BEAM-BASED HOM MEASUREMENTS IN CORNELL'S ERL MAIN LINAC CAVITY*

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Abstract

A search for HOMs in Cornell's ERL main linac cavity installed in a Horizontal Test Cryomodule (HTC) has been carried out using a bunch charge modulation method, as part of the effort towards building an Energy Recovery Linac (ERL). The beam-based HOM measurements offer the significant advantage of being able to detect trapped modes invisible to both the RF pickup probes and the HOM damping loads, and allow for measuring the R/Q of the modes. For each HOM detected during the search, measurements were taken to determine its nature (monopole, dipole, etc.), frequency, loaded quality factor and shunt impedance. A selection of the most notable modes found is presented, compared to 3D HOM simulations, and their potential impact on the BBU current of the future Cornell ERL is discussed.

INTRODUCTION

In the interests of constructing an Energy Recovery Linac (ERL), Cornell has been developing 7-cell 1.3 GHz cavities that are capable of sustaining a continuous beam current of 100 mA at a CW operating field of 16 MV/m with a quality factor of at least 2×10^{10} at 1.8 K. A prototype ERL cavity that was recently tested [1] in a Horizontal Test Cryomodule (HTC) achieved a quality factor of $(6.2 \pm 0.6) \times 10^{10}$ at 16 MV/m, exceeding the efficiency specifications by a factor of 3. This result does not however determine whether the required beam current can be sustained.

To sustain continuous beam currents of 100 mA in ERL operation, the cavity and its higher order mode (HOM) loads must be capable of suppressing dangerous HOMs that might cause Beam Break-Up (BBU) instabilities. Simulations [2] performed using CLANS [3] were used to optimise the cavity shape to maximise the suppression of these modes as well as minimise the potential for trapped modes. The results of these simulations indicate that the cavity design used in Ref. [1] is capable of sustaining beam currents of >100 mA.

In this paper we present results from a beam-based HOM search and measurement method used to verify the results of these simulations. The theory behind the method is briefly explained and the experimental setup described in detail. The results of the experiment are then given, together with what conclusions can as of yet be drawn.

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METHOD AND THEORY

The method used to search for HOMs is a beam-based method introduced in Ref. [4], and seen used in Ref. [5], that utilises bunch charge modulation to excite a HOM. To excite the mode it is necessary to pass the beam through the cavity with some radial displacement from the mode centre, albeit ensuring that the path of the beam remains parallel to the cavity axis. The transverse kick induced by this HOM is then analysed using a beam position monitor (BPM). The radial dependence of the kick can be used to determine the R/Q of the mode. Additionally, the decay constant of the kick once the modulation exciting the HOM has been turned off gives the loaded quality factor per unit frequency, Q_L/f, of the mode. Knowledge of these two values is important since work presented in Ref. [2] demonstrates that the threshold current at which BBU onsets for a single cavity in an ERL configuration is a linear function of greatest dipole mode $(R/Q)Q/f$, and hence measurement of this value will determine whether or not the cavity is suitable for the proposed ERL.

To induce the excitation of a specific HOM, the beam bunch charge is modulated with some frequency f_m, with a bunch repetition rate of f_b. For a HOM of frequency f_{HOM}, the HOM is excited if

$$f_{\mathrm{HOM}} = n f_b \pm f_m \,, \qquad (1)$$

where n is an integer. To cover the entire frequency spectrum, it is necessary that the maximum attainable value of $f_m = f_b/2$. In modulating from $f_m = 0$ to $f_m = f_b/2$, the entire HOM spectrum is seen, folded into a spectrum of width $f_b/2$.

While the modulation is on, the modulation frequency dominates any signal seen on the BPM used for measurement. However, if a HOM is being excited and the modulation is turned off, the signal will decay with some characteristic time τ that can be used to determined the loaded quality factor of the mode, Q_L. The peak of this decay, corresponding to the instant in which the modulation is turned off, gives the kick amplitude of the mode.

The magnitude of the kick as a function of the radial and azimuthal displacement of the beam from the cavity axis can be used to determine the R/Q of the mode as well as its nature (dipole, etc.). Since the presence of the couplers and other machining defects breaks the symmetry of the cavity, the polarisation of the HOMs becomes fixed, with different polarisations of the mode differing in frequency. Hence, a single polarisation can be excited and so an integer number of azimuthal zeroes - 1 for a dipole, 2 for a quadrupole, and

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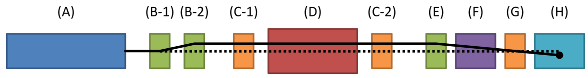

Figure 1: A simple schematic of the experimental layout. The beam leaves the ICM (A), going left to right, and is deflected transversely by the scanner combo (B-1/2) such that it travels through the HTC (D) with a radial displacement. The passage through the HTC is monitored with two BPMs (C-1/2) at either end. The beam is corrected using a third scanner (E) such that it passes through the centre of a third BPM (G) when no HOM is being excited, and then diverted by 2° (F) as it heads towards the dump (H).

so on - are expected in the functional form of a HOM's kick. Fitting to this functional form gives the nature and R/Q of the mode.

EXPERIMENTAL SETUP

The HTC was incorporated into the beamline of the ERL injector prototype, as shown in Fig. 1. The beam proceeded from the Injector Cryomodule (ICM) through a set of scanner (dipole) magnets that were used to translate the beam radially by a chosen distance. The straight, radially displaced passage through the HTC was monitored using a set of BPMs mounted directly before and after the HTC. The beam was then passed through a third scanner magnet that deflected the beam such that, when no HOM was being excited, it passed through the centre of the third BPM before continuing into the beam dump.

A 50 MHz repetition rate laser, coupled with a voltage-controlled oscillator, was used to modulate the charge of each bunch at a chosen modulation frequency in the range of 0.5 – 25 MHz. The modulation frequency was set using an Aeroflex 3280 spectrum analyser connected to the third BPM, with the latter operating in difference mode such that a beam passing through the centre of the BPM gave a voltage output of zero. The time intervals for which the modulation was on (t_{on}) and off (t_{off}) were set using an Agilent 33210A signal generator.

For one capture, a modulation frequency was set between 0.5 – 25 MHz, and after each interval t_{on} the spectrum analyser captured a zero-span spectrum power trace at that modulation frequency. This trace was averaged over 256 captures to form a trace that exhibited exponential decay if a HOM was being excited. Traces were taken at 10 kHz intervals to construct a folded HOM spectrum as shown in Fig. 2.

The choice of step interval and spectrum analyser resolution bandwidth were chosen to limit data taking to 1-2 weeks. As a result, the measurement was limited to only being able to measure HOMs whose Q was between 10^5 and 10^8. Furthermore, the sensitivity of the BPMs limited the minimum kick, and hence R/Q, that could be measured. However, a calculation of the minimum $(R/Q)Q/f$ detectable, obtained from a measurement of the noise floor, demonstrates that the experiment is capable of detecting modes which could cause BBU at beam currents below 100 mA. A plot of the resolution of the experiment, as well as the regions in which BBU is highly likely and the location of the simulated dipole modes as determined using CLANS is shown in Fig. 3.

Once the entire spectrum had been measured, the Aeroflex spectrum analyser was moved to the BPM located before (from the perspective of the beam) the HTC, and the spectrum measurement was repeated to determine which modes seen in the original spectrum were due to HOMs excited in the ICM. These modes were then discarded from those listed for further study.

The kick of the modes confirmed to be present within the HTC was then measured at different radial displacements, both horizontally and vertically, to determine the kick of the mode as a function of distance from the mode centre. Finally, the mode frequency was determined – provided the mode was not trapped or in some other way invisible – by using an Agilent E4440 spectrum analyser connected to the HOM pickup probe of the cavity.

RESULTS

A total of 8 modes were found to be present within the HTC at the conclusion of data taking. Of these, 1 was identified to be a monopole mode in the fundamental passband, with a frequency of 1.295 GHz. Of the remaining 7, only 1 – the weakest – was not found using the HOM pickup probe. Of the 6 non-monopole modes whose frequencies could be determined, 2 were found to lie within the first quadrupole passband and 4 within the second. A list of the modes found, together with their frequencies and loaded quality factors is shown in Table 1.

Although the measurements taken at different radial displacements horizontally and vertically for most modes did

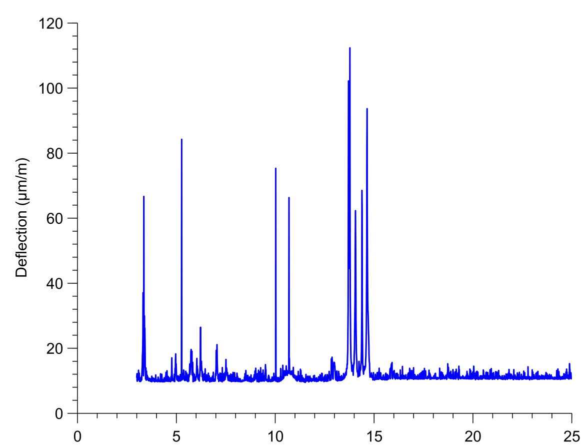

Figure 2: A folded HOM spectrum taken between 3 MHz and 25 MHz; the spectrum between 0.5 and 3 MHz was taken separately and is not shown here. The densely populated region in the region around 14 MHz was found to be a HOM passband within the ICM. The beam deflection is given in terms of μm of transverse displacement per m travelled forward.

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

Modulation frequency (MHz)	Mode frequency (GHz)	Loaded quality factor	Mode location
5.27	1.295	4.3×10^7	Fundamental monopole passband
10.03	2.290	1.3×10^7	First quadrupole passband
3.36	2.303	8.3×10^6	"
24.30	2.476	4.7×10^6	Second quadrupole passband
10.70	2.489	1.7×10^6	"
5.52	2.494	2.0×10^7	"
5.11	2.495	1.1×10^7	"
8.86	??	1.5×10^4 (GHz^{-1})	Unknown

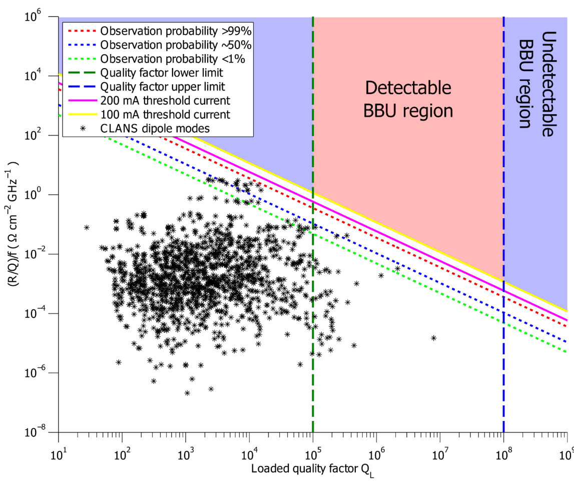

Figure 3: A plot of the resolution of the experiment in terms of the space $(R/Q)/f$ vs. Q_L, with the BBU threshold shown. Also plotted is the location of the dipole modes as obtained from a CLANS simulation of the cavity with attached HOM loads. Modes substantially enhanced by machining defects are expected to move to the right into the detectable BBU region.

demonstrate the expected radial dependence of a quadrupole, the data does not show the azimuthal zeroes expected from either a dipole or a quadrupole. The fit obtained from the current expected functional form is unsatisfactory and so does not yet yield an accurate R/Q. However, the transverse direction of the kick as a function of the azimuthal angle strongly suggests that at least 3 of the modes are quadrupoles.

DISCUSSION

The beam-based HOM search method identified 6 HOMs, all located within the first two quadrupole bands. Of the remaining two, 1 was identified as being a monopole mode of the fundamental passband. The final mode could not be located using the HOM pickup probe. Although this might indicate that the mode is trapped, the extremely weak kick of the mode suggests that it is more likely that the mode lies beneath the noise floor of the HOM pickup probe and is therefore invisible to it.

The detection of a monopole mode, which by the nature of its field pattern is not expected to kick the beam, suggests that there is an unaccounted factor in the beamline converting beam energy spread into a transverse kick. This is most likely due to the presence of the beam dump dipole magnet and third scanner magnet before the detection BPM, and whose effects are not yet incorporated into the expected functional form of the kick. However, calculations performed using the measured kick amplitude and the angles of the two magnets result in an (R/Q) of $< 1\ \Omega$, as expected for a non-π member of the fundamental monopole passband.

It is possible that for many of the modes seen that multiple polarisations of the modes were being excited, which would explain the absence of azimuthal zeroes in the functional form of the kick. However, the likelihood that this is the case is uncertain due to the considerable symmetry breaking effects of the coupler and other machining defects mentioned earlier.

In conclusion, the location of the modes and the direction in which they deflect the beam suggests that all the non-monopole modes whose frequencies could be identified are quadrupoles, and hence are not a danger to BBU in the ERL. Furthermore, the comparatively small number of modes found compared to searches done without HOM loads using a network analyser indicate that the HOM loads are as effective as expected. Although not yet fully conclusive, this is a promising result towards validating the ERL main linac cavity design.

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