ERL MAIN LINAC CRYOMODULE CAVITY PERFORMANCE AND EFFECT OF THERMAL CYCLING

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Abstract

The main linac cryomodule (MLC) for the future energy-recovery linac (ERL) based X-ray light source at Cornell University has been designed, fabricated, and tested. It houses six 7-cell SRF cavities with individual higher order-modes (HOMs) absorbers, cavity frequency tuners, and high power RF input couplers. Cavities have achieved the specification values of 16.2 MV/m with high-Q of $2.0\text{x}10^{10}$ at 1.8 K in continuous wave (CW) mode. Here we report RF test results of the 7-cell cavities in the MLC after initial cool down and several thermal cycles with different cool down conditions.

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 1.3 GHz, 2 ps bunch length, 100 mA aver-age current in each of the accelerating and decelerating beams, normalized emittance of 0.3 mm-mrad, and energy ranging from 5 GeV down to 10 MeV, at which point the spent beam is directed to a beam stop [1, 2]. The design of main linac prototype cryomodule (MLC) for Cornell ERL had been completed in 2012. The fabrication and testing of MLC components (cavity, high power input coupler, HOM dampers, tuners, etc.,) and assembly of MLC cold mass had been completed in 2014 [3, 4]. In parallel with the MLC fabrication (Figure 1), a one-cavity Horizontal Test Cryomodule (HTC) was also developed and tested with a prototype 7-cell cavity [5]. After the 7-cell studies in the HTC, high-Q 9-cell cavity studies have also been performed in the HTC for LCLS-II project at SLAC [6, 7]. These studies in the HTC have revealed two key features for a high-Q cryomodule. The first one is an excellent magnetic shielding, and the second one is controlling thermal current effect during cool down. Improved magnetic shielding directly brought a reduction of residual surface resistance (R_{res}) of the cavities in cryomodule, which resulted in increased of quality factors (Q_0) of cavities. Therefore, careful design of the magnetic shielding in a horizontal cryomodule is important. In this paper, we focus on the second aspect of high A cryomodule operation, i.e. thermal currents effect in a horizontal cryomodule, and impacts of different cool down conditions on the performance of the cavities in the MLC.

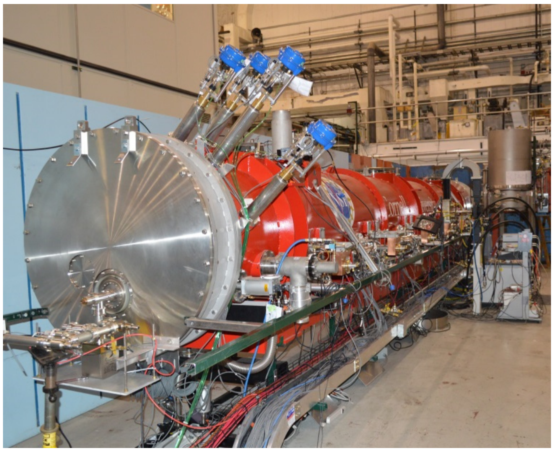

Figure 1: The Main Linac Cryomodule (MLC).

THERMAL CURRENTS IN HORIZONTAL TEST

The cavities in horizontal cryomodule are primary cooled down from bottom to top via a pre-cooling line on the bottom of helium tank. So the cavities could have a spatial temperature gradient in both vertical direction ($dT_{vertical}$) and horizontal direction ($dT_{horizontal}$) during cool down. The niobium cavity is welded into a titanium helium tank. Due to Seeback effect, this bimetal arrangement, under the spatial temperature gradients, causes thermo-currents to flow through the cavity and back through the tank, thereby producing significant magnetic fields [8]. If the cavity temperature had cylindrical symmetry, the thermo-currents induced by $dT_{horizontal}$ do not have much impact on R_{res} of cavity. But a non-zero $dT_{vertical}$ results in a variation of the electric conductivity from top to bottom of the cavity, and cylindrical symmetry is broken. This leads to non-symmetric thermo-currents flow through the cavity (Figure 2), and results in higher generated magnetic fields and thus higher trapped flux at the cavity inner surface, thereby increasing of R_{res} [6, 8, 9]. However, R&Ds on dressed and un-dressed cavity tested also

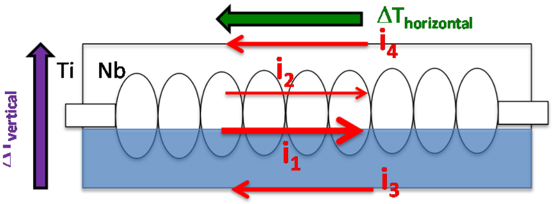

Figure 2: Image of thermo-current flow on the cavity in horizontal cryomodule.

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* Work is supported by NSF awards NSF DMR-0807731 and NSF PHY-1002467
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showed that large $dT_{vertical}$ has the benefits of more efficient magnetic field expulsion, which reduces R_{res} of cavities. [10, 11]. Therefore, the ideal cavity cool down condition in horizontal cryomodule is to generate large vertical spatial temperature gradient, while keeping horizontal spatial temperature gradient as small as possible [6].

THERMAL CYCLING OF THE MLC

Thermocouples

Each 7-cell cavity in the MCL has two thermocouples to determine the cavity temperature. One is located on the top middle of the helium tank outside and the other is on the bottom middle of the 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 3 shows the image of thermocouples location on helium tank.

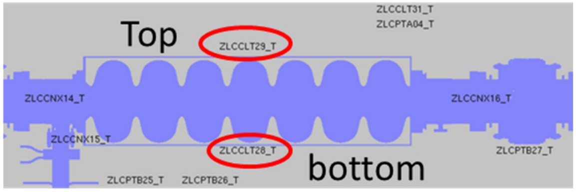

Figure 3: The location of thermocouples on helium tank.

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 80 K to 4 K.The details of initial cool down can be found in reference [12].

Fast and Slow Cool Down

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

RF TESTS OF MLC CAVITIES

After the initial cool down and each thermal cycle, we performed one-by-one RF test of all six cavities in 1.8 K.

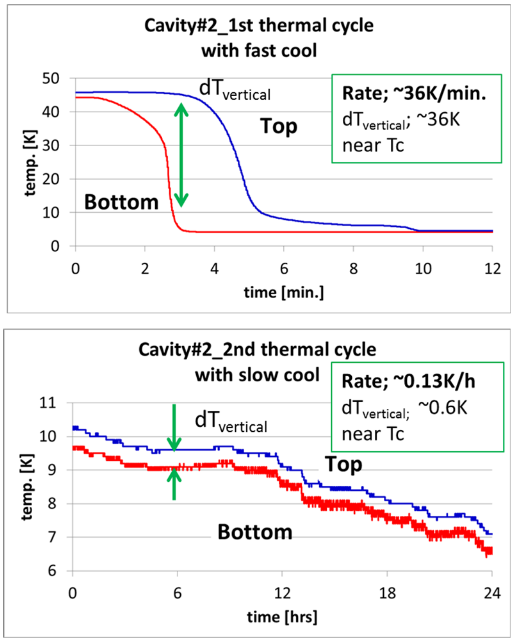

Figure 4: The temperature profiles during "fast" and "slow" cool down of cavity#2.

Each cavity has a single 5 kW coaxial RF input coupler which transfers power from a solid-state 5kW high power RF amplifier to the cavity.

Q_0 vs. Eacc Measurements

Figure 5 shows plots of the quality factor (Q_0) vs. field gradient (Eacc) for the six cavities at 1.8 K. The blue, red, and yellow dots 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 16.2 MV/m in the first power rise. The target Q_0 of $2.0x10^{10}$ at 16.2 MV/m, 1.8 K was also achieved with those three cavities after the thermal cycle. Cavity gradients were administratively limited at 16.2 MV/m, and no quench or field emission was observed. Cavity #4 was limited by quench at 14 MV/m, with Q_0 of $1.4x10^{10}$, and no radiation was detected. RF processing and thermal cycles did not improve the Q_0 and the field noticeably. 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, but some field emission and Q_0 degradation at 16.2 MV/m remained. Cavity#6 had field emission starting at 14 MV/m with Q_0 of $1.4x10^{10}$, degraded Q_0 to $0.9x10^{10}$ at 16.2 MV/m with severe field emission. Thermal cycles and RF processing did not significantly improve the performance of this cavity. Figure 6 shows the cavity performance summary from the RF tests. Five of the six cavities achieved the target field gradient of 16.2 MV/m and one cavity was limited by quench at 14 MV/m. Four of the six cavities achieved the designed Q_0 of $2.0x10^{10}$ at 16.2 MV/m at 1.8 K and two cavities had a small Q_0 degradation by field emission.

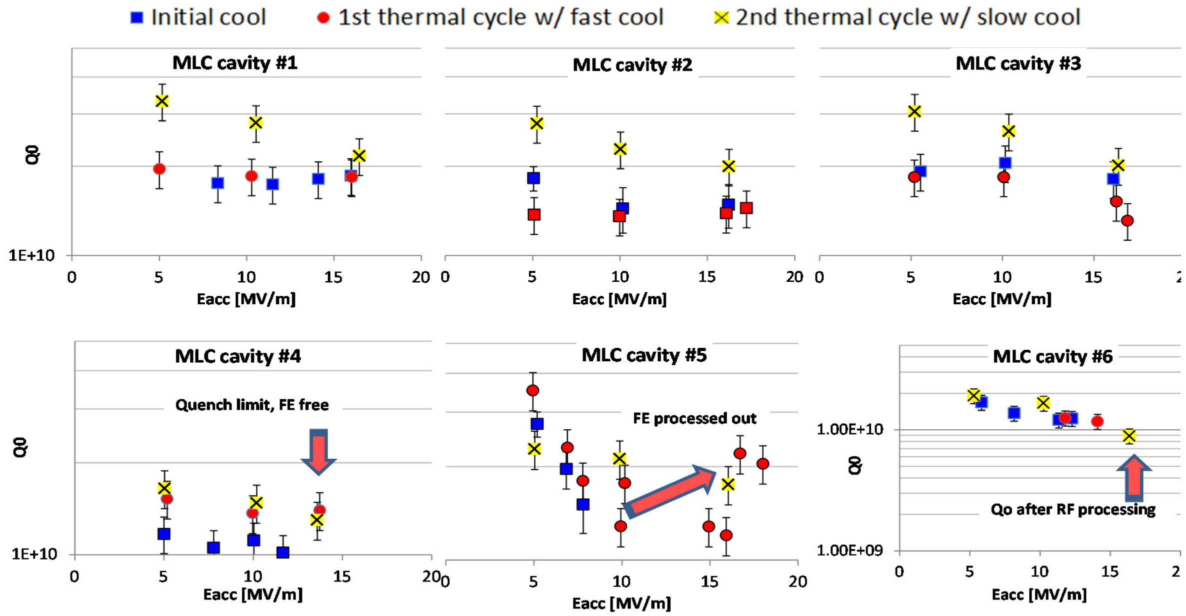

Figure 5: Performances of MLC cavities in 1.8K after thermal cycles.

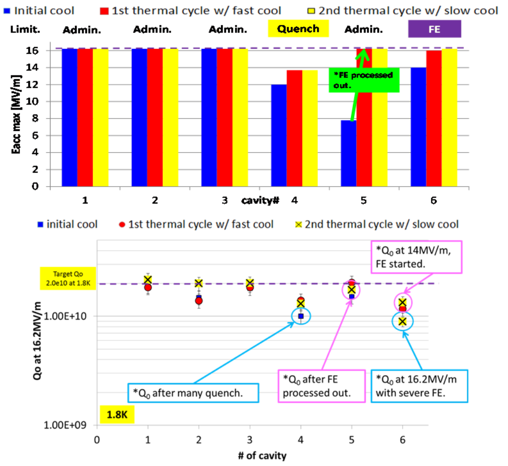

Figure 6: summary of MLC cavities performance.

Discussions

Cavities #1, #2, and #3, which were not limited by field emission or early quench, showed improved performance after slow cool down as is shown in Fig. 5. The Q_0 at low field were improved from ~2×10^{10} to ~3×10^{10}. It is reasonable to assume that the smaller $dT_{vertical}$ in slow cool down also came with smaller spatial temperature gradient in the horizontal direction ($dT_{horizontal}$). Therefore the benefit of slow cool down with small $dT_{horizontal}$ is likely due to a reduction of thermal-currents and their induced magnetic fields , which in turn resulted in increased Q_0 of the cavities in the cryomodule. The first thermal cycle with fast cool down 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 diping) 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.

SUMMARY

The Cornell Main Linac Cryomodule has been cooled down from 300 K to 1.8 K successfully. The 7-cell cavities in the MLC have been tested with different cool down conditions and on average have achieved the specification values of 16.2 MV/m with Q_0 of 2.0×10^{10} in 1.8 K. High-Q performance was maintained through cryomodule assembly to cool down and RF testing. Field emission caused mild Q_0 degradation on some cavities. Thermal cycle with small temperature gradient ("slow" cool down) gave the highest Q_0 for the cavities in the MLC prototype.

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