PERFORMANCE OF THE NOVEL CORNELL ERL MAIN LINAC PROTOTYPE CRYOMODULE*

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Abstract

The main linac cryomodule (MLC) for a future energy-recovery linac (ERL) based X-ray light source at Cornell has been designed, fabricated, and tested. It houses six 7-cell SRF cavities with individual higher order-modes (HOMs) absorbers, cavity frequency tuners, and one magnet/BPM section. Cavities have achieved the specification values of 16.2MV/m with high-Q of 2.0e10 in 1.8K in continuous wave (CW) mode. During initial MLC cavity testing, we encountered some field emission, reducing Q and lowering quench field. To overcome field emission and find optimal cool-down parameters, RF processing and thermal cycles with different cool-down conditions have been done. Here we report on these studies and present final results from the MLC cavity performance.

INTRODUCTION

Cornell University has proposed to build an Energy Recovery Linac (ERL) as driver for a hard x-ray source because of its ability to produce electron bunches with small, flexible cross sections and short lengths at high repetition rates. The proposed Cornell ERL is designed to operate in CW at 1.3GHz, 2ps bunch length, 100mA average current in each of the accelerating and decelerating beams, normalized emittance of 0.3mm- mrad, and energy ranging from 5GeV down to 10MeV, at which point the spent beam is directed to a beam stop [1, 2]. The design of main linac prototype cryomodule (MLC) for the Cornell ERL had been completed in 2012. Figure 1 shows the 3D model of the MLC. The key parameters are listed in Table 1. Table 2 shows the surface preparations of the MLC 7-cell cavity. The fabrication and testing of MLC components (cavity, high power input coupler, HOM dampers, tuners, etc.,) and assembly of the MLC cold mass had been completed in 2014 [3, 4]. RF tests with different cool down conditions, including the first cool down, have been performed in 2015. In this paper, we summarize the results from these tests.

Table 1: MLC Parameters

Item	Parameter
Number of 7 cell cavities	6
Accelerating gradient	16.2MV/m
R/Q (linac definition)	774 Ohm
Q_{ext}	6.0 x 10^7
Total 2K/5K/8K loads	76 W / 70 W / 150 W
Number of HOM loads	7
HOM power per cavity	200 W
Couplers per cavity	1
RF power per cavity	5 kW
Amplitude/phase stability	10^{-4} / 0.05°
Module length	9.8 m

Table 2: Surface Preparation of the 7-Cell Cavities

Process	Parameter
Bulk BCP	140 µm
Degassing	650 degC, 4days
Frequency tuning	Field flatness >90%
Light BCP	10 µm
Baking	120degC, 48hrs
HF rinse	10 min.

HTC STUDIES

In parallel with the MLC fabrication, a one-cavity Horizontal Test Cryomodule (HTC) was also developed. The HTC is powerful tool to investigate cavity performance in a horizontal cryomodule with various conditions, especially under the different cool down protocols. A prototype 7-cell cavity for the Cornell ERL and high-Q 9-cell cavities for the LCLS-II project at SLAC have been tested in the HTC [5, 6, 7] and important lessons have been learned for. The HTC studies revealed two key features

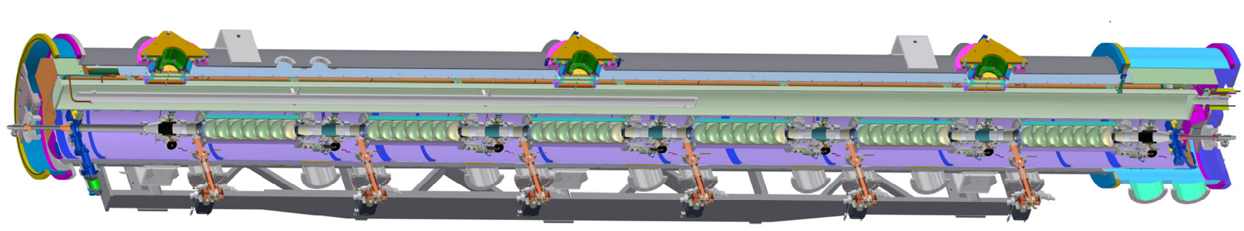

Figure 1: The Main Linac Cryomodule (MLC)

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for a high-Q cryomodule. The first one is an excellent magnetic shielding. Improved magnetic shielding directly brought a reduction of residual surface resistance (R_{res}) of the cavities in the cryomodule, which resulted in increased quality factors (Q_0) of the cavities. Therefore, careful design of the magnetic shielding in a horizontal cryomodule is important. The second one is controlling the spatial temperature gradient in both vertical direction ($dT_{vertical}$) and horizontal direction ($dT_{horizontal}$) during cool down. Larger $dT_{vertical}$ make more efficient magnetic field expulsion [8, 9]. Reduction of $dT_{horizontal}$ results in reduced thermal currents and their induced magnetic fields. Controlling both temperature gradientis critical for reduction of R_{res}, and so maximizing Q_0 of the cavity [6].

THERMAL CYCLING OF THE MLC

Thermocouples

Each 7-cell cavity in the MCL has two thermocouples to determine the cavity's temperature. One is located on the top middle outside of the helium tank and the other is on the bottom middle outside of the helium tank. These two thermocouples were used to identify the vertical spatial temperature gradient of each cavity during cool down. Unfortunately, the thermocouples on the top of cavity #1, and the top and bottom on cavity#6 did not work correctly. Figure 2 shows the image of thermocouples location on the helium tank.

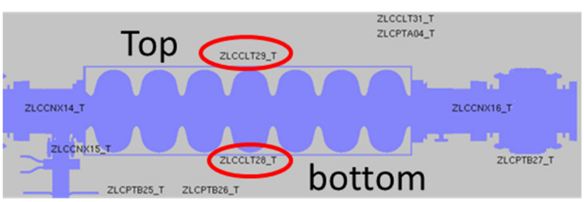

Figure 2: The locations of thermocouples on the helium tank.

Initial Cool Down

The initial cool down of the MLC had two parts. The first part was the cool down from room temperature to 80K. It took about 12hrs. The second part was a faster cool down from 80K to 4K. Details of initial cool down can be found in reference [10].

Fast and Slow Cool Down

The first thermal cycle was done with "fast" final cool down. All six cavities were warmed up to ~45K, and then quickly cooled down from 45K to 4K within 10 min with large vertical spatial temperature gradient ($dT_{vertical}$). The thermocouples on bottom of the helium tanks showed cool down rates of ~36K/min., with large $dT_{vertical}$ of 36K when the cavities passed the critical temperature T_c of niobium (9.2K). The second thermal cycle was performed with a "slow" final cool down. Cavities were warmed up to ~20K, and then cooled down very slowly to maintain $dT_{vertical}$ as small as possible. The cool down rate was 0.23mK/min. on average, and a small $dT_{vertical}$ of 0.6K was maintained during the slow cool from 15K to 4K. Figure 3 shows the temperature profiles of cavity #2 during fast and slow cool down.

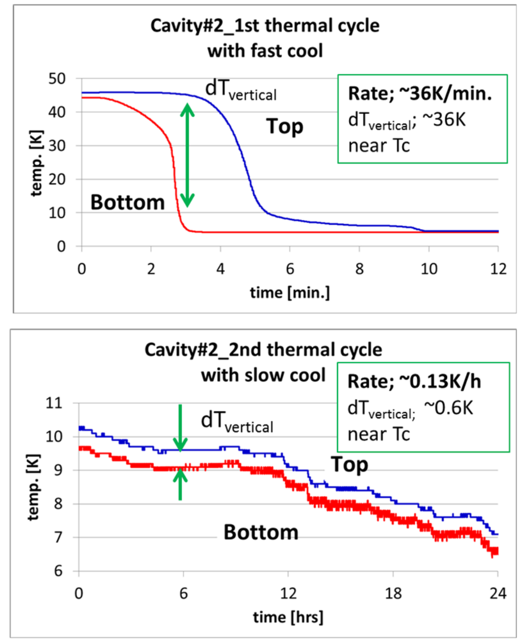

Figure 3: The temperature profiles during "fast" and "slow" cool down of cavity#2.

RF TESTS OF MLC CAVITIES

After the initial cool down and after each thermal cycle, we performed one-by-one RF test of all six cavities in 1.8K. Each cavity has a single 5kW coaxial RF input coupler which transfers power from a solid-state 5kW high power RF amplifier to the cavity. Figure 4 shows plots of the quality factor (Q_0) vs. field gradient (Eacc) for the six cavities at 1.8K. The blue, red, and yellow data points show the measurement results after the initial cool down, the first thermal cycle (fast cool), and the second thermal cycle (slow cool), respectively. Cavity #1, #2, and #3 achieved the target gradient of 16.2MV/m in the first power rise without field emission. Cavity #5 and #6 achieved the target gradient after thermal cycles and RF processing. Cavity gradients were administratively limited to 16.2MV/m. Cavity #4 was limited by quench at 14MV/m without field emission. RF processing and thermal cycles did not improve the quench field noticeably. The target Q_0 of 2.0×10^{10} at 16.2MV/m, 1.8K was achieved with cavity #1, #2, #3, and #5 after thermal cycles. Cavity #5 initially had severe field emission with resulting Q_0 degradation. During the RF test after the second thermal cycle, field emission was processed by RF processing. Q_0 of Cavity #4 was 1.4×10^{10} at the quench limitation of 14MV/m. RF processing and thermal cycles did not improve the Q_0. Cavity#6 had field emission starting at 14MV/m with Q_0 of 1.4×10^{10}, degraded Q_0 to 0.9×10^{10} at 16.2MV/m with severe field emission. Thermal cycles and RF processing did not significantly improve the Q_0 of this cavity.

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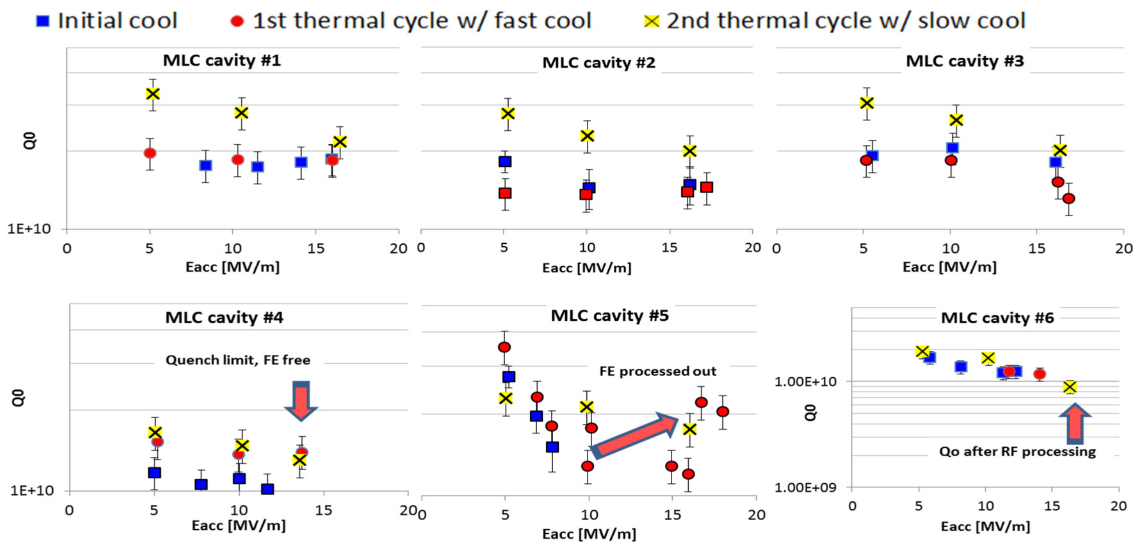

Figure 4: Performances of MLC cavities at 1.8K after thermal cycles.

Impact of Thermal Cycles on Q_0

The Q_0 of cavity #1, #2, and #3 at low field were improved from ~$2x10^{10}$ to ~$3x10^{10}$ by the thermal cycle with smaller $dT_{vertical}$. It is reasonable to assume that the smaller $dT_{vertical}$ in slow cool down also came with smaller $dT_{horizontal}$. Therefore the benefit of slow cool down on the MLC is likely due to a reduction of thermal-currents and their induced magnetic fields. The first thermal cycle with large $dT_{vertical}$ showed no clear impact on the MLC cavity performances. This might be caused by two competing effects. The first one is that the larger $dT_{vertical}$ during fast cool down were beneficial for efficient magnetic field expulsion, which by itself would result in a reduction of R_{res} of the cavities. The second effect however is the increased $dT_{horizontal}$ during fast cool, which by itself would give increased thermo-currents and thus larger R_{res} of the cavities. These two aspects partly compensate each other; and for the MLC cavities, no net impact on cavity Q_0 was seen. It should be noted that a different surface preparation (e.g. nitrogen doping) than what was used for the MLC cavities, can shift the relative balance between the two competing effects, and therefore some cavities can instead show optimal performance after fast cool down. MLC cavities #4, #5, and #6 were impacted by early quench or field emission, and thus the impact of thermal cycles is less visible.

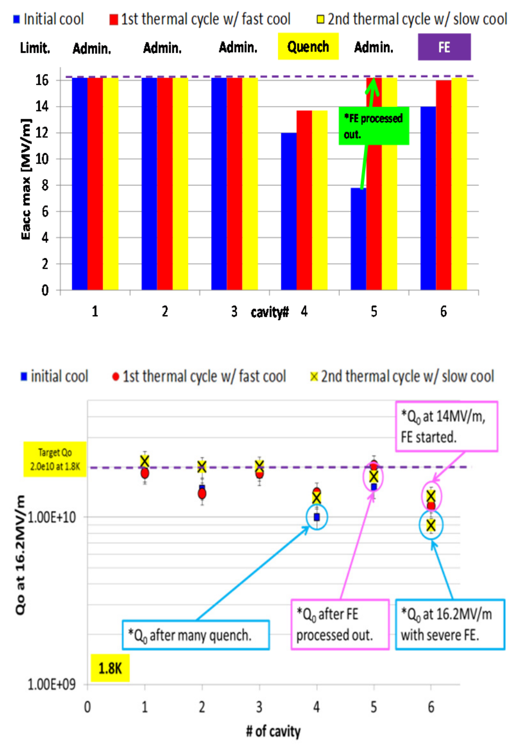

Figure 5: Summary of the performance of the MLC cavities.

SUMMARY

The 7-cell cavities in the Cornell Main Linac Cryomodule have been tested successfully after different cool down conditions and on average have achieved the specification values of 16.2MV/m with Q_0 of $2.0x10^{10}$ at 1.8K Figure 5 summarizes Qo (1.8K) and maximum field performance of the MLC cavities. Our results show that a slow cool down with small horizontal spatial temperature gradient gave the highest Q_0 for the 7-cell cavities in the MLC prototype.

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