METHODS FOR MEASURING AND CONTROLLING BEAM BREAKUP IN HIGH CURRENT ERLS*

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Abstract

It is well known that high current Energy Recovery Linacs (ERL) utilizing superconducting cavities are susceptible to a regenerative type of beam breakup (BBU). The BBU instability is caused by the high impedance transverse deflecting higher-order modes (HOMs) of the cavities. This multipass, multibunch instability has been observed at Jefferson Laboratory's FEL Upgrade driver. Some preliminary measurements are presented. To combat the harmful effects of a particularly dangerous mode, two methods of directly damping HOMs through the cavity HOM couplers were demonstrated. In an effort to suppress the BBU in the presence of multiple, dangerous HOMs, a conceptual design for an injector beam-based transverse feedback system has been developed. By implementing beam-based feedback, the threshold for instability can be increased substantially.

INTRODUCTION

The BBU measurement and suppression techniques described in this paper have application to any ERL based machine. However, for simplicity we will restrict ourselves to Jefferson Lab's Free-Electron Laser (FEL) Upgrade. The driver is an energy-recovery based linear accelerator used to condition an electron beam for high power lasing [1]. 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 beam is extracted to a dump.

MULTIPASS, MULTIBUNCH BBU

At sufficiently high average beam current, ERLs are susceptible to a regenerative type of beam breakup (BBU). The BBU instability is caused by the high impedance transverse deflecting higher-order modes (HOMs) of the cavities. The underlying mechanism is that with insufficient damping of cavity HOMs, a positive feedback loop will be created between the cavity and the recirculated beam. This feedback can create an energy exchange between the cavity fields and beam which can lead to exponential growth of the beam offset. For a single cavity, containing one HOM oriented at an angle α with respect to the horizontal axis and with a single recirculation, the expression for the threshold current of the instability is given by

$$I_{th} = -\frac{2V_b}{k(R/Q)Q\,M_{12}^{*}\sin(\omega T_r)}$$

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

where V_b is the beam voltage at the cavity, k is the wavenumber of the mode, $(R/Q)Q$ 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 (which can describe coupled transverse motion) [2]. The purpose of this paper is to present methods of increasing the threshold current by using feedback methods to effectively modify the shunt impedance of the HOM or the M_{12}^{*} term. Other means of suppressing the onset of BBU by a judicious choice of beam optics are given elsewhere [3] [4].

BBU MEASUREMENTS

On May 27, 2004 the multipass, multibunch beam breakup instability was observed at 3 mA of average beam current at the FEL for the first time. Using Schottky diodes on each of the two HOM ports per cavity (8 cavities x 2 ports = 16 diodes total) we were able to monitor the total HOM power levels from each cavity in the second cryomodule – which, for these operating conditions, exhibits insufficient HOM damping. At the onset of the instability we saw the HOM power levels in cavity 4 grow exponentially until the beam losses tripped off the machine (see Figure 1).

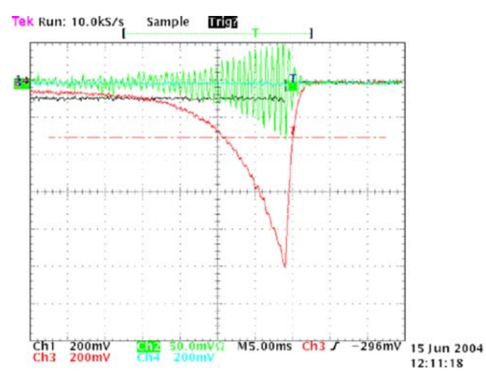

Figure 1: An oscilloscope trace from a BBU induced machine trip. The green trace is the cavity HOM voltage and the red trace is the total HOM power as measured from the Schottky diode. The time scale is 5 msec/div.

Repeated BBU-induced trips continued to be caused by cavity 4, leaving no doubt that the mode causing the instability was located in this cavity. Having successfully located the offending HOM, the next step was to extract

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the frequency of the mode causing the breakup. To do this, we measured the HOM voltage from cavity 4 during a BBU induced machine trip. A Fast-Fourier Transform (FFT) of the signal yielded an HOM frequency of 2114.156 MHz, in agreement with simulation results [5] and previous RF measurements of the frequencies and quality factors of the dipole modes. With the knowledge that beam breakup is a real limitation to machine operation, the focus turns to finding means of suppressing the instability.

HOM DAMPING SCHEMES

In an effort to provide a relatively quick method for raising the threshold current in the FEL, two HOM damping schemes have been developed. These methods are intended to be short-term solutions. The primary disadvantage of these damping methods is that they are effective for damping only a single HOM per cavity.

Active Damping

The first scheme uses a self-excited feedback loop to damp a dangerous HOM. The idea is as follows: couple power from one of the HOM ports, shift the signal 180 degrees in phase, amplify the signal and feed it back through the same HOM port. A measurement to prove the validity of such a scheme was performed on a cold cavity (without beam). For a specifically chosen HOM (1936 MHz) the loaded Q was lowered by a factor of ~ 4 (see Figure 2). Because the threshold current is inversely proportional to the Q of the offending mode, the ability to provide a factor of 4 reduction in the loaded Q corresponds to an increase in the threshold current by the same amount. In optimizing the setup, one must ensure that the gain of the feedback loop is less than unity otherwise the loop becomes unstable. Ideally, one would use a bandpass filter to allow only the frequency of the HOM of interest through to the feedback loop. Without a filter, the quality factors of other HOMs can be damped - or even enhanced - depending on the phase advance of the feedback loop.

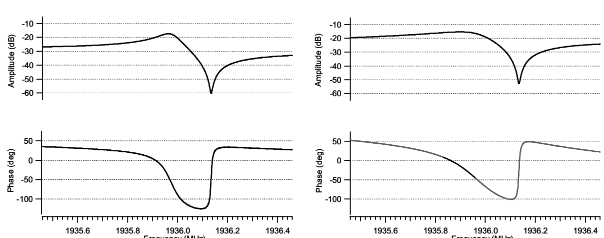

Figure 2: Demonstration of active damping of an HOM. The effect of the damping (right picture) is to decrease the loaded Q by a factor of ~ 4.

Passive Damping

We adopted a concept similar to that of the active damping scheme by connecting a 3-stub tuner between the HOM coupler and the damping load. Three stubs (λ/4 apart) can act as a reactive tuner to match any load at any location. In other words, this passive device can simply reflect the HOM wave back to the HOM coupler input. With this circuit setup without a beam present, we measured a factor of 2 reduction in the loaded Q on a chosen HOM (2106.007 MHz). A quantitative analysis of reactive coupling by a network method has been successfully applied in the operation of CEBAF. The 3-stub tuners there are used to increase or decrease the external Q of RF input couplers [6].

BEAM-BASED FEEDBACK SYSTEMS

Although the aforementioned HOM damping schemes are promising, they require a very accurate knowledge of the frequency of the HOM causing beam breakup and the cavity in which it is located. Furthermore, the method is only effective for a single mode per cavity. To suppress BBU due to many HOMs (whose identity may not be known), the more conventional method of beam-based feedback systems can be utilized. We describe two systems in particular, both of which are well suited for ERL-based accelerators.

Bunch-by-Bunch Feedback System

Initially the feasibility of a bunch-by-bunch feedback system [7] was investigated for use in the FEL Upgrade driver. The essential algorithm requires two position measurements from Beam Position Monitors (BPM) separated by 90 degrees of betatron phase. With sufficient knowledge of the recirculator optics, the two positions can be used to generate a correction signal used to drive downstream kickers [8]. Unlike a bunch-by-bunch feedback system in a storage ring where the transverse oscillations can be slowly damped over many turns, in an ERL electrons are dumped after two passes through the linac (in a 2-pass machine) after which, new electrons are injected. Thus the kickers need to provide enough power to completely damp the oscillation within the same turn on which the oscillations are detected. This type of feedback system may be suitable for larger ERL based machines; however, upon further inspection it became clear that such a system is not optimally suited for a machine like the FEL Upgrade driver. The issues prohibiting the implementation of this type of feedback are:

- *Relative size and geometry of the machine*. The FEL is a relatively small accelerator, with a recirculation time of 433 ns and consequently, there is not sufficient time to allow for the required signal processing.
- *Relative phase advances between the pairs of pickups and kickers*. For the feedback to be most efficient, the two pickups should be separated by 90 degrees of betatron phase and likewise for the two kickers. Due to the limited space available on either side of the linac, this requirement becomes difficult to achieve.

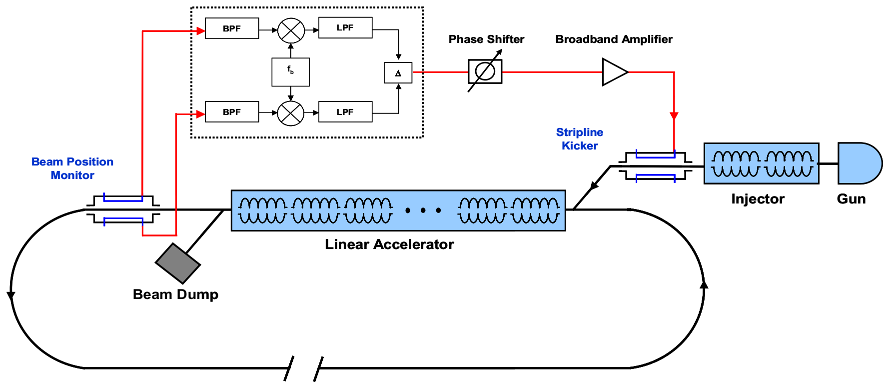

Figure 3: Schematic for an injector beam-based feedback system. A heterodyne receiver mixes down a BPM signal which is shifted in phase, amplified and used to drive a kicker in the injection region.

- *Small betatron functions at the locations of the pickups and kickers*. The feedback system operates most efficiently when the pickups and kickers are in regions of large betatron functions. However, for the nominal FEL optics configuration, the smallest betatron functions are found precisely in the locations where the pickups and kickers would need to be placed (on either side of the linac).

Injector-Based Feedback

To alleviate the stringent requirements of a bunch-by-bunch feedback system, we propose the injector beam-based feedback system as shown in Figure 3. The basic idea is that the signal from a BPM located downstream of the linac is amplified, shifted in phase by 180 degrees and then used to drive a kicker in the injection line. The primary advantage of this system is that the strict time requirements are eliminated since it is not a bunch-by-bunch feedback. In addition the requirements on the kicker power needed to produce a suitable correction signal are greatly relaxed since the kicks will be imparted in the low energy (injector) region. This is especially important for future ERL machines which will have injection energies on the order of 10 MeV and final energies of several GeV. Thus, rather than investing in specially designed kickers and powerful amplifiers to correct a GeV beam, this scheme which uses a stripline kicker and relatively low power amplifier to correct a low energy beam in the injector, may be sufficient.

CONCLUSIONS

The best defense against the beam breakup instability is to fabricate cavities which provide adequate HOM damping. However, in the event that beam breakup does pose a threat below nominal operating beam currents, then the suppression techniques described in this paper may be required. The encouraging results of our preliminary evaluations suggest that these schemes should be pursued.

The following activities are expected to take place in the near future:

- After the successful commissioning process, a thorough and systematic study of beam breakup in the FEL Upgrade driver will take place.
- Experimentally determine the effectiveness of increasing the beam breakup threshold current by means of the HOM damping schemes described in this paper
- Incorporate the injector beam-based feedback scheme into our BBU simulation code and assess the effectiveness of such a system.

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