

SUPPRESSION OF MULTIPASS, MULTIBUNCH BEAM BREAKUP IN TWO PASS RECIRCULATING ACCELERATORS*

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Abstract

Beam Breakup (BBU) occurs in all accelerators at sufficiently high currents. In recirculating accelerators, such as the energy recovery linacs used for high power FELs, the maximum current has historically been limited by multipass, multibunch BBU, a form that occurs when the electron beam interacts with the higher-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°, first proposed by Smith and Rand in 1980 [1], should significantly increase the threshold current of the multibunch BBU. Using a newly developed two-dimensional tracking code, we study the effect of optical suppression techniques on the threshold current of the JLAB FEL Upgrade. We examine several optical rotator schemes and evaluate their performance in terms of the instability threshold current increase.

INTRODUCTION

In May of 2004 the multipass, multibunch beam breakup instability was observed at 3 mA of average beam current for the first time in the Jefferson Lab FEL Upgrade Driver. At the onset of the instability we observed HOM power levels in one particular cavity grow exponentially until the beam losses tripped off the machine (see Figure 1). With the knowledge that beam breakup is a real limitation to machine operation, the focus turns to finding a means of suppressing the instability.

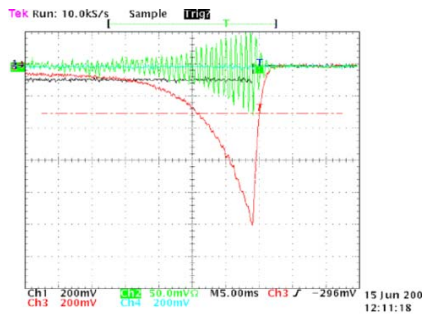


Figure 1: An oscilloscope trace from a BBU induced machine trip. The green trace is the cavity HOM voltage and the red trace is the total HOM power as measured from a Schottky diode. The time scale is 5 msec/div.

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The intent of this paper is to describe how BBU can be suppressed, or eliminated altogether, by modifying the recirculation transfer matrix from an unstable cavity back to itself in such a way that BBU cannot develop (or it does so at a sufficiently high average current). Applying conventional means of suppressing beam instabilities - such as beam-based feedback and HOM damping techniques - to BBU are discussed elsewhere [2]. The techniques described in this paper are applicable to any two-pass ERL machine; however, for simplicity we study the effect of applying this method to Jefferson Lab's FEL Upgrade Driver.

The Driver is an energy-recovery based linear accelerator used to condition an electron beam for high power lasing [3]. Electrons are injected at 10 MeV and are accelerated to 145 MeV through three cryomodules (each containing 8 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 phased in such a way that the beam is decelerated through the linac region on the second pass. Upon exiting the linac, the 10 MeV recirculated beam is extracted to a dump (see Figure 2 for a layout of the FEL).

EFFECTS OF ARBITRARY MODE POLARIZATION AND GENERALIZED TRANSPORT ON BBU

A beam bunch will excite dipole HOMs in a cavity if it passes through the cavity off-axis. The magnetic field of the excited mode then acts to deflect the following bunches. The kick produced by the mode is translated into a transverse displacement at the cavity after recirculation. Thus, the recirculated beam constitutes a feedback which can cause the voltage of the HOMs to grow. An approach based on the consideration of energy deposited by the beam into a cavity HOM was used to derive the threshold current. We consider only a single cavity and a single beam recirculation. However, instead of limiting the HOM orientations to either 0° or 90°, we allow for an arbitrary orientation angle, α , with respect to the horizontal axis. We also allow for a full 4x4 recirculation matrix (i.e. the off-diagonal 2x2 matrices need not be zero). The threshold current is then given by the following expression [4]:

$$I_{th} = -\frac{2p_b c}{ek(R/Q)Q M_{12}^* \sin(\omega T_r)} \quad (1)$$

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

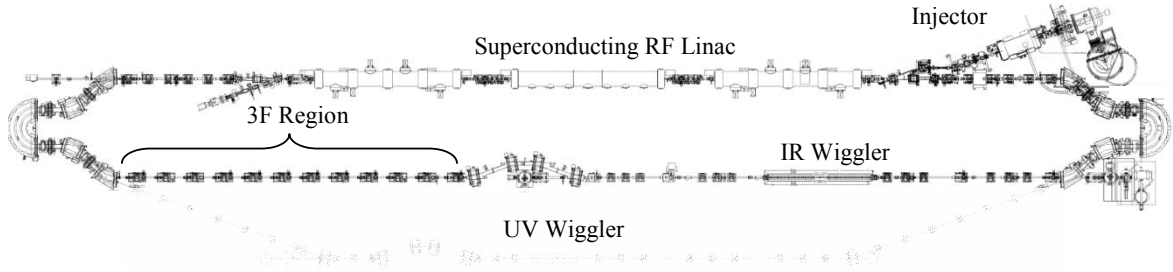


Figure 2: Layout of the JLab FEL Upgrade Driver (the UV transport line is currently being installed).

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

OPTICAL SUPPRESSION SCHEMES

We consider two methods for beam optical control of BBU. The first method is a reflection which is most effective at suppressing BBU when the HOMs are oriented at 0° or 90° , while the second method utilizes a 90° rotation of the betatron planes in which BBU is eliminated regardless of HOM orientation.

Reflection

The transport matrix describing a reflection about a plane at 45° to the horizontal or vertical axis takes the following form, where each element represents a 2×2 matrix;

$$\begin{pmatrix} 0 & M \\ M & 0 \end{pmatrix}. \quad (2)$$

The 2×2 sub-block transport matrix M is the same for both exchanges (x to y , y to x). Thus, such a reflector cleanly exchanges the horizontal and vertical phase spaces.

To see how a reflection can be effective in suppressing BBU, consider equations (1) and (2). Since $M_{12} = M_{34} = 0$, for a mode oriented at 0° or 90° the threshold current becomes infinity. However, if an HOM is rotated at an angle α , not equal to 0° or 90° , then the recirculated beam will not come back to the cavity with the angle $(\alpha + 90^\circ)$ and its projection on the HOM will be non-zero. To get an infinite threshold for all HOM polarizations requires that $M_{32} = -M_{14}$.

A practical implementation of a reflector using skew-quadrupoles has been non-invasively embedded in the 3F “backleg” region of the FEL Upgrade Driver (see Figure 2) [5]. Operationally, normal quadrupoles upstream and downstream of the module are used as betatron matching telescopes. These allow transverse matching of the phase spaces across the reflector, so that the 3F region, in its entirety, remains transparent to the rest of the machine - save for the exchange of horizontal and vertical emittance, the interchange of incident steering, and possible

differences in phase advance, nothing is changed. While the skew-quadrupoles produce a reflection across the 3F region, the transport matrix of interest for suppressing BBU is from the unstable cavity back to itself. Thus, with nominal operating conditions, the effect of the embedded skew-quadrupole reflector is to produce a pseudo-reflection; a matrix similar in form to equation (2) but with the off-diagonal matrices not exactly equal to each other.

Rotation

A more robust optical scheme which suppresses BBU regardless of HOM orientation is a 90° rotation. The transport matrix describing a 90° rotation takes the following form, where as before, each element represents a 2×2 matrix;

$$\begin{pmatrix} 0 & M \\ -M & 0 \end{pmatrix}. \quad (3)$$

Consider now equations (1) and (3). Since $M_{12} = M_{34} = 0$ and $M_{32} = -M_{14}$, the threshold current is infinity and BBU is eliminated - independent of the mode orientation. A rotation implemented in a two-pass system effectively breaks the feedback loop formed between the beam and cavity HOM so there can be no exchange of energy. The idea is conceptually simple and is illustrated in Figure 3. If on the first pass an offending mode imparts an angular deflection α to a bunch, then on the second pass (and after a 90° rotation), the resultant displacement will be orthogonal to the deflection. Thus the bunch will be unable to couple energy to the mode that caused the deflection.

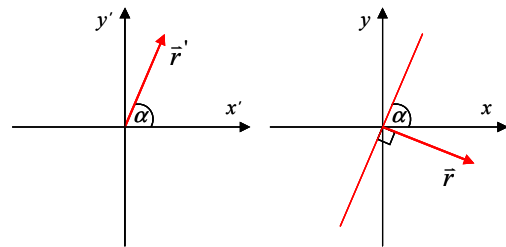


Figure 3: The effect of a 90° rotation. A deflection on the first pass (left) is transformed to a displacement which is orthogonal to the deflection which caused it (right).

One way of implementing a rotation is by the use of a solenoid. 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 [6].

DESCRIPTION OF THE TWO-DIMENSIONAL BBU SIMULATION CODE

Simulations to study the effectiveness of the optical suppression schemes described above were performed using a newly developed BBU code (yet to be named) [7]. The code was written in the Standard ANSI C++ language and the first version of the code has been tested and benchmarked. 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 orientations. The code works by tracking particles through a machine characterized by transfer matrices and follows the HOM energy buildups in accelerating cavities. In the present configuration, the code simulates beam dynamics in a two-pass recirculating accelerator.

The code has been used to simulate beam breakup 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 Jefferson Laboratory, TDBBU [8, 9] and MATBBU [10]. Because the results for two-dimensional simulations have not been compared with existing BBU codes, the results were compared to the formula given in equation (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.

SIMULATION RESULTS

To see the effectiveness of the two aforementioned methods for beam optical control of BBU, two-dimensional simulations were performed. The simulation model uses the FEL design optics including the RF focusing effects and uses measured data to describe the HOMs (frequencies and loaded Q s). The only unknown is the polarization of each HOM. Thus two sets of simulations were performed. The first set simulates HOMs with orientations of either 0° or 90° ("aligned modes"). A second simulation was performed with the orientations "skewed" slightly. Each mode from the first set was changed (randomly) by an amount between 1° and 15° to see the effects of different HOM orientations ("skewed modes"). For each set, three different machine optics were simulated: (1) nominal, uncoupled optics

(2) pseudo-reflector optics (3) rotated optics. The results are summarized in Table 1.

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

Table 1: Simulation results of the BBU threshold currents.

Nominal Optics

With no suppression techniques applied, the threshold current for the case of "aligned modes" is just under 3 mA. The threshold current remains virtually unchanged for the "skewed modes" case.

Pseudo-Reflector Optics

With the modes "aligned" the threshold current is increased substantially from the nominal optics case (by a factor of ~ 100). The threshold is not infinite - as one might expect - since coupling between HOMs is possible due to the finite Q 's and frequency separation, thus facilitating BBU at lower currents. The point of interest, however, is that due to mode orientations being "skewed", a pseudo-reflection alone does not effectively suppress BBU. The factor of 6 increase in the threshold current is consistent with a misaligned mode as given in equation (1), but is significantly less effective than with the modes "aligned" (e.g. 18.3 mA versus 288 mA). Thus, unless it is known that dangerous HOMs are oriented very nearly to 0° or 90° , a reflection scheme may not adequately suppress BBU. Figure 4 illustrates the effects of the pseudo-reflected optics as given by the BBU simulation code. Each plot shows the transverse displacement (horizontal and vertical) versus time. The average beam current for the simulations was 100 mA. In the case of "aligned modes" initial beam offsets 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.

Rotated Optics

For the case of "aligned modes" the threshold current is increased by a factor of ~ 200 . In theory, BBU should be eliminated altogether with a pure 90° rotation of betatron planes (see equation (1)). However, the recirculation matrix used for the unstable region back to itself is not a perfect rotation (i.e. the 2×2 off-diagonal matrices are of opposite sign, but are not exactly equal). Hence BBU occurs at a finite current. With the modes "skewed", a rotation is still very effective in raising the threshold current. This is expected since, as discussed previously, a rotation suppresses BBU regardless of the mode orientations.

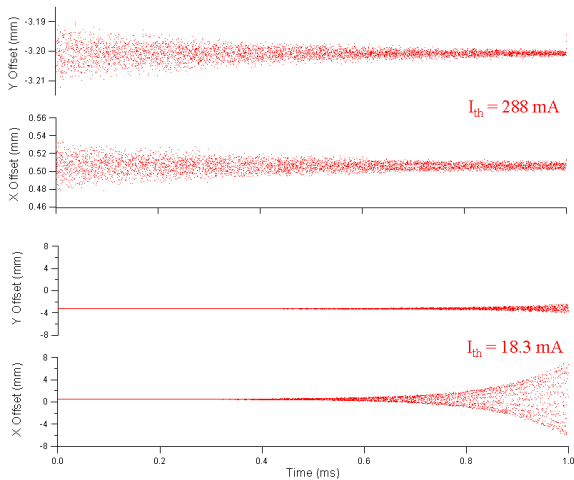


Figure 4: Transverse displacement versus time for “aligned modes” (top) and “skewed modes” (bottom) with pseudo-reflection optics. The average beam current for each simulation is 100 mA.

FIRST OPERATIONAL EXPERIENCE

Operational experience with the FEL Upgrade is consistent with this discussion of instability control. By tuning the betatron phase advances and match, it was possible to vary the BBU-driven current limit from as low as 1 mA to over 5 mA (the usual operational current). Such configurations did not always reproduce over the course of days due to irreproducibility in the transport system quadrupoles. When problematic, thresholds could be moved to acceptable levels – often without invoking adjustments in betatron phase advance – by improving betatron matching and current transmission.

We have, further, succeeded at operating at over 8 mA by use of the aforementioned skew-quadrupole reflection. When activated, we have verified this system completely cross-couples the two transverse planes. Modeling further suggests that certain choices of phase advance render the installed system a true reflection [12]. We note however that this configuration awaits operational evaluation. Though it is possible to manipulate the transfer matrix in this manner, it is not certain that the machine will perform properly, as internal mismatch can generate beam loss that limits machine performance just as surely as BBU. Conversely, it was found during FEL operation that simply matching the machine well (so as to clean up the transport, but ignoring BBU altogether) could result in a factor of 4 or 5 improvement in the threshold current.

CONCLUSIONS

The multipass, multibunch beam breakup instability has been observed at the Jefferson Lab 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° rotation of the betatron planes is the most effective means to suppress the instability in a two-pass recirculator. Experimentally, the skew-quadrupole reflector has been successfully commissioned in the FEL Upgrade Driver. A systematic and quantitative study of its effect on the threshold current has yet to be performed. However, operational experience has shown that the threshold is increased from 5 mA to over 8 mA using the reflector without any evidence of BBU induced machine trips.

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