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TITLE PROJECTED PERFORMANCE OF RF-LINAC-DRIVEN FREE-ELECTRON LASERS IN THE VUV AND SOFT X-RAY REGIONS

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Projected Performance of RF-Linac-Driven Free-Electron Lasers in the VUV and Soft X-Ray Regions

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For the past three years, a multidisciplinary team of Los Alamos scientists, supported by the U.S. Department of Energy, has been developing the requisite technologies to extend free-electron laser (FEL) operation from infrared and visible wavelengths into the extreme-ultraviolet below 100 nm using rf-linear accelerator technology. The goal is to establish an XUV Free-Electron Laser User Facility, the next-generation light source that will make available to researchers optical power more than one-million times greater than provided by synchrotron light sources. Based primarily on a series of FEL oscillators driven by a single, rf-linac, the Los Alamos facility is designed to generate broadly tunable, picosecond-pulse, coherent radiation spanning the soft x-ray through the ultraviolet to the visible spectral ranges from 1 nm to 400 nm.

An rf-linac is an alternative to a storage ring as the source of the very bright electron beam (high peak current, low transverse emittance and energy spread) needed to enable FELs to reach XUV wavelengths. Their use offers several potential advantages which include: 1) the electrons pass through the FEL only once at 10^7 to 10^8 Hz without the constraints imposed by beam storage, 2) the linear geometry allows unrestricted and variable undulator length, 3) a number of FEL oscillators can be driven in series restricted only by the available laboratory space, 4) the electrons exiting the FELs can be used to generate neutrons, positrons, and gamma rays for additional experiments in synchronism with the FEL photons, and 5) the linac FELs can simultaneously produce both high-peak and high-average output power.

The conceptual design of the multiple-oscillator FEL facility, driven by a single rf linac, is shown in Figure 1 and design specifics are given in Table 1. The shortest wavelength oscillators are ordered first in the sequence since they require the highest quality electron

Table 1. Design Parameters for a Free-Electron Laser Facility for the Ultraviolet to the Soft X-Ray Region

ELECTRON BEAM	
• Energy:	100 to 500 MeV, FEL oscillators 750 MeV to 1 GeV, FEL amplifier
• Peak Current:	100 to 200 A
• Normalized Emittance: (90% of electrons)	25π to 40π mm-mr, for oscillators ≤4π mm-mr, for 16-m amplifier undulator (Amplified Spontaneous Emission)
• Energy Spread:	0.1 to 0.2%, FWHM
UNDULATORS:	
• Length:	8 m for 50 nm, 12 m for 10 nm
• Period:	1.6 cm
• Peak Axial Field:	7.5 kG
• Undulator Parameter, K:	1.1, peak
RESONATOR MIRRORS:	
• End Mirrors:	R ≥40%, Multifaceted metal films of Al, Si, Ag, and Rh; also, CVD SiC for ≥60 nm
• Beam-Expanding Hyperboloids:	Au coating on SiC or Si

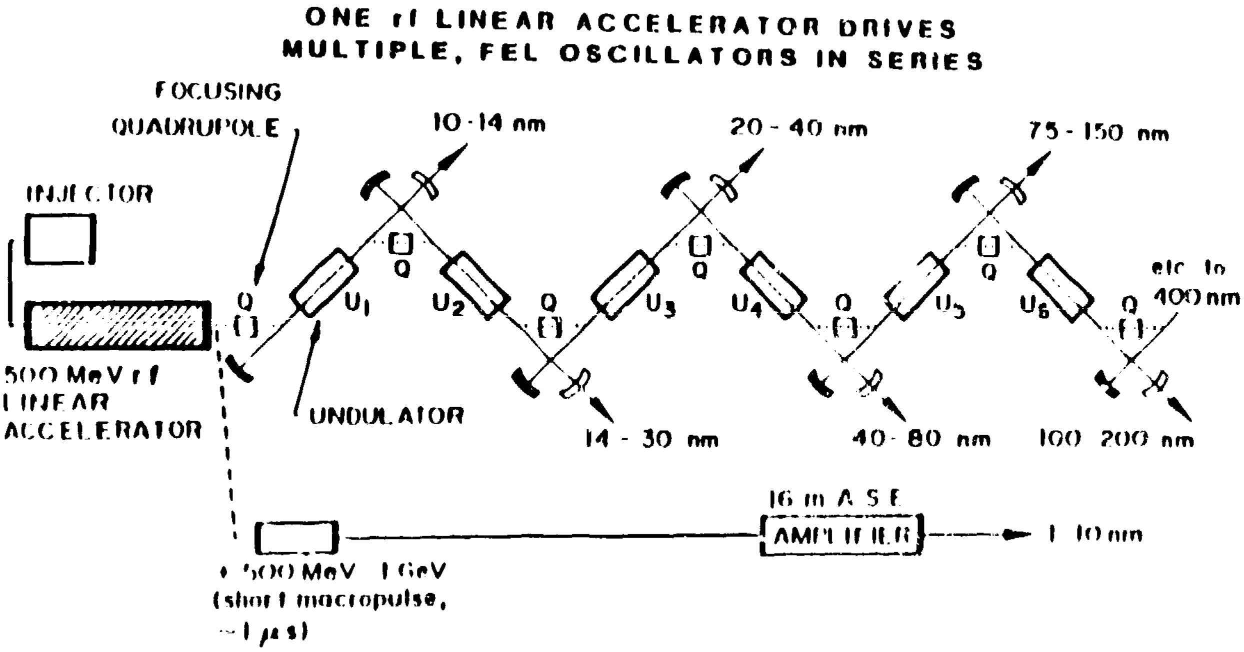

Figure 1 Configuration of the proposed Los Alamos UV/XUV FEL facility (1 nm to 400 nm)

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 is minimized by proper design. The number of oscillators may be increased arbitrarily, consistent with the amount of accumulated energy spread and/or emittance degradation in the electron beam. A broad range of wavelengths, limited only by the high-reflectance bandwidth of the resonator mirrors, can be reached by varying the electron energy. At a given setting of electron energy, the operating wavelength of the individual FEL oscillators may be tuned independently over a smaller range by adjusting the undulator gap.

Since mirror reflectance drops rapidly below 10 nm, a long, single-pass undulator will be used to produce coherent pulses between 1 nm and 10 nm by self-amplified spontaneous emission. Alternatively, using the best mirrors available, a two- or three-pass regenerative amplifier may produce more power or allow use of a shorter undulator. (Even with 10% reflectance mirrors, the soft x-ray beam feedback for the second pass should have more power than the spontaneous emission produced in the first few meters of the long undulator.)

Recent experimental progress at Los Alamos in two key areas provides optimism that operation in the XUV is feasible. These include development of high-reflectance metal-film mirrors in a multifaceted configuration and a low-emittance, high-peak current, electron-linac injector. Prior to building a complete facility, Los Alamos proposes a series of FEL oscillator demonstrations at progressively shorter wavelengths, the first of which will be from 50 to 100 nm. Additional accelerator structure will permit operation down to ≤10 nm.

Numerical simulations of FEL operation below 200 nm using the Los Alamos 3-D FEL Code "FELEX" predict that the peak- and average-power output of these oscillators and amplifiers should surpass the capabilities of any existing, continuously tunable photon sources by many orders of magnitude. Table 2 lists the FEL output radiation characteristics, and comparisons with sychrotron radiation sources are given in Table 3 and Figures 2 and 3. With increases in power of the order of 10^6 plus transform-limited bandwidth, a linac based UV/XUV FEL user facility should greatly enhance research capabilities at the frontiers of a number of scientific disciplines.

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

• Micropulse Duration:	10 - 30 ps; possibly compressible to < 1 ps
• Micropulse Repetition Rate:	10^7 - 10^8 Hz
• Macropulse Duration:	300-μs, Rep. @ 30 Hz
• Facility Wavelength Span :	1 nm to 400 nm, multi-oscillators and amplified spontan. emission amplifier
• Spectral Bandwidth	1 cm^{-1} Fourier-transform limit of 10-ps pulse up to ~1% if sidebands are allowed to grow.
• Peak Power at sample:	1 to ≥10 MW, for 12 to 100 nm 10 W, at 4 nm (3rd harmonic of 12 nm) ≥200 kW, at 4 nm (ASE Amplifier)
• Average Power at sample:	1 to >10 W for oscillators
• Photon Flux at sample:	10^{21} - 10^{28} photons/10-ps pulse 10^{15} - 10^{20} photons/sec, average
• Spectral Brightness:	$\geq 10^{26}$ photons/10-ps pulse/$(mm\text{-}mr)^2$/1cm^{-1}BW $\geq 10^{20}$ photons/sec/$(mm\text{-}mr)^2$/1cm^{-1}BW, aver.
• Polarization	Linear with circular/elliptical option
• Temporal Coherence	Limited by Fourier transform of micropulse
• Spatial Coherence	Near diffraction-limited focusability

Table 3.

Predicted Performance *at 100 nm* of an RF-Linac-Driven XUV Free-Electron Laser Compared with Synchrotron Sources

	SSRL WIGGLER [a]	ALS UNDULATOR [b]	XUV FEL[c,d]
PHOTONS/Sec at SAMPLE	10^{12}	10^{13}	10^{19}
PEAK POWER at SAMPLE	10^{-3} W	10^{-2} W	$>10^{+6}$ W
AVERAGE POWER at SAMPLE	10^{-6} W	10^{-5} W	>1 W
AVER. SPECTRAL BRIGHTNESS at SAMPLE (photons/sec/(mm-mr)^2/BW)	10^{12}	10^{14}	10^{20}

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[a] Stanford Synchrotron Research Laboratory wiggler;
0.1 % spectral bandwidth after a monochromator with 1% efficiency assumed.

[b] Predicted performance of undulator D in the Advanced Light Source ring beginning construction at Lawrence Berkeley Laboratory.
0.1% spectral bandwidth after a monochromator with 1% 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.
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.

[d] Multiply all above FEL figures by another **10X** with **500-MeV** linac source!

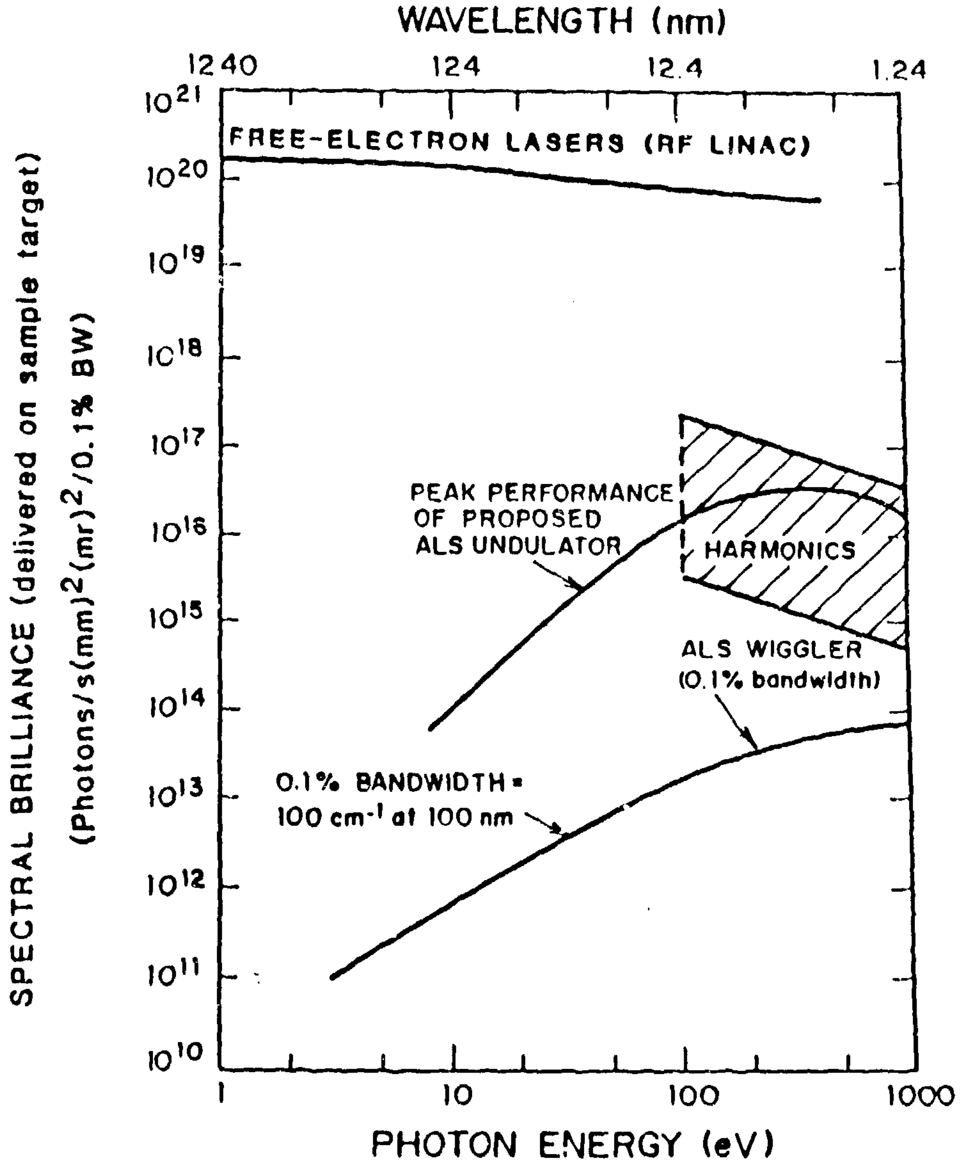

Figure 2. Time-average spectral brightness (delivered on target) of FELs will far exceed that of the most powerful storage-rings with insertion devices (undulators and wigglers) such as that of the Advanced Light Source to be constructed at Lawrence Berkeley Laboratory. (A monochromator efficiency of 1% was applied to the calculated insertion-device output.) Besides the narrower spectral bandwidth, the FEL has an additional factor of 10^4 advantage in comparisons of peak spectral brightness. To convert the time-average curves in Fig. 2 to peak brightness, the appropriate conversion factor for the FEL is 10^8 (10 ps pulse every 100 ns during the 300 µs macropulse repeated at 30 Hz); that for the storage-ring insertion devices is $\sim 10^2$.

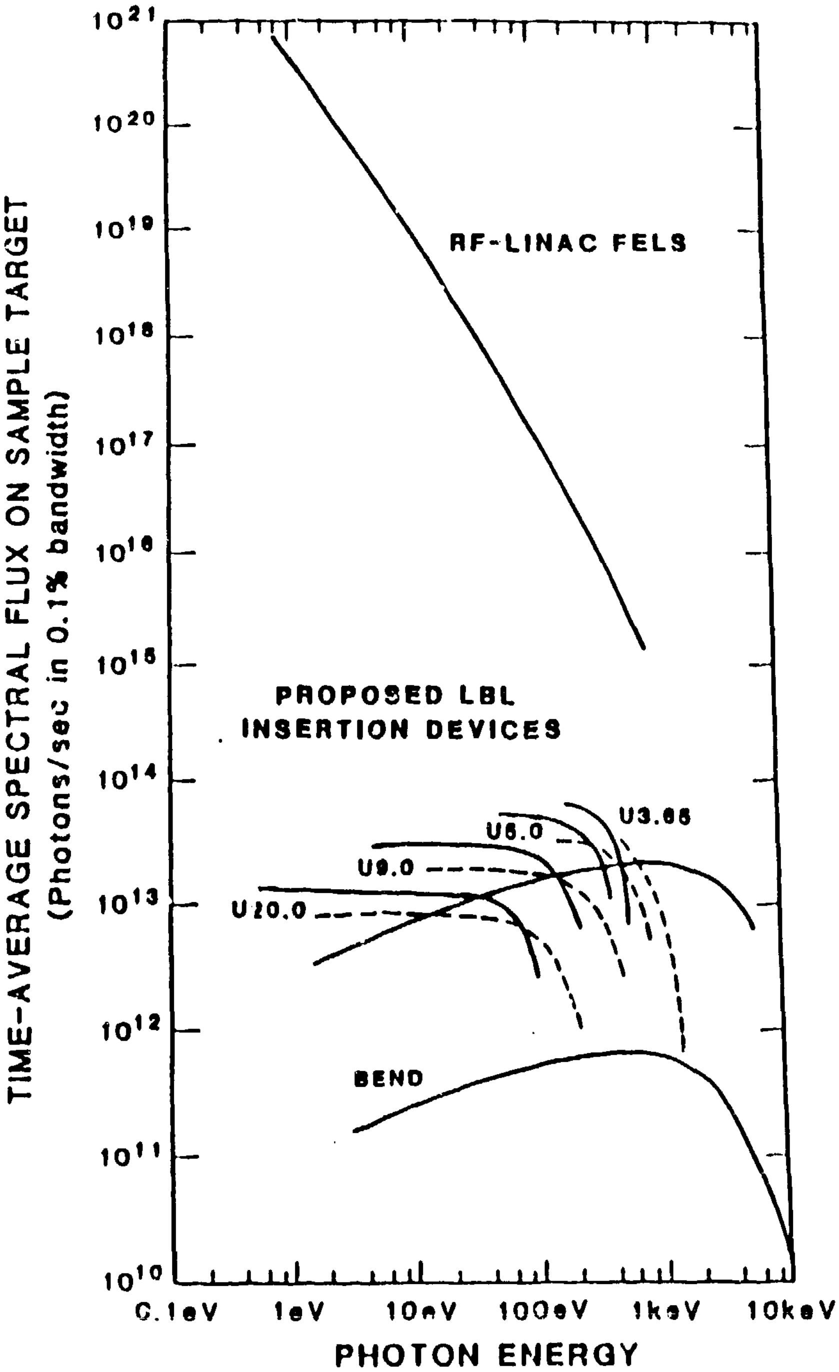

Figure 3. The time-average spectral flux (delivered on target) of FELs will far exceed that from synchrotron sources. (A monochromator efficiency of 1% was applied to the calculated insertion-device output.) As in the case of spectral brightness shown in figure 2, the FEL has an additional factor of 10^4 advantage in terms of <u>peak</u> spectral brightness. The appropriate multiplier to convert to <u>peak</u> flux values is 10^6 for the FEL and $\sim 10^2$ for the storage-ring insertion devices.