HIGHER-ORDER-MODES AND BEAM BREAKUP SIMULATIONS IN THE JEFFERSON LAB FEL RECIRCULATING LINAC*

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Abstract

Measurements were performed of the frequencies and external Q's of the first two Higher-Order Mode (HOM) dipole passbands in the eight superconducting cavities of the cryomodule used in the recirculating linac of the driver accelerator of JLab's IRFEL. Anomalous high-Q resonances were found, which could lead to beam instabilities at currents close to the operating current of the machine. These results led to more detailed simulations of its beam breakup (BBU) behavior. The analysis indicates that a few modes are responsible for the relatively low value of 27 mA of the threshold current. A simple modification of the superconducting cavities could lead to an increase of the threshold current by an order of magnitude.

1 INTRODUCTION

The Jefferson Lab Free Electron Laser is presently being commissioned at current levels of about 1 mA [1]. The driver accelerator is based on a recirculation design, which incorporates energy recovery as an important feature. The accelerating-decelerating linac consists of a slightly modified CEBAF 2 K cryomodule, containing eight 5-cell superconducting cavities operating in the TM_{010} π mode at 1497 MHz.

The Higher Order Modes (HOM) are extracted by two mutually orthogonal waveguides, with a frequency cutoff of 1900 MHz, terminated in loads thermally anchored at 50 K. Modes at frequencies below 1.9 GHz can only be extracted via the fundamental power couple (FPC). Four out of five dipole modes of the TE_{111} passband fall into this category, and their external Q's can be lowered only if some component of their fields is aligned with the FPC. In the case of strong polarization, orthogonal modes could exhibit large values of Q_{ext}.

Due to the energy recovery feature of this accelerator and the relatively low number of superconducting cavities involved in the process, even a few poorly damped modes can have a devastating effect on the beam, especially at the low energy end in either one of the passes through the cavities.

In this paper we describe the results of the measurements of frequencies and Q_{ext} values of the first two HOM dipole bands (TE_{111} and TM_{110}).

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From these measurements, rough estimates of the upper and lower limits of the BBU threshold current were derived, which bracketed the operating current of 5 mA. This result forced us to more carefully re-evaluate the instability threshold by using the simulation code TDBBU [2] and the actual measured values, as described below.

2 MEASUREMENTS OF HOM'S

The TE_{111} and TM_{110} passbands' frequencies and Q's were systematically measured for all the superconducting cavities in the FEL linac [3]. Several modes exhibited high Q's (see table 1), with the highest Q's associated with the vertical polarization of the TE_{111} $\pi/5$ mode.

Figure 1 shows the correlation of Q's for all the modes observed. All modes except the TE_{111} $\pi/5$ (large circles) show a direct correlation, pointing to no preferred polarization alignment. The TE_{111} $\pi/5$ does not follow this correlation, indicating that the extraction efficiency is subject to strong polarization. Since this particular mode has most of the energy stored in the center cell, the strong polarization is possibly associated with overall mechanical bending of the cavity in the vertical plane, thus preventing that polarization to couple to the FPC.

Although the TE_{111} $\pi/5$ mode has been observed to have the highest Q_{ext}, it is actually the $4\pi/5$ mode which contributes more to possible beam instabilities because of its substantially higher transverse impedance (Table 1).

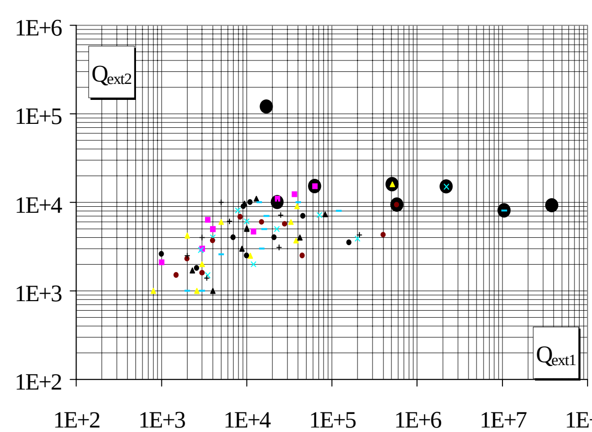

Figure 1 Distribution of external Q's for the first two dipole passbands in the eight FEL superconducting cavities. ● represents the TE_{111} $\pi/5$ modes.

Table 1. Previously reported by Amato [4] (denoted by subscript A) and presently measured (subscript M) parameters for the most relevant modes for the FEL. The Q_M's in this Table are the highest measured in the whole cryomodule.

TE_{111}	$(Z''T^2/Q)_A$	$(Z''T^2/Q)Q_A$	Q_M	$(Z''T^2/Q)Q_M$
π/5 -x	2.0 E2	6.2 E6	1.2 E5	2.4 E7
π/5-y	2.0 E2	6.2 E6	3.8 E7	7.6 E9
4π/5-x	7.0 E4	1.1 E9	1.2 E4	8.6 E8
4π/5-y	7.0 E4	1.1 E9	4.0 E5	2.8 E10

Six out of eight cavities show that the vertically polarized TE_{111} 4π/5 mode has a Q high enough to generate a shunt impedance of 1-3 10^{10}, two orders of magnitude larger than what originally measured by Amato [4]. The frequency of this mode falls right below the cutoff of the HOM extraction waveguides. A more effective extraction of this dangerous mode could be attained if a slight modification of future cavities could be made to allow propagation of this mode.

The simulations described below were performed both for the real system and for a modified system with realistically decreased Q_{ext} of the six cavities TE_{111} 4π/5 modes.

3 SIMULATIONS

3.1 Method

Simulations of beam breakup were performed using the code TDBBU [2]. In it, every bunch is characterized by a phase space vector which gets updated according to the fundamental equations of dynamics described in Reference [5], as deflecting modes in each cavity impart kicks in the horizontal and vertical directions.

In the FEL simulations, a 10 MeV beam is injected into the linac, interacts with the HOM fields of each cavity, gets transported around the recirculation path and enters the linac again, 180° out of phase for energy recovery. As the decelerated beam traverses the RF cavities, it interacts with the HOM fields of the cavities again, and, as the beam energy becomes smaller, the transverse deflections imparted to the beam have a stronger effect. Therefore, we expect the threshold current to be lower in the case of recirculation with energy recovery than in the absence of energy recovery.

The beam is injected into the linac with energy equal to 10 MeV with a bunch repetition frequency of 37.4 MHz, the 40^{th} sub-harmonic of the RF frequency. Each cavity is described by a 0.25m drift delivering an energy gain of 2 MV, followed by the "HOM-kick" section for the particular cavity and this is followed by another 0.25m drift delivering 2 MV energy gain, for a total of 8 MV/m acceleration gradient per cavity.

The "HOM kick" section includes all five TE_{111} and five TM_{110} horizontal and vertical modes. Each mode is characterized by its Q value, frequency, and transverse shunt impedance, as given in Ref. [4] scaled by the frequency of the mode.

The total path length of the recirculation is 501.5 RF wavelengths [5] and the transport matrix elements are calculated using DIMAD.

3.2 Results

The threshold current for a system containing the real cavity parameters and optics for the FEL was determined via several runs and found to be about 27 mA.

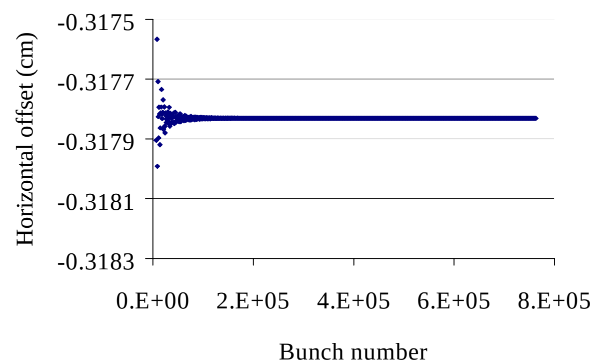

Figure 2 Horizontal bunch offset as a function of bunch number at 25 mA. The beam damps rapidly to a stable condition in the horizontal plane.

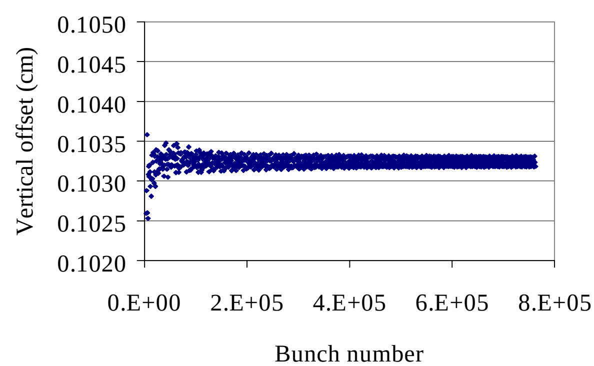

Figure 3 Vertical bunch offset at 25 mA. In the vertical plane the damping occurs more slowly than in the horizontal plane.

Figure 2 shows the convergence behavior at 25 mA for the horizontal plane and Figure 3 shows the convergence in the vertical plane at the same current. A clear divergence in the vertical place is observed at 28 mA (Figure 4).

In the horizontal plane, on the contrary, no instability is observed at these current values, since the relevant modes are polarized in such a way that those aligned with the horizontal axis are well damped by the fundamental power coupler.

Several other simulations with currents well above threshold were performed to determine the growth rate of the instability and to extract the functional dependence of growth rate on current. Figure 5 shows a typical run performed for currents well above threshold. In Figure 6 the growth rate is plotted as a function of current. From it, it is possible to get a relatively good agreement with the actual estimate of the threshold by direct simulation, by making only two simulation runs above threshold and extrapolating the threshold via the plot in Figure 6. The value thus obtained is approximately 35 mA, about 25% higher than what obtained by direct simulation.

The analysis of the mode impedance for the real cavities shows clearly that the TE_{111} $4\pi/5$ mode is in most cavities the one responsible for a major part of the current limitations. This mode often falls only a few MHz below the threshold for propagation in the HOM waveguide and it would be damped more effectively if the cutoff frequency of the HOM waveguide could be lowered by only one percent or so.

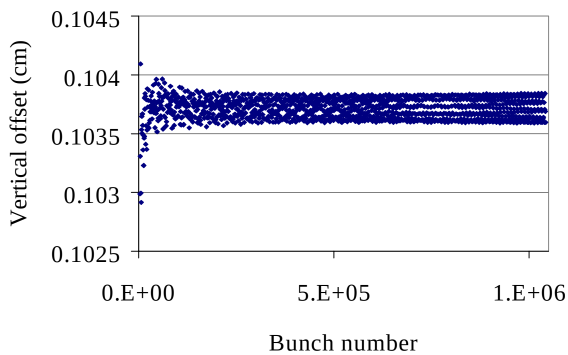

Figure 4 Vertical bunch offset at 28 mA. The beam becomes unstable at this threshold current.

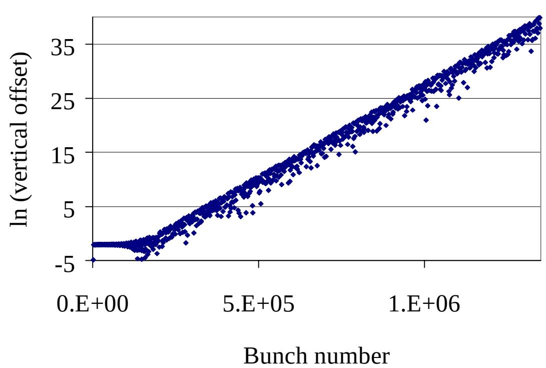

Figure 5 Logarithmic representation of the bunch offset for a current well above threshold, 200 mA in this case.

Such mechanical modification of the coupler might be possible with minimal effort [6]. Based on that assumption, we have recalculated the threshold current for the case in which the Q's of the TE_{111} $4\pi/5$ modes are lowered by a factor of 10 if above 10^5. This was done for cavities 1-6 in the cryomodule. The cavities with Q's already below 10^5 (7 and 8) were left untouched.

It is possible that the Q's of these modes is limited to about 5 x 10^5 because at these frequencies, slightly below the HOM waveguide cutoff, there is enough leakage of the evanescent mode in the waveguide to effect some damping. The $\pi/5$ mode, being at lower frequencies, exhibit considerably higher Q's, even two orders of magnitude larger.

The results of the simulations, performed in exactly the same manner as for the real measured Q's, indicate that the threshold current is now increased to 207 mA.

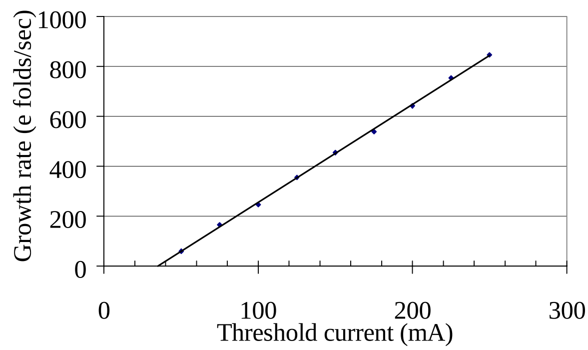

Figure 6 Growth rate of the bunch offset as a function of current. This plot can be used to estimate the threshold current as the abscissa intercept.

4 CONCLUSIONS

Detailed measurements of the Q's and frequencies of the first two dipole Higher Order Modes in the FEL linac indicated that the vertical polarization of some modes in several cavities are only marginally damped.

TDBBU simulations of the Beam Breakup threshold performed with the actual configuration yield a value of threshold current of 27 mA, only a factor of 5 higher than the design operating current.

Analysis of the mode shunt impedance indicates that with a slight modification of the cavities, a few dangerous modes could be more adequately damped. With such modification, the TDBBU estimate of the threshold current would be increased above 200 mA.

5 REFERENCES

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