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TITLE: DEVELOPMENT OF A FREE-ELECTRON LASER USER FACILITY FOR THE EXTREME ULTRAVIOLET

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Development of a Free-Electron Laser User Facility for the Extreme Ultraviolet*

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Abstract

A free-electron laser user facility for scientific experimentation in the extreme ultraviolet is being developed at Los Alamos. A series of laser oscillators and amplifiers, driven by a single, rf linear accelerator, will generate broadly tunable, picosecond-pulse, coherent radiation from 1 nm to 400 nm. The design and output parameters of this facility are described, comparison with synchrotron radiation sources is made, and recent progress in developing the three primary components (electron beam, undulator, and resonator mirrors) is reviewed, and various categories of scientific applications are indicated.

Introduction

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 (XUV) 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 spectral ranges from 1 nm to 400 nm.

With recent improvements, 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.[1] (Reference 2 reviews the various methods of generating FEL radiation below 100 nm.) RF-linac FELs offer 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 storing a recirculating beam including peak-current density limitation by the Touschek 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.

Los Alamos National Laboratory has been operating an infrared rf-linac-driven FEL since 1983. Recently, the Los Alamos linac has delivered peak currents ≥300 A, resulting in large values of optical gain (up to 200%/pass) at 10-μm from a short, 1-m undulator. Experience with this system provides an invaluable reference point from which to design a linac-based FEL light source as a scientific research facility in the extreme ultraviolet.[3-9] Over the last three

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years these efforts have resulted in the 3-D numerical code FELEX that correctly simulates emittance-dominated FEL physics in the XUV,[10] experimental development of a new high-brightness linac injector,[11] and progress toward producing XUV resonator mirrors with adequate reflectance.[12,13]

XUV FEL Facility Design

FEL Oscillator Chain

The conceptual design of the Los Alamos XUV FEL Facility is shown in Fig. 1, and design specifics are given in Table 1. It consists of 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.

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 200 A
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
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 ≥40% multifaceted flats + paraboloids with metal coatings: Al, Si, Ag, and Rh; also, CVD SiC for ≥60 nm
Beam-expanding hyperboloids:	Au coating on SiC or Si

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 60 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 achieve single-pass optical gain of ~1000 which is only possible in the exponential-gain regime, much brighter electron beams and longer undulators will be required than for FEL oscillators. For example, according to 3-D numerical calculations by Goldstein, et al.,[14] 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.[9]

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.[14] and Kim,[15] 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 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.[16] (The power in the even harmonics is considerably smaller than that of the odd harmonics, declining with wavelength, and may be of limited usefulness.)

Coherent optical harmonics can be generated by an alternative method that uses an external laser focused within the undulator to overlap and bunch the electrons on an optical wavelength scale. Like the SASE amplifier, this eliminates the need for resonator mirrors, a considerable simplification. The radiation is still generated spontaneously, so that the peak powers are much lower ($\sim 10^{-3}$ less) than the fundamental output from an FEL oscillator. Using a frequency-doubled Nd:YAG pump with peak power of 36 MW focused within the ACO storage ring undulator at Orsay, Prazeres et al.[17] produced 1.5×10^7 coherent photons per pulse at 177.3 nm (third harmonic) and ~10^5 photons per pulse at 106.4 nm (fifth harmonic). When these same experiments are repeated in their new Super ACO ring, the number of harmonic photons should increase by a factor of 100, and the seventh harmonic at 76 nm should then be measurable. To make this method versatile for users, the external laser should be broadly tunable so that the harmonic wavelengths can be varied continuously.

Predicted XUV FEL Output

We have performed 3-D numerical simulations using the FEL code FELEX[10] and its derivatives to predict the single-pass and multiple-pass gain in an XUV FEL resonator, the spectral bandwidth, and output power versus wavelength. Table 2 provides an abbreviated summary.

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
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
Photon flux at target:	10^8 - 10^{15} photons/10-ps pulse, 1 - 400 nm, resp. 10^{15} - 10^{20} 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

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. Such comparisons are presented versus wavelength in

Figs. 2 and 3 and at 100 nm in Table 3. For wavelengths longer than 100 nm, FELs have even larger advantage than shown in Table 3 and less so at shorter wavelengths.

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^{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
Average *& peak* spectral brightness at sample (photons/sec/(mm-mr)^2/BW)	10^{11}, *10^{14}*	10^{15}, *10^{18}*	10^{20}, *10^{26}*

a Stanford Synchrotron Research Laboratory wiggler;[18]
0.1 % spectral bandwidth after a monochromator with 1% efficiency assumed.

b Predicted performance of undulator B in the Advanced Light Source storage ring beginning construction at Lawrence Berkeley Laboratory.[18-20]
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; e.g., 1% BW increases the above FEL output values by 5 X.

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

Technological Developments Required for FEL Operation in the XUV

Operation in the XUV poses severe requirements on each of the three primary components (electron beam, undulator, and resonator mirrors) of an FEL oscillator. Substantial progress in each of these areas has been encouraging.

High-Brightness Electron Beam

Production of an adequately high-quality electron beam from an rf linac to achieve >400% single-pass gain in the XUV is a major challenge. Several-hundred ampere peak currents have been produced by rf linacs, but not yet with the desired small energy spread and low emittance.

For example, the 20-MeV rf-linac driving the Los Alamos FEL has delivered peak current exceeding 300 A in 2000 10-ps micropulses, each containing ≤ 5 nC, within a 100-μs macropulse train.[21] In recent operation, the corresponding energy spread and normalized emittance (containing 90% of the electrons) have been ~1% FWHM and 200-300π mm-mrad, respectively.[22] This is to be compared with the Los Alamos design for an XUV FEL at 50 nm that requires a beam energy of 250 MeV, $\leq 0.2\%$ FWHM energy spread, 150-A peak current, and $\leq 40\pi$ mm-mr normalized emittance). According to numerical simulations by Carlsten[23] using the beam-propagation code PARMELA, an electron gun with a planar cathode similar to that used in the rf linac at Boeing Aerospace Corp. will, after appropriate beam filtering, yield the desired 40π emittance and < 0.2% energy spread.

Although an rf linac with a conventional subharmonic buncher may marginally meet the FEL requirements for laser oscillation down to 50 nm, a beam with even lower emittance is desired both to provide a safety margin and to allow extension to even shorter wavelengths. Recently, a new electron injector comprised of a laser-irradiated, Cs_3Sb photocathode in a 1-MeV accelerating cavity has been developed at Los Alamos by Fraser and Sheffield.[11] The pulseform of the emitted electrons is essentially identical to that of the modelocked and frequency-doubled Nd:YAG laser: 75-ps micropulses at 108 MHz. By immediate acceleration to ≥ 1 MeV, this injector eliminates the need for conventional subharmonic bunching in a long drift region at low energy where most of the emittance growth is suspected to occur. Fraser's arrangement[24] for the front end of an rf linac starting with a photocathode injector is shown as Fig. 4. Based on its performance in the first series of experiments indicated in Fig. 5, the photocathode injector should be able to provide an electron beam to the linac that will more than meet the beam requirements for FELs operating at XUV wavelengths as short as 10 nm.[25] Furthermore, the working group on electron guns at the 1987 ICFA Workshop on Low Emittance Electron Beams concluded that an rf-linac driven by a laser photocathode gun has the best chance of supplying the high-brightness electron beam needed to produce coherent soft x-rays below 10 nm.[26]

Long Undulators

Every FEL research center is now devising ways to fabricate, diagnose, and correct long undulators with high precision to minimize the gain degradation resulting from random errors in magnet strength and orientation. Certainly, increasing the number of undulator periods results in higher gain, but the cumulative influence of uncorrected random errors increases with length as well. A very effective method of maximizing the gain for a given electron beam and undulator length is the use of magnets that provide equal, two-plane magnetic focusing to increase the emittance acceptance. Three-dimensional numerical calculations for a 50-nm FEL oscillator have shown that the small-signal gain can thereby be increased by 60% over that with a planar magnet. Two methods are being used to attain two-plane focusing. The first uses canting of the individual magnets by a small angle to obtain a distributed quadrupole field.[27] According to the measurements of Robinson, et al.,[28] the hybrid-undulator design (incorporating permeable vanadium pemendur for the pole tips) requires less cant angle than does the pure samarium-cobalt permanent-magnet design (7 mrad vs. 47 mrad) to obtain the same amount of focusing. Canted magnets have been used successfully in constructing a 5-m hybrid undulator for the Boeing/STI visible FEL experiments.[29] The second approach, devised by Scharlemann,[30] achieves sextupole focusing to minimize betatron-synchrotron resonances by machining a parabolic curve on the tips of the magnetic poles. More recently, Warren[31] has suggested a planar-magnet design with adjustable side poles to achieve sextupole focusing. From analysis of both quadrupole and sextupole focusing schemes, Wang and Cooper[32,33] determined that, for long undulators with several-hundred periods, higher gain will be realized with the sextupole focusing.

To prevent serious degradation in FEL gain, the magnitude of individual, random magnet errors that can be tolerated decreases as the number of undulator periods increases, e.g. to below

0.1% for several hundred periods.[34] Fortunately, this limitation can be largely overcome by periodic undulator segmentation and correction which relaxes the tolerances on magnet imprecision to the order of 0.7%.[35] Kincaid[36] and Warren[37] have both suggested a correction scheme using external, computer-controlled, correcting coils superimposed on the fields of magnet groups. Warren's pulsed-wire field measuring technique,[31,37] shown in Fig. 6, may prove invaluable for monitoring and correcting magnetic-field errors on a routine basis while the undulator is in use. The feasibility of such a scheme for a pure, rare-earth magnet undulator should be evaluated at Los Alamos in the next year.

Resonator Mirrors

One of the major technological constraints presently blocking extension of FELs into the XUV is the inherently low reflectance of available resonator mirrors, of the order of 10 to 20%. Unless this limitation is overcome, very high values of single-pass optical gain will be needed. For example, if each resonator mirror were to have a reflectance of only 25%, the small-signal gain would have to exceed 1600% just to begin oscillation, a value which may be difficult to achieve. Development of resonator mirrors with reflectance ≥40% appears to be a prerequisite for future operation of FEL oscillators at wavelengths below 100 nm. Furthermore, the 40% reflectance level can not be allowed to degrade rapidly with time as a result of oxide and/or carbon epifilm contamination.

There are four types of normal-incidence reflectors under development for the XUV. First, smooth surfaces of chemically vapor-deposited (CVD), single-crystal, **silicon carbide (SiC)** have been produced and used successfully in synchrotron radiation beam lines. The highest measured values of the normal-incidence reflectance for CVD-SiC have varied nonuniformly between 40 to 50% for wavelengths between 60 and 220 nm.[38,39] Scattering losses due to surface roughness, however, can reduce the specular reflectance below these levels. Below 60 nm, CVD-SiC reflectance drops rapidly to less than 10%. Although research continues to develop still better mirrors, CVD-SiC reflectors may well be used in the first XUV FEL oscillators for wavelengths longer than 60 nm.

Simple metallic films represent a second type of reflector. Only for wavelengths longer than 250 nm does their reflectance exceed our minimum 40% requirement. The notable exception are aluminum films freshly deposited on smooth substrates in ultra-high vacuum (10^{-9} to 10^{-10} Torr). With care, the reflectance at normal incidence can exceed 40% for wavelengths as short as 80 nm.[40-42] However, even in high vacuum the reflectance gradually decreases with time as an oxide forms on the surface. Overcoating with a layer of MgF_2 does prevent the oxidation, but high reflectance (≥80%) is then limited to wavelengths longer than 120 nm.

The third class of reflector includes **multilayer thin-film structures** which operate on the principle of standing-wave interference of multiple reflections from the film interfaces. Since all dielectric materials are absorbing for wavelengths shorter than 110 nm, alternating metal layers having differing absorption coefficients are used (the real part of the index is near unity). For the soft X-ray and XUV spectral regions from 10 nm to 110 nm, this technology generally has yielded reflectances less than 40% for near-normal incidence with bandwidths limited to ≤10%. The interested reader is referred to the excellent review by E. Spiller,[43] a pioneer in the development of multilayer reflectors for the XUV. The highest reflectance reported up to this time for a multilayer is that of Barbee et al.[44] for a Mo-Si mirror with measured reflectance at 17 nm between 40 to 70%, the variation occuring across an apparently nonuniformly coated surface. Subsequent attempts to match this attainment, even with the same materials, have realized lower reflectances of the order of 40 to 45%. Although the useful reflectance is limited in spectral range, it is probable that some multilayer reflectors will be useful in XUV FEL resonators.

Multifacet metal reflectors, the fourth type of XUV reflector, involve multiple reflections from a series of metal mirrors. These make use of the principle of total external reflectance (TER) which occurs for angles of incidence beyond a critical angle (often near 60°) when the refractive index is less than unity and the material has zero absorption. Now, all materials absorb light to some degree, but over certain spectral ranges in the XUV, in which the extinction coefficient is sufficiently less than unity, a few metals do exhibit high reflectance, or semi-TER (R <100%). Thus, with a sequence of reflections, surprisingly high values of retroreflectance (redirection of the optical beam by 180°) are possible, especially with S-plane polarization and large angles of incidence.

Previously, Vinogradov, et al.[45] had recognized the potential for high values of retroreflection for certain metals over relatively broad spectral ranges in the soft x-ray range for photon energies above 100 eV (12.4 nm). In their theoretical analysis, they derived an analytical expression for the net reflectance after a near-infinite number of grazing-incidence reflections from cylindrical reflectors. Subsequently, Newnam[12] proposed a multiple-facet arrangement of flat mirrors for use as the end reflectors in FEL resonators (see Fig. 7) operating at XUV wavelengths between 35 and 100 nm. The flat-configuration (plus one off-axis paraboloid to collimate the beam) practically eliminates the problem of astigmatism that is inherent with large-angle reflections from a cylindrical reflector.

In contrast to multilayer mirrors based on interference, the high reflectance of multifacet metal mirrors can extend over a relatively broad range, a feature that well suits the inherently broad tunability of FEL oscillators. Such behavior is predicted for aluminum films between 35 nm and 90 nm, as shown in Fig. 8. Since the reflectance at each facet can exceed 95% for large angles of incidence, such as 80°, these reflectors offer another advantage: relatively high resistance to laser damage and thermal distortion.

Motivated by the obvious potential advantages, Scott, Arendt, and Newnam began an R&D program at Los Alamos in 1986 to determine the limitations of the multifacet metal mirrors and to implement full-scale prototypes. The candidate metals include Al, Si, Rh and Ag which, based on measured values of the optical constants, should yield retroreflectance ≥ 50%. Since contamination by oxide and carbon epifilms can severely increase the absorption, thereby eliminating TER, the contamination rates were measured in different vacuum environments.[13,46,47] Fortunately, at sufficiently high vacuum levels with low oxygen and water partial pressures, e.g. 10^{-10} Torr, the oxidation of aluminum films proceeded very slowly. Using reflectance measurements at 58.4 nm (Fig. 9) to calculate oxide layer growth, a two-week exposure of a fresh aluminum film to a vacuum of 2 X 10^{-9} Torr, primarily He, resulted in formation of only 1/4 of an oxide monolayer.[17] Repeated measurements after four weeks indicted no further growth of the oxide layer.[48] With this encouraging result, the next stage of development will include fabrication of multifacet reflectors of practical dimensions with up to 10 facets for the several candidate metals.

If the results of the research at Los Alamos continue to be encouraging, multifacet retroreflectors will be used in an XUV FEL resonator as shown in Fig. 7. Obviously, to avoid needless contamination, the metal films should be deposited on the mirror substrates mounted in place in ultra-high vacuum. With this provision, it will be possible to periodically overcoat the metallic films as required to offset the effects of any gradual deterioration that may occur while in the FEL resonator. Of course, the total thickness of the films must not become too great or else surface roughness will increase scatter loss. It is probable, too, that an ion gun mounted in the vacuum chamber can be used to periodically sputter away aged films and then evaporate fresh layers. Certainly, initial removal of carbonaceous compounds from the vacuum environment by use of an rf plasma discharge of appropriate gas, as demonstrated by Johnson, et al.[49] will also be beneficial.

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 will 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 self-amplification of spontaneous emission (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 the projected output radiation characteristics given in Table 2.

Free-Electron Laser Applications in the XUV

Numerous potential applications await the development and commissioning of a free-electron laser user facility operating in the extreme ultraviolet. As described by experts in various disciplines, the availability of several orders-of-magnitude more monochromatic photons per unit time (compared with of 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. For details of particular applications that are anticipated for XUV FELs, the interested reader should consult some of the papers presented at the Workshops at Castelgandolfo (1984)[50] and Los Alamos (1986),[51] and the forthcoming OSA Topical Conference on *Free-Electron Laser Applications in the Ultraviolet* to be held at Cloudcroft, New Mexico on March 2-5, 1988.[52]

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Figures

Figure 1. Configuration of the proposed Los Alamos XUV/UV FEL facility (1 to 400 nm). One rf-linear accelerator drives multiple, FEL oscillators in series. An additional long undulator will be used to produce 1- to 10-nm coherent pulses by SASE or in a regenerative (2- or 3-pass) amplifier using available mirrors.

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.[18-20] The FEL curve was calculated for the Los Alamos rf-linac FEL design, and a monochromator efficiency of 1% was applied to the published undulator output curves. (Dashed curves are for the third harmonic.) 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 is 10^6 (10-ps pulse every 100 ns during a 300-µs macropulse repeated at 30 Hz) and that for the storage-ring insertion devices is ~300.

Figure 3. 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) such as that of the LBL Advanced Light Source.[18-20] Additional remarks in Fig. 2 caption apply here as well.

Figure 4. Block diagram of a staged injector linac comprising a photoelectric RF gun source, a subharmonic linac, a magnetic phase-compression system followed by a second injector linac at the main linac frequency and a second magnetic compressor. After Fraser.[24]

Figure 5. The photocathode injector performance has surpassed the emittance goals for the Los Alamos 12- and 50-nm FEL designs using an rf linac.

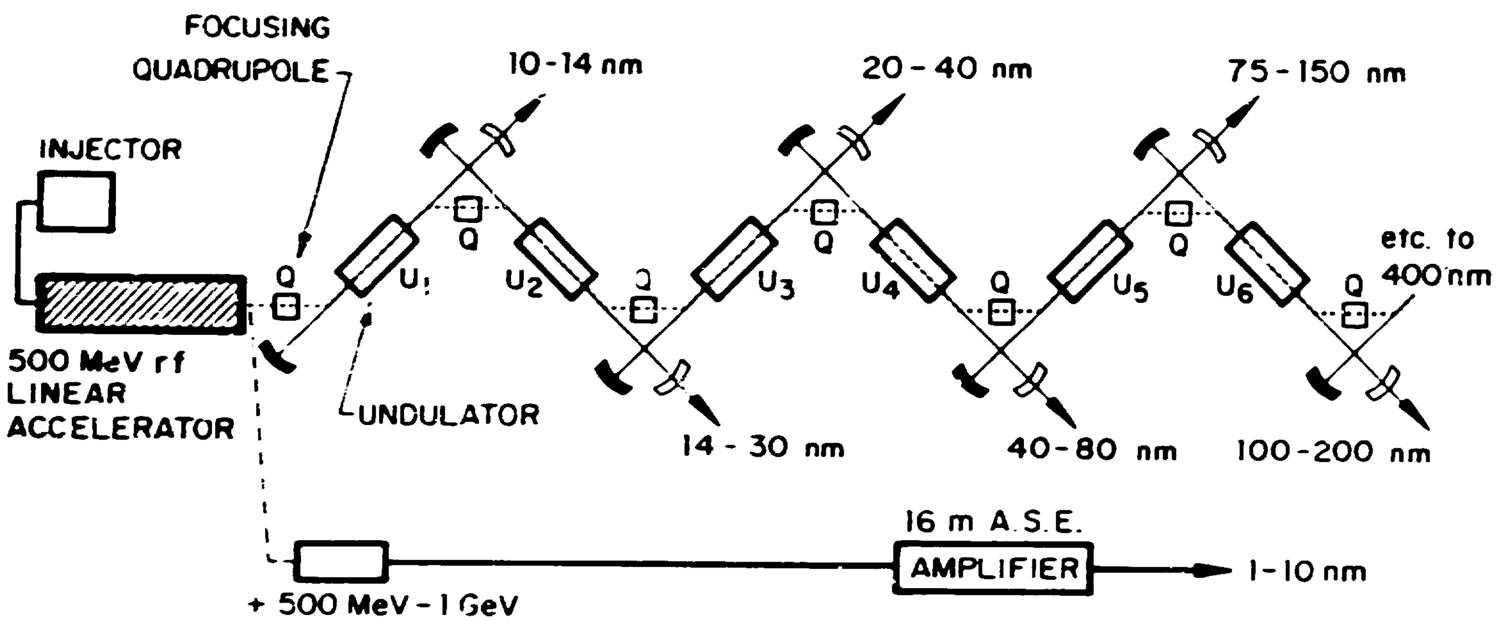
Figure 6. On-line application of Warren's pulsed-wire monitor of wiggler-magnet precision. After Warren.[31,37]

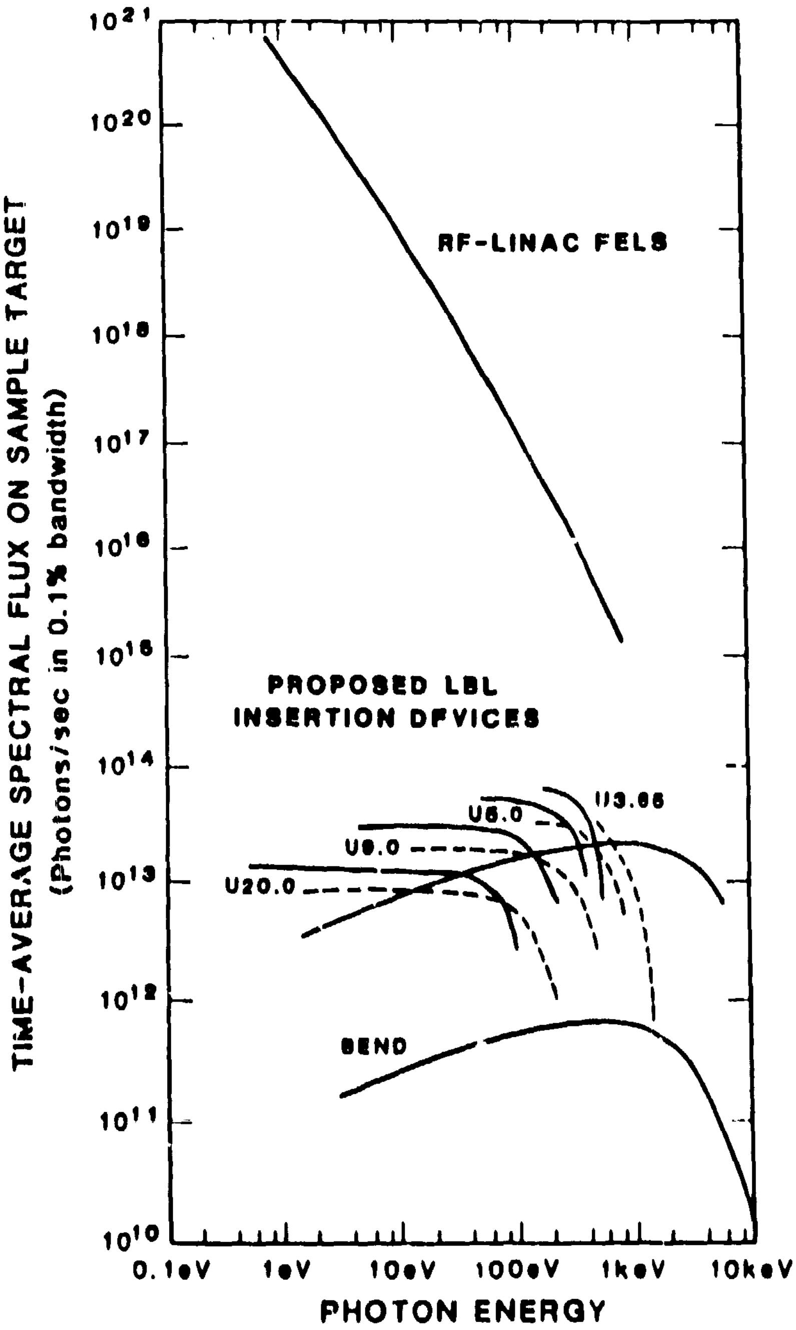
Figure 7. Multifacet, all-metal mirrors based on total external reflection at large angles of incidence (~80°) will provide the necessary ≥40% retroreflection for an FEL oscillator over broad spectral ranges in the XUV. After Newnam.[12]

Figure 8. The calculated retroreflectancee of multifaceted Al mirror exceeds 50% for XUV and VUV wavelengths >40 nm. After Newnam.[12]

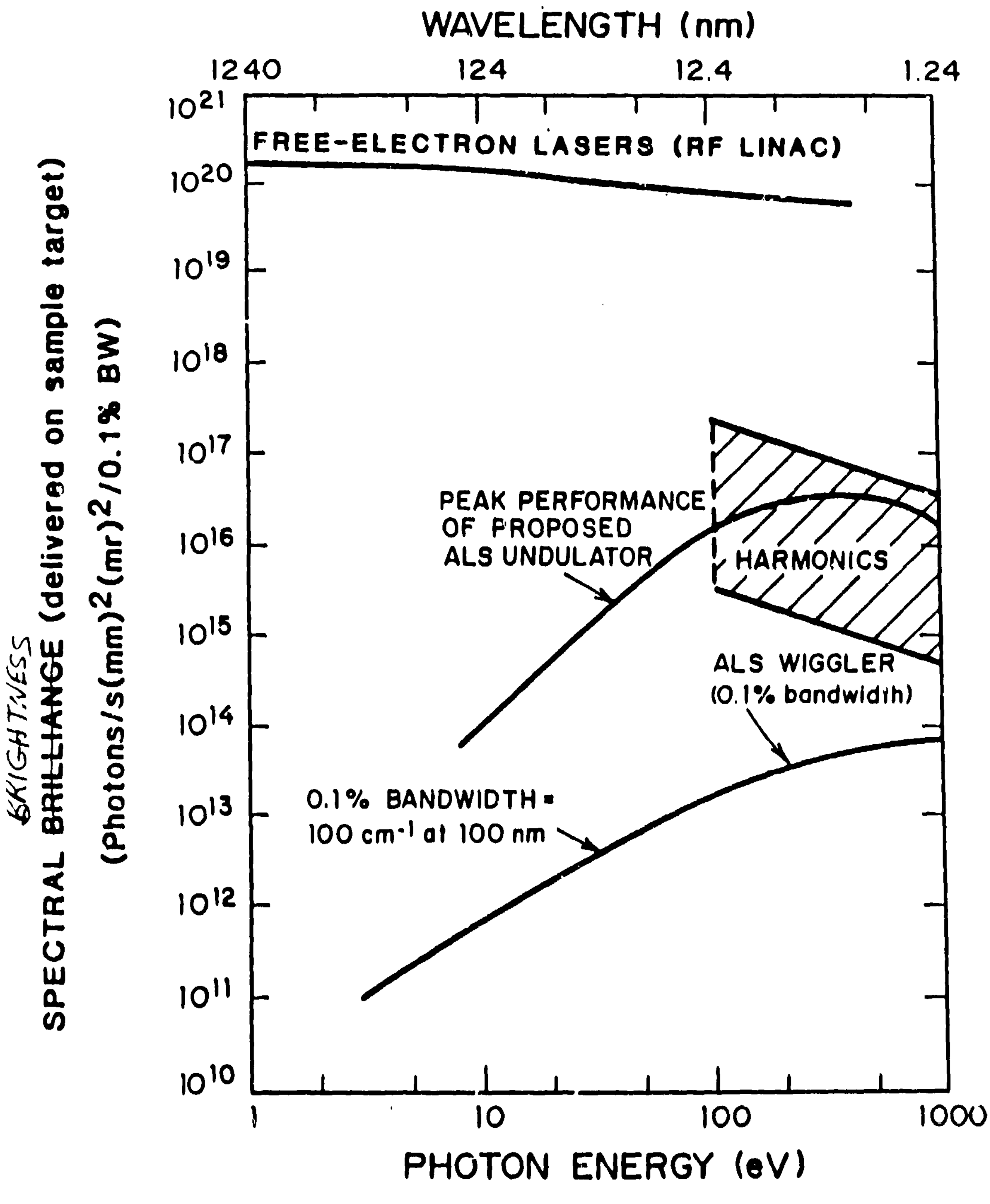
Figure 9. The reflectance of an aluminum film measured versus angle of incidence at 58.4 nm clearly exhibits the onset of total external reflectance at ~40°. After two weeks in a vacuum chamber containing primarily helium at 2 X 10^{-9} Torr, the reflectance had degraded slightly corresponding to growth of an oxide epifilm only 1/4 monolayer thick. (The interference effect exhibited between 35° and 45° is due to subsurface reflections from the substrate covered with a previously deposited Al film and its oxide overcoat.) After Scott, et al.[13]

ONE rf LINEAR ACCELERATOR DRIVES MULTIPLE, FEL OSCILLATORS IN SERIES



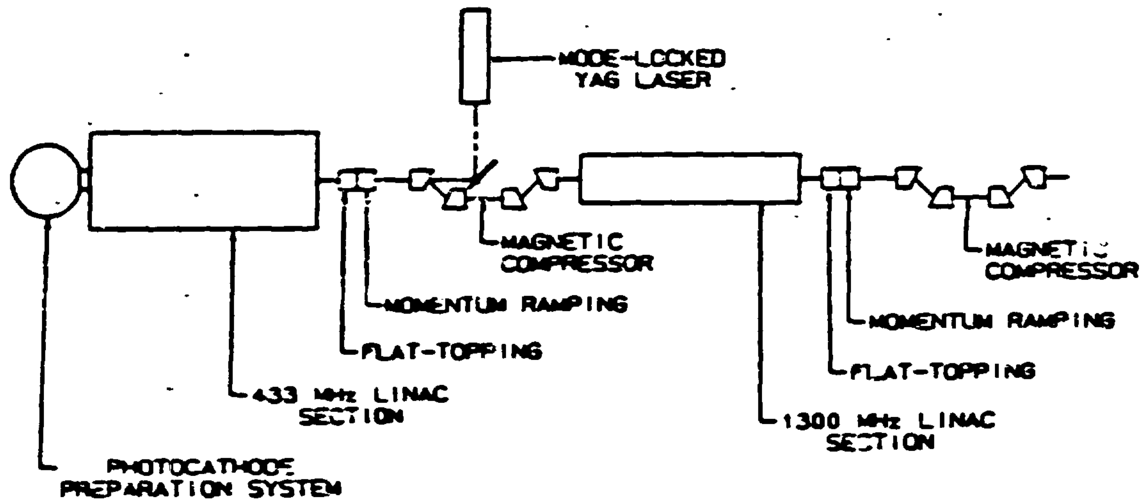


TIME-AVERAGE SPECTRAL FLUX ON SAMPLE TARGET
(Photons/sec in 0.1% bandwidth)
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
RF-LINAC FELS
PROPOSED LBL
INSERTION DEVICES
U3.65
U5.0
U8.0
U20.0
BEND
0.1eV
1eV
10eV
100eV
1keV
10keV
PHOTON ENERGY

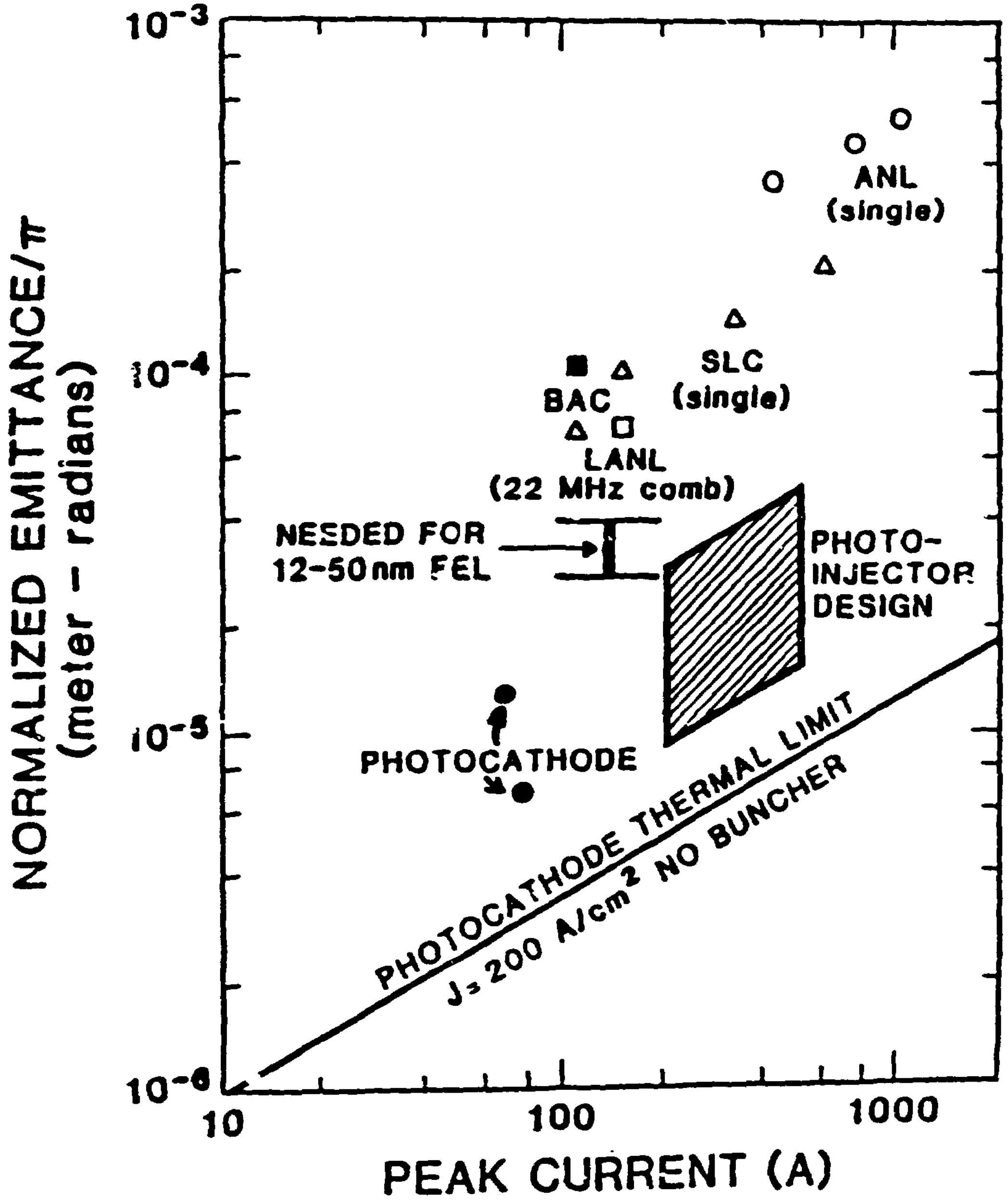

WAVELENGTH (nm)
1240
124
12.4
1.24
FREE-ELECTRON LASERS (RF LINAC)
PEAK PERFORMANCE
OF PROPOSED
ALS UNDULATOR
HARMONICS
ALS WIGGLER
(0.1% bandwidth)
0.1% BANDWIDTH =
100 cm-1 at 100 nm
BRIGHTNESS
SPECTRAL BRILLIANCE (delivered on sample target)
(Photons/s(mm)2(mr)2/0.1% BW)
1
10
100
1000
PHOTON ENERGY (eV)

CHM-VG-4037F

Fig. 4


MODE-LOCKED YAG LASER
MAGNETIC COMPRESSOR
MOMENTUM RAMPING
FLAT-TOPPING
433 MHz LINAC SECTION
PHOTOCATHODE PREPARATION SYSTEM
MAGNETI
COMPRESSOR
MOMENTUM RAMPING
FLAT-TOPPING
1300 MHz LINAC SECTION

PHOTOCATHODE INJECTOR PERFORMANCE SURPASSES EMITTANCE GOAL FOR 12- TO 50-nm XUV FREE-ELECTRON LASER DESIGNS



ON-LINE USE

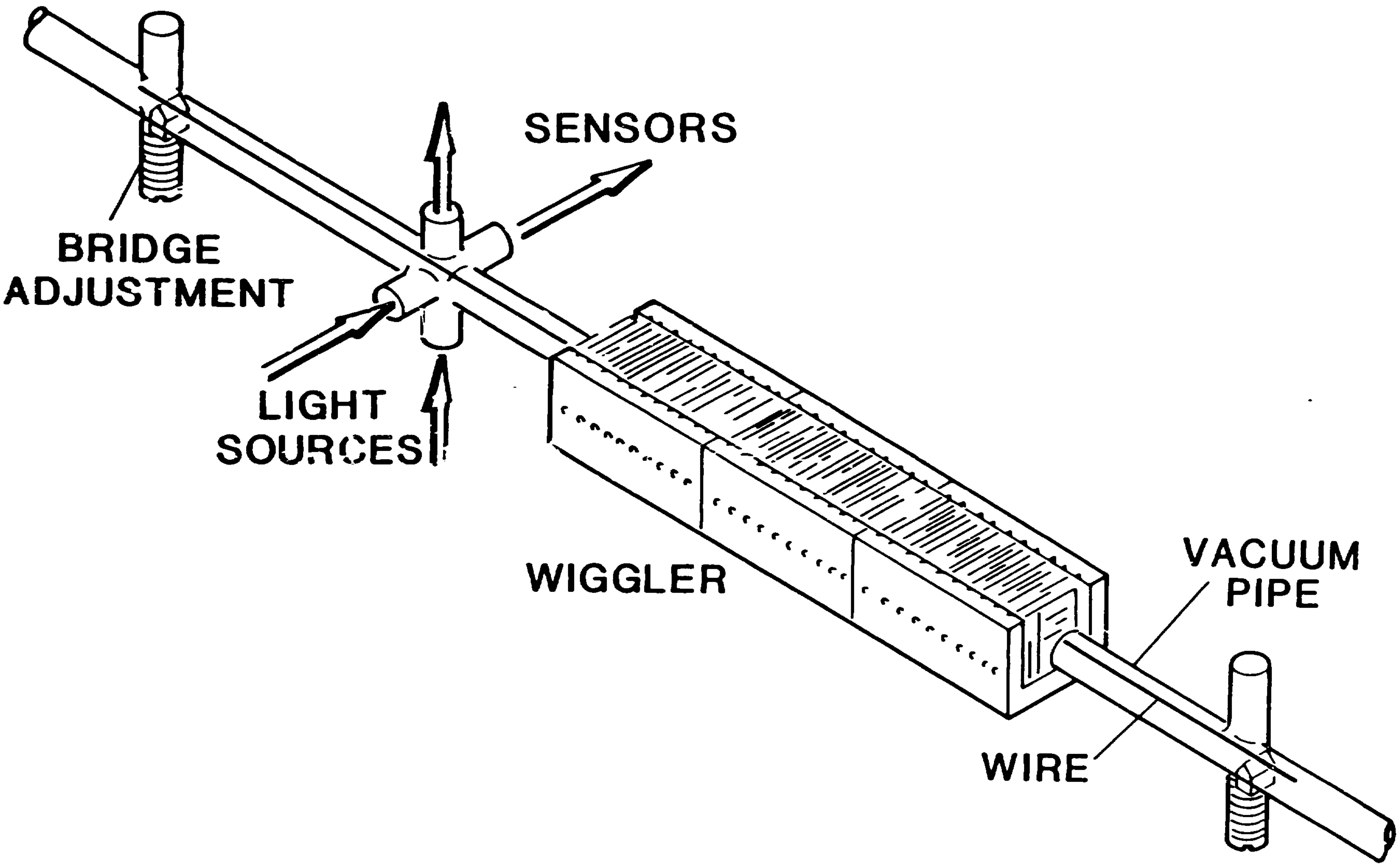
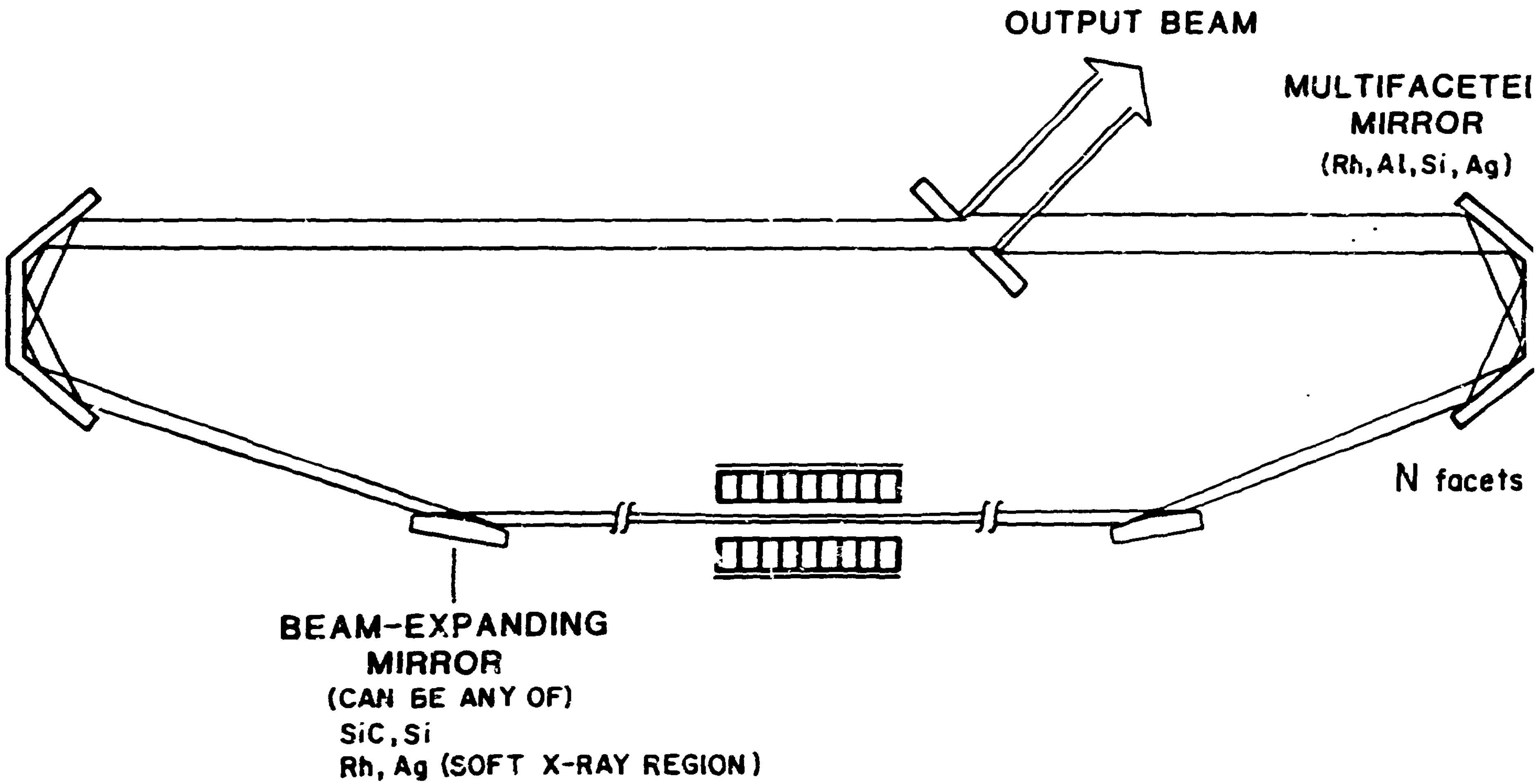

SENSORS
BRIDGE
ADJUSTMENT
LIGHT
SOURCES
WIGGLER
VACUUM
PIPE
WIRE

Fig. 7.

MULTIFACET, ALL-METAL MIRRORS WITHSTAND HIGH INTENSITY IN RING RESONATOR



CHM-VG-8141B

CALCULATED RETROREFLECTANCE OF MULTIFACETED ALUMINUM MIRROR EXCEEDS 50% FOR XUV AND VUV WAVELENGTHS >40nm

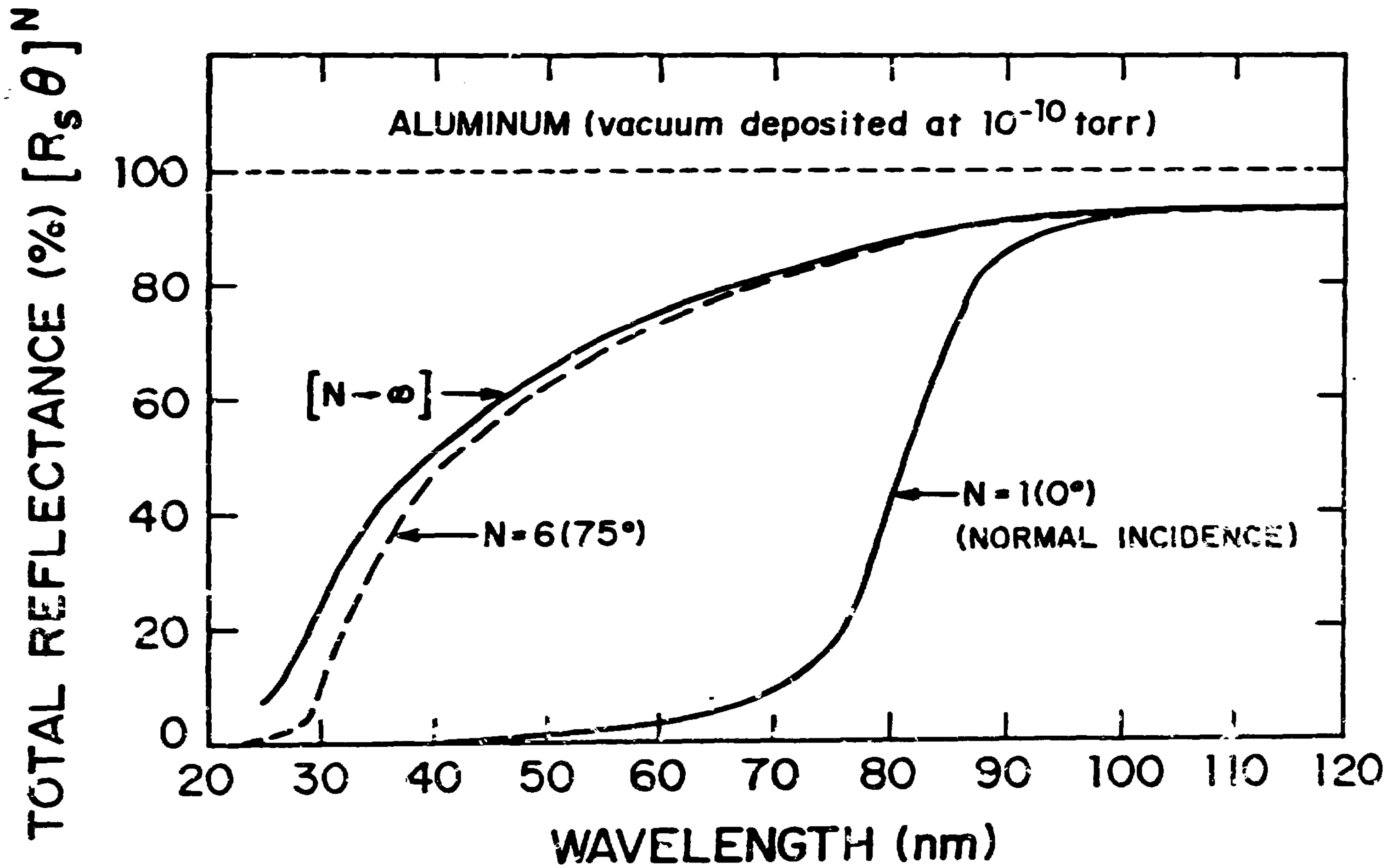
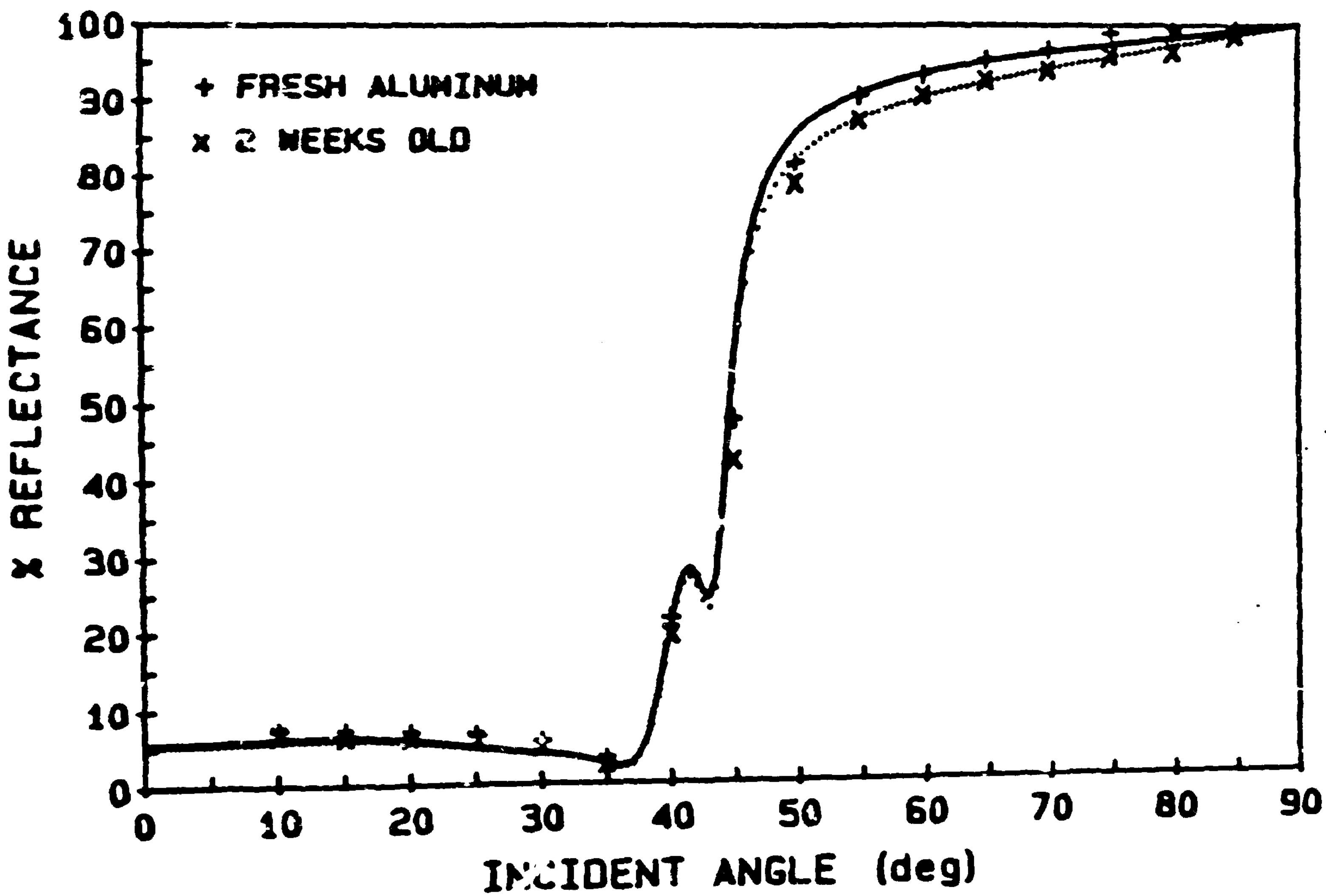


Fig. 8

CHM-VG-8265

FIG. 69


+ FRESH ALUMINUM
x 2 WEEKS OLD
% REFLECTANCE
INCIDENT ANGLE (deg)
0
10
20
30
40
50
60
70
80
90
100