BEAM-BASED HOM STUDIES OF THE CORNELL ENERGY RECOVERY LINAC 7-CELL SRF CAVITY*

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Abstract

The 1.3 GHz 7-cell SRF cavity for the Cornell ERL main linac is optimized for high beam current ERL operation with injected CW beam currents of 100 mA. Beam stability at 100 mA requires very strong damping of the Higher-Order-Modes (HOM) in the cavity by HOM beamline absorbers at the ends of the cavity. To verify the optimized design of the cavity and the HOM damping scheme, a prototype 7-cell main linac cavity was installed into the Cornell Horizontal Test Cryomodule (HTC), and inserted into the beamline of the Cornell ERL high current photo-injector. A beam-based method was then used to search for the presence of dangerous HOMs. Individual HOMs were excited using a charge-modulated beam, after which their effect upon an unmodulated beam was observed using a BPM. Data collected was used to calculate the R/Q and Q of observed HOMs. Results show that no dangerous dipole modes were found to be present in the HTC. In addition, measurements of the temperature rise of the HOM absorber rings during high current CW beam tests were consistent with simulations, indicating that the optimized main linac cavity is capable of operating at the specified current of 100 mA in an ERL configuration.

INTRODUCTION

In the interest of building an Energy Recovery Linac (ERL), Cornell has designed and constructed 1.3 GHz 7-cell cavities that have been optimised for operation in an ERL [1]. The cavities must be capable of sustaining 100 mA of beam current at 2 ps bunch length while operating at 16 MV/m in CW with a quality factor Q_0 of at least 2×10^{10} at a bath temperature of 1.8 K. A prototype 7-cell ERL cavity tested in a cryomodule obtained a record 1.8 K Q_0 of $(6.2 \pm 0.6) \times 10^{10}$ at 16 MV/m [2, 3], exceeding the required efficiency specifications by a factor of 3.

In this paper we present results from two separate yet linked experiments performed on the prototype 7-cell cavity test in [2] using beam provided from the Cornell ERL high-current Injector Cryomodule (ICM). The first of these qualified the monopole HOMs and the power dissipated in the HOM loads located at either end of the cavity. This experiment was also used to investigate the possible advantages of coating the beampipes near the HOM loads with copper to reduce the dynamic heat load from resistive losses in the beampipe walls. The second experiment was a beam-based HOM search used to search for any HOMs that might potentially cause BBU instabilities when operated at 100 mA in an ERL configuration.

EXPERIMENTAL PROCEDURE

To test the cavity with beam, it was installed into Cornell's Horizontal Test Cryomodule (HTC). The cryomodule was equipped with all the accessories that are expected to be used in the final ERL Main Linac Cryomodule: HOM loads at either end of the cavity, a high-current input coupler and an RF field probe for HOM diagnostics. The cavity was installed in the beamline of the ERL injector, directly after the ICM.

HOM Load Heating

The first experiment, to qualify the power dissipation and heat load on the HOM loads during beam operation, involved measuring the temperature increase of the 80K HOM load cooling system at different beam currents. The injector was operated at two different beam currents, 25 mA and 40 mA, using both a 3.4 ps and 2.7 ps long bunch. As the beam was passed through the centre of the cavity, the increase in temperature of the 80 K cooling loop that cooled both of the HOM loads was measured. A cross-section diagram of the cavity and its attached HOM loads illustrating the regions of interest for measurement is shown in Fig. 1. Using heaters installed in the HOM load near the 80 K cooling coil, this raise in temperature was calibrated to provide a relation between the temperature rise of the 80 K system, ΔT, and the power dissipated in the HOM loads, P_{load}. Using the

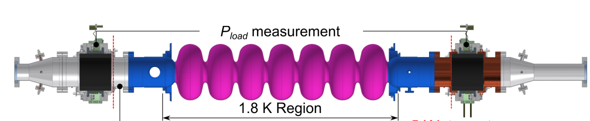

Figure 1: A cross-section diagram of the cavity and attached HOM loads, one of which has had its beampipes coated with copper. The 1.8 K region extends just beyond the cavity, and is separated from the HOM load 80 K system by the 5 K intersect. The power dissipated in the HOM loads is measured using the combined 80 K cooling system of the loads. A temperature sensor mounted between the 5 K and 1.8 K regions on the HOM load with steel beampipes measures the temperature rise of the steel beampipe under beam loading.

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known relation that the power dissipated in the HOM load scales with the beam current I and the bunch length σ,

$$P_{load} \propto \frac{I^2}{\sqrt{\sigma}}\,, \tag{1}$$

the value of P_{load} at 100 mA of beam current can be determined. To convert this loss from operation in a Linac to that of an ERL, an extra factor of 2 must be included in Equation 1 to account for the decelerating portion of the beam; i.e. $P^{(\mathrm{ERL})}_{load} = 2P^{(\mathrm{Linac})}_{load}$.

To measure the increase in temperature that would occur at 100 mA in ERL configuration on the wall of the beampipes of the HOM loads, a temperature sensor was mounted onto the beampipe region of the HOM load whose beampipes had not been coated with copper, as shown in Fig. 1. Since the ΔT of this measurement scales in the same way as P_{load} in Equation 1, the temperature rise of the steel-walled beampipe of the HOM load at 100 mA in ERL configuration can be determined.

Beam-based HOM Search

The second experiment involved using the beam to excite and probe individual HOMs in the cavity, with the purpose of measuring their loaded quality factor Q_L and the deflection they impose on the probe beam. The method was first described in [4], and first seen utilised in [5]. The description provided here will be brief; further detail on its implementation at Cornell can be found in [6], together with a more detailed discussion of the results of this beam-based HOM search.

The bunch charge of the beam provided by the ICM is modulated by applying a frequency signal to the laser impacting upon the photocathode. By choosing the correct frequency with which to modulate the bunch charge, an individual HOM in the cavity can be excited. This excitation is further increased by moving the beam transversely off-axis, using two scanner dipole magnets located before the HTC, to increase the coupling from the beam to the HOM in question. Once sufficient energy has been deposited into the HOM, the modulation is turned off and the beam, now with constant bunch charge, is passed along the same path through the cavity. The kick imparted upon beam by the presence of the HOM is measured using a BPM located further down the beampipe from the HTC. The decay of the kick that occurs as energy in the HOM is dissipated is used to determine the Q_L of the mode. The RF field probe in the cavity is used to determine the real frequency of the excited HOM, provided that it is not trapped (and therefore invisible to the probe) or that its excitation is too weak to be detected above the noise floor of the spectrum analyser connected to the probe.

RESULTS

HOM Loading Heating Measurements

A plot of the P_{load} against beam current for beams of 2 different bunch lengths is shown in Figure 2. Also shown is the fit given by Equation 1, from which it can be determined that the power dissipated in the HOM loads at 100 mA in ERL configuration is 90 W per cavity, considerably less than the 200 W average HOM power value estimated from the cavity longitudinal loss factor. One must consider however that a portion of the HOM spectrum is not bound to the region of the cavity and its adjacent HOM loads due to it being above the cut-off frequency of the beampipe. A high-frequency HOM wakefield can therefore propagate beyond the HOM load without losing all its energy. Although in the Main Linac Cryomodule this propagating wave will eventually traverse enough HOM loads to be completely absorbed, in the one-cavity HTC the wave can propagate beyond either one of the two HOM loads and be lost to measurement. The calculated value of 90 W, therefore, is an underestimate; however, simulations show that this underestimation is no greater than a factor of 2, and that therefore the worst case scenario is that $P^{(\mathrm{ERL})}_{load} = 180$ W per cavity, which is still beneath the specified design value.

The measurement of the heating on the steel beampipe of one of the HOM loads is shown in Figure 3. Fitting the rise in temperature with the same scaling relation as Equation 1, the rise in temperature at 100 mA in an ERL configuration is found to be $\Delta T = 3$ K for an uncoated steel beampipe. Since this heating would be occurring on the beampipe walls, on the cavity side of the 5 K cooling intersect that protects the cavity from the power dissipated in the HOM loads, this heating could potentially spread to the cavity beampipes and end cells, resulting in an increased load to the 1.8 K region, with a consequent rise in temperature of the cavity beam tubes and therefore an increase in the BCS surface resistance of the cavity end sections. It is therefore beneficial to coat the beampipes of the HOM loads with copper to reduce this dynamic 1.8 K heat load.

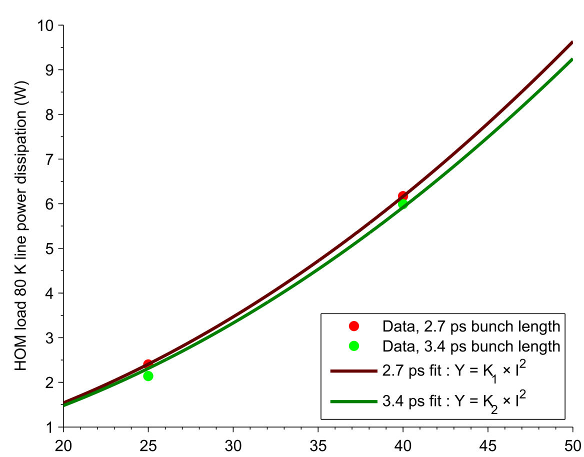

Figure 2: Data taken measuring the power dissipated in the HOM loads at 2 different values of beam current and bunch length. The scaling relation in Equation 1 has been fitted to both sets of data. At 100 mA beam current in an ERL configuration with a 2 ps long bunch, $P^{(\mathrm{ERL})}_{load} = 90$ W.

Table 1: A List of the HOMs Found in the ERL 7-Cell Main Linac Prototype Cavity

Mode frequency (GHz)	Loaded quality factor	Mode location
1.295	4.3×10^7	Fundamental monopole passband
2.290	1.3×10^7	First quadrupole passband
2.303	8.3×10^6	"
2.476	4.7×10^6	Second quadrupole passband
2.489	1.7×10^6	"
2.494	2.0×10^7	"
2.495	1.1×10^7	"
?? - Frequency unknown	1.5×10^4 (GHz^{-1})	Unknown - undetected by RF probe

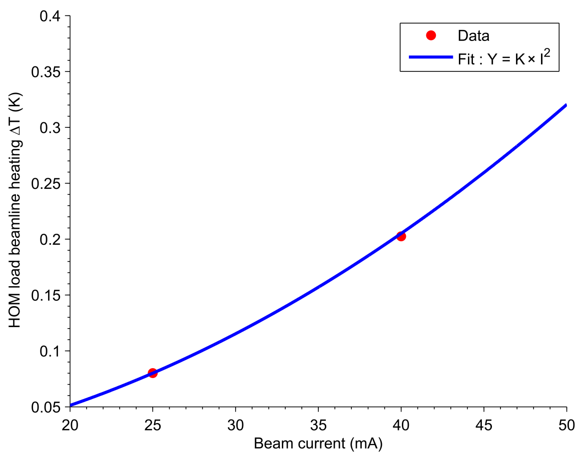

Figure 3: Data taken measuring the rise in temperature of the stainless steel beampipes of the HOM load whose beampipes had not been coated with copper, at 2 different values of beam current and scaled to a bunch length of 2 ps. At 100 mA in an ERL configuration, $\Delta T = 3$ K.

Beam-based HOM Search

A list of the 8 modes found during the beam-based HOM search is shown in Table 1. The detection of modes with a $Q_L < 10^5$ was not possible due to the choice of instrument parameters used during the experiment, necessary to limit the data taking period to within a couple of weeks.

The detection of a monopole mode is due to the fact that the BPM used to detect the presence of a kick induced by an excited mode lies after a dipole magnet used to bend the beam by 1° into the beam dump. The energy spread induced by the longitudinal voltage of the monopole mode is converted into a transverse kick, which is then detected. This also occurs for non-monopole HOMs; however, the kick due to the transverse component of the mode's voltage dominates in this case.

Only one mode could not be detected on the RF field probe. Given the comparatively low Q/f, it is more likely that the excitation of this mode lay below the noise floor of the probe than that it was trapped. All other non-monopole modes were found to lie within the first two quadrupole passbands; given their high Q_L, it is highly likely that these are all quadrupole modes and that they are therefore not a BBU risk for the ERL. However, decisive confirmation of this using theoretical fits to the relation between the kick imparted by each mode and the transverse offset of the beam in the cavity has as of yet proved inconclusive.

CONCLUSION

Beam-based measurements of the prototype 7-cell ERL HTC have shown that no monopole modes are present that result in excessive power dissipation in the HOM loads, and that it is advantageous to coat the beampipes of the HOM loads with copper to reduce the dynamic heat load going to the 1.8 K region. A beam-based HOM search revealed the presence of only 8 modes with a $Q_L > 10^5$, all of which are highly unlikely to pose any danger of causing BBU in the ERL; further analysis is still underway to confirm this. This result is a strong indicator that the Cornell 7-cell cavity and cryomodule design is more than sufficient to achieve the demanding specifications of the proposed Energy Recovery Linac.

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