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A High-Average-Power FEL for Industrial Applications†

H. F. Dylla, S. Benson, J. Bisognano, C. L. Bohn, L. Cardman, D. Engwall, J. Fugitt, K. Jordan, D. Kehne,
Z. Li, H. Liu, L. Merminga, G. R. Neil, D. Neuffer, M. Shinn, C. Sinclair,
M. Wiseman, CEBAF, L. J. Brillson, Xerox, D. P. Henkel, AS&M, Inc.,
H. Helvajian, Aerospace Corp., M. J. Kelley, DuPont

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Abstract

CEBAF has developed a comprehensive conceptual design of an industrial user facility based on a kilowatt UV (150–1000 nm) and IR (2–25 micron) FEL driven by a recirculating, energy-recovering 200 MeV superconducting radio-frequency (SRF) accelerator. FEL users—CEBAF's partners in the Laser Processing Consortium, including AT&T, DuPont, IBM, Northrop-Grumman, 3M, and Xerox—plan to develop applications such as polymer surface processing, metals and ceramics micromachining, and metal surface processing, with the overall effort leading to later scale-up to industrial systems at 50–100 kW. Representative applications are described. The proposed high-average-power FEL overcomes limitations of conventional laser sources in available power, cost-effectiveness, tunability and pulse structure.

Introduction

The Laser Processing Consortium—a collaboration involving nine U.S. corporations and companies, seven research universities, and a national accelerator laboratory—intends to develop a profitable, production-scale capability to use laser light in manufacturing. We propose to develop a cost-effective, high-average-power free-electron laser (FEL) that would deliver light at wavelengths fully adjustable across the infrared (IR), ultraviolet (UV), and deep ultraviolet (DUV) portions of the spectrum [1]. Such an FEL would address markets totaling hundreds of billions of dollars by fundamentally improving industry's abilities to: modify polymer film, fiber, and composite surfaces; process metal surfaces and electronic materials; micromachine metals, ceramics, semiconductors, and polymers; and non-destructively evaluate industrial processes.

In principle, energy in the form of laser light offers distinct advantages for manufacturing. Laser light's coherence and high brightness allow delivery of high power densities onto material substrates. Its monochromaticity allows precise matching to narrow-band absorption. In short pulses, it can modify surfaces without the counterproductive side effect of bulk heating. Moreover, environmentally benign laser processing can replace wet-chemistry processing methods that produce enormous amounts of dilute aqueous waste.

Conventional lasers suffer limitations in cost, power, and choice of wavelength. Therefore industry needs a fundamental improvement in laser technology: a laser that can affordably deliver precisely controlled light at average power levels that are orders of magnitude higher than now available, and at wavelengths fully selectable across the IR, the UV, and especially the DUV. An FEL driven with a superconducting radio-frequency (SRF) electron accelerator can meet these cost and performance requirements.

A production-scale manufacturing FEL's driver accelerator is its key subsystem and technological challenge especially since industrial applications require continuous-wave (cw) light.

With the maturity of SRF technology at laboratories such as CEBAF, CERN, DESY, and KEK, it is clearly demonstrated that high average power, cw electron accelerators can be built and operated. A comparatively small, CEBAF-type SRF accelerator would be ideally suited to drive a cost-effective FEL for industrial applications.

Therefore we propose a two-phase program of developing SRF-based FELs for industry. In Phase 1, we plan to build and commission at CEBAF a demonstration-and-development user facility centered on a kilowatt-scale FEL which will operate across the IR, UV, and DUV for industrial application. The Phase 1 FEL is hereafter called the UV Demo, since its UV/DUV capability is the major focus of commercial interest. In Phase 2, we will scale up from this UV Demo and build a 50 to 100 kW version, a prototype for cost-effective use at industrial sites.

Industrial application of high-power laser light

Most prospective light-based manufacturing will involve modifying materials' surfaces and will take place in the UV. The appeal of surface modification as a final, high-value-adding step has been recognized for several decades. Numerous desired product enhancements stem from improvements in the performance of surfaces, including interfaces subsequently made from them. Chemical treatments, coatings, and platings are widely applied, mature technologies. Familiar examples are to be found in anti-stain carpets, improved corrosion resistance in auto bodies, modern food packaging, and composite materials. In fact, a major share of U.S. industrial output depends on surface or interface characteristics in the final product or on surface processing as a means of manufacture. These industries now depend on wet-chemical (e.g., solvent coating, plating, etching) or mechanical (e.g., grinding, burnishing) processes, but light-based processing is now also a prospect. Surface modification by light can add value to existing products, serve as the value basis for new products, or be incorporated into special interfaces of packaging materials or structural composites. Such modified surfaces can be formed by physical or chemical rearrangements caused by intense, carefully tailored energy absorption in the transformed region, especially energy in the form of UV light.

Existing UV sources—including lamps that provide incoherent light, harmonically converted Nd-doped solid state lasers, and excimer lasers—suffer severe limitations for such work. None offers high enough average power, a cw duty factor, or low enough cost per delivered kilojoule for general production purposes, and the light output from the coherent sources is not available at, or tunable to, wavelengths overlapping specific absorption bands of interest.

Nonetheless, a few conventional lasers—UV excimer lasers in particular—have seemed to offer tantalizing promise. Since excimers became available about ten years ago, many researchers have used them for surface processing. Absorption coefficients in the 10^4–10^5 cm^{-1} range result in

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essentially all the energy being deposited in the outermost few hundred nanometers. Consequently, novel materials or material states can be created on the surface while leaving the desirable properties of the bulk intact. Further, with a proper choice of conditions, laser-induced ablation can remove material, allowing micromachining to the dimensional scale of the light wavelength itself.

Commercially viable applications for conventional-laser materials processing, have been limited primarily to cutting and welding tasks. With increased reliability in pulsed lasers, especially pulsed excimers, other applications have been developed including lithography, pulsed-laser deposition/etching, and micrometer-scale machining/surface texturing.

Certain specialized applications with excimer lasers have been notably cost-effective: those requiring limited irradiation doses at one of four fixed excimer laser wavelengths, and those requiring relatively few intense pulses for high-fluence ablation. The low-duty cycle of these lasers limits their applicability to large-area processing. The pulse intensity unnecessarily affects a large volume of material by removing or altering bulk material, thereby damaging the surrounding area via thermal and plasma effects and wasting incident laser energy. To mitigate these effects, the laser fluence is commonly reduced, which is tantamount to significantly increasing the processing time. Given the low (sub-kilohertz) repetition rate of high-power conventional lasers, the additional processing time makes the application too costly. High-fluence laser processing does have applications in advanced-materials development, but more applications become possible if each processing step can be made to affect less material.

So despite some limited successes, despite industrial potential *markedly superior* to that of other light sources, despite the intrinsic utility of laser light, and despite substantial R&D investment by industry, conventional laser technology is not destined to improve U.S. manufacturing capability in any fundamental way. Commercially available excimer lasers present perhaps the best illustration: they remain limited to tenths of kilowatts, tens of cents per kilojoule, and a few isolated specific wavelengths, while large-scale exploitation of UV surface processing will require sources providing at least a few tens of kilowatts, light that costs a few tenths of a cent per kilojoule, and *full* wavelength tunability.

UV Demo FEL

The UV Demo FEL briefly described in this section will provide light that will allow users to demonstrate and develop laser applications like those listed in Table 1.

Table 1

Representative Industrial Applications of FELs

Polymer Surface Processing	Electronic Materials Processing	Metal Surface Processing
Surface texturing	Flat-panel displays	Laser glazing and annealing
Surface amorphization	Large-area photovoltaics	Metglass coatings

Requirements for the UV Demo appear in Table 2. Figure 1 contrasts UV Demo performance in power and wavelength with that of conventional lasers. Delivered photons are expected to cost in the \$1/kJ range. For the much higher-power Phase 2 device, the cost is expected to drop to below \$0.01/kJ.

Table 2

Output Requirements for the UV Demo

	User Requirement	Design Goal
Wavelength range	190–300 nm 3000–20000 nm	160–1000 nm 2500–25000 nm
Power	1 kW	1.7 kW
Optical beam quality	<2× diffraction-limit	1.2× diffraction-limit
Bandwidth	4 × Fourier limit	Fourier-limited

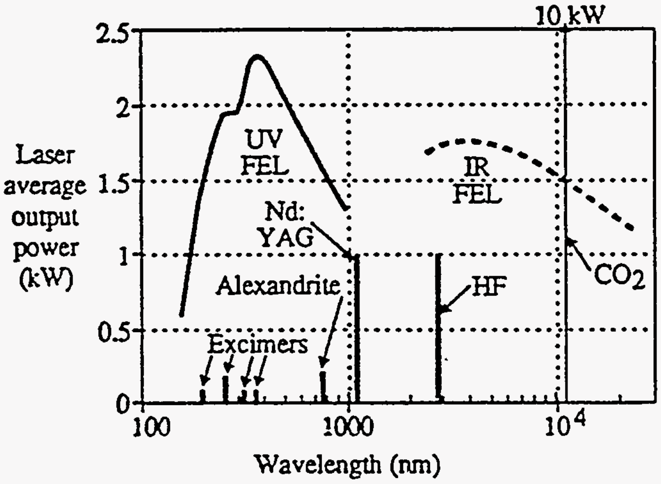

Figure 1. Power vs. wavelength for the UV Demo FEL

In addition to the characteristics shown in Table 2, the FEL will provide a picosecond pulse (at 37 MHz) ideally suited for rapid thermal annealing or ablation of near-surface regions. This pulse length matches the characteristic times of surface vibrations and surface molecular rearrangements. It is much shorter than the nanosecond time scales of vaporization or thermalization. These undesirable effects therefore do not appear, and surface processing with the UV Demo is highly efficient.

A schematic of the UV Demo appears in Figure 2. The injector consists of a Nd:YLF-laser-driven 500 kV DC photoemission electron source, a copper cavity to bunch the beam, and a two-SRF-cavity cryomodule [2]. It feeds a 10 MeV beam into the driver linac consisting of three CEBAF-type cryomodules, each containing four pairs of integrally linked 1.5 GHz SRF accelerating cavities [3]. The injected beam will:

- Accelerate through the driver linac, which will provide a nominal energy gain of 96 MV.
- Recirculate back to the injection point by transiting clockwise through the low-energy recirculator line for a second acceleration pass.
- Enter an FEL wiggler at up to 200 MeV to yield about 0.5% of the beam power in the form of laser light. Approximately 13% of the light will be outcoupled from the

optical cavity for applications in a dedicated user laboratory.

- Decelerate through two energy-recovery passes in the linac and deposit its remaining energy in a cooled, shielded copper beam dump at about 10 MeV. Energy freed during deceleration appears as rf-field energy at the operating frequency of the cavities and is used to accelerate other electrons. Thus, energy recovery greatly enhances (by more than an order of magnitude) the operating efficiency of the device.

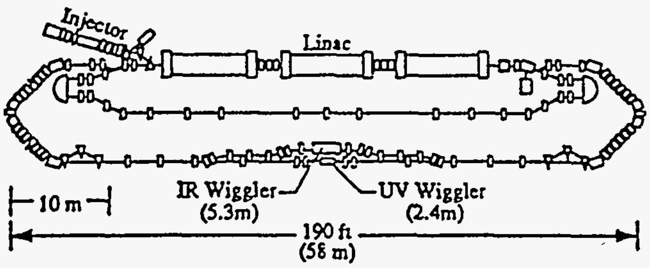

Figure 2. Layout of the UV demo FEL

We are trying to achieve cost-effective operation during Phase 1 in preparation for the Phase 2 scale-up to a production-scale device. The existing CEBAF accelerator combines SRF technology with electron-beam recirculation, and thus there is a base of experience from which to draw. Energy recovery adds efficiency and eliminates the need for large-scale radiation-management measures. A 200 MeV beam at 5 mA without energy recovery would require a megawatt-scale beam dump, but a beam decelerated to approximately its original injection energy requires far less: for the UV Demo, a *50 kW* beam dump. Recirculation lowers capital cost by minimizing the number of superconducting components, lowers operating cost by reducing the cryogenic load, and substantially reduces system footprint size.

Table 3 lists some of the key machine specifications for both the driver accelerator and the UV laser.

Table 3
UV Demo FEL Specifications

Driver Accelerator		Wiggler and Optical Cavity	
Electron kinetic energy	100–200 MeV	Wiggler length	2.38 m
Pulse repetition frequency	2.3–37.4 MHz	Wiggler wavelength	3.3 cm
Charge/bunch	135 pC	Maximum field	0.75 T
Bunch length	0.2 psec	Wiggler gap	11.5 mm
Peak current	270 A	Optical cavity length	64.09 m
Average current	5 mA		

Phase 2: Technology Scale-Up

Successful demonstration and development efforts at the kilowatt scale in the Phase 1 industrial user facility will focus and intensify needs for systems operating at much higher power levels, and will also provide hard data and practical experience for meeting these needs. In Phase 2 we will build a prototype of a 50 to 100 kW industrial UV FEL system suitable for cost-effective production at individual industrial sites, and at regional processing centers serving multiple manufacturers.

The prototype must be cost-effective, robust, reliable, and easy to operate. For an operational commercial system, the capital cost and the operating cost are key considerations which lead to an overall figure of merit, the cost per delivered kilojoule. A key goal is to produce UV light in the 0.2 cents per kilojoule range, two orders of magnitude cheaper than that obtained with conventional lasers.

Although detailed analysis of Phase 2 can only be prepared based on actual Phase 1 data and experience, preliminary analysis has been carried out. It is clear that developing the capability for higher powers will require attention to:

- Injector performance. The injector is a challenge because of the desire for high average current with a long cathode life, and because of the high brightness specifications on the required electron beam. Average current more than an order of magnitude higher than that for Phase 1 will place increased demands on the electron source, so a critical goal during Phase 1 will be to develop a high-intensity, high-quality source.
- Optical cavity performance. The optical cavity is a challenge because of the high intracavity intensity exacerbated by relatively high mirror-coating absorptions at short wavelengths which can lead to deleterious mirror deformation.
- Operating frequency, the choice of which requires tradeoff between SRF cavity design, transport characteristics of the lattice design, RF source efficiency, and cryogenic system performance.
- Lattice design, including optimizing the number of recirculation passes.

Details of our cost analysis for high-power FELs are given in a companion paper [4].

Summary

The Laser Processing Consortium has identified industrial applications of UV laser light that involve surface modification of polymers, metals, and electronic materials. Substantial commercial development of these applications that would incorporate the benefits of light-based manufacturing is impeded by the present lack of cost-effective, high-average power UV sources.

The consortium has proposed a two-phase plan for developing high-average-power UV sources that meet the industry cost goals based on SRF-linac-driven free-electron lasers.

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