CRYOMODULE PERFORMANCE OF THE MAIN LINAC PROTOTYPE CAVITY FOR CORNELL'S ENERGY RECOVERY LINAC*

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Abstract

Energy Recovery Linacs (ERLs) require strong damping of higher-order modes in main linac cavities to avoid beam loss from beam break-up effects. In addition, the cavities need to have very high intrinsic quality factors to minimize the size of cryogenic plants in CW cavity operation. 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 residual surface resistance of 1.1 nΩ, which is more than three times better than the Q_0 design specification.

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 E_{acc}=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, which have been discussed elsewhere.[6] The instrumentation effecting fundamental mode performance is summarized in Table 1.

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Table 1: Key Elements Affecting the 7-cell's HOM Spectrum Incorporated in Each Iteration of the Horizontal Test Cryomodule Experiments. The fundamental mode couples to the on-axis input coupler with $Q_{ext} = 9 \times 10^{10}$ and the high-power coupler with $Q_{ext} = 5 \times 10^7$.

Stage	RF input method	HOM absorbers
HTC-1	On-axis coupler	none
HTC-2	High-power input coupler	none
HTC-3	High-power input coupler	2 SiC absorbers

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

This paper details the final results of the three HTC experimental runs, focusing on the fundamental mode properties. Investigations of the higher-order mode spectrum are presented elsewhere.[7] 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[8] and preparation of the prototype main-linac 7-cell cavity, ERL 7.1, for HTC-1 has been described elsewhere.[5] An overview is presented here.

Following fabrication, ERL 7.1 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 reached 26 MV/m, limited by available RF power.

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 over coupled.

The final stage of the HTC tests, HTC-3, added beamline higher-order mode absorbers at each end of the cavity.

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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.[6] In HTC-1 the Q_0 vs E points were measured through standard RF methods–utilizing two RF probe ports[9]–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 over coupled high-power input coupler would not yield accurate Q_0 measurements.[5]

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.

The BCS losses of the superconductor can be calculated with SRIMP, a code by J. Halbritter, which in turn can be used to determine material properties of the cavity from the temperature dependence of the quality factor.

RESULTS

HTC-1

Q_0 vs E measurements were performed after several thermal cycles.[6] 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 $\sim$5.8 nΩ.[5] Thermally cycling the structure led to a 50% increase in Q_0 at the operating temperature, and was maintained even after an intentionally fast cooldown.

After thermally cycling, the cavity exceeded the design specification of $Q(16.2\,\text{MV/m}, 1.8\,\text{K}) = 2\times10^{10}$ by 50%. The cavity set a world 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. 1.

HTC-2

In HTC-2, the quality factor was again measured over several rounds of thermal cycling, described in [6]. After the first 15 K thermal cycle the mid-field Q_0 improved $\sim$50% at both 1.6 K and 1.8 K.[6] Administrative limits prevented quench field determination.

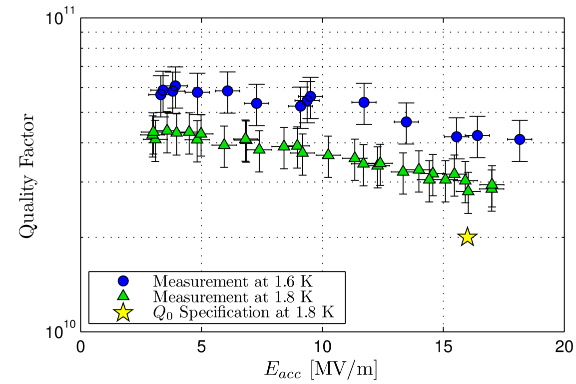

Figure 1: Q_0 vs E_{acc} measurement of ERL 7.1 in HTC-1.

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. 2

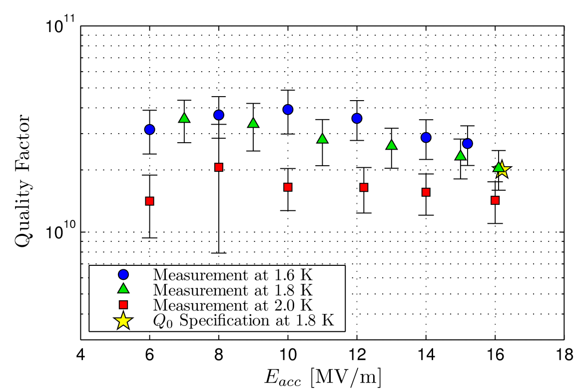

Figure 2: Q_0 vs E_{acc} measurement of ERL 7.1 in HTC-2.

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 exceeded the design specification,[6] but a thermal cycle was performed to determine whether or not additional improvement in Q_0 was possible. Fig. 3 shows the Q_0 vs E measurements post 10 K thermal cycle.

The prototype cavity ERL 7.1 was measured to have $Q_0(1.8\text{ K}) = 3.6 \times 10^{10}$, $Q_0(1.8\text{ K}) = 6.1 \times 10^{11}$ 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.

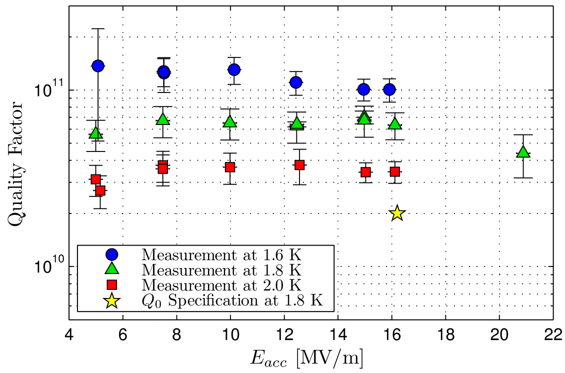

Figure 3: Final Q_0 vs E_{acc} measurement of ERL 7.1 in HTC-3. At the operating accelerating gradient and temperature, the cavity's Q_0 exceeds design specification by a factor of three, reaching 6×10^{10}. Accelerating gradients of 21 MV/m were achieved.

Finally, the superconducting parameters were characterized using SRIMP, finding that the residual resistance after thermal cycling was reduced from $\sim$3 nΩ to a very low value of just $\sim$1 nΩ.[6]

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,[10] and demonstrating that very high Q_0 is achievable in horizontal cryomodules.

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.[6] This is clearly demonstrated by Fig. 4, which shows higher quality factors in the HTC-1 experiment than the vertical test, even though no surface treatment was performed between the tests.

Very high values of Q_0 in the HTC experiments are attributed to three factors: First, there are two layers of magnetic shielding in the cryomodule, compared with a single layer in the vertical dewar reducing 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

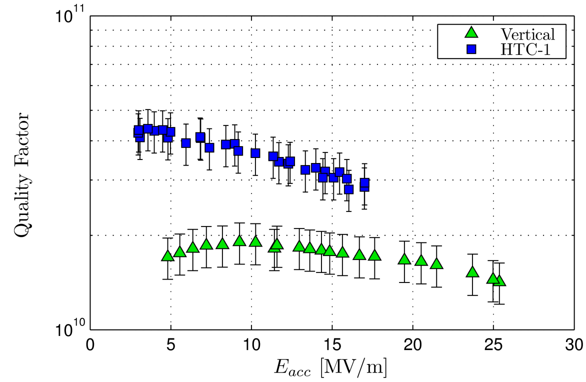

Figure 4: Comparison of Q_0 vs E measurements at 1.8 K of ERL 7.1 in the vertical test and HTC-1. HTC-1 exhibits much higher Q_0 than in the vertical case, though no surface processing was done between the two measurements.

in the superconductor. Third, the combination of HF rinse and a very uniform 120°C bake in a large furnace leads to surfaces having low BCS resistance.

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.

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