RF STABILITY IN ENERGY RECOVERING FREE ELECTRON LASERS: THEORY AND EXPERIMENT

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ABSTRACT

Phenomena that result from the interaction of the beam with the rf fields in superconducting cavities, and can potentially limit the performance of high average power Energy Recovering Free Electron Lasers (FELs), are reviewed. These phenomena include transverse and longitudinal multipass, multibunch beam breakup, longitudinal beam-loading type of instabilities and their interaction with the FEL, Higher Order Mode power dissipation and rf control issues. We present experimental data obtained at the Jefferson Lab IR FEL with average current up to 5 mA, compare with analytic calculations and simulations and extrapolate the performance of Energy Recovering FELs to much higher average currents, up to approximately 100 mA.

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1. INTRODUCTION

Energy recovery is the process by which the energy invested in accelerating a beam is returned to the rf cavities by decelerating the same beam. There have been several energy recovery experiments to date, the first one at the Stanford Superconducting Accelerator FEL (SCA/FEL) [1]. The largest scale demonstration of energy recovery is at the Jefferson Lab (JLab) IR FEL, where 5 mA of average current has been accelerated to 50 MeV and energy recovered [2]. Energy recovery is used routinely for the operation of the JLab FEL as a user facility. Inspired by the success of the Jefferson Lab IR FEL, recirculating, energy recovering linacs (ERLs) have been proposed for a variety of applications: high average power Free Electron Laser (FEL) drivers [3], drivers for synchrotron light sources [4,5], and electron accelerators in the linac-ring scenarios of electron-ion colliders [6,7]. There are several benefits to energy recovery. One of the most important ones is that the required linac rf power becomes nearly independent of beam current. In addition to the direct savings resulting from this benefit, the overall system efficiency increases.

To quantify the efficiency of energy recovering linacs we use the concept of "rf to beam multiplication factor" κ, defined as $\kappa \equiv P_{beam}/P_{RF}$, the ratio of the beam power at its highest energy E_f to the rf power required to accelerate the beam to E_f. For an electron beam of average current I_b injected into an ERL with injection energy E_{inj}, accelerated to E_f and then energy recovered, the multiplication factor is given by

$$\kappa \equiv \frac{P_{beam}}{P_{\rm RF}} \simeq \frac{JE_f}{(J-1)E_{inj}+E_f}$$

where the normalized current J is given by,

$$J = \frac{4I_b(r/Q)Q_L}{G_a} ,$$

and Q_L is the loaded quality factor, G_a the accelerating gradient and *(r/Q)* the shunt impedance per unit length of the linac rf cavities. This expression is valid in the limit of perfect energy recovery (exact cancellation of the accelerating and decelerating beam vectors). Figure 1 is a plot of the multiplication factor κ as function of the average beam current, for parameters close to the Cornell ERL [4] design: Q_L=2x10^7, G_a=20 MV/m, *(r/Q)*=1000 Ω/m, E_{inj} = 10 MeV and E_f = 7 GeV. First note that for beam currents of order 200 mA, the multiplication factor is ~500, approaching efficiencies typical of storage rings, while maintaining beam quality characteristics of linacs: emittance and energy spread determined by the source properties and the ability to have sub-picosecond short bunches. Second, the multiplication factor increases with average beam current, and asymptotically approaches E_f/E_{inj} . Therefore, the higher the beam current is, the higher the overall system efficiency becomes.

2. MULTIBUNCH INSTABILITIES – SINGLE CAVITY MODEL

The price to be paid for increasing the beam current and therefore the overall system efficiency is that a number of collective effects, driven predominantly by the high-Q superconducting rf cavities, become important and can potentially limit the average current. In a recirculating linac, there is a feedback system formed between the beam and the rf cavities, which is closed and instabilities can arise at sufficiently high currents. Instabilities can result from: a) the interaction of the beam with the fundamental accelerating mode (beam-loading instabilities) [8,9], b) the interaction of the beam with transverse Higher Order Modes (HOMs) (transverse Beam Breakup (BBU)) [10,11] and c) the interaction of the beam with longitudinal HOMs (longitudinal BBU) [12]. The physical mechanisms that drive these instabilities have been described previously and will not be repeated here. Although these three types of instabilities differ in the details, there is a fundamental similarity, which allows one to define a threshold current that occurs when the power fed into the mode equals the mode power dissipation. In the simple case of a single mode, single cavity, single recirculation, one can derive a generalized expression for the threshold current, applicable to all three instabilities:

$$I_{th}^{(1)} = \frac{-2p_r c}{e(R/Q)_m Q_m k_m M_{ij} \sin\left(\omega_m t_r + \frac{l\pi}{2}\right) e^{\omega_m t_r / 2Q_m}}$$

where *(r/Q)* and *Q* are the shunt impedance and quality factor of the mode *m* with frequency ω_m, M_{ij} is the *(i,j)* transfer matrix element of the recirculator, $k=\omega/c$ is the wavenumber of the mode, t_r is the recirculation time, and p_r is the momentum of the recirculating beam. The integer *l* is equal to 1 when *m* denotes a longitudinal HOM, and it is equal to 0 otherwise. The above equation is valid only when $M_{ij}sin(\omega t)<0$. Further discussion on the sign of the equation can be found in [11] and [13]. When *i,j*=1,2 or 3,4 and *m* denotes a transverse HOM, this expression gives the threshold current of the transverse BBU. When *i,j*=5,6 and *m* denotes a longitudinal HOM, this expression gives the threshold of the longitudinal BBU, and when *i,j*=5,6 and *m* denotes the fundamental accelerating mode, this expression gives the threshold of the beam loading instabilities. This approximate expression is useful for understanding the parametric dependence of the threshold current on accelerator and beam parameters, and, under certain conditions, it may also be useful for obtaining estimates of the threshold of these instabilities. In general, however, numerical codes that take into account the details of a given configuration and the possible interaction among several modes should be used to calculate the threshold current.

As we will see later, out of the three kinds of multibunch instabilities, transverse BBU appears to be the limiting instability in recirculating, energy recovering linacs. The longitudinal BBU appears to have the highest threshold current because typical values of M_{56} are an order of magnitude smaller than M_{12} or M_{34}, while typical damping of the strongest longitudinal HOMs is at the 10^4- 10^5 level, similar to the transverse HOMs. The beam loading instabilities can exhibit open loop threshold currents close to the design currents contemplated in upcoming ERL projects. However, the low level rf control feedback raises the threshold by more than an order of magnitude [8].

In the following, we discuss recent theoretical and experimental work done on the topics of transverse BBU and higher order mode power dissipation, as both are important for future ERL-based projects.

3. TRANSVERSE BEAM BREAKUP

The theory of transverse BBU is quite mature. The most recent highlights include an analysis of the effect for arbitrary number of cavities and recirculations based on the impulse approximation [10]. A generalization of the theory to include subharmonic bunching was obtained in 1991 [14]. For *M* recirculations and *N* cavities, the final solution is obtained by solving for the eigenvalues of an *M*-dimensional matrix. In the case of subharmonic bunching the dimensionality increases to NxM-1.

In 1987 a two-dimensional simulation code, called TDBBU, was written to predict the threshold of the transverse BBU instability for arbitrary recirculating linac configurations [15]. Recently, a new code is being developed, called MATBBU, as a numerical tool complimentary to TDBBU. MATBBU solves the exact equations of motion for a given configuration and calculates the eigenvalues of the matrix [16]. Both TDBBU and MATBBU accept identical input files. The output of TDBBU is a plot of the bunch offset as function of bunch number. The output of MATBBU is a plot of the real vs. imaginary part of the beam current as the frequency of the HOMs is swept over a range of frequencies. The lowest value of the real part of the beam current that has zero imaginary part, determines the threshold of the instability. Figure 2 shows a close-up (around the (0,0) point) of the stability plot for the JLab IR FEL. All the rf input parameters, including Q's of HOMs, shunt impedances and frequencies as well as the recirculation time have measured values. The optics transfer matrix elements have calculated values from DIMAD [17]. From the stability plot the threshold current of the present FEL configuration is determined to be 26.3 mA. This result is in excellent agreement with TDBBU's prediction of 27 mA [18].

Neither code has been benchmarked against experimental data despite previous attempts [19] in the Injector of the CEBAF accelerator. Therefore we proposed and carried out a series of experiments in the Jefferson Lab IR FEL in order to: a) Attempt to induce the BBU instability, and b) measure beam transfer functions in the recirculation mode. The experiment aimed towards inducing the BBU instability consisted of both changing the optics of the recirculator so that larger beta functions in the cavity locations were obtained, and lowering the injection energy into the linac to 5 MeV and the highest energy to 20 MeV. Under these conditions the predicted threshold was just under 5 mA. However during the execution of the experiment, the beam quality was sufficiently poor that the beam tripped at 3.5 mA and the instability was not observed.

The second experiment consisted of beam transfer function measurements in the recirculating mode. Although these measurements can be performed at beam currents below the threshold current, yet they lead to clear estimates of the instability threshold. A broadband Beam Position Monitor (BPM) wired oppositely was used to impart transverse momentum to the beam with the modulating frequency of the HOM under study. A network analyzer was driving a broadband amplifier at the proper frequency, sweeping the frequency across the HOM frequency. The signal from the cavities was fed back to the network analyzer's input port to complete the S_{21} measurement. Data were recorded by exciting different HOMs at several different cavities, with different associated r/Q and Q values, at two different energies, and several optics settings. The data were fitted to first and second order models and the threshold current for each configuration was derived from the fits. A complete account of the different experimental setups and the corresponding threshold currents is presented in [13]. We found that under the various accelerator configurations the threshold current varied between 7 mA and 32 mA. For the nominal FEL configuration the threshold was between 16 mA and 21 mA. This is to be compared with the theoretical prediction of 27 mA, resulting in agreement at the 40% level or better. The observed dependence of the threshold current on the recirculator optics has not been quantified yet. Further experiments and extension of the analysis tools are planned.

4. HIGHER ORDER MODE POWER DISSIPATION

High average current, short bunch length beams in superconducting rf cavities excite HOMs. The power dissipated by the beam in exciting these modes is given by:

$$P_{HOM} = 2\, k_{||}\, Q^2 f_{bunch}$$

where $k_{||}$ is the loss factor of the superconducting rf cavities, a function of bunch length σ_z, and the factor of 2 accounts for the two beams in the linac (accelerating and decelerating). At high currents, the amount of dissipated power can be quite high. For example, for an average current of 100 mA, bunch charge equal to 0.5nC and $k_{||}$ =10 V/pC, the HOM power dissipation is approximately equal to 1 kW per cavity. (In contrast, the maximum HOM power dissipated to date in the JLab IR FEL is approximately 6 W per cavity) The interesting question is where this power is going. Most of it is expected to be transferred to loads and be dissipated in room temperature environment. It is, however, important to quantify the fraction of the power that is dissipated in the cavity walls, because it can potentially limit the average and peak current due to finite cryogenic capacity. In superconducting rf environments there exists a mechanism by which HOM power generated by very short bunches can be increasingly dissipated in the cavity walls. From the BCS theory, the surface resistance of Nb increases with the square of the frequency, therefore the power dissipated in the cavity walls increases as the frequency of the electromagnetic radiation increases. A simple model, which provides an estimate of the fraction of HOM power lost in the walls, has been developed [20]. It predicts that >90% of the HOM power is in frequencies up to approximately 100 GHz, although frequencies up to 600 GHz are excited by the ~psec long bunches. The model predicts that the fraction of power lost in the walls is much smaller than the fundamental power load, as most of the power escapes the cavity via the various cavity openings and can, in principle, be absorbed in locations between cavities and/or cryomodules by cooled absorbers [21].

The issue of HOM power is nevertheless an important and potentially limiting one, so experimental measurements of the power dissipation under varying beam parameters was pursued at the JLab IR FEL. The amount of HOM power transferred to the loads was measured and compared with calculations. Temperature diodes were placed on the two HOM loads of a linac cavity and temperature data were recorded for values of the charge per bunch ranging from 0 to 80 pC, in steps of 20 pC and three values of the bunch repetition frequency: 18.7, 37.5 and 75 MHz (each a factor of 2 higher than the previous one). Figure 3 displays the measured HOM power vs. charge in one of the two HOM loads per cavity, for the three frequencies. The data were fitted to curves of the form aQ^2, $2aQ^2$ and $4aQ^2$ (to account for the frequency ratios) and the loss factor was derived from the fit. The sum of the loss factors from the two loads is 9.4 V/pC, whereas the calculated loss factor from URMEL is 11 V/pC for 1 ps bunch, implying agreement at the 15% level. At the present time no statement can be made about the amount of power dissipated in the cryogenic environment because no instrumentation was in place to measure it.

5. DISCUSSION AND CONCLUSIONS

Based on the information outlined above, we now attempt to extrapolate the prospects for rf stability to higher currents and higher power energy recovering linacs. Thus far, for the 5 mA ERL of the Jefferson Lab IR FEL, the calculated threshold for the transverse BBU instability is 27 mA, the threshold for the beam-loading instability is 27 mA open loop and close to 1 A when the low level rf control feedback is taken into account, and the HOM power dissipation is approximately 6 W per cavity. For the 10 mA ERL of the JLab IR FEL Upgrade, the calculated threshold for the transverse BBU instability is 50 mA provided that the HOMs of the 7-cell cavities are damped to $\sim 10^5$ level. The calculated threshold for the beam-loading instabilities is 27 mA without feedback and again it rises to approximately 1 A with feedback. The calculated HOM power dissipation is 40 W per cavity. For the 100 mA ERL of the Cornell ERL, the calculated threshold of the transverse BBU is approximately 200 mA, the beam-loading instabilities threshold is calculated to 22 mA without feedback rising to approximately 1 A with feedback, and the HOM power dissipation is calculated to be 160 W per cavity. It is clear that design currents begin to approach the limits imposed by stability considerations. So one might ask "What is the maximum average current that can be recirculated and energy recovered?"

At the present time, it appears that transverse BBU is the limiting rf stability mechanism. However, one could imagine that a focused effort could result in better HOM damping in multi-cell cavities. Furthermore, bunch-by-bunch transverse feedback, similar to the one used in B-Factories, where bunches are separated by 4 nsecs, may be feasible. Both approaches should help raise the stability threshold to a value closer to 0.5 A to 1 A. Of course one must not preclude the possibility that a different, not thought of yet, phenomenon could provide a limit at a lower current.

In conclusion, rf stability in recirculating, energy recovering linacs is theoretically well understood. The experimental verification of simulation codes and models is being pursued in the JLab IR FEL. Quantitative agreement between codes and experimental data has been demonstrated. Greater capabilities for experimental verification of the models will be offered with the 10 mA JLab IR FEL Upgrade and the 100 mA Cornell ERL Prototype.

Furthermore, inspired by the Jefferson Lab IR FEL success, energy recovery is emerging as a powerful application of rf superconductivity. An interesting question to ask is how far can one push the limits of energy recovery in the multi-dimensional space of average current, energy, bunch charge, bunch length and other fundamental accelerator and beam parameters. The work described here attempts to address one aspect of this important question.

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FIGURE CAPTIONS

Figure 1. RF to beam multiplication factor κ as function of beam current, in the limit of perfect energy recovery.

Figure 2. Complex current eigenvalues as the coherent frequency is swept in real frequency, for the JLab IR FEL calculated using MATBBU. An arbitrarily small imaginary part corresponds to growth. The 7 families of complex current eigenvalues have been determined and the actual threshold current corresponds to the smallest positive real value.

Figure 3. HOM power measured in one of the two HOM loads of the CEBAF 5-cell cavities vs. bunch charge for 3 different bunch repetition rates.

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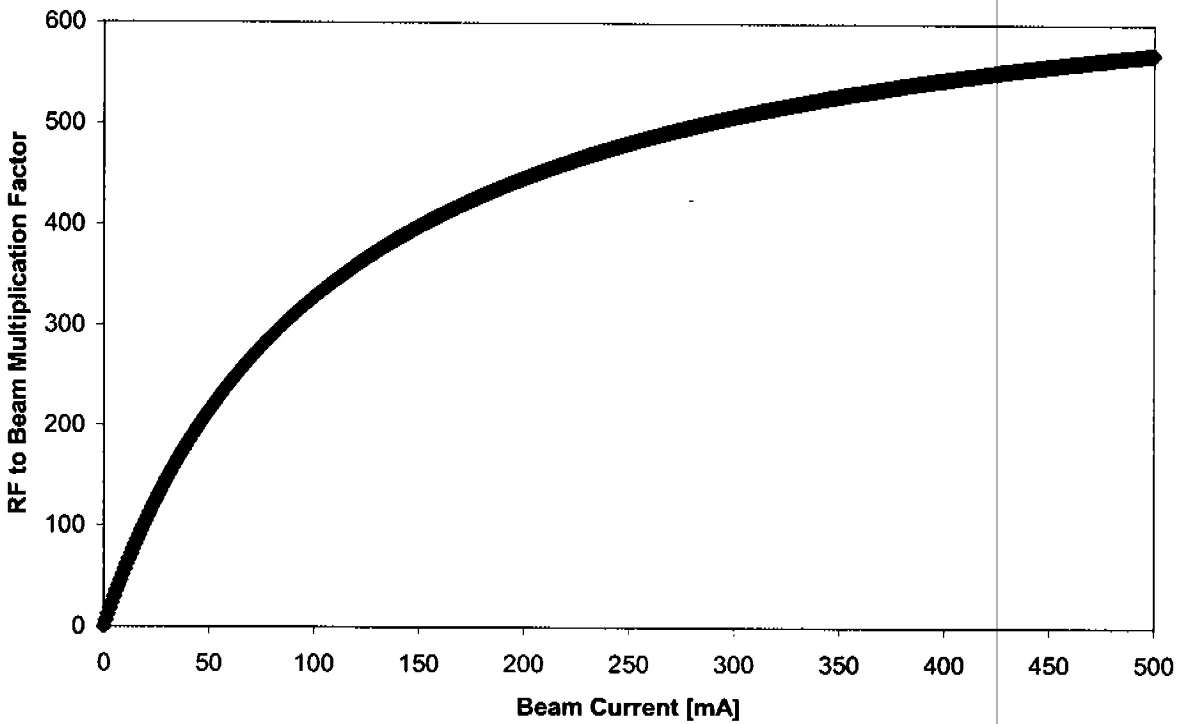

600
500
400
300
200
100
0
RF to Beam Multiplication Factor
0
50
100
150
200
250
300
350
400
450
500
Beam Current [mA]

Figure 1

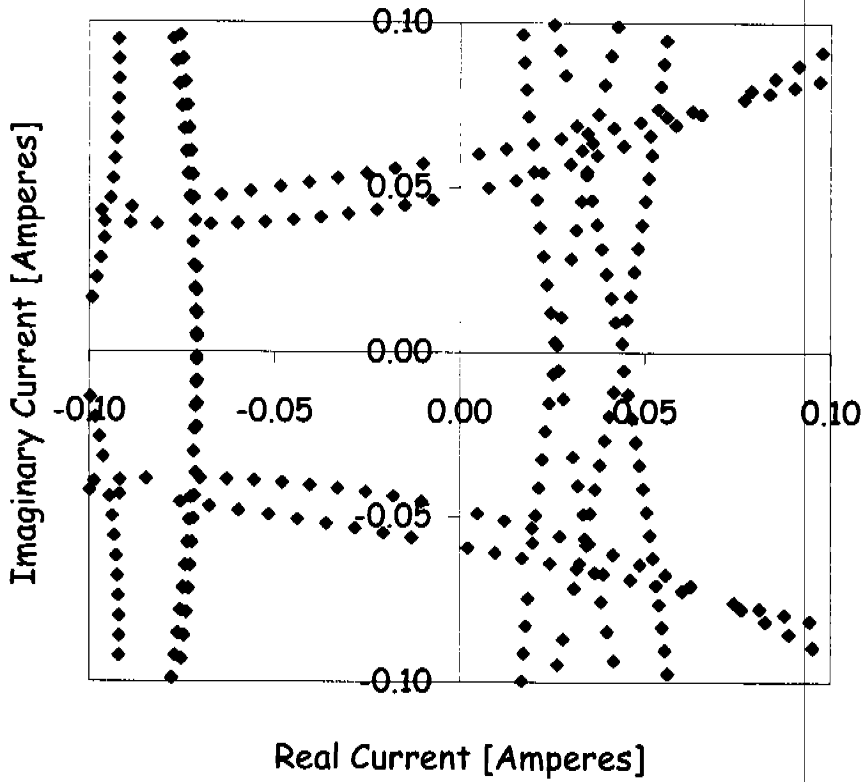
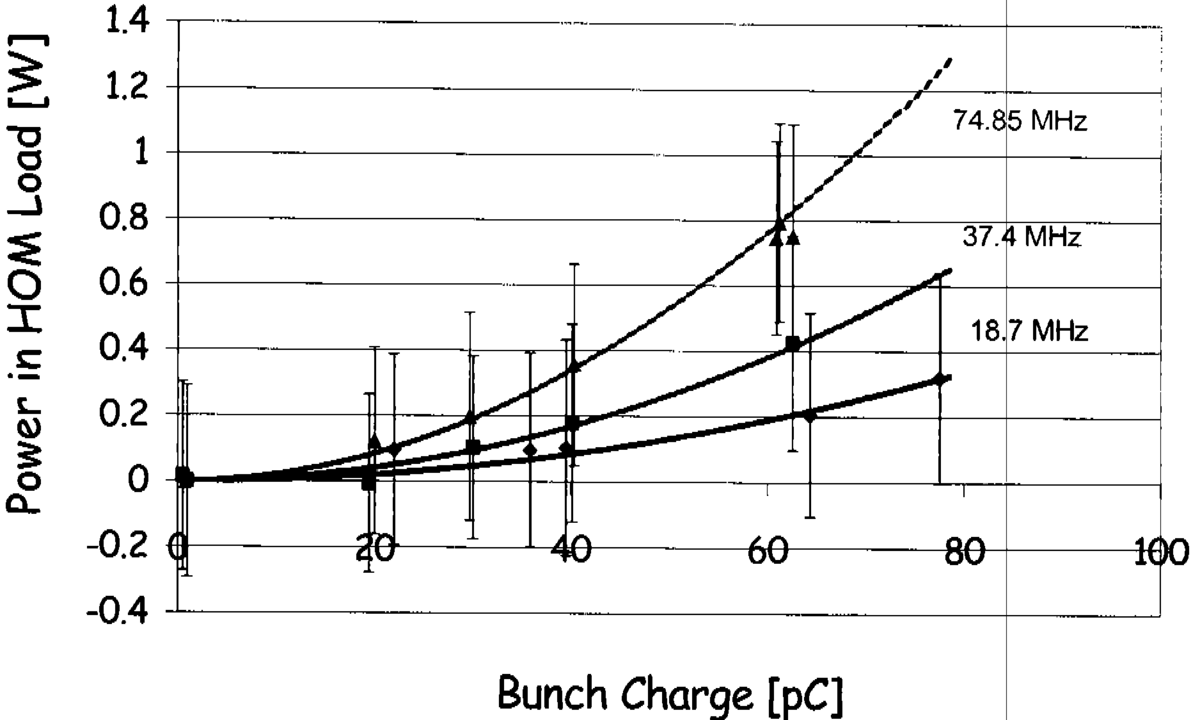

0.10
0.05
0.00
-0.05
-0.10
-0.10
-0.05
0.00
0.05
0.10
Imaginary Current [Amperes]
Real Current [Amperes]

Figure 2



Power in HOM Load [W]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
20
40
60
80
100
74.85 MHz
37.4 MHz
18.7 MHz
Bunch Charge [pC]

Figure 3