BEAM BREAKUP SIMULATIONS FOR THE JEFFERSON LAB FEL UPGRADE*

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Abstract

As the Jefferson Lab Free Electron Laser steadily approaches its goal of producing 1 kW of IR radiation at 5 mA of beam current at 42 MeV, plans are being considered for possible upgrade scenarios, which will extend the IR power output and allow generation of UV radiation.

The upgrade scenario presently considered will bring the beam current to 10 mA and increase the energy to values close to 200 MeV. These parameters will most likely be realized in a machine configuration with a single recirculation loop for energy recovery and a linac consisting of three IRFEL-type cryomodules.

Measurements of frequencies and external Q's of the first two HOM passbands in the eight IRFEL cavities revealed anomalous high-Q resonances which could lead to transverse BBU instabilities at currents close to the operating current of the machine. In this paper we use the simulation code TDBBU to study the BBU behavior of the FEL upgrade and estimate its threshold current under nominal settings. Furthermore we study its dependencies on small variations of machine parameters, such as the path length of the recirculator and the frequency of selected HOMs, around their nominal points.

1 INTRODUCTION

The Jefferson Lab Free Electron Laser is currently configured as a recirculating machine capable of producing 1 kW of IR radiation at 5 mA of beam current at 42 MeV. Its most recent record has been 710 W of 4.8 μm radiation produced by 3.6 mA of beam current at 38.5 MeV [1], [2]. As the FEL is starting to operate as a user facility, plans are being considered for upgrade scenarios, which will extend the IR power output and allow generation of UV radiation [3].

The most likely upgrade scenario will bring the beam current up to 10 mA and increase the energy to values close to 200 MeV, thereby allowing production of greater than 10 kW in the IR wavelengths between 1 to 2 μm, as well as production of approximately 1 kW in the UV wavelengths, between 250 and 350 nm.

According to the present thinking [3], the above parameters are to be realized in a machine configuration very much similar to the IRFEL, with a single recirculation loop for energy recovery, and a linac consisting of three slightly modified, CEBAF type 2 K cryomodules containing eight 5-cell superconducting rf (srf) cavities operating in the TM_{010} π mode at 1497 MHz.

Measurements of the frequencies and external Q's of the first two higher order mode (HOM) passbands in the eight srf cavities of the IRFEL cryomodule revealed anomalous high-Q resonances [4] which could lead to beam instabilities at currents close to the operating current of the machine. These results motivated detailed simulations of the beam breakup (BBU) behavior of the IRFEL. The analysis indicated that a few modes are responsible for the relatively low value of 28 mA of the threshold current.

As the operating current of the FEL upgrade is planned to be raised to 10 mA, it is essential that we understand the BBU behavior of this machine and its sensitivities to machine parameters, and that we ensure that the final design has a BBU threshold current with a comfortable margin from the operating current.

In this paper we first present a brief description of the FEL upgrade machine configuration and the results of the HOM measurements and simulations done on the IRFEL. We then describe the BBU simulations we performed for the FEL upgrade, starting first with a short description of the simulation code, TDBBU [5], the assumptions and the results.

2 A POSSIBLE FEL UPGRADE CONFIGURATION

Figure 1 shows a possible configuration for the FEL upgrade. As in the IRFEL, the injector produces and accelerates electrons to 10 MeV. For modeling purposes the linac is assumed to consist of three cryomodules capable of delivering energy gains of 55, 60 and 55 MV, for a final beam energy of 180 MeV. After lasing the beam will be transported to the linac for energy recovery, to a final energy of 10 MeV. The design current of 10 mA can be reached in three different combinations of charge per bunch and bunch repetition frequency: 37.425 MHz at roughly 250 pC per bunch, 74.85 MHz at roughly 120 pC per bunch and 149.7 MHz at roughly 60 pC per bunch.

One of the goals of this study is to assess whether a preferred combination of charge per bunch and bunch repetition frequency exists from the point of view of BBU instabilities.

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*Supported by US DOE Contract No. DE-AC05-84ER40150.

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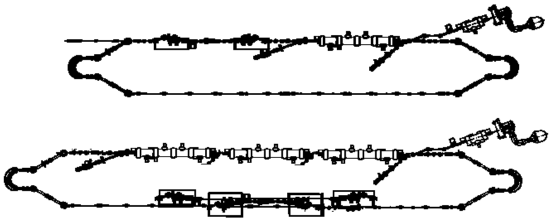

Figure 1: Top: Present FEL configuration. Bottom: Proposed FEL Upgrade configuration.

2.1 Lattice

The recirculator delivers beam to a set of wigglers (IR and UV) with the phase space configured properly for lasing, then transports spent beam from the wigglers back to the linac for deceleration to the injection energy.

Of interest in this context is the implementation of transverse and longitudinal matching in the recirculator. As it will be based on the Bates-like transport system design used in the Jefferson Lab IRFEL project [6], full six dimensional phase space matching of the recirculated beam will be available. At present, the linac beam envelopes will be reflectively symmetric about the recirculator, with average (peak) beam envelope functions of 10 (20) m amplitude and nearly a full betatron wavelength phase advance in either transverse plane during both acceleration and energy recovery. The total recirculation path length will nominally be (n+1/2)*(RF wavelength), with the integral part being chosen to minimize instability effects as dictated by work in progress. At present, the recirculator is expected to have integer betatron phase advance. This, coupled with the linac phase advance, will insure that the beam will have no positional offset during energy recovery at any linac location where there was imposed an impedance-driven impulse during acceleration. This design choice will thereby maximize thresholds for impedance-driven instabilities. As in the IRFEL, available beamline matching modules (including quadrupole telescopes for transverse matching and magnetic bunch length compressors/decompressors for longitudinal matching) will allow operation variation of this condition to provide opportunity to study impedance driven effects [7].

2.2 Linac Cavities

The accelerating-decelerating linac consists of three IRFEL cryomodules, each one containing eight 5-cell cavities. The HOMs are extracted by two mutually orthogonal waveguides, with a frequency cutoff of 1900 MHz, terminated in loads thermally anchored at 50 K. Modes at frequencies below 1.9 GHz can only be extracted via the fundamental power coupler (FPC). Four out of five dipole modes of the TE_{111} passband fall into this category, and their external Q's can be lowered only if some component of their fields is aligned with the FPC. In the case of strong polarization, orthogonal modes could exhibit large values of Q_{ext}.

The TE_{111} and TM_{110} passbands frequencies and Q's were systematically measured for all eight cavities in the IRFEL linac. Several modes exhibited high Q's, with the highest Q's associated with the vertical polarization of the TE_{111} $\pi/5$ mode [8], [9].

Although this mode was observed to have the highest Q_{ext}, it was actually the $4\pi/5$ mode which contributed more to possible beam instabilities because of its substantially higher transverse impedance. Six out of eight cavities showed that the vertically polarized TE_{111} $4\pi/5$ mode has a Q high enough to generate a shunt impedance of 1-3 $\times 10^{10}$, two orders of magnitude larger than what originally was measured by Amato [10].

As the only data available to date are from the IRFEL cavities, the simulations described below assume that the three cryomodules are identical, consisting of cavities whose HOM characteristics are identical to the IRFEL cavities. Clearly these studies are only preliminary and will have to be repeated when either data from the second and third cryomodule become available, or with statistically distributed frequencies and Q's among the 24 cavities.

3 BEAM BREAKUP SIMULATIONS

3.1 Method

The BBU simulations were performed using the code TDBBU. In it, every bunch is characterized by a phase space vector which gets updated according to the fundamental equations of dynamics, as deflecting modes in each cavity impart kicks in the horizontal and vertical directions.

In the FEL upgrade simulations, a 10 MeV beam is injected into the linac, interacts with the HOM fields of each cavity, gets transported around the recirculation path and enters the linac again, 180° out of phase for energy recovery. As the decelerated beam traverses the RF cavities, it interacts with the HOM fields of the cavities again, and, as the beam energy becomes smaller, the transverse deflections imparted to the beam have a stronger effect.

Each cavity in TDBBU is described by a 0.25 m drift delivering an energy gain equal to half the nominal energy gain per cavity, followed by the "HOM-kick" section for the particular cavity and this is followed by another 0.25 m drift delivering another half of the nominal energy gain.

The "HOM-kick" section includes all five TE_{111} and five TM_{110} horizontal and vertical modes. Each mode is characterized by its Q value, frequency, and transverse shunt impedance, as given by Amato scaled by the frequency of the mode.

The total path length of the recirculator is 715.5 RF wavelengths and the transport matrix elements are calculated using DIMAD.

3.2 Results

The threshold current for the system at the nominal design point was determined to be about 75 mA. This result is independent of the bunch repetition frequency. The limiting modes afect the stability in the vertical plane. In the horizontal plane no instability is observed at these current values, since the relevant modes are polarized in such a way that those aligned with the horizontal axis are well damped by the FPC.

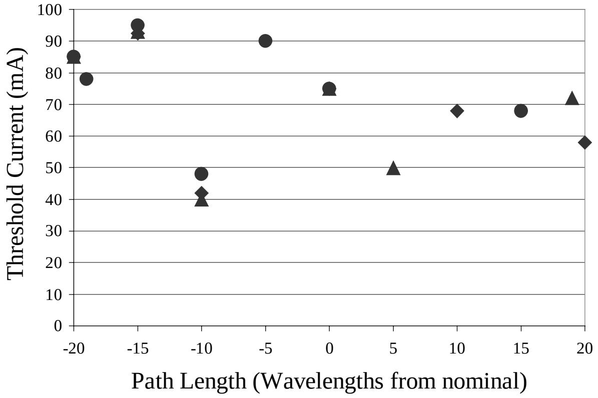

Figure 2: Dependence of I_{th} on recirculator pathlength

To understand the sensitivity of the BBU threshold current on some of the design parameters, simulations were performed for a system with recirculation path length which differs from nominal by ±20 rf wavelengths. Figure 2 shows a graph of threshold current vs. recirculation path length. A minimum threshold of 40 mA is possible, indicating increased sensitivity to the setup of the recirculator.

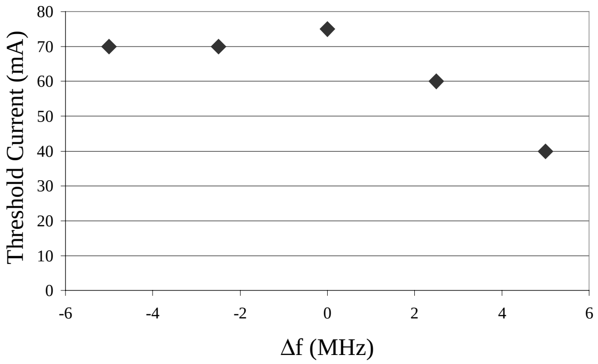

Figure 3: Dependence of I_{th} on the frequency of the 4π/5 TE_{111} mode.

Finally the sensitivity of the threshold current on the frequency of the HOMs was studied. The frequency of the TE_{111} 4π/5 mode, which is the mode most responsible for the value of the threshold current, was varied by ±5 MHz, in all 24 cavities, and the new threshold current was determined. Threshold currents as low as 40 mA are possible as shown in Figure 3. Although this case can be considered as a worst case scenario, the resulting large variations of the threshold current are a sufficient motivation for further understanding.

4 CONCLUSIONS

Preliminary BBU simulations performed on the present version of Jefferson Lab's FEL upgrade driver accelerator show that a threshold current of about 75 mA is possible. Small variations in machine parameters such as the path length of the recirculator, and the frequency of the HOM most responsible for the threshold current, can result in much reduced threshold currents, possibly dangerously close to the operating current. Measurements of HOM frequencies and Q's should be done as soon as the other two cryomodules become available. Given realistic HOM parameters, a thorough study of the BBU is essential with fixed parameters, before an engineering design starts.

A machine design with a BBU threshold current that is a factor of 3-4 higher than the operating current could be acceptable, under certain conditions. One of them has to be the unconditional confidence in the simulation tools that only benchmarking against experimental data can provide [7].

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