HOM STUDIES OF THE CORNELL ERL PROTOTYPE CAVITY IN A HORIZONTAL TEST CRYOMODULE*

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Abstract

The main linac 7-cell cavity for Cornell's Energy Recovery Linac was optimized to maximize threshold current through the ERL. This was achieved by designing center and end cells that reduce the strength of dipole higher-order modes. A prototype cavity was fabricated based on the optimized RF design and found to meet fundamental mode specifications in a vertical test. The higher-order-mode spectrum was measured when the cavity was installed in a horizontal test cryomodule and is compared to simulations. A method to measure HOM properties via charge modulation of an electron beam is presented.

INTRODUCTION

To meet design specifications of Cornell's ERL,[1] accurate fabrication of the main linac cavities are essential. Operation at 100 mA current requires suppression of higher-order modes (HOMs) that can lead to beam-break up. The 7-cell cavity design maximized the threshold current through the ERL, while maintaining high quality factor of the fundamental mode and keeping peak electric and magnetic fields low.[2, 3]

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–could support current in excess of 400 mA.[4] To check whether HOMs are damped strongly enough in an actual cavity fully outfitted with helium jacket, tuner and other instrumentation, the prototype 7-cell was installed in a horizontal test cryostat (Fig. 1) and the HOM spectrum was measured.

For this first experiment, beamline higher-order mode absorbers were not installed so damping is only done by stainless steel beam pipe sections, and thus HOM Q values are higher than for the baseline cavity design, which was optimized in conjunction with HOM absorber geometry. Measured HOM values of loaded Q and resonant frequency are compared with simulation.

Finally, a method to use charge modulation of an electron beam to measure R/Q is discussed.

METHODS

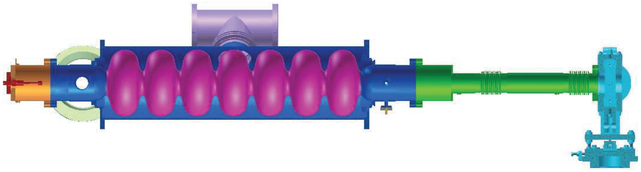

Figure 1: CAD model of the first main linac prototype cavity as installed in the horizontal test cryostat. The initial test did not include installed higher-order mode absorbers. Fundamental power coupler is on the left side in red, and served as the input port for the $|S_{21}|$ measurement. The transmitted power probe served as the output port, and is on the underside of the right beam tube, just before the junction between the cavity and the green vacuum line.

The prototype cavity was installed in a horizontal test cryomodule. To ensure that cavity performance is maintained at or above design specification for the entire assembly, cryomodule development is progressing in stages. For the first horizontal test of the cavity, no higher-order mode absorbers were installed, nor was a high power RF input coupler. Instead probes were attached similar to that of a vertical test, allowing standard RF methods to be used to measure cavity quality factor and accelerating gradient.[5]

Instead of the side mounted high-power fundamental power coupler with an external Q of 6.5×10^7, an on-axis coupler with external Q of 9×10^{10} was mounted on the end of the beam pipe. This coupling allowed strong coupling to the fundamental mode of the cavity, and also could more easily excite HOMs than the high power coupler that will be present in future experiments.

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 input port was an axial probe located at the end of one beam pipe. The output port was located at the other end of cavity on a side port, with a probe with coupling of $\approx 1 \times 10^{12}$ 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 by fitting the excitation curves with a Breit-Wigner curve. This curve has the form:

$$|S_{21}|\,(f; Q_L, f_0) \propto \left[\frac{1}{Q_L^2} + \left(\frac{f}{f_0} - \frac{f_0}{f}\right)^2\right]^{-1/2}, \quad (1)$$

where f is the sampled frequency, f_0 is the resonant frequency and Q_L is the loaded quality factor of the mode.

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* Work supported by NSF Grants NSF DMR-0807731 and NSF PHY-1002467

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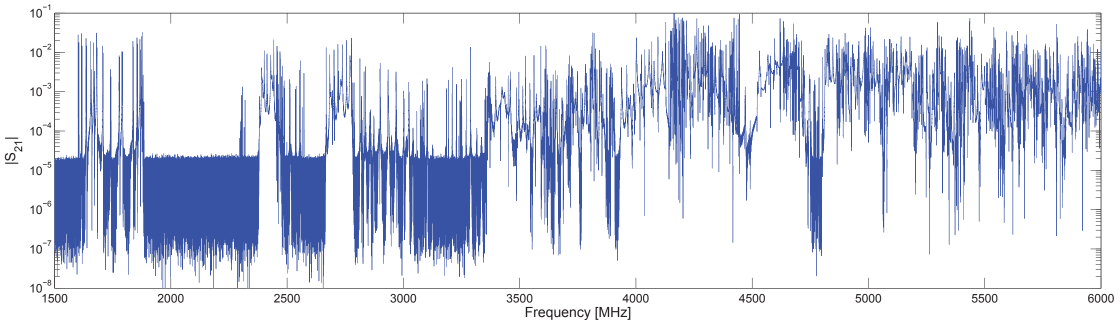

Figure 2: Excitation response of main-linac 7-cell cavity from 1.5 to 6.0 GHz. During the measurement, the cavity temperature was maintained at 1.8 K.

Least-squares was used to fit the resonance curves and extract resonant frequency and loaded Q information. The parametrization

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

was used in the curve fitting algorithm, because 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 the horizontal test cryostat was simulated in 2D in CLANS2, an electromagnetic field solver that was used to compute the dipole HOM spectrum in the cavity optimization.[6] 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.

RESULTS

The higher-order mode spectrum as measured by a network analyzer is shown in Fig. 2. The simulation results and modes measured from the network analyzer sweep are presented in Fig. 3, which shows higher-order mode quality factor vs resonant mode frequency.

Modes under 3600 MHz were fit from the frequency scan, as previous simulations showed that higher frequency modes couple very strongly to the higher-order mode absorbers and are not limiting the BBU current.

The low quality factors of the dipole modes are consistent with simulations, suggesting that the optimized properties of the baseline design have been preserved through the cavity fabrication and installation process. The quality factors of the first few quadrupole, sextupole and octupole passbands are higher in simulations than in experimental data. Possible explanations for this is two-fold. First, it is difficult to accurately measure high quality factor modes due to their narrow widths, which may only be a few Hz, so measurement errors of at least 30% for very high Q modes should be taken into account. Second, in the real cavity, symmetry is broken by coupler ports, machining variation, slight elliptical variations in the cells and other sources which could remove the degeneracy of these modes and allow them to couple to the propagating modes in the stainless steel pipes, causing increased losses.

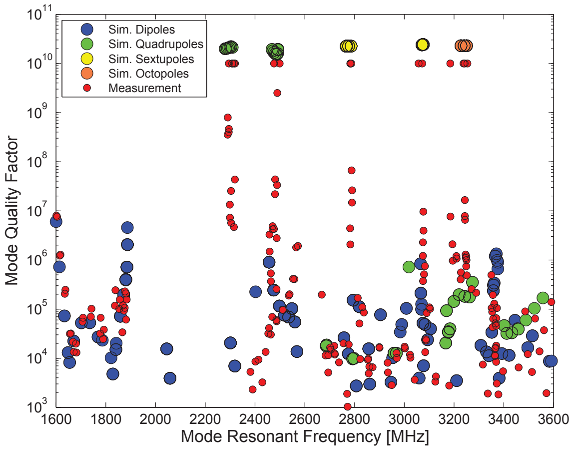

Figure 3: Comparison of simulated HOM spectrum and measured modes (red) in the prototype cavity. CLANS2 was used to compute dipole (blue), quadrupole (green), sextupole (yellow) and octopole (orange) modes from a 2D model. The error bars of 20% in measured quality factors have been suppressed for visual clarity. Importantly, for the first test, there are not higher-order mode absorbers installed, so these measured and simulated Q's are larger than what will be achieved in the completed cryomodule.

BEAM-BASED HOM MEASUREMENT

We plan to measure HOMs in the HTC cavity by individually exciting them with a current modulated beam from the Cornell prototype ERL injector. This technique is detailed in Refs. [7, 8]. Briefly, if f_b is the bunch repetition frequency, then a HOM resonating at frequency f_λ can be excited when the n^th bunch charge is given by

$$q_n = q_0\left[1 + a_\mathrm{mod}\sin\left(2\pi n f_\mathrm{mod}/f_\mathrm{b} + \phi_\mathrm{mod}\right)\right]. \qquad (3)$$

ISBN 978-3-95450-115-1

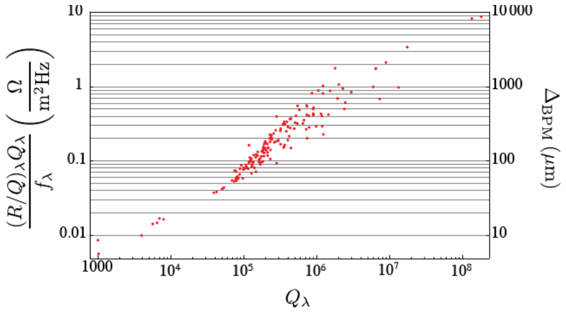

Figure 4: Simulated HOMs of the 7-cell cavity in the HTC. If a single HOM is resonantly driven by bunches with charges according to Eq. (3), then we expect a maximum spread in offsets Δ_{BPM} encountered by a BPM downstream according to Eq. (4). The axis on the right shows Δ_{BPM} for these HOMs assuming a modulation amplitude $a_{\mathrm{mod}} = 0.8$, beam offset $x_{\mathrm{offset}} = 1\,\mathrm{cm}$, distance to BPM $d_{\mathrm{BPM}} = 5\,\mathrm{m}$, average charge $q_0 = 1\,\mathrm{pC}$, bunch repetition frequency $f_{\mathrm{b}} = 1.3\,\mathrm{GHz}$, and energy $\mathcal{E} = 5\,\mathrm{MeV}$.

Here q_0 is the average bunch charge, a_{mod} is the modulation amplitude, f_{mod} and ϕ_{mod} are the modulation frequency and initial phase, respectively. The mode resonates when $f_{\mathrm{mod}} = |f_\lambda - m f_{\mathrm{b}}|$ for an integer m.

On resonance, bunches with energy $\mathcal{E}$ entering a cavity with position offset x_{offset} will be kicked by this mode over a range of angles. A BPM downstream at a distance d_{BPM} will then encounter bunches with a maximum spread in offsets

$$\Delta_{\mathrm{BPM}} \approx \frac{c}{\pi} a_{\mathrm{mod}}\, x_{\mathrm{offset}}\, d_{\mathrm{BPM}}\, q_0\, f_{\mathrm{b}}\, \frac{e}{\mathcal{E}} \frac{(R/Q)_\lambda\, Q_\lambda}{f_\lambda}. \quad (4)$$

Such a measurement is of particular interest because the beam-breakup (BBU) instability can limit the operating current in an ERL to below a threshold current which is proportional to the quantity $f_\lambda / [(R/Q)_\lambda\, Q_\lambda]$, assuming that a single HOM occupies all cavities [9]. Simulated HOMs in the HTC cavity are shown in Fig. 4, along with corresponding Δ_{BPM}, assuming realistic operational parameters.

Experimentally, the signal from a single BPM button should consist of sidebands at $m f_{\mathrm{b}} \pm f_{\mathrm{mod}}$ due to a_{mod}, and sidebands at $m f_{\mathrm{b}} \pm 2 f_{\mathrm{mod}}$ due to Δ_{BPM}, for $m = 1, 2, \ldots$. The actual determination of Δ_{BPM} from this second set of sidebands may be challenging, depending on the purity of the current modulation and the BPM noise floor.

CONCLUSIONS

The prototype 7-cell cavity has been fabricated to within design tolerances (±0.5 mm) and successfully installed in the horizontal test cryomodule. 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.

Though this experiment measured HOMs of a cavity without a high-order mode absorber installed, the agreement between simulation and measurement gives confidence that the cavity optimization, which relied upon the same code is trustworthy.

It is important to note that the measured spectrum shows that the there are no modes at 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. Frequency domain measurements show that the design was successful in avoiding this danger.

Finally, we presented a method to measure HOM properties with beam via charge modulation. Future work with the main linac 7-cell will include installing beamline higher-order mode absorbers and measuring the higher-order mode spectrum with and without beam.

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