High Average Power Free-Electron Lasers - A New Laser Source for Materials Processing

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ABSTRACT

Material processing with lasers has grown greatly in the previous decade, with annual sales in excess of $1 B (US). In general, the processing consists of material removal steps such as drilling, cutting, as well as joining. Here lasers that are either cw or pulsed with pulsewidths in the μs time regime have done well. Some applications, such as the surface processing of polymers to improve look and feel, or treating metals to improve corrosion resistance, require the economical production of laser powers of the tens of kilowatts, and therefore are not yet commercial processes. The development of FELs based on superconducting RF (SRF) linac technology provides a scaleable path to laser outputs above 50 kW, rendering these applications economically viable, since the cost/photon drops as the output power increases. Such FELs will provide quasi-cw (PRFs in the tens of MHz), of ultrafast (pulsewidth ~ 1 ps) output with very high beam quality. The first example of such an FEL is the IR Demo FEL at the Thomas Jefferson National Accelerator Facility (Jefferson Lab), which produces nearly 2 kW of high average power on a routine basis. Housed in a multilaboratory user facility, we as well as members of our user community have started materials process studies in the areas mentioned earlier. I will present some of the first results of these studies. I will also briefly discuss the status of our DOD-funded project to upgrade the FEL to 10 kW in the mid IR.

Keywords: Free-electron laser, high average power laser, materials processing, ultrafast lasers

1. INTRODUCTION

The use of lasers for material processing was recognized fairly early, but their expense and unreliability impeded their adoption in shops and factories. Only some 15 years after the invention of the ruby laser did companies making "industrial" lasers begin having reasonable sales.[1] The decade of the 1990s saw sales of all lasers used for material processing (except those based on diode lasers) quadruple, with sales now exceeding $1B (US). The majority of these lasers are CO_2 or Nd:YAG technologies with cw or long-pulsed (ms long pulses at 100s of Hz rates) temporal formats, although excimer lasers have gained in popularity. Basic physics constraints on the stored energy per unit volume and gain sets the output of single-rod Nd:YAG lasers at about 1 kW, and a few hundred watts for excimer lasers. For the processing steps performed, such as welding, cutting, and drilling, these lasers are adequate. However, there are processing opportunities with lasers that are unexploited because they are best performed by a laser with a short pulse (ns to ps) and high PRF (100 kHz to MHz) output with average power above 10 kW.[2]

As will be explained in more detail, one type of laser can meet these requirements: a free-electron laser (FEL) using a superconducting radiofrequency (SRF) linac. Recognizing this, staff at the Thomas Jefferson National Accelerator Facility (Jefferson Lab), the United State's center of expertise in SRF technology, in partnership with industry and academia, proposed building a kilowatt-class laser that received funding in FY97 from the U.S. Department of the Navy. Along with funding from the U.S. Department of Energy, the Commonwealth of Virginia, and industry, this FEL (called the IR Demo) completed commissioning in August 1999. Producing over 1.5 kW of average power at 3.1 μm, we have concentrated our efforts on quantifying its performance, and making the accompanying user facility operational. Previous reports provide details about the FEL driver accelerator, the laser itself, and the facility so these topics will be touched on only briefly.[3,4] This paper concerns itself with the use of high average power (many tens of kilowatts) FELs built using the same technology as the IR Demo to do materials processing at scales that make these processes commercially viable. Some of these processes, such as pulsed laser deposition (PLD), are well known, but are currently unexploited, or have limited

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impact on markets, because of the limitations of the laser systems employed. The initial results on PLD and other processing presented here bolster the case for using a laser with characteristics like an FEL.

2. THE IR DEMO FEL

2.1 Accelerator

A schematic of the IR Demo FEL is shown in Fig. 1. The driver accelerator uses superconducting RF (SRF) accelerator technology consisting of a 10 MeV injector (containing a DC photocathode gun driven by a Nd:YLF laser) and another SRF linac (whose gradient may be as high as ~ 38 MeV) to produce an electron beam with an average current of ~ 4.5 mA at PRFs as high as 74.85 MHz. About one percent of the electron beam power is converted to outcoupled laser radiation, the rest is transported back through the linac where the e-beam is decelerated and ~ 75% of its kinetic energy is converted into RF power. This reduces the IR Demo's utility demands 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.

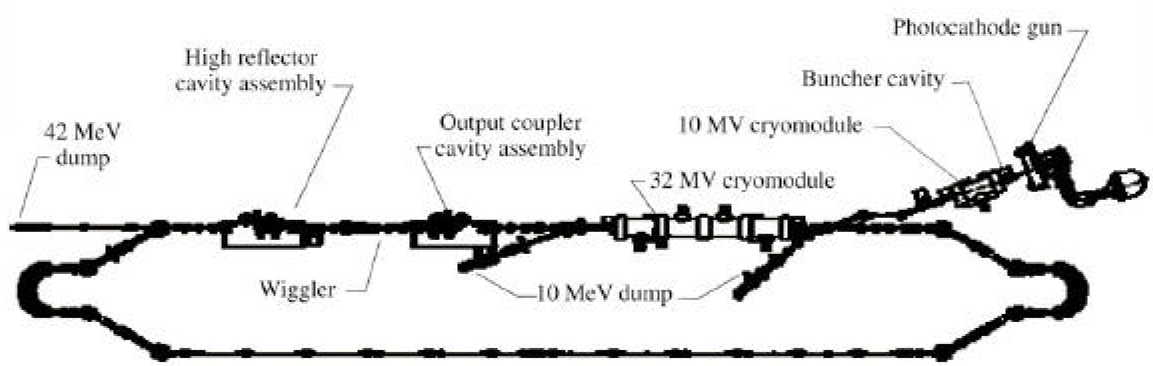

Figure 1 Schematic drawing of the IR Demo.

2.2 FEL Optical Cavity

The optical cavity is a near-concentric resonator with dielectrically coated mirrors. The choice of substrate is dictated by the wavelength range; typically sapphire is used for $\lambda < 4$ µm, and ZnSe is used for longer wavelengths. We have also used calcium fluoride as a substrate, but it's thermomechanical properties limit the laser output to less than a kilowatt. Typical outcoupling is on the order of 10%. The laser wavelength is tuned by setting the electron beam energy so that the wiggler radiation is in the range where the cavity has adequate Q. For a given set of mirrors, we can typically tune over a range of 300-500 nm. To date, we have mirrors that permit operation centered at the following wavelength regions: 3.2 µm, 5 µm, and 6 µm. The performance of the IR Demo is given in Table 1.

Table 1 IR Demo Specifications and Measured Performance

Property	Specification	Achieved
Average Power (W)	600-1000	1720
Wavelength range (µm)	6.5-3	6.2-3
Micropulse energy (µJ)	~ 25	23
Pulselength (ps)	~ 2	0.5-1.7
PRF (MHz)	37.425, 18.7	74.85, 37.425, 18.7
Bandwidth ($\Delta\lambda/\lambda$)%	~ 0.2-0.5	0.2–3.3
Timing jitter (ps)	< 0.2	Not yet measured
Amplitude jitter (p-p)	< 20%	< 10%
Wavelength jitter (RMS)	0.02%	Not yet measured
Linear polarization	> 100:1	> 6000:1
Transverse mode quality (M^2)	< 2	≤ 2

Beam diameter in labs (cm)	2-4	1.5-3.5

2.3 The User Facility

The user facility is a two story building constructed of reinforced concrete that is "floated" on compacted earth, with the first floor built below grade for radiation containment. A schematic drawing of the second floor is shown in Fig. 2. A box structure of reinforced concrete and compacted earth provides the shielding between the first and second floors, and provides a well-damped platform for the beam transport optical components. The FEL output is transported in a vacuum (at ~ 10 mTorr), to avoid absorption by the atmosphere. The beam is transported along the ceiling of the accelerator vault for a distance of ~ 50 m and then directed through a penetration in the second floor to the Optical Control room (*c.f.* Fig. 2), where ~ 0.1% of the output is reflected by a CaF_2 window placed near Brewster's angle. This beam is then distributed to the diagnostic suite of instruments. The majority of the beam then continues down the transport line that runs along the back wall of each user lab, and is distributed into the labs. If desired, it is possible for more than one lab to receive beam. All mirrors in the transport are protected silver on uncooled metal substrates. The choice of metal coatings allows us to transport the wide tuning range of the IR Demo 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 is the loss of ~ 30% of the laser output to absorption and scatter. Each of the six user labs (total area ~600 m^2) is marked with an application that is either on going or proposed. The second floor also includes areas for RF power, a Class 10000 clean room that houses the drive laser for the injector, the Control Room, and the Optical Control Room. 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 it's 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 network, which provides another way for remote instrument control. About half the labs have chemical hoods.

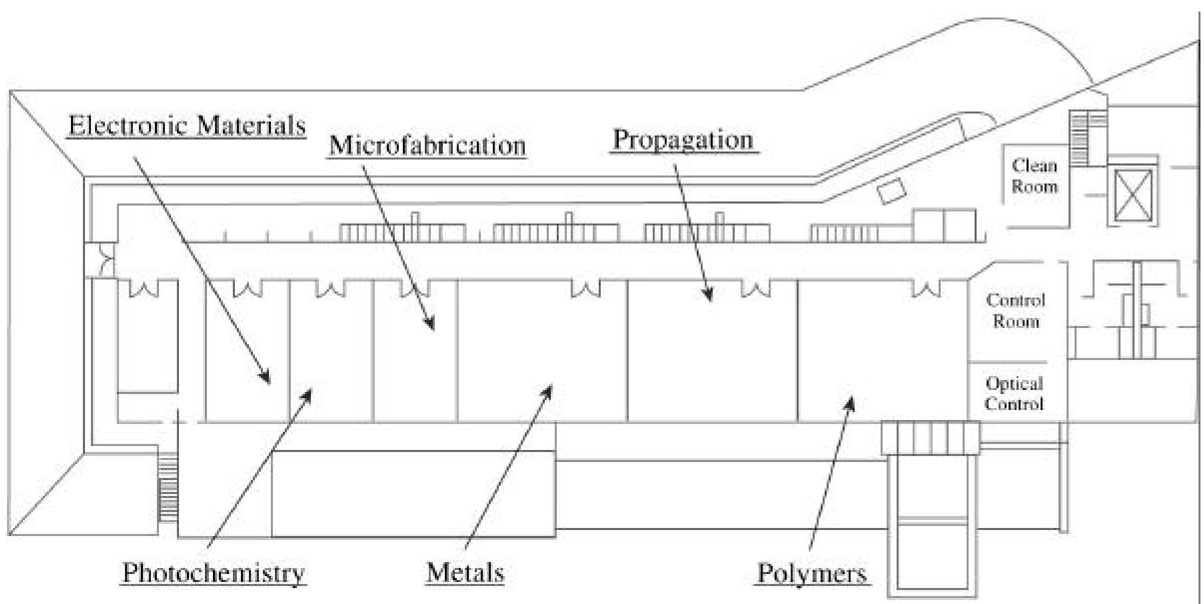

Figure 2 Schematic drawing of 2nd floor of the IR Demo User Facility

3. HIGH AVERAGE POWER MATERIAL PROCESSING OPPORTUNITIES

Considering the high average power lasers in industry today, the standards are Nd:YAG lasers of about 1 kW output, and CO_2 lasers of about 6 kW output. Both do well enough, but there has been little impetus to go to higher power versions, since they are well matched to the processing steps. Considering applications of high average power lasers with outputs above 10 kW, for the most part they fall into one of two categories: thermal processing or ablative processing. A list is given in Table 2.

Table 2 High Average Power Applications

Processing Type	Example
Thermal	Surface texturing
	Surface amorphization
	Laser glazing and annealing
	Adhesive bond pretreatment
	Crystallizing amorphous silicon
	Laser annealing, deposition, and cutting for photovoltaics
	Solvent-free cleaning
Ablative	Micromachining
	Cutting and slitting
	Deposition of large area thin films

For many of these processes, the benefits of using a laser was proven (and often patented) using lower powered lasers at subindustrial scales. However, these processes haven't become prevalent because the power of the lasers used can't be scaled to the levels (> 10 kW) required. For example, despite a large number of publications showing the benefits of various short-pulsed (particularly ultrafast) lasers in materials processing[5,6], their presence in a commercial environment has been limited. Ultrafast lasers have not achieved high average power status, and based on the nature of the amplification process, aren't likely to. And yet, there are compelling reasons to use ultrafast lasers; such as (1) a lower threshold for ablation, (2) more deterministic damage, (3) ablation with minimal heat-affected zone in metals, and no cracking or melting in insulators and ceramics. Along with a short-pulse time structure, other desirable properties of a high power laser are a high PRF (many 10 kHz to MHz) and wavelength agility, so absorption bands (if present) in the material can be accessed. Comparing these criteria to the performance of the IR Demo FEL, one sees that there is an excellent match. However, a case must be made that the cost/photon for an SRF-FEL is comparable to the industrial lasers now in use.

4. THE ECONOMICS OF HIGH AVERAGE POWER FELS

Casual inspection of Fig. 1 suggests that the IR Demo is large. Indeed, the long axis of the accelerator is about 40 m. Given the research nature of our facility, we made the machine much larger than needed to investigate (and possibly mitigate) some accelerator-physics-related issues, and to have a generous amount of electron beam diagnostics. The current machine could be about one half the length, knowing what we know now. Of more relevance is the fact that the upgraded FEL we are designing is not much longer than the current machine, but delivers ten times the power. This is achieved by raising the beam current and adding more sections to the linac to increase the electron beam energy, since the FEL output is proportional to the electron beam power (the product of the current and energy). This highlights a unique feature of FELs: the power can be scaled up without an enormous penalty in space. As mentioned in the Introduction, basic physics constraints on the energy density achievable with lasers based on other technologies means buying more lasers in order to increase the power available for a material processing procedure. Over and beyond space constraints, the complexity of then combining the output of these lasers and possibly synchronizing them as well comes into play.

The question then is: can FELs, which are big, complex machines, provide laser light at a cost that is commensurate with other laser sources? To answer this, we have chosen the cost/photon delivered, in $/kJ, as the quantity for comparison. The cost model accounts for the capital and operating costs, with amortization over 10 years. For the FEL, costs for items like cryogens, the He refrigerator, accelerator modules, etc., were drawn from JLab experience.[7] For other laser systems, costing was done using catalog prices.[8-10] The results are shown in Table 3. For comparison, the projected costs for an FEL using recirculation and energy recovery are shown in Fig. 3.

Table 3 Cost/photon Estimates For Various Lasers

Laser Type	Output Power	Cost/kJ
Nd:YAG	3 kW	$0.002
CO_2	6 kW	$0.002
KrF excimer	100 W	$0.20
ArF excimer	100 W	$0.50

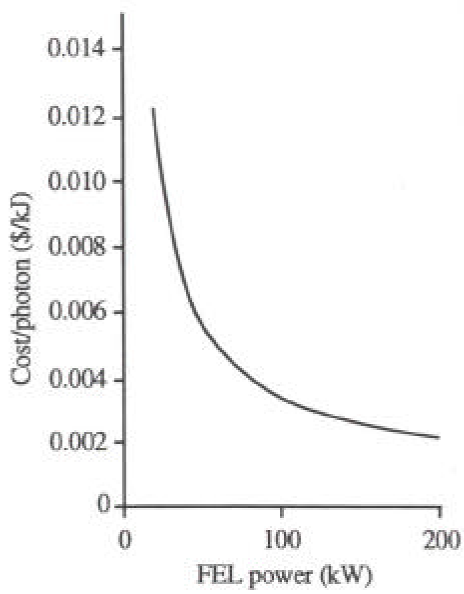

Figure 3 Cost/photon as a function of power for an energy-recovering, recirculating FEL.

From the figure, the cost/photon for an FEL becomes comparable (within a factor of two) to industrial CO_2 and Nd:YAG lasers in the 50-200 kW range. This matches up well for some of the applications shown in Table 2.

5. INITIAL MATERIAL PROCESSING RESULTS

5.1 Metal processing

Cutting as well as drilling of holes in metal parts is often a processing step, and the rates for various cw lasers are known.[1] More recently, work at LLNL has given ablation rates for different metals as a function of fluence, or for a fixed fluence, as a function of thickness.[11,12] Using their data, for a fluence of about 1 J/cm^2, an ablation rate of about 20 nm/pulse was determined for 306 stainless steel. At a PRF of 1kHz, this results in long times (tens of seconds) to cut through even thin plates of steel. Since the IR Demo can achieve this fluence, and has a PRF some 10^4 times higher than other ultrafast lasers, our burnthrough rates should be faster. How much faster was an unknown, since the high PRF means laser pulses after the first one will interact with the ablation plume.[2] I measured this rate using the IR Demo, for a single thickness (750 μm) of 304 stainless steel. Measurements were done at a 37.425 MHz PRF, with a micropulse energy of 10 μJ. Focused to a waist radius of ~ 30 μm, this yields a peak fluence per micropulse of 0.7 J/cm^2. The sample was irradiated at 3.1 μm with a 1 sec long train of micropulses. Measurements showed that the time for complete burnthrough, defined as the time at which the transmitted intensity of the FEL harmonics becomes constant, occurred in 4 ms. This yields an average ablation rate of 5 nm/pulse, lower than that measured by Banks *et al.*[11], but of the same order. This burnthrough time is ~ 10^4 times faster than reported by Stuart *et al.*[12], and results in a drilling rate comparable to cw lasers. It should be pointed out that these results are preliminary, and analyses of data taken at a lower PRF remains to be done before the question of plume clearing can be answered.

5.2 Pulsed laser deposition

Pulsed laser deposition (PLD) has a long research history, but has made little progress in the commercial sector.[13] While capable of depositing materials that would be difficult if not impossible by traditional CVD techniques, control of defects such as particulates is still a topic of discussion in much of the literature. Traditionally, excimer lasers are used for pulsed laser deposition (PLD). The PRFs are low, a few 100 Hz or less and the fluence at the target high, 2-10 J/cm^2. This exacerbates the creation of particulates, because the quantity of material ablated by the laser is high. Also, the 30 ns (or longer) pulsewidths of the laser generally melts the target in the lower fluence region of the irradiated spot, and this material is then lofted by the expelled plasma. Recent work by Rode and coworkers showed that by using a modelocked laser with pulsewidth ~ 60 ps and high PRF (76 MHz), the particulate problem was essentially eliminated, and the growth rate up to an order of magnitude higher than with traditional lasers.[14,15].

Several years ago, A. Reilly proposed using the FEL as the laser source for PLD. As Table 1 shows, the IR Demo's pulse structure mimics that of the modelocked laser used by Rode and coworkers, but its energy per pulse is higher by nearly two orders of magnitude. Reilly's results are encouraging, with growth rates of ~ 20 nm/sec, and low (or absent) particulate generation.[16] We have recently begun exploring the use of the FEL to do PLD of Nb, and are getting similar deposition rates.[17] This rate is an order of magnitude higher than found by Rode and coworkers, and thus is about 100 times higher than that obtained with conventional lasers.

So, to summarize these early results, the IR Demo FEL, with it's moderately low fluence, cuts metals far faster than other ultrafast lasers and deposits films at faster rates than other lasers (ultrafast or traditional). Using FELs of higher average power (and similar PRFs) will allow higher rates of material processing, with a lower cost/photon, both desirable goals for a manufacturing environment.

6. FUTURE DIRECTIONS: THE FEL UPGRADE

The successful completion of the IR Demo FEL the first results from the users of our facility, and the results of our own experiments have all added impetus to upgrade the present machine. The goal of the Upgrade FEL project, as it is currently called, meets our three primary stakeholders (DOE/academia, Industry, and the Navy) interests to make the machine cover a larger spectral range (initially 2–14 µm) at a higher average power (>10 kW). To do this, we will add two more linac units, raising the electron beam energy to ~160 MeV, and raise the beam current to 10 mA. The optical cavity will be changed from a near-concentric resonator with a transmissive outcoupler to a ring resonator with a scraper outcoupler. The new cavity will be scaleable to outputs on the order of 100 kW in the IR. At the time of this Conference, we have received funds from the Southeastern University Research Association and will soon receive our FY00 funding from the Department of the Navy to begin building prototypes and actual components to make this goal a reality. With follow-on funding in succeeding fiscal years, the Upgrade FEL should be operational sometime in FY03. We are also pursuing funding to add another wiggler and optical cavity to produce kilowatt-class output in the UV and visible portions of the spectrum.

7. CONCLUSIONS

The goal of this paper is to serve as an introduction to the capabilities of a high average power FEL, and to illustrate, by extrapolation from other lasers, as well as our own results, how an FEL could be deployed for industrial-scale materials processing. Materials processing with an FEL combine the advantages of ultrafast, low average power lasers with high average power, cw lasers. While it isn't the ideal laser for all applications, when appropriately matched to the scale (or added value) of an application, it should enable some that have previously gone unexploited.

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