CEBAF UV/IR FEL subsystem testing and validation program

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Abstract

A design has been established for IR and UV FELs within the Laser Processing Consortium's (LPC) program for development and application of high-average-power FELs for materials processing. Hardware prototyping and testing for the IR portion of the system are underway. The driver portion has been designed based on the superconducting radio-frequency (SRF) technology now seeing large-scale application in the commissioning of CEBAF, the Continuous Electron Beam Accelerator Facility, where LPC activities are centered. As of July 1994, measurements of beam performance confirm SRF's benefits in beam quality and stability, which are applicable to high-average-power FELs.

1. Introduction

The Continuous Electron Beam Accelerator Facility (CEBAF), a DOE nuclear physics laboratory, has joined with industrial corporations and universities to form the Laser Processing Consortium (LPC) to develop a new capability for production-scale processing of polymer, ceramic, and metal surfaces using UV and IR light from high-average-power free electron lasers [1]. While conventional lasers have limited application for industrial-scale surface processing – with cost per photon 100 to 1000 times too high and available wavelengths fixed and few – numerous compelling applications exist if high-average-power FEL technology can be demonstrated [2].

The initial stages of the LPC program include a kilowatt-level IR FEL and involve DOE-funded injector hardware and Commonwealth of Virginia-funded wiggler and optical cavity. Injector fabrication is underway, and driver component testing is proceeding using CEBAF superconducting radio-frequency (SRF) linac performance to qualify hardware designs. The data accumulated through mid-1994 represents substantial progress in quantifying the large-scale performance of SRF accelerators in daily use, thereby providing validation of SRF's potential for driving high-average-power FELs. This paper, after summarizing the laser design, addresses subsystem testing and validation status.

2. FEL design overview

Fig. 1 shows the LPC/CEBAF FEL, driven by a cost-efficient SRF three-cryomodule linac similar to CEBAF's two 20-module linacs [3]. The accelerating gradient will be 8 MV/m for a net energy gain of approximately 96 MeV. A photocathode gun designed at the University of Illinois will produce the electron beam [4]. The first-pass accelerated beam will recirculate back to the injection point for a second acceleration pass, enter the wiggler at up to 200 MeV energy, yield laser light, and finally decelerate through two energy-recovery passes in the linac before its remaining energy is absorbed in a copper beam dump at about 10 MeV. The UV FEL will use a taperable high-field wiggler similar to those recently purchased by several synchrotron light sources and FEL projects around the world. (See Robinson et al., this conference.) The IR FEL wiggler will be an electromagnet similar to a half-length version of the highly successful OK-4 undulator used at the Novosibirsk FEL project [5]. The UV FEL optical cavity will consist of a retro-reflecting reimaged ring resonator (R5) cavity [6,7]. Table 1 summarizes the machine specifications for both the driver accelerator and the laser. The predicted output power vs. wavelength shown in Fig. 2 is based on a scaling model by Benson [3] with tuning achieved by varying the wiggler field strength.

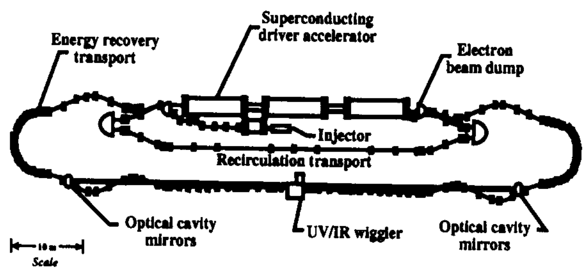

Fig. 1. Layout of the kilowatt demonstrator FEL.

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3. Subsystem testing and validation status

The sections below discuss FEL subsystems, for which a number of hardware elements have been tested in prototype or in CEBAF accelerator commissioning. In most cases we have found their demonstrated performance exceeds the FEL requirements.

3.1. Injector

The design goals for the FEL injector require electron bunches of 200 pC delivered at a 24.95 MHz repetition rate, for an average beam current of 5 mA. This precludes the use of RF guns using room-temperature RF systems, since these structures in CW operation cannot support the high fields required to deliver the necessary bunch charge within the specified emittance and energy spread. (An SRF gun has been demonstrated, but this technology is insufficiently mature.)

Our baseline gun design is to operate at 500 kV DC with 10 MV/m field at the cathode, leading to less than 13 MV/m maximum field on the cathode electrode structure. We have modeled the single-electron-bunch performance of our proposed gun using a version of PARMELA modified by McDonald [8] and adapted to the DC gun case by substituting fields calculated by POISSON (DC gun case) as suggested to us by Herrmannsfeldt [9]. The results of extensive calculations for this DC gun case indicate that this gun will deliver sufficient single-bunch charge suitable for bunching and acceleration by CEBAF SRF cavities. (See Liu et al., this conference.)

Table 1
Machine specifications

Driver accelerator	
Electron kinetic energy	50–200 MeV
Pulse repetition frequency (design goal)	24.95 MHz
Charge/bunch (design goal)	200 pC
Momentum spread (σ_p/p) [a]	2×10^{-3} to 1×10^{-3}
Bunch length (σ_t)	0.4 ps
Peak current (I)	100–200 A
Normalized emittance (ε_N)	12 π mm mrad
Beta functions at wiggler center	88 cm (round beam)
UV wiggler and UV optical cavity	
Wiggler length (L)	1.44 m
Wiggler wavelength (λ_W)	3 cm
Maximum field (B_{max})	0.8 T
Wiggler gap ($2h$)	7.5 mm
Effective Rayleigh range	79 cm
Optical mode waist (w_0)	0.20 mm at 200 mm
Optical cavity length (L_{cav})	60.08 m
Output radiation characteristics	
Optical tuning range (UV)	150–1000 nm
Optical tuning range (IR)	2–28 μm
Pulse duration	1 ps (FWHM), 2 ps IR
Pulse repetition rate	2.5, 4.99, ··· 24.95 MHz
Spectral bandwidth ($\delta\lambda/\lambda$)	< 0.5% FWHM
Polarization	linear
Peak power	100–160 MW
Transverse mode quality	< 2 × diffraction limit

[a] Since absolute energy spread should remain constant as the energy is changed, the range of energy spread shown reflects a factor of two change in energy.

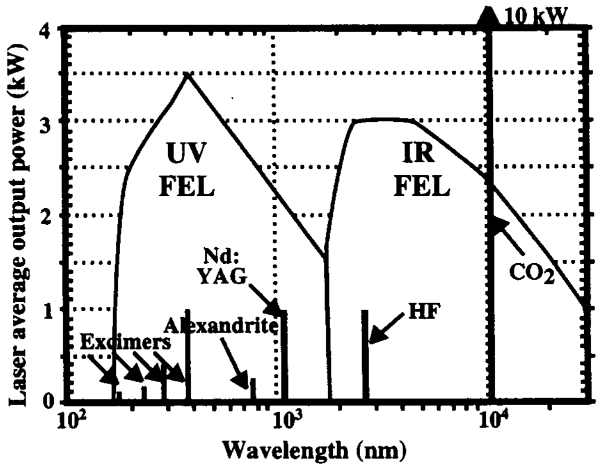

Fig. 2. Predicted output power vs. wavelength for the FEL with energy recovery, assuming the electron beam parameters listed in Table 1. The power output of conventional commercial lasers is also shown.

The photocathode will be illuminated by a commercial CW mode-locked Nd:YLF laser, operating at 74.85 MHz and frequency doubled to 527 nm in an LBO crystal. The laser provides in excess of 5 W at 527 nm in the mode-locked pulse train at 74.85 MHz. One pulse of every three will be selected electro-optically to provide the 24.95 MHz pulse train to the photoemission gun. The $\frac{5}{3}$ W of useful laser light will support the required 5 mA average current for cathodes with quantum efficiencies greater than 0.7%. Typical GaAs photoemission cathode quantum efficiencies are an order of magnitude greater than this at the 527 nm wavelength, providing a reasonable operating margin, although the lifetime at these average currents has not been demonstrated. Particular attention will be given to the cathode vacuum environment. The measured auto-correlated output of the laser is 42.9 ps FWHM pulse length. Amplitude stability is excellent: < 0.3% p–p on subsecond time scales and < 0.5% p–p on 30 min time scales. No accurate phase stability data has yet been obtained.

Following the 500 kV photocathode gun, the beam enters a one-cell fundamental-frequency room-temperature prebuncher. A two-cavity cryounit (quarter-cryomodule) follows the prebuncher. These cavities provide an appropriate amount of additional bunching and focusing for suitable injection into the first cryomodule in the driver accelerator while accelerating the electrons to an energy of

10 MeV. Both cavities are operated at an accelerating gradient of 10 to 11 MV/m.

3.2. SRF

Performance of the driver accelerator's three cryomodules must be comparable to that routinely achieved during CEBAF's tests of 42 cryomodules: $Q = 5 \times 10^9$ at a gradient of 8 MV/m. No modifications are necessary for the superconducting cavities, although some modifications to auxiliary components mounted on the cavities are desirable. These modifications are driven by the increase in higher-order-mode (HOM) power resulting from the increase in bunch charge. The power absorbed in each HOM load increases from 0.1 W in the CEBAF case to 30 W in the FEL. A design for taking the HOM power to 50 K (as opposed to 2 K as in CEBAF) has been produced.

CEBAF linac cavity performance has been exemplary and validates the high reliability and beam stability expected of SRF cavities. In a recent accelerator test of these cavities, 600 MeV beam was provided to CEBAF's Hall C for nuclear physics research for the first time. In a subsequent test with 286 cavities operating (of 338 total in the injector and both linacs), maximum energy was 808 MeV, with an average gradient of 5.65 MV/m. For this test RF power (and consequently beam energy) was limited due to our desire not to set a high demand charge on electricity during the rest of the year.

Reliability was excellent; in an initial 65-h run beam was on target 69.7% of the time. During a typical 8 h shift during this run, trips from various interlocks and hardware safety systems occurred approximately once an hour and were quickly reset by the operators. No re-steering of the beam was required. It should be noted, finally, that in over a year of operation no degradation of cavity performance has been observed. Since the number of components in the FEL will be less than 1/10 the number in CEBAF, we expect to achieve excellent beam availability.

3.3. RF

Driver linac cavities will use energy recovery to reduce RF requirements to < 5 kW, a level comparable to demonstrated CEBAF performance. Thus each will use a standard CEBAF 5 kW klystron. Injector cavities, operating without energy recovery, will each require about 30 kW including the reactive load. An appropriate source is presently being procured.

The RF phase and amplitude control requirements are strict in the FEL; however, we have succeeded in demonstrating in most cases our ability to meet and exceed these requirements, although with low beam loading and on resonance. Table 2 shows the requirements and the demonstrated performance of this system. Further information on the design and performance of this control module is available in Ref. [10].

It must be noted that the RF control in the recirculated, energy-recovered system has some elements which are not fully tested in the present system. In the FEL injector, beam loading will occur which exceeds our experience base. In the linac, the average detuning angle will need to be around $-64°$ rather than zero so that there is substantial phase/amplitude coupling. A modification of the control circuitry will minimize this issue, but beam testing is needed to confirm control algorithms. Further, overall system stability of energy recovery during FEL operation needs further study. (See Edighoffer, this conference.)

3.4. Cryogenics

An SRF FEL needs a capable and reliable refrigerator system, and at 1500 MHz this system must operate subatmospheric. Until 1994, experience with subatmospheric compressors had been limited to low total refrigeration power on the TORE-SUPRA tokamak. But in the 6 months between February and August 1994, substantial experience was gained on the CEBAF CHL, which provides in excess of 4800 W of cooling capacity at the 2 K operating

Table 2
RF requirements and demonstrated performance

Parameter	Requirement	Demonstrated
Power	2 kW linac, 30 kW injector	5 kW
Amplitude stability	$\sigma_A/A \leq 1 \times 10^{-3}$	2×10^{-4} correlated and 3×10^{-5} uncorrelated
Phase stability	$\sigma_\phi \leq 1°$	$\leq 0.10°$
Microphonic noise	less than 20° peak–peak	< 13° peak–peak typical
Operating gradient	8 MV/m ± 5%	8 MV/m
Loaded Q	6.6×10^6	$6.6 \times 10^6 \pm 20\%$
He-pressure sensitivity	< 10 Hz/mbar	< 10 Hz/mbar
Lorentz force	$3\ Hz/(MV/m)^2 \pm 10\%$	$3\ Hz/(MV/m)^2$
HOM power	< 30 W/load	< 0.5 W/load

temperature of CEBAF. Continuous runs exceeding 800 h were achieved.

The CHL system has demonstrated the 2 K capacity to maintain operation of the FEL simultaneously with the CEBAF linac. The heat load due to all of CEBAF is only about 3000 W at 2 K. The FEL will contribute less than an additional 500 W at 2 K. During commissioning of the system over 5000 W of cooling capacity was demonstrated. An additional liquefier will be needed for the FEL to support the 2300 W of 50 K cryogenic loads. This will be achieved with a minor upgrade on the 12000 W capacity already in existence.

3.5. Transport

The two-pass FEL design with energy recovery requires considerable manipulation of longitudinal and transverse beam dynamics to provide the bunch lengths required at the wiggler and to make stable energy recovery feasible. Two recent tests on the CEBAF accelerator provide guidance for the FEL beam transport. In one, total path length was accurately set to better than 4 parts in 10^7 out of a total length of 1.4 km by comparison of beam arrival times with a pickup loop. Recent operational experience has also shown that M_{56} (energy-path length interdependence) control to the level required in the FEL driver is feasible.

By modulating the beam energy and measuring the arrival phase of the beam using a precision phase detector between a reference signal from the final RF control module and a beam position monitor at the 90° point of one arc, the linear transfer matrix can be determined. In the recent commissioning work, setting nominal values of currents into the arc magnets resulted in an M_{56} of 18.5 cm. After application of small corrections on the order of 3% to the compaction control quadrupoles, the M_{56} was measured to be 1.8 cm over a path of approximately 125 m, more than 1.5 times the corresponding FEL path length. The technique can probably be used to measure M_{56} to an accuracy of better than 3 mm, giving us confidence that the M_{56}'s required in the FEL to bunch and decompress the electron beam before and after the wiggler can be properly set to their design values of order 1 m.

3.6. Optical systems

The UV FEL optical cavity will consist of a retro-reflecting reimaged ring resonator (R5) cavity [6,7]. This design allows the cavity to be rather long (60 m) without the requirement of state-of-the-art active angular controls for the mirrors. The resonator has a number of useful properties including uniform mirror loading and insensitivity to spherical aberration. The UV FEL will use commercially available high-power dielectric coatings on cooled silicon carbide substrates. The IR FEL mirrors will use protected silver coatings on silicon carbide substrates. The IR cavity will use a more conventional near-confocal resonator due to the relaxed angular tolerances at the longer wavelengths. Both optical cavities will use scraper mirror output coupling.

4. Conclusions

A design has been established for the CEBAF IR and UV FELs as standalone systems. The IR portion of the system – consisting of the injector, $1\frac{1}{4}$ cryomodules, IR wiggler, and optical system – is funded and work is proceeding in construction, prototyping and testing of the hardware components. Measurements of beam performance have been made using the CEBAF linacs, which support the chosen design parameters. The benefits of the superconducting design in terms of beam quality and stability are evident. The crucial performance tests will come this year as the injector is commissioned.

Acknowledgements

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References

[1] Proposal: High-Power Ultraviolet and Infrared Free-Electron Laser for Industrial Processing, Laser Processing Consortium, May 1994, available from CEBAF, 12000 Jefferson Avenue, Newport News, VA 23606.

[2] M.J. Kelley et al., Proc. Int. Conf. on Radiation Processing, Orlando, 1994 (Radtech, 1994).

[3] Reference Design Report: High-Power Ultraviolet and Infrared Free-Electron Laser for Industrial Processing, Laser Processing Consortium, May 1994, available from CEBAF.

[4] C.K. Sinclair, Nucl. Instr. and Meth. A 318 (1992) 410.

[5] I.B. Drobyazko et al., Nucl. Instr. and Meth. A 282 (1989) 424.

[6] Chun-Ching Shih and Su-Miau Shih, Nucl. Instr. and Meth. A 304 (1991) 788.

[7] C.C. Shih, G.J. Linford, S.W. Quon and A.J. Schmit, SPIE Proc. 1224 (1990).

[8] K.T. McDonald, IEEE Trans. Electron Devices ED-35 (1988) 2052.

[9] W. Herrmannsfeldt, private communication.

[10] S. Simrock, Proc. 1991 IEEE Particle Accelerator Conf., San Francisco, May 1991, p. 2515.