JLAB-ACC-99-18

A Kilowatt Average Power Laser for Sub-Picosecond Materials Processing

Stephen V. Benson, George R. Neil, C. Bohn[a], G. Biallas, D. Douglas, F. Dylla, J. Fugitt, K. Jordan, G. Krafft, L. Merminga, J. Preble, M. Shinn, T. Siggins, R. Walker, and B. Yunn

Thomas Jefferson National Accelerator Facility
12000 Jefferson Ave Newport News VA 23606 USA

[a]Fermi National Laboratory
Batavia Illinois

ABSTRACT

The performance of laser pulses in the sub-picosecond range for materials processing is substantially enhanced over similar fluences delivered in longer pulses. Recent advances in the development of solid state lasers have progressed significantly toward the higher average powers potentially useful for many applications. Nonetheless, prospects remain distant for multi-kilowatt sub-picosecond solid state systems such as would be required for industrial scale surface processing of metals and polymers. We present operational results from the world's first kilowatt scale ultra-fast materials processing laser. 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. In its initial operation at high average power it is capable of wavelengths in the 2 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 in the near future will extend operation beyond 10 kW CW average power in the near IR and kilowatt levels of power at wavelengths from 0.3 to 60 microns. This paper will cover the design and performance of this groundbreaking laser and operational aspects of the User Facility.

Keywords: Free-electron laser, energy recovery, picosecond pulses, laser processing

1. INTRODUCTION

The Thomas Jefferson National Accelerator Facility, a $600 million U.S. Department of Energy national laboratory, serves basic science by carrying out a primary mission of nuclear and particle physics research. To enable this basic science, Jefferson Lab developed technology and constructed, commissioned, and is now operating the world's pioneering large superconducting radio-frequency (SRF) electron accelerator, CEBAF,[1] a 6 GeV accelerator. At more modest energies, such linacs are also the key to producing coherent, single-wavelength light—that is, laser light—with much higher average power than is available from most conventional lasers, and, also unlike conventional lasers, with tunability to any of a wide range of wavelengths while providing picosecond pulses. Industry has defined a clear need for a cost-effective source of such light, and has identified Jefferson Lab's SRF technology as a key technology for achieving it.

The sections below summarize this opportunity represented by SRF-driven FELs and reports on the cooperative industry-university-government-laboratory program now underway at Jefferson Lab to develop them. We begin with a discussion of the rationale that drives these applications to FELs.

2. WHY FELS?

In principle, laser light offers an efficient, spatially and chemically precise, and environmentally benign way to process materials, as in surface-modifying polymers and metals and in micromachining. Recently it has been shown that picosecond pulses can greatly increase the efficiency of laser material processing[2]. Light of a single wavelength can also enhance the specificity and efficiency of laser processing. However, cost, capacity, wavelength, and pulse-length constraints have limited or even stymied progress with conventional lasers. Therefore a number of high-technology corporations (some of which are listed below) and research universities, believing in the potential of SRF-driven FELs to overcome these constraints, have formed the Laser Processing Consortium, and have joined with Jefferson Lab to develop the needed laser technology. Consortium members plan a range of industrial applications.

In the area of polymer surface processing, they intend to develop:

- Amorphization to enhance adhesion (3M)
- Fabric surface texturing (DuPont)
- Enhanced food packaging (DuPont/TetraPak)
- Induced surface conductivity (Xerox)

In micromachining:

- Ultrahigh-density CD-ROM technology (3M, Aerospace)
- Surface texturing; micro-optical components (3M)
- Micro-Electrical Mechanical Systems (MEMS) (Northrop Grumman, Aerospace)
- In metal surface processing:
- Laser glazing for corrosion resistance; adhesion pre-treatments (Ford, GM, Newport News Shipbuilding, Armco, Virginia Power)

In electronic materials processing:

- Large-area processing (flat-panel displays); laser-based "cluster tool" for combined deposition, etching, *in situ* diagnostics (IBM, Xerox, Lucent)

3. POTENTIAL PRODUCTS

Further details of two of these applications will illustrate a typical rationale for development. Polymer processing, for example, is expanding in both traditional and new applications. World wide synthetic fiber capacity was projected to have reached 60.3 billion pounds in 1997[3]. The use of PET packaging continues to grow rapidly. Bottle capacity alone was expected to reach 13.7 billion pounds in 1997[3]. Aseptic systems that extend the unrefrigerated shelf life of foods are expected to increase as use expands in newly developing countries. These applications already rely on a number of chemically induced modifications to the basic polymer to achieve the desired functionality.

Processing with photons offers the possibility of achieving similar enhancements in an environmentally benign way. For example, in the case of surface texturing it has been demonstrated that use of an excimer laser pulse on fabric results in surface melting of the fibers producing a ridged effect on a spatial scale similar to natural fibers[3]. This texturing results in fibers which feel softer, are more hydrophilic, and have more intense colors on dying due to the elimination of reflective backscatter. Workers at 3M showed that improved adhesion for polyester[4] and polyimide[5] to themselves and to metals could be obtained using a single pulse of 248 nm excimer laser light at 30 mJ/cm^2. The application of 200 nm light on nylon has also been shown to produce a photochemical effect on the surface, which renders the polymer surface permanently anti microbial. [6]

The potential market for such applications is enormous. Standing in the way is the development of a suitable light source. Requirements for the light source include power, wavelength, cost per kilojoule of light delivered, etc. A serious aspect to consider is scale. A typical new fiber plant produces between 1 and 3 x 10^{10} m^2/yr of surface area. At 1 J/cm^2 fluence this would require more than 10 kW of average power on target running continuously year round. Power outputs at this level exist commercially at only a few specific wavelengths with continuous wave lasers, which may not coincide with the industrial process requirements. No light source other than FELs has the potential to meet the power and wavelength requirements.

In a second example application area, metals surface processing, a number of new metals surface characteristics are desired which may be achievable using FELs. For example, it is well known that amorphous Fe-C metals exceed their crystalline counterparts in strength (by 250%), toughness (600%), and resistance to corrosion (down by two orders of magnitude)[8]. A surface amorphous layer could therefore result in considerably improved surface sensitive properties such as wear, erosion, fatigue, and corrosion resistance. Both CO_2 and pulsed excimer laser treatments have demonstrated improvements in hardness, wear, and fatigue resistance. However, neither laser is capable of producing amorphous layers on structural alloys.

Here the short pulses at high pulse repetition rates is key to making the process work. The picosecond pulses produced by the FEL are temporally at the transition between heat transfer directly to the electrons and transfer to the bulk lattice. The pulse duration determines both the cooling rate and the depth of the melt zone. For such short pulses a shallow zone of melting will occur for single pulses and cooling might occur at rates as high as 10^{13} °K/sec[9], that is, rapid enough to prevent crystallization. This exceeds by more than three orders the cooling rates achieved with longer pulse lasers such as excimers or Nd:YAG lasers. With pulsed excimers in the ns regime typical modified surface layers on structural ferrous alloys are microcrystalline, and the melt-modified layer is on the order of microns[10,11]. Although the diffusion length is expected to be a few atomic spacings during the few hundred picosecond melt lifetimes, rapidly repeated local application of FEL pulses is expected to permit us to vary the depth and duration of the melt and thus the diffusion. Mixing of compounds or alloys applied at the surface also may be feasible. Potential products are wide ranging: turbine blades, bearing surfaces, exposed structural components, etc.

Further opportunities exist for metal and semiconductor micromachining because of the sub-picosecond nature of the FEL output pulse. A number of ongoing research programs have identified the higher efficiency of micromachining that occurs for pulse lengths down to of order of a picosecond2. While such research has been reported only for pulse repetition rates up to 1 kHz, FELs can produce such pulses at substantially higher rates. For example, the JLAB IR Demo FEL operates at up to 74.7 MHz. This opens the possibility of extremely efficient large-scale production using such a machine. The key thing to note is that while the advantages of short pulse ablation are clear, only the FEL has a clear path to achieving the high average powers to take advantage of that physics in a major commercial environment.

4. FEL DEVELOPMENT

To explore the feasibility of these applications it was desirable to have a subscale testbed which would permit study of both the desired process and the technical limits to power scalability in the FEL. By 1993 the Laser Processing Consortium had coalesced from interested industry and university partners to form a development plan. Thanks to funding from the Office of Naval Research, the result of that effort is now operational: a kilowatt-output infrared (IR) device called the IR Demo. Experience gained with this proof-of-principle IR Demo FEL is planned to lead to FELs at still higher powers not only in the IR but also in the ultraviolet (UV), eventually leading to a 100 kW prototype device for cost-effective manufacturing use at industrial sites. Figure 1 shows the power output of the IR Demo FELs at the wavelengths through which it has lased so far. Other picosecond sources in this wavelength range would not even show up on this graph. In providing more than two orders of magnitude higher average output than other sources that cover this wavelength range or pulse length, this user facility might be considered the world's first fourth-generation light source.

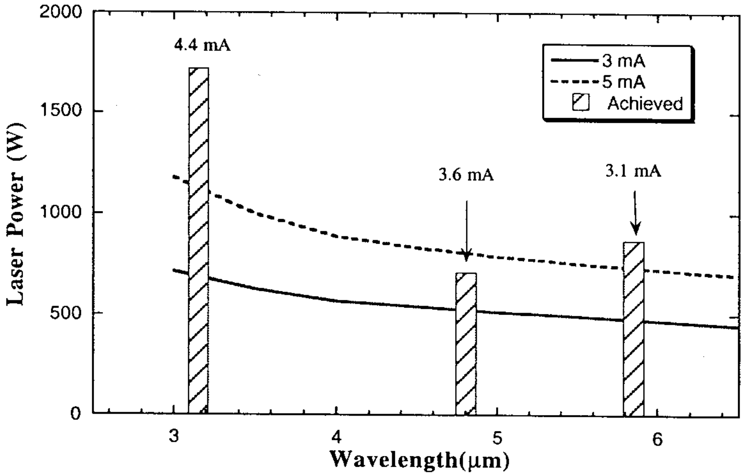


Figure 1. Predicted power versus wavelength for IR Demo with 3 and 5 mA of beam current and the power achieved with three different mirror sets and the currents at which they were achieved.

Figure 2 shows the IR Demo FEL schematically. The 1 kW device is designed to provide laser light at wavelengths from 3.0 to 6.6 μm, with optical beam quality two times the diffraction limit. In this first FEL, about 99% of the energy from acceleration in the 40 MeV cryomodule is recovered. (When the 10 MeV of pre-acceleration from the injector is accounted for, this actually represents only about 80% of the beam's overall energy. In planned future FELs, with higher ratios of accelerator energy to injector energy, this difference will lessen, with a corresponding rise in the benefit of energy recovery.)

In initial experiments without energy recovery, the laser power reached 311 W with 1.1 mA of electron beam current[12]. We repeat the FEL design parameters in Table 1 for reference. 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, presumably due to mirror heating. 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_2 mirrors 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.

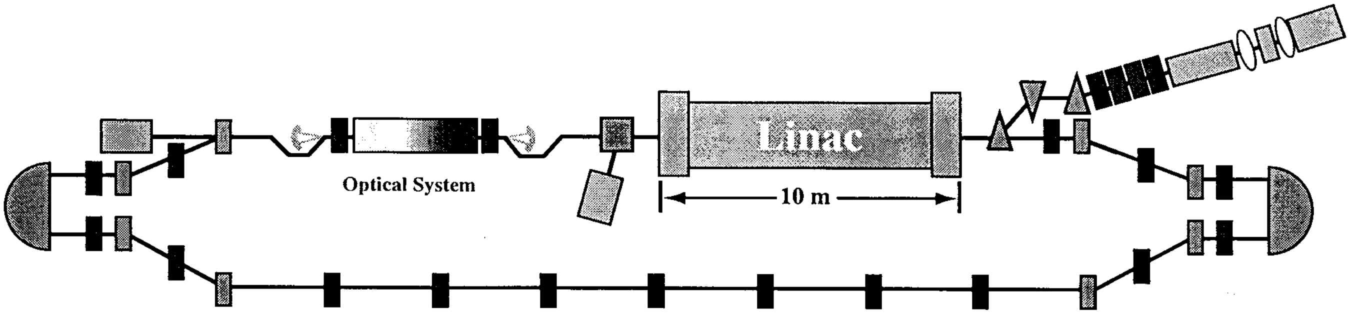


Figure 2. Layout of IR Demo FEL. The electron originates in a photocathode DC gun, is bunched and accelerated to 10 MeV in the injector cavities, and is injected into a 40 MeV cryomodule. At full energy the beam is bent around the two mirrors of the optical cavity and travels through the wiggler. The spent beam is transported back around, decelerated in the accelerator module, and dumped at the injection energy of 10 MeV.

The power limit in lasing up to this time 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 optical cavity[13]. Even small absorption can cause a change in the radius of curvature of the mirror that leads to significant changes in the Rayleigh range in the wiggler. For the 5 micron mirrors, the implied coating absorption is on the order of 0.04% or 3 watts per mirror.

Table 1: 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

Despite a thermalization time of several seconds in the mirrors, changes in the local curvature can happen quickly, on the order of milliseconds as was observed for 18.7 MHz operation versus 37.4 MHz. Within 0.05 second the output power becomes identical despite twice the current in the 37.4 MHz case (see Figure 3). It should be emphasized that these effects occur despite aggressive measures taken to edge-cool the mirrors in thermally stabilized, water-cooled copper holders.

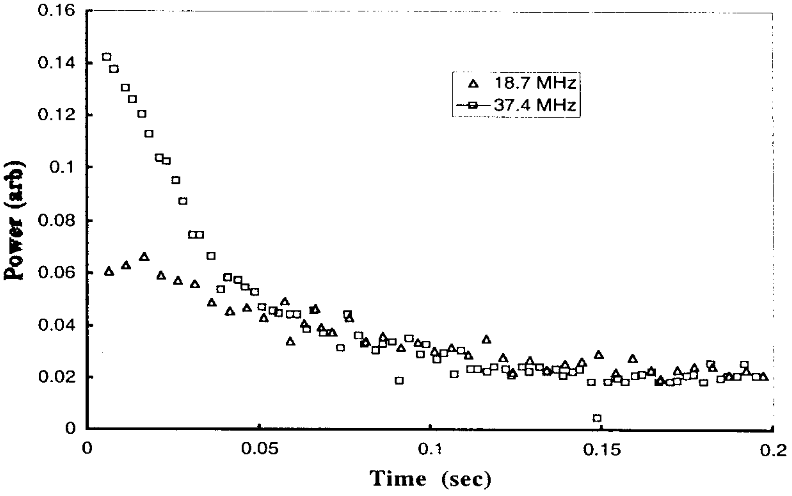
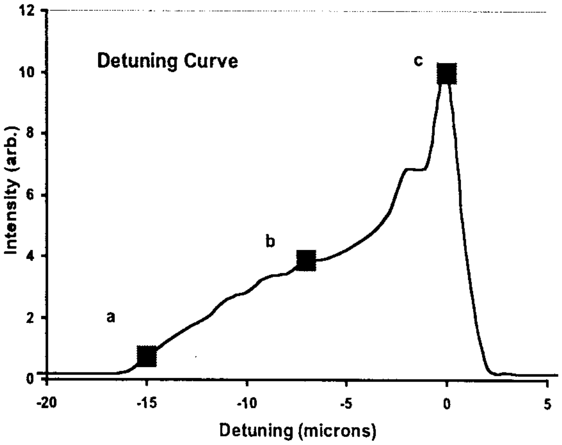


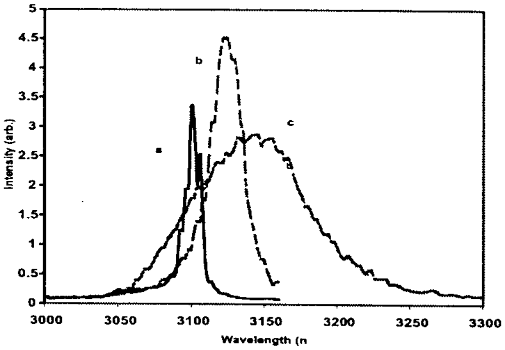
Figure 3. Power versus time during long pulsed lasing. The electron beam conditions are the same for the two curves except that the repetition rate of the micropulses has doubled in the 37.4 MHz case. The laser power is the same after a short time due to the mirror distortion.

By operating at 47.8 MeV and 4.4 mA for an electron beam power in excess of 200 kW and replacing MLD coated calcium fluoride mirrors with sapphire mirrors with a similar low loss (<0.1%) mirror coating, 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 could lase stably for hours at powers > 1000W.

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 9 (see figure 4). Recent measurements at 5 microns indicate that the pulses are nearly transform limited there and that pulses as short at 600 fsec FWHM can be achieved at that wavelength. Even shorter pulses are expected at 3 microns.



(a)



(b)

Figure 4. The power versus cavity length is shown in (a). The spectra at the points indicated in (a) are shown in (b).

5. 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.

6. ACKNOWLEDGMENTS

This paper represents the efforts of the Jefferson Lab Accelerator Division and the Jefferson Lab FEL Team. Work is supported by Navy/DOE Interagency Agreement No. 1846-J053A1, DOE Contract # DE-AC05-84ER40150, and by the Commonwealth of Virginia and the Laser Processing Consortium.

7. REFERENCES

1. H. Grunder, "CEBAF Commissioning and Future Plans," Proceedings of the 1995 Particle Accelerator Conference.
2. B.C. Stuart, S. Herman, and M.D. Perry, "Laser-induced damage in dielectrics with nanosecond to subpicosecond pulses I. Experimental", SPIE 2428 (1995), pp. 568-578 .
3. Michael J. Kelley, " An FEL for the Polymer Processing Industries", SPIE 2988 (1997), pp 240-243.
4. A. J. Ouderkirk, D. S. Dunn, R. W. Warner, U. S. Patent 4,822,451, April 18, 1989.
5. A. J. Ouderkirk and D. S. Dunn, Euro. Patent Appl. 0-566-790-A1, August 25, 1993.
6. J. D. Cohen, C. W. Erkenbrecher, S. L. Haynie, M. J. Kelley, H. Kobsa, A. N. Roe, and M. H. Scholla, U. S. Patent 5,428,078, June 27, 1995.
7. G. R. Neil, "A Cost Estimation Model for High Average Power FELs," Proceedings of the 1995 Particle Accelerator Conference.
8. J. J. Gilman, "Overview of the Technology and Significance of Metallic Glasses", J. de Physique (C8) (8) (41) (1980) pp C8-811 to C8-819.
9. C. –J. Lin and F. Spaepen, "Fe-B Glasses Formed by Picosecond Laser Pulse Quenching", Appl. Phys. Lett. 41, (8) (1982) pp 721-723.
10. O. V. Akgun, O. T. Inal, M. L. Lovato, and T. J. Jervis, " Effect of Laser Surface Melting on Tensile Properties of Type 304L Stainless Steel", Scripta Met. 27 (1992) pp 191-194.
11. J. –P. Hiroven, T. R. Jervis, and T. G. Zocco, " Migration of Carbon in Tempered Martensitic Steel During Excimer Laser Melting" Mat. Res. Symp. Proc. 157 (1990) pp 431-436.
12. S. Benson et al., "First Lasing of the Jefferson Lab IR Demo FEL", Nucl. Inst. And Meth. A 429 (1999)pp. 27–32.
13. S. V. Benson, P. S. Davidson, R. Jain, P. K. Kloeppel, G. R. Neil, and M. D. Shinn, "Optical modeling of the Jefferson Laboratory IR Demo FEL", Nucl. Inst. and Meth. A407 (1998) 401–406.