The Jefferson Lab Free Electron Laser Program

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A Free Electron Laser (FEL) called the IR Demo is operational as a user facility at Thomas Jefferson National Accelerator Facility in Newport News, Virginia, USA. It utilizes a 48 MeV superconducting accelerator that not only accelerates the beam but also recovers about 80% of the electron-beam power that remains after the FEL interaction. Utilizing this recirculation loop the machine has recovered cw average currents up to 5 mA, and has lased cw above 2 kW output at 3.1 microns. It is capable of output in the 1 to 6 micron range and can produce ~ 0.7 ps pulses in a continuous train at ~ 75 MHz. This pulse length has been shown to be nearly optimal for deposition of energy in materials at the surface. Upgrades under construction will extend operation beyond 10 kW average power in the near IR and produce multi-kilowatt levels of power from 0.3 to 25 microns. This talk will cover the performance measurements of this groundbreaking laser, scaling in near-term planned upgrades, and highlight some of the user activities at the facility.

KEYWORD Free Electron Laser (FEL), superconducting, accelerator, energy recovering linac

1. Introduction

A Free Electron Laser (FEL) called the IR Demo is operational as a user facility at Thomas Jefferson National Accelerator Facility in Newport News, Virginia, USA. The IR Demo installation was completed in September 1998. A layout is shown in Fig. 1. The system was commissioned over a period of about 9 months and has now produced over 2 kW (averaged over minutes) of mode-locked outcoupled laser power at 3 microns¹⁾. The electron beam for this was running at 4.5 mA CW in a 74.85 MHz train of 60 pC, 48 MeV sub-picosecond pulses. The machine is presently being upgraded to operation at 160 MeV which will permit lasing at > 10 kW in the IR and multi-kW in the UV region. The sections below will discuss key technologies developed for this system followed by a discussion of the user activities and future development plans

Fig. 1 A layout of the IR Demo FEL. The distance between recirculation arcs was approximately 30 m. A more compact system would result from placing the wiggler in the return leg but this was not done in the initial configuration due to fear of coherent synchrotron radiation induced emittance growth. That effect has now been shown to be inconsequential for this system's operational

2. Injector

The injector is the critical technology for operation of systems such as this; it must produce high average currents at high brightness. We utilized a high brightness CW injector based on a high voltage DC photo-gun. The 5 mA DC gun is presently being upgraded to 10 mA and planning is underway for a 100 mA version of this source that would power a 100 kW FEL. Although ultimately a SRF photocathode gun such as under development in Dresden²⁾ may be the most desirable, this system utilizes a DC photocathode operating at 320 kV³⁾.

This gun produces the highest average brightness of any injector gun in the world. The cathode of this device has delivered in excess of 5.3 kilocoulombs from a single GaAs crystal with only occasional cleaning and re-cathodizations required in its two and a half year life⁴⁾. It delivers over 1%

quantum efficiency operating with green light from a doubled Nd:YLF laser beam. The 20 ps rms bunch length electron bunches were bunched by a copper fundamental cavity to around 3 ps and accelerated to 9.5 MeV in an SRF cavity pair operating at 1497 MHz. To achieve 10 mA operation for the upgrade the charge per bunch will be doubled to 130 pC. Through improvements in the cesiation system and cathode surface treatment we also intend to operate the gun at up to 500 kV to improve the emittance for UV operation.

3. Accelerator

From injection the beam was accelerated to between 36 and 48 MeV in a slightly modified CEBAF cryomodule⁵⁾. The beam was bent around the optical cavity mirror in a chicane, compressed by the chicane dispersion working on a slight energy slew of the micropulse and sent through the wiggler with roughly 60 A peak current in a micropulse of less than 1 ps FWHM. Approximately 0.5% of the electron beam FEL energy was extracted in the NdBFe hybrid wiggler with 41 periods of 2.7 cm. The waste beam has a large energy spread; full width can exceed 6%. Nonetheless, the beam was brought around the second mirror in an identical chicane, then through a 180 degree arc based on the Bates design⁶⁾. A FODO lattice brought the beam to another arc and the beam was re-injected to the accelerator in the deceleration phase of the RF. As the beam decelerates its energy spread was compressed and the resultant beam was dumped at 10 MeV, now with less than 6% full energy spread. Tables 1 and 2 show the beam performance and FEL system parameters.

4. Energy Recovery

When operated without energy recovery the beam current was limited by RF power to 1.1 mA average producing over 300 W from the FEL. In recirculation mode the recovered power permits operation to the gun power supply average current limit of 5 mA. Fig. 2 shows the measured RF power in several cavities illustrating the independence of RF power on accelerated current. Nearly 250 kW of electron beam power was being generated from only 66 kW of RF.

The motivation to use energy recovery as a key feature in the IR Demo design was to demonstrate the efficient and cost effective scalability of the system to yet higher average power⁷⁾. Because of the low electron beam energy (48 MeV) it does not yet substantially improve the wall plug efficiency (only 2x to 3x). It should be emphasized that several systems

have not been optimized for low power consumption and one could expect further improvements in a system focussed on this aspect.

In the absence of energy recovery the AC power for linac RF would have to have been increased by 500 to 900 kW. Energy recovery thus improved system performance by 58% to 64%. The benefits will be even more striking at the higher beam energies and powers shown in Table 3 for the IR Demo Upgrade.

Table 1 Beam Performance at Wiggler

Parameter	Required	Measured
Kinetic Energy	48 MeV	48.0 MeV
Average current	5 mA	4.8 mA
Bunch charge	60 pC	Up to 60 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

Table 2 FEL System Parameters

Parameter	Design	Measured
Wiggler period (cm)	2.7	2.7
Number of periods	40	40.5
K_{ms}	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

For a scale-up to 10 mA, 160 MeV, energy recovery will improve system performance by roughly 78%, reducing power draw from ~ 4700 kW to ~1075 kW. The required RF generation will be reduced by over 1700 kW saving over \$ 5M in capital costs. These factors become even more dominating as the power of the FEL grows to the very high levels required for an industrially useful device (~ 100 kW).

The use of energy recovery brought additional benefits to the IR Demo beyond reducing the RF capital cost and improving the system electrical efficiency:

- 1) It reduced the dissipated power in the beam dumps by >4x. The electron beam was transported with virtually no losses to the dump so the power that was handled on the dump face was reduced to 50 kW from 240 kW.
- 2) It virtually eliminated induced radioactivity in the dump region by dropping the terminal energy below the photo-neutron production threshold. For a copper beam dump,

Fig. 2 Measured average RF power to each linac cavity with and without energy recovery (ER) as a function of current. At zero current power is required to establish the acceleration fields in the cavity (in equilibrium the power is reflected back to a load except for a minor amount which gets dissipated on the cavity walls) but no additional power is required as current is increased provided energy recovery is utilized.

reducing the energy to below 10 MeV can essentially eliminate the neutron production which activates surrounding components. Operating experience demonstrated radiation backgrounds during energy recovered running reduced by 10^4 or more. This increased lifetimes of electronic components and significantly impacted the ease with which system maintenance was performed.

5. Lasing Performance

The laser produced up to 2.1 kW at 3 microns or 150 times the CW average power of any other FEL in the world. The wavelength produced by the FEL was controlled by tuning the electron beam energy but suitable mirrors had to be used for each wavelength band to maximize the power output. The system lased in three primary wavelength bands of 3, 5, and 6 microns dictated by user interest as shown in Fig. 3.

Fig. 3 Projected and achieved performance of the IR Demo FEL. The full available performance can be achieved by using specialized mirrors for each wavelength band.

Given the measured values of the electron-beam parameters, a small-signal gain of 90% was expected. The IR Demo lased at reduced pulse-repetition frequencies (PRFs), implying very high gain. Strong lasing at 4.7 MHz (cavity round trip frequency is 18.7 MHz) with an effective (7 μm mirror movement times 4 passes per gain pass) detuning width of 28 μm indicated that the gain was well in excess of 60%. Generally, the performance of the laser itself was in agreement with predictions. One exception was the detuning width which at around 30 μm was narrower than expected for the high gain achieved. A possible explanation is optical guiding effects⁷⁾.

In addition to the fundamental output the system produced 4 watts on the fifth harmonic at 1 micron. It produced useful amounts of power at the third harmonic, 300 W continuously⁸⁾, and even conversion of this to green (~60W) and UV (~15 W CW) at high efficiency in doubling, tripling and quadrupling crystals. We also lased at 2 microns on the second harmonic producing interesting TM₀₂ mode struc-

ture⁹⁾. Up to 10^9 photons/sec of Thompson scattered X-rays in the 5 to 15 keV range were produced when the FEL pulse scattered off the subsequent electron bunch¹⁰⁾. Also the system synchronously produced ~50 W of sub-picosecond THz pulses from coherent synchrotron emission in a bend.

Approximately 70% of the FEL power was delivered to user labs for application experiments. Our operational efforts focussed on providing this light for a range of scientific and industrial applications^{11,12,13,14)} 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.

6. Applications

The JLab IR FEL enabled a rich applied and basic science program that included the investigation of both linear and nonlinear phenomena in proteins, ceramics, and metals, pulsed laser ablation and deposition, laser nitriding, synthesizing carbon nanotubes and micromachining. Linear dynamics using pump-probe techniques was applied to amide-I absorption at 5 to 8 mm in proteins¹⁵⁾, and to hydrogen defects in silicon at 3 mm^{16,17)}. In the following we expand on some of these applications of a high power, high repetition rate IR FEL.

Pulsed laser ablation and deposition is a potential application for manufacturing large-area films. The FEL's ultra fast pulses offer a low ablation threshold, substantially lessened target damage, and particulate elimination. High repetition rate implies high deposition rate, and may mean greater control over ablation and growth dynamics. Wavelength tunability results in enhanced ablation and deposition with resonant absorption, such as in polymers, using specific resonances to control growth processes. We have demonstrated PLD of metals such as niobium and steel¹⁸⁾. We also have performed substantial work on PLD of polymers¹⁹⁾.

Laser nitriding is a method of modifying the properties of metals to obtain a harder surface with better corrosion resistance and the ability to hold higher standoff voltages. The JLab FEL was successfully used to produce high-quality nitride films on iron, titanium, and silicon²⁰⁾. Most interestingly the work showed successful nitriding could be achieved at atmospheric pressure without resort to a vacuum chamber. This implies much lower process costs in an industrial setting.

Carbon nanotube structures present a range of production challenges that might be circumvented or better understood by use of the JLab FEL's repetition rate, wavelength tuning and power. Studies were performed to determine how the structures are formed to discover optimum conditions for making them with tailored properties, as well as to learn more about real-time process monitoring and control. The JLab FEL with 3 μm light at 400 to 600 W average power synthesized single-wall carbon nanotubes with smaller diameters than nanotubes produced by direct current arc or table-top pulsed laser vaporization. Production rates were measured in milligrams per minute rather than milligrams per hour²¹⁾.

Micromachining is used applied on metals for automotive engine applications, and on glasses and ceramics for the fabrication of true three-dimensional microstructures. With

nano-scale engineering of key features, it is hoped that satellites could be reduced to the size of baseballs or smaller²²⁾. We intend to explore the development of this application more extensively using the UV output of the UV Upgrade presently under construction. Production rates should be significant and the greatly e

be varied continuously over a large range. The optical klystron has two wigglers of 12 periods each separated by a dispersion section with 40 periods of path length delay at the highest wiggler strength. The wiggler period is 20 cm and the maximum rms K^2 is 16. See Fig. 5 for the IR tuning range.

Fig. 4 Layout of the IR/UV upgrades presently under construction.

7. Upgrade

We are now extending the capability to lase at average powers in excess of 10 kW in the infrared (Fig. 4)^{23,24)}. This upgrade will also produce over 1 kW in the UV. The power increase will be achieved by increasing the electron beam energy by a factor of four, and the beam current and the FEL design efficiency each by a factor of two. Utilization of a near-concentric optical cavity is enabled by the use of very low loss state-of-the-art mirror coatings. The FEL will be placed in the return leg of the electron beam transport, giving a machine footprint quite similar to that of the existing 1 kW IR device.

Some features of the Upgrade are straightforward extensions of those in the present 1 kW design; others break new ground and present new challenges. The design specifications for such an Upgrade linac are shown in Table 3. The electron beam energy is increased by adding two cryomodules, one the same as the present cryomodule and one including 7-cell cavities producing higher total energy gain (> 70 MeV). We will move the wiggler to the return leg. Calculations show that the emittance growth due to CSR is not a problem for this design²⁴⁾.

An electromagnetic optical klystron was chosen for the wiggler. This will allow the gain and extraction efficiency to

For the optical resonator we have developed a technology which allows us to change the radius of curvature of a backplane cooled mirror while holding the figure to better than $1/20^{\text{th}}$ of a wave. We plan to use this type of mirror for the high reflector of the resonator. This means that it is possible to keep the Rayleigh range constant as the output coupler heats up. The power limit is now set by the induced aberration, waist movement, and the intensity on the mirrors.

8. Energy Recovering Linacs

The technology developed from the IR Demo enables the consideration of a new class of 4th generation light sources termed Energy Recovering Linacs (ERLs) designed to take synchrotron sources to the next level of performance^{25,26,27)}. Although synchrotron light sources have been extremely successful they do have a number of technical limitations:

- a) The light is not coherent which limits the brilliance.
- b) The beam transport lattice typically prevents the achievement of pulse lengths shorter than a few hundred

Table 3 Upgrade Beam Specifications at Wiggler

Fig. 5 Projected performance of the IR Upgrade with an electromagnetic 20 cm period optical klystron donated to Jefferson Laboratory by Northrup-Grumman.

picoseconds so that most chemical reactions and transient molecular phenomena are inaccessible due to their sub-100 femtosecond temporal response.

c) A practical issue is that since the dynamics of the lattice couple all devices together changing the lattice or adding long wigglers to the system is awkward.

d) In addition both the beamline impedance must be low and the field quality of insertion devices must be very high since the beam circulates through these structures millions of times per second and any degrading effects quickly build up.

The use of energy recovery makes it cost and energy efficient to consider ERLs as a replacement for synchrotrons and overcome the above limitations. Advancements in CW injector performance as in the JLab FEL and the ability to put very long wigglers or undulators in the lattice could produce higher brightnesses from these machines than is available from third generation sources while retaining large numbers of ports. In addition:

- a) since the beam only goes through the system once, impedances are not as crucial;
- b) reconfiguration of the machine is easier and its transport lattice is much more flexible; and
- c) finally, the pulse length can be very short, limited only by the longitudinal emittance.

Two proposals and two white papers for construction of such systems have been produced^{28,29,30,31)} and others are under consideration. This technology will likely be a major driver in the construction of new light sources over the next decade. Beam powers under consideration are huge with currents on the order of 0.1 A average and beam energies of

Parameter	Required
Kinetic Energy	80 - 210 MeV
Average current	10 mA
Bunch charge	135 pC
Bunch length (rms)	0.2 ps
Peak current	270 A
Trans. Emittance (rms)	<30 mm-mr
Long. Emittance (rms)	35 keV-deg
Pulse repetition frequency (PRF)	3.9 -74.85 MHz in 2x steps

up to 5 GeV. Essentially all the technology exists for such a system except the injector, which has been designed but awaits experimental validation.

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