TESTING OF THE MAIN-LINAC PROTOTYPE CAVITY IN A HORIZONTAL TEST CRYOMODULE FOR THE CORNELL ERL*

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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. The cavity construction met all necessary fabrication constraints. After a bulk BCP, 650°C outgassing, final BCP, and 120°C bake the cavity was vertically tested. The cavity met quality factor and gradient specifications (2×10^{10} at 16.2 MV/m) in the vertical test. Progressing with the ERL linac development, the cavity was installed in a horizontal test cryomodule and the quality factor versus accelerating gradient was again measured and found to exceed design specifications. This baseline measurement is the first in a sequence of tests of the main linac cavity in the test cryomodule. Subsequent tests will be with increased complexity of the beam line, e.g. with power coupler and HOM beamline loads installed, to study potential sources of reducing the cavitys quality factor.

INTRODUCTION

Cornell University has been developing an energy recovery linac (ERL), with high current (100 mA), and small emittances–less than 30 pm at 5 GeV and 77 pC bunch charge. To function with minimal cryogenic power consumption at 1.8 K, main-linac cavities need to have quality factors of 2×10^{10} at 16.2 MV/m.[1]

Development of a full prototype cryomodule is progressing incrementally. A horizontal test cryomodule (HTC), a schematic of which is shown in Fig. 1, has been developed as a precursor for the much larger main linac cryomodule that will be capable of holding six 7-cell cavities with beam line HOM absorbers. The HTC allows the prototype cavity to be tested in various stages of hardware development.

The prototype 7-cell cavity passed design specifications in a vertical test, and is now in a horizontal testing phase. After an initial test to verify clean installation and determine a baseline quality factor of the cavity, high power couplers will be added, and the cavity will be remeasured. Following that experiment, beamline higher-order mode (HOM) absorbers will be installed, and the performance of the complete structure will be determined. After successful experiments at these intermediate stages, the components will be ready to assemble a full cryomodule.

This paper details the results of the first measurement of the prototype Cornell ERL main linac 7-cell cavity in the HTC, before a high power coupler or beamline HOM absorbers have been installed. We present quality factor measurements via standard RF and cryogenic methods and demonstrate that the cavity designed and fabricated at Cornell exceeds design specifications.

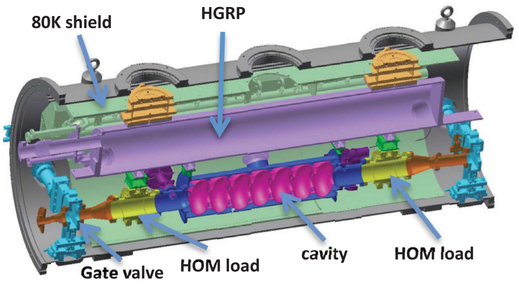

Figure 1: Cutaway of a CAD model of the horizontal test cryomodule. The helium gas return pipe (HGRP) sits above the cavity and connects to a heat exchanging cryogenic system. For the first HTC experiment, beam line higher-order mode (HOM) loads were not present.

METHODS

Cavity Preparation and Cryomodule Assembly

A prototype 1.3 GHz 7-cell main-linac cavity was fabricated based on a design that maximized the beam-break up current through the linac.[2, 3, 4, 5, 6, 7] After stamping half-cells and welding them into dumbbells, their resonant frequencies were measured and trimmed to meet specifications,[8] and then welded together to form an entire cavity.

The cavity received a bulk buffer-chemical polish (BCP) of 150 μm, was outgassed at 650 °C for 12 hours, and was tuned to 1297.425 MHz, and then received a final 10 μm BCP and two eight-hour high pressure rinses. The cavity was then cleanly assembled and attached to a stand for vertical testing. On the test stand the cavity was baked at 120°C for 48 hours.

After meeting quality factor and gradient specifications in the vertical test, the cavity was removed from the vertical test stand, and while still maintaining a clean RF surface, temperature sensors were attached to the outer surface and a helium jacket was welded to the cavity. Instead of the high-power side mounted coupler, a high Q_{ext} on-axis coupler was installed to allow for RF Q vs E measurements. Network analyzer measurements determined that the resonant frequency did not significantly shift during welding.

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A slow tuner based on the Saclay I tuner, with minor modifications was installed. This tuner included fast piezo actuators which can compensate for microphonics.[16] The cavity with tuner was mounted to the cold mass of the cryomodule and the entire cold mass was rolled into the HTC vacuum vessel.[9]

The HTC assembly was completed and connected to a cryogenic system. More details about the HTC design are discussed elsewhere,[12] and results of other HTC-related experiments can be found in other papers.[13, 14, 15]

Experimental Procedure

The prototype cavity tests in the HTC 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 ascertain whether temperature cycles of warming up and cooling down had any effect on cavity performance.

Initially, the cavity was slowly cooled from 300 K to 1.8 K while maintaining a small temperature gradient across the cavity in an attempt to prevent thermal-electric currents from trapping flux and degrading the quality factor of the cavity. The Q vs E points were measured through standard RF methods–utilizing two RF probe ports[10]–and cryogenically by determining the power dissipated from the cavity.

Cryogenic quality factor measurements used two methods: by measuring helium gas mass flow passing through pumps, and by watching the helium level drop. For both techniques, the 1.8 K helium input valve was shut, and calibrations were performed by using a heater to boil off helium while keeping constant bath temperature.

The mass flow at the pumps and rate of helium drop directly relate to the power dissipated in the helium bath. When there is RF in the cavity, the power absorbed by the helium bath is simply the sum of RF power dissipated in the cavity walls, heat from a heater and the static heat load. Knowing the field in the cavity, the quality factor is easily determined by subtracting heater power and static heat load from the total power extracted by the cryogenic system.

After measuring the cavity's quality factor, field in the cavity was increased to reach the quench field, 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 10 K–in case the quench caused caused flux to be pinned in the cavity walls–and then slowly cooled to 1.8 K.

In total, the above procedure of warming up, followed by a slow cool down–maintaining a temperature gradient of the 6 cernox sensors on the cavity to less than 0.3 K–and quality factor measurements was repeated three times, with the third warm-up reaching above 100 K, allowing adsorbed gas to be released and pumped out.

After Q vs E measurements at each cycle, a final temperature cycle was carried out, this time cooling down with the largest possible temperature gradient across the cavity (up to 2 K) to determine whether this would adversely effect the cavity's quality factor.

RESULTS

Testing began by measuring the quality factor vs temperature of the cavity. By fitting the surface resistance, as a function of temperature, shown in Fig. 2, the niobium's material properties can be characterized. A computer code, SRIMP[11] was used to fit the BCS resistance vs temperature data using least squares and determined the material properties of the niobium. The residual resistance was found to be 6.5 nΩ, and the RRR of the RF surface was 11.8.

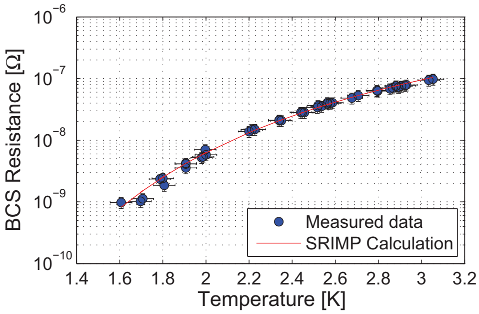

Figure 2: BCS resistance vs temperature. The least squares fit yields the residual resistance of 6.5 $n\Omega$, critical temperature $T_c = 9.15$ K and RRR=11.8, all of which are consistent with vertical test results.

The quality factor of the 7-cell cavity was measured via both RF and cryogenic methods. For cryogenic measurements, knowing the static heat load is critical. The static heat loads for the HTC were measured to be 27.5 ± 2.5 W at 80 K, 1.3 ± 0.5 W at 5 K, and 1.5 ± 0.5 W at 1.8 K. A plot showing all three methods used to measure Q vs E points is presented in Fig. 3. There is excellent agreement between the RF and cryogenic Q measurements.

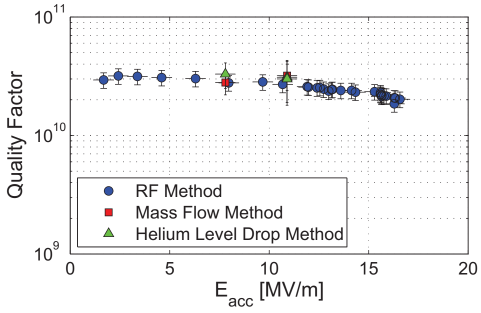

Figure 3: Q vs E points at 1.8 K for a variety of measurement techniques made on the first cool down of the HTC. The RF methods have smaller error bars than either mass flow or helium level drop methods largely due to the uncertainty in the static heat load at 1.8 K which is (1.5 ± 0.5) W.

Initially, the quality factor of the cavity at 16.2 MV/m

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was 2.2×10^{10}, exceeding design specification, with radiation up to 1 Rad/hr. The cavity quenched at 17.3 MV/m, and prior to quench showed very little Q-degradation.

Q vs E measurements as a function of temperature cycle is presented in Fig. 4. The quality factor increased with temperature cycling, eventually reaching 3×10^{10} at 16.2 MV/m and 1.8 K.

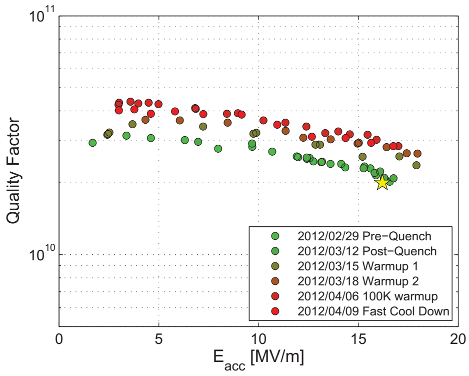

Figure 4: Q vs E curves (taken at 1.8 K) vs temperature cycle. The star marks the design specification for the main linac cavities. For visual clarity, error bars of 10% in quality factor have been suppressed. The first two curves show that quenching the cavity did not cause quality factor degradation. There is a general trend of increasing quality factor with more temperature cycles. A final, fast cool down did not cause significant quality factor reduction.

The best Q vs E measurement was obtained after the warm-up to 100 K and subsequent slow cool down, shown in Fig. 5. The quality factor at operating gradient and temperature exceeded design value by 50%.

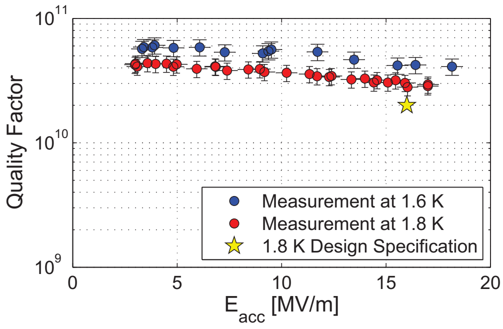

Figure 5: Q vs E curves at 1.6 K and 1.8 K after a slow cool down from 100 K. The highest quality factor measured is 6×10^{10} at 1.6 K and 4 MV/m, a record for a multi-cell cavity installed in a horizontal cryostat. Radiation at highest fields reached up to 1 R/hr.

CONCLUSIONS

The main linac cavity exceeds design specifications on its first test in a horizontal test cryostat. The quality factor at 16.2 MV/m was 50% larger than the goal for the test, at 3.0×10^{10}, a remarkable result for a BCP cavity at 1.8 K.

In addition, this cavity test sets the record for highest quality factor of a multi-cell cavity installed in a horizontal cryostat with a Q of 6.1×10^{10} at 1.6 K.

Temperature cycling helped to improve the quality factor of the cavity. The quench field also improved over temperature cycling, and after quench conditioning was increased from 17.3 MV/m to 20.0 MV/m. This was most likely due to the removal of adsorbed gas from the RF surface.

Future work with this cavity will include testing with a high-power input coupler, which is scheduled for Fall 2012. After this test, a beam line-higher order mode load will be installed, and the cavity retested in the HTC.

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