EXPERIENCE AND PLANS OF THE JLAB FEL FACILITY AS A USER FACILITY*

Michelle D. Shinn#, Thomas Jefferson National Accelerator Facility, 1200 Jefferson ave., Newport News, VA 23606, USA

Abstract

Jefferson Lab's IR Upgrade FEL building was planned from the beginning to be a user facility, and includes an associated 600 m^2 area containing seven laboratories. The high average power capability (multikilowatt-level) in the near-infrared (1-3 microns), and many hundreds of watts at longer wavelengths, along with an ultrafast (~ 1 ps) high PRF (10's MHz) temporal structure makes this laser a unique source for both applied and basic research. In addition to the FEL, we have a dedicated laboratory capable of delivering high power (many tens of watts) of broadband THz light. After commissioning the IR Upgrade, we once again began delivering beam to users in 2005. In this presentation, I will give an overview of the FEL facility and its current performance, lessons learned over the last two years, and a synopsis of current and future experiments.

INTRODUCTION

The Free-electron laser (FEL) User Facility at Jefferson Lab (JLab) saw first light in 1998, and ran as a User Facility from 1999-2001. We then decommissioned our first FEL, the IR Demo, so we could install the IR Upgrade, which had almost an order of magnitude higher output and a larger tuning range. We once again began providing light to users in 2005. Previous reports [1,2] provide details of the uniqueness of the FEL driver accelerator, so this will be touched on only briefly. Along with the capability of the IR Demo to produce high average power, are other unique properties for a laser source (even compared to other FELs) in the mid-IR. To exploit the IR Demo the building that houses it was designed to be a user facility. An earlier report [3] gave some of the details of the facility while it was being built. This paper updates the current status of the facility, including measured values of the laser output, and discusses some of the infrastructure needed to run a user facility efficiently and safely. We then consider some of the interesting applied and basic research which is being done, and conclude with future plans for the facility.

*Work supported by the Commonwealth of Virginia and DOE Contract DE-AC05-06OR23177

#shinn@jlab.org

THE IR UPGRADE FEL

The Electron Accelerator

The driver accelerator of the IR Upgrade FEL uses SRF accelerator technology consisting of a 10 MeV injector (containing a DC photocathode gun driven by a Nd:YLF laser) and a SRF linac (whose total accelerating voltage may be as high as ~ 150 MeV) to produce an electron beam with an average current of ~ 10 mA at a PRF of 74.85 MHz. More than one percent of the electron beam power is converted to outcoupled laser radiation. The beam is then transported back through the linac where it is decelerated and most of the kinetic energy increase due to the linac is converted back into RF power. The use of an energy-recovering linac (ERL) greatly reduces the utility demands and installed RF power and has an added benefit that the waste beam is dumped at an energy below the giant photonuclear resonance threshold, eliminating activation of the beam dump.

This type of FEL was first demonstrated at the Jefferson Lab in the spring of 1999 and, its design and performance has been the subject of a number of papers. [4,5] The FEL is housed in the vault of the user facility [3] and has delivered several thousand hours of laser beam time to users. Given our desire to develop the FEL as an industrial tool, a generous amount of this beam time was delivered to users working on potential industrial applications. [6,7]

The advantage of ERL FELs is the ability to scale the output power to very high levels, many 10's of kW in the IR, without greatly increasing the space required to house it. This is because the FEL output power scales with electron beam power, which can be varied either with electron beam current or energy. Another advantage is the ability to lase at wavelengths that aren't accessible with conventional laser sources and at higher output powers. A disadvantage is that FELs are larger and more complex than conventional laser sources, however, an industrial version could be built which is more compact, and we have already demonstrated high availability (approaching 95% over 80 hours).

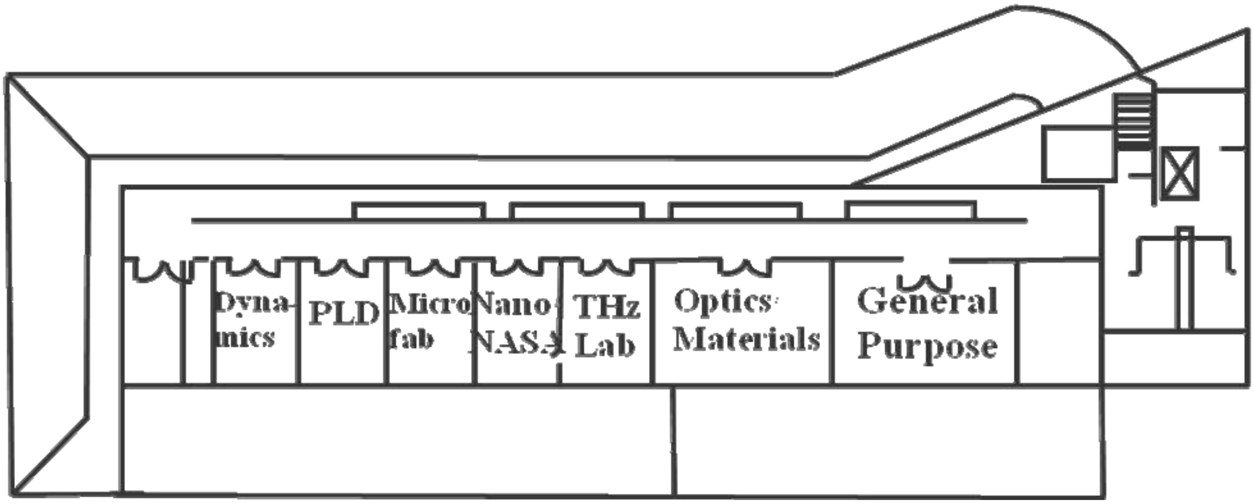

Figure 1 Layout and purpose of user labs in the JLab FEL Facility

The Optical Cavity and Transport

The optical cavity of the FEL is based on a nearly-concentric resonator design of 32.016m length. Mirrors for up to 4 different wavelength regions can be installed in the mirror vessels; operators can switch wavelengths, and be lasing again in about 15 minutes. Some of the design features of the cavity are available in another publication [8].

Currently, the IR Upgrade currently uses a permanent magnet, variable gap wiggler. The highest output at several wavelengths is shown in Table 1. Outcoupling is through a partially reflecting cavity mirror, where it is then collimated and transported upstairs first into the room where the optical diagnostics are located, and then onto the User Labs. (Fig. 1) Diagnosis and beam delivery are simultaneous, only ~0.05% of the laser power is delivered to the diagnostics, giving us the ability to provide realtime information on power, wavelength, and pulselength to our users.

Table 1: IR Upgrade FEL Output Power at several wavelengths.

Wavelength (μm)	Average Power (kW)
1.1	2.2
1.6	14.3
2.8	6.7

All mirrors in the cavity and transport are water cooled to minimize thermally-induced surface aberrations that would degrade the wavefront, and shielded to minimize absorption of stray light on the mounting hardware that cause beam steering. Presently, all mirrors in the transport are silicon with protected silver coatings. The choice of metal coatings allows us to transport the wide tuning range of the IR Upgrade without changing mirrors. When lasing on the fundamental, the FEL still produces harmonics with powers in the μW to mW range, which can be used as probes or for alignment purposes. A down side to this choice of coating is the loss of ~ 25% of the laser output to absorption and scatter. The beam is transported in a high vacuum (at ~ 10^{-7} Torr), to avoid absorption by the atmosphere. In order to send beam into any one lab there is a mirror cassette, an assembly containing mirrors on a linear translation stage. Currently, every mirror cassette contains a metal reflector, eventually two more mirrors will be added, each with dielectric coatings for higher reflectivity at a particular wavelength. There is also a home position, where the beam traverses the cassette without intersecting a mirror The mirror cassette diverts the beam into a short line containing an insertable mirror that directs the beam into a water-cooled dump; this serves as a local shutter for the user. When withdrawn, the beam then exits into the lab through a calcium fluoride or fused silica Brewster window.

The THz Beamline

As shown in Fig. 1, there is a THz lab located near the center of the laboratory area. As discussed elsewhere [9,10] we take advantage of the multiparticle coherence of our electron beam to extract broadband radiation in the THz region of the spectrum and transport it into a lab. The lower power (~ 100 W) of the THz beam makes it unnecessary to cool the optics in the beamline. Transport is also in vacuum, with a diamond window placed at a point where the beam is imaged to a waist, and is thus small. From there the beam continues in vacuum, but at a higher pressure (mTorr) than the initial part of the beamline. The beam exits into a hutch within the lab through a second diamond window, where it can travel through evacuated chambers containing the experiment, or in air.

Laser Personnel Safety System (LPSS)

Transport of a beam with such high power requires safety procedures and controls to protect personnel as well as equipment. This was implemented through

PLC-based hardware (with status passed to the controls software) to prevent inadvertent transport of beam into an area that has not been properly interlocked. Several different modes exist. For delivery of the FEL to a lab, either the entire lab can be interlocked (exclusionary mode) or the experiment is enclosed in an interlocked hutch (hutch mode). When a lab's LPSS in made up, a maglock energizes. Entry (when permitted) is by a "smart card" system that allows access only to personnel and users that are aware of the FEL and other hazards in a particular room. Recognizing that for many types of experiments, e.g., pump-probe, alignment is critical and difficult to optimize remotely, we have defined a state of operation known as "alignment mode". In this mode, the accelerator is locked into a state where the laser produces a low duty factor pulsed beam operating at 2 Hz with a pulsewidth of 250 μsec. During this time users can be in what normally be considered an exclusionary lab, or a user can be in the hutch. In the usual mode of operation, known as "laser permit", the lab is "swept", that is, checked to make sure that all personnel are outside the lab before the interlocks are engaged. Failure of an interlock causes the lab to become safe, inserting the local shutter, an intracavity shutter to prevent lasing, and setting the mirror cassette to the home position. However, the accelerator remains on. This allows us to maintain stable operations and more quickly resume lasing after the problem is corrected.

Most labs also have Class 4 laser systems in them, capable of operating without the FEL. To allow FEL beam delivery to one lab, and use of a laser system in another lab, we have a "local laser" mode, whereby the lab must still be swept and the interlocks made up. However, FEL beam delivery is prevented in several ways.

FEL operators and users receive formal training, through documentation and a walk-through by the Laser Systems Supervisor for the FEL. They are then given a test that must be passed before their badge allows them into the lab they will be working in. FEL operators are trained for all labs.

Facility Administration

Formal training of staff and users is just one facet of the administration of a user facility. We have modeled our procedures on those in place at the various synchrotron light sources in the United States; these have an experience based on over two decades of operations. Potential users must submit a request for beam time that is then reviewed externally by a Program Advisory Committee (PAC) and internally for feasibility. If accepted, users must submit two other forms that state what beam conditions and, possibly, changes to the hardware or software that they require, and, an evaluation of any hazards associated with the experiment, *e.g.*, solvents used, or toxic materials produced as a byproduct of exposure to the beam. This latter document is evaluated by the laboratory safety professionals and an experiment cannot proceed without their approval.

APPLICATIONS

Ablative processing of materials

Carbon nanotubes are increasingly utilized in various technologies. Demand for the single-wall variety is such that the price for high-quality material is currently about $500/gm, with pure material priced at over $2K/gm [11]. Current techniques produce about 0.2 gm/hr. [12] In comparison, worldwide demand is of order of thousands of kilograms annually. [13]. Using the IR Demo FEL and delivering an average power of about 300 W onto the target, researchers obtained yields of 1.5 gm/hr, far higher than competing techniques. [14] Work to optimize yield and dimensions have continued using the IR Upgrade FEL delivering about 1 kW of 1.6 μm light into the reactor.

The processing of nonmetallic materials was also studied with the IR Demo FEL. One study [15], showed the benefits of wavelength tunability. In this investigation polyimide (DuPont Kapton HN100) was irradiated at two wavelengths, 3.1 μm (off-resonance) and at 5.8 μm (on-resonance). Processing at the shorter wavelength, where the material was transparent, resulted in blackening of the material, a sign that the polymer has been thermally degraded. Tuning the laser to the longer wavelength resulted in cleanly-drilled holes, indicating the processing was nonthermal. This "cold-cutting" mode exhibited by IR FELs has been noted in earlier studies [16], enabling PLD of polymers.

Surface Processing

Besides ablative processes, thermal (or physiochemical) processes can be employed to perform surface modifications. No material is lost, merely melted and then resolidified, or while quite hot, transformed by oxidation, nitriding, or

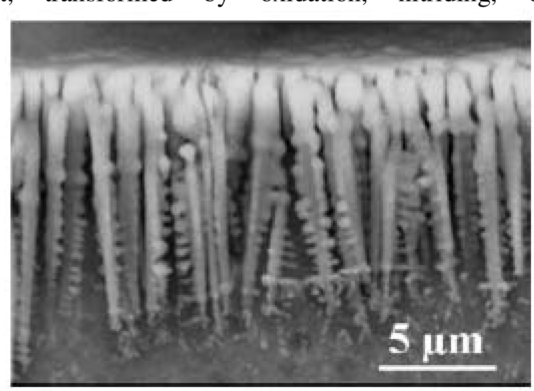

Fig. 2 Formation of dendrites of δ-TiN_x after bursts of FEL irradiation at 3.15 microns. From Ref 19

carburization. An example which is familiar to many is the application of titanium nitride (TiN) on tool bits. This gives the bit a distinctive gold color. TiN is also used to improve the biocompatibility and wear characteristics of replacement joints [17]. In a series of papers, P. Schaaf and coworkers from the University of Göttingen have published the results for the nitriding of Ti metal with the FEL. The FEL was operated at 3 μm, usually in a burst mode (also known as a macropulse). Compared to other types of laser nitrided titanium, the FEL-produced material had a thicker and harder coating [18]. This appears to be due to the formation of oriented (200) dendrites of δ-TiN_x, as shown in Fig. 2. While one might think that this would result in a rough surface, in fact it is fairly smooth. [19]

Medical Applications

With the wavelength and timing flexibility of the IR Upgrade FEL, it is natural to use it in medical applications. One such application is known as selective photothermolysis, the selective heating of tissues with light. By carefully choosing a wavelength in the near infrared, researchers targeted lipid-rich cells and heated them preferentially without heating the surrounding tissue. This study [20] paves the way for a laser treatment of acne, a condition where a sebaceous gland is producing too much lipid. Only the over-active glands, located a few millimeters under the surface of the skin are killed by the absorption of light, leaving the other cells unaffected. This technique also shows promise in the treatment of atherosclerosis, which if left untreated leads to heart disease and stroke.

THz Applications

The spectral region covered by THz radiation, roughly 1 mm to 0.1 mm in wavelength, is absorbed by transitions between electronic states and/or vibrational states in matter. Because these states are specific to a particular molecule, or ion, spectroscopy, either in the time domain, or in the frequency domain can be used for location and identification. This makes the use of the THz region of the spectrum attractive for applications such as medical imaging or hazardous material detection and nondestructive testing. While the list of applications is long, progress from the lab to the field has been hampered by the lack of high average power (several watts) sources. The THz source at JLab, is capable of producing high power, broadband, ultrashort pulsed radiation to evaluate the utility of some of these applications. It was recently used to make full-field video-frame rate images of a moving object [21]. We anticipate exciting results from the research occurring in this lab.

LESSONS LEARNED

While one might think that the user experiments occurring over the last two years were simply a continuation of the IR Demo user runs, with few new lessons to learn, in fact, that wasn't the case. The IR Upgrade was built in part to make it more attractive to users. And, we took the lessons learned from the first several years of operation to improve how we treated beam delivery to the labs, particularly in the use of hutches. By housing experiments in a hutch, the users are in close proximity to their hardware, making interfacing and sample changes far easier. Since the hutch eliminates the need to wear laser safety eyewear while the experiment is underway, we've found that users prefer this mode of operation. The preplanning of an experiment that is necessitated by the proposal and approval process encourages a lot of dialog between the users and members of the facility. This lessens the amount of time lost because the experiment isn't ready, time that is particularly at a premium when the users have come from a distance and have a well-defined period during which their experiment is supposed to run.

Ultimately, when running a user facility, what makes it work is the attitude and aptitude of the staff. The operators of the FEL are also its builders, and thus can respond to requests for unusual modes of machine operation.

CONCLUSIONS

Since the last paper on the JLab FEL User Facility [3], there have been a number of improvements to the facility over and above the upgraded IR FEL. In addition to outlining some of these improvements, I've highlighted some applications and experiments that an ERL-based FEL enables more readily than other lasers. Even then, this is merely a sampling; space does not permit me to discuss all the applications currently envisioned for an IR FEL, much less one that operates in the UV. Indeed, the prevailing view is that the best application for a FEL has yet to be found.

ACKNOWLEDGEMENTS

I'd like to acknowledge my colleagues in the FEL Division at Jefferson Lab, whom I have had the privilege to work with. I would also like to thank our users for sharing their results and enthusiasm for working at our facility

REFERENCES

[1] C. L. Bohn, et al, "Performance of the Accelerator Driver of Jefferson Laboratory's Free-Electron Laser," *Proceedings of the 18th Particle Accelerator Conference (PAC 99)*, New York, NY, March 29-April 2, 1999.

[2] G. R. Neil, *et al*., "Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery," Phys. Rev. Lett. 84 (2000) pp 662-665.

[3] M. D. Shinn, *et al*., "The Jefferson Lab FEL User Facility," in *Laser-Induced Damage in Optical Materials: 1999*, Gregory Exharos, Arthur Guenther, Keith Lewis, M. J. Soileau, Editors, Proceedings of SPIE 3902, (2000) pp. 355-360.

[4] Christopher Behre, Stephen Benson, George Biallas, James Boyce, Christopher Curtis and Others, "First Lasing of the IR Upgrade FEL at Jefferson Lab", Nuclear Instruments & Methods in Physics Research, A528, (2004) pg 19.

[5] G. R. Neil, C. Behre, S. V. Benson, M. Bevins, G. Biallas, J. Boyce, J.Coleman, L.A. Dillon-Townes, D. Douglas, H. F. Dylla, R. Evans, A. Grippo, D. Gruber, J. Gubeli, D. Hardy, C. Hernandez-Garcia, K. Jordan, M. J. Kelley, L. Merminga, J. Mammosser, W. Moore, N. Nishimori, E. Pozdeyev, J. Preble, R. Rimmer, M.Shinn, T. Siggins, C. Tennant, R. Walker, G. P. Williams, and S. Zhang, "The JLab High Power ERL Light Source", Nuclear Instr. & Methods A557 (2006) pg 9.

[6] M. D. Shinn, "High Average Power Free-Electron Lasers - A New Laser Source for Materials Processing," in *High Power Laser Ablation*, Claude A. Phipps, Editor, Proceedings of SPIE 4065, (2000) pp 434-440.

[7] G. R. Neil, "Applications for Energy Recovering Free-Electron Lasers", paper MOZBC03, Proceedings of the 22nd Particle Accelerator Conference (PAC07) Albuquerque, NM, June 25-29 2007.

[8] M. D. Shinn, G. R. Baker, C. P. Behre, S. V. Benson, M. E. Bevins, L. A. Dillon-Townes, H. F. Dylla, E. J. Feldl, J. F. Gubeli, R. D. Lassiter, F. D. Martin, and G. R. Neil "Design of the Jefferson Lab IR Upgrade FEL Optical Cavity," Nuclear Instruments and Methods A507, (2003) pp 196-199.

[9] G.P. Williams, "Far-IR/THz radiation from the Jefferson Lab FEL Energy Recovered Linac", Rev. Sci. Instr. 73 (2002).1461.

[10] G.L. Carr, M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil and G.P. Williams, "High Power Terahertz Radiation from Relativistic Electrons", Nature 420 (2002) pp 153-156.

[11] See Carbon Nanotechnologies Inc. web site: http://www.cnanotech.com/pages/store/6-0_online_store.html .

[12] M.W. Smith, private communication 2003.

[13] J. Ouellette, "Building the Nanofuture with Carbon Tubes," The Industrial Physicist 8(6) 2002 pp18-21.

[14] P.C. Elkund, B.K. Pradhan, U.J. Kim, Q. Xiong, J.E. Fischer, A.D. Friedman, B.C. Holloway, K. Jordan, and M.W. Smith, "Large-Scale Production of Single-Walled Carbon Nanotubes Using Ultrafast Pulses from a Free Electron Laser," Nanoletters 2, (2002) pp 561-566.

[15] M. Kelley, "Surface processing and micromachining of polyimide driven by a high average power infra-red free electron laser", Mat. Res. Soc. Symp. (2000) pg 617.

[16] D. Bubb et al, "Resonant infrared pulsed-laser deposition of polymer films using a free-electron laser", J. Vac. Sci. Tech A19 2001 pp 2698-2702.

[17] E. Carpene, P. Schaaf, M. Han, K.-P. Lieb and M. Shinn, "Reactive Surface Processing by Irradiation with Excimer Laser, Nd:YAG Laser, Free-Electron Laser and Ti: Sapphire Laser in Nitrogen Atmosphere" Applied Surface Science 186 (2002) pp 195-199.

[18] E. Carpene, M.Shinn, and P. Schaaf, "Synthesis of highly oriented TiNx coatings by free-electron laser processing of titanium in nitrogen gas", Appl. Phys. A247, (2005) pp 307-312.

[19] P.Schaaf, M. Shinn, E. Carpene, and J. Kaspar, "Direct Laser Synthesis of functional coatings by FEL treatments", Proceedings of the Third Intl WLT-Conf on Lasers in Manufacturing, (2005) pg 399.

[20] R. Rox Anderson, William Farinelli, Hans Laubach, Dieter Manstein, Anna N. Yaroslavsky, Joseph Gubeli III, Kevin Jordan, George R. Neil, Michelle Shinn, Walter Chandler, Gwyn P. Williams, Steven V. Benson, David R. Douglas, H.F. Dylla, "Selective photothermolysis of lipid-rich tissues: A free electron laser study", Lasers in Surgery and Medicine 38,(10), pp 913-919

[21] J. Michael Klopf, Matthew Coppinger, Nathan Sustersic, James Kolodzey, and Gwyn P. Williams, "High-Power Terahertz Source Opens the Door for Full-Field Video-Rate Terahertz Imaging", prepared for Nature.