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TITLE: DEVELOPMENT OF AN XUV-IR FREE-ELECTRON LASER USER FACILITY
FOR SCIENTIFIC RESEARCH AND INDUSTRIAL APPLICATIONS

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Development of an XUV-IR free-electron laser user facility for scientific research and industrial applications*

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ABSTRACT

Los Alamos has designed and proposes to establish an XUV-IR free-electron laser (FEL) user facility for scientific research and industrial applications based on coherent radiation ranging from soft x-rays as short as 1 nm to far-infrared wavelengths as long as 100 μm . As the next-generation light source beyond low-emittance storage rings with undulator insertion devices, this proposed national FEL user facility should make available to researchers broadly tunable, picosecond-pulse, coherent radiation with 10^4 to 10^7 greater spectral flux and brightness. The facility design is based on two series of FEL oscillators including one regenerative amplifier. The primary series of seven FEL oscillators, driven by a single, 1-GeV rf linac, spans the short-wavelength range from 1 to 600 nm. A second 60-MeV rf linac, synchronized with the first, drives a series of three Vis/IR FEL oscillators to cover the 0.5 to 100- μm range. This paper presents the motivation for such a facility arising from its inherently high power per unit bandwidth and its potential use for an array of scientific and industrial applications, describes the facility design, output parameters, and user laboratories, makes comparisons with synchrotron radiation sources, and summarizes recent technical progress that supports the technical feasibility.

1. INTRODUCTION

Free-electron lasers (FELs) for the vacuum-ultraviolet and soft x-ray spectral regions (together termed the XUV) are being developed at Los Alamos for integration into a future national XUV-IR FEL user facility for scientific experimentation and for industrial applications.¹⁻⁵ Since 1984, a multi-disciplinary project team of Los Alamos scientists has been developing the theoretical basis and the requisite technologies needed to extend rf-linac-driven free-electron lasers into the extreme-ultraviolet below 100 nm. This activity has been a natural spinoff from the DoD/SDI high-power FEL program at Los Alamos, which requires visible and near-infrared devices. The XUV-FEL project has enjoyed the sponsorship of both the DOE Office of Basic Energy Sciences and Los Alamos Institutional Supporting R&D.

Los Alamos work on extending FELs into the XUV began in earnest after Newnam et al.⁶ and Goldstein et al.⁷ determined in 1983 that rf linacs needed only modest improvements to be able to meet the electron beam quality requirements for operation at wavelengths ≤ 100 nm. Since that time, Los Alamos National Laboratory,⁸⁻¹³ Stanford University,^{14,15} and Boeing Aerospace and Electronics^{16,17} have operated rf-linac-driven FEL oscillators in the visible and near infrared for a cumulative total of several thousand hours. Experience with these systems has provided invaluable insight and data with which to design rf-linac-driven FEL oscillators for operation in the XUV spectral range.^{6,7,18-25} An important distinction of the Los Alamos IR FEL has been its very high 500-A peak current capability and correspondingly large single-pass optical gain from a short, 1-m undulator (250% small-signal gain/pass at 10 μm with 300-400 A peak current).^{9,10} Such are the magnitudes of the parameters that will be required to operate FEL oscillators in the XUV.^{26,27}

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To realize the potential of FEL operation in the XUV, 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 and at other FEL centers supports our conviction that operation in the XUV down to 50 nm is ready to be implemented in the next few years followed by phased extensions down to 10 nm and below. Key achievements have included:

- Design, construction, and characterization of a new photocathode injector that produces electron beams 10-100 x brighter than possible with thermionic cathode injectors,^{12,13,28-31}
- Construction of high-precision undulators (permanent-magnet and hybrid)³²⁻³⁴ and high-field superconducting undulators^{35,36} and pulsed electromagnet wigglers^{37,38} with periods <1 cm and $a_w \sim 1$,
- Invention and implementation of R. Warren's pulsed-wire technique for sensitive detection, correction, and on-line monitoring of magnetic-field errors,³⁹⁻⁴¹ and
- Design and demonstration of high-reflectance, multifacet metal mirrors needed for resonators below 100 nm.⁴²⁻⁴⁴ Especially noteworthy was the attainment of 89% retroreflectance at 58 nm by a nine-facet Al reflector, which is more than a factor-of-two higher than previously exhibited by any other reflector at this XUV wavelength.⁴⁴

These advances are discussed in more detail in the Appendix of Section 9. In the following Section 2, we enumerate the scientific and industrial applications that are awaiting FELs in the VUV and XUV regions. Section 3 presents the FEL facility design and plans for user laboratories. Section 4 details the predicted output optical parameters of the FELs, and Section 5 compares these with third-generation synchrotron radiation sources now under construction. The development schedule for the proposed facility is discussed in Section 6. Finally, the Appendix of Section 9 reviews the FEL technology developments that will enable FEL operation in the XUV.

2. POTENTIAL APPLICATIONS FOR FEL SOURCES OF UV AND XUV RADIATION

The FEL facility proposed by Los Alamos National Laboratory is designed to operate over a broad spectral range for applications requiring both XUV and IR photons from 1 nm to 100 μm . Although it will be useful for a wealth of research opportunities in the infrared, the focus of this proposed facility is primarily in the VUV/XUV range below 200 nm where the technical challenges are the greatest and, arguably, where FEL radiation will find greatest application. The Los Alamos facility should complement the capabilities of other existing and planned FEL user facilities, all of which operate in the visible to far infrared as indicated in Fig. 1. Among these are the operating FELs at the University of California at Santa Barbara, Stanford University, Vanderbilt University, Duke University, and the FOM-Institute for Plasmaphysics in the Netherlands. These Vis/IR FEL facilities are being used for experimental studies of a variety of scientific applications as reported in the 1989 Special Issue of the Journal of the Optical Society-B on *Physics of Free-Electron Laser Applications*.⁴⁵ In addition, a number of workshops have been convened to consider the possible applications for Vis-IR FEL radiation.^{46,47}

According to experts in various scientific disciplines, numerous potential applications are awaiting the development and commissioning of FEL user facilities operating in the vacuum ultraviolet and extreme ultraviolet. The availability of several orders-of-magnitude more monochromatic photons per unit time (compared with synchrotron radiation sources) in trains of picosecond pulses will significantly impact atomic and molecular science, photochemistry, biology, physics of materials, interfaces and surfaces, and detectors and optics. The high intensities can be used to induce nonlinear physical phenomena, diagnose short-lived phenomena in low-density targets, and outshine keV plasmas in terms of spectral brightness. The greater number of photons per second will increase the signal-to-noise-ratio of experiments that heretofore could not be conducted or will provide snapshots of temporally unstable targets. The FEL applications workshop at Castelgandolfo (1984)⁴⁶ and especially the OSA Topical Conference on *Free-Electron Laser Applications in the Ultraviolet* held in 1988 at Cloudcroft, New Mexico^{49,50} addressed the short-wavelength applications. At the Cloudcroft meeting the participants weighed the proposed applications for UV/XUV FELs against two criteria: 1) uniqueness (possible only with FEL radiation), and 2) significant improvement (applications that FELs should satisfy much better than existing photon sources). A partial listing of those applications and source requirements that can be met by an FEL is given in Table 1.

Figure 1. Successful free-electron laser operation in the near-ultraviolet to the far-infrared provides the experience base for extension below 0.1 μm . (The weak output at the two VUV wavelengths was coherent spontaneous emission from electrons bunched within an undulator by an external 532-nm laser.⁴⁸)

Table 1. Applications for UV/XUV free-electron lasers and parameter requirements^{49,50}

Materials science and processing:

- 0.1-micron resolution XUV projection lithography
10 - 60 nm; 5 - 10 nm for 0.05 μm resolution
- Spin-resolved photoelectron spectroscopy to develop new magnetic materials
Highest possible resolution, e.g., 1 meV at 100 nm
- Stimulation and analysis of VUV damage of amorphous dielectrics (e.g. laser gyro lifetimes)
Wavelengths ≤ 100 nm
- Superconductor band-gap measurements: photoelectron spectroscopy
VUV wavelengths with $\Delta\lambda/\lambda = 10^{-4} - 10^{-5}$ for low- T_c materials

Biology and medicine:

- Structure of macromolecules
120 - 200 nm for circular dichroism measurements
VUV wavelengths resonant with molecular scale; polarization-resolved scattering
- Radiation effects on cells and tissue
10 - 100 nm range
- Soft-x-ray holography of living cells
Single-shot, ps-pulse recordings at 44 Å
- Angiography
33 keV using Compton back scattering; $\leq$ millisec irradiation times

Physics and chemistry:

- Photoelectron spectroscopy of actinide band structure
 $\Delta\lambda/\lambda = 10^{-4}$ to 10^{-5} at 100 eV & 40 eV
- Photofluorescent measurement of metallic cluster properties
 $10^{18} - 10^{19}$ photons/sec, $\Delta\lambda/\lambda < 10^{-3}$
- Photoionization spectroscopy of gases and trace amounts of free radicals
 $10^{18} - 10^{19}$ photons/sec, $\Delta\lambda/\lambda \sim 10^{-4} - 10^{-6}$

Potential industrial applications cited at Cloudcroft included XUV-FEL photolithography for commercial production of gigabit integrated circuits and photochemical processing. In a review presented at the 1991 International FEL Conference in Santa Fe, New Mexico, C. Yamanaka⁵¹ added materials surface processing, isotope photochemistry, and group chemical separation for reprocessing nuclear fuels to the list of possibilities.

3. PROPOSED XUV-IR FEL USER FACILITY

3.1 FEL configuration

The FEL facility design proposed by Los Alamos uses one high-energy rf linac (≤ 1 GeV) to drive a series of seven FEL oscillators that will produce trains of coherent, picosecond pulses spanning the spectral range from 1 to 600 nm. A second series of three FEL oscillators, driven by a separate 60-MeV rf linac synchronized with the first, will produce wavelengths from the visible to the far infrared from 0.5 μm to 100 μm . Rf linacs are preferred for this facility because they offer several advantages which include:

- The electrons pass through the FEL only once at $\sim 10^9$ Hz without the constraints imposed by storing a recirculating beam.
- The linac FELs can produce both high-peak and high-average output power simultaneously.
- The linear geometry allows unrestricted and variable undulator length.
- Multiple FEL oscillators can be driven in series restricted only by the available laboratory space.
- 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.

The conceptual design of the proposed Los Alamos XUV-IR FEL facility is shown in Fig. 2. Figures 3, 4, and 5 are engineering plan sketches, and design specifics are given in Table 2. This system has several distinguishing characteristics. First, it comprises VUV-XUV FEL oscillator configurations rather than single-pass SASE amplifiers without optics. Although more complex than a simple amplifier, use of a resonator reduces the requirements on the electron beam and undulator. The single-pass gain ($< 10^3$) required for XUV-FEL oscillators can be achieved with 10-100X lower electron beam brightness and undulators with half as many periods as needed for an amplifier starting from noise. The single-pass gain corresponding to exponential rise of the laser power through a long amplifier undulator would be $> 10^4$, which would be very difficult to attain. Also, FEL resonator lengths can be adjusted to tune the spectral bandwidth either to the Fourier Transform limit of the individual ps-duration micropulses or up to several per cent via sideband generation.

The second obvious feature is that there are seven XUV-Vis FELs (1-600 nm) arranged in series and synchronized with three Vis-IR FELs (0.5 -100 μm) in series. The number of oscillators may be increased arbitrarily, consistent with the amount of accumulated energy spread and/or emittance degradation in the electron beam that can be tolerated and, of course, the available shielded laboratory space. The series configuration provides the maximum time-averaged photon flux to all users, rather than distributing the beam to parallel FELs. Only one beam dump is required for each FEL series. Third, 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 0.1% or less. Further beam degradation by wakefield effects in the beamline and magnetic undulator will be avoided by minimizing beam transport angles and discontinuities. Fourth, only uniform-period undulators are used to maximize optical gain.

The operating wavelengths of each of the FELs will either be tuned as a group over a 2.5x range by varying the electron energy or tuned independently over a smaller $\sim 50\%$ range by adjusting the undulator gaps. Automatic computer control of the focusing magnets will be provided to focus the electron beam properly into and out of the undulators. The spectral ranges of consecutive XUV/Vis FEL oscillators, listed in Table 3, are set to partially overlap with the criterion that the multifacet resonator mirrors have at least 40% reflectance. Hole-coupled Cu metal resonator mirrors will be used for the Vis/IR FEL oscillators. A mirror gallery will distribute radiation from any of the ten FELs to each of six experimental laboratories on a scheduled basis.

Figure 2. Source configuration of the proposed Los Alamos XUV-IR Free-Electron Laser National User Facility producing coherent radiation from 1 nm to 100 μm. A series of seven XUV/UV FEL oscillators spanning 1 to 600 nm is driven by one 1-GeV rf-linac. A second 60-MeV rf-linac, synchronized with the first, drives a series of three Vis/IR FEL oscillators to cover the 0.5- to 100-μm range. The FELs are sited below ground to provide radiation shielding, and a series of user-laboratory suites are in an above-ground facility adjacent to the FELs.

Figure 3. Lower-level floor plan of the facility which contains the FEL systems and relay optics.

Figure 4. Upper-level floor plan of the facility which contains the user laboratories, reflector switchyard, offices, and support shops.

Figure 5. Cross-sectional view of the FEL vault and beam delivery to one of the user laboratories.

Table 2. Parameters for the proposed Los Alamos rf-Ilvac-driven XUV-IR FEL user facility**Electron beam**

Energy:	≤1 GeV for XUV/Vis FEL series, adjustable for λ tuning ≤60 MeV for Vis/IR FELs
Peak current:	300 to 400 A in ~10-ps micropulses
Normalized emittance: (90% of electrons)	10π mm-mr for <10 nm 30π mm-mr for >50 nm
Energy spread:	0.1% to 0.2%, FWHM

Undulator *For 12-nm FEL; the length, period, and K scale for other- λ FELs*

Length:	12 m
Period, (Pole gap):	1.6 cm, (4.5 mm)
Peak axial field:	7.5 kG, 2-plane sextupole focusing
Undulator parameter, K:	1.1, peak

Resonator mirrors *Listed here for VUV/XUV FELs only; Cu and Ag coatings for Vis/IR FELs*

End mirrors:	R ≥40%, multifaceted retroreflectors for VUV/XUV FELs TER metal coatings on Si for λ <100 nm. CVD SiC for ≥60 nm, Al/MgF ₂ for ≥120 nm
Intracavity hyperboloids:	Au coating on Si or SiC substrates

Table 3. Operating ranges of the seven XUV-Visible Wavelength FEL oscillators ^a

<u>Oscillator Number</u>	<u>Operating Spectral Range</u>	<u>Multifacet Mirror Coating</u>
1	4.5 - 11 nm 1.5 nm (3rd harmonic)	Rh/B ₄ C multilayer (4.5-10 nm) Pd or Rh (9-11nm)
2	9 - 20 nm	Pd (9-11nm), Rh (10-14 nm) Y (14-20 nm)
3	16 - 40 nm	Y (16-22 nm), Se (22-38 nm) Si (35-40 nm)
4	35 - 80 nm	Al or crystalline Si in UHV
5	50 - 125 nm	Al in UHV
6	120 - 300 nm	Al/MgF ₂ , R > 80%
7	240 - 600 nm	Al/MgF ₂ , R > 80%

^a Corresponding to the bandwidths over which the multifacet resonator mirror reflectance is at least 40%.

At this time, the rf linac is designed for room-temperature operation. All of the past Los Alamos infrared FEL experiments have used an L-band (1.3 GHz), side-coupled, standing-wave rf linac operated at slightly above ambient temperature. Linac design calculations for advanced, standing-wave linac structures have been performed for energies from 100 MeV to 1 GeV for as a driver for an XUV FEL. Cryogenic and 500-MHz superconducting (at 4K) cavity options also are being examined, because they offer potential advantages of cw macropulse operation and improved pulse-to-pulse power and wavelength stability. Another advantage is the lower net electrical cost due to less power dissipation in the linac structure. However, the capability of either of these alternate configurations to provide several-hundred amperes of peak current with high beam brightness must yet be demonstrated. This will require adequate damping of higher-order modes which, according to G. Neil, et al.⁵² should be demonstrated on the CEBAF superconducting linac facility within the next two years.

3.2 User laboratories

Due to the wide range of the proposed applications and the interest in multi-color experiments, the user laboratories of this facility have been designed for the various types of user applications rather than based on the wavelength range. An initial set of six laboratories shown in Fig. 4 has been selected and will be equipped for: 1) surface physics & chemistry and general XUV-IR spectroscopy, 2) gas-phase atoms, ions, molecules, and beams, 3) biophysics and linear/nonlinear UV-Vis-IR spectroscopy, 4) lithography and fabrication of nanocircuitry, 5) medical procedures and studies, and 6) multiple-purpose, specialized experiments. If user demand grows as anticipated, the number of laboratory suites can be expanded along the linear dimension of the FEL facility. The high FEL photon flux will allow for short exposure times for many experiments. Therefore, associated with each exposure laboratory, we have included adjacent preparation/set-up labs for waiting experiments. Additionally, each lab will have access to radiation from any of the seven XUV-Vis FELs and three Vis-IR FELs by scheduled distribution by a reflective optical switching system. As seen in Fig. 5, the user labs will be located on the ground surface level safely distant from the underground laser gallery. A description of each of the initial six laboratories follows.⁵³

Surface physics & chemistry and general XUV spectroscopy laboratory: Surface science will be performed in a UHV chamber. This will be equipped with an electron analyzer for photoemission measurements, which must be spin sensitive for studies of magnetic materials, mass spectrometers for desorption work and sample characterization, ion guns, LEED spectrometers, and other instruments for sample preparation and analysis, and photon detectors for all regions from the IR through the XUV. Certain types of experiments can not be run on the same chamber, so more than one will be provided. Supplementary radiation sources will be available for measurements prior to the connection of the chamber to the light port. Spectral microscopy will be possible by scanning with a sample stage with the requisite spatial resolution.

Gas-phase atoms, ions, molecules, and beams laboratory: These experiments will require a source for the different types of beams and a UHV chamber which is compatible with beam experiments. Electron, mass, and light detectors on this chamber will all be necessary for acquiring the signal from the sample.

Biophysics and linear/nonlinear UV-Vis-IR spectroscopy laboratory: This laboratory will be used for measurements on samples which do not require UHV conditions, including circular and magnetic circular dichroism spectroscopy, soft x-ray microscopy, Raman spectroscopy, and measurements of second- and third-harmonic generation. It will be equipped with circular dichroism and magnetic circular dichroism spectrometers, the optical components for multiple wave mixing, conventional spectrometers, and chemical and biochemical apparatus for sample preparation and characterization.

The use of these first three laboratories for advanced spectroscopic measurements, which might be conducted independently of the FEL or used in some multicolor experiments, will require additional general spectroscopy instrumentation. This will include support lasers, spectrometers, both standard and multichannel detectors, signal processing electronics, and standard optical hardware which can be used in each laboratory.

Lithography and micro/nanofabrication laboratory: Since the ultimate goal of XUV projection lithography is the fabrication of devices with $\leq 0.1 \mu\text{m}$ features,^{51,54} a lithographic stepper with this capability is

necessary. The exposure lab itself will have to be a Class-10 clean room if actual circuits are to be fabricated, and facilities for preparing and developing resists and coating wafers will be present. On-site characterization will be performed with a scanning electron microscope.

Medical procedures laboratory: This lab will be used to study the interaction of FEL radiation with tissue, both isolated from and within the body, for potential medical applications. Equipment for removing tissue from animals, treating it and maintaining its viability, and exposing it will be provided. Characterization of exposed tissue will be performed with microscopes and by chemical and biochemical analysis. Apparatus for containing and aligning live animals may also be included, as well as the corresponding clinically certified equipment for treating human subjects.

Multiple-purpose laboratory for specialized experiments: Many experiments, especially in the category of technological applications, will require interfacing the FEL output with elaborate equipment specific to each project, *e.g.*, jet engines for fluid mechanics measurements or high-resolution mass spectrometers for resonance ion mass spectrometry. This lab will be dedicated to projects such as these for periods of time compatible with such complicated setups. Because experimenters will need to bring their own unique equipment and instrumentation, that available for this lab will be limited to general optical apparatus.

4. PREDICTED XUV-IR FEL OUTPUT

We have performed 3-D numerical simulations using B. McVey's FEL code FELEX⁵⁵ and its derivatives to predict the single-pass and multiple-pass gain in XUV-FEL resonators, and the spectral bandwidth, output power, and spectral brightness versus wavelength. Tables 4 and 5 provide an abbreviated summary. Over the range of high single-pass FEL gain, the predicted peak- and average-output powers, especially below 300 nm, should surpass the capabilities of any existing, continuously tunable photon source by four to seven orders of magnitude. In addition, the spectral bandwidth may be sufficiently narrow, *e.g.* $\leq 10^{-4}$ at 100 eV, that use of a monochromator may be optional for many applications.

Table 4. Radiation properties of the proposed LANL rf-linac-driven XUV-IR FEL user facility

Micropulse duration:	10-20 ps (FWHM) compressible to <2 ps
Micropulse repetition rate:	32 MHz
Macropulse duration:	100- μ s, Rep. @ 100 Hz (1% duty)
Facility wavelength span:	1 nm to 600 nm, 7 FEL oscillators (0.5-100 μ m, 3 Vis-IR FELs w/2nd 60-MeV linac)
Spectral bandwidth: (for single, 10-ps pulses)	≥ 1 cm ⁻¹ Fourier-transform limit 10 ⁻⁴ w/25 klystrons, possibly 10 ⁻⁵ up to ~1% if sidebands are allowed
Polarization:	Linear, w/circular/elliptical options
Temporal coherence:	Limited by micropulse Fourier trans.
Spatial coherence:	Near-diffraction-limited focusability

Table 5. Power and brightness predictions for the proposed LANL XUV-IR FEL user facility

Peak power at target: bw $\sim 1 \text{ cm}^{-1}$, single pulse and $\Delta\lambda/\lambda \sim 10^{-4}$, macropulse average	1- to $\geq 10 \text{ MW}$, 12 to 100 nm >20 MW, for >100 nm
$\Delta\lambda/\lambda \geq 1\%$, w/sidebands	10- to $\geq 50 \text{ MW}$, 12 to 100 nm, 5 MW at 4 nm
Average power at target: @ 1% duty	1- to >10 W, w/o sidebands 30 to 200 W, w/sidebands
Photon flux at target: from 1 - 600 nm, resp.	10^8 - 10^{15} photons/10-ps pulse 10^{15} - 10^{20} photons/s, aver. @1% duty
Spectral brightness (Peak):	10^{28} photons/s/(mm-mr) 2 /bw
Spectral brightness (Aver.):	10^{22} photons/s/(mm-mr) 2 /bw/@1% duty $\Delta\lambda/\lambda \sim 10^{-4}$, macropulse average

Electrical power cost considerations will limit the year-long average duty factor to $\sim 1\%$ for ambient-temperature linac structures, but occasional operation at $\geq 10\%$ duty is feasible with proper cooling of the accelerator cavities, and 100% duty may be possible if either a cryogenic or a superconducting linac design is adopted. Practically, the duty factor will be limited by laser-induced thermal distortion of the FEL resonator mirrors.⁵⁶ The latter limitation can be avoided entirely if exponential single-pass gain (net $\sim 10^4$) can be realized in FEL amplifiers via self-amplification of spontaneous emission.

5. COMPARISON WITH THIRD-GENERATION SYNCHROTRON RADIATION SOURCES

The third-generation synchrotron radiation sources presently being constructed for use with undulator insertion devices should deliver 10^3 - 10^4 brighter photon beams than storage rings presently in operation. These include the Advanced Light Source at Lawrence Berkeley Laboratory, the Advanced Photon Source at Argonne National Laboratory, the European Synchrotron Radiation Facility at the Institut Louis Langevin, and the Super Photon Ring-8 at Himeji, Japan. However, the low transverse emittance designs of these storage rings restricts the average circulating current. Thus, while undulators spontaneously radiate much brighter beams than do bending magnets, they do not deliver significantly more average power.

By emitting stimulated emission, FELs produce much brighter beams and, especially those driven by rf linacs, can produce higher average-power per unit spectral bandwidth as well. Figure 6 presents a comparison of the predicted time-averaged spectral brightness (photons/s/(mm-mr) 2 per 0.1% bandwidth) delivered to a target as a function of wavelength, and Table 6 lists the flux and power output at 100 nm predicted for an rf-linac-FEL for comparison with that of two storage-ring devices. At 10 eV (124 nm) the FEL will produce 10^4 to 10^6 higher average spectral flux on target; at 100 eV (12 nm), the FEL advantage will decrease to a factor of 10^2 to 10^4 , depending on the FEL duty factor. Moreover, the corresponding peak flux output of the rf-linac FEL (@ 1% duty) will exceed that of synchrotron undulators by an additional factor of 10^3 . The much higher spectral radiance of FELs argues for their development.

6. DEVELOPMENT SCHEDULE

Prior to building the complete user facility, the Los Alamos FEL team will conduct a series of FEL oscillator demonstrations at progressively shorter wavelengths, the first of which will be from 50 to 100 nm. Overall, it appears that the electron-beam, undulator, and mirror technologies are now sufficiently developed to support

Figure 6. Time-average spectral brightness (delivered on target) of FELs will far exceed that of the most powerful storage rings designed with insertion devices (undulators and wigglers). The FEL curves were calculated for the Los Alamos rf-linac FEL design, and a monochromator efficiency of 10% was applied to the published undulator output curves. To convert the time-average curves to peak values, the appropriate conversion factors are 3×10^5 for the FEL @ 1% duty and $\sim 3 \times 10^2$ for the storage-ring insertion devices.

such experiments. However, there are still some required prototype demonstrations for the electron beam and optical components. Concerning the electron beam, it will be necessary to preserve the $\sim 10^{11}$ A/(m-rad)² brightness of the beam delivered by the photoinjector as it is accelerated up to energies >100 MeV and to develop a long-life photocathode that has sufficient quantum efficiency $\sim 1\%$. Optical elements needing development include engineering design and test of the XUV ring resonator with multifacet mirrors, measurement of multifacet mirror reflectance for wavelengths <35 nm, and demonstration of the viability of *in situ* renewal of multifacet mirror coatings. It will also be necessary to demonstrate operation of two XUV FELs in a series configuration.

The second-phase objective will be to operate an FEL oscillator in the 10- to 14-nm region, corresponding to the high-reflectance band of a Rh multifaceted mirror.^{23,59} This will require higher electron beam energy (additional accelerator structure) and an brighter electron beam possible only with a photocathode injector. Since the reflectance of mirrors below 10 nm is not high enough for laser oscillators, the objective of the third phase will be to produce coherent, 1- to 10-nm radiation by use of a regenerative amplifier consisting of a very long amplifier undulator with partial feedback by use of low-reflectance ($\sim 20\%$) mirrors. Successful completion of these three stages will enable the short-wavelength portion of the FEL facility to cover the entire 1- to 600-nm range with the projected output radiation characteristics given previously in Tables 4 and 5. As with all proposed major facilities, sufficient funding must be obtained to support the conduct of these demonstration experiments as well as the construction of the proposed facility.

Table 6. Comparison of rf-linac-driven FEL and synchrotron radiation sources at 100 nm

	SSRL <u>WIGGLER</u> ^a	ALS <u>UNDULATOR</u> ^b	RF-LINAC <u>XUV FEL</u> ^c
Spectral flux (Photons/sec) at target	10 ¹³	4x10 ¹⁴	10 ¹⁹
Average power (W) at target	10 ⁻⁵	10 ⁻³	20
Peak power (W) at target	10 ⁻²	10 ⁻¹	10 ⁷
Average & peak spectral brightness at target (photons/sec/(mm-mr) ² /bw)	10 ^{12,1015}	10 ^{16,1019}	10 ^{22,1028}

a Stanford Synchrotron Research Laboratory wiggler.⁵⁷

0.1% spectral bandwidth after monochromator with 10% efficiency.

b Predicted performance of undulator U8.0 designed for the Advanced Light Source (ALS) storage ring at Lawrence Berkeley Laboratory.⁵⁸

0.1% spectral bandwidth after monochromator with 10% efficiency.

c Single-pass, rf-linac FEL operated at 180 MeV with 1% duty factor. Multiply listed FEL powers by 10X if driven by a 500-MeV beam.

FEL spectral bandwidth = 0.01%, limited by rf-power noise.

7. SUMMARY

Free-electron lasers represent the next generation of coherent-radiation sources with peak- and average-power output capabilities that should surpass those of any existing, continuously tunable photon sources by

many orders-of-magnitude. Recent successes in the development of FEL component technologies (electron injector, resonator mirrors, and magnetic undulator) should enable these devices to operate in the XUV from <4 nm to 100 nm as well as at more easily achieved longer wavelengths. These include the high-brightness photoinjector, multifaceted resonator mirrors with retroreflectance >40%, and high-precision undulators with >200 periods. An rf-linac-based, multiple-FEL user facility, spanning wavelengths from 1 nm to 100 μ m, has been designed and is proposed by Los Alamos National Laboratory for scientific research and those industrial applications requiring expanded photon-parameter ranges.

8. ACKNOWLEDGMENTS

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9. APPENDIX:

DEVELOPMENT OF FEL TECHNOLOGIES REQUIRED FOR OPERATION IN THE XUV

Although FELs as a class must yet be reduced in wavelength by a factor of 2.5 from the short-wavelength operating record of 240 nm for an FEL oscillator⁶⁰ to enter into the XUV region, significant improvements of the primary components (electron beam, undulator, and resonator mirrors) are either ready for implementation or have been conceived and provide confidence that lasing at such wavelengths is feasible.

9.1 High-brightness photoinjector

As was emphasized in the Introduction, the future operation of an FEL oscillator in the XUV will require that the a very bright electron beam (defined as 2 X ratio of peak current and normalized emittance-squared). As an example, Goldstein et al.²⁴ determined from 3-D numerical simulations that a 12-nm FEL oscillator will require a beam brightness of 1.2×10^{11} A/(m-r)², corresponding to a peak current of 300 A and normalized transverse emittance of 23π mm-mr (90% of particles), with energy spread of 0.1% (FWHM) at 535 MeV. Until the development and experimental demonstration of the laser photoinjector by Fraser and Sheffield,²⁸⁻³¹ electron beams with such high brightness had not been generated in an rf linac. [The beam brightness capabilities of thermionic, dispenser, and semiconductor photocathode injectors are 0.08, 2, and 30×10^{11} A/(m-rad)², respectively.³¹]

The photocathode is positioned on the end wall of the first accelerating cavity of the linac injector where it is irradiated by a train of ps-duration, visible to ultraviolet laser pulses. By applying a very high accelerating gradient, e.g., 30 MeV/m, the photoelectrons attain a relativistic energy of 1 to >3 MeV in the first cavity, thereby minimizing their susceptibility to perturbations that cause emittance growth. Photocathodes with varying levels of quantum efficiencies (QE), depending on the exposure wavelength, are being used in FEL injectors: CsK₂Sb ($\leq 10\%$ QE) at Los Alamos National Laboratory,^{12,13} copper (<0.1% QE) at Brookhaven National Laboratory,⁶¹ and LaB₆ (0.01% QE) at Stanford University.⁶²

The CsK₂Sb cathode is most susceptible to poisoning by contamination and must be operated in high vacuum of 10^{-10} Torr in order to have a practical lifetime with QE >1%. Recent lifetime measurements of this cathode, while mounted within the photoinjector cavity at 2×10^{-10} Torr and without laser irradiation, indicated that the QE declined only by ~10% in a 36-hour period followed by no change until the test ended at 68 hours.⁶³ However, in the presence of full rf-drive power, Los Alamos experimenters found that CsK₂Sb photocathodes have lifetimes limited to one to two days. The degradation occurs only when the accelerating rf power is applied. It is suspected that water vapor and carbonaceous gas compounds, desorbed from the cavity walls of the photoinjector, poison the cathode. Los Alamos scientists have determined that the lifetime of semiconductor photocathodes can be increased by exposing the photoinjector accelerating cavities to high rf fields for long periods, and an 18-hour lifetime with full rf-drive power was obtained at a given laser intensity.³⁰ The effective lifetime has been extended even more by raising the drive-laser power level enough to compensate for the declining quantum efficiency. Glow-discharge cleaning of the cavity walls is now being implemented to augment electron-beam desorption of contaminant gases.

It appears that semiconductor photocathodes with high quantum efficiency are more susceptible to degradation by contamination than metal photocathodes, such as Y and Cu. However, to generate electron pulses with large charges, e.g. 3-4 nC/pulse to attain the desired 300-400 A peak current in 10-ps pulses, it is necessary to have the product of the drive-laser pulse energy and QE be sufficiently large. The experience of the Los Alamos FEL team is that a photoinjector with a CsK₂Sb-cathode irradiated with 532-nm laser pulses produces a micropulse charge of $Q(\text{nC/pulse}) = 4.5\text{QE}(\%) \times E(\mu\text{J/pulse})$.¹² Although it becomes increasingly difficult and expensive to generate higher-energy, cw-modelocked laser pulses, it is possible to use lower-QE cathodes with longer lifetimes with a more powerful drive laser. If the thermal emittance of the electrons leaving the cathode does not become dominant, a shorter drive laser wavelength, e.g. 355 nm, may be used to increase both the QE and lifetime.

The concentrated efforts of several research groups^{13,61,62} to implement photoinjectors on rf linacs designed for FELs should eventually make rf linacs reliable sources of high-current, low-emittance electron beams. If the high brightness of such beams can be maintained without degradation during acceleration to high energy, then numerical simulations predict that FEL gain should be high enough for oscillator operation at wavelengths as short as 4 nm.^{24,27} A high-current photoinjector has been integrated into the Los Alamos infrared FEL. As reported by Feldman et al.,¹¹ measurements of the beam quality at 17 MeV were in agreement with predicted values for the normalized design emittance, $\sim 30\pi$ and 40π mm-mr (90% of electrons) for 2-nC and 5-nC bunches, respectively.

9.2 Long, short-period, magnetic undulators

Long, high-precision magnetic undulators will be needed to attain sufficient gain for single-pass FEL amplifiers to overcome the resonator mirror and output coupling losses in FEL oscillators. Increasing the number of undulator periods results in higher gain, but the cumulative influence of uncorrected random magnet errors increases with length as well. To prevent serious degradation in FEL gain, the magnitude of individual magnet errors (strength and orientation) that can be tolerated decreases as the number of undulator periods increases, e.g. to below 0.1% for several hundred periods.^{64,65} Fortunately, several solutions for this problem have been devised. Elliott and McVey⁶⁵ determined that the effect of magnet imprecision as large as 0.7% can be mostly overcome by measuring the beam position at a sufficiently large number of points along the undulator, e.g. every 25 periods, and by applying a like number of correction fields. Warren^{39,40} has developed a very sensitive pulsed-wire field-measuring technique that has proven useful in rapidly indicating the location and magnitude of needed corrections to reduce steering errors to a low level. Subsequently, Feldman and Warren⁴¹ have wedded this system with a series of field-correcting dipole coils using computer control. From a series of rapid, on-line measurements of the field errors, an automatic correction is applied. This system is expected to prove invaluable for monitoring and correcting magnetic-field errors that may develop while the undulator is in use.

Attainment of high-precision uniformity of undulator magnetic fields has also been demonstrated by several other groups. Curtin et al.³² used the technique of simulated annealing to computationally determine the opti-

mum ordering of the individual SmCo_5 magnets within a 2-m-long undulator in order to minimize the trajectory wander. A deviation of less than $25\text{ }\mu\text{m}$ was obtained for a 40-MeV beam and 3.3-kG axial undulator field. Gottschalk et al.,³³ have demonstrated a correction technique that can reduce the rms field errors to only 0.1% by placing thin iron shims on individual magnets. Another effective scheme devised by Ramian et al.³⁴ uses a moving, robotic screwdriver to individually adjust the magnetic fields in response to measurements of field imperfections.

Since a photoinjector offers the promise of at least an order-of-magnitude increase in beam brightness over thermionic guns, it appears possible that FELs might be operated at a given wavelength with much lower electron beam energies than heretofore. Lower beam energies will directly reduce the accelerator length and cost which is essential if FELs are to become affordable for a wide range of applications. To this end, a number of groups are trying to build undulators with very short periods, e.g. 1-10 mm, while keeping the product of the peak axial magnetic field and undulator period near 1 cm-Tesla to maintain high FEL gain. Warren³⁵ has identified the pulsed electromagnet as a promising design for this objective. The minimum period of such undulator designs is $\sim 1\text{ mm}$, limited mainly by thermal transport away from the magnet wires, and the number of periods (which sets the tolerable limit on electron energy spread in an FEL) is limited by the necessity of applying periodic correction fields and the ripple in the pulsed current supply. The rate of thermal transport limits the repetition frequency of this wiggler and thus the average power of the FEL. Warren's new slotted tube version of the pulsed microwiggler should increase the thermal transport.³⁶

Superconducting undulators are of interest because they can be run continuously and are capable of achieving an undulator parameter K near unity with periods of 1 cm and less for usefully large magnet gaps.³⁷ A superconducting undulator, as realized by Ben Zvi et al. (8.8 mm period and 0.51T on-axis field)³⁸ may be especially well suited for a scientific user facility where cw operation is desired and where maximum stability of the lasing wavelength is required. If such an undulator can be constructed with several hundred periods or more, it may permit the electron energy of the rf linac needed for XUV FEL operation below 10 nm to be scaled down from the present 1-GeV design.

9.3 Resonator mirrors for XUV FELs

FEL oscillator operation in the XUV will require resonator mirrors with sufficiently high retroreflectance to provide a substantial advantage over a single-pass amplifier. By setting the reflectance requirement at an arbitrary value of $\geq 40\%$ for each of the two end mirrors, the resonator losses can be offset by a single-pass gain of $>600\%$, which is attainable.

Below 100 nm, few materials have reflectance exceeding 40% for normal incidence. For wavelengths from 60-100 nm, polished chemically vapor-deposited (CVD) silicon carbide (SiC), deposited on hot SiC substrates, exhibits a reflectance between 35-40% at normal incidence.^{66,67} From 80 nm to 100 nm, the reflectance of unoxidized Al films increases with wavelength from 40% to $>90\%$.⁶⁸ Elemental metal surfaces of Pt, Ir, Os, and Au, depending on surface condition, have reflectance no higher than 25% down to 55 nm, falling rapidly at shorter wavelengths. For shorter wavelengths $\leq 20\text{ nm}$, a few multilayer mirror designs have useful normal-incidence reflectance. In the range from 4.5 to 10 nm multilayer reflectors of Ru/ B_4C have been produced with reflectance up to 20%,⁶⁹ and in the 14-20 nm range, multilayer Mo/Si mirrors reflect from 40% up to $\sim 60\%$.⁷⁰

In addition to sufficiently high reflectance to minimize the FEL gain requirements, the total beam-induced thermal distortion of the mirror surfaces must be restricted to a small fraction ($\sim 1/4$) of the operating wavelength. Thus, high mirror reflectance $\geq 95\%$, i.e., absorptance $\leq 5\%$, is essential.^{24,56} The multifacet XUV metal mirror design proposed by Newnam^{42,71} and shown in Fig. 7 should satisfy both requirements in the spectral regions where retroreflectance $\geq 40\%$ and absorptance $\leq 5\%$ per facet is obtained. This mirror system exploits the phenomenon of total external reflectance (TER) at large angles of incidence. As pointed out by Vinogradov et al.,⁷² materials with refractive index (both real and imaginary parts) sufficiently less than unity can provide surprisingly high retroreflectance by using a sequence of reflections beyond the critical angle, typically larger than 60° . Unoxidized Al and crystalline Si, for example, have the necessary optical constants to attain $\geq 40\%$ retroreflectance from 35 nm to 100 nm.

Figure 7. Multifacet, all-metal mirrors based on total external reflectance at large angles of incidence ($\sim 80^\circ$) can provide the necessary $\geq 40\%$ retroreflection for FEL ring oscillators over broad spectral ranges in the XUV. Intracavity, grazing incidence, hyperboloidal mirrors diverge the beam to reduce beam-induced thermal distortion on the multifacet mirrors and allow shorter resonator lengths. The off-axis paraboloidal figure of the upper facet of the multifacet mirrors collimates the reflected beam. After Newnam.⁴²

The seven oscillators of the Los Alamos XUV-Vis FEL series, shown in Fig. 2, each have a ring resonator incorporating multifaceted retroreflectors. The appropriate reflective coatings will depend on the spectral operating range: ~ 35 - 100 nm using Al films or crystalline silicon, and 9 - 14 nm with Pd, Ag, Ru, and Rh films.^{42,59,68,72} For wavelengths between 9 and 35 nm, other single-layer films that could exhibit sufficiently high TER include Y and Se.⁷³ Their use in specific FEL oscillators over spectral ranges where their multifacet reflectance is $\geq 40\%$ is indicated in Table 3. An important advantage of these single-layer reflectors is that they can be deposited (and renewed) on the multifaceted Si or SiC mirror substrates without removing them from the ring resonator.

Los Alamos researchers have experimented primarily with aluminum thin films deposited with an electron gun on polished silicon substrates in an ultra-high vacuum (UHV) of $\sim 10^{-10}$ Torr to minimize surface oxidation. At 58.4 nm using a He-discharge source and 80° incidence, Scott⁷⁴ measured the *in situ* reflectance of single, Al-coated mirrors to be $98.7 \pm 2\%$. Under similar conditions, the net retroreflectance of a nine-facet Al-coated retroreflector, was $89 \pm 3\%$, in agreement with the single-facet measurement. This value of retroreflectance is more than a factor-of-two higher than reported for any other XUV mirror in the vicinity of 60 nm. At 30.4 nm, additional UHV single-mirror measurements indicated that this same nine-mirror array should have a retroreflectance value of $\sim 33\%$. As evident in Fig. 8, these measured retroreflectance values actually exceeded those computed using literature values for the Al optical constants,⁶⁸ indicating that our films were more ideal.

Contamination of the resonator mirrors must be prevented and/or controlled in the FEL oscillators. Mirror contamination will reduce the reflectance, raise the gain threshold for lasing, and decrease the steady-state output power. Additionally, contaminated external beam-steering mirrors will reduce the useful power on target for either oscillator or amplifier configuration, and excess absorption of the incident energy will distort the mirror surface figure, thereby degrading the beam brightness. Fortunately, at sufficient vacuum levels with low oxygen and water partial pressures, the oxidation of aluminum films proceeds at a slow rate. For example, a two-week exposure of a fresh aluminum film in a 2×10^{-9} Torr vacuum, primarily with residual He, resulted in formation of only $1/4$ of an oxide monolayer (see Fig. 9).⁷⁵ Measurements after four weeks indicated that negligible additional growth of the oxide layer had occurred.⁷⁶

Figure 8. The measured retroreflectance⁷⁴ at 30.4 and 58.4 nm of a nine-faceted aluminum retro-mirror (deposited on Si substrates in 10^{-10} Torr vacuum) verified the predicted performance, based on measured optical constants,⁶⁸ and exceeds 40% for wavelengths greater than 35 nm.

Figure 9. Net retroreflectance vs number of facets of a multifacet aluminum mirror calculated from measured values of reflectance versus angle of incidence for an aluminum film deposited on a Si substrate. This same film was measured again after one and two weeks in a UHV system at a helium pressure of $\geq 2 \times 10^{-9}$ Torr. Little change is seen between one and two weeks. After Scott et al.⁷⁵

Growth of carbon contaminant films on the areas of the reflectors exposed to the XUV beam is a concern. A valuable review of this carbon problem and its mitigation has been published by Rehn.⁷⁷ It is possible that an initial clearing of the UHV system of carbonaceous compounds by using the rf-discharge technique developed by Johnson et al.,^{78,79} (followed by *in situ* deposition of the reflecting films) will yield adequately long lifetimes with high reflectance. Another option is to periodically overcoat the contaminated metallic films with fresh material to offset the effects of gradual deterioration that may occur while in the FEL resonator. Of course, the total thickness of the films must not become too great lest surface roughness increase. An ion gun, mounted in the vacuum chamber and used with specific beam parameters, may be an effective way to periodically sputter away aged films prior to evaporation of a fresh film.

In summary, multifaceted mirrors of certain single-layer metals offer high reflectance over a broad spectral ranges and they can be deposited on the multifaceted Si substrates mounted within the ring resonators. Without breaking vacuum, they can be overcoated or treated with an ion beam to remove the oxide after a period of use. Finally, this retroreflector design is inherently resistant to thermal and optical wavefront distortions, as well as to laser-induced damage. This is due to the high reflectance of S-plane polarized light from metal surfaces at large angles-of-incidence and the $\cos\theta$ spatial dilution of the beam intensity over the tilted surfaces. It remains to implement the multifacet mirrors in ring resonators to test predictions of their optical stability.⁸⁰

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