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Multipass, Multibunch Beam Breakup Suppression in Two-Pass Recirculating Accelerators

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At sufficiently high currents beam breakup (BBU) occurs in all accelerators. In recirculating accelerators, such as the energy recovery linacs used for high-power free-electron lasers (FELs), the maximum current has historically been limited by multipass, multibunch BBU, a form that occurs when the electron beam interacts with the high-order modes (HOMs) of an accelerating cavity on one pass and then again on the second pass. This effect is of particular concern in the designs of modern high-average-current energy recovery accelerators utilizing superconducting technology. In such two-pass machines rotation of the betatron planes by 90 deg, first proposed by Smith and Rand in 1980, is expected to significantly increase the threshold current of the multibunch BBU. The effect of rotation on the threshold current of the Jefferson Laboratory FEL Upgrade is being studied experimentally and with a newly developed four-dimensional tracking code. Several optical rotator schemes based on quadrupoles and solenoids are being evaluated for their performance in terms of the instability threshold current increase and their effect on FEL optics. Results of experiments and simulations are presented.

KEYWORDS: BBU, Energy recovery, ERL, Threshold current

1. Introduction

In May 2004, the multipass, multibunch beam breakup (BBU) instability was observed at a beam current of approximately 3 mA in the Jefferson Laboratory (JLAB) FEL Upgrade Driver. At the threshold of the instability we observed an exponential growth of the higher-order mode (HOM) voltage in one particular cavity (Fig. 1). With the knowledge that BBU is a real limitation to machine operation, the focus turns to finding a means of suppressing the instability.

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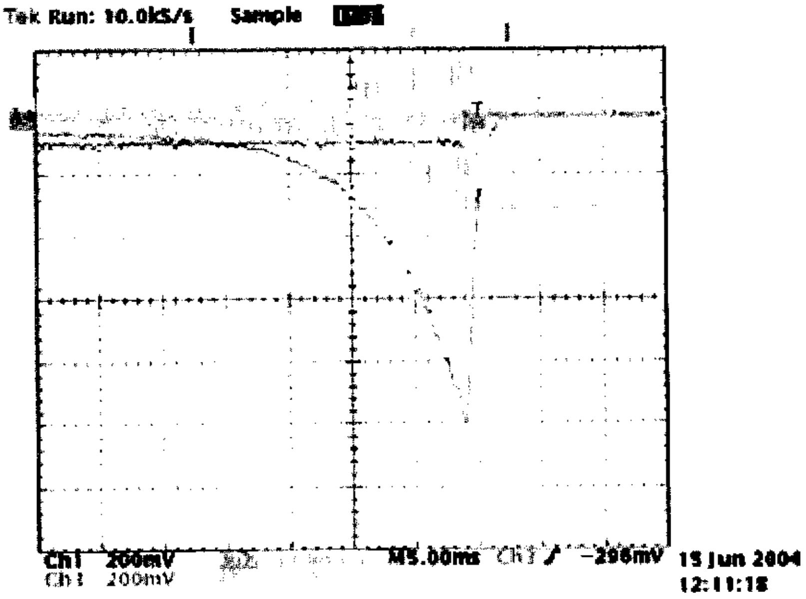

Fig. 1. Signal and its power from an HOM port of cavity 4 of the third cryomodule, measured at the frequency of the 2,114 MHz TM (transverse magnetic) dipole HOM. The signal grows until the beam loss monitors trip off the machine. The timescale is 5 ms/div.

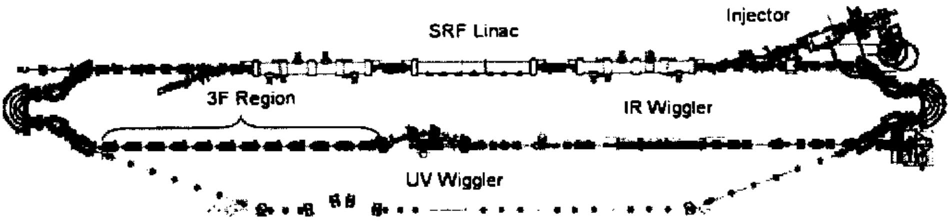

Fig. 2. Layout of the JLAB FEL Upgrade. (The UV transport line has not been installed.)

This paper describes how BBU can be suppressed, or eliminated altogether, by a specific choice of the recirculation matrix. We study the effect of applying this method to JLAB's FEL Upgrade Driver, although the technique described in this paper is applicable to any two-pass energy recovery linac (ERL) machine. Other means of suppressing beam instabilities, such as beam-based feedback and HOM damping techniques, to BBU are discussed elsewhere.[12]

The FEL Upgrade Driver is a two-pass linear accelerator with energy recovery.[3] Electrons are injected at 10 MeV and are accelerated to 145 MeV through three cryomodules, containing eight superconducting niobium cavities. The beam is transported to a wiggler where up to 10 kW of laser power is generated. The spent electron beam is recirculated and decelerated through the linac region on the second pass, recovering the energy that was spent for beam acceleration on the first pass. Upon exiting the linac, the 10-MeV recirculated beam is extracted to a dump (Fig. 2).

2. Equation for BBU Threshold for a Single Dipole HOM with Arbitrary Polarization

In a two-pass machine an on-axis beam deflected by the magnetic field of a dipole HOM on the first pass comes back to the same cavity with a displacement on the second pass. The off-axis second-pass beam will then induce an HOM electric field that will add to the original field. Depending on the magnitude and direction of the beam displacement, the feedback constituted by the beam can result in the HOM fields growing exponentially if the beam current exceeds a threshold value. Exactly at the threshold, the beam deposits energy in an HOM at the same rate as the HOM energy is dissipated by the cavity. Under the assumption that the beam interacts with only a single HOM (valid when the dipole mode degeneracy is lifted adequately by loading probes, power couplers, mechanical imperfections, etc.), one can derive an equation describing the threshold of regenerative multipass BBU in a two-pass accelerator with a general-form, 4 × 4 recirculation matrix[8]:

$$I_{\text{th}} = -\frac{2p_b c}{ek(R/Q)QM_{12}^* \sin(\omega T_r)},$$

$$M_{12}^* \equiv M_{12}\cos^2\alpha + (M_{14}+M_{32})\sin\alpha\cos\alpha + M_{34}\sin^2\alpha, \tag{1}$$

where α is the HOM's polarization with respect to the horizontal axis, p_b is the beam momentum at the cavity, c is the speed of light, e is the electron charge, k is the wave number (ω/c) of the HOM, $(R/Q)Q$ is the shunt impedance of the HOM, T_r is the recirculation time, and M_{ij} are the elements of the recirculation transport matrix from the cavity back to itself (which can describe coupled transverse motion).

3. Optical Suppression Schemes

An early consideration of the possibility of BBU suppression by optical means was given by Rand and Smith.[10] In their paper, the authors investigated an effect of rotation or reflection of the vector of the beam displacement on the second pass.

3.1. Reflection and pseudo-reflection

The 4 × 4 transport matrix of the form

$$\begin{pmatrix} 0 & M \\ M & 0 \end{pmatrix}, \tag{2}$$

where M is 2 × 2 block matrix, provides reflection of the beam displacement with respect to the $x = y$ plane. If an HOM is oriented at 0 deg, the vector of the beam displacement after an optical transformation given by matrix (2) will be oriented at 90 deg. This yields a zero projection of the beam displacement on the mode polarization. As a result of the reflection, the threshold current becomes infinite. The threshold will be also infinite if the mode polarization is 90 deg. However, if an HOM is not bound to the horizontal or vertical plane, the recirculated beam will not come back to the cavity with the angle $\alpha + 90$ deg and its projection on the HOM will be nonzero. As will be shown later, this can significantly reduce effectiveness of BBU suppression if HOMs are not bound to the x or y planes.

A reflector with the transformation matrix given by matrix (2) consisting of five skew-quadrupoles has been noninvasively embedded in the 3F "backleg" region of the FEL

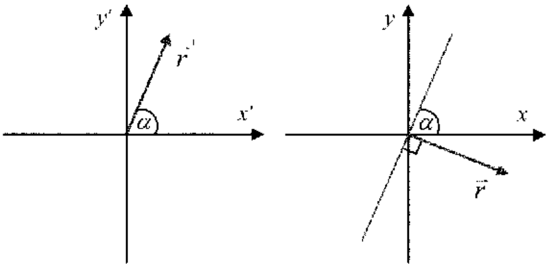

Fig. 3. Effect of 90 deg rotation. A deflection on the first pass (left) is transformed to a displacement that is orthogonal to the deflection that caused it (right).

Upgrade Driver (Fig. 2).[4] The skew-quadrupoles of the reflector were installed between normal quadrupoles of the driver, leaving a possibility to run the machine in the conventional, uncoupled mode. Note that the reflector produces a reflection across the 3F region, while the total recirculation matrix has a form similar to matrix (2) but with the off-diagonal matrices not equal to each other.

3.2. 90-deg rotation

Regenerative BBU can be completely suppressed for a single-dipole HOM in a two-pass accelerator if the 4×4 recirculation matrix has the form

$$\begin{pmatrix} 0 & M \\ -M & 0 \end{pmatrix}, \tag{3}$$

which provides 90 deg rotation of the beam on the second pass. The M_{12}^* given by Eq. (1) is zero for a matrix of form (3), yielding an infinite threshold for any HOM polarization.

The mechanism of BBU suppression in the case of a 90 deg rotation is illustrated in Fig. 3. If on the first pass an offending mode deflects the beam at the angle α, then on the second pass (and after a 90-deg rotation), the vector of the of the beam displacement will have an angle of $\alpha + 90$ deg and will be orthogonal to the vector of the deflection on the first pass. Because the projection of the beam displacement on the HOM polarization is zero after 90-deg rotation, the beam cannot deposit energy to the mode on the second pass. This disrupts the positive feedback constituted by the recirculated beam, which causes the regenerative BBU.

One way of implementing 90 deg rotation is by the use of solenoids. However, in high-energy machines a solenoid becomes impractical because of the large magnetic field integral required. In addition, a solenoid introduces undesirable strong transverse focusing. Another way of implementing a rotation is via a reflection. An embedded reflection in the recirculator can, in principle, be made to produce a pure rotation from the unstable cryomodule back to itself.[5]

4. New Two-Dimensional BBU Code

A new two-dimensional tracking BBU code, which still has to be named, was developed at JLAB.[9] The primary motivation for developing a new code was the necessity for a correct treatment of two-dimensional transverse beam dynamics and the capability to handle HOMs with arbitrary orientation. The code was written in the Standard ANSI C++ language, and the first version of the code has been tested and benchmarked. In the present configuration, the code simulates beam dynamics in a two-pass recirculating accelerator.

The code has been used to simulate BBU in several one-dimensional cases including the FEL Upgrade Driver. The results are in 3% agreement with results simulated by the previous BBU simulation codes used at JLAB, TDBBU[2,7] and MATBBU.[1] Because the results for two-dimensional simulations have not been compared with existing BBU codes, the results were compared to the formula given in Eq. (1). The simulation results for two-dimensional cases show excellent agreement with the theory.[11] In addition to the capability of handling two-dimensional transverse motion and arbitrarily oriented HOMs, the new code is faster than TDBBU and MATBBU by an order of magnitude or more, depending on the particular problem.

5. Simulation Results

To show the effectiveness of optical reflection and rotation for BBU suppression, we simulated regenerative BBU in the JLAB FEL Upgrade. The simulation model used the free-electron laser (FEL) design optics including the RF focusing and measured data to describe the HOMs (frequencies and loaded Qs). The only unknown was the polarization of each HOM.

Two sets of simulations were performed. In the first case, which we will call "aligned modes," all simulated HOMs were bound to the x or y planes. In the second case, which will be called "skewed modes," vectors of HOM polarization for different HOMs were randomly distributed between 1 and 15 deg to simulate the effects of different HOM orientations. For each case, three different machine optics were simulated: 1) nominal, uncoupled optics; 2) optics interchanging x and y planes (pseudo-reflection); and 3) rotated optics. The results are summarized in Table 1.

5.1. Nominal optics

In the case of the nominal, uncoupled optics, the threshold current for "aligned" modes is just under 3 mA. Small deviations of the HOM polarization from 0 or 90 deg in the case of "skewed" modes have little effect on the BBU threshold.

5.2. Pseudo-reflector optics

As mentioned before, the recirculation matrix of the JLAB FEL Upgrade with the optical reflector insertion in the 3F region has the off-diagonal form similar to matrix (2) but with

Table 1. Simulated BBU threshold current in the JLAB FEL Upgrade for different cases of the recirculation optics and HOM alignment

Mode	Nominal	Pseudo-reflection	Rotation
"Aligned"	2.83 mA	288 mA	613 mA
"Skewed"	2.87 mA	18.3 mA	208 mA

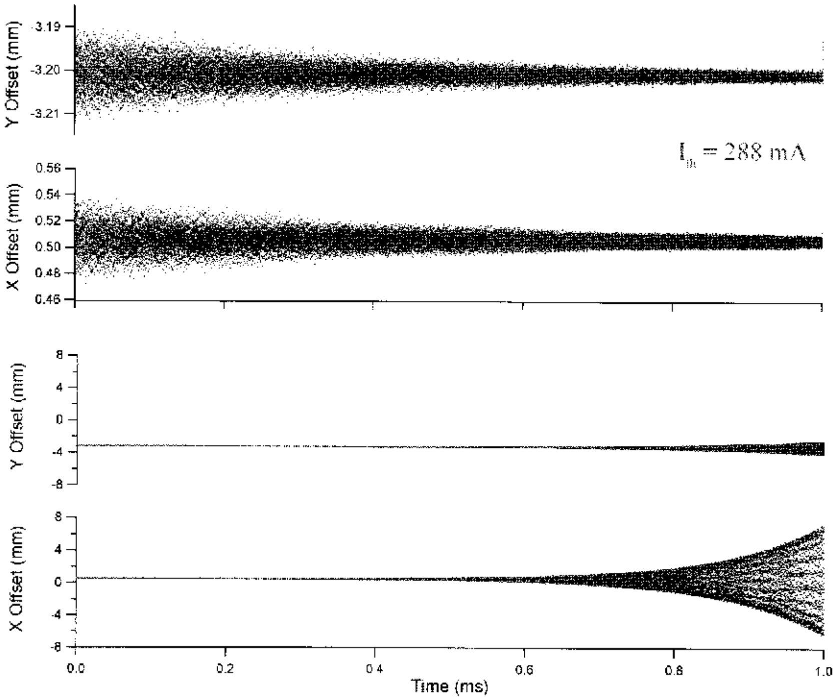

Fig. 4. Transverse displacement versus time for "aligned" modes (top) and "skewed" modes (bottom) with pseudo-reflection optics. The average beam current for each simulation is 100 mA. The numbers show the threshold for each given case.

the off-diagonal matrices not equal to each other. This optical transformation interchanges x and y planes but does not provide reflection if the HOM polarization angle is not equal to 0 or 90 deg.

With the modes "aligned," the threshold current in the case of pseudo-reflection is approximately two orders of magnitude higher than that in the nominal optics case. However, the threshold is not infinite as one might expect, which is, most likely, due to interaction between the HOMs. The effectiveness of BBU suppression degrades significantly if the modes are not bound to the x or y planes, yielding a factor-of-six increase in the threshold current. Figure 4 shows the output of the new BBU code for the "aligned" and "skewed" modes. The average beam current was 100 mA in both cases. In the case of "aligned" modes, initial beam oscillations damp down and the beam is stable. In the case of the "skewed" modes, the threshold current is much lower than the current simulated and hence BBU develops and the beam offset grows exponentially.

5.3. Rotated optics

The optics of the JLAB FEL Upgrade model with the reflector in the F3 region was tuned to produce a recirculation matrix for the middle cryomodule of the form given by matrix (3). The resulting recirculation matrix was not a perfect 90-deg rotation matrix with elements of the off-diagonal 2×2 block matrices of opposite sign but slightly different in the absolute value.

For the case of "aligned" modes the simulated threshold current was a factor of ~200 higher than for the nominal optics. With the modes "skewed," a rotation was still very effective in raising the threshold current. This was expected since 90-deg rotation suppresses BBU regardless of the mode orientations.

6. First Operational Experience with the Reflector

As mentioned before, the regenerative BBU was observed in the JLAB FEL Upgrade with the nominal uncoupled optics at a beam current of several milliamperes. By adjusting the recirculation matrix elements and improving betatron matching and current transmission, it was possible to increase the BBU threshold current to approximately 5 mA.

Initial operational experience with the reflector showed an increase in the BBU threshold current from 5 mA to a level above 8.5 mA (Ref. 6). The maximum current was limited by the injector performance at the time of the experiment. Further studies of the reflector performance are planned.

7. Conclusions

The multipass, multibunch beam breakup (BBU) instability has been observed at the Jefferson Laboratory FEL Upgrade Driver. This has prompted investigations of methods for beam optical control of BBU.

From a simple, analytical model and from two-dimensional BBU simulations, it was shown that a 90-deg rotation of the betatron planes is the most effective means to suppress the instability in a two-pass recirculator.

The skew-quadrupole reflector has been installed and successfully tested in the FEL Upgrade Driver. The first operational experience with the reflector has shown that the threshold was increased from 5 mA to more than 8 mA. A systematic and quantitative study of its effect on the threshold current has yet to be performed.

8. Acknowledgments

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