HOM STUDIES OF THE CORNELL ERL MAIN LINAC CAVITY: HTC-1 THROUGH HTC-3

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Abstract

The Cornell energy recovery linac is designed to run a high energy (5 GeV), high current (100 mA), very low emittance beam (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) 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) from initial RF test, to being fully outfitted with side-mounted input coupler and beam line absorbers. We compare the simulated results of the optimized cavity geometry with measurements from all three HTC experiments, showing strong HOM damping in the completed HTC.

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) 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 and found to meet 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 [5, 6]. 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.

Table 1: Summary of the key elements 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 $Q_{ext} = 5 \times 10^{10}$.

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 $Q_{ext} \sim 3 \times 10^{11}$.

Central to this work is the investigation of the functioning of the beamline higher-order mode absorbers in the linac. While many characterizations of these absorbers have been made [7], this will be the first test of this type of absorber in a horizontal linac cryomodule.

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 changed the RF input power scheme to the cavity, adding a side mounted high power (5 kW) RF input coupler as well as the axial probe. 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 end of the cavity. The purpose

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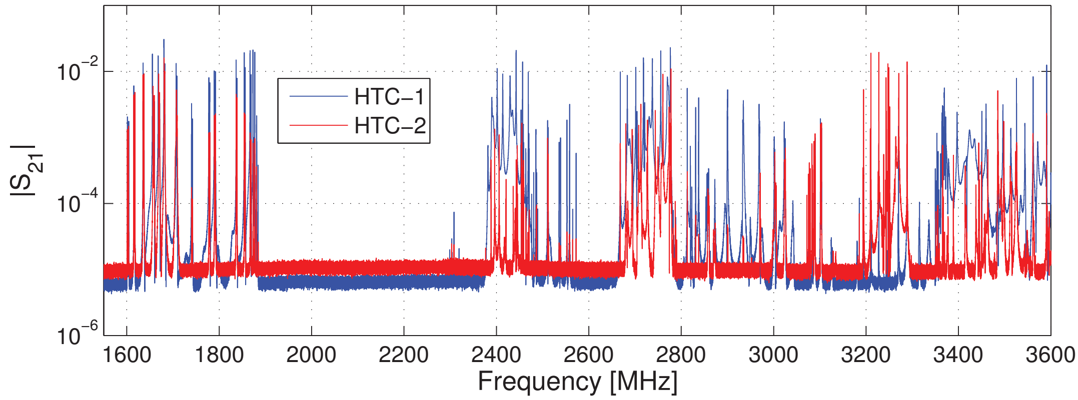

Figure 1: Amplitude of the scattering parameter S_{21} in the first two HTC experiments. The large quality factor of the modes are due to the fact that there were no HOM loads installed in HTC-1 and HTC-2. The mode frequencies agree with 2D simulations.

of this stage is to measure the quality factors of HOMs with a realistic damping scheme.

While the cavity was installed in the cryostat, and at 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 $\approx 2 \times 10^{11}$ 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 and loaded Q information via the parametrization

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

This 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.

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 [8]. 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 modelled by CLANS, so ACE3P [9] was used to simulate the coupling of the high power input coupler to the HOMs.

RESULTS

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

The HOMs in HTC-1 can be compared with 2.5D simulations performed in CLANS in Fig. 3, which is reproduced from a previous paper for completeness [10].

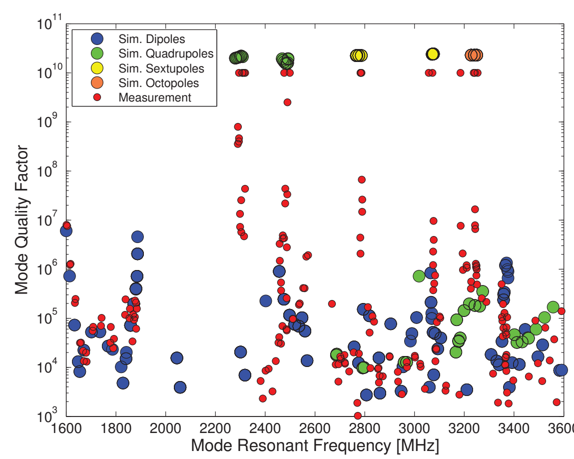

Figure 3: Reproduced from [10]. Comparison of simulated HOM spectrum and measured modes (red) in HTC-1. CLANS2 was used to compute dipole (blue), quadrupole (green), sextupole (yellow) and octopole (orange) modes from a 2D model. Error bars of 20% in quality factors have been suppressed for visual clarity. These Q's are high because of lack of HOM absorbers.

The HTC-3 experiment incorporated broadband dielectric SiC beamline absorbers. These SiC loads have good DC conductivity and have permittivity $\epsilon \approx (50-25i)\epsilon_0$ and $\mu = \mu_0$. The scattering parameter S_{21} is plotted in Fig 2.

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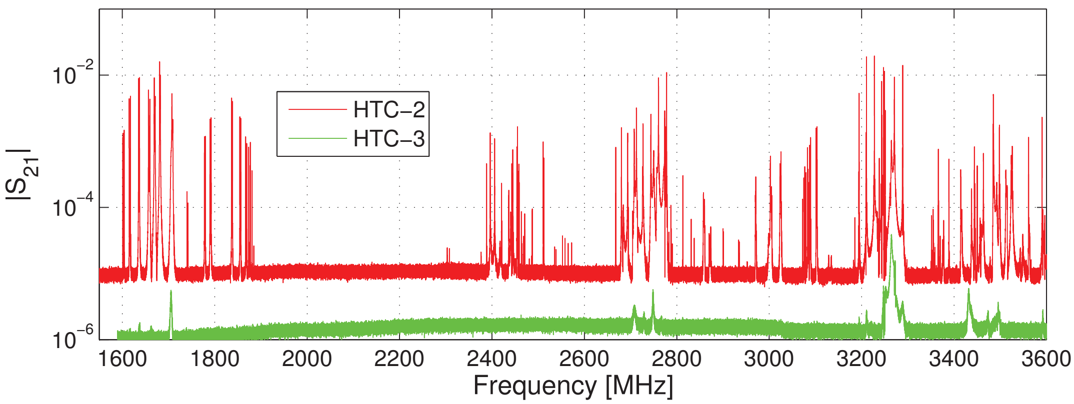

Figure 2: Amplitude of the scattering parameter S_{21} in the HTC-2 and HTC-3 experiments. The only significant change between the two runs is the beamline HOMs in HTC-3, showing strong damping of all modes.

The resulting spectrum in Fig. 4 shows that the HOM loads strongly suppress the quality factors of the cavity's higher-order modes to within acceptable limits.

Measured modes in HTC-3 have lower quality factors than simulations. ACE3P calculates modes in the quadrupole, sextupole and octopole bands that were not seen in HTC-3 spectral measurements. These higher-multipole modes' quality factors are within acceptable limits such that they should not lead to BBU below 100 mA beam current.

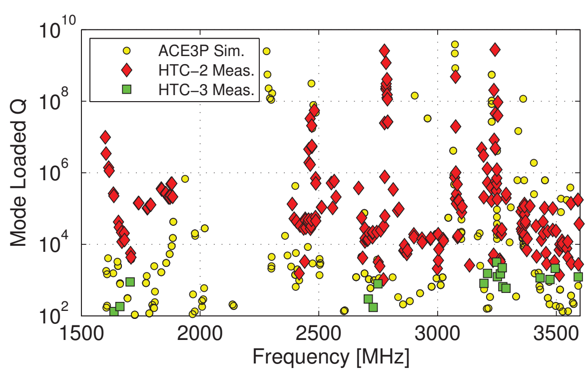

Figure 4: Mode quality factor vs frequency for the HTC-2, HTC-3 and ACE3P simulations. ACE3P simulated HTC-3, incorporating lossy HOM loads and the RF input coupler/waveguide assembly. Simulated modes with high Qs are from the quadrupole, sextupole and octopole bands.

CONCLUSIONS

The prototype 7-cell cavity has been fabricated to within design tolerances (± 0.5 mm) and successfully tested with a horizontal test cryomodule in three stages, HTC-1, -2 and -3. The higher-order mode spectrum and damping was successfully measured and found to be consistent with expected machining variation. Simulations and experimental results agree, suggesting that the optimized baseline cavity design, which minimized the effect of strong HOMs, was maintained in the prototype 7-cell.

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 in the Summer of 2013.

REFERENCES

[1] J. A. Crittenden et. al. "Developments for Cornell's X-Ray ERL," PAC 2009.

[2] V. D. Shemelin "Suppression of HOMs in a Multicell Superconducting Cavity for Cornell ERL," SRF 2009.

[3] N. Valles and M. Liepe, "Seven-cell Cavity Optimization for Cornell's Energy Recovery Linac," SRF 2009.

[4] N. Valles, D. S. Klein and M. Liepe, "Beam Break-Up Studies for Cornell's Energy Recovery Linac," SRF 2011.

[5] N. Valles, et. al, "Testing of the Main-Linac Prototype Cavity in a Horizontal Test Cryomodule for the Cornell ERL," IPAC 2012.

[6] N. Valles, et al, "Cornell ERL Main Linac 7-cell Cavity Performance in Horizontal Test Cryomodule Qualifications," IPAC 2013.

[7] R. Eichhorn, et. al, "Cornell's HOM Beamline Absorbers," IPAC 2013.

[8] D.G. Myakishev, "CLANS2-A Code for Calculation of Multipole Modes in Axisymmetric Cavities...," PAC 1999, pp 2775-2777.

[9] L. Lee, Z. Li, C. Ng, and K. Ko, "Omega3P: A Parallel Finite-Element Eigenmode Analysis Code for Accelerator Cavities," SLAC-PUB-13529. (2009)

[10] N. Valles, M.G. Billing, G.H. Hoffstaetter, M. Liepe, C.E. Mayes, "HOM Studies on the Cornell ERL Prototype Cavity in a Horizontal Test Cryomodule," IPAC 2012.