# PERFORMANCE OF THE CORNELL ERL MAIN LINAC PROTOTYPE CRYOMODULE

F. Furuta#, B. Clasby, R. Eichhorn, B. Elmore, M. Ge, D. Gonnella, D. Hall, G. Hoffstaetter, R. Kaplan, J. Kaufman, M. Liepe, T. O'Connell, S. Posen, P. Quigley, D. Sabol, J. Sears, E. Smith, V. Veshcherevich, Cornell University, Ithaca, NY 14850, USA

*Abstract*

Cornell has designed, fabricated, and completed initial cool down test of a high current (100 mA) CW SRF main linac prototype cryomodule for the Cornell ERL. This paper will report on the design and performance of this very high Q0 CW cryomodule including design issues and mitigation strategies.

## INTRODUCTION

Cornell University has proposed to build Energy Recovery Linac (ERL) as drivers for hard x-ray sources because of their 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 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. MLC installation and cooldown preparations began in this summer. We will describe about MLC and initial cool down results in this proceeding.

## MLC GENERAL LAYOUT

The general layout of an ERL main linac cryomodule (MLC) is shown in Fig. 1. It is 9.8 m long and houses six 1.3 GHz 7-cell superconducting cavities with Individual HOM absorbers and one magnet/BPM section. Each cavity has a single coaxial RF input coupler which transfers power from an RF power source to the beam loaded cavity. The specification values of 7-cell cavities are Qo of 2.0e10 at 16.2MV/m, 1.8K. Due to the high beam current combined with the short bunch operation, a careful control and efficient damping of higher order modes (HOMs) is essential. So HOMs are installed next to each cavity. To minimize ambient magnetic field of high-Q 7-cell cavities, MLC has three layers of magnetic shielding; 1) Vacuum Vessel (carbon steel), 2) 80/40 K magnetic shield enclosing the cold mass, and 3) 2 K magnetic shield enclosing individual cavities. All components within the cryomodule are suspended from the Helium Gas Return Pipe (HGRP). This large diameter (280mm) titanium pipe will return the gaseous helium boiled off the cavity vessel to the liquefier and act as a central support girder. The HGRP will be supported by 3 support post. The middle one is fixed; the other side posts are not and will slide by 7-9mm respectively during the cooldown from room temperature to cold.

## 7-CELL CAVITIES FOR MLC

### *Vertical Test Results*

All 7-cell cavities for MLC were fabricated in house. Three of six cavities were stiffened cavity and the other three were un-stiffened cavity. Cavity surface preparation recipe consists of bulk Buffered Chemical Polishing (BCP, 140um), degassing (650degC*4days), frequency and field flatness tuning, light BCP (10um), low temperature baking (120degC*48hrs), and HF rinse [3]. Figure 2 shows best Q(E)curve of MLC 7-cell cavities during vertical test (VT) at 1.8K. All 7-cell cavities had surpassed the specification values of Qo=2.0e10 at 16.2MV/m, 1.8K. In fact, average Qo=(3.0±0.3)*1e10 had been achieved during VT at 16.2MV/m, 1.8K. All VT was limited by administrative limit, no radiation or no quench were detected during VT.

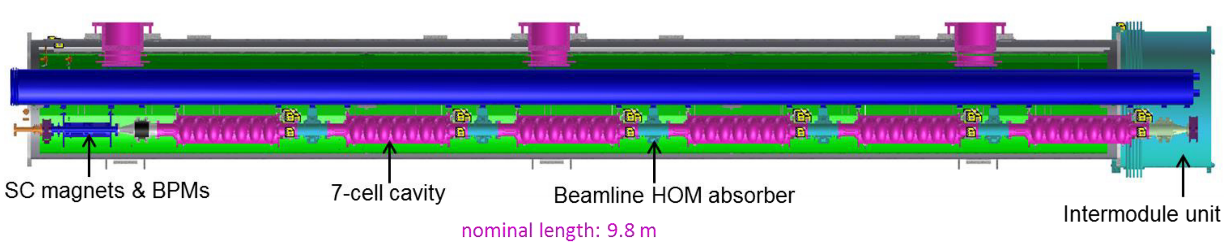


Figure 1: Cornell ERL Main Linac Prototype Cryomodule

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#ff97@cornell.edu


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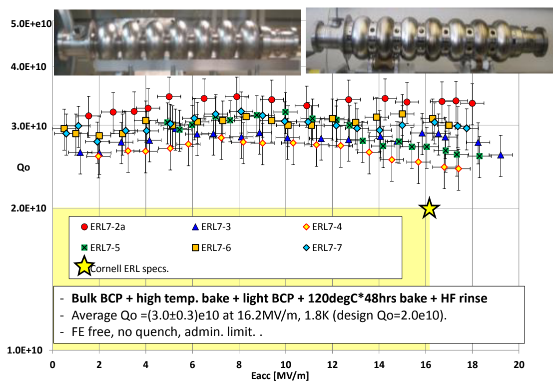


Figure 2: VT results of ERL 7-cells at 1.8K

### *Horizontal Test Results*

In parallel with six 7-cell cavities fabrication and VT for MLC, the first prototype 7-cell cavity, ERL7-1, was tested and qualified in one cavity Horizontal Test Cryomodule (HTC) through three stages of hardware implementation [4]. Figure 3 shows Q(E) comparison between VT and HTC-1 at 1.8K. Higher Qo of 3.5e10 at 16.2MV/m, 1.8K than that of VT (Qo of 1.9e10) was achieved in HTC-1. HTC was special cryomodule designed for high-Q cavity operation and had much better magnetic shielding than VT pit, this better magnetic shielding was one of the essences which provided higher Qo in HTC. Estimated residual resistance ($R_{res}$) of ERL7-1 during cryogenic testing was reduced from 11nOhm (VT) to 3.2nOhm (HTC-1). The other essence was suppression of thermocurrent effect. During the cooldown through Tc, cavity usually had some temperature gradient over cavity. This could provide thermocurrent and more chance of flux trapping into cavity. During the 7cell VT, we clearly saw the temperature gradient affected on cavity Qo [5]. In case of 7-cell VT processed with BCP and 120C bake, the smaller temperature gradient between cavity top and bottom provided higher Qo (lower $R_{res}$). This means smaller temperature gradient was effective to suppress induced flux by thermocurrent, and minimize $R_{res}$ of 7-cell. In HTC case, applying several thermal cycles to above Tc could be effective to reduce temperature gradient and suppress flux trapping induced

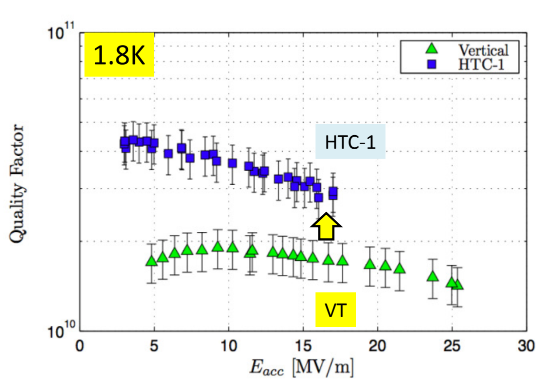


Figure 3: Q(E) comparison between VT and HTC-1

by thermocurrent. After applying thermal cycles on HTC, the world record Qo of 6.0e10 at 16.2MV/m, 1.8K was obtained in HTC. The conditions when cavity had achieved highest Qo were 10K thermal cycle with small temperature gradient over cavity (~0.2K) and slow cool down rate near Tc (~0.4K/h). This result was very encouraging, because it suggested that the highest Qo in cryomodule could be achievable by flux control with temperature gradient control during the cooldown. On the other hand, we applied the rapid cooldown with larger temperature gradient at the last thermal cycle of HTC, but this did not make any negative impact on Qo [4]. So once thermocurrent effect was well suppressed by repeated thermal cycles, temperature gradient over cavity might not become issues. Figure 4 and 5 shows Q(E) plot and surface resistance ($R_s$) plot before/after thermal cycles as comparison.

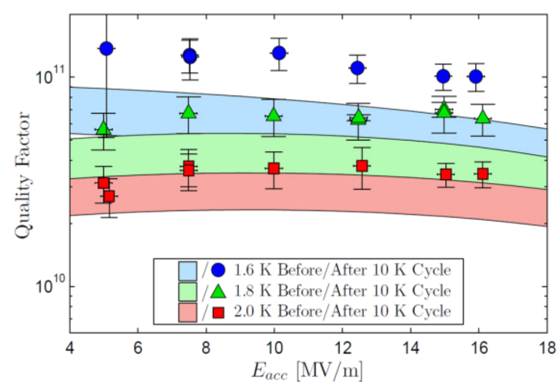


Figure 4: Q(E) before/after thermal cycle

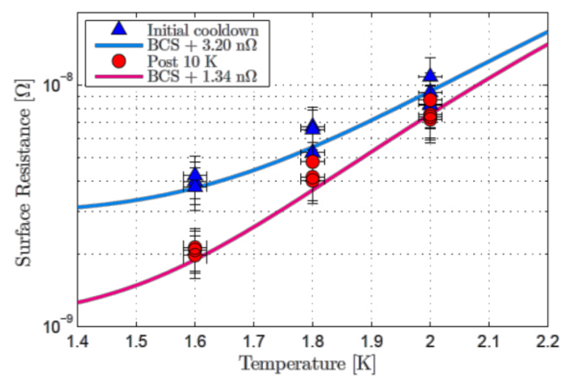


Figure 5: Rs before/after thermal cycle

## HIGH ORDER MODES DAMPERS

Figure 6 shows a cross section view of the production version of the Cornell HOM Absorber. For these production pieces, the absorbing material is Silicon Carbide, SC-35® from Coorstek [6]. For the HTC cavity testing, 3 prototypes of the HOM absorber have been built with a slightly different design [7]. These prototypes where built using the same absorbing ceramics. Within the HTC, a 7-cell ERL cavity is placed between two HOM absorbers. We achieved an excellent higher order mode damping (Figure 7) with preserving the high quality factor of the fundamental mode. More details and beam test results were seen on reference [8]

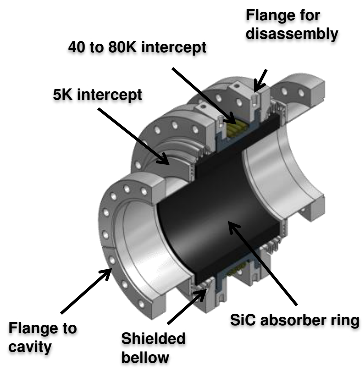


Figure 6: cross section view of HOM

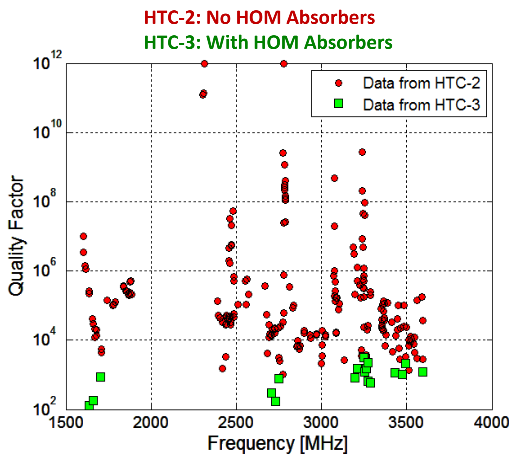


Figure 7: HOM meas. during HTC-2 and HTC-3

## HIGH POWER INPUT COUPLER

For the Cornell ERL, the input coupler must deliver up to 5 kW CW RF power to a main linac cavity, though under nominal conditions it will operate with 2 kW average and 5 kW peak power. During the linac operation, there is almost no beam loading due to energy recovery: the accelerating beam takes the power but the decelerating beam gives it back. Due to that, the coupler always operates in standing wave mode, with almost full reflection. A 3D CAD model of the ERL main linac coupler is shown in Figure 8 [9]. To make the design more economical, the couplers provide fixed coupling to the cavities with the $Q_{ext}$=6.5e7. If necessary,

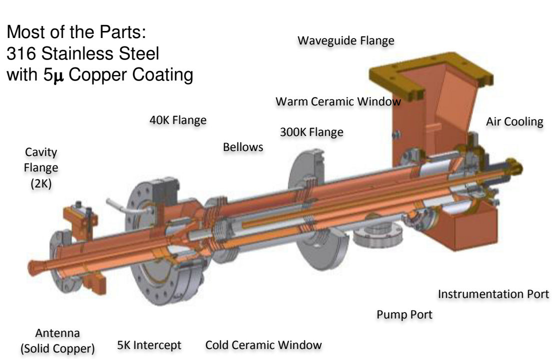


Figure 8: High Power Input Coupler for MLC

the coupling adjustability can be achieved using three-stub tuners in input transmission lines to have a range of $Q_{ext}$ from 2.0e7 to 1.0e8. ERL linac couplers must accommodate movement of the cavities during cool down including a lateral movement of up to 10mm since one end of the coupler is attached to the moving cavity and the other end is attached to the fixed vacuum vessel port. A special coupler test stand with overcoupled (β=17) copper cavity was built to test couplers in similar operation condition. Overcoupling is not as strong as for the accelerating cavity (β=300), however it is a good model of real operation. Figure 9 shows the coupler assembled with the cavity and the waveguide on the test stand. A 5kW solid state simplifier was used for tests. All the tests were smooth. Couplers showed good performance during the tests on the test stand and on the horizontal test cryomodule with a main linac cavity [4, 9]. Figures 10 shows the plots of RF power, vacuum pressure in the coupler during one of the tests.

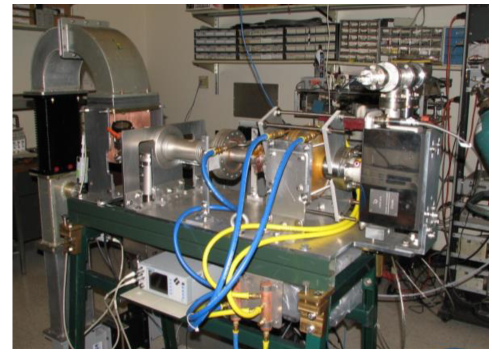

Figure 9: High Power Input Coupler test stand

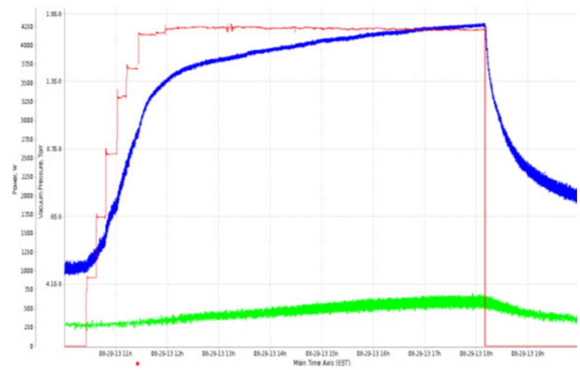

Figure 10: High Power Input Coupler Test results

## MLC COOLDOWN

All MLC components had been successfully fabricated and demonstrated well with good performance. String assembly of six 7-cell cavities/HOMs/cold part of input coupler was completed in clean room. Cold mass assembly was completed at outside of clean on the end of 2014. MLC had final short journey from Newman lab. to Wilson lab. on March 2015. MLC installation in Wilson L0E and cooldown preparation had started this summer. The initial cooldown starts on September 2015. Detail analysis on cooldown data is ongoing now. We will describe some preliminary results below.




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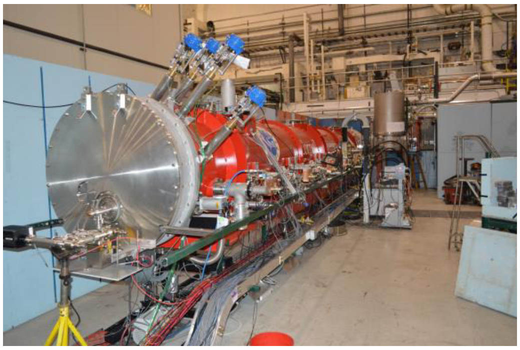

Figure 11: MLC at Wilson L0E

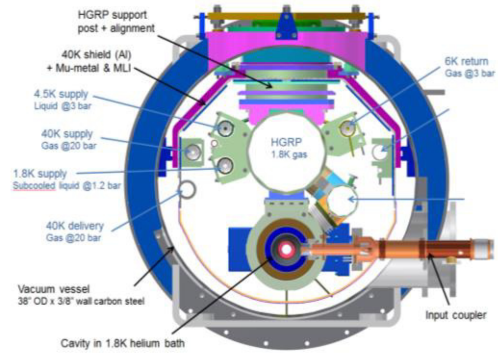


Figure 13: Cross section of module

## *Cryogenic Scheme*

The cryogenic scheme of MLC consists in principle of three different loops, so called 2K, 5K, and 80K loop. The 2K loop has one line as 2K supply. The pre-cooling gas was obtained by a pre-cool valve from 2K supply into pre-cool lines. Each cavity has two pre-cooling gas lines on the bottom of helium vessel. This allows us to control the temperature gradient over cavity during the cooldown more carefully. The cavities were cooled by liquid helium which was obtained by a JT-valve from 2K supply and transferred into 2K helium bath via 2K-2phase line. Sub-cooled to 1.8K by pumping the He-atmosphere down to 16mBar ensures an optimum operation regime for the superconducting cavities. To minimize the pressure drop over the whole linac string, a big aperture for the helium gas return pipe (HGRP) was chosen. In order to suppress pressure fluctuations, a single chimney connects all cavities within one module to HGRP. The 5K loop controlled by 5K adjust valve has two lines, one for the thermal intercept for HOM absorbers and couplers, the others for removing 2/3 dynamic heat load. The 80K loop controlled by 80K adjust valve has three lines, one for the thermal intercept for HOM absorbers and couplers, one for the 80K thermal radiation shield, and the last one for removing 90% heat load from HOMs. A JT, pre-cool, 5K adjust, and 80K adjust valves are located at the module entrance (Figure 11). The cryogenic scheme is shown in figure 12. Figure 13 gives the cross section of the module showing the spatial arrangement.

## *80K Cooldown*

The initial important stage of cool down was between room temperature and 80K. During this cooling stage, we had to maintain the temperature gradient over 80K shield below 20K to avoid any too much thermal, mechanical stress or damage on cold mass. In the beginning, the 80K loop had mixed gas of 80K helium gas provided from heat exchanger can and a room temperature helium gas. The temperature of mixed gas was controlled by 80K cooldown adjust valve on room temperature helium gas line. The 5K loop also had mixed helium gas from 80K gas and room temperature gas controlled by 5K cooldown adjust valve. The 2K pre-cool line had gotten mixed helium gas from 5K loop in this stage. By closing these cooldown adjust valve, the temperature of mixed gas induced into the three loops were controlled. Figure 14 shows the time vs. temperatures of MLC 80K shield. The 80K cooldown was successfully completed, temperature went down very smoothly, and temperature gradient was kept below 15K over 80K shield. The cooldown rate during this stage was about 1.3K/h, it took about a week

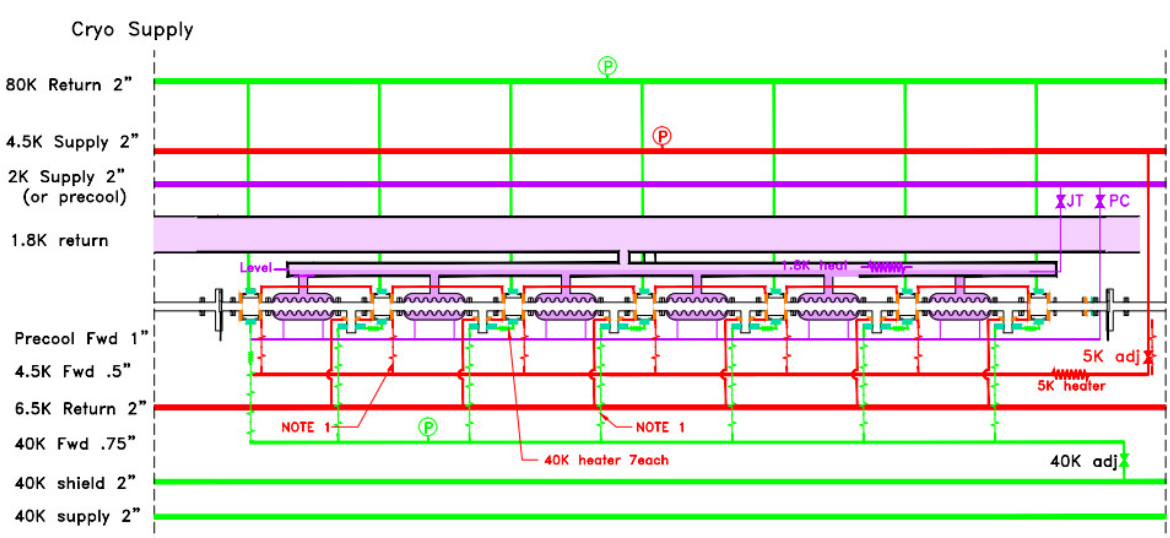


Figure 12: Diagram of different loops within MLC

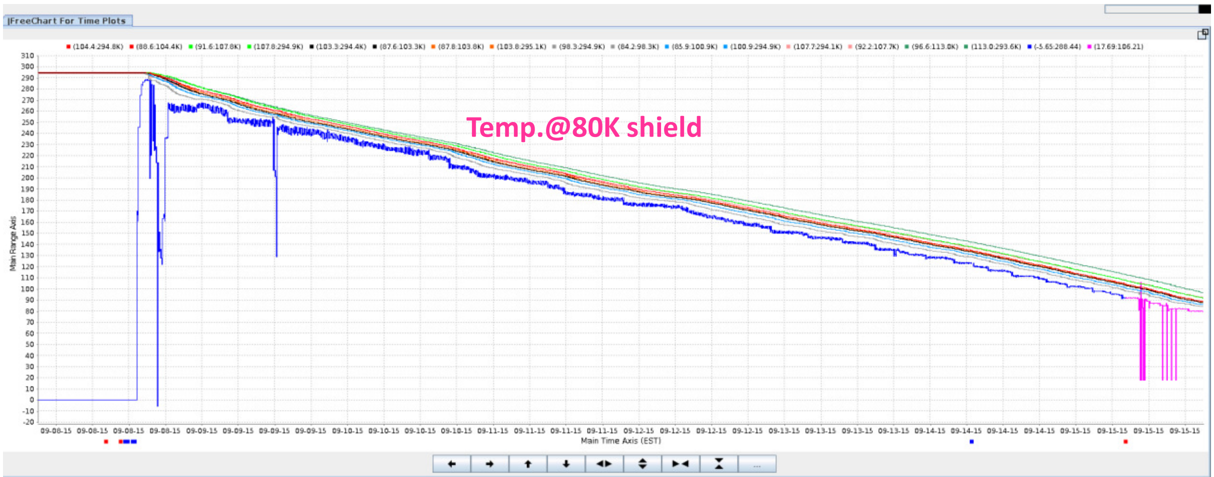


Figure 14: 80K cooldown

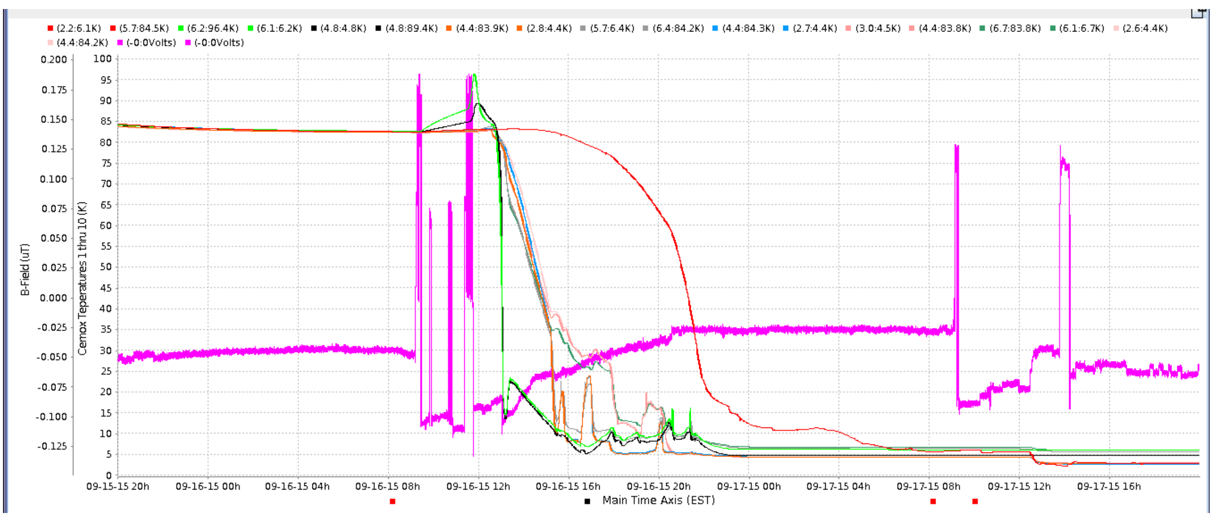


Figure 15: 1.8K cooldown

to reach 80K.

### *Cooldown to 1.8K*

During the cool down from 80K to 20K, the cooldown rate was set around 10K/h. At 20K, the rate was slowed as system cooled through Tc. Figure 15 shows very preliminary graph of temperature monitoring from 80K to 1.8K. Data analysis on these monitoring data is ongoing now. MLC had been successfully cooldown to 1.8K during initial cooldown.

### *MLC Shrinkage During the Initial Cooldown*

As mentioned before, MLC cold mass will have a shrink and the side support posts were expected to slide by 7~9mm. Figure 16 shows the amount of support post sliding during the 80K cool. Both support post slid about 6mm during 80K cool, it was very consistent with estimation.

### *MLC cavity RF Test Plan*

Next step of MLC testing was cavity RF test. We will perform RF test one cavity at once. 5kW high power RF amplifier was sit next to the MLC and wave guide were set to deliver RF power into cavity via high power coupler (Figure 17). We estimate it will take 2weeks for each cavity test and we could complete six 7-cell cavities test by the end of 2015.

## SUMMARY

All MLC components had been tested successfully and assembled into cold mass. Especially, world record high-Qs of 3.5e10 (2K), 6e10 (1.8K) 1e11 (1.6K) at 16.2MV/m had achieved with prototype ERL 7-cell cavity during HTC test. Essences of Cornell ERL high-Q achievements were 1) special designed horizontal test cryomodule with minimized ambient magnetic field by good shielding, 2) thermal cycles to above Tc. to suppress thermocurrent effect. The initial MLC cool down had been completed successfully; MLC stays at 1.8K and being prepared for cavity RF testing (one cavity test at once, 2weeks/cavity). Cooldown rate during the room temperature to 80K was about 1.3K/h and temperature gradient over 80K shield was kept below 15K. Depend on the performance,




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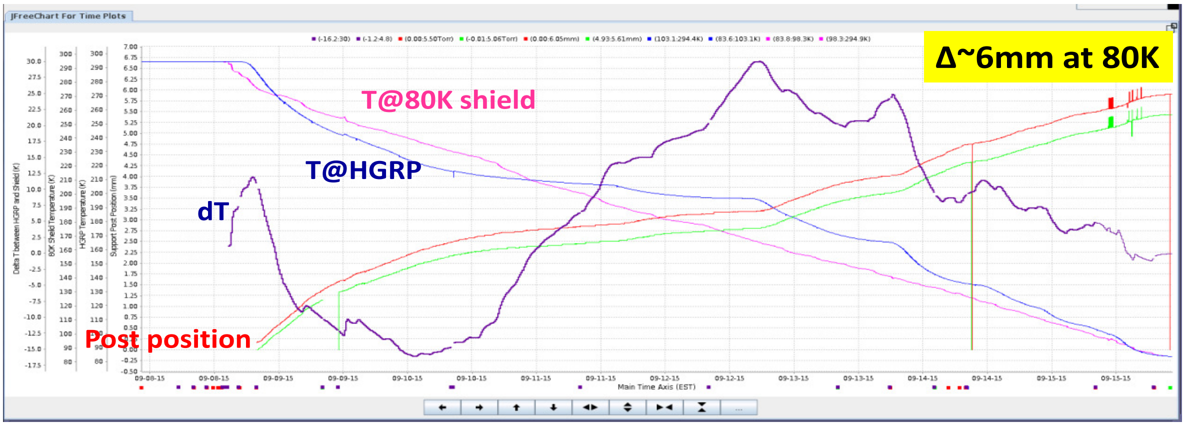


Figure 16: Position of sliding posts during cooldown

thermal cycle will be applied to improve cavity Qo. As a future plan of usage of MLC, white paper of the Cornell-BNL FFAG-ERL Test Accelerator is submitted on arxiv [10].

## ACKNOWLEDGMENT

We would like to say special thank you to the MLC preparation and cooldown team staff, they made this important part of ERL project possible.

Figure 17: MLC cavity RF test set-up

## REFERENCES

[1] G. H. Hoffstaetter, S. Gruner, M. Tigner, eds., “Cornell Energy Recovery Linac Project Definition Design Report”, http://erl.chess.cornell.edu/PDDR
[2] C.E. Mayes et al., “Cornell ERL Research and Development” Proc. of the PAC2011, New York, NY, USA (2011)
[3] F. Furuta et al., “Preparation and VT results of ERL-7-cell at Cornell”, Proc. of the SRF2013 (2013)
[4] N. R. A. Valles et al., “Record Quality Factor Performance of the Prototype Cornell ERL Main Linac Cavity in the Horizontal Test Cryomodule”, Proc. of the SRF2013 (2013)
[5] R. Eichhorn et al., “Investigation of Thermocurrents limiting the Performance of Superconducting Cavities”, Proc, of the IPAC2014 (2014)
[6] www.coorstek.com
[7] R. Eichhorn et al., “Cornell's HOM Beamline Absorbers”, Proc. of the 2013 Intern. Part. Acc. Conf. (2013)
[8] R. Eichhorn, et al., “Higher Order Mode Absorbers for High Current SRF Applications”, in these proceedings
[9] V. Veshcherevich et al., “Input Coupler for Cornell ERL Main Linac,” Proc. of SRF2013 (2013)
[10] http://arxiv.org/abs/1504.00588