XUV FREE-ELECTRON LASER DEVELOPMENT AT LOS ALAMOS*

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Abstract

Free-electron lasers (FELs) for the vacuum-ultraviolet and soft x-ray spectral regions (together termed the XUV) are being designed at Los Alamos for integration into a future national UV/XUV FEL user facility for scientific experimentation. As proposed, this facility would consist of a sequence of up to 15 FEL oscillators and amplifiers, driven by a single, rf-linear accelerator, that will generate broadly tunable, picosecond-pulse, coherent radiation over the range from 1 to 400 nm. Below 300 nm, the peak- and average-power output of these FEL devices should surpass the capabilities of any existing, continuously tunable photon sources by many orders-of-magnitude. We describe the design parameters and predicted output of these FELs and make comparison with synchrotron radiation sources. Brief mention is given to our recent progress in developing the three primary components (electron beam, magnetic undulator, and resonator mirrors).

Introduction

Since 1984, a multi-disciplinary team of Los Alamos scientists has been developing the requisite technologies needed to extend rf-linac-driven free-electron lasers into the extreme-ultraviolet below 100 nm. This activity, sponsored by the U. S. Department of Energy, was a natural spinoff from the DoD high-power FEL program at Los Alamos which requires visible and near-infrared devices. Confident that a sufficiently bright electron beam can be generated and preserved by an rf linear accelerator, we have designed a series of FEL oscillators and amplifiers that will generate broadly tunable, picosecond-pulsetrains spanning the ultraviolet to the soft x-ray spectral range from 1 to 400 nm. Our numerical simulations predict that below 300 nm the peak- and average-power output of these devices should surpass the capabilities of any existing, continuously tunable photon sources by many orders-of-magnitude. (The interested reader should consult Refs. 1 and 2 in which various proposed FEL systems for generating coherent XUV radiation are reviewed.) According to the participants at the recent OSA Topical Meeting on *FEL Applications in the Ultraviolet*[3] (Cloudcroft, New Mexico, March 2-5, 1988), such photon sources, when developed into user facilities, will greatly enhance the research capabilities of a number of scientific disciplines.

With recent improvements, especially the Los Alamos photoinjector[4], rf-linear accelerators now appear to be a viable alternative to storage rings as sources of the very bright electron beams (high peak current, low transverse emittance and energy spread) needed to enable FELs to operate in the XUV.[5] RF-linac FELs offer several potential advantages which include: 1) the electrons pass through the FEL only once at 10^9 Hz without the constraints imposed by storing a recirculating beam including peak-current density limitation by the Toushek effect, 2) linac FELs can produce both high-peak and high-average output power simultaneously, 3) the linear geometry allows unrestricted and variable undulator length, 4) a number of FEL oscillators can be driven in series restricted only by the available laboratory space, and 5) the electrons exiting the FELs can be used to generate neutrons, positrons, and gamma rays for additional experiments in synchronism, if desired, with the FEL photons.

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Los Alamos work on extending FELs into the XUV began in earnest after Newnam, et al.[6] and Goldstein, et al.[7] determined that rf linacs needed only modest improvements to be able to meet the electron beam quality requirements operation at wavelengths ≤100 nm. Since that time, we have had the practical benefit of approximately 2000 hours operation (1983-1988) of the Los Alamos infrared FEL (9 - 45 μm) with high-peak currents (≥500 A) resulting in large values of optical gain (up to 400%/pass) at 10-12 μm from a short, 1-m undulator. Experience with this system has provided invaluable insight and data with which to design a XUV-wavelength, linac-based FEL light source as a scientific research facility.[6-15] To determine realistic operating parameters for XUV FEL amplifiers and multiple-pass oscillators, B. McVey[16] formulated the 3-D simulation code FELEX which has proved invaluable in simulating the emittance-limited FEL interactions.

To realize the potential of FELs, we have concentrated on improving the state-of-the-art of the three basic components of an FEL: electron beam, magnetic undulator, and resonator mirrors. Recent experimental progress at Los Alamos supports our optimism that operation in the XUV can be achieved in the next few years using FEL oscillators down to 50 nm (and probably to 10 nm) and between 1 to 10 nm using amplifier configurations. Our key achievements have included: 1) design, construction, and characterization of a high-brightness, photocathode injector[4,17-19], 2) invention and implementation of Warren's pulsed-wire technique for sensitive detection, correction, and on-line monitoring of magnetic-field errors[20,21], and 3) design and demonstration of high-reflectance, multifacet metal mirrors needed for resonators below 100 nm.[22-24] Especially noteworthy is the attainment of 89% retroreflectance at 58 nm by a nine-facet Al reflector, which is a factor-of-three higher than previously exhibited by any other reflector at this XUV wavelength.[24]

XUV FEL Facility Design

FEL Oscillator Chain

The conceptual design of the proposed Los Alamos XUV FEL Facility is shown in Fig. 1, and design specifics are given in Table 1. It includes a series of FEL oscillators, driven by a single rf-linac, that should simultaneously span the soft x-ray through the ultraviolet spectral ranges from 1 nm to 400 nm. The shortest-wavelength oscillators are ordered first in the sequence since they require the highest-quality electron beam; the gain at longer wavelengths is less affected by beam degradation. Even so, all of the oscillators are designed to perturb the electron beam energy only very slightly, with the energy-extraction efficiency being less than 0.1%. Further beam degradation by wakefield effects in the beamline and magnetic undulator must be prevented by minimizing discontinuities. The number of oscillators may be increased arbitrarily, consistent with the amount of accumulated energy spread and/or emittance degradation in the electron beam. The operating wavelengths of each of the FELs will either be tuned as a group by varying the electron energy or independently over a smaller range by adjusting the undulator gaps.

The rf linac structure may be either a room-temperature, cryogenic, or superconducting design. All of the past infrared FEL experiments at Los Alamos have used a side-coupled, standing-wave L-band (1.3 GHz) rf-linac operated at slightly above ambient

Figure 1. CONFIGURATION OF THE PROPOSED LOS ALAMOS XUV/UV FREE-ELECTRON LASER FACILITY (1 to 400nm)

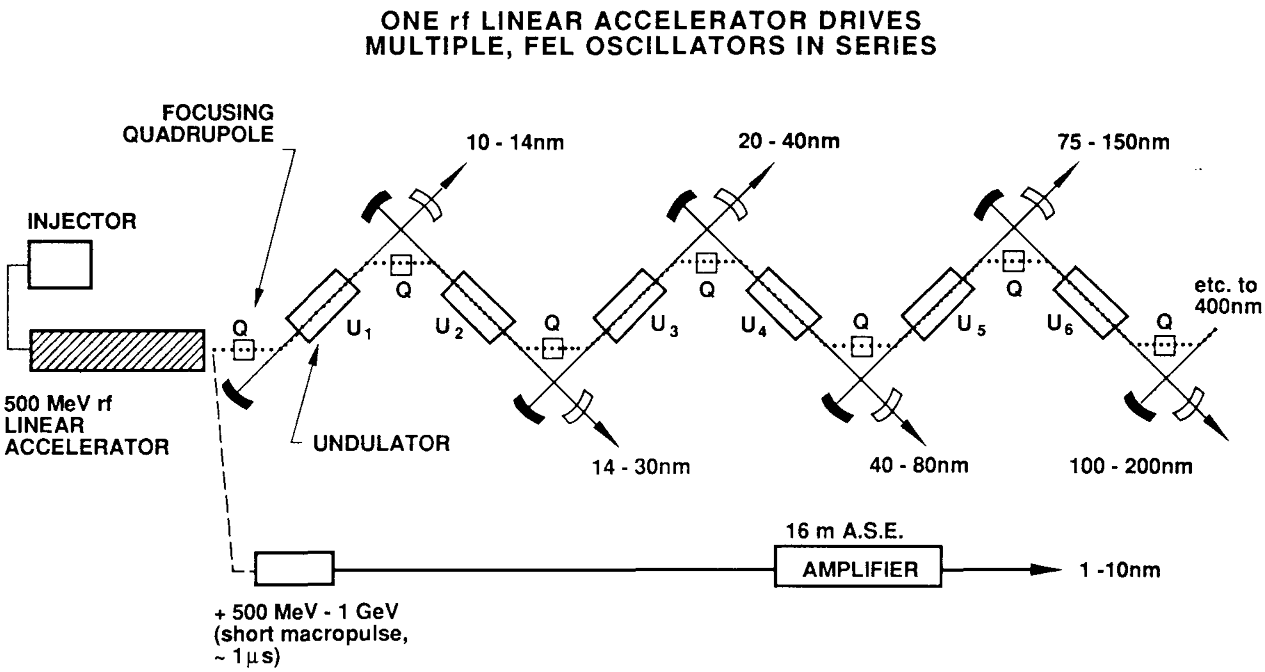

Table 1. Design Parameters for RF-Linac FELs for the Ultraviolet to the Soft X-Ray Region

Electron beam	
Energy:	100 to 500 MeV, FEL oscillators 750 MeV to 1 GeV, FEL SASE amplifier
Peak current:	100 to 400 A, as required
Normalized emittance: (90% of electrons)	25π to 40π mm-mr, for oscillators $\leq 4\pi$ mm-mr, for a 16-m SASE amplifier
Energy spread:	0.1% to 0.2%, FWHM
Macropulse duration:	≤ 300 µs for room-temperature linac option $\leq$ cw for superconducting linac option
Macropulse duty factor:	1 to 10% for RT linac option 100% for superconducting linac option
Undulators	
Length:	8 m: 50-nm oscillator, 12 m: 10-nm oscillator
Period:	1.6 cm
Peak Axial Field:	7.5 kG
Resonator mirrors	
End mirrors:	R $\geq$40%, multifaceted flats + paraboloids with metal coatings of Al and Si for 35-100 nm; Ag and Rh for 10-14 nm; multilayers for 14-35 nm CVD SiC for $\geq$60 nm, optional.
Beam-expanding hyperboloids:	Au coating on SiC or Si

temperature, and we have performed extensive design calculations for similar linac structures from 100 MeV to 1 GeV for an XUV FEL. However, the cryogenic and superconducting (at 4K) options are being examined also because they offer potential advantages of cw macropulse operation, improved pulse-to-pulse stability, and reduced electrical cost due to lower power dissipation in the structure.

FEL Amplifiers Based on Self-Amplified Spontaneous Emission

The feasibility of and output power from FEL oscillators will depend on the availability of resonator mirrors with sufficiently high reflectance to match the attainable small-signal gain. Satisfactory broadband mirrors have yet to be produced below 35 nm, and this spectral region may well become the domain of either coherent harmonic radiation generated within FEL oscillators or higher-power, single-pass FEL amplifiers based on self-amplified spontaneous emission (SASE). As indicated in Fig. 1, the proposed Los Alamos XUV FEL Facility will include a long SASE amplifier for wavelengths below 10 nm. SASE amplifiers are attractive since the problems of thermal distortion, laser damage, and cost of resonator mirrors are avoided.

To produce useful power levels in the SASE mode of operation, the single-pass optical gain must exceed ~1000. In this regime, much brighter electron beams and longer undulators will be required than for FEL oscillators. Fortunately, with these conditions, the FEL gain increases exponentially with peak current and undulator length. For example, 3-D numerical calculations by Goldstein, et al.,[25] predict that generation of ~12 MW peak power at 6 nm will require a 900-MeV electron beam with 200-A peak current, energy spread ≤0.1 %, and energy-normalized emittance (90% of electrons) of 4π mm-mr even with an ideal 30-m undulator amplifier with 1500 periods. These beam emittance and undulator requirements are especially demanding! At longer wavelengths from 20 to 40 nm, the requirements for amplifier operation are less stringent, but still demanding. At 20 nm, for example, 500 kW peak SASE power might be generated from a 16-m undulator with 1000 periods and a beam emittance twice as large (8π mm-mr) as needed for 6 nm.[12] If brighter electron beams do become achievable with the photocathode injector, even higher powers will produced.

Regenerative FEL Amplifiers

An intermediate variant between an FEL oscillator and an FEL amplifier based on SASE is a regenerative amplifier which uses two or more passes through the undulator to reach the final beam intensity. This scheme, suggested by both Goldstein et al.[25] and Kim,[26] requires end mirrors separated by half the arrival time of the electrons, as in an oscillator, but the mirror reflectance may be low, such as 10%. The required undulator length would be intermediate between that needed for an oscillator and a single-pass SASE amplifier. The process begins with SASE radiation generated from the first bunch of electrons. If the mirror reflectance returns more radiation to the undulator entrance than is generated by spontaneous emission from the next electron bunch of the pulse train, then the returned optical beam will experience more gain and will grow to a much higher level than by SASE alone. This method may be the most effective way of generating FEL radiation below 10 nm since a less demanding tradeoff can be made between the electron beam quality and the undulator length than is possible with a single-pass amplifier.

Optical Harmonic Generation

Optical harmonics are naturally generated within FELs using planar undulators by the nonuniform axial motion of the electrons. *Coherent* harmonic radiation is radiated by the electrons bunched on the wavelength scale of the fundamental lasing intensity. Outcoupling the optical harmonics is a very good method of extending the wavelength coverage to much shorter wavelengths, although at much reduced power, than can be supported by the gain or mirror reflectance bandwidth of a given FEL oscillator. For example, the first FEL oscillator shown in Fig. 1, operating at 12 ± 2 nm, should produce harmonics below 10 nm with significant power. With 1-MW peak intracavity power at 12 nm and 1% uncorrected random field errors, the powers produced in the third (4 nm), fifth (2.4 nm) and seventh (1.7 nm) harmonics will be 6 W, 100 mW, and 40 mW, respectively.[27] (The power in the even harmonics is considerably smaller than that of the odd harmonics, declining with wavelength, and may be less important.)

Predicted XUV FEL Output

We have performed 3-D numerical simulations using the FEL code FELEX[16] and its derivatives to predict the single-pass and multiple-pass gain in an XUV FEL resonator, the spectral bandwidth, and output power and spectral brightness versus wavelength. Table 2 provides an abbreviated summary. Operation at both 1% and 10% duty is feasible with proper cooling of the accelerator cavities, and 100% duty may be possible with either a cryogenic or a superconducting linac.

Comparison with Synchrotron Light Sources

Since FELs appear to be the natural finale in the progression of light sources based on radiation from relativistic electrons passing through magnetic undulators, it is appropriate to compare their output performance with synchrotron radiation sources such as storage rings with wiggler and undulator insertion devices. A comparison of the predicted time-averaged flux (photons/s/0.1% bandwidth) delivered to a sample target is presented versus wavelength in Fig. 2 and at 100 nm in Table 3. At 10 eV (124 nm) the FELs will produce 10^4 to 10^6 higher average flux; at 100 eV (12 nm), the FEL advantage will decrease to a factor of 500 to 50,000, depending on the repetition rate of the system. In terms of peak flux, the FEL operated at a 1% duty factor will exceed that of the synchrotron undulators by an additional factor of 3000 X!

Development Schedule for an XUV FEL Facility

Prior to building a complete user facility, the Los Alamos FEL team proposes to conduct a series of FEL oscillator demonstrations at progressively shorter wavelengths, the first of which would be from 50 to 100 nm. By mid-1989, the status of the electron-beam, undulator, and mirror technologies should well support this experiment. The second-phase objective will be FEL oscillation in the 10- to 14-nm region, corresponding to the high-reflectance band of a Rh multifaceted mirror. This will require higher electron beam energy (additional accelerator structure) and a low-emittance electron beam possible only with a photocathode injector. Since the reflectance of mirrors below 10 nm is not high enough for laser oscillators, the third phase will produce coherent, 1- to 10-nm radiation by SASE within very long amplifier undulators. Successful completion of these three stages, will enable the multi-FEL facility to cover the entire 1- to 400-nm range with projected output radiation characteristics that were given in Table 2.

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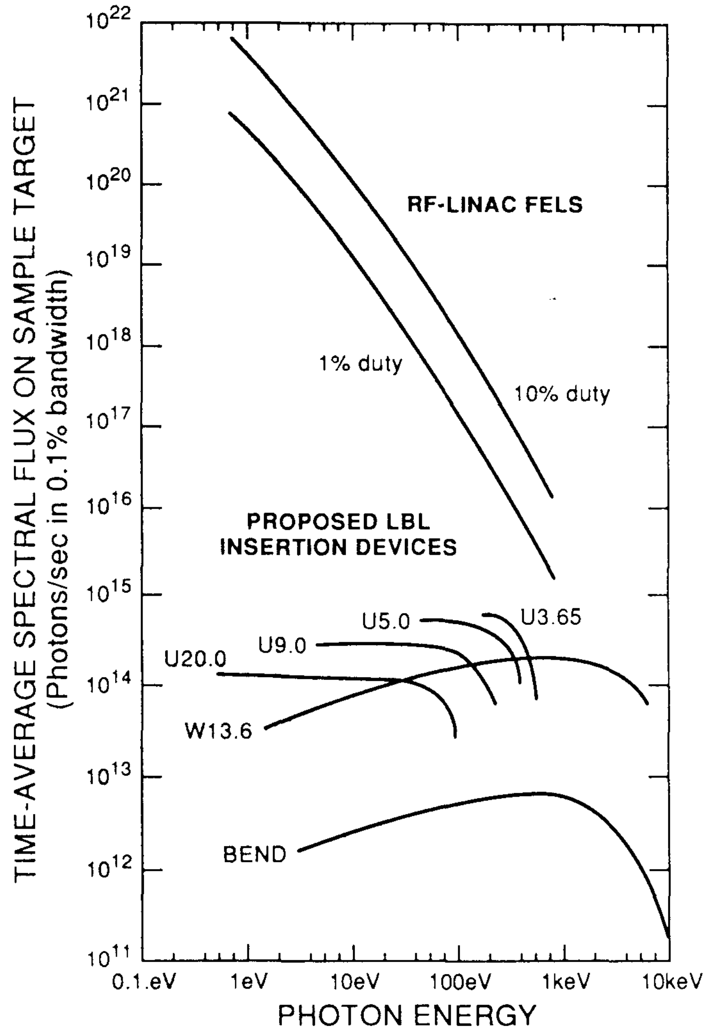

Figure 2. The time-average spectral flux delivered on target by rf-linac FELs is compared with that predicted for the most powerful synchrotron light source designs represented by undulators in the LBL Advanced Light Source.[28-30] The FEL curves were calculated for Los Alamos rf-linac FEL designs for 1% duty (10-ps pulse every 100 ns during a 300-μs macropulse repeated at 30 Hz) and 10% duty factors. A 100% duty factor could be possible with a superconducting rf linac driver. For the synchrotron radiation performance, a monochromator efficiency of 10% was applied to the published undulator output curves. Besides narrower spectral bandwidth of ~1 cm^{-1}, the FEL has an additional factor of 3000 advantage in comparisons of peak spectral flux. To convert the time-average curves to peak values, the appropriate multiplier for the FEL at 1% duty is 10^6 and that for the storage-ring insertion devices is ~300.

Table 2. Projected Output Properties of the Proposed Los Alamos RF-Linac-Driven UV/XUV FEL Facility

Micropulse duration:	10 - 30 ps (FWHM); possibly compressible to < 1 ps
Micropulse repetition rate:	10^7 - 10^8 Hz
Macropulse duration:	300-µs, Rep. @ 30 Hz; 300 Hz optional for RT linac ≤CW for superconducting linac option
Facility wavelength span :	1 nm to 400 nm, oscillators and SASE amplifiers
Spectral bandwidth:	1 cm^{-1} Fourier-transform limit of 10-ps pulse, up to ~1% if sidebands are allowed
Peak power at target:	>20 MW, for 200 to 400 nm, (1 cm^{-1} BW) 1 to ≥10 MW, for 12 to 100 nm, (1 cm^{-1} BW) 10 W, at 4 nm (3rd harmonic of 12 nm) 12 MW, at 6 nm (SASE amplifier)
Average power at target:	1 to >10 W for oscillators, for RT linac ≤ 1 kW at 100 nm for superconducting linac option
Photon flux at target:	10^8 - 10^{15} photons/10-ps pulse, 1 - 400 nm, resp. 10^{15} - 10^{22} photons/sec, average, " " "
Spectral brightness:	≥10^{26}photons/sec/(mm-mr)^2/1cm^{-1} BW, peak ≥10^{20} photons/sec/(mm-mr)^2/1-cm^{-1} BW, aver.
Polarization:	Linear with circular/elliptical option
Temporal coherence:	Limited by Fourier transform of micropulses
Spatial coherence:	Near diffraction-limited focusability

Table 3. Comparison of Output from FEL (RF-Linac-Driven) and Synchrotron Radiation Sources at 100 nm

	SSRL WIGGLER [a]	ALS UNDULATOR [b]	XUV FEL [c,d]
Photons/sec at sample	10^{12}	10^{14}	10^{19}, 10^{20}
Peak power at sample	10^{-2} W	10^{-1} W	>10^{+6} W
Average power at sample	10^{-5} W	10^{-4} W	>1 W, >10 W
Average & *peak* spectral brightness at sample (photons/sec/(mm-mr)^2/BW)	10^{12},*10^{15}*	10^{16},*10^{19}*	10^{20},*10^{26}*

a Stanford Synchrotron Research Laboratory wiggler;[28]
0.1 % spectral bandwidth after a monochromator with 10% efficiency assumed.

b Predicted performance of undulator B in the Advanced Light Source storage ring beginning construction at Lawrence Berkeley Laboratory.[28-30]
0.1% spectral bandwidth after a monochromator with 10% efficiency assumed.

c Single-pass, 180-MeV rf-linac FEL operated at 30 Hz with 300-mA average current during the 300-µs macropulse, i.e. 1% duty factor; output for 10% duty is also given.
Minimum spectral bandwidth is limited by the Fourier transform of 10-ps micropulses, i.e. ~1 cm^{-1} (0.001% at 100 nm).
Wider bandwidth with higher output power, limited by mirror distortion, is attainable by allowing controlled side-band growth; e.g., 1% BW increases the above FEL output values by 6X.

d Multiply all FEL output values by another **10X** if driven by a **500-MeV** linac.