CORNELL ERL MAIN LINAC 7-CELL CAVITY PERFORMANCE IN HORIZONTAL TEST CRYOMODULE QUALIFICATIONS*

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Abstract

Cornell has recently finished producing and testing the first prototype 7-cell main linac cavity for the Cornell Energy Recovery Linac, and completed the prototype cavity qualification program. This paper presents quality factor results from the second and third horizontal test cryomodule (HTC) measurements, HTC-2 and HTC-3. We investigate the effect of thermal cycling on cavity quality factor and show that high quality factors can be preserved from initial mounting to fully outfitting the cavity with side-mounted input coupler and beamline HOM absorbers, achieving Q(20 MV/m, 1.8 K) = 3.0×10^{10}. also discuss the production of six additional main-linac cavities as we progress toward constructing a full 6-cavity cryomodule.

INTRODUCTION

Cornell University is developing a 5 GeV energy recovery linac (ERL). This next generation light source is designed to support two high current (each at 100 mA) beams, with small emitance–less than 30 pm at 77 pC bunch charge. These demanding beam requirements set tight constraints for electromagnetic and higher-order mode properties of the 1.3 GHz main-linac cavities.[1, 2] 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.[3]

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 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.

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. 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 meets or exceeds design specifications.

METHODS

Cavity Preparation and Cryomodule Assembly

The construction[7] and preparation of the 7-cell cavity 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 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,

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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 cleaning the cavity, HOM absorbers and the high-power RF coupler was 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 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. In HTC-1 the Q 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 overcoupled high-power input coupler would not yield accurate Q 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 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.

Temperature cycles were performed to low (15 K), medium (100 K) or high temperatures (300 K). In general, cooldown rates were slow (<5 K/hr) except in cases when intentionally large thermal gradients ($\Delta T \sim 2$ K) were produced to investigate the effect on cavity performance.

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,[10] which in turn can be used to determine material properties of the cavity from the temperature dependence of the quality factor.

HTC-1: 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 $Q(5.0\ \text{MV/m}, 1.6\ \text{K}) = 6 \times 10^{10}$. The Q vs E measurements are shown in Fig. 1. RF and cryogenic measurements of Q were in agreement. The quench field was 17.3 MV/m, and prior to quenching the cavity produced radiation at about 1 R/hr. The residual resistance of the cavity was $\sim$7 nΩ.[5]

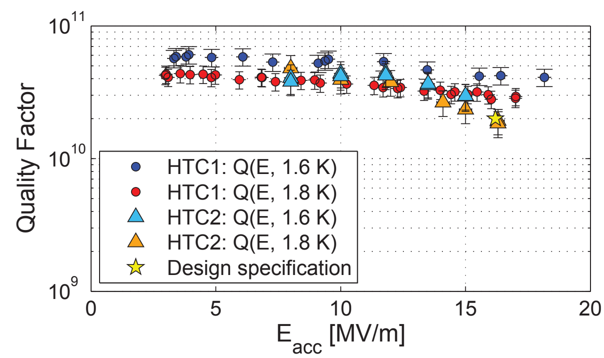

Figure 1: Quality factor measurements for HTC-1 and HTC-2 at 1.6 and 1.8 K after thermal cycling.

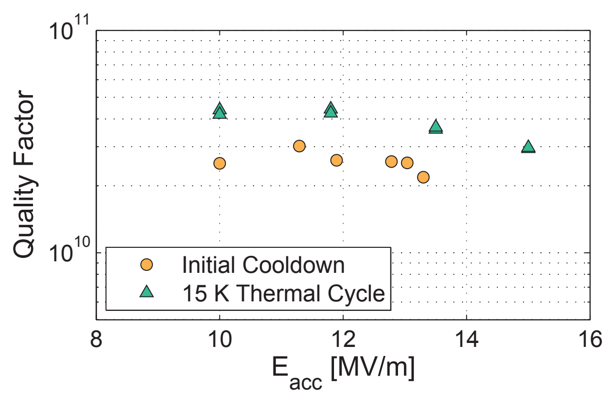

Figure 2: Quality factor in HTC-2 of the prototype cavity at 1.6 K measured before and after a 15 K thermal cycle. Vertical error bars (20%) have been suppressed for clarity.

In HTC-2, the quality factor was again measured over several rounds of thermal cycling. There were 2 low temperature thermal cycles, a medium temperature thermal cycle and a high temperature cycle. Finally, a thermal cycle to 8.9 K was performed to test whether flux could be expelled at temperatures below T_c, as has been suggested by other laboratories.[11] Thermal cycling's effect on Q is presented in Figs 2 and 3. After the first 15 K thermal cycle the mid field Q improved ~50% at both 1.6 K and 1.8 K. Administrative limits prevented quench field determination.

As in HTC-1, in HTC-2 the cavity performance exceeded the design specification. The quality factor curves are presented in Fig. 1.

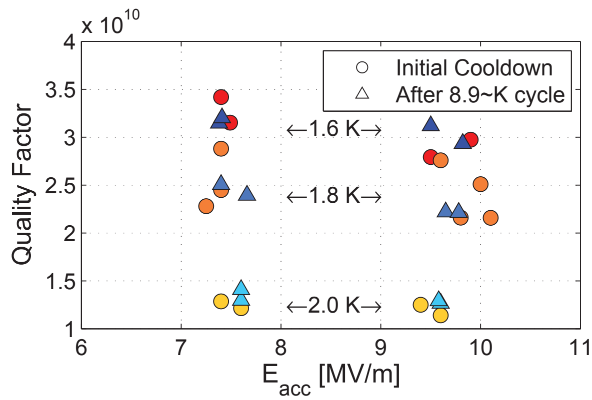

Figure 3: Quality factor in HTC-2 before (circles) and after (triangles) an 8.9 K thermal cycle. The colors correspond to data taken at the same temperature. There is no statistically significant change in mid-field Q in this measurement. Vertical error bars (20%) have been suppressed for visual clarity.

In HTC-3, initial measurements of cavity's quality factor were performed at 1.6, 1.8 and 2.0 K. Preliminary results of Q vs E measurements, showing Q at 1.8 K and 15 MV/m of 3.0×10^{10}, for HTC-3 are presented in Fig 4.

Using typical niobium material properties and estimating the RRR of the RF layer as 10, usual for cavities receiving a 120°C bake, SRIMP gives the residual resistance of the cavity as 1.5 ± 1.0 nΩ.

CONCLUSIONS

The main linac cavity exceeded design specifications in HTC-1 and HTC-2. Temperature cycling helped to improve the quality factor of the cavity by about 50%, and measurements from HTC-2 suggest that temperatures must be increased above 8.9 K for benefit to be realized.

Initial measurements of HTC-3 with full beamline absorbers shows exceptional Q vs E data, exceeding the design gradient and quality factor at 1.8 K by 50%. The figure of merit, Q(16.2 MV/M)=2×10^{10} was achieved at 2.0 K. This demonstrates that high quality factors can be preserved in a fully equipped cryomodule. Thermal cycling investigations will continue, with low, medium and high temperature cycles.

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

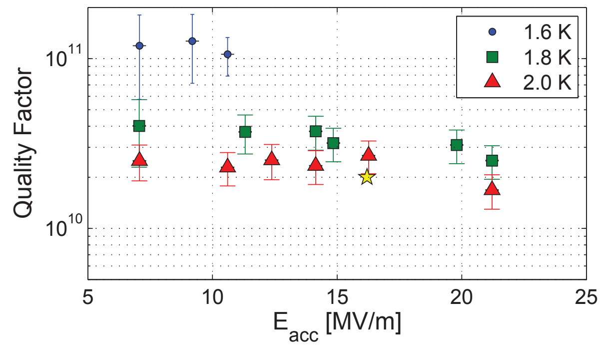

Figure 4: Initial Q vs E measurements for HTC-3. The star denotes the design specification for 1.8 K operation. The cavity field reached 21.2 MV/m, limited by available pumping capacity. Radiation at highest fields was < 1 R/hr. The large uncertainties in the 1.6 K points arises from the small level of dissipated power, but are consistent with BCS predictions for a very low residual resistance cavity.

in Cornell's Injector Cryomodule in August 2013. These measurements will use beam to measure the Q, R/Q and frequencies of higher-order modes in the HTC.

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