

# HOM MEASUREMENTS FOR CORNELL'S HIGH-CURRENT CW ERL CRYOMODULE

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## Abstract

The main linac cryomodule (MLC) for the future energy-recovery linac (ERL) based X-ray source at Cornell has been designed, fabricated, and tested. It houses six 7-cell SRF cavities with individual higher order-modes (HOMs) absorbers, cavity frequency tuners, and high power RF input couplers. HOMs in MLC cavities have been scanned at the operating temperature of 1.8K. The results show effective damping of HOMs, and also agree well with simulation results and previous HOM scan results on one 7-cell cavity prototype test cryomodule. Here we report first results from the MLC HOM study.

## INTRODUCTION

Cornell University has proposed to build an Energy Recovery Linac (ERL) as drivers for a hard x-ray source because of its ability to produce electron bunches with small, flexible cross sections and short lengths at high repetition rates. The proposed Cornell ERL is designed to operate in CW at 1.3 GHz, 2 ps bunch length, 100 mA average current in each of the accelerating and decelerating beams, normalized emittance of 0.3 mm-mrad, and energy ranging from 5 GeV down to 10 MeV, at which point the spent beam is directed to a beam stop [1, 2]. For this type of high current machine, the suppression of high order modes (HOMs) excited by the beam in the SRF cavities is essential, because HOMs could lead a deflection of the beam. Especially, the dipole modes which could make a transverse kick on the beam bunch and start a bunch oscillation around the design orbit need to be damped strongly to avoid resulting beam break up (BBU).

## HOM ABSORBER IN MLC

### MLC General

Figure 1 shows an image of the Cornell ERL main linac cryomodule (MLC). It is 9.8 m long and houses six 1.3 GHz 7-cell superconducting cavities with Individual HOM absorbers. Each cavity has a single 5 kW coaxial RF input coupler which transfers power from an solid-state RF power source to the cavity. The specification values of the 7-cell cavities are  $Q_0$  of  $2.0 \times 10^{10}$  at 16.2 MV/m, 1.8 K. Due to the high beam current combined with the short bunch operation, a careful control and efficient damping of higher order modes (HOMs) is essential. Therefore, HOM beamline absorbers are installed at the beam pipe ends of each cavity (Fig. 1, bottom).

### HOM Absorber

Figure 2 shows a cross section view of the production version of the Cornell HOM absorber. For these production versions, the absorbing material is Silicon Carbide, SC-35® from Coorstek [3]. Two prototypes were initially built using the same absorbing ceramics and tested together with a prototype 7-cell cavity in the Cornell one-cavity Horizontal-Test-Cryomodule (HTC). Within the HTC, a 7-cell ERL cavity was placed between two HOM absorbers. HOM measurements demonstrated excellent higher order mode damping, and a successful high current (40mA) beam test was done. More details about the beam test results can be found in reference [4].

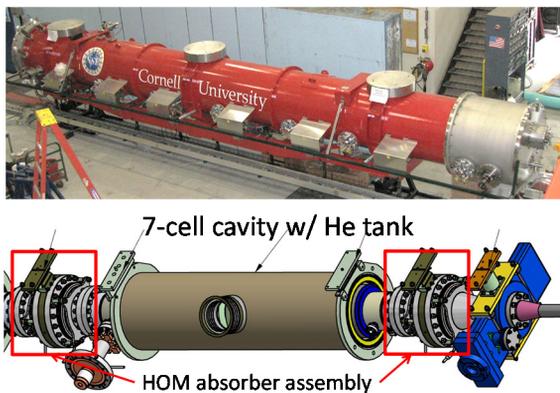


Figure 1: MLC (top), 3D image of a one-cavity section of the string assembly (bottom).

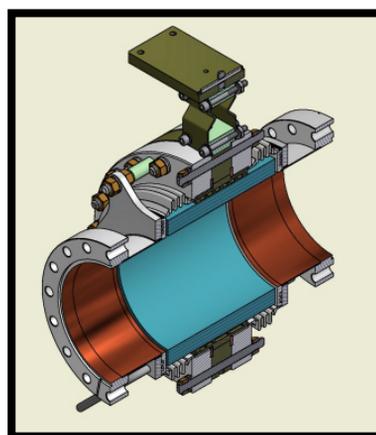


Figure 2: Cornell's HOM absorber used in the main linac cryomodule (MLC). The absorbing material is SC-35 from Coorstek, shrink-fitted into a Ti cylinder.

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

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## MLC HOM SCANS AND ANALYSIS

### Scan

HOMs in the MLC were scanned via S21 Network analyzer measurements at 1.8K. High power RF input couplers were used as input port and field pick up probes were used as output. The scanned frequency range was 1.5 GHz to 6 GHz with the frequency step (df) of 125 Hz. A Matlab GUI was programmed for the scan. Figure 3 shows the set-up for the HOM scans with the MLC. Figure 4 shows the measured S21 curves from 1.5 to 6 GHz for three of the cavities.

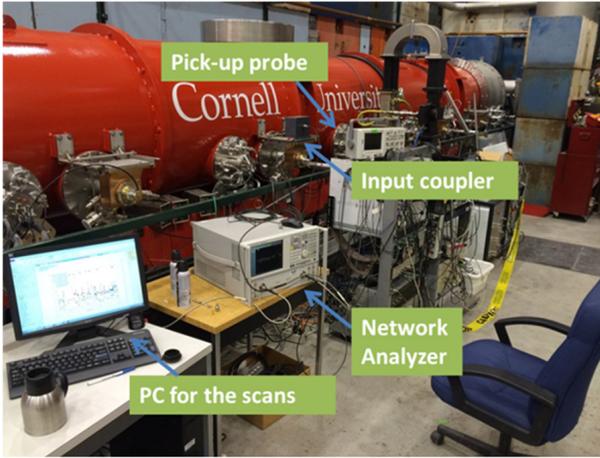


Figure 3: HOM scan set-up for the MLC.

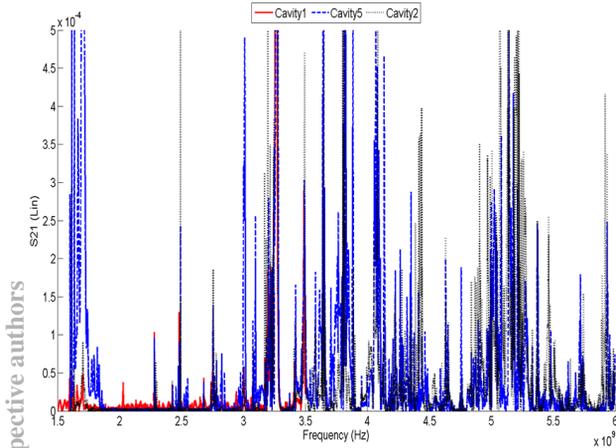


Figure 4: Measured S21 resonances for 3 cavities from 1.5 to 6GHz.

### HOM Analysis

The measured S21 curves showed resonant modes (HOMs) in the cavities. Those modes can be divided into two groups. The first group are monopole modes which have a single peak for each mode. Loaded quality factors ( $Q_L$ ) were extracted by fitting the individual S21 resonance curves using Eq. (1) [5]. Figure 5 shows an example a fit together with the measured S21 resonance curves.

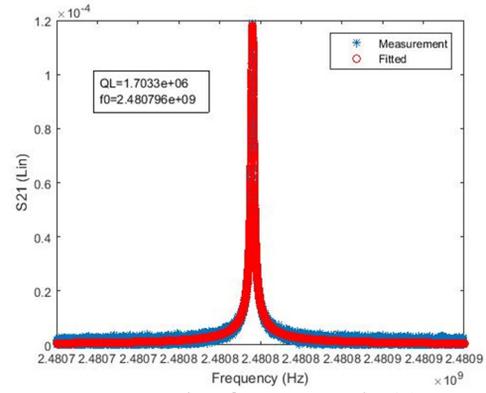


Figure 5: An example of a measured S21 curve fit with single resonance curve.

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

The second group of modes are non-monopole modes such as dipole, quadrupole, etc. modes, having more than one peak for each mode type because of different polarizations. These modes have mode mixing issue, e.g. a dipole has two peaks mixed together (see for example Fig. 6), distorting their S21 curve. Equation (2) was used

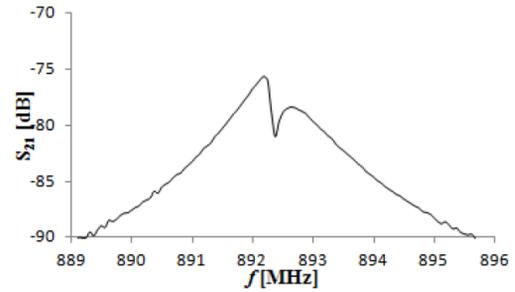


Figure 6: An example of a measured S21 curve, which had mode mixing.

to fitting  $Q_L$  for these modes [6].

$$S_{21} = \sqrt{\frac{D_1^2}{1+\Delta_1^2} + \frac{D_2^2}{1+\Delta_2^2} - \frac{2D_1D_2\cos(\pi-\theta)}{\sqrt{1+\Delta_1^2}\sqrt{1+\Delta_2^2}}}, \quad (2)$$

where  $\Delta = Q_L \left( \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right)$ .

### HOM Simulations

For calculation of the higher order modes of the cavity with the dielectric HOM absorbers we used a full cavity model without the coupler and field probe ports. Without ports, it is axially symmetric and we used 2D electromagnetic solvers CLANS [7] for simulation of monopole modes and CLANS2 [8] for simulation of multipole modes. Simulations were made for absorbers having parameters:  $\text{Re}\{\epsilon\} = 60$ ,  $\text{Im}\{\epsilon\} = 20$ ,  $\text{Re}\{\mu\} = 1$ ,  $\text{Im}\{\mu\} = 0$ . These numbers are close to average values of the real absorber material for a wide frequency range.

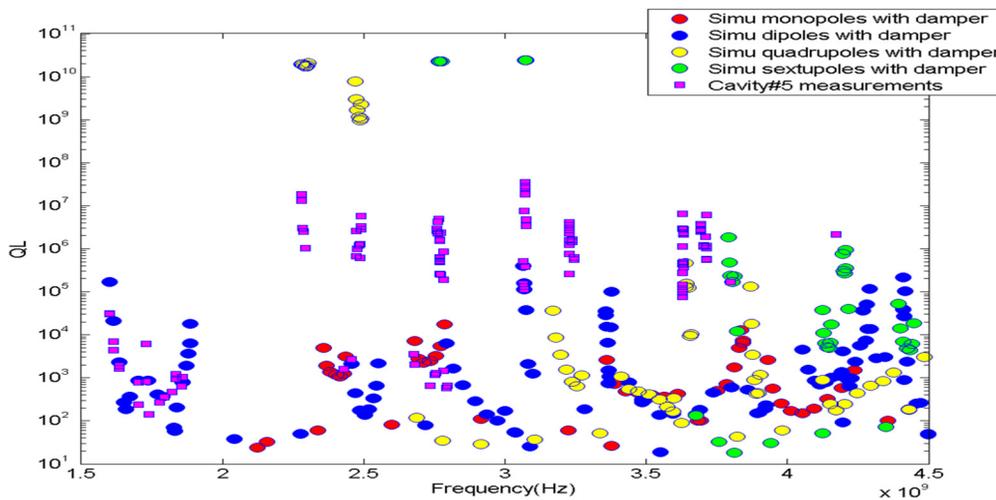


Figure 7: Comparison of MLC HOM measurement results and HOM damping simulation results.

Comparison of Analysis and Simulation

Figure 7 shows a comparison of the MLC HOM loaded quality factor ( $Q_L$ ) between measurements and simulation. The purple squares show the  $Q_L$  results from the HOM scans of cavity#5 (ERL7-2a, un-stiffened cavity). The blue dots show  $Q_L$  values of dipole modes from the simulations for an MLC cavity with HOM dampers. The comparison indicates 1) scanned HOM frequencies agreed well with simulation results, and 2)  $Q_L$  of dipole HOMs of the MLC cavities are strongly damped below the target value of  $\sim 10^4$ . Figure 7 also agreed well with previous HOM study on a prototype 7-cell cavity in the Horizontal Test Cryomodule (HTC) [3]. The results from the HOM analysis in the HTC are shown in Fig. 8.

SUMMARY

HOM absorbers for Cornell Main Linac Cryomodule have been fabricated, assembled into the cavity string, and cooled down to 1.8K successfully. HOMs scans on the MLC cavities and  $Q_L$  analysis results agree well with

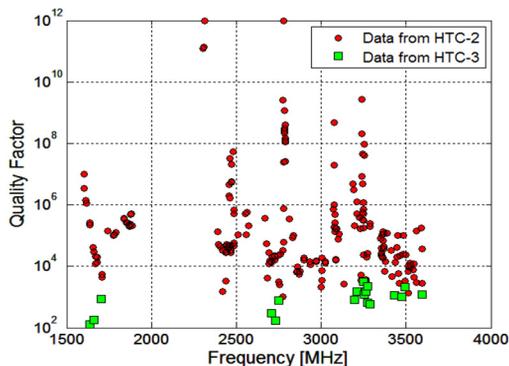


Figure 8: HOM scan and analysis results of one 7-cell cav in the Horizontal Test Cryomodule; HTC-2 has no HO beamline absorbers and HTC-3 had HOM absorbers [3].

previous prototype test and simulation results. Extracted loaded quality factors  $Q_L$  of dipole modes in the MLC cavities verified effective damping by the HOM absorbers. High performance and reliability of the HOM beam-line absorber design during fabrication, installation, and cryomodule operation has been demonstrated for future cryomodules through the MLC work at Cornell.

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