c) shows the temperature versus magnetic field for both the ILC geometry (dashed blue) and the proposed modified version (dotted red). In both cases an alumina ceramic, a stainless steel connector pin and stainless steel sleeve were assumed. Thermal quench analysis projects that the proposed modified design could handle up to 161 mT (~39 MV/m), compared to 58 mT (~ 14 MV/m) in the case of the conventional ILC antenna. The temperature profile of both geometries at the quench field is also shown. On the other hand, an XFEL/JLAB combination of sapphire ceramic, a molybdenum pin, and a copper sleeve will boost the performance of the antenna beyond the 200mT hard quench limit of niobium cavities, as shown in solid orange.

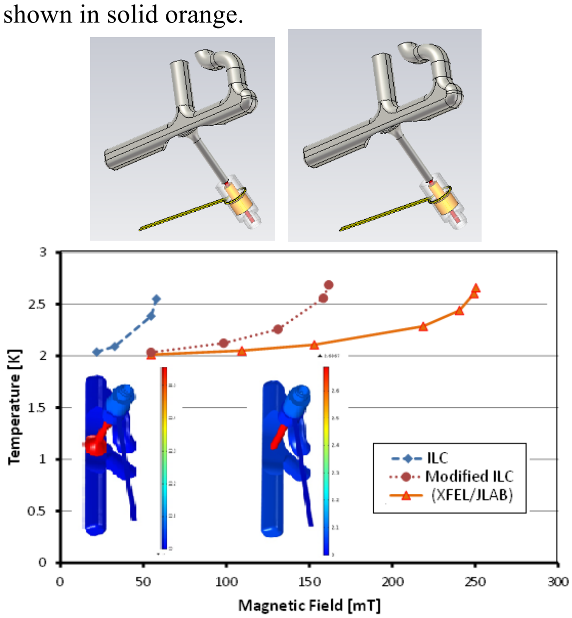

Figure 4: Thermal analysis of both (a) the conventional ILC antenna (b) and the modified one. (c) Temperature versus magnetic field for the ILC design, modified ILC design, and XFEL/JLAB design with ILC antenna tip.

HOM CABLES AND HEAT REMOVAL

The heat deposited due to the higher order modes propagation will need to be removed from the cavity through RF cables with specially designed cooling straps at 5 K, 50 K and 300 K spaced every 1 m along the cable. At 2 K the feedthrough is anchored to the 2 phase pipe with straps, as shown in Figure 8. The RF losses along the cable originate from the heat flux deposited on the HOM antenna surface coming from the fundamental mode, while the cable will have significant RF losses depending on its loss per meter (dB/m) and proportional to the power flow out of the HOM port. The attenuation of the cable was also assumed as a function of temperature defined by the cable materials.

In the process of choosing a suitable cable for the LCLS-II cryo-module, we first had to decide whether we should pick a stainless steel or a copper based RF cable as we are using in ILC style cryo-modules. Stainless steel cables are a good choice to reduce the static heat load, while copper based cables are much better to reduce the dynamic heat load. Figure 5 demonstrates the performance of a stainless steel cable versus a copper one under various power flow scenarios. Clearly, the stainless steel cable won't safely operate with more than 0.5 W, while the copper cable can reach the 10 W design goal. It is worth noting how the static heat load (no RF power flow) is better for the SS cable, however the dynamic heat load is way better for the copper cable once the amount of power flow increases beyond 0.3 W. Since we expect power flows on the order of several watts for LCLS-II, the dynamic heat load is the main concern and definitely copper cables have to be used.

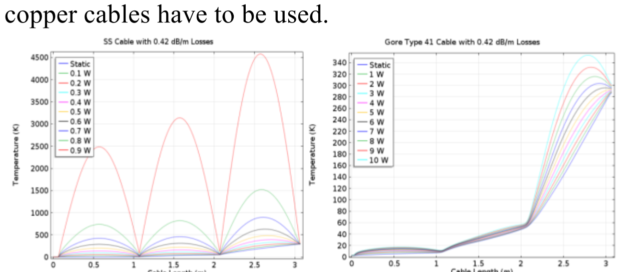

Figure 5: Performance of SS vs copper cables. (a) SS cable temperature distribution under various power flow conditions (up to 0.9W) (b) copper cable temperature distribution under various power flow (up to 10 W).

The second decision about the RF cables is to determine the acceptable loss in dB/m of the cable and therefore the diameter of the cable. It was decided that the temperature along the cable shouldn't exceed 80º C. Based on this criterion the cable size was determined. Specifically, we have considered three cables with losses of 0.6 dB/m, 0.42 dB/m, and 0.2 dB/m at 1 GHz. It is clear that the cable loss plays the dominant role in determining the maximum temperature along the cable, especially near the warm lead at 300 K. In the case of the 0.6 dB/m cable the maximum temperature will reach 230º C, while in case of the 0.42 (0.2) dB/m cable it is 75º C (23º C). Based on this analysis we have set a goal for the

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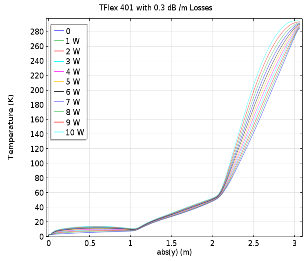
cable loss to be 0.3 dB/m at 1 GHz, in order to meet our criterion of not exceeding 80ºC with some safety margin.



Tflex401 0.3 dB/m				
Power [W]	2K [mW]	5K [mW]	50K [mW]	300K [mW]
0	6.30	189.88	287.86	-484.04
1	12.38	204.31	323.62	-438.61
2	18.46	218.83	360.99	-391.48
3	24.55	233.44	400.10	-342.50
4	**30.64**	**248.16**	**441.10**	**-291.53**
5	36.73	263.00	484.19	-238.40
6	42.83	277.96	529.54	-182.92
7	48.95	293.05	577.40	-124.88
8	55.09	308.28	628.01	-64.05
9	61.25	323.66	681.64	-0.16
10	67.42	339.23	738.62	67.10

Figure 6: Cable choice for LCLS-II CM. (a) Temperature distribution. (b) Thermal intercepted power by cooling.

For the LCLS-II prototype cryo-modules to be built by Fermilab and JLAB, Tflex 401 cables that exhibit 0.28 dB/m loss at 1 GHz are to be used. Figure 6 demonstrates the performance of the selected cable showing the heat distribution along the cable and the thermal intercepted power by the cooling leads.

EXPERIMENTAL RESULTS

Based on simulation results, the XFEL feedthrough was accepted as a baseline solution for LCLS-II project. To validate the performance of the HOM coupler in the CW regime of operation, several tests were performed at Fermilab in vertical and horizontal cryostats. The major questions addressed in these tests were heating issues and possible reduction of the cavity unloaded quality factor, Q_0. Sources of antenna heating are RF losses, power returned back from losses in the cable and possible multipactoring in HOM coupler. It is worth noting here that nitrogen doped technology [9] developed for the LCLS-II project is able to provide much higher Q_0 than conventional technology used in other projects (XFEL, ILC, etc.). In fact, the LCLS-II acceptance criterion for cavities at 2K is $Q_0 > 2.7e10$ at 16 MV/m.

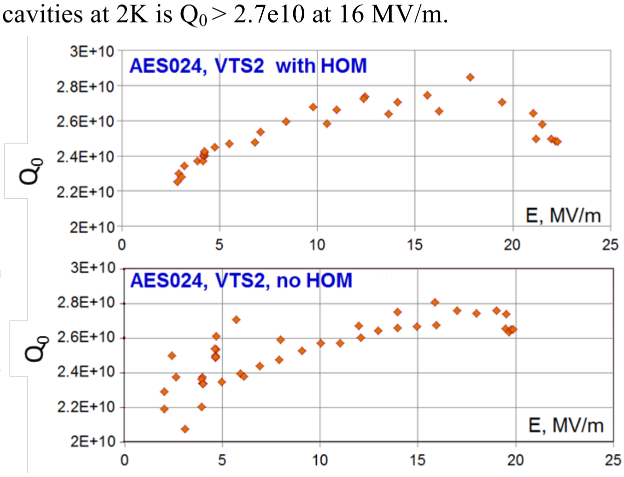


Figure 7: Experimental testing of TB9AES024: Q_0 vs E for the cavity with and w/o HOMs.

A high-Q_0 cavity was tested in a vertical cryostat at 2K with and without HOM coupler feedthroughs. After assembly of the feedthroughs, the cavity was high-pressure rinsed and the HOM rejection frequency was tuned to minimize power leakage for the fundamental mode. Results of Q_0 measurements are presented in Figure 7. One can see that Q_0 is preserved when HOM feedthroughs are mounted on the cavity. In production mode all cavities delivered from the vendor will be under vacuum with a unity fundamental coupler and HOM feedthroughs installed ready for the vertical test. This result confirms that properly tuned and cleaned HOM couplers/feedthroughs will not affect the Q_0 of the cavity.

Cooling conditions of the HOM coupler in a cryo-module are different from those in a vertical cryostat, where the HOM coupler is cooled by liquid helium. To provide a good thermal intercept of power from the HOM feedthrough, a special double strap copper braid was used to connect the HOM to the 2 K two-phase helium line (similar to the design used in XFEL, shown in Figure 8). Straps are clamped around the copper sleeve on the feedthrough.

Figure 8: Copper braids for thermal connection of the HOM feedthrough to the 2K two-phase pipe in a cryo-module.

Two tests of a cavity with assembled XFEL feedthroughs and JLAB feedthroughs (modified design of the feedthrough used for JLAB's 12 GeV upgrade) were done in a horizontal cryostat (HTS). In these tests we used the ILC type cavity TB9ACC021 (not doped) with Q_0~1.5e10 at 20 MV/m. The gradient of this cavity in the CW regime was limited by average dissipated power in the cavity of ~25 W (chimney limit), which corresponds to ~19 MV/m. In this regime in both tests, the HOM heating was small. To increase the field in the HOM couplers, the cavity was tested in the 8/9pi mode, where the maximum fields are in the cavity end cells. It allows us to achieve a field level at the HOMs corresponding to 23 MV/m of equivalent gradient. Results for both tests (which were performed with a cavity helium bath temperature of 2 K) are presented in Figure 9, where the blue trace shows accelerating gradient in the cavity as measured by the field probe. Other traces show temperature measurements on the HOM body (between the two welded legs of the f-part) and the HOM feedthrough (measured on the copper sleeve) for both HOMc and HOMpu. The maximum measured power leakage from the operating mode in all cases was less than 300 mW. One can see that the temperature rise at the HOM feedthroughs was ~1 K for 23 MV/m.

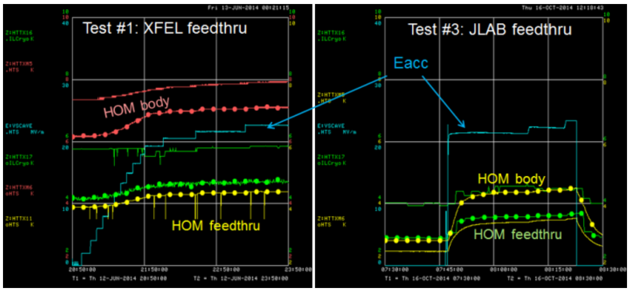


Figure 9: Test results for XFEL feedthroughs ~1° K rise on HOM body and ~0.5° K on feedthrough (left). Test results for JLAB-type feedthroughs: ~2.7° K rise on HOM body,: ~0.85° K on feedthrough (right).

The latest results from the first integrated HTS test of an LCLS-II cavity (TB9AES021) [10], fully assembled for installation in a real cryostat, are shown in Figure 10. This test included auxiliaries that were newly designed or modified for CW operation in LCLS-II, such as the main coupler, XFEL HOM feedthroughs, the tuner, the helium vessel, and 2-layer magnetic shielding. The test result proves that the Q_0 of the cavity will not be compromised by the auxiliaries and is the same as measured for the bare cavity in a vertical test cryostat: Q_0=3.e10.

Figure 10 shows the heating of the HOM couplers and the HOM power measured in the integrated test. One can see that the power leakage was below 50 mW at 20 MV/m and the maximum temperature rise was also small, below 200mK in this test.

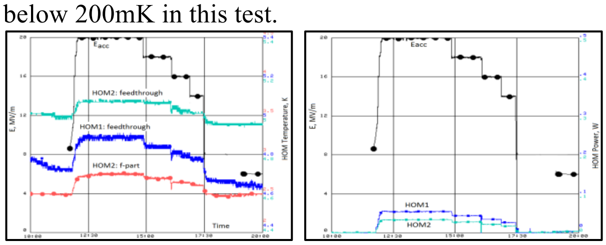


Figure 10: (left) - Temperature of the HOM coupler and feedthrough and cavity gradient. (right) – HOM power.

CONCLUSION

Electromagnetic analysis shows that possible modifications to the shape of the HOM antenna can help in reducing the HOM heating. Additionally, thermal quench analysis projects that the proposed HOM antenna would handle up to 161 mT (~39 MV/m), compared to the conventional ILC antenna which handles only 58 mT (~ 14 MV/m).

The performance of the antenna could be improved further by changing the material of the ceramic to sapphire, brazing the antenna to the ceramic window, and making the sleeve all-copper, similar to what has been suggested by DESY for XFEL and JLAB for CEBAF.

Heat removal can be achieved using copper based RF cables with attenuation <0.3dB/m to handle the relatively high dynamic load. The cable has to be properly cooled through straps attached as close as possible to the cooling sink with relatively short (~1m) distance between straps to avoid excessive heating.

Experimental results have shown that the XFEL/JLAB feedthroughs can be adopted for LCLS-II without degrading the quality factors of the cavities. In properly cooled HOM couplers the temperature rise at the nominal accelerating gradient 16 MV/m is below 1 K, which is acceptable for LCLS-II operation.

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