The Jefferson Laboratory IR Demo Project

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ABSTRACT

The Thomas Jefferson National Accelerator Facility (formerly known as CEBAF) has embarked on the construction of a 1 kW free-electron laser operating initially at 5 microns that is designed for laser-material interaction experiments and to explore the feasibility of scaling the system in power for Navy defense and industrial applications. The accelerator system for this IR Demo includes a 10 MeV photocathode-based injector, a 32 MeV CEBAF-style superconducting radio-frequency linac, and single-pass transport that accelerates the beam from injector to wiggler, followed by energy-recovery deceleration to a dump. The initial optical configuration is a conventional near-concentric resonator with transmissive outcoupling. Following commissioning, the laser output will be extended to an operating range of 3-to-6.6 microns, and distributed to six labs in a user facility built with funds from the Commonwealth of Virginia. A description of the machine and facility and the project status are presented.

Keywords: free-electron lasers (FEL), DC photoemission electron gun, high average power lasers

1. INTRODUCTION

The Thomas Jefferson National Accelerator Facility (Jefferson Lab) received funding this year from the U.S. Department of the Navy, U.S. DOE, the Commonwealth of Virginia, and Industry to demonstrate a high average power (kilowatt-level) free-electron laser. Initially, lasing will be in the mid-IR in order to test the technologies and physics required to scale the system to higher powers (on the order of 100 kW or higher). Members of the Laser Processing Consortium (LPC), as well as the Navy, are planning experiments to explore the potential of high power FELs at wavelengths within the 3 - 6.6 μm tuning range. Later upgrades will lower the laser wavelength to 1-2 μm and finally, to around 0.2 μm. The accelerator and FEL hardware are scheduled to be installed by September 1997. This ambitious schedule requires we use existing technologies wherever possible. In addition, we are minimizing design and construction time by tapping the experience, infrastructure, and designs developed for the 4 GeV accelerator at Jefferson Lab.

2. IR DEMO FEL

A schematic representation of the infrared demonstration FEL (IR Demo FEL) is shown in Fig. 1. Electrons are produced in the energy range 350-500 keV by a DC photocathode gun[1] driven by a Nd:YLF laser[2] and accelerated to 10 MeV in a superconducting RF (SRF) "cryounit", an accelerator of about 1 m active length. These electrons are then accelerated to 42 MeV by another SRF accelerator, a "cryomodule" (essentially 4 cryounits). The FEL is placed at the exit of the linac, the electron beam is deflected around the two optical cavity mirrors and then has two possible paths. One is straight ahead into a beam dump used for initial commissioning and tune up. The other is into a recirculation loop based on the isochronous achromats used in the Bates accelerator[3]. This latter path allows the electron beam to be recirculated for energy recovery and deceleration in a 10 MeV dump[4,5].

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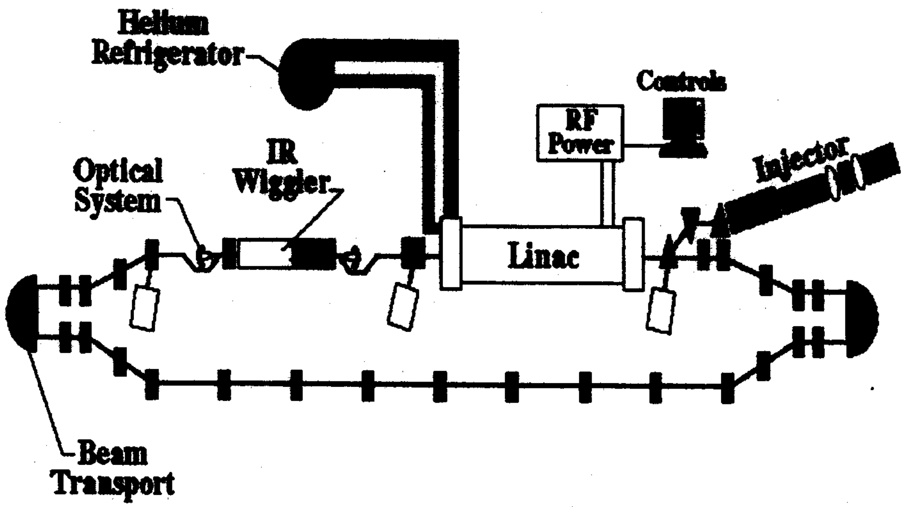

Figure 1. **Layout of the IR Demo FEL. The electron beam is injected into the accelerator at 10 MeV, is accelerated to 42 MeV, goes through the FEL, is recirculated back to the linac, and is decelerated back down to 10 MeV and dumped.**

Table 1 summarizes the electron beam parameters for the IR Demo FEL. Using parametrizations of the FEL equations[6], the laser output at 3 μm should be 980 W. The output time structure will mimic that of the electrons', i.e., ~ 1 psec pulses at a 37.425 MHz repetition rate. It is the production of high average power with ultrashort laser pulses that makes the IR Demo FEL so attractive to industry. The following describes the other subsystems designs in order to meet this goal.

Table 1. Electron beam parameters for the IR Demo FEL

Electron Beam Parameter	Value
Kinetic energy	42 MeV
Average current	5 mA
Repetition rate	37.425 MHz
Charge per bunch	135 pC
Norm. transverse emittance	13 mm-mrad
Longitudinal emittance	50 keV-deg
β function at wiggler center	50 cm
Energy spread (σ_γ/γ)	0.20 %
Peak current	50 A
Bunch length (rms)	1 psec

Wiggler

The wiggler parameters are summarized in Table 2. It is a hybrid permanent magnet design, using neodymium-iron-boron. Its gap is nominally fixed, but it is designed to be reset to another gap to permit lasing on the third harmonic. If the transverse and longitudinal emittances given in Table 1 are met, it should be fairly straightforward to initiate third harmonic lasing (at 1.35 μm, due to the shift in the fundamental caused by the different K value) with about one-third of the fundamental's power.

Table 2. Wiggler parameters for the IR Demo FEL

Wiggler Parameter	Value
Period	2.7 cm
Number of periods	40
rms K^2	0.5 (optionally 1.0)
Phase noise	< 5° rms
Maximum electron trajectory wander	$y < \pm 100$ μm $y' < \pm 500$ μrad

Optical Cavity

The optical cavity requirements are summarized in Table 3. The choice of a near-concentric design was based on the short delivery schedule and modeling that showed it was feasible.[7] Like other FELs, the cavity mirrors are in a vacuum, and the mounting assemblies are designed to be aligned and optimized remotely. Unlike other FELs, the high average power the mirrors will be subjected to requires heat sinking. We are testing an indium braze to thermally sink the mirror to a copper sleeve, which in turn is placed in a large, (6" dia.) water-cooled copper mount.

Table 3. Optical cavity requirements

Parameter	Requirement	Comments
Resonator type	Stable near-concentric	Best choice for low gain oscillator with small waist and large mode size on mirrors.
Center wavelength (λ)	3 - 4 μm	Compromise design wavelength determined from wiggler design with margin for lower energy.
Cavity length (L)	8.0105m	Compromise between mirror loading and tilt sensitivity
Rayleigh range (z_R)	40 cm	Nearly optimum for FEL gain.
Output coupling	13%	Provision must be made for larger and smaller values.
Length stability	0.5 μm rms	Passive control preferred.
Controls and diagnostics	Remotely controlled and read out.	Should also be computer interfaced.
Extraneous losses	<1% from all sources but output coupling.	Should be as low as possible.
Mirror tilt tolerance	2.6 μrad rms	This in a symmetric mode
Mirror radius	2.54 cm	Commercially available and larger than required for 7 μm operation
Mirror radius of curvature	4.045±0.008 m	Cold cavity tolerance

The broad tuning range envisioned for this laser initially argued for cavity mirrors using CaF_2 substrates. However, the relatively high thermal expansion coefficient and low thermal conductivity results in a higher amount of mirror distortion per unit of power absorbed, either in the coating or the bulk. This is expressed as the figure of merit (FOM), given by:

$$FOM = \frac{k_{th}}{h \alpha_e \alpha}$$

where k_{th} is the thermal conductivity, h is the substrate thickness, α_e is the linear expansion coefficient, and α is the absorption coefficient.[8] FOMs for several infrared materials are given in Table 4

Table 4. Figures of Merit for Infrared Materials

Material	k_{th} (W/mK)	α_e (K^{-1})	α (cm^{-1}) @ 3 μm	FOM*
ZBLA	1.0	15.7×10^{-6}	6.5×10^{-4}	1.54×10^{8}
CaF_2	9.7	18.85×10^{-6}	5×10^{-4}	1.62×10^{9}
MgF_2	21	8.48×10^{-6}	5.5×10^{-3}	7.1×10^{8}
ZnSe	18	8.56×10^{-6}	5×10^{-4}	6.61×10^{9}
Al_2O_3	28	6.7×10^{-6}	1×10^{-3} **	6.57×10^{9}
Si	148	4.68×10^{-6}	8×10^{-3}	6.22×10^{9}

* Assuming h = 0.635 cm

Based on our modeling results, we have chosen super-polished sapphire substrates for lasing in the 3 μm region. At longer wavelengths we will initially use CaF_2 substrates; we are also considering silicon, and metal mirrors with hole outcoupling.

Optical Transport

The FEL will be on the ground floor of the FEL facility, with six user labs on the second floor. Given the wide tuning range of the IR Demo FEL, plus the desire to upgrade it, we will transport the laser output primarily using metal mirrors. The entire path will be in a vacuum, to avoid absorption by the atmosphere. To accommodate this choice, as well as to preserve beam quality through the ~ 50 m path through the user labs, we will collimate the beam at the position where it has expanded to twice its original diameter. The collimator, positioned close to the output mirror, also directs the beam to the ceiling, whose construction provides a well-damped surface to mount the turning mirror assemblies. The beam enters the second floor in the Optical Control room, where ~ 1% of the output is sampled by a CaF_2 window placed near Brewster's angle. This beam is then distributed to diagnostics described later. The rest of the beam is then sent down the transport line that runs along the back wall of each user lab. In each lab is one or more mirror cassettes, a cylindrical assembly containing mirrors on a linear translation stage. This allows three modes of operation:

Table 5. Beam delivery modes for the IR Demo FEL

Operation Mode	Description
Alignment	Primary output not intersected. Alignment He-Ne available
Low Power	Primary output intersected by CaF_2 window, about 3% power available
High Power	Primary output intersected by metal mirror.

To compensate for the beam deviation through the window during low power operation, another CaF_2 window is placed at 90°to it. The mirror cassette diverts the beam into a short line containing an insertable beam dump; it then exits into the user's experiment through a Brewster window.

Transport of a beam with such high power requires safety procedures to protect personnel as well as equipment. This will be implemented through hardware (with status passed to the controls software) and through a control system to prevent inadvertent transport of beam into an area that has not been properly interlocked.

Optical Diagnostics

The majority of the optical diagnostics for the FEL are the canonical set used to optimize the laser's performance. The diagnostic beam is analyzed by a pyroelectric camera to determine the beam profile, a monochromator/spectrograph to determine the spectrum of the fundamental and harmonics, a power meter, and an autocorrelator to determine the pulsewidth. FELs are also very sensitive to changes in the cavity length. While our building design minimizes cavity drift, we are considering a plan to monitor it using an unequal-arm Mach-Zehnder interferometer. In this way we can determine the amount and direction the cavity length drifted. Tests proceed on a prototype and have turned up no problems.

User Facility

The user facility will be housed on the main accelerator site to take advantage of the main accelerator's utilities and cryogenics. It is constructed of reinforced concrete "floated" on compacted earth, with the first floor built below grade for radiation containment. This has the additional advantage of thermally sinking the building. A box structure of reinforced concrete and compacted earth provides the shielding between the first and second floor and, as mentioned earlier, provides an excellent mounting platform for the beam transport optics. The second floor includes areas for the RF power, the drive laser for the injector, the control room, and space for six or more laboratories. Each lab will be serviced with low-conductivity water, chilled water, dry N_2, chemical hoods and exhausts.

3. PROJECT STATUS

As of January 1997, the photocathode gun has been operated at 250 kV. The data are being analyzed and will be presented later.[9] With the fabrication of new components, we will begin a new round of tests with a goal to operate reliably at 350 kV or higher. The gun will then be mated with the cryounit and characterized at 10 MV. The injector will then be moved to the FEL User Facility. The lattice design is frozen and we are in the process of procuring and fabricating components. The optical cavity assemblies are also being fabricated, and we are having measurements made on representative coatings to quantify the reflectivity, and absorption. The User Facility's first floor is nearly ready for beneficial occupancy; some work, such as installation of the cryogenics, is in progress. If construction proceeds on schedule, we will have beneficial occupancy of the second floor in late March. We plan to have all hardware installed by the end of September, with first light occurring before the end of the year.

To characterize the machine's performance, our plan for first light will send the electrons into the 42 MeV beam dump after the downstream mirror assembly. Without recirculation and energy recovery, the beam current is limited to ~ 1 mA, and the output of the laser will be on the order of 100 W. During the first light phase of the project, we will study the effect of the wiggler on the emittance spread. We will then measure the emittance as the beam is transported around the Bates bends. This will allow us to determine the effect of various coulombic and radiative interactions, particularly, coherent synchrotron radiation.[10] Assuming these effects do not cause the emittance to grow beyond the acceptance of the cryomodule, we should be able to recover ~ 90% of the energy, and boost our recirculated electron beam current to the design goal of 5 mA. We will then characterize the FEL in preparation of delivering beam to users in 1998.

4. CONCLUSIONS

The FEL program at Jefferson Lab was created in response to the LPC's need for low-cost generation of tens of kilowatts of laser light for industrial processes. With funds from the DOD, our mission has expanded to include support for ship self-defense programs administered by the Department of the Navy. The IR Demo FEL described in this paper, while not fulfilling all the original objectives of the LPC, will allow us to build the same injector, and test our schemes for energy recovery and emittance preservation proposed earlier.[4,5] The resulting kilowatt-class FEL will do much to advance our understanding of laser- surface interactions with picosecond pulses in the mid-infrared.

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