THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY FEL INDUSTRIAL APPLICATIONS

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Abstract

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. A technologically related secondary mission now also exists for Jefferson Lab: applied research to develop superconducting radio-frequency (SRF) -based free-electron lasers as cost-effective new manufacturing capabilities for industry. A number of high-technology corporations and research universities, believing in the potential of SRF-driven FELs to overcome the constraints of cost, capacity, wavelength, and pulse-length, 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, fabric surface texturing, enhanced food packaging, and induced surface conductivity. In micromachining, applications are ultrahigh-density CD-ROM technology, surface texturing; micro-optical components, and Micro-Electrical Mechanical Systems (MEMS). In metal surface processing proposed applications are laser glazing for corrosion resistance and adhesion pre-treatments. In electronic materials processing we will investigate large-area processing (flat-panel displays) and a laser-based "cluster tool" for combined deposition, etching, and *in situ* diagnostics. The potential commercial value of the technology is significant, impacting several multibillion-dollar markets. Moreover, significant additional applications exist in basic and applied research.

The FEL is laid out in a racetrack configuration to utilize energy recovery of the spent electron beam. The electrons are produced in a 350 kV DC photocathode gun and accelerated to 10 MeV in a superconducting accelerating unit with 1 meter of active length. The electrons are then accelerated in an SRF cryomodule up to an energy of 57 MeV. In order to minimize emittance-growth effects and to accelerate the commissioning process, the FEL is placed at the exit of the linac. The electron beam is deflected around two cavity mirrors in two magnetic chicanes with a path-length dispersion (M56) of 30 cm. After the FEL, the beam can be recirculated for energy recovery and dumped at the injection energy of 10 MeV. The recirculation loop is based on the isochronous achromat used in the MIT Bates accelerator but designed with an energy acceptance of 6%. We estimate that the power output at 3 μm should be 980 W with a small signal gain of 46%.

This paper will explore the technical and economic justification of the design and present the commissioning progress to date.

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. A technologically related secondary mission now also exists for Jefferson Lab: applied research to develop SRF-based free-electron lasers. Powerful, multipurpose free-electron lasers (FELs) driven by SRF electron accelerators prospectively represent substantial, cost-effective new manufacturing capabilities for industry.

To conduct its primary mission, Jefferson Lab uses its Continuous Electron Beam Accelerator Facility (CEBAF),[1] in which the laboratory's 4 GeV SRF accelerator cost-effectively provides high-quality, CW electron beams to three experiment halls. Such beams are the key to the basic research conducted at Jefferson Lab. At more modest energies, such beams 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. 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.

1.1 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. However, cost, capacity, wavelength, and pulse-length constraints have limited or even stymied progress with conventional lasers. Therefore a number of high-technology corporations and research universities, believing in the potential of SRF-driven FELs to overcome these constraints, have formed the Laser Processing Consortium, (see acknowledgments) 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
- Fabric surface texturing
- Enhanced food packaging
- Induced surface conductivity

In micromachining:

- Ultrahigh-density CD-ROM technology
- Surface texturing; micro-optical components
- Micro-Electrical Mechanical Systems (MEMS)

In metal surface processing:

- Laser glazing for corrosion resistance; adhesion pre-treatments

In electronic materials processing:

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

Concerning these prospective applications, an independently convened government review panel reported that the "potential commercial value of the technology is significant, impacting several multibillion-dollar markets."[2] Moreover, significant additional applications exist in basic and applied research.

1.2 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 modifications to the basic polymer to achieve the desired functionality. For example, the surface of fibers may be textured through use of special forming dies or altered through wet chemistry. As a different example, polymer packaging usually will consist of multiple layers to permit printing, increase strength or prevent permeation by oxygen, CO_2, or water. These treatments are costly and they complicate recycling efforts. They can result in environmentally undesirable effluent from the processing plant, and they may be only marginally successful at achieving 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 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 1J/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, 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.

The cost goals, while ambitious, also appear possible. Few surface modification procedures can be found which exceed 5 to 10 cents/m^2 in added value. When the desired fluence is considered (order 1 J/cm^2) it is clear that fully amortized costs of less than 1 cent/kJ are required. Scaling studies have projected that FELs can meet these cost goals provided single unit power outputs in excess of 10 kW can be achieved. [7]

The technical maturity of these applications varies from scientifically proven to speculative. In the case of surface texturing the phenomenology has been explored at UV wavelengths with excimers. Research at the Jefferson Lab FEL is aimed at exploring possible extensions into the IR where FELs are technologically easier and probably more cost effective. Other polymer applications await extensions of the FEL operation into the UV where research will explore the differences produced by the short pulse format of the FEL as compared to the excimer while utilizing the FEL's tunability to excite specific transitions.

In the second application area, metals 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 will occur at rates of 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 YAGs. 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. The level of cost sensitivity varies with the application but delivered costs of the light still need to be in the less than 1 cent/kilojoule range to make most of the applications attractive.

2 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. A plan was formulated for beginning FEL development with a kilowatt-scale infrared (IR) device—about two orders of magnitude more powerful than previous, non-SRF FELs. Experience gained with this initial "IR Demo" FEL, funded mainly by the U.S. Navy, is planned to lead to FELs at still higher powers not only in the IR but also in the ultraviolet (UV), where many of the most compelling potential applications lie. After the IR Demo and an upgrade of the IR Demo, the consortium intends to build a kilowatt-scale ultraviolet demonstrator FEL (the UV Demo), to be followed by scale-up and further development eventually leading to a 50–100 kW prototype device for cost-effective manufacturing use at industrial sites. Figure 1 shows the power output of the IR and UV Demo FELs at the various wavelengths through which they are tunable, and, for contrast, shows capabilities of typical conventional lasers as well. In providing more than two orders of magnitude higher average output than existing sources which cover this wavelength range, this user facility will be the world's first fourth-generation light source.

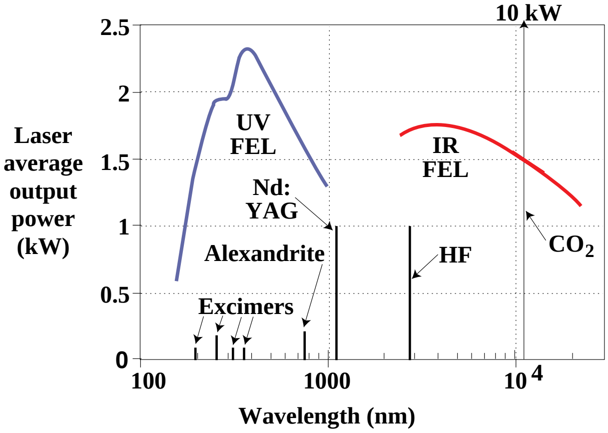

Figure 1: Power vs. wavelength for the IR and UV Demo FELs.

Consortium industrial members seek a power-efficient, high-average-power, wavelength-tunable, picosecond-pulse-length laser light source for materials processing. University members seek to participate in technology development, and also to exploit the basic science opportunities that these FELs will represent. Jefferson Lab seeks to profit from synergistic development in SRF-related technologies crucial for future CEBAF accelerator upgrades for advancing basic physics research. The industrial stakeholders in particular have committed substantial resources to the outfitting of the FEL User Facility. They are supplemented by a number of local universities that intend to perform basic and applied research covering similar topics. We are encouraging these universities to form partnerships with the industrial members whenever feasible. Not only does this strengthen the technical capability of the research team, but should synergistically enhance both the fundamental and applied efforts and encourage student participation.

Figure 2, the user facility second-floor plan, shows the arrangement and initial assignments of the six laser-light applications-development labs. The light produced by the laser will be brought through the optical control room to one or more user labs totaling more than 600 m^2 in area. Operation of the system with multiple users is considered crucial to keeping the operating cost modest. Insertable mirrors of fixed reflectivity, e.g. 1%, 50 %, 100%, are inserted into the optical transport line to extract beam for a particular application. Consortium members in other labs can utilize the remaining beam for alignment, etc., on a non-interfering basis.

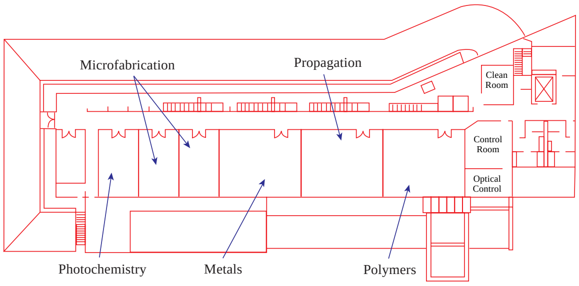

Figure 2: Layout of the Jefferson Lab Free-Electron Laser User Facility's user lab spaces.

2.1 *First Step: "IR Demo" FEL*

Figure 3 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, and with electron beam losses of less than 5 µA at energies above 25 MeV. In this first FEL, about 99% of the energy from acceleration in the 32 MeV cryomodule will be recovered. (When the 10 MeV of pre-acceleration from the injector is accounted for, this actually represents only about 75% 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.).

The main parameters of the IR Demo system are shown in Table 1. The wiggler was located downstream of the cryomodule to minimize, before the FEL, such degrading effects as wakefields and emittance growth due to coherent synchrotron emission. Initial lasing involves sending the spent beam to a beam dump. Following that, full-power operation with energy recovery will be performed.

Table 1. Parameters for the IR Demo FEL

Electron Beam		Wiggler	
Kinetic Energy	42 MeV	Period	2.7 cm
Average current	5 mA	Number of periods	40
Repetition rate	37.425 MHz	rms K^2	0.5 (optionally 1.0)
Charge per bunch	135 pC	Phase noise	<5° rms
Norm. transverse emittance	13 mm-mrad	Trajectory wander	x <±100 µm y <±500 µrad
Longitudinal emittance	50 keV-deg		
ß function at wiggler center	50 cm		
Energy spread (σ_γ/γ)	0.20%		
Peak current	50 A		
Bunch length (rms)	1 psec		

The IR Demo's driver accelerator and its injector require, respectively, energy gain of 32 MeV (8 MV/m gradient) in a single cryomodule and 10 MeV (10

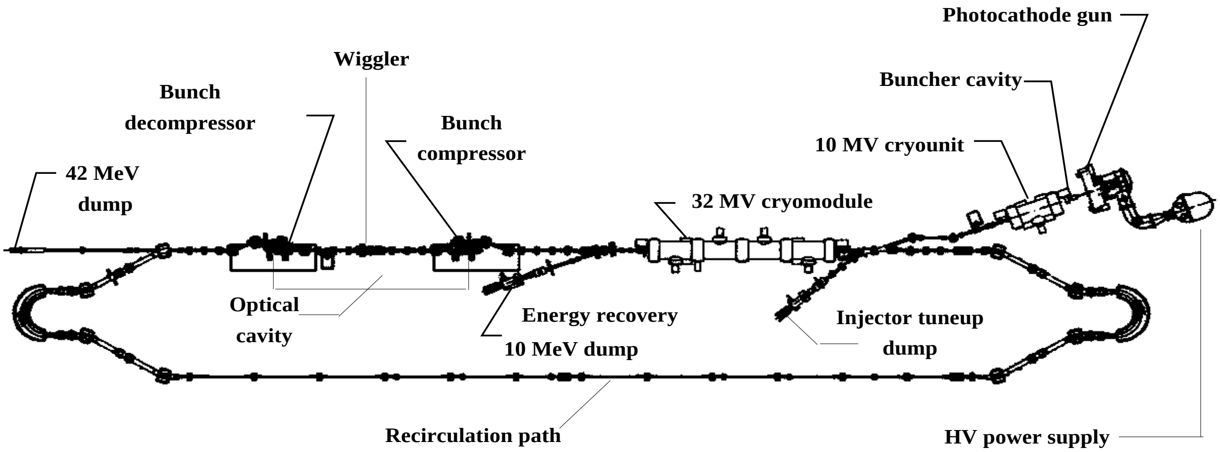

Figure 3: In the IR Demo FEL 10 MeV electrons are accelerated to 42 MeV, before yielding 1/2% of their energy to light in the wiggler. The e-beam is recirculated and its energy recovered to 10 MeV via deceleration.

MV/m gradient) in a quarter-cryomodule. In actuality the quarter-cryomodule operates at its design gradient and the cryomodule substantially exceeds its specifications, operating at nearly 12 MV/m average gradient. Average quality factor Q at 8 MV/m in CEBAF has been twice that needed for the FEL driver. Some of the cryomodule components have been modified to handle the FEL's higher peak current and its 5 mA average current. The higher beam currents required only minor changes to our standard cryomodule.

The FEL injector's most technically demanding component is the 350 kV DC gallium arsenide photoemission gun. It was designed in collaboration with the University of Illinois, based on experience with an earlier gun at Stanford Linear Accelerator Center in California. DC was chosen because room-temperature RF structures require very high average power CW RF power sources and are thermally limited in gradient capability, and because the technology of CW RF guns based on superconducting cavities is not mature. The photoemission cathode was chosen to attain short pulse length and low emittance. Use of gallium arsenide integrates the nuclear and particle physics program goals. To overcome the gun's technical challenges requires excellent vacuum conditions in the vicinity of the photocathode and limited field-emission currents from the electrode structures. The gun has been successfully tested at 350 keV. Work is continuing to ascertain if the GaAs in the present physical configuration can achieve the original design gradients (currently 60% baseline) and reasonable lifetime with full average current (currently ≈10–20 hours at 1 mA).

2.2 Status and Fiscal Year 1998 Plan

In Fall, 1997, injector components were tested, with the 350 keV characterization of the photocathode gun in the new FEL building while incorporating operation of the 10 MeV quarter-cryomodule at full gradient. In December beam was accelerated to 42 MeV into the straight-ahead dump at low average current. The wiggler and optical systems have been installed and are ready for lasing; user experiments start this year.

A development path for proceeding beyond this initial IR Demo FEL has been outlined. Near-term steps will be incremental IR Demo upgrades followed by the UV Demo. The concept for the UV Demo, in which a 200 MeV SRF linac will alternately drive an IR and a UV wiggler, with IR output of 3.0–6.6 μm at 10 kW and 1.0–2.0 μm at 2 kW, and with deep ultraviolet (DUV) output down to 0.2 μm at 1 kW. The more distant future plans will be determined experience with the Demo FELs, but it is expected that industry will ultimately want cost-effective, low-maintenance, easily operated 100 kW FELs operating in the IR at 5 μm and in the DUV down to 0.2 μm.

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