BEAM BREAK-UP STUDIES FOR CORNELL'S ENERGY RECOVERY LINAC*

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Abstract

New results are presented of beam break-up (BBU) studies for the Cornell ERL main linac. Previously, a 1.3 GHz main linac 7-cell cavity was optimized to maximize the BBU current through the accelerator. This work realistically models the ERL main linac cavity shapes by taking into account small machining variations in ellipse dimensions. Cavity shapes were simulated with random errors from a uniform distribution, and their higher-order mode spectrum computed. The strongest higher-order modes can cause resonant excitations in the beam which can lead to beam loss. The threshold current through the accelerator is determined resulting from a linac comprised of cavities with machining variations using particle tracking and demonstrates that the threshold current is well above the 100 mA design goal for the Cornell's Energy Recovery Linac.

INTRODUCTION

Beam break-up (BBU) current is the maximal current that can travel through an accelerator before the beam becomes unstable and is lost. Primary contributors to this effect are dipole higher-order modes (HOM) in the superconducting cavities that give transverse kicks to off-axis particles. For the first time we present a detailed simulation of realistic cavities in the latest lattice for the Cornell ERL and compute the threshold current that is attainable as a function of expected fabrication tolerances. This is important to ensure that the linac can support the design current of 100 mA [1].

Previous work optimized a superconducting 1.3 GHz 7-cell main linac cavity with respect to the BBU current through the accelerator. We demonstrated that BBU current is related to the worst higher-order mode's (HOM) figure of merit

$$\xi_\lambda = (R/Q)_\lambda \frac{\sqrt{(Q_L)_\lambda}}{f_\lambda}, \tag{1}$$

where λ is an index across HOMs [2].

In reality, cavities can not be made to conform ideally to the optimized geometry, nor should they be. Slight shape variations that arise from small machining errors cause a spread in HOM frequencies that can have the desired effect of reducing coherent kicks given to the beam by multiple cavities. Reducing coherent HOM excitation in multiple cavities increases the BBU current. However, cell shape errors can have the highly undesired effect of increasing the R/Q and/or Q_L of some of the HOMs. In extreme cases, modes can even become trapped with very high Qs. Thus, it is necessary to ensure that shape variation introduced by machining tolerances are large enough to introduce frequency spread that yields high BBU current, but not so large that they cause strong adverse effects on the HOM R/Q, Q_L or lead to trapped modes.

Previous investigations into shape variations showed even very small machining perturbations can lead to very poor HOM properties, but this was overcome by introducing a more robust center cell shape and increasing the cell-to-cell coupling in the structure [3]. In another example, the ERL at Jefferson lab was limited to low BBU current due to a single cavity with a large shape error [4], demonstrating why it is essential to understand and carefully control machining errors.

METHODS

Shape variations in the optimized 7-cell cavity geometry were simulated by adding random errors to each ellipse parameter from a uniform distribution for the error cases of $\pm 1/8$, $\pm 1/4$, $\pm 1/2$ and ± 1 mm. These resulting cavity shapes were tuned cell by cell to 1.3 GHz to ensure field flatness. Subsequently the dipole mode spectrum was calculated up to 10 GHz, using 4 boundary conditions at the at the center plane of the HOM beamline absorbers at the ends of the cavity beamtubes (electric-electric, magnetic-magnetic, electric-magnetic and magnetic-electric) to simulate the superposition of HOMs that are possible for a cavity in a long cavity string.

In this way, 400 unique cavities were generated per error size, and 384 cavities were randomly placed into the Cornell ERL lattice (version 8.4). The HOMs for each cavity were chosen as the 5 modes with the largest BBU parameter, ξ. These HOMs were included in two polarizations. Finally 100 different ERLs were simulated by placing these cavities at random locations.

Particle tracking was done with a subroutine based on BMAD that calculates the maximum current that can be supported through the ERL [5]. Since each cavity is unique, no artificial frequency spread is introduced into the simulation. The only source of frequency spread in our simulations is in the differences in HOM mode variations arising from machining errors.

RESULTS

The results of the 400 BBU calculations (100 simulated ERL runs/error size) are presented in Figs. 1–4. In the optimized cavity geometry, the strongest mode limiting thresh-

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old current through the cavity is in the 2.5 GHz passband. In the simulations, most of the modes that caused the beam to break up were from this passband, though the (R/Q) and Q_L of these modes generally increased from their optimized values.

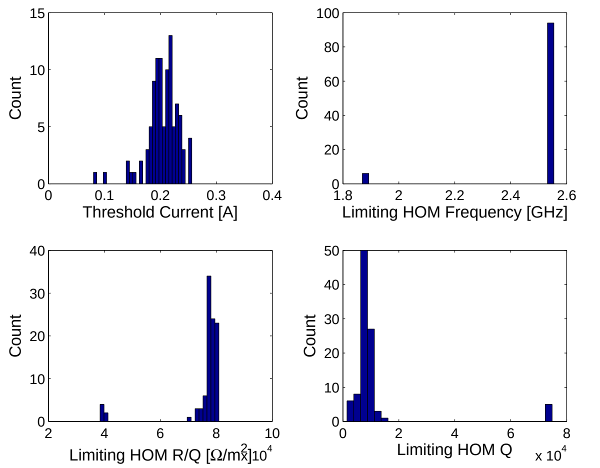

Figure 1: Histogram of BBU results for ± 0.125 mm error. Top left shows the histogram of threshold current. Other histograms show the frequency, R/Q and Q_L of the mode causing beam break-up.

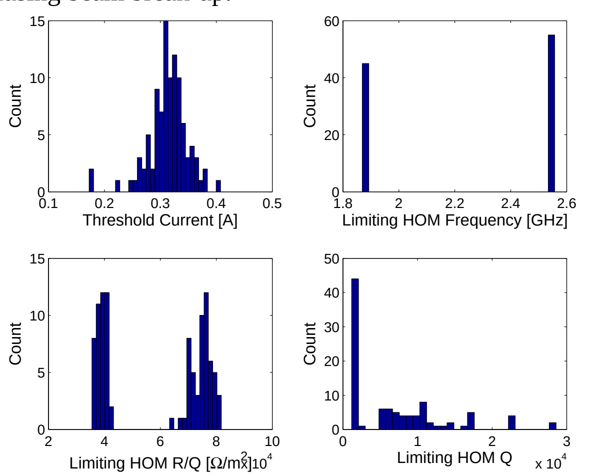

Figure 2: Histogram of BBU results for ± 0.250 mm error. Top left shows the histogram of threshold current. Other histograms show the frequency, R/Q and Q_L of the mode causing beam break-up.

In the two smallest error cases, the threshold current is substantially above the 100 mA design value for the Cornell ERL. Comparing the differences in Figs. 1 and 2, one can see the distribution of the modes responsible for beam break-up shift from mostly in the the 2.5 GHz band to a more equitable distribution between the 1.9 GHz band and the 2.5 GHz passband. This demonstrates that the shape variations are causing modes that were not limiting current previously to interact more strongly with the beam.

The results of the 0.500 mm case show a much larger spread in threshold current, centered around a significantly

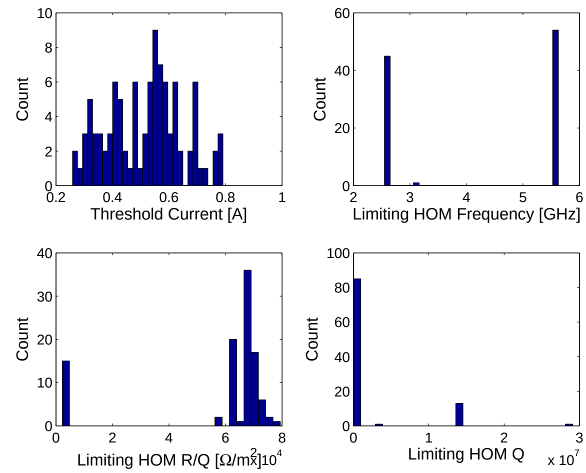

Figure 3: Histogram of BBU results for ± 0.500 mm error. Top left shows the histogram of threshold current. Other histograms show the frequency, R/Q and Q_L of the mode causing beam break-up.

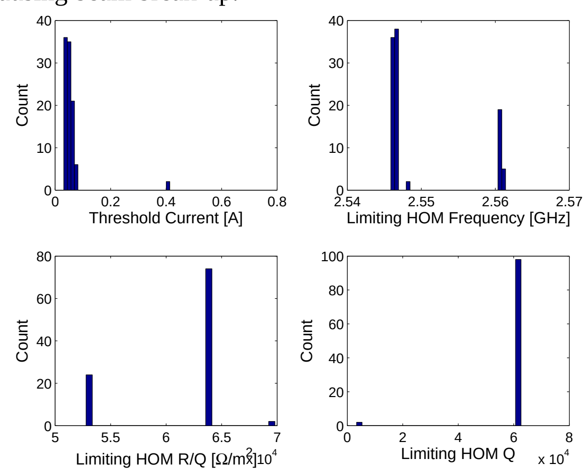

Figure 4: Histogram of BBU results for ± 1.000 mm error. Top left shows the histogram of threshold current. Other histograms show the frequency, R/Q and Q_L of the mode causing beam break-up.

higher value than the smaller variation cases. Also modes around 5.7 GHz start to have a large effect on the threshold current.

Finally, the case of 1.000 mm error shows that the introduced variation yields cavities far away from the optimized geometry HOM properties which no longer preserves the characteristics of the ideal design. This leads to very low beam currents, much lower than the Cornell ERL design value, and must be avoided for real cavity fabrication.

Note that the bulk of the cases generated have HOMs that are worse than the baseline design, in terms of optimized beam break-up parameter, ξ, but nevertheless result in threshold currents increasing with variation size (except at large variations of 1.000 mm). This is because the frequency spreads of the HOM passbands increase with increasing errors, which compensates for the degrading

HOM properties, and gives larger BBU current as long as no particularly strong HOMs are generated. A plot illustrating this phenomena is shown in Fig. 5.

A plot showing the beam break-up current versus frequency spread (which depends on the cell shape variation) is presented in Fig. 6.

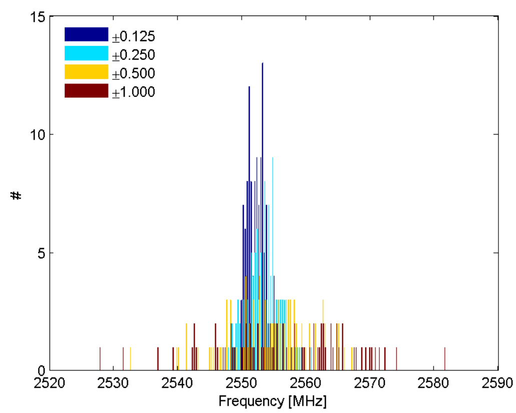

Figure 5: Histogram of frequency distribution of modes from the 2.5 GHz band, for the four error sizes. As the error size increases the RMS frequency spread of the modes also increases.

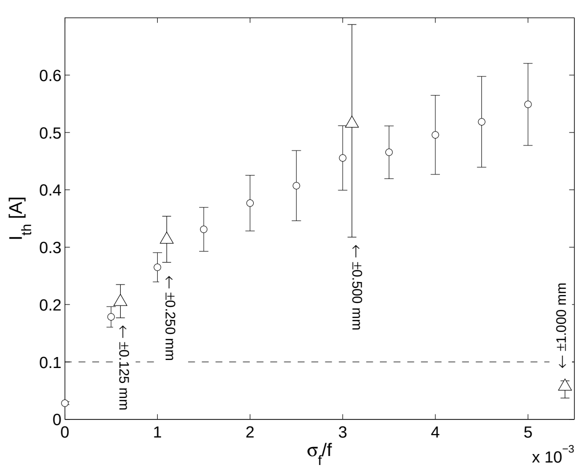

Figure 6: Threshold current versus frequency spread (which is related to fabrication variation size). Circles mark points obtained from the HOM spectrum of the optimized cavity with artificially introduced frequency spread, and triangles denote the mean values from realistic ERLs with cavity shape errors and no artificial frequency spread. The error bars mark the lowest and highest current obtained by the middle 80% of the runs.

CONCLUSIONS

Current half-cell fabrication tolerances at Cornell are approximately ± 0.125 mm, giving error in the finished dumbell of ± 0.250 mm. From Fig. 6, this variation corresponds to about 300 mA of threshold current, which gives a safety factor of 3 above the design value of 100 mA operational current. The low threshold current in the case of ± 1.000 mm tolerances shows that the fabrication accuracy should not be pushed beyond ± 0.500 mm.

While loosening machining tolerances can increase frequency spread and yield even higher threshold currents than the 300 mA value, it is important to avoid machining errors that could create very dangerous HOMs. However, keeping machining tolerances at their current tight levels does not have to mean loosing the benefit of frequency spread. As shown in our previous work, one can introduce multiple cavity classes that preserve the fundamental mode properties and varying (but locally optimized to satisfy BBU requirements) HOM properties to increase cavity-to-cavity frequency spread [6]. In this case, well controlled modulations of the baseline cavity designs can fill a large region of frequency space without creating dangerous HOMs, yielding benefits of higher currents without any drawbacks of unexpected or undesired HOM property variation.

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