HOM STUDIES OF THE CORNELL ERL MAIN LINAC CAVITY IN THE HORIZONTAL TEST CRYOMODULE*

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Abstract

The Cornell energy recovery linac will accelerate a 100 mA beam to 5 GeV, while maintaining very low emittance (30 pm at 77 pC bunch charge). A major challenge to running such a large current continuously through the machine is the effect of strong higher-order modes (HOMs) in the SRF cavities that can lead to beam breakup. This paper presents the results of HOM studies for the prototype 7-cell cavity installed in a horizontal test cryomodule (HTC). HOM measurements were done for three HTC assembly stages, from initial measurements on the bare cavity to being fully outtted with side-mounted RF input coupler and beam line HOM absorbers. We compare the simulated results of the optimized cavity geometry with measurements from all three HTC experiments, demonstrating excellent damping of all dipole higher order modes.

INTRODUCTION

Cornell's Energy Recovery Linac (ERL) is designed to operate with low emittance, 77 pC bunches spaced with a frequency of 2.6 GHz, with alternating bunches being accelerated and decelerated.[1] The proper operation of this next generation light source hinges on the ability to suppress higher-order modes (HOMs) in the superconducing main linac structures that can lead to beam breakup. Previous work has produced a 1.3 GHz, 7-cell cavity design that can support threshold current through the linac well in excess of the 100 mA design specification, and satisfies all other electromagnetic and mechanical constraints.[2, 3]

Fabricating structures that preserve the optimized properties of the 7-cell cavity is essential to proper operation of the ERL. Previous particle tracking simulations demonstrated that an ERL constructed of realistically shaped cavities–meaning cavities that had geometry deformations consistent with expected machining fabrication tolerances of ± 0.5 mm–could support current in excess of 400 mA.[4]

A prototype 7-cell cavity has been fabricated, ERL 7.1, and found to exceed design specifications for the fundamental mode in both vertical and horizontal tests.[5, 6] Whether the HOM properties can be preserved from fabrication through installation in a linac cryomodule is an important question. The horizontal test cryomodule (HTC) experiments seek to answer this question by assembling the fully equipped cryomodule in stages and measuring the effect of each stage on the HOM spectrum.

The HTC experiments were done in three stages, and the essential elements effecting HOM measurements are outlined in Table 1. A detailed description of HTC assembly and instrumentation is available elsewhere.[7, 5] Here we simply note that each stage adds a key component to the horizontal assembly eventually resulting in a fully equipped cryomodule in HTC-3 that incorporates all the systems needed for a full main linac cryomodule consisting of six 7-cell accelerating structures.[8]

Table 1: Key elements effecting 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

The cavity's HOM spectrum was measured in each HTC experiment from the RF input coupler to a field probe that couples to the fundamental mode with $Q_{ext} \sim 3 \times 10^{11}$.

The SiC absorbers have been characterized outside of a cryomodule,[9] but it is necessary to evaluate their efficacy at damping HOMs in a real structure before they can be deployed on a larger scale.

METHODS

The prototype cavity was characterized inside a horizontal test cryomodule. To ensure that cavity performance is maintained at or above design specification for the entire assembly, cryomodule development progressed in stages.

HTC-1 contained the prototype cavity with an axial high Q_{ext} RF input coupler, replicating the conditions of the vertical test. There were no HOM absorbers.

HTC-2 exchanged the axial RF input power coupler with a side mounted high-power (5 kW) RF input coupler.[10] Though the axial coupler was still present, it was unused for RF testing. This stage allowed the coupler assembly process to be qualified. This also allowed the first experimental investigations into the coupling between the high power coupler and higher-order modes.

HTC-3 reconfigured the cavity instrumentation, removing the axial power coupler and adding two broadband beamline HOM absorbers to each end of the cavity. The purpose of this stage is to measure the quality factors of

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HOMs with a realistic damping scheme. The broadband dielectric SiC beamline absorbers were ceramics loaded with SiC. The loads have good DC conductivity and have electromagnetic properties $\epsilon \approx (50 - 25i)\epsilon_0$ and $\mu = \mu_0$.

After the cavity was installed in the cryomodule and cooled to the operating temperature of 1.8K, the scattering parameter, S_{21}, was measured with a network analyzer between 1.5 and 6 GHz. The RF coupler was used as the input port; the axial coupler in HTC-1 and the high power coupler in HTC-2 & HTC-3. The output port was located at the other end of cavity on a side port, with a probe with coupling of $\approx 3 \times 10^{11}$ for the fundamental mode. The frequency scan used a 500 Hz step size with certain ranges including high-Q modes measured with a 10 Hz step size.

The resonant frequency of the modes and their quality factors of the experimental data can be determined in several ways. This work uses a least-squares fit to extract resonant frequency, f_0 and loaded quality factor, Q_L, information via the parameterization

$$|S_{21}|\,(f; a, b, f_0) = \frac{10^{-a}}{\sqrt{10^{-2b} + \left(\frac{f}{f_0} - \frac{f_0}{f}\right)^2}}, \qquad (1)$$

where $Q_L = 10^{-b}$, and a is used to generate the proportionality constant.

The above formulation allows the fit parameters to easily vary over orders of magnitude while having less chance of being trapped in local minima due to numerical noise.[11]

In addition, phase versus frequency information was used to characterize the Q_L of the HOMs using the relationship:

$$\phi(f) = \phi_0 + \tan^{-1}\left[Q_L \cdot \left(\frac{f}{f_0} - \frac{f_0}{f}\right)\right], \qquad (2)$$

where ϕ_0 the phase measured at resonance.[12]

The geometry of the cavity installed in HTC-1 was simulated in 2D in CLANS2, an electromagnetic field solver that was used to compute the dipole HOM spectrum in the cavity optimization.[13] The code assumes symmetry about the beam axis and monopoles, dipoles, quadrupoles, etc. can be calculated by specifying the number of azimuthal variations of the mode.

For HTC-2 & HTC-3, the side mounted coupler introduces effects that cannot be modeled by CLANS, so ACE3P[14] was used to simulate the coupling of the high power input coupler to the HOMs. A simulation showing the electric field amplitude of the lowest dipole mode is presented in Fig. 1.

An example showing the damping provided by the HOM absorbers can be seen in Fig. 2, where a dipole mode is solved with and without HOM material present, and the electric field amplitude is calculated on a line parallel to the beam axis. In this case, the HOM loads reduce the Q_L by a factor of 10^3.

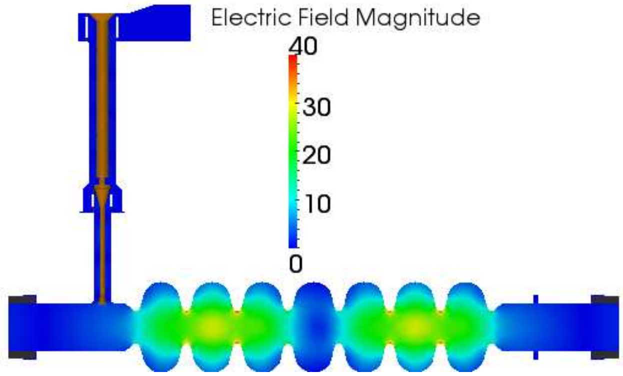

Figure 1: Magnitude of the electric field (in arbitrary units) for a dipole mode in the lowest HOM passband. The absorbing load is in gray, and the white areas are alumina dielectrics isolating the cavity vacuum space from the cold and warm spaces.

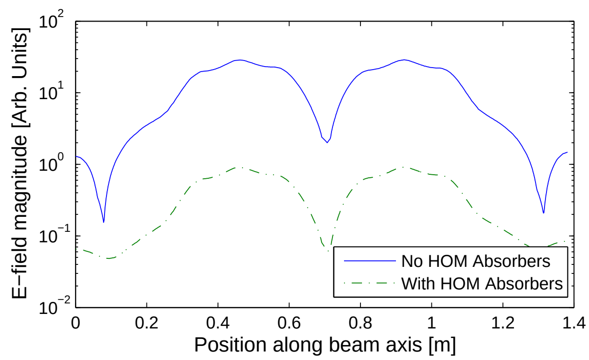

Figure 2: Simulated magnitude of electric field component along a line parallel to the beam axis and offset toward the high power coupler by 1 mm for a geometry with and without absorbing loads. The absorbing load properties were ϵ = (50 - 25i) ϵ_0 and $\mu = \mu_0$. The presence of the HOM load significantly reduces the electric field amplitude near the beam axis.

RESULTS

The higher-order mode spectra as measured in HTC-1 & HTC-2 is shown in Fig. 3. The large quality factors of these modes are due to the lack of HOM absorbers in these experiments. Very small damping is provided by short sections of stainless steel pipe connecting the cavity to the vacuum system.

The HOMs in HTC-1 was compared with 2.5D simulations performed in CLANS and showed agreement in the lower passbands of the HOM spectrum, and frequency correspondence up to 3600 MHz.[15]

After reconfiguring the cryomodule for HTC-3 and adding beamline HOM absorbers, the transfer function was remeasured. The scattering parameter S_{21} is plotted in Fig 4. ACE3P's eigenmode solver was used to compute modes near the resonances in the HTC-3 HOM spectrum.

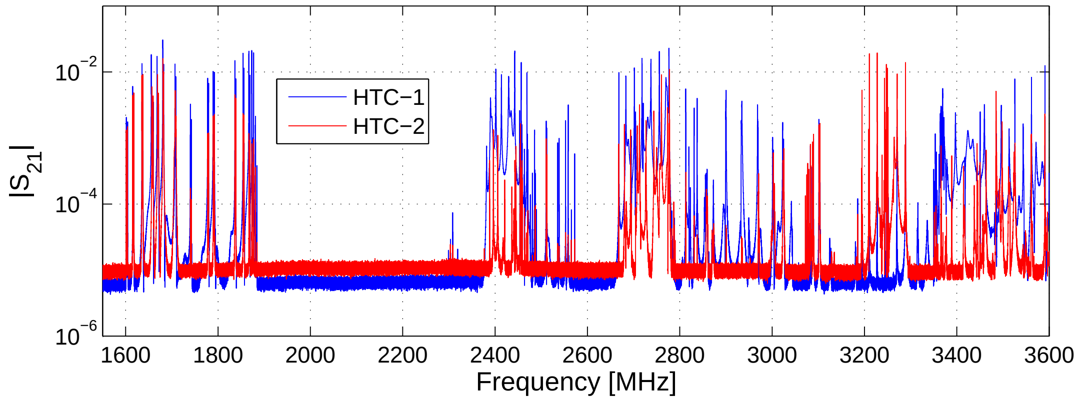

Figure 3: Amplitude of the scattering parameter S_{21} in the first two HTC experiments. The large quality factor of the modes are due to the fact that there were no HOM loads installed in HTC-1 and HTC-2. The mode frequencies agree with 2D simulations.

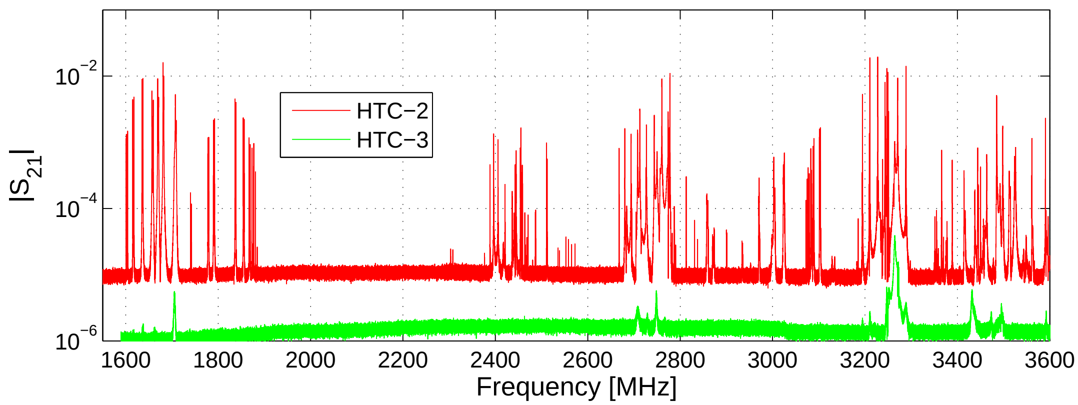

Figure 4: Amplitude of the scattering parameter S_{21} in the HTC-2 and HTC-3 experiments. The only significant change between the two runs is the beamline HOMs in HTC-3, showing strong damping of all modes.

The measured loaded quality factors are compared with simulations in Fig. 5.

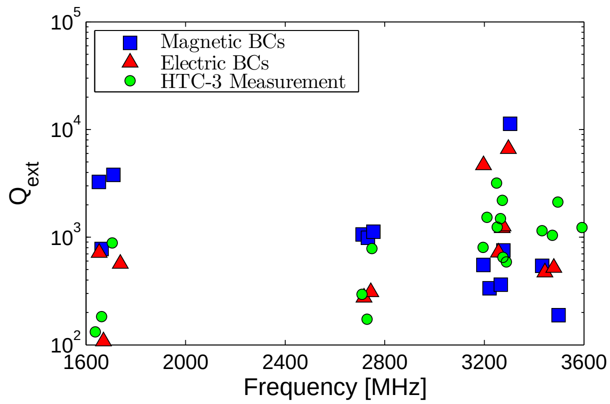

Figure 5: Comparison between HOMs measured in the HTC-3 and ACE3P simulations. Some discrepancy between the simulated and measured points is expected due to machining variation.

The rough agreement between simulations and measured quality factors is expected due to fabrication variation. What is important to note is that all the measured modes have quality factors within acceptable limits such that they should not lead to beam break-up current below the 100 mA design specification.[4]

CONCLUSIONS

The prototype 7-cell cavity has been fabricated to within design tolerances (± 0.5 mm) and successfully tested in a fully outfitted cryomodule. The higher-order mode spectrum was successfully measured and the SiC absorbers provide strong damping of higher order modes. Measurements using both the magnitude of the scattering parameter and the phase dependence of HOMs yield consistent measurements of HOM's Q_L. Simulations are in rough agreement with results, but are an area of ongoing investigation.

All three measurements of the scattering parameter find no modes near harmonics of 2600 MHz (2 beams at 1300 MHz). If the beam could resonantly drive an HOM on one of these resonances, the resulting HOM power could overload the HOM absorber. Fortunately, frequency domain measurements show that the design was successful in avoiding this danger.

Future work will measure HOM properties of the cavity with beamline dampers using beam from Cornell's ERL Injector. These experiments are scheduled to begin Fall 2013.

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