JLAB-ACT-99-06

First Operation of an FEL in Same-cell Energy Recovery Mode

G. R. Neil, S. Benson, G. Biallas, C. L. Bohn, D. Douglas, H. F. Dylla, R. Evans, J. Fugitt, J. Gubeli, R. Hill, K. Jordan, G. Krafft, R. Li, L. Merminga, D. Oepts, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn

Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

Abstract

The driver for Jefferson Lab's kW-level infrared free-electron laser (FEL) is a superconducting, recirculating accelerator that recovers 75% of the electron-beam power and converts it to radio frequency power. As reported in FEL'98, the accelerator operated "straight-ahead" to deliver 38 MeV, 1.1 mA cw current for lasing at wavelengths in the vicinity of 5 microns. The waste beam was sent directly to a dump, bypassing the recirculation loop. Stable operation at up to 311 W cw was achieved in this mode. The machine has now recirculated cw average current up to 4.7 mA, and has lased cw with energy recovery up to 1720 W output at 3.1 microns. This is the first FEL to ever operate in the "same-cell" energy recovery mode. Energy recovery offers several advantages (reduced RF power and dramatically reduced radio-nuclide production at the dump) and several challenges (potential for instabilities and difficult beam transport due to large energy spreads). Solutions to these challenges will be described. We have observed heating effects in the mirrors which will be described. We will also report on the additional performance measurements of the FEL that have been performed and connect those measurements to standard models.

Keywords: Lasing; Free-electron laser; Recirculation

1. Introduction

Thomas Jefferson National Accelerator Facility has commissioned a cw, kW-level, 3-6 μm free-electron laser (called the IR Demo). The design of the machine is discussed in [1], and the layout is shown in Figure 1.

The IR Demo incorporates a superconducting accelerator comprising a 10 MeV injector and a 38 MeV linac to produce a 48 MeV electron beam for kW-level cw lasing. It is designed to achieve the top-level electron-beam requirements listed in Table 1 while transforming 75% of the beam power back into rf power.

Last year we reported first lasing of the machine in the straight-ahead mode with beam deposited in the 42 MeV dump. Subsequently the machine was run in the "recirculation" mode with pulsed beam and with energy recovery from the pulses, first without lasing, then with lasing. In this mode, the beam lands in the "10 MeV dump" after decelerating through the cryomodule.

The eight klystrons powering the eight cryomodule cavities can each deliver up to 8 kW. This available power limits the cw average current to a maximum of 1.1 mA in the straight-ahead mode. However, once recirculation with energy recovery is established, the decelerated beam powers the accelerated beam, and the recirculation mode thereby provides for currents up to 5 mA limited by the gun power supply.

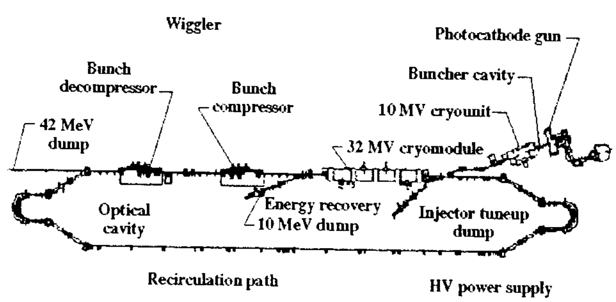


Figure 1. Schematic of IR Demo; dimensions of the recirculation loop are roughly 49m x 6m.

2. Energy Recovery

The use of energy recovery was incorporated as a key feature in the design in order to demonstrate the efficient and cost effective scalability of the system to yet higher

#*Corresponding author. Tel + 1-757-269-7443; fax =1-757-269-5510.*
E-mail address: neil@jlab.org (G. Neil)

Table 1: Beam Requirements at Wiggler for First Lasing.

Parameter	Required	Measured
Kinetic Energy	48 MeV	48.0 MeV
Average current	5 mA	5 mA
Bunch charge	60 pC	Up to 80 pC
Bunch length (rms)	<1 ps	0.4 +/-0.1 ps
Peak current	22 A	Up to 60 A
Trans. Emittance (rms)	<8.7 mm-mr	7.5 +/-1.5 mm-mr
Long. Emittance (rms)	33 keV-deg	26 +/-7 keV-deg
Pulse repetition frequency (PRF)	18.7 MHz, x2	18.7 MHz, x0.25, x0.5, x2, and x4

average powers [3]. Because of the low electron beam energy it does not yet substantially improve the wall plug efficiency (only 2x to 3x). It should be emphasized that the following systems have not been optimized for low power consumption but except where noted we report actual AC powers used:

AC Wall Plug Powers

Injector RF	220 kW
Linac RF	175 kW
He refrigerator	70 kW (est.)
Magnets, Computers, etc.	43 kW
Total	508 kW

In the absence of energy recovery the AC power for linac RF would have been increased by 700 to 900 kW at the same efficiency of the injector RF supply. Energy recovery has thus improved system performance by 58% to 64%. The benefits will be even more striking at higher beam energies and powers. For our planned scaleup to 10 mA, 160 MeV, energy recovery will improve system performance by roughly 78%, reducing power draw from ~4750 kW to ~1025 kW. The required RF generation will be reduced by over 1700 kW with substantial capital cost benefits.

Even in the present system energy recovery reduces the required linac RF drive power by 5x, it reduces the dissipated power in the beam dumps by 4x, and it virtually eliminates induced radioactivity in the dump region by dropping the terminal energy below the photo-neutron production threshold. However, there were several issues that had to be addressed to utilize such an approach: stability of the electron beam, stability of the lasing process in such an energy recovered system, management of transport of large energy spread beams with low beam loss, and minimization of coherent synchrotron radiation induced emittance growth. These were all successfully handled by design optimizations as discussed in the references [4,5,6].

3. FEL Performance

At FEL'98 we reported the power reached 311 W with 1.1 mA current into the straight ahead dump without energy recovery [7]. We repeat the FEL design parameters in Table 2 for reference.

Table 2: FEL performance parameters

Parameter	Design	Measured
Wiggler period (cm)	2.7	2.7
Number of periods	40	40.5
K (rms)	1	0.98
Wiggler phase error (rms)	<5°	2.6°
Trajectory wander (μm p-p)	100	<100
Optical Cavity Length (m)	8.0105	8.0105 stable daily to 2 μm
Rayleigh range (cm)	40	40 +/- 2
Mirror radii (cm)	2.54	2.54
Mirror tilt tolerance (μrad)	5	~5
Output Wavelength (μm)	3-6	3.0-3.2, 4.8-5.3, 5.8-6.2
Output coupler reflectivity (%)	98, 90	97.6, 90.5
HR reflectivity (%)	>99.5	99.85

While we were quickly able to establish lasing with recirculated beam, initial attempts to increase laser power with increasing recirculated currents showed saturation of the power output. The beam was stable and no evidence of instabilities in the FEL transport interaction was observed in the beam transport even during turn-on transients. By replacing one of the CaF_2mirrors with a silicon mirror we were eventually able to obtain 710 W of power output at 4.9 microns. Some power-dependent steering of the output beam was observed but this could be manually compensated without serious difficulty.

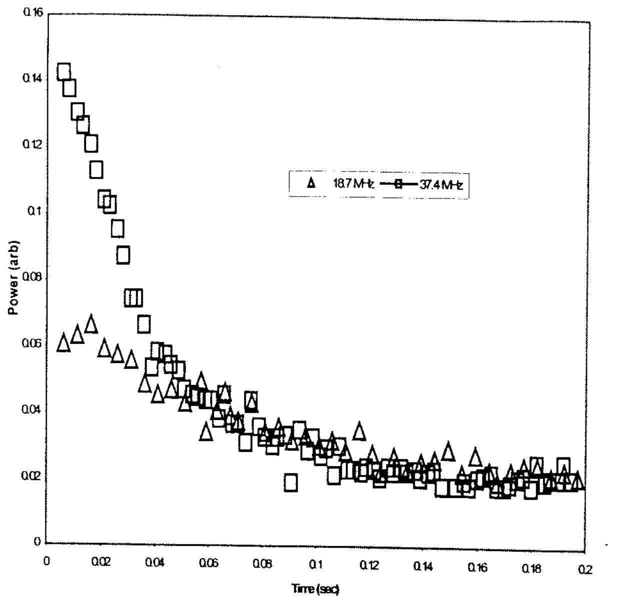


Figure 2. Power versus time for two pulse repetion rates, 18.7 and 37.4 MHz. All other beam parameters were the same. It can be seen that the 2x higher initial power quickly relaxes to the same power output despite twice the average current. The effect is ascribed to mirror heating due to 0.4% losses per mirror.

This power limit was ascribed to heating effects in mirrors and is not surprising given the sensitivity of electron beam/optical mode match to mirror parameters and high circulating power in optical cavity [8]. Even small absorption can cause a change in the radius of curvature of the mirror which leads to significant changes in the Rayleigh range in the wiggler. For the 5 micron mirrors the implied power loss is on the order of 0.04% or 3 watts per mirror.

Despite the several second thermalization time in the mirrors [9] changes in the local curvature happen quickly, on the order of milliseconds as was observed for 18.7 MHz operation versus 37.4 MHz. Within 0.04 second the output power becomes identical despite twice the current in the 37.4 MHz case (see Figure 2). It should be emphasized that these effects occur despite extraordinary measures taken to edge-cool the mirrors in thermally stabilized, water-cooled copper holders.

By operating at 47.8 MeV and 4.4 mA for near-maximum electron beam power and replacing MLD coated sapphire mirrors with exceptionally low loss (<0.1%)mirrors from another vendor we were able to achieve 1720 W of output power at 3.1 μm. No significant steering or distortion effects were observed. Achieving higher power was limited by electron beam interception of the beam pipe. The system lased stably for hours at powers > 1000W.

A set of typical detuning curves is shown in Figure 3. Key features to note include the transition from concave to convex curvature at high currents and the presence of a secondary peak at the higher charge levels. The secondary peak may be due to anomalous tails in the electron beam and is still under investigation. The tuning width is essentially constant above 2.2 mA. The change in curvature is due to mirror reoptimization at 3.4 mA.

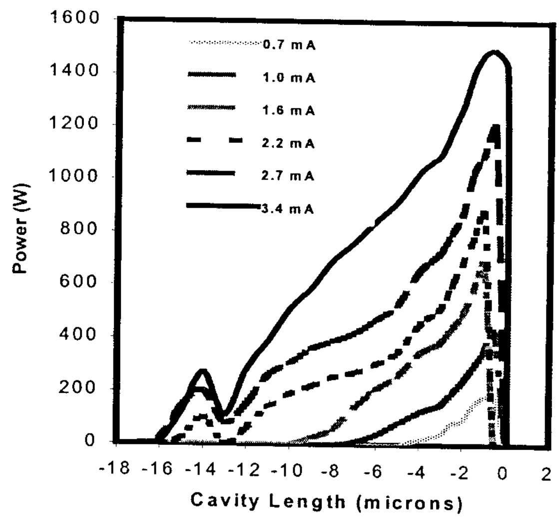
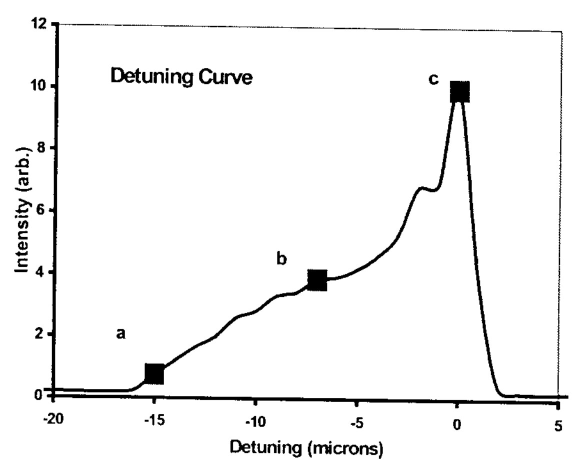
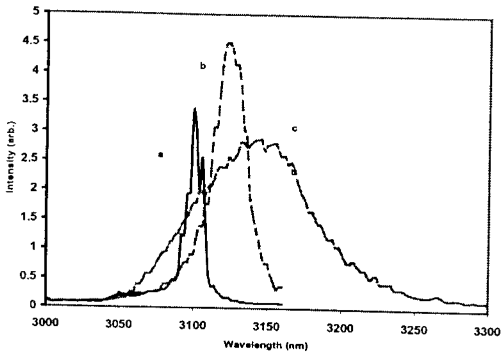


Figure 3. Typical detuning curves as a function of beam current. This data was taken at 48.7 MeV while lasing at 3.1 microns.

Lasing has been achieved in three wavelength bands (3.0-3.3 microns, 4.8-5.3 microns and 5.8–6.0 microns) with narrow or broad spectral output depending on proximity to zero detuning (Figure 4). We have also achieved 5th harmonic lasing at 1 micron which will be discussed elsewhere at this conference.



(a)



(b)

Figure 4. a) Typical detuning curve and b) lasing spectrum at detunings a, b, and c.

4. Summary

The IR Demo has exceeded design specifications, reproducibly recirculating in excess of 4 mA of cw beam and providing up to 1720 W of stable cw laser power. Approximately 70% of this power can be delivered to user labs for application experiments. The electron beam can be quickly and reproducibly set up to run with any of a set of three available high power mirrors covering the 3 to 6 micron range. We have demonstrated the operation of same-cell energy recovery in superconducting RF cavities for the production of high average power FEL output. Physics and engineering constraints to scaling the system to higher average power appear manageable through careful design. Our operational efforts will now focus on providing this light for a range of scientific and industrial applications and using the machine to explore accelerator and FEL physics issues, especially those relevant to our planned upgrade to 10 kilowatts output at 1 micron and kilowatt powers in the UV.

Acknowledgements

The authors would like to thank all those at Jefferson Lab who helped make this demonstration a success. Work was supported by the U. S. Department of Energy under contract DE-AC05-84-ER40150, the Office of Naval Research, the Commonwealth of Virginia, and the Laser Processing Consortium.

References

[1] C. L. Bohn, "Recirculating Accelerator Driver for a High-Power FEL: A Design Overview", Proc. 1997 Part. Accel. Conf., IEEE Cat. No. 97CH36167, pp. 909-911 (1998).

[2] D. Engwall, C. Bohn, L. Cardman, B. Dunham, D. Kehne, R. Legg, H. Liu, G. Neil, M. Shinn, C. Sinclair, "A High-DC-Voltage GaAs Photoemission Gun: Transverse Emittance and Momentum Spread Measurements", Proc. 1997 Part. Accel. Conf., *ibid.*, pp. 2693-2695 (1998).

[3] Neil, G. R.: A Cost Estimation Model for High Power FELs. IEEE Particle Accelerator Conference, May 1995, vol. 1, pp. 137-139.

[4] Campisi, I., Douglas, D., Hovater, C., Krafft, G., Merminga, L., Yunn, B., "Beam Current Limitations in the Jefferson Lab FEL: Simulations and Analysis of Proposed Beam Break-up Experiments". Proceedings of the 18th Particle Accelerator Conference (PAC 99), New York, NY, March 29-April 2, 1999.

[5] Merminga, L., Alexeev, P., Benson, S., Bolshakov, A., Doolittle, L. and Neil, G.: Analysis of the FEL-RF Interaction in Recirculating, Energy-Recovering Linacs with an FEL. Nuclear Instruments and Methods in Physics Research A 429 (1999) 58-64.

[6] Douglas, D.: Lattice Design for a High-Power Infrared FEL. Proceedings of the 1997 Particle Accelerator Conference, Vancouver, B.C., Canada, May 11-15, 1997.

[7] S. Benson, G. Biallas, C. L. Bohn, D. Douglas, H. F. Dylla, R. Evans, J. Fugitt, R. Hill, K. Jordan, G. Krafft, R. Legg, R. Li, L. Merminga, G. R. Neil, D. Oepts, P. Piot, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn, "First Lasing of the Jefferson Lab IR Demo FEL", Nuclear Instruments and Methods in Physics Research A 409 (1999) 27-32.

[8] Benson, S. V. et al: Optical Modeling of the Jefferson Laboratory IR Demo FEL. Nuclear Instruments and Methods in Physics Research A 407 (1998) pp. 401-406.

[9] George R. Neil, Stephen V. Benson, Michelle D. Shinn, Paul C. Davidson, and Peter K. Kloepple, "Optical Modeling of the Jefferson Laboratory IR Demo FEL" SPIE Vol. 2989 (1997) 160- 171.