Jefferson Lab Free-Electron Laser Starts Operation with Sustained Lasing at the Kilowatt Level

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One of the newest 4th generation light-source user facilities to come on line is the IR Free Electron Laser at the US Department-of-Energy-funded Thomas Jefferson National Accelerator Facility in Newport News, Virginia. Called the IR Demo, this FEL was specially designed to produce high-average-power coherent infrared light by combining the continuous-wave operation of superconducting radiofrequency (SRF) accelerator cavities with an approach to recover the "waste" energy of the electron beam after it has been used for lasing.

On 15 July 1999 the FEL lased stably at average powers up to 1.72 kW at 3.1 μm wavelength. Its demonstrated average-power capability is noteworthy, being a full two orders of magnitude higher than the previous average-power record for FELs (11 W at Vanderbilt University in 1990 [1]). However, the foremost achievement is a convincing demonstration of the underlying, enabling technology, namely same-cell energy recovery (SCER). Previous work demonstrated SCER without lasing [2] or lasing with energy recovery in a second linac [3]. The IR Demo incorporates SCER in a manner that is scalable to considerably higher average power.

Table 1. Beam Requirements at Wiggler for *kW* Lasing.

Parameter	Required	Measured
Kinetic Energy	48 MeV	48.0 MeV
Average current	5 mA	4.8 mA
Bunch charge	60 pC	>60 pC
Bunch length (rms)	<1 ps	0.4±0.1 ps
Peak current	22 A	>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

Machine Details

The layout of the machine is shown in Figure 1. The electron-beam parameters and measured performance are listed in Tables 1 and 2. Microbunches with an rms bunch length of 20 psec are produced in a DC photocathode gun [4] and accelerated to 320 keV. The bunches are shortened by a copper buncher cavity operating at the fundamental accelerating frequency of 1.497 GHz. They then pass through a pair of high-performance SRF cavities operating at a mean gradient of 10 MV/m. The output beam is injected into an eight-cavity SRF cryomodule, where it is accelerated up to ~48 MeV. The beam then passes through the wiggler, having detoured around each cavity mirror by way of a chicane. Afterward it either gets deposited straight ahead in a cooled copper dump, or it is recirculated (through two achromatic bends separated by a

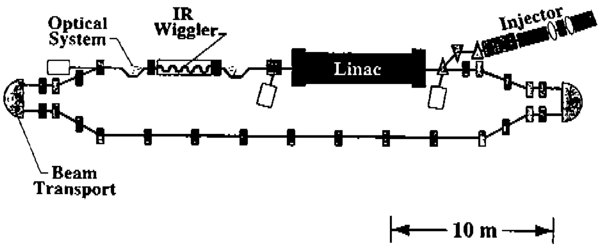

Figure 1. Schematic of the > 1 kW Jefferson Laboratory IR Free Electron Laser with superconducting rf cavities and a recirculating electron beam for energy recovery.

Table 2. FEL System Parameters.

Parameter	Design	Measured
Wiggler period (cm)	2.7	2.7
Number of periods	40	41 effective
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 at peak
HR reflectivity (%)	>99.5	99.85

quadrupole transport line) back through the cryomodule in the decelerating rf phase and dumped at the injection energy of ~10 MeV. In the latter case, the reduction of electron-beam energy shows up as rf power used to accelerate the injected beam, and SCER is thereby established.

The eight klystrons powering the eight cryomodule cavities can each deliver a maximum of 8 kW, thereby limiting the cw average current to a maximum of 1.0 mA at 48 MeV in the straight-ahead mode. However, once SCER is established, the decelerated beam powers the accelerated beam, and the recirculation mode thereby provides for currents up to 5 mA, at which point the gun power supply becomes the limit.

SCER was incorporated as a key feature in the design to demonstrate the efficient and cost-effective scalability of the system to yet higher average powers [5]. In view of the modest electron-beam energy increment (~40 MeV) associated with the use of only one cryomodule, SCER improves the wall-plug efficiency of the IR Demo only modestly (~2x). Nonetheless, it reduces the required rf drive power for the cryomodule 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, several issues needed to be resolved to validate the approach: stability of the electron beam against beam breakup, stability of SCER against electron-beam loss in the presence of lasing, and preservation of electron-beam quality in the presence of coherent synchrotron radiation. Each of these issues is a major topic and further details are contained in ref [6].

FEL Performance History

The IR Demo achieved first light on 15 June 1998 at 4.9 µm wavelength, within six hours from turn-on of the electron beam after wiggler installation [7]. Two days later it lased stably at up to 155 W cw with 1.1 mA current (60 pC bunches at 18.7 MHz). First light involved a 2% outcoupling mirror that was subsequently replaced with a 10% outcoupling mirror. On 28 July 1998 the power reached 311 W, again with 1.1 mA current into the straight-ahead dump without energy recovery.

Given the measured values of the electron-beam parameters, a small signal gain of 90% is expected. The IR Demo lases at reduced pulse-repetition frequencies (PRFs), implying very high gain. Specifically, we sent electron bunches into the optical cavity at double and quadruple the optical cavity period. The total cavity loss was 11% per round trip so the threshold gain was 12.4% for 18.7 MHz PRF, 26.3% for 9.4 MHz PRF, and 59.4% for 4.7 MHz PRF. Strong lasing at 4.7 MHz with an effective (7 μm mirror movement times 4 passes per gain pass) detuning width of 28 μm indicates that the gain is well in excess of 60%. The electron beam in this case was pulsed with a 1.2% duty cycle with 250 microsecond macropulses, so mirror heating should not have been significant. Generally, the performance of the laser itself is in agreement with predictions. One exception is the detuning width that, at around 30 μm, is narrower than expected for the high gain achieved. A possible explanation is optical guiding effects.

While we were quickly able to establish lasing with recirculated beam, initial attempts to increase power by increasing recirculated currents showed saturation of the power output. The beam was stable while lasing, and no evidence of instabilities in SCER was observed in the beam transport, even during turn-on transients. By replacing one of the CaF_2 mirrors with a silicon mirror, we were eventually able to obtain 710 W of power output at 4.9 μm on 11 March 1999.

This limit was ascribed to heating effects in the mirrors and is not surprising given the sensitivity of electron-beam/optical-mode match to mirror parameters and high circulating power in the optical cavity [8]. Measured laser power is in good agreement with model calculations based on [9], as shown in Figure 3. For these mirrors the implied power loss is on the order of 0.04%.

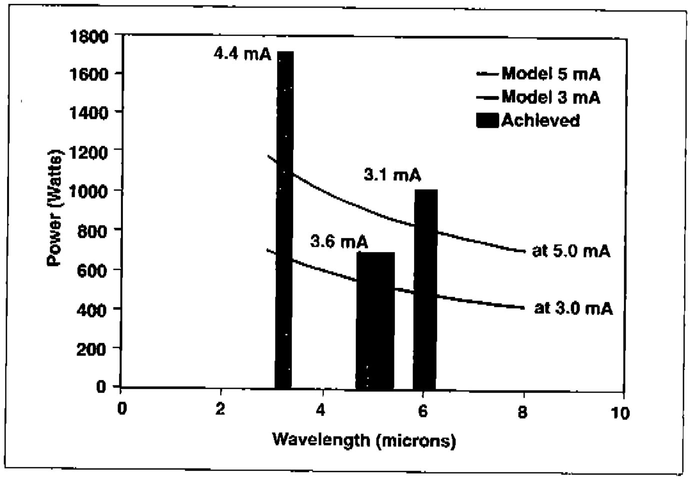

Figure 2. Calculated and measured output power as a function of wavelength of the Jefferson Laboratory IR Free Electron Laser.

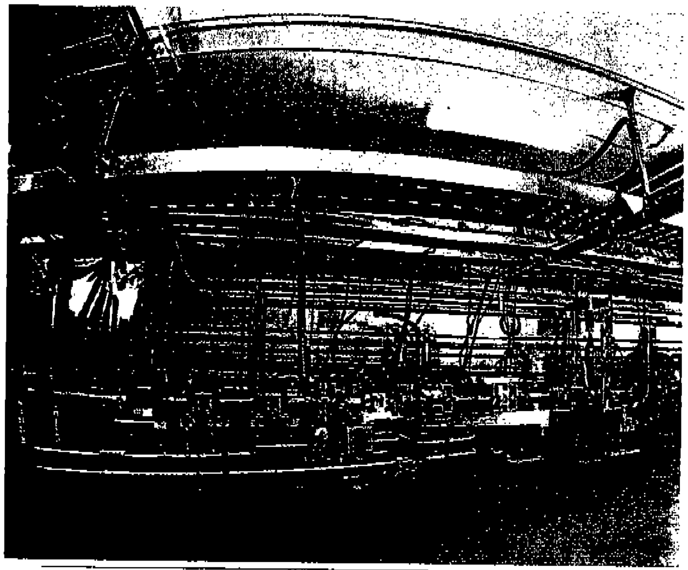

Figure 3. Photograph of the Jlab FEL showing the electron beam accelerating section with the superconducting radio-frequency cavity at right.

On 15 July 1999, operating at 47.8 MeV and 4.4 mA, we achieved 1720 W of output power at 3.1 microns by using multilayer dielectric-coated sapphire mirrors of exceptionally low loss (~0.03%). No significant steering or distortion effects were observed on these mirrors. Higher average currents or operating the FEL closer to zero detuning for higher lasing efficiency resulted in electron-beam interception of greater than 1 μA, causing shutoff of the beam by means of automatic protection systems.

The system lased stably (fluctuations < 10% p-p; subsequently we measured the noise to be ± 3% at the stable operating point) for several hours at powers >1 kW; and we produced nearly 100 hours of equivalent full-power running in the period July to October 1999 incidental to our materials applications studies. Typical detuning curves remain triangular and >20 microns wide (see [11] for detailed curves) and spectral bandwidths ranging from transform limited around 0.1% FWHM at 3 microns far from zero detuning to 5% FWHM at near zero detuning. At the end of our optical transport system employing 14 mirror reflections, the beam quality has been verified as better than 2x diffraction limited. It is now straightforward to restore the recirculating machine from a file of saved settings and run it for prolonged periods at kilowatt levels. Lasing has been achieved in three wavelength bands (3.0–3.3 microns, 4.8–5.3 microns and 5.8–6.4 microns) corresponding to the peak reflectivity of our high-power cavity mirrors. We have also lased at 1 micron in the fifth harmonic[12].

An additional feature of the FEL is the fact that 500 femtosecond X-ray pulses are produced within the cavity by the Thomson scattering of the laser light with the electron beam. This has recently been measured [13], and confirms theoretical predictions. X-ray energies are (~5 keV with average photon fluxes of (10^8 photons/sec. Since they are emitted into narrow angles from a small source, they are bright and, being synchronized with the IR pulses, it is expected that they will be useful for ultra-fast structural dynamics experiments.

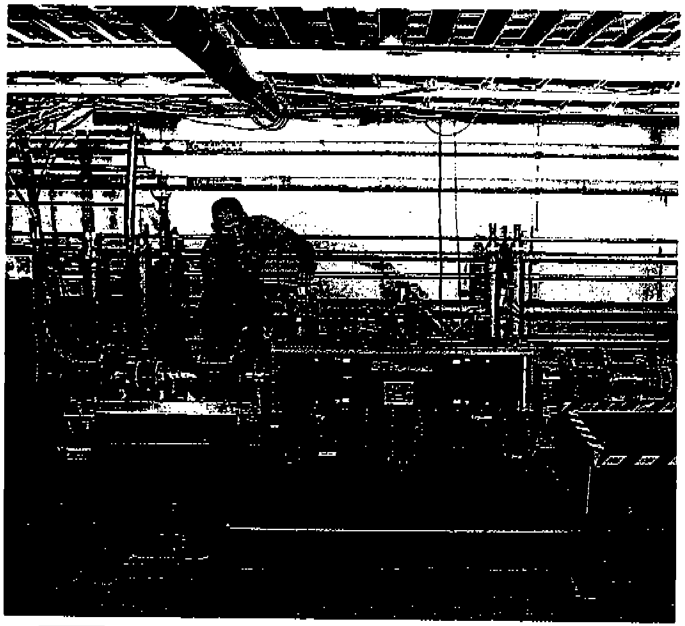

Figure 4. Photograph of Franz Gayle, USMC, behind the wiggler at the Jlab FEL.

Current Status

The IR Demo has performed admirably to date, 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 μm range. Our operational efforts focus on providing this light for a range of scientific and industrial applications [14] and using the machine to explore accelerator and FEL physics issues, especially those relevant to our planned upgrade to 10 kW output power at 1 μm.

The IR Demo is a unique source of tunable mid-IR light, producing the highest average power of any ultrafast laser source. With its high beam quality and modest energy/pulse, the brightness is of order 1×10^{20} photons/sec/0.1% bandwidth/$\text{mrad}^2/\text{mm}^2$, and by using a moderately short focal length lens, we routinely achieve intensities on the order of 10^{12} W/cm^2. Such an intensity can initiate nonlinear effects in materials, and coupled with the high PRF, and thus flux, enables detection of weakly absorbing species. The properties of the laser also enable material processing opportunities that heretofore were rendered uneconomical by the relatively slow (Hz to 1kHz) PRFs of other laser sources. As the FEL program has always been user-oriented, the facility was designed with approximately 600 m^2 of the second story for user labs. Each lab is equipped with utilities such as low conductivity water, temperature-regulated chilled water, dry nitrogen, and compressed air. Each lab also has purge lines leading outside the building (*e.g.*, for vacuum pump exhaust) and its own cable tray so that users have a convenient way for routing signal cabling to data acquisition equipment. All labs are connected to the lab data network, which provides another way for remote instrument control. About half the labs have chemical hoods.

Our first user experimental period occurred in July/August of 1999, and as of this writing we are providing beam time to users for one month per quarter, with four of the six experimental areas operational. Proposed experiments are reviewed by a program advisory committee, and those selected for a given period receive an allotment (plus contingency) of beam time based on the difficulty of the experiment. During the last two experimental periods (Oct./Nov. 1999 and Feb./Mar. 2000) we had an up time of ~ 70%. As we gain more experience, we believe we can increase our availability. ■

Acknowledgement

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