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 
multipass beam breakup instabilities in the machine and to 
test the predictions of the numerical code TDDBU. 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 instabilities 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 TDDBU [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 of 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 TDDBU 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’s excitations up to 
hundreds of GHz, the inverse time length of the 
submillimeter long bunch. The dominant dipole bands 
TE_{11} and TM_{11} 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_{11} 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 x 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 $M_x/M_y$ 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.](image)

Figures 2 and 3 show simulations for a modified recirculator optics with vertical beta function at the reinsertion point into the cryomodule increased by a factor of a hundred from nominal to $\beta_y$=500 m, and the phase advance from the exit of the cryomodule back to the reinsertion 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.](image)

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 $\Delta x$ (or $\Delta y$) at the HOM frequencies or subharmonics.

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 $\text{TE}_{11}$ mode around 1.9 GHz, as described by Lynes [9]. The third method uses beam current modulation at static displacement and the fourth requires tuning of the relevant HOM frequencies of an unpaved cavity to match a resonance condition with the bunch repetition frequency [10], [11], [12].

As a third experiment, we plan to measure the singlepass 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 unpaved 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 second 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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6 REFERENCES


