FEL DESIGN USING THE CEBAF LINAC*

G. R. Neil, J. J. Bisognano, D. Douglas, H. F. Dylla, G. A. Krafft,
C. W. Leemann, P. Liger, D. V. Neuffer, C. K. Sinclair, B. Yunn

Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue
Newport News, VA 23602

Abstract

The applicability of the high quality, continuous electron beam from the CEBAF accelerator to free electron laser (FEL) research and photon production has been examined. A simple electromagnetic wiggler utilizing the output of the CEBAF injector (modified to include a new, continuous pulse train, high brightness photo-emission gun) would produce output powers of ~ 1 kW CW in the $4.5 - 20$ micron wavelength range. With a similar 6 cm wavelength EM wiggler of twice the length with a 400 MeV beam from the North Linac comparable laser output could be achieved at wavelengths around 200 nm. Analysis to date includes conceptual design optimization and more detailed modeling of the optimized parameter space. Program plans as well as designs for the two FELs are presented.

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Overview

We propose the design, construction, and operation of two versatile, high-power FELs with optical output spanning the infrared (IR) and deep ultraviolet (DUV) wavelengths. The proposed devices will use existing superconducting radio-frequency (SRF) accelerator technology and hardware at CEBAF and demonstrate the unique capability of SRF accelerators as FEL drivers. This technology development program would be essentially transparent to the existing nuclear physics program.

SRF technology provides both significant cost and technical advantages for FEL design. Technical advantages of SRF accelerating cavities over conventional copper cavities include the capability of accelerating high peak and average electron currents, which results in high optical gain and average optical power outputs, respectively, in the laser system. The unique specifications of the CEBAF superconducting linac, which for the FEL provides low emittance (15 mm-mrad), exceptional energy stability ($\Delta E/E \sim 10^{-3}$), and CW operation, significantly improve FEL operation.

The IR FEL will be driven by the 45 MeV output of the CEBAF injector, producing an average power output of $\sim$ 1 kW at IR wavelengths of 4.5–20 μm. Facility options which allow the injector to be operated at energies between 25 and 85 MeV extend the IR tunability range to 1.2–25 μm. A second optical cavity will be driven by the 400 MeV output of the CEBAF North Linac. This second device will provide deep UV (150–260 nm) light at similarly high average power levels. Electromagnetic wigglers will be used for both the IR-FEL and the UV-FEL to allow user control of the output wavelengths. Figure 1 shows the IR and UV FELs schematically with the accelerator.

Background

The CEBAF accelerator will be a 4 GeV, 200 μA CW electron accelerator for basic research in nuclear physics [1]. It achieves continuous operation through the use of 1.5 GHz superconducting rf cavities operating with helium refrigeration at 2K. The projected electron beam quality and energy spread are excellent with a design emittance of 2 nm at 1 GeV and an energy spread of better than 10^{-4}. The machine uses five passes through two antiparallel linacs to achieve full energy. The 5-cell superconducting cavities were originally designed at Cornell and are manufactured by Interatom. Processing, assembling the cavities into cryostats, and testing is performed at CEBAF. Of the > 110 cavities manufactured to date, all have met the specification for gradient (5 MV/m) and most meet the Q specification of 2.4×10^9 at 5 MeV. In fact, the average gradient is close to 10 MV/m with the best cavities exceeding three times baseline gradient.

The linac was designed, is being built, and will be operated by the Southeast Universities Research Association (SURA) for the DOE nuclear physics program. Total project cost is ~\$500 M. At present the project has 70% of the contracts awarded with commissioning underway (the injector is operational at 45 MeV). During FY91 the project passed 50% completion. The project is on schedule with start of physics anticipated to be in early calendar 1994. Over 7000 hours of beam time for nuclear physics has been awarded.

FEL Parameters

The specifications of the proposed CEBAF FELs are summarized in Tables 1, 2 and 3. Two points need to be recognized to understand the performance characteristics. First, when the CEBAF injector is in dedicated FEL use, the injector can operate at 25 MeV to 85 MeV either by reducing cavity gradients or using the CEBAF injector recirculator. These injector options extend the output tuning range of the IR-FEL to 1.2–25 μm.

Second, the ability to control electron beam parameters is restricted during simultaneous operation with nuclear physics experimentation. We have taken the conservative approach of treating such restricted performance as our baseline design. Dedicated use of the linac for FEL operation permits a wider set of operational parameters as shown in the tables. The physics limitations on simultaneous operations is treated more fully in the paper by Bisognano, *et al.*, this conference. FEL output radiation characteristics under these two modes of operation are illustrated in Figure 2.

The UV-FEL design assumes operation of the North Linac at the nominal specification for nuclear physics operation. Riding 25° off-crest, the FEL electron beam will be at 400 MeV. At this electron energy the UV-FEL will produce kilowatt-level power output at 200 nm with the proposed UV optical resonator and electromagnetic wiggler. The operating range of the UV FEL falls into three categories delineated by operating wavelength.

In the longer-wavelength range ($\lambda > 200$ nm), the availability of high-reflectivity mirrors indicates high average power ($\sim$ kW) operation is low risk. In the next shorter wavelength range (200 nm $\gtrsim \lambda \gtrsim$ 150 nm), high-power operation will depend on achieving small signal gains in excess of 40%. Although our FEL simulation codes presently predict gains of this order (see paper by Colson *et al.*, this conference), the sensitivity of such calculations to details of the electron distribution means that performance measurements of the system are needed before more accurate predictions can be made. For 150 $\gtrsim \lambda \gtrsim$ 100 nm, operation must necessarily be low average power (< 10 W) until a mirror/resonator is available which can handle the high power with low losses. The output power at wavelengths less than 150 nm will depend on the reflectivity and power-handling limits of the UV optics. Dedicated operation of the North Linac at accelerating energies less than 400 MeV allows an extended tuning range through the visible wavelengths to a long-wavelength limit of 1860 nm.

Both proposed FEL devices require the addition of a high-current (120 pC) electron source that is described more fully in the papers by Sinclair and by Liger *et al.*, this conference.

The wiggler design for both FELs (see Figure 3 for tuning range) is a conventional electromagnetic one with flat pole faces, since the wiggler is so short that divergence of the electron beam will not be significant. The configuration of the UV wiggler will be as an optical klystron with two wiggler sections separated by an electromagnetic dispersion section to permit real time optimization of gain.

The optical system for the IR FEL is a straightforward near-concentric cavity. The chosen values lead to a mirror loading (1-3 kW/cm^2) at the highest average currents which may exceed the capability of uncooled mirrors. As a practical approach the current (and thus the output power) may be reduced to a level which does not stress the optics. For a point of comparison, the average power loading for commercial CO_2 lasers (10.6 μm in wavelength) is generally < 1000 W/cm^2 on cooled copper mirrors. Optics vendors will guarantee the performance of their mirrors at loadings of < 1000 W/cm^2. A typical mirror coating for this wavelength region is dielectric overcoated silver on a ZnSe or (1.5-8 μm) silicon substrate.

Outcoupling the power will be accomplished either through a hole in the mirror or by using a partial reflector with a transparent substrate. The former can handle higher powers but has been observed to lead to mirror damage near the hole. The optical mode size on the mirror is larger, however, and provides more uniform thermal loading. Windows transmit the optical beam from the linac vacuum region. For high power broadband lasers such as this IR FEL design, ZnSe is a good window material.

To deal with the high UV intensity, the UV optical resonator approach is based on a novel design called a re-imaged retro-reflecting ring resonator [2]. Unlike conventional resonator designs, the resonator is extremely insensitive to alignment (10 mrad tolerance). The design exhibits several other useful properties. The optical mode has a uniform intensity profile so that mirror loading is more easily managed. With this technique an average power of 1 kW yields an incident flux of 300 W/cm^2. With an assumed reflectivity of 99%, the absorbed heat flux is 3 W/cm^2, a value consistent with the use of an uncooled silicon carbide substrate or even fused silica for initial testing. Six ring mirrors are required plus a scraper for outcoupling. Four of these mirrors are planar and two are chosen with an appropriate radius of curvature.

The basic components for the FELs, (wiggler assemblies and the optical elements) will be placed within available space in the North Linac tunnel displaced from the CEBAF beamline. The output from both FELs will be transmitted to the ground-level North Linac Service Building and then routed to a proposed FEL User Laboratory area. The User Laboratory provides clean laboratory space with vibration-isolated optical tables for setup of FEL application and diagnostic experiments. Phase I of the project includes initial operation of both FELs and is expected to be completed in three years from start of funding.

References

[1] H. A. Grunder, in 1988 Lin. Acc. Conf. Proc. CEBAF Report-89-011, (1988).

[2] Chun-Ching Shih and Su-Miau Shih, Nuc. Inst. Meth. in Phys Research A304 (1991) 788-791.

Figure Captions

Figure 1 CEBAF IR and UV FEL configuration.

Figure 2 CEBAF FEL power output vs. wavelength.

Figure 3 Wavelength dependence on electron energy and wiggler K value.

Table 1

CEBAF FEL Specifications

	IR	UV
Electron energy (E)	45 MeV	400 MeV
Pulse repetition freq.	7.485 MHz	7.485 MHz
Charge/bunch	120 pC	120 pC
Momentum spread (σ_p/p)	$2 \cdot 10^{-3}$	$2 \cdot 10^{-3}$
Bunch length (τ) (4σ)	2 ps	1 ps[a)]
Peak current (I_p)	60 A	120 A[a)]
Normalized emittance (ε_n)[b)]	15 mm-mrad	15 mm-mrad
Wiggler length (L)	1.5 m	$2 \cdot 1.5$ m
Wiggler wavelength (λw)	6 cm	6 cm
Number of periods (N)	25	50
Type	electromagnetic	electromagnetic
K_{rms} (max)	2.1	2.1
Gap ($2h$)	11 mm	11 mm
Rayleigh range (R_L)	0.75 m	1.5 m
Optical beam radius (w_0)	1.9 mm @ 15.8 μm	0.31 mm @ 200 nm
Optical cavity length (L_{cav})	20.027 m	60.08 m

a) With magnetic bunch compression to 1 ps; without compression $\tau = 2$ ps, $I_p = 60$ A

b) $\sigma_x = \sqrt{\beta \varepsilon_n / \gamma}$

Table 2

CEBAF IR-FEL Radiation Characteristics

	Baseline[a]	Options[b] I	Options[b] II
Electron energy (MeV)	45	17–45	29–85
Output tuning range (μm)	4.5–20	4.5–25	1.2–25
Pulse duration (ps)	2	2	6.7
Pulse repetition freq. (MHz)	7.485	7.485	7.485
Spectral bandwidth	Fourier transform limited		
Polarization	Linear		
Peak power (MW)[c]	53	20–53	8–20
Average power (kW)[c]	0.8	0.3–0.8	0.4–1.2

[a] Baseline operation at 45 MeV is compatible with simultaneous CEBAF nuclear physics operations.

[b] Dedicated options with the CEBAF injector operating with gradients between 1.5–5.0 MV/m and without (I) or with (II) the CEBAF Injector recirculator.

[c] Assumes nominal $1/2N$ efficiency at saturation.

Table 3

CEBAF UV-FEL Radiation Characteristics

	Baseline[a]	Option[b]
Electron energy (MeV)	400	150–445
Output tuning range[c] (nm)	150–260	150–1860
Pulse duration (ps)	1	1
Pulse repetition freq. (MHz)	7.485	7.485
Spectral bandwidth	Fourier transform limited	
Polarization	Linear	
Peak power (MW)	480	160–530
Average power (kW)		
@ 100–150 nm	0	TBD[c]
@ 150–200 nm	TBD[c]	TBD[c]
@ 200–260 nm	3.6	4
@ 260–1860 nm	–	4–1.2

[a] Baseline operation at 400 MeV is compatible with simultaneous CEBAF nuclear physics operations.

[b] Dedicated option with variable energy (150–400 MeV) operation of the CEBAF North Linac.

[c] Short-wavelength limit is very sensitive to mirror reflectivity and gain limitations due to electron energy spread.