HIGH-POWER INFRARED AND ULTRAVIOLET FREE ELECTRON LASERS AT CEBAF*

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ABSTRACT

In response to requirements for national laboratory technology transfer, CEBAF has proposed an industrial R&D initiative: a Free Electron Laser (FEL) User Facility based on an infrared FEL and an ultraviolet FEL, with the injector and the north linac of the CEBAF superconducting, recirculating accelerator serving as drivers. The initiative is a collaborative effort with four U.S. corporate partners and capitalizes on CEBAF's superconducting rf technology. The FELs will provide monochromatic, tunable (3.6 to 17 μm and 150 to 260 nm), high-average-power ($\sim\text{kW}$) light for technical applications and basic science studies. FEL capabilities will be competitive with those of similar initiatives worldwide. FEL operation will not impair beam delivered to CEBAF's nuclear physics experiments. Substantial commitments are in hand from the industry partners and the Commonwealth of Virginia for cost-sharing the project with the Federal Government.

OVERVIEW

In response to new mandates for national laboratory contributions to U.S. competitiveness through technology development and transfer, CEBAF has collaborated with industry for optimally applying CEBAF's unique resources and capabilities in superconducting accelerator technology. An Industrial Advisory Board (IAB) representing Xerox Research, IBM Research, DuPont, and AT&T Bell Laboratories has recommended a specific technology R&D program: two versatile, high-power free electron lasers (FELs) driven by portions of the accelerator and providing coherent infrared (IR) and ultraviolet (UV) light at unprecedented power levels to experiments and technical applications in a user laboratory. A collaborative industry/university/national laboratory FEL effort based on this recommendation is being developed. A previous publication¹ and CEBAF's FEL proposal² provide a detailed description of the initiative.

The chief boundary condition for the FEL program is that it be operationally transparent to CEBAF's nuclear physics research. Detailed studies show that simultaneous operation can be realized while maintaining high beam quality. It is expected that the FEL program will complement and support the primary physics mission by widening CEBAF's visibility and by increasing the general recognition of CEBAF's practical value.

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The proposed FELs will have a unique combination of technical capabilities, competitive with those of similar initiatives worldwide and affording significant opportunities for industrial R&D and basic science studies. These include kilowatt-range average power output, broad tunability over wavelengths inaccessible to existing light sources (3.6–17 μm with options for 1.2–25 μm in the IR, and 150–260 nm with an option for up to 1860 nm in the UV), extremely short pulse duration (2 ps) for fast time-resolved applications, diffraction-limited propagation, Fourier transform-limited linewidth, and linear polarization. Figure 1 shows CEBAF FEL power output vs. wavelength.

Figure 1 CEBAF FEL power output vs. wavelength.

CEBAF superconducting rf (SRF) technology provides significant cost and technical advantages for FEL design. The chief cost advantage is use of existing accelerator sections as FEL drivers, thereby avoiding the largest single cost any comparable FEL facility would incur. Technical advantages of SRF accelerating cavities over conventional copper cavities include high peak and high average electron currents, leading to high optical gain and high average optical power outputs, respectively, in the laser system. For FEL operation, CEBAF's low emittance (15 mm-mrad), exceptional energy stability ($\Delta E/E < 10^{-4}$), and cw operation provide optimal match to the wiggler design.

FEL DESIGN AND OPERATION

The proposed FELs would require relatively modest additions to the capital investment in equipment which will have been installed at CEBAF by the end of 1992. To the existing injector would be added a high-current (60 A peak) photoemission electron source, which could also be useful for nuclear physics.

The basic components for the FELs—consisting of electromagnetic wiggler assemblies (for user control of output wavelengths), optical cavities, and output coupling optics—would be placed within available space in the north linac tunnel, together with extraction beamlines and beam dumps. The IR FEL is to be driven at 50 MeV by beam originating from the 10 MeV FEL source and accelerated in the injector's two 20 MeV cryomodules. The UV FEL is to be driven by 400 MeV electrons from the north linac. Laser light output would be transmitted to the ground-level north linac service building and then routed to a proposed multi-room FEL user laboratory. Figure 2 shows the layout of the IR and UV lasers and the user laboratory on the CEBAF accelerator site.

Figure 2 Proposed IR and UV free electron lasers and user laboratory.

FEL output radiation characteristics are defined in Tables 1 and 2 for both baseline operation and for options that allow wavelength tuning range extensions. In baseline operation—i.e., simultaneously with nuclear physics—only one FEL is used at a time. FEL bunches are separated from nuclear physics bunches through 10% energy offset by 25° off-crest acceleration. Wakefield effects do not compromise beam quality for nuclear physics. Hardware and operational features that combine to ensure beam quality are the low SRF impedance, the excellent HOM damping, and the planned temporal offset and moderate FEL-bunch charge.

Table 1
CEBAF IR FEL Radiation Characteristics

	<u>Baseline^{a)}</u>	<u>Options^{b)}</u>	
		<u>I</u>	<u>II</u>
Electron energy (MeV)	50	17-50	17-50
Output tuning range (μm)	3.6-17	3.6-25	1.2-7
Pulse duration (ps)	2	2	2
Pulse repetition freq. (MHz)	7.485	7.485	7.485
Peak power (MW)	60	20-60	20-60
Average power (kW)	0.9	0.3-0.9	0.3-0.9

^{a)} Baseline operation at 50 MeV (with simultaneous nuclear physics operation).

^{b)} Option I: at fundamental frequency with the CEBAF injector operating at gradients between 1.5 and 5.0 MV/m in FEL-dedicated use. Option II: with the FEL oscillating on the third harmonic (during concurrent FEL-nuclear physics operations).

Table 2
CEBAF UV FEL Radiation Characteristics

	<u>Baseline^{a)}</u>	<u>Option^{b)}</u>
Electron energy (MeV)	400	150-445
Output tuning range ^{c)} (nm)	150-260	150-1860
Pulse duration (ps)	1	1
Pulse repetition freq. (MHz)	2.495 or 7.485	2.495 or 7.485
Peak power (MW)	480	160-530
Average power (kW)		
@ 150-200 nm	1.2 or 3.6	6
@ 200-260 nm	1.2 or 3.6	6
@ 260-1860 nm	-	4-1.2

^{a)} Baseline operation at 400 MeV (with simultaneous nuclear physics operation).

^{b)} Option for FEL-dedicated north linac operation with variable energy (150-400 MeV), and possible higher-harmonic operation.

CEBAF FEL Applications

R&D and technology transfer applications are being planned by industry, universities, and NASA Langley Research Center:

- Materials science and technology: manufacturing of electronic, optical, and magnetic materials, surface modification of polymers, and laser diagnostics for materials analysis and process monitoring.
- Biophysics and biomedicine: laser tomography, laser microscopy, photodynamic therapy, and ultraviolet cell damage studies.

- Atmospheric sciences: pollutant detection, greenhouse gas monitoring, and LIDAR (laser radar).
- Laser manufacturing: welding, joining, and cutting of high-strength metals, polymers, and composites.

Significant potential also exists for the development of photochemical processing technology. Photo-etching, photo-ablation, and photo-enhanced CVD are of particular interest, and photochemical separation of isotopes and photochemical purification have received considerable attention.

Potential basic science studies include:

- Surface science: pump-probe surface state monitoring, photodesorption of low-coverage or low-cross-section species, and sum-frequency spectroscopy.
- Materials characterization: high-resolution photoemission spectroscopy and spin-polarized photoemission.
- Photophysics/photochemistry: high-resolution spectroscopy, pump-probe studies, minority species characterization (radicals, clusters), and Doppler cooling of hydrogen.

COST, SCHEDULE, AND OUTLOOK

The projected cost (\$28M) is at least a factor of two less expensive than similar initiatives worldwide. Cost sharing with the Federal Government is planned. In hand from industry and the Commonwealth of Virginia are commitments of over \$10M.

The FEL User Facility could be built in three years. Significant FEL experiments could begin in parallel with CEBAF accelerator commissioning activities (now under way) with start of funding in FY 1993.

In the longer term, the presently proposed program could lead to two second-phase CEBAF FEL development efforts. A dedicated, stand-alone UV FEL could be designed and constructed which is cost- and size-optimized for commercial use in laser machining, industrial and medical imaging, and industrial photochemical processing in the 200 nm range. The driver accelerator would incorporate improvements in SRF cavity technology developed at CEBAF since the start of the accelerator project. The other future effort could be a single-pass, high-gain FEL using both CEBAF linacs and serving as a test bed for development of high-brightness, coherent UV radiation sources extending to x ray (< 20 nm) wavelengths for holographic imaging of biological molecules and frontier development of biomedical imaging technology.

REFERENCES

1. G. R. Neil *et al.*, Nucl. Instrum. Methods **A318**, 212 (1992).
2. *Proposal: High-Power UV and IR Free Electron Lasers Using the CEBAF Superconducting Accelerator*, May 1992, available from Accelerator Division, CEBAF, 12000 Jefferson Avenue, Newport News, VA 23606.