7/102

A HIGH-AVERAGE-POWER FREE ELECTRON LASER FOR MICROFABRICATION AND SURFACE PROCESSING 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, Henkel Metallurgical Tech.,
H. Helvajian, Aerospace Corp., M. J. Kelley, DuPont,
Shanti Nair, University of Massachusetts

Abstract
CEBAF has developed a comprehensive conceptual design of an industrial user facility based on a kilowatt UV (160–1000 nm) and IR (2–25 micron) free electron laser (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—are developing applications such as metal, ceramic and electronic material microfabrication, and polymer 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 Department of Energy accelerator laboratory (CEBAF)—is planning to take the first of two steps in developing a profitable, production-scale capability to use laser light for high-volume manufacturing processes (1). 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. Such an FEL would address multibillion-dollar markets by fundamentally improving industry's abilities to

- modify polymer film, fiber, and composite surfaces,
- process metal surfaces and electronic materials,
- micromachine or surface-finish metals, ceramics, semiconductors, and polymers, and
- evaluate materials nondestructively and monitor manufacturing processes.

Laser light offers distinct advantages for the work of manufacturing. Laser light's coherence and high brightness allow delivery of high power densities onto material substrates. Its monochromaticity allows precise matching to typical 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. For all of these reasons, industry has become interested in lasers, and in fact is using them widely for cutting and welding. Laser Processing Consortium industrial members now have substantial commercial interest in seeing lasers further developed for a wide range of production applications.

†Supported by U.S. DOE Contract #DE-AC05-84ER40150 and the Commonwealth of Virginia.

But 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" by electrons from a superconducting radio-frequency (SRF) electron accelerator can meet these cost and performance requirements (2, 3).

A production-scale manufacturing FEL's driver accelerator is its key subsystem and technological challenge. Even though FELs have been in development for nearly two decades, mainly using nonsuperconducting acceleration technologies, FELs currently operating in the U.S. reach only about 10 W of average power. But superconducting accelerators, in contrast to pulsed, room-temperature, copper-cavity-based accelerators, permit continuous-wave (CW) operation, which automatically means high average power in the electron beam. The virtual absence of ohmic losses in the accelerating structures means vastly superior energy efficiency. However, even though SRF has matured as a technology in recent years, no high-average-power SRF-based FELs exist. This consortium believes cost-effective FEL for industrial applications can be built using a comparatively small, CEBAF-type SRF accelerator.

Therefore we propose a two-phase development program. In Phase 1, capitalizing on existing infrastructure and expertise within the consortium, we will design, build, and commission at CEBAF a demonstration-and-development user facility centered on a kilowatt-scale FEL, which we will operate across the IR, UV, and DUV for

- development, analysis, and refinement of commercial applications,
- investigation of opportunities for widening the commercial potential of high-average-power FELs, and
- demonstration of the key subsystem technologies to allow confident scale-up of SRF-based FELs to higher-power, lower-cost operation.

The Phase 1 FEL is hereafter called the *Demo FEL*. In Phase 2, we will scale up from the Demo FEL and build a 50–100 kW version, a prototype for cost-effective production use at industrial sites.

Surface Processing and Microfabrication with Light

Most prospective light-based manufacturing will involve modifying materials' surfaces and will take place in the UV, although applications in the IR will be significant, such as surface processing at IR wavelengths that match strong absorptions in solid materials and modest resolution (2–10 μm) micromachining.

In principle, UV light offers an array of opportunities for substantially increasing both the applications and the commercial value of surface modification. But existing UV sources—including lamps that provide incoherent light, harmonically converted Nd-doped solid state lasers, and conventional excimer lasers—suffer severe limitations for such work. None offers high enough average power or low enough cost per delivered kilojoule of light 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 promise. A laser is a nonintrusive, *in situ* processing tool which can perform multiple tasks simultaneously, including serving as a process monitor. It is easily amenable to automation and is commonly used in specific-area processing. Furthermore, lasers can be used as diagnostics for monitoring surface character, quantifying the integrity of an embedded interface, and spectroscopically identifying adsorbates and ablated material. The key point is that a laser can be used to both deposit and remove material while serving as a diagnostic probe, all *in situ*. This multiuse, multirole, *in situ* capability is not offered with other advanced materials-processing techniques like molecular beam epitaxy (MBE), chemical vapor deposition (CVD), fast ion bombardment (FIB), and magnetron/plasma sputtering. And a further benefit is the elimination of the environmental costs of processing with wet chemistry.

Since excimers became available about ten years ago, many researchers have taken advantage of the intense absorption found at their wavelengths to explore surface processing with light. Absorption coefficients in the 10^4–10^5 cm^{-1} range result in essentially all the energy being deposited in the outermost few tenths micron or less of a material. Consequently, novel materials or material states can be created on the surface while leaving the desirable properties of the bulk intact. Depending on the details of wavelength, irradiance, and fluence, UV light can transform chemistry, morphology, and topography. Further, with a proper choice of conditions, laser-induced ablation can remove material, allowing micromachining to the dimensional scale of the light wavelength itself.

To date, a few commercially viable applications have been developed for conventional-laser material processing, mostly limited until very recently to cutting and welding tasks. Newly increased reliability in pulsed lasers, especially pulsed excimers, has resulted in other applications, including lithography, pulsed-laser deposition/etching, and micrometer-scale machining/surface texturing. "Machined" or "grown" materials include metals, semiconductors, superconductors, ceramics, insulators, and biocompatible materials. In addition, a number of multicomponent, device-quality, "tailored" thin films have been grown by pulsed-laser deposition processing.

Certain specialized, high-value-added conventional-laser applications 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 of high-fluence ablation. The former approach has limited application to large-area processing given the low duty cycle of current laser systems. The latter approach unnecessarily affects a large volume of the material workpiece by removing, cutting, or altering material. This damages the surrounding area via thermal and plasma effects, generating debris and thereby wasting incident laser energy through absorption in the above-surface plasma. To mitigate these effects, the laser fluence is commonly reduced, which is tantamount to significantly increasing the processing time. Given the low (subkilohertz) repetition rate of current high-power 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—a measured approach that would add precision to processing, but is not economically viable with present laser technology.

Figure 1 illustrates the fluence and processing-rate limitations of conventional lasers for typical surface transformation and surface melt treatments of metals. The figure compares the approximate minimum fluence requirements for CO_2, Nd:YAG, and excimer lasers with those of the Demo FEL (4). Because the high absorptivity and short (picosecond) pulse length of the Demo FEL light greatly reduce its fluence requirements, the estimated processing rate of the Demo FEL is several orders of magnitude faster than those of the conventional lasers.

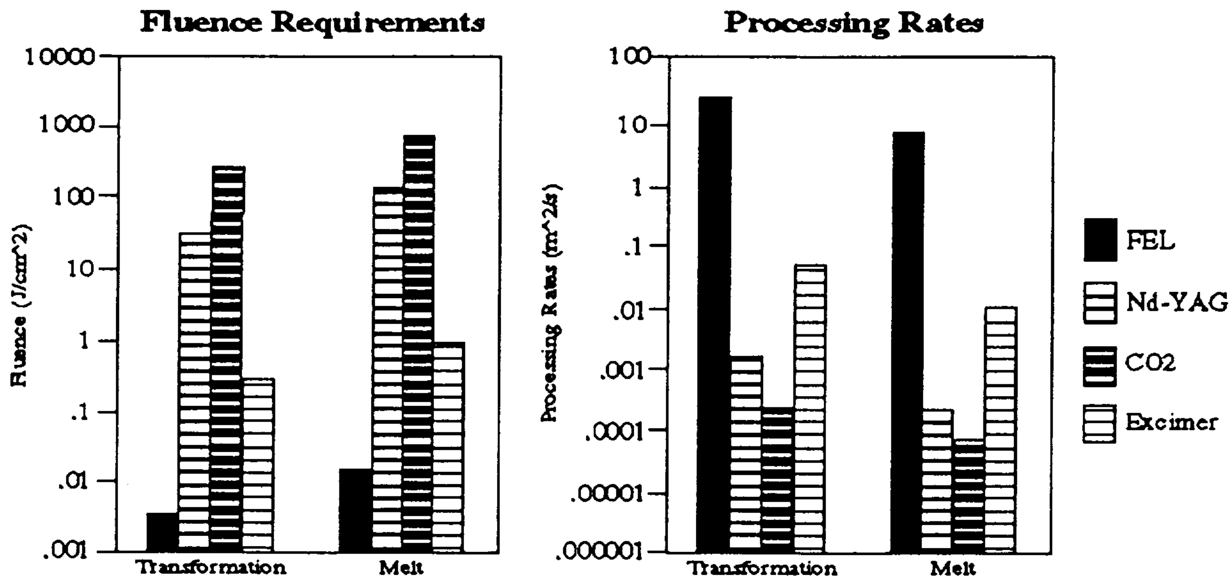

Figure 1. Calculated laser fluence and processing rates for metal surface processing by conventional lasers (Nd:YAG at 1 kW, CO_2 at 10 kW, excimer at 200 W) and the Demo FEL (at 1 kW).

So despite substantial industrial R&D investment and some limited successes, conventional laser technology is not likely 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 of at least a few tens of kilowatts, light that costs under a cent per kilojoule, and full wavelength tunability.

Therefore the Laser Processing Consortium's industrial members have become increasingly interested in precompetitive FEL R&D to prepare for manufacturing in the twenty-first century.

Phase 1: Technology Demonstration and Development

Applications Development in the Demo FEL User Facility

The proposed Phase 1 project is to build and operate on the CEBAF accelerator site a user facility centered on the Demo FEL—a kilowatt-scale, SRF-driven FEL producing light in the UV (160–1000 nm) and the IR (2500–25,000 nm). In user laboratories in the facility, we intend to exploit the Demo FEL's capabilities to benchmark and extend the industrial utility of FEL manufacturing applications and to investigate the technology required for Phase 2 development of a 50–100 kW production-scale device. The key goal for ultimate commercialization in Phase 2 is to achieve light at a total cost (capital plus operational) of less than a cent per kilojoule.

Each user laboratory will have a particular technology focus and will be equipped by the user industries with exposure stations for large-area samples, vacuum systems for analytic equipment, and optical diagnostics for light-source characterization. Computer control interfaces will be provided in each laboratory to allow the users to control the beam parameters and optimize performance for each process. Provision will be made not only for proprietary research, but in a few cases for actual commercial use of the facility. Industry members have committed equipment for four of the user laboratories for: (1) large-area surface processing of polymers, (2) micromachining and microfabrication, (3) laser-photochemical processing, and (4) laser-material surface diagnostics.

Industrial applications identified by consortium members include:

- Polymer microtexturing. Polymer film or fiber surfaces can be microughened with exposure to 248 nm UV laser light, a processing treatment that can give the product new friction, filtration, wetting, or visual-appearance characteristics (5). Commercially important applications include better adhesion for forming multicomponent film products or composite structures, more effective fibers for use in filters, and improved "feel" of synthetic fiber fabrics. For commercial viability, the treatment would require a fluence of 200 to 600 mJ/cm^2 at about a penny per kilojoule and at a minimum power of 25 kW.

- Microfabrication. Laser-micromachining can fashion micron-scale structures with nanometer-scale control. Through subthreshold ablation (6) with light from a low-fluence (0.1–100 mJ/cm^2), high-repetition-rate (> Mhz) tunable UV laser (200–300 nm), a host of novel materials processing applications would become possible, such as micro-optics, ultrahigh-density storage media (>5 $Gbits/in^2$), adhesiveless microfasteners (i.e., micro-Velcro), and precision abrasive surfaces.

- Surface conductivity. Delivering from 10 to 40 J/cm^2 at a fluence near the ablation threshold drives polymer decomposition toward graphite, imparting electrical conductivity (7). Stable, durable "wires" as narrow as 30 nm could be directly written onto polyimide substrates for microelectronics applications. The treatment requires 10 kW; a tolerable production cost is pennies per kilojoule.

- Laser annealing. A slow cool resulting from a low-velocity laser scan can alter a metal surface grain structure in a manner similar to bulk furnace annealing, resulting in improved resistance to fatigue-crack nucleation (8). The Demo FEL could be wavelength-tuned for full absorption at possible annealing rates of 10 m^2/sec.

- Large-area diamond coating. Thin-film diamond has lucrative applications in microelectronics packaging (e.g., insulating layers in flip-chip technology), tribology (e.g., bearings and contact surfaces), and flat-panel displays (e.g., field-emission sources). Currently, coatings of amorphous diamond on materials are accomplished by using the 10 nsec pulses from solid state lasers (e.g., Nd:YAG) (9). The Demo FEL's repetition rate is expected to be 10^6 times faster; this means an ability to coat roughly 100 times the area (1 m by 1 m) in one second.

The Demo FEL

High-average-power, wavelength-tunable laser light from the Demo FEL briefly described in this section will allow users to demonstrate and develop FEL applications as discussed above. Figure 2 contrasts Demo FEL performance with that of conventional lasers.

The Demo FEL will provide average powers in the kilowatt range. In addition, the output of the Demo FEL will have the following characteristics:

- **Tunability**: Existing sources are not tunable and/or available at wavelengths overlapping specific absorption bands of interest. The Demo FEL will provide light which is tunable across the UV (160–1000 nm) and the IR (2500–25,000 nm). As a bonus, the entire visible spectrum will be accessible (350–750 nm). This light will have all of the characteristics of high-quality laser emission: narrow bandwidth (typically <0.1%), spatial coherence (1–2 times the diffraction limit), and linear polarization.

- **Temporal Structure**: Existing sources are either CW at low intensity or have pulses that are much too long to enable efficient surface processing. By contrast, the Demo FEL will generate very short pulses (1 psec) that are ideally suited to rapid thermal annealing or ablation of near-surface regions. This pulse length matches the time scales of surface molecular rearrangements and vibrations. In ablation applications using high-power excimer lasers, pulse lengths exceed 10 nsec, and these pulses are long enough to interact with gas-phase ejecta with an associated loss of surface-interaction efficiency. The FEL circumvents this problem.

- **Efficiency/Cost**: The cost per unit energy of light delivered from conventional UV sources is too high (of order $0.10/kJ) for profitable industrial applications. For demonstration and development purposes, the Demo FEL will provide light at about $1/kJ. Prospective goals for the Phase 2 UV FEL are operation at 10% wall-plug efficiency and a cost of delivered light below $0.01/kJ.

Figure 2. Demo FEL power vs. wavelength. Conventional laser outputs appear as narrow lines at fixed wavelengths.

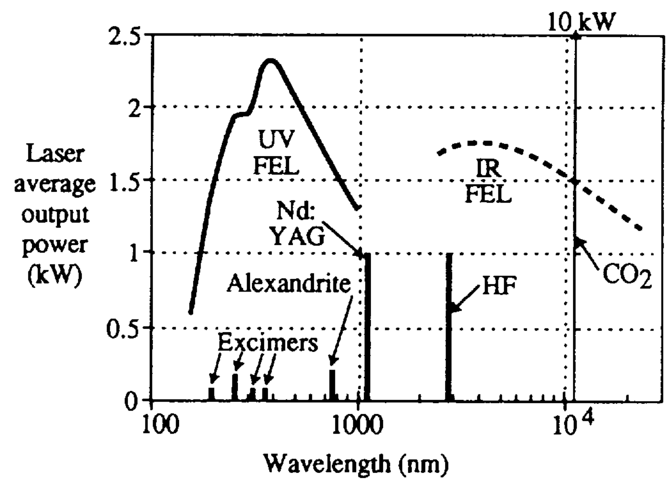

Figure 3 is the Demo FEL layout. To provide the needed light, the FEL will extract energy from electrons accelerated in two passes through a recirculating, energy-recovering SRF driver linac (linear accelerator) (10). The linac will consist of three cryomodules, cryostats closely similar to those used at CEBAF, each containing four pairs of linked SRF accelerating cavities. For superconducting operation at 2.0 K, the linac will tap the excess capacity of CEBAF's nearby main refrigerator, the Central Helium Liquefier (CHL). The electron beam will originate in an injector with three main elements: an Nd:YLF-laser-driven 500 kV DC photoemission electron source, a copper cavity to bunch the beam, and a two-SRF-cavity quarter-cryomodule. Development work directly useful for the injector—a key technological challenge for Phase 1—is already under way at CEBAF, thanks in large part to support from the Commonwealth of Virginia.

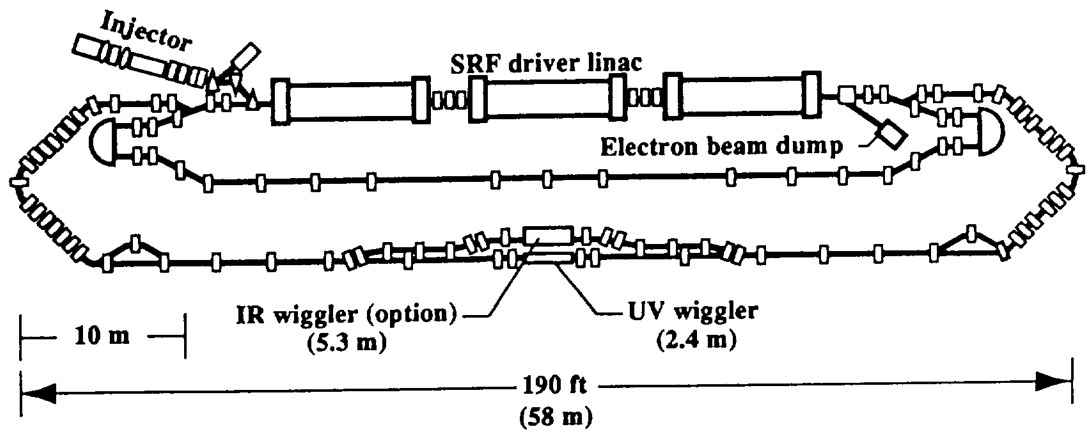

Figure 3. Demo FEL layout.

Demo FEL operation can be summarized as follows. An electron beam at 10 MeV energy from the injector attains 105 MeV in the first of two acceleration passes through the linac. After recirculating back to the injection point clockwise through the low-energy recirculator line (at the center of the machine, between the linac and the wigglers), the beam attains 200 MeV by the end of its second acceleration pass. Then it is directed to an FEL wiggler, where it yields about 0.5% of its power in the form of laser light. In the sinusoidal magnetostatic field of either the UV or the IR wiggler, relativistic accelerated electrons undulate transversely. The resulting light output is initially spontaneous emission, but the light bounces back and forth in an optical cavity, extracting energy from the beam until it is amplified to saturation. Light is outcoupled from the optical cavity and delivered for user applications. The electron beam then decelerates in two energy-recovery passes back through the linac. Energy recovery extracts the substantial energy the electron beam retains after it has transited the wiggler—in effect recycling the energy by converting it back to RF power at the linac cavities' resonant frequency. Finally, about 10 MeV of remaining energy is absorbed in a cooled, shielded copper beam dump.

SRF technology, energy recovery, and electron beam recirculation have already been combined and demonstrated at lower average current at CEBAF. With these key, integrally linked design features we are aiming at overall cost-effectiveness in the Demo FEL, with specific emphasis on developing cost-reducing and reliability-enhancing measures for the Phase 2 production-scale device. An SRF linac is intrinsically efficient, requiring substantially less RF power input than does a room-temperature system equipped with energy recovery. And if the SRF linac itself uses energy recovery, an additional RF efficiency advantage of more than an order of magnitude can be gained. Moreover, energy recovery 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 Demo FEL, 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.

The Demo FEL user facility is proposed to be built at CEBAF, the DOE-owned site of a new 4 GeV accelerator, a user facility for nuclear physics research. Beyond ensuring technical, cost, and schedule success, important project management goals include exploiting advantageous synergisms. These synergisms include CEBAF's SRF and electron-source technology expertise and infrastructure, the excess liquid helium capacity of the main refrigerator that serves the 4 GeV accelerator, and CEBAF's already existing environmental and radiation-monitoring permits.

Phase 2: Technology Scale-Up

We expect that successful demonstration and development efforts in Phase 1 will focus and intensify needs already identified by industry 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 50–100 kW industrial FEL suitable for cost-effective production use at individual industrial sites and at regional processing centers serving multiple manufacturers.

Research and testing will ensure that the device is industrially useful. The prototype must be cost-effective, robust, reliable, and easy to operate. For an operational commercial system, capital cost and operating cost are key considerations which lead to an overall figure of merit, the cost per delivered kilojoule. Present commercially available excimer laser systems cost between 10 and 20 cents per delivered kilojoule when both operating and capital costs are taken into account. A key goal for the Phase 2 program is to produce UV light at around 0.2 cents per kilojoule.

Although detailed analyses of Phase 2 can only be prepared based on actual Phase 1 data and experience, preliminary analyses have 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 long cathode life, and because of the high brightness (emittance) specifications for the 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 absorption at short wavelengths and tight limits on mirror deformation. A modest R&D program for high-reflectivity coatings will be conducted in conjunction with Phase 1.

- Operating frequency. This choice requires tradeoffs involving not only SRF cavity design, but also transport characteristics of the lattice design, RF source efficiency, and cryogenic system performance.

- Lattice design. The lattice design effort includes optimizing the number of recirculation passes.

Program Status (November 1995)

The Laser Processing Consortium, its objectives, and its resources have grown and evolved steadily since 1991, the year CEBAF organized an advisory group of high-technology corporations to analyze prospects for market-oriented applications of CEBAF technology

A NASA-sponsored peer review panel convened in March 1994 and a similar DOE-sponsored panel convened in May 1995 confirmed industry's need for FELs and strongly endorsed this consortium's approach for developing them.

The Laser Processing Consortium's proposal to develop free-electron lasers for industry already has obtained state and private-sector support. . The Commonwealth of Virginia, where CEBAF is located, is providing substantial support for the FEL enterprise, including matching funds already in use for electron source development and funds for the FEL User Facility building. Industry and university members of the consortium have made commitments for most of the required end station equipment in the User Facility. The first matching Federal funds to begin constructing the FEL hardware are expected in FY96.

References

1. Laser Processing Consortium Proposal: Free-Electron Lasers for Industry, Vol. 1 and 2 (May 1995).

2. H. F. Dylla et al., Proc. 1995 Particle Accelerator Conf., Dallas (IEEE, in press).

3. G. R. Neil and S. Benson, Proc. 1995 Particle Accelerator Conf., Dallas (IEEE, in press).

4. S. Nair, "Applications of Free Electron Lasers to Metals and Ceramics Processing," CEBAF/DOE TN No. 94-057, (Nov. 1994).

5. W. Kesting, D. Knittel, T. Bahners, and E. Schollmeyer, Appl. Surf. Sci., 54, (1992) 330.

6. H. Helvajian, L. Wiedeman and H.-S. Kim, Adv. Mat. for Optics and Elect: 2, (1993) 31.

7. J. L. Hohman, K. B. Keating and M. J. Kelley, Mat. Res. Soc. Symp. Proc., 354, (1995) in press.

8. B. Brenner et al., in Laser Treatment of Materials, B. L. Mordike et al., (DGM Informationsgesellschatt, Verlag, Germany) (1992), 199.

9. C. B. Collins, F. Davanloc, H. Park, SPIE Proc. 2403, (1995).

10. D. Neuffer et al., Proc. 1995 Particle Accelerator Conference, Dallas (IEEE, in press).