BEAM CURRENT LIMITATIONS IN THE JEFFERSON LAB FEL: SIMULATIONS AND ANALYSIS OF PROPOSED BEAM BREAKUP EXPERIMENTS*

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Abstract

A series of beam experiments is being planned in the Jefferson Lab FEL driver accelerator in order to study multi-pass beam breakup instabilities in the machine and to test the predictions of the numerical code TDBBU. The tests are extensions of previously performed or proposed experiments, and will be considerably more sensitive with the present configuration. The experiments will include: a) observing the onset of instabilities by lowering the threshold current through manipulation of the beam energy, phase advance, and beam transfer matrices; b) measurements of beam transfer functions in the recirculating mode; and c) measurements of the single pass beam transfer functions to obtain direct measurements of the transverse shunt impedance of cavity modes with strong coupling to the beam. Simulations of the different experiments and studies of the sensitivities to the accelerator and beam parameters are presented.

1 INTRODUCTION

The Jefferson Lab Free-Electron Laser's driver accelerator is a 42 MeV recirculated superconducting linac, presently being operated in the energy-recovery mode for production of IR radiation [1].

The beam stability against multipass beam breakup in the FEL is predicated upon the appropriate damping of higher-order modes in the superconducting cavities and on the installed optics and path lengths.

Recent measurements of the dominant dipole modes' external Q's and frequencies [2] have been used to perform computer simulations using the code TDBBU [3], [4]. The results of those simulations have indicated that threshold currents of a few tens of mA should be expected, only a few times larger than 5 mA, the nominal operating current of the machine.

In this paper we describe briefly the results of the simulations performed on the beam breakup simulations performed on the FEL driver and then discuss a number of planned experiments which are designed to both establish a solid experimental counterpart to the numerical simulations and to more carefully determine the limits which the FEL might encounter in the future operation [5]. The investigations of the validity of the numerical simulations offer, in addition, a reliable baseline for the use of TDBBU in the design of the future CEBAF Energy Upgrade [6], [7]. In addition, these experimental activities are important for the qualification and the testing of the HOM performance of the Upgrade Cryomodule cavities. This will allow us to detect potentially trapped modes and this information can be utilized for the final design of the cryomodules before the full production is under way.

2 BACKGROUND

2.1 HOM measurements

The 5-cell, 1.497 GHz Nb superconducting cavities in the FEL cryomodule can have HOM excitations up to hundreds of GHz, the inverse time length of the submillimeter long bunch. The dominant dipole bands TE_{111} and TM_{110} occur between 1.720 GHz and 2.125 GHz. The damping of modes above 1.9 GHz is effected via the HOM coupling waveguides, which can extract both polarizations of the dipoles.

Below 1.9 GHz the only possible coupling can occur through the fundamental power coupler. The first four doublets of the TE_{111} passband fall in this category. The data taken on the HOM's show that the two polarizations of these modes possess very different external Q's, indicating poor coupling of one of the polarizations, possibly due to self-polarizing effects of the coupler itself. Some of the lightly damped modes have external Q's as high as 4×10^7.

2.2 Simulations

The measurements of HOM's prompted us to study more in detail the possible thresholds for transverse instabilities. From these simulations it appears that the presently configured FEL may become unstable at around 28 mA. Given the uncertainties of the simulations and of the unknown sensitivities to optics and transfer matrix variations, the safety factor of five seemed too small to safely extend operations past the design value and to comfortably prepare for upgrades of both the FEL and CEBAF with HOM's Q's in the 10^7 range.

The closeness of the predicted instability and of the operating current presents itself as an extraordinary opportunity to study the detailed physics of the instability

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and to establish once and for all the accuracy of the predictions of the TDBBU simulations.

The ability to do so can translate into the possibility of tailoring specific cavity characteristics and HOM damping requirements to the specific application with a degree of reliability impossible till now.

The availability of TDBBU as a tested tool will translate into a more efficient design of the Upgrade Cryomodule cavities for the CEBAF Energy Upgrade and of future FEL upgrades.

3 PROPOSED EXPERIMENTS

We propose to perform three experiments. In the first experiment we will attempt to induce BBU instabilities in the FEL driver in the energy recovery mode by lowering the beam energy, and varying the phase advance and transfer matrix elements M_{12}/M_{34} in the recirculation arcs.

Figure 1 shows the clear convergence of the vertical beam offset versus bunch number, as predicted by TDBBU with the nominal recirculator optics at 5 mA.

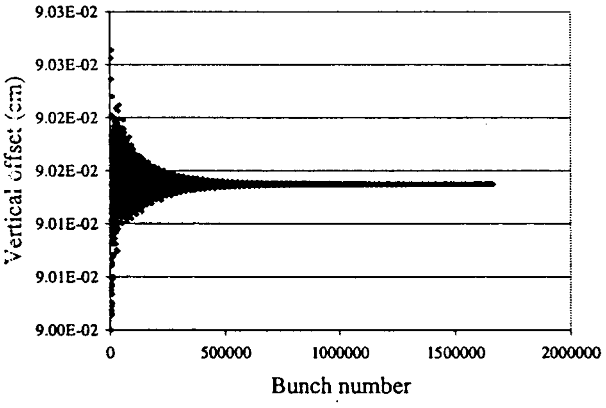

Figure 1:BBU simulations at 5 mA with nominal optics.

Figures 2 and 3 show simulations for a modified recirculator optics with vertical beta function at the reinjection point into the cryomodule increased by a factor of a hundred from nominal to β_y=500 m, and the phase advance from the exit of the cryomodule back to the reinjection point into the cryomodule set equal to exactly a quarter integer. With this modified optics the new threshold current is somewhere between 4 and 5 mA with a clear divergence at 5 mA (Figure 3) that is within the capability of the present FEL gun.

Additional sensitivity can be obtained by lowering the beam energy. Operational experience indicates that the accelerator configuration is flexible enough to allow for ample energy changes. We expect that this experiment will be performed in the near future.

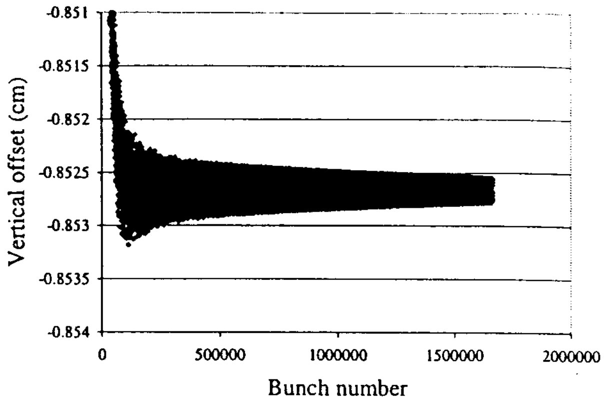

Figure 2: BBU simulations at 4 mA with modified optics.

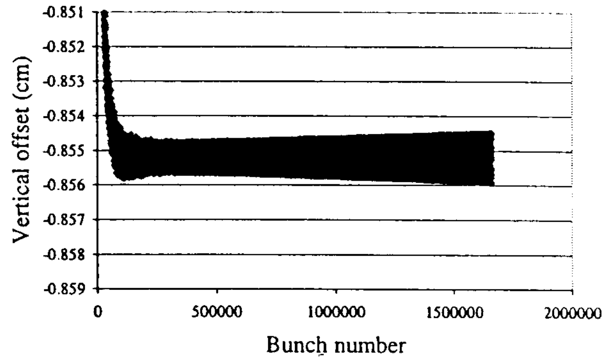

Figure 3: BBU simulations at 5 mA with modified optics.

In the second experiment we plan to measure the beam transfer functions in the recirculating mode. These measurements can be performed at currents considerably lower than the threshold current, yet lead to clear indirect estimates of the instability threshold in the event that the first experiment would not yield a direct observation of the onset of instability.

These measurements require modulation of the current moment $I\Delta x$ (or Δy) at the HOM frequencies or sub-harmonics.

The modulation can be achieved in several different ways. We plan to employ four separate techniques, to achieve independent confirmation of the threshold estimates.

In the first method, which employs modulation of beam displacement at constant current [8], the basic RF measurements consist in using a broadband RF kicker, which in our case is a stripline BPM already installed in the accelerator, to excite the beam. The detection of the modulation can either be done with one of the SRF cavities' field probe, or by a dedicated broadband pickup BPM. The optimal location for maximum signal of the kicker BPM is in the 10 MeV injection line, near an existing BPM.

The second method consists in injecting RF power at selected HOM frequencies in an unpowered cavity with an

external 300 W broadband generator and exciting a TE_{111} mode around 1.9 GHz., as described by Lyneis [9].
The third method uses beam current modulation at static displacement and the fourth requires tuning of the relevant HOM frequencies of an unpowered cavity to match a resonance condition with the bunch repetition frequency [10], [11], [12].

As a third experiment, we plan to measure the single-pass transfer functions of the present 5-cell cavities, and in the future of the 7-cell CEBAF Upgrade cavities and of strings of cavities, to obtain direct measurements of the shunt impedance of transverse HOM's. These measurements will be implemented on an unpowered two-cavity cryomodule placed in the return line of the FEL at first, possibly followed by tests on a half cryomodule. The measurements on this four-cavity module will also allow us to uncover long range trapped modes in the cavity string.

The proposed experiments will be carried out with a minimal disruption to the present configuration of the FEL accelerator and to its schedule.

The first experiment requires no hardware installation. Only dedicated time is required to perform studies of new optics and beam dynamics outside the canonical configuration.

The third experiment requires the installation of the cavity (-ies) under study in the accelerator beam line. It will require a drastic reconfiguration of the accelerator hardware. The detailed design of this activity is under way.

4 CONCLUSIONS

The FEL accelerator at Jefferson Lab presents itself as an unparalleled instrument to perform tests to establish the beam stability limitation in multi-pass BBU. These tests will not only shed light on the ultimate performance of the FEL itself, but will also determine the high-current limitations of the 1.5 GHz superconducting cavity technology for these types of applications. The proposed studies will also assess the accuracy of the numerical codes used to estimate BBU in recirculated electron linacs and to determine the HOM damping requirements for the CEBAF Energy Upgrade cavities.

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