RECORD QUALITY FACTOR PERFORMANCE OF THE PROTOTYPE CORNELL ERL MAIN LINAC CAVITY IN THE HORIZONTAL TEST CRYOMODULE*

N. Valles†, R. Eichhorn, F. Furuta, M. Ge, D. Gonnella, D.N. Hall, Y. He, V. Ho, G. Hoffstaetter, M. Liepe, T. O'Connell, S. Posen, P. Quigley, J. Sears and V. Veshcherevich
Cornell University, CLASSE, Ithaca, NY 14853, USA

Abstract

Future SRF linac driven accelerators operated in CW mode will require very efficient SRF cavities with high intrinsic quality factors, Q_0, at medium accelerating fields. Cornell has recently finished testing the fully equipped 1.3 GHz, 7-cell main linac cavity for the Cornell Energy Recovery Linac in a horizontal test cryomodule (HTC). Measurements characterizing the fundamental modes quality factor have been completed, showing record Q_0 performance. In this paper, we present detailed quality factor vs gradient results for three HTC assembly stages. We show that the performance of an SRF cavity can be maintained when installed into a cryomodule, and that thermal cycling reduces residual surface resistance. We present world record results for a fully equipped multicell cavity in a cryomodule, reaching intrinsic quality factors at operating accelerating field of Q_0(E =16.2 MV/m, 1.8 K) $> 6.0 \times 10^{10}$ and Q_0(E =16.2 MV/m, 1.6 K) $= 1.0 \times 10^{11}$, corresponding to a very low residual surface resistance of 1.1 nΩ.

INTRODUCTION

Cornell University is developing a 5 GeV energy recovery linac (ERL). The SRF main linac of this ERL is designed to support high current beams, each at 100 mA with 77 pC bunch charge (one beam is accelerated and the returning beam is decelerated in the main linac), with small emittance.[1] These demanding beam requirements set tight constraints for electromagnetic and higher-order mode properties of the 1.3 GHz main-linac cavities [2, 3]. In addition to these RF properties of the cavity, the feasibility of operating a 5 GeV SRF linac in continuous wave mode requires the main-linac cavities to have 1.8 K quality factors of at least 2×10^{10} at the operating gradient of 16.2 MV/m [1].

Eventually, six 7-cell cavities along with other instrumentation will be commissioned within a prototype main linac cryomodule (MLC) [4]. The precursor to the MLC is the horizontal test cryomodule (HTC) which can contain a single 7-cell cavity, two higher-order mode (HOM) absorbers and other experimental instrumentation.

The first prototype cavity has been fabricated [5] and is being qualified in the HTC through several stages of hardware implementation. By performing measurements at various stages of implementation, the effects on the quality factor and higher-order mode spectrum can be characterized systematically, leading to tight control of the performance of the structure. In total, there are three verification stages.

HTC-1 tests the prototype cavity with an on-axis, high Q_{ext} RF input coupler, and no HOM absorbers. The goal of this test was to replicate the results of an initial vertical test in a horizontal cryomodule. The axial RF input coupler allowed accurate measurement of the quality factor of the cavity via standard RF methods and verification of the cryogenic load measurements.

HTC-2 modified the RF input power scheme to the cavity, adding a side mounted high power (5 kW) RF input coupler in addition to the axial probe. This stage allowed the coupler assembly process to be qualified, as well as preliminary investigations into the coupling between the high power coupler and higher-order modes.

HTC-3 reconfigures the assembly, removing the axial power coupler and adding two broadband beamline HOM absorbers–one on each end of the cavity. Prior to assembly, the cavity surface was retreated.

Meeting gradient and quality factor specifications in each of these tests would demonstrate the feasibility of the all the main systems needed for the MLC.

This paper details the results of the three HTC experimental runs, focusing on the fundamental mode properties. Investigations of the higher-order mode spectrum are presented elsewhere [6]. We present quality factor measurements for all three tests and demonstrate that the cavity fabricated at Cornell exceeds design specifications.

METHODS

Cavity Preparation and Cryomodule Assembly

The construction [7] and preparation of the prototype main-linac 7-cell cavity, ERL 7.1, for HTC-1 has been described elsewhere [5, 8]. A brief summary of the steps prior to HTC-2 are presented here for completeness.

After fabrication, the cavity received a bulk etch of 150 μm and was outgassed at 650 °C for 10 hours. Next the cavity received a 10 μm BCP, a 16 hour high-pressure rinse (HPR), was then cleanly assembled and baked at 120°C for 48 hours.

The cavity was vertically tested, and found to exceed quality factor and gradient specifications. The cavity's Q vs E curve only showed mild medium field Q slope and

* Work supported by NSF Grants NSF DMR-0807731 and NSF PHY-1002467
† nrv5@cornell.edu

Copyright © 2013 by the respective authors

reached 26 MV/m before being limited by available RF power.

The initial horizontal cryomodule test served to check several aspects of prototype commissioning. First, the helium jacket needed to be welded to the cavity without modifying the cavity's underlying geometry, which could effect the higher-order mode spectrum. Second, the entire assembly should shield the cavity from as much residual magnetic flux as possible to push to the highest achievable quality factors. Finally, it was necessary to demonstrate that the cavity could be cleanly assembled in a horizontal orientation and maintain a very high quality factor. Thus, these factors were the only large changes between the vertical test and HTC-1.

Following the successful vertical test, while maintaining a clean RF surface, the cavity was outfitted with a helium jacket, and installed in a horizontal test cryomodule for HTC-1. An axial RF coupler, (fundamental mode $Q_{ext} = 9 \times 10^{10}$) similar to the one used in the vertical test, was installed on the end of the cavity.

At the next stage of the tests, HTC-2, a high-power side mounted RF input coupler was added to the HTC-1 assembly. This antenna couples to the fundamental mode with $Q_{ext} = 4.5 \times 10^{7}$, so is strongly overcoupled.

The final stage of the HTC tests, HTC-3, adds beamline higher-order mode absorbers at each end of the cavity. To install these absorbers, HTC-2 had to be disassembled to allow removal of the axial coupler. After HTC-2, the cavity was reprocessed with a 5 μm BCP, 120°C bake, and an HF rinse to mitigate field emission in the HTC-2 experiment. HOM absorbers and the high-power RF coupler were installed and the cryomodule tested in its final configuration.

Experimental Procedure

The HTC cavity tests had three main goals: to measure the quality factor vs accelerating field (Q_0 vs E) of the cavity, to determine the quench field of the cavity, and to qualify each major stage of the assembly.

For each HTC experiment, the cavity was slowly cooled from 300 K to 1.8 K while maintaining a small temperature gradient (< 0.3 K) across the cavity in an attempt to prevent thermal-electric currents from trapping flux and degrading the quality factor of the cavity [9]. In HTC-1 the Q_0 vs E points were measured through standard RF methods–utilizing two RF probe ports [10]–and cryogenically by using the helium boil-off rate to determine the power dissipated from the cavity. Quality factor measurements in HTC-2 and HTC-3 required cryogenic methods to determine the performance of the structure, since the strongly overcoupled high-power input coupler would not yield accurate Q_0 measurements.

The quality factor can be measured with cryogenic means through the gas flow rate of helium through a gas meter at the output of the HTC. The heat capacity of the gas is a function of temperature, which then directly yields the power dissipated in the helium bath. A heater attached to the outside of the helium vessel allows the flow rate to be calibrated as a function of heater power.

After measuring the cavity's quality factor at 1.6, 1.8 and 2.0 K, the quench field was determined and a Q_0 vs E curve was remeasured to determine whether quenching had a deleterious effect on the quality factor. Subsequently, to return the cavity to its original superconducting state, the cavity temperature was cycled to above its critical temperature, T_c, and the quality factor remeasured.

RESULTS

Quality factor vs accelerating gradient at 1.6, 1.8 and 2.0 K was measured for each of the HTC experiments. The BCS losses of the superconductor can be calculated with SRIMP [11], which in turn can be used to determine material properties of the cavity from the temperature dependence of the quality factor.

HTC-1

The Q_0 vs E measurements over several thermal cycles are shown in Fig. 1. RF and cryogenic measurements of Q_0 were in agreement. The quench field was 17.3 MV/m, and prior to quenching the cavity produced radiation at about 1 R/hr. After the 100 K cycle, the residual resistance of the cavity was ∼5.8 nΩ [5]. Thermally cycling the structure led to a 50% increase in Q_0 at the operating temperature. The high Q_0 was maintained even after an intentionally fast cooldown.

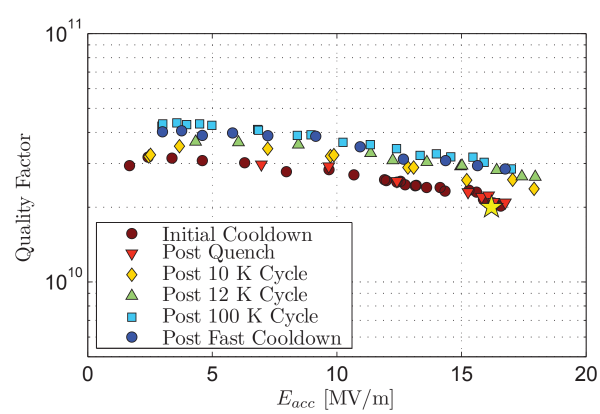

Figure 1: Q_0 vs E_{acc} measurements at 1.8 K before and after thermally cycling ERL7-1 in HTC-1. The star denotes the Q_0 specification at 1.8 K. The Q_0 at design gradient increased by ∼50% after thermally cycling to low temperatures. 10% error bars in Q_0 are suppressed for visual clarity.

After thermally cycling, the cavity exceeded the design specification of $Q(16.2\ \text{MV/m}, 1.8\ \text{K}) = 2 \times 10^{10}$ by 50%. Furthermore the cavity set a record for quality factor of a multicell cavity installed in a horizontal test cryomodule reaching $Q(5.0\ \text{MV/m}, 1.6\ \text{K}) = 6 \times 10^{10}$, as shown in Fig. 2.

ISBN 978-3-95450-143-4

Copyright © 2013 by the respective authors

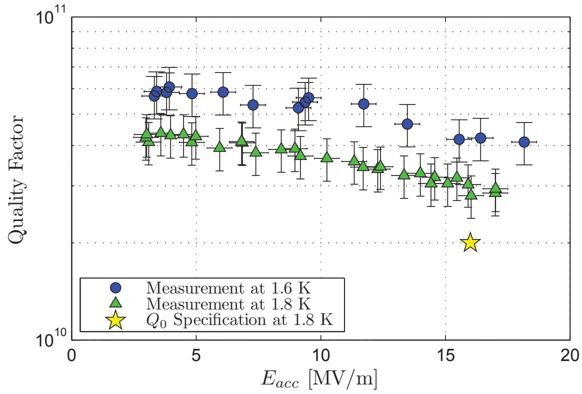

Figure 2: Final Q_0 vs E_{acc} measurement of ERL 7.1 in HTC-1.

HTC-2

In HTC-2, the quality factor was again measured over several rounds of thermal cycling, described in [9]. Thermal cycling's effect on Q_0 is presented in Fig. 3. After the first 15 K thermal cycle the mid-field Q_0 improved $\sim$50% at both 1.6 K and 1.8 K. Administrative limits prevented quench field determination.

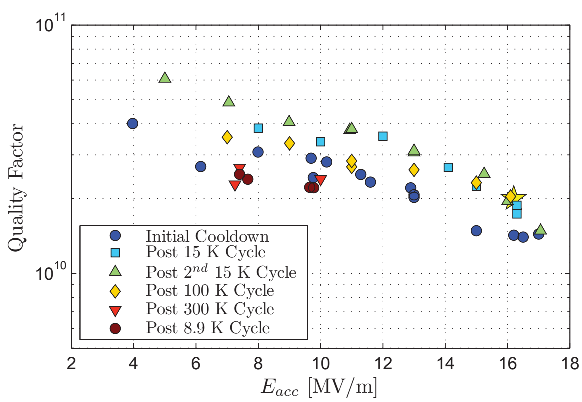

Figure 3: Q_0 vs E_{acc} measurements at 1.8 K before and after thermally cycling the ERL 7-1 in the HTC-2 experiment. Star denotes 1.8 K Q_0 specification. The most benefit in reduced surface resistance (higher Q_0) was obtained after the first 15 K thermal cycle. For visual clarity, 20% error bars in Q_0 have been suppressed.

Thermal cycles to 8.9 K and to room temperature did not increase Q_0 in HTC-2. This suggests that the most benefit for thermal cycles is obtained from peak temperatures in the region between 9.0 and 100 K.

In HTC-2, ERL 7.1's met the design specifications, but was limited by field emission coming from the end cell far from the high power coupler. The final Q_0 vs E plot is shown in Fig. 4.

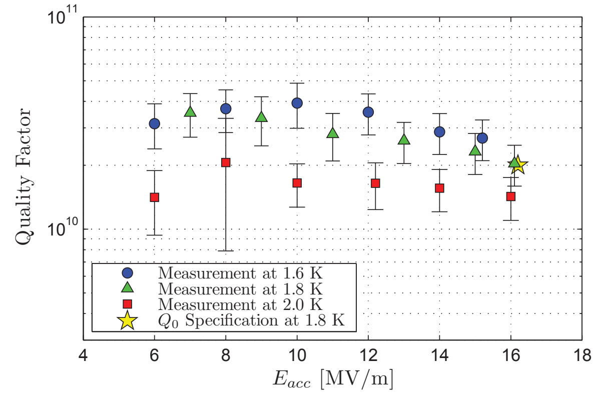

Figure 4: Final Q_0 vs E_{acc} measurement of ERL 7.1 in HTC-2.

HTC-3

The final stage of the HTC experiments included all the components and instrumentation that would be used in a full 6 cavity cryomodule for Cornell's Energy Recovery Linac. Initial measurements of cavity's quality factor were performed at 1.6, 1.8 and 2.0 K. Q_0 vs E measurements after the first cooldown are presented in Fig 5.

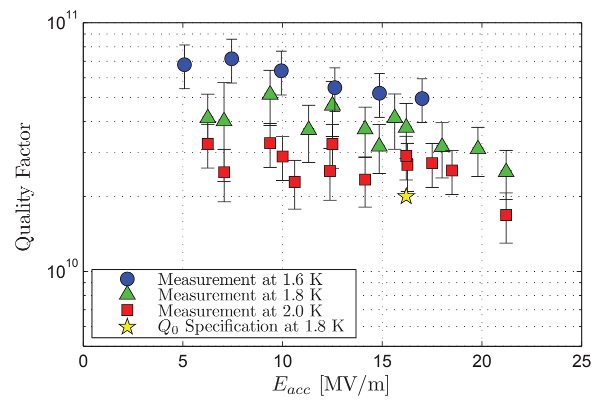

Figure 5: Initial Q_0 vs E measurement of ERL 7.1 in HTC-3. The star denotes the design specification for 1.8 K operation. The cavity field reached 21.2 MV/m, limited by available pumping capacity. Radiation at highest fields was < 1 R/hr. The large uncertainties in the 1.6 K points arises from the small level of dissipated power, but are consistent with BCS predictions for a very low residual resistance cavity.

As in the other experiments, the cavity was thermally cycled. Since most benefits were seen for cycles just above T_c, it was chosen to cycle to above 10 K before recooling to 1.8 K. Fig. 6 shows the Q_0 vs E measurements post thermal cycle.

The prototype cavity ERL 7.1 was measured to have $Q_0(1.8\text{ K}) = 3.6 \times 10^{10}$, $Q_0(1.8\text{ K}) = 6.1 \times 10^{10}$ and $Q_0(1.6\text{ K}) = 1.0 \times 10^{11}$ at the operational gradient of 16.2 MV/m, setting the world record Q_0 for a multicell cavity operating in a horizontal cryomodule.

Copyright © 2013 by the respective authors

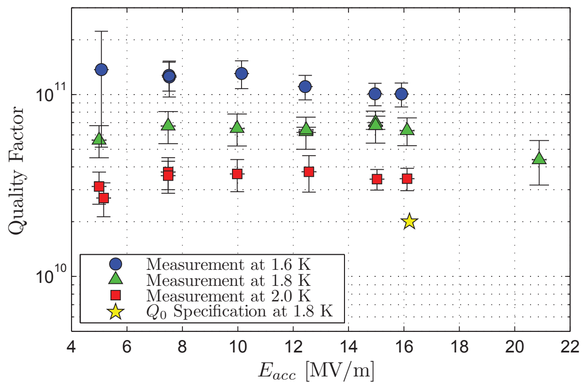

Figure 6: Final Q_0 vs E_{acc} measurement of ERL 7.1 in HTC-3. At the operating accelerating gradient and temperature, the cavity's Q_0 exceeds design specification by a factor of three, reaching 6×10^{10}. Accelerating gradients of 21 MV/m were achieved.

Finally, the superconducting parameters was characterized using SRIMP [11] and Fig. 7 shows that the residual resistance after thermal cycling was reduced from $\sim$3 nΩ to a very low value of just $\sim$1 nΩ.

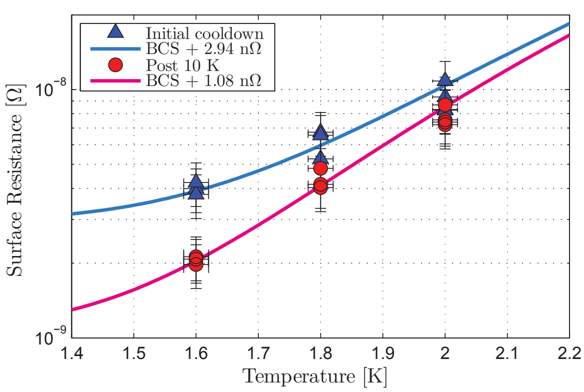

Figure 7: R_s vs temperature measurements before and after thermally cycling ERL 7.1 to 10 K in HTC-3.

CONCLUSIONS

The main linac cavity exceeded design specifications in all three HTC experiments. Temperature cycling helped to improve the quality factor of the cavity by about 50%, with the most benefit being realized after thermally cycling to low temperatures above T_c.

Measurements of the prototype cavity outfitted with a high power coupler and two beamline HOM absorbers shows exceptional quality factor results at gradients up to 21 MV/m. At 1.8 K, the quality factor specification was exceeded by a factor of three. In addition, ERL 7.1 reached Q_0(16.2 MV/M, 1.6 K)=1.0×10^{11} in a fully outfitted cryomodule in HTC-3, breaking the world record that was set in HTC-1 [12] and demonstrating that very high Q_0 is achievable in horizontal cryomodules.

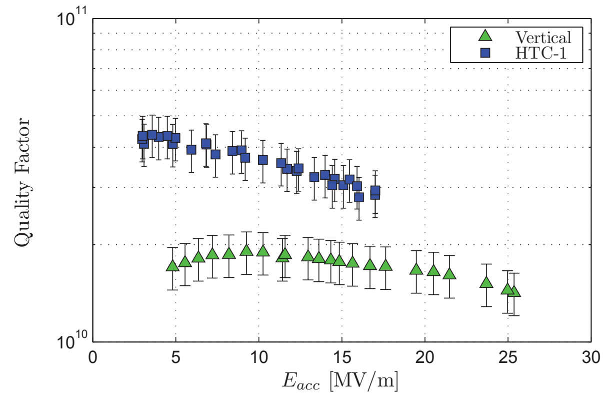

Figure 8: Comparison of Q_0 vs E measurements of ERL 7.1 in the vertical test and HTC-1. Both data sets were taken at 1.8 K. HTC-1 exhibits much higher Q_0 than in the vertical case, even though no surface processing was done between the two measurements.

The HTC experiments demonstrate that extremely high quality factors can be preserved in a fully equipped cryomodule, and Q_0 does not necessarily have to degrade between vertical and horizontal testing. This is clearly demonstrated by Fig. 8, which shows higher quality factors in the HTC-1 experiment than the vertical test, even though the surface preparation and instrumentation was identical between the two.

We attribute the very high values of Q_0 in the HTC experiments to three factors: First, there are two layers of magnetic shielding in the cryomodule, compared with a single layer in the vertical dewar. The additional shielding reduces the ambient magnetic flux in the cryomodule, which leads to a smaller residual resistance. Second, the tightly controlled cooling process of the cavity in the cryomodule minimizes both spatial and temporal gradients across the cavity, reducing flux pinning in the superconductor. Third, the combination of HF rinse and a very uniform 120°C bake in a large furnace leads to high quality surfaces having low BCS resistance.

Six additional main-linac cavities have been fabricated. Three of the cavities have stiffening rings and three others are unstiffened. Initial vertical cavity tests were successful.

Future work with this cavity will include beam tests in Cornell's Injector Cryomodule in the Fall of 2013. These measurements will use beam to measure the Q_0, R/Q and frequencies of higher-order modes in the HTC.

REFERENCES

[1] J. A. Crittenden, I. V. Bazarov, S. A. Belomestnykh, D. H. Bilderback, M. G. Billing, J. D. Brock, E. P. Chojnacki, B. M. Dunham, M. P. Ehrlichman, M. J. Forster, S. M. Gruner, G. H. Hoffstaetter, C. J. Johnston, Y. Li, M. U. Liepe, C. E. Mayes, A. A. Mikhailichenko, H. S. Padamsee, S. B. Peck, D. C. Sagan, V. D. Shemelin, A. Temnykh,

Copyright © 2013 by the respective authors

M. Tigner, and V. Veshcherevich. Developments for Cornell's X-ray ERL. In *Proceedings of PAC 2009*, 2009.

[2] V. D. Shemelin. Suppression of HOMs in a multicell superconducting cavity for Cornell's ERL. In *Proceedings of SRF 2009*, 2009.

[3] N. Valles and M. Liepe. Seven-cell cavity optimization for Cornell's energy recovery linac. In *Proceedings of SRF 2009*, 2009.

[4] R. Eichhorn, B. Bullock, Y. He, G. Hoffstaetter, M. Liepe, P. Quigley, D. Sabol, J. Sears, E. Smith, and V. Veshcherevich. Design and construction of the main linac cryomodule for the energy recovery linac project at cornell. In *Proceedings of SRF 2013*, 2013. MOP074.

[5] N. Valles, F. Furuta, M. Ge, Y. He, K. M. V. Ho, G. H. Hoffstaetter, M. Liepe, T. O'Connell, S. Posen, P. Quigley, J. Sears, M. Tigner, and V. Veshcherevich. Testing of the main-linac prototype cavity in a horizontal test cryomodule for the Cornell ERL. In *Proceedings of IPAC 2012*, 2012.

[6] N. Valles, R. Eichhorn, G. H. Hoffstaetter, and M. Liepe. HOM Studies of the Cornell ERL Main Linac Cavity: HTC-1 through HTC-3. In *Proceedings of IPAC 2013*, 2013.

[7] V. Shemelin and P. Carriere. Frequency control in the process of a multicell superconducting cavity production. *Review of Scientific Instruments*, 83(4):043304, 2012.

[8] M. Liepe., F. Furuta, M. Ge, D. Gonnella, Y. He, G. Hoffstaetter, T. OConnell, S. Posen, P. Quigley, J. Sears, E. Smith, M. Tigner, N. Valles, and V. Veshcherevich. Progress on superconducting RF work for the Cornell ERL. In *Proceedings of IPAC 2012*, 2012.

[9] N. Valles, R. Eichhorn, F. Furuta, M. Ge, D. Gonnella, Y. He, K. Ho, G. Hoffstaetter, M. Liepe, T. O'Connell, S. Posen, P. Quigley, J. Sears, and V. Veshcherevich. Cornell ERL main linac 7-cell cavity performance in horizontal test cryomodule qualifications. In *Proceedings of IPAC 2013*. CLASSE, 2013.

[10] H. Padamsee, J. Knobloch, and T. Hays. *RF superconductivity for accelerators*. Wiley, New York, 1998.

[11] J. Halbritter. Fortran-program for the computation of the surface impedance of superconductors. *KAROLA - OA-Volltextserver des Forschungszentrums Karlsruhe [http://opac.fzk.de:81/oai/oai-2.0.cmp.S] (Germany)*, 1970.

[12] N. Valles, M. Liepe, F. Furuta, M. Gi, D. Gonnella, Y. He, K. Ho, G. Hoffstaetter, D.S. Klein, T. O'Connell, S. Posen, P. Quigley, J. Sears, G.Q. Stedman, M. Tigner, and V. Veshcherevich. The main linac cavity for cornell's energy recovery linac: Cavity design through horizontal cryomodule prototype test. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, (0):–, 2013.

Copyright © 2013 by the respective authors