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Short Wavelength FELS*

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Abstract

The generation of coherent ultraviolet and shorter wavelength light is presently limited to synchrotron sources. The recent progress in the development of brighter electron beams enables the use of much lower energy electron rf linacs to reach short-wavelengths than previously considered possible. This paper will summarize the present results obtained with synchrotron sources, review proposed short-wavelength FEL designs and then present a new design which is capable of over an order of magnitude higher power in the extreme ultraviolet.

I. Introduction

Optical radiation below 200 nm has many potential uses [1]. The class of uses generally fall into two categories: basic research in such areas as biological processes, solid state physics, chemical processes, snapshots of temporally unstable targets, and photolithography for semiconductor processing. Biological studies include UV damage of DNA, Raman spectroscopy, and time resolved fluorescence spectroscopy. Solid state physics research covers ultra-high resolution photoemission from interfaces and surfaces, detectors, optics, and nonlinear harmonic generation. Chemical research include dynamics of highly excited states, gas-phase photochemistry, and surface photochemistry.

Advanced lithographic technologies require feature sizes of less than 0.25 microns [2]. Optical projection lithography is currently used with mecury lamps or excimer lasers and is the process of choice for semiconductor processing. Projection lithography below 0.25 microns was not thought to be possible because of the high power levels (10 to 100 watts) in the 10 to 100 nm wavelength band which is required for adequate wafer throughput. Consequently, large research sums have been spent on alternate technologies (such as x-ray transmission using proximity masks).

Electron synchrotrons can generate radiation from less than 0.1 nm to greater than 100 nm. Even though synchrotrons can produce a wide range of wavelengths, the output power in a narrow bandwidth is limited (Fig. 1) relative to that attainable by free-electron lasers (FELs). More of the above mentioned research applications require higher power levels than synchrotron sources either for increasing the signal to noise ratio or for multiphoton processes. Photolithography requires several orders increase in average power over synchrotrons. The increased power requirements have driven research into the use of free-electron lasers for the generation of short wavelength light.

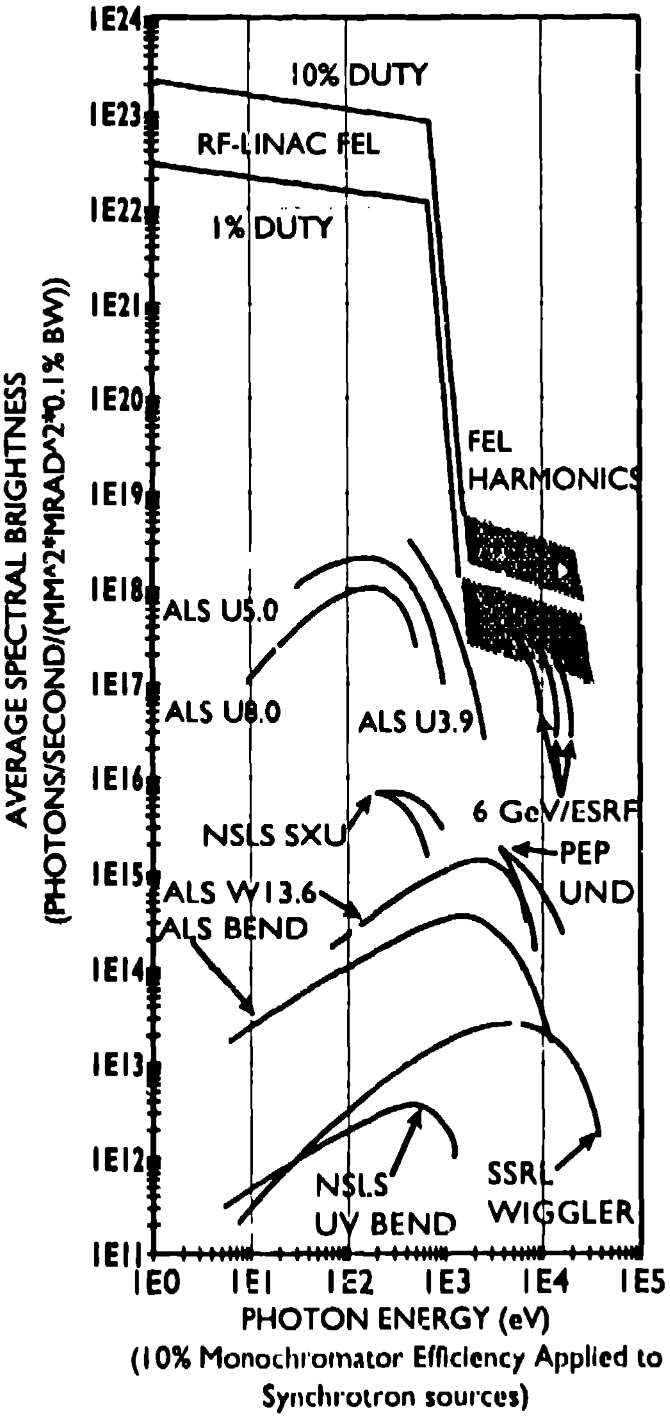

Figure 1. Time-average spectral brightness (delivered on target).

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II. Free-Electron Lasers

A free-electron laser (FEL) converts electron beam energy into a highly collimated, high-power beam of light by stimulated emission. An FEL produces an laser beam of good optical quality and narrow bandwidth and is tunable over a wide wavelength range. A schematic of an rf linac based FEL in an oscillator configuration is shown in Fig. 2. The essential components of an FEL are the electron accelerator and a transversely-oscillating magnetic field (called a wiggler or undulator depending on the magnitude of the on-axis magnetic field). The magnetic field initially causes the electron beam to oscillate, thereby generating spontaneous optical radiation. Later in the process, the magnetic field couples the electron beam motion to the optical field which has built up in the optical resonator for an FEL oscillator or the amplifier wiggler for an FEL amplifier. This motion forces the electrons to do work against the optical field, further increasing the energy in the optical radiation. The performance of the FEL depends to a large degree on the brightness of the electron beam and the wiggler design. Because of recent improvements in the de: _ 1 of electron sources [3]-[4], FELs can now operate in the extreme ultraviolet and soft x-ray regime at relatively low energies (<1 GeV). Since the wavelength of the radiation from the FEL is proportional to the wiggler period, significant research effort is being directed to the design of shorter-period wiggler fields [5]-[7].

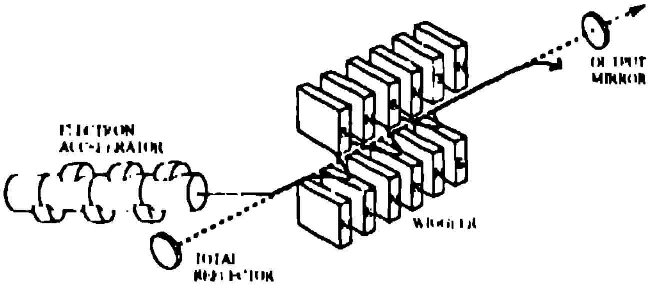

Figure 2. Basic components of a rf linac FEL.

Short-wavelength free-electron lasers fall into two categories: rf linac based and storage ring based. I will briefly describe representative FEL designs for both of the categories.

III. RF LINAC FELS

The rf linac category can be divided into two approaches based on the type of FEL optical system used. The two approaches are an optical resonator and a single pass amplifier. In an optical resonator, the light recirculates in a resonator so that the optical power can build up to very high levels, increasing the electron beam to light extraction efficiency. However, mirrors have very low reflectivity in the sub-100 nm region and thus the optical gain must be very high to overcome resonator losses. In an amplifier, the light is single pass and so there are no resonator losses, but the wiggler must be very long (approximately twice as long as in an oscillator) to allow the light to build up to high power levels.

Brian Newnam of Los Alamos National Laboratory has proposed an extreme ultraviolet (XUV) FEL operating down to 1 nm [8]. A system schematic is shown in Fig. 3. The system consists of a single linac driving seven different oscillators, each oscillator producing a different wavelength. Over certain wavelength regions, normal incidence optics have sufficient reflectivity to be used as resonator mirrors [8]. From 60 to 100 nm, polished chemically-vapor-deposited (CVD) silicon carbide exhibits 40 to 50% reflectance at normal incidence. From 80 to 100 nm, unoxidized aluminum films go from 40% to greater than 90% reflectivity. From 10 to 20 nm, Mo and Si multilayer reflectors have between 40 to 50% reflectivity. At the present time, normal incidence optics do not exist for the wavelengths between 20 to 60 nm and below 10 nm. To provide

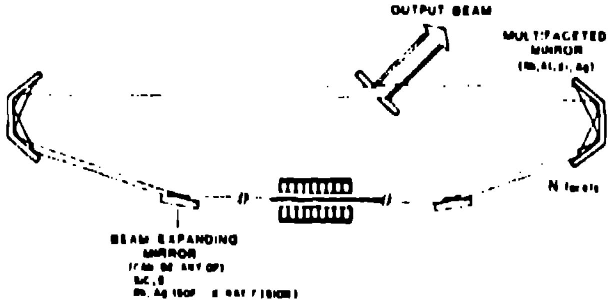

Figure 4. Multifaceted, all-metal mirror grazing-incidence ring resonator. The light from the wiggler first reflects from hyperboloidal mirrors which causes the beam to diverge to reduce thermal distortion of the multifaceted mirrors.

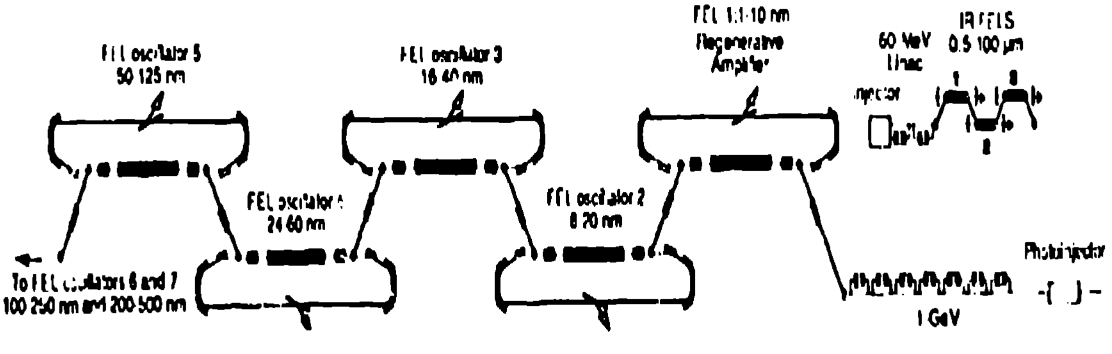

Figure 3. Proposed Los Alamos XUV FEL National User Facility.

mirrors for the remaining wavelengths and to reduce beam-induced thermal distortion of the mirror surfaces, Newnam has proposed a ring resonator with multifaceted mirrors [9], schematically shown in Fig. 4. This mirror system uses the increase in reflectance (greater than 95% per surface at these wavelengths), enabled by total external reflection. The machine parameters are: maximum beam energy of 1 GeV, peak currents of 300 to 400 A, normalized 90% emittance (the 90% emittance = 4 ξ the rms emittance) of <30 π mm-mrad, and a 0.1% energy spread. The wiggler is 5 m long for 50 nm and 12 m long for 4 nm with a wiggler period of 1.6 cm.

The other rf linac designs operate in an FEL amplifier configuration. Two representative designs, one from Brookhaven National Laboratory (BNL) and the other from University of California at Los Angeles (UCLA), follow.

BNL has proposed a Ultraviolet Free-Electron Laser User Facility [10] to be used in conjunction with the National Synchrotron Light Source (NSLS). This FEL operates as an injection-locked amplifier with the seed radiation produced by a conventional tunable laser. A schematic of the system is shown in Fig. 5. The major system features are a photoinjector electron source, a superconducting recirculating linac, and two FEL amplifier beamlines. The repetition rate for the electron pulses from the accelerator is 1 kHz. Each amplifier beamline operates at 0.55 kHz and the output optical pulses from the amplifiers have an adjustable relative timing with respect to each other. The output optical pulses from each amplifier will be split between two experimental stations by rotating mirrors. The machine offers low energy spread (0.1%) and short pulse durations (possibly down to 200 fs). The machine parameters are: 250 MeV final energy, peak current of 300 A, normalized 90% emittance of 32 π mm-mrad, and an energy spread of 0.1%. The wiggler is composed of a short (2.5 m) subharmonic wiggler with 3.5 cm period and a longer (11 m) main wiggler with a 2.2 cm period. The main wiggler has a 4.5 m section which has a 1.2% taper. Research is also presently being conducted on a superconducting wiggler with a 8.8 mm period. At 100 nm, the calculated average power is 1 watt.

At UCLA, an x-ray linear light source (LLS) has been proposed [6]. In this design, very high accelerator gradients (near 200 MeV/m) are used to reduce the overall machine length. To attain the very high gradients, a high frequency (10-30 GHz) accelerator structure is driven by a relativistic klystron, under development by LLNL/LBL/SLAC [11]. A schematic of the relativistic klystron and its induction linac driver is shown in Fig. 6. The FEL designs are based on self-amplified spontaneous-emission (SASE)

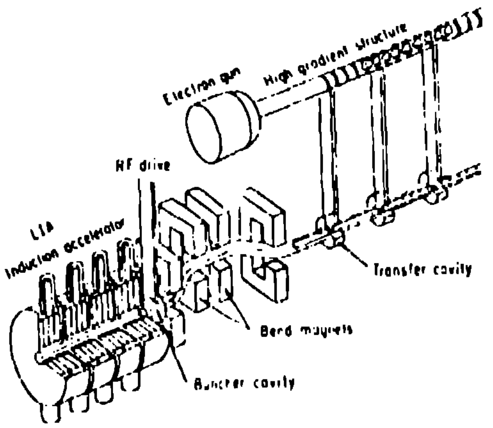

Figure 6. Relativistic klystron driver for UCLA XUV machine.

IV. Storage rings

Another technique for producing short wavelength light is to use storage rings with long straight sections for an FEL oscillator. Proposals have been made by Stanford University [12] (work on this proposal is proceeding at Duke University) and University of Dortmund [13].

The Stanford design is based on a 1 GeV storage ring. A schematic of the machine is shown in Fig. 7. In the long straight section is space for a 27 m long undulator. A 1 GeV linac will inject electrons into the ring at full energy. Alternately, positrons will be injected to increase the lifetime of the stored

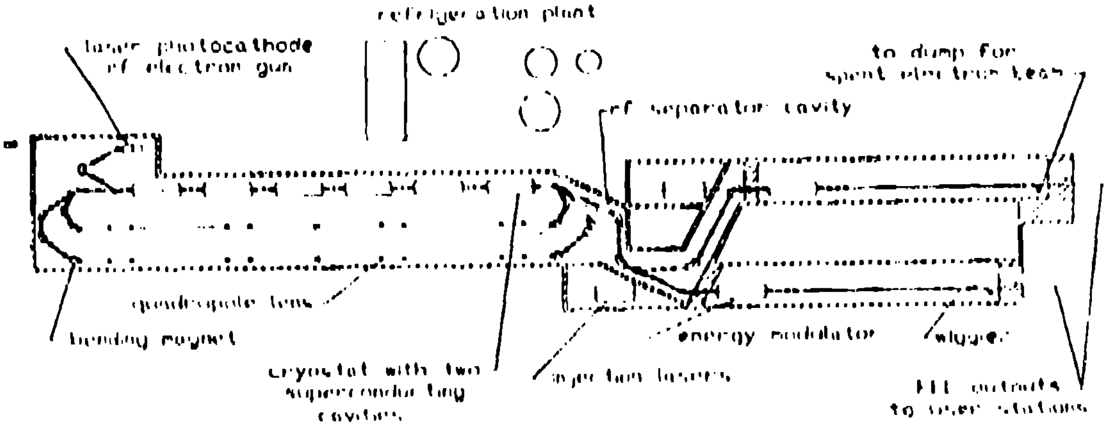

Figure 5. Proposed BNL UV FEL.

beam. In an FEL, electrons gain an energy spread as the electrons interact with the optical field. In storage rings, the induced energy spread is then damped by synchrotron radiation losses with an ~10 ms time constant. The peak current in this design is 270 A with a 90% normalized emittance of 170 π mm-mrad. The machine is designed to produce optical radiation from greater than 100 nm to less than 30 nm.

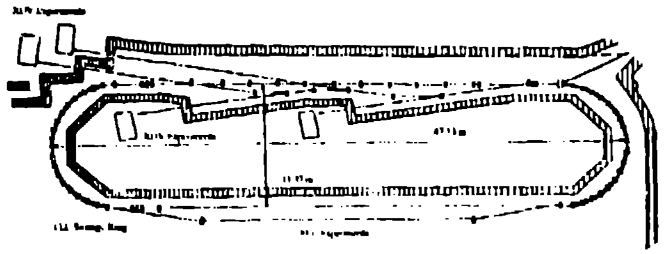

Figure 7. Schematic of Stanford University's 1 GeV storage ring.

The storage ring at the University of Dortmund is called DELTA. The ring has a maximum energy capability of 1.5 GeV. A schematic of the machine is shown is Fig. 8. The DELTA lattice was optimized for FEL operation. Two straight sections approximately 20 m long with zero dispersion and with nearly constant beta functions are available for insertion devices. The ring has a low 90% normalized emittance of 40 π mm-mrad at 1 GeV, short damping time (~ 0.2 s), high peak currents (180 A), and long beam lifetime. The machine is designed to produce optical radiation from 400 nm to 25 nm.

V. Compact Short-Wavelength FEL

A study at Los Alamos National Laboratory was started to determine if a (relatively) small, less costly XUV FEL is now possible using the advances in FEL system components in the last several years. In particular, significant developments have occurred in high-brightness electron linacs [14] and short-

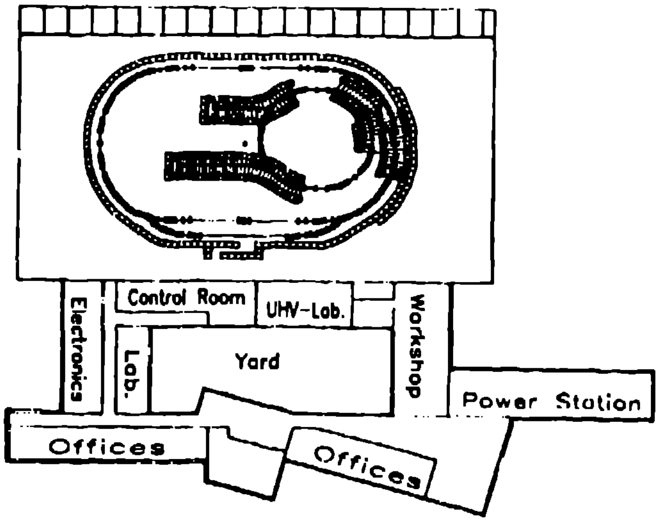

Figure 8. Layout of the Dortmund storage ring, showing the linac, the full-energy booster and the main storage ring.

wavelength wigglers [15]. This study is directed at providing a machine for photolithographic processing applications. The design follows from the Advanced Free-Electron Laser Initiative (AFELI) at Los Alamos National Laboratory.

The AFELI program goals are to build an Advanced FEL (AFEL) using a high-brightness electron beam and a microwiggler, while minimizing size and cost. A schematic of the AFEL is shown in Fig. 9. Extensive linac design calculations have been made using a modified version of PARMELA. This version of PARMELA directly incorporates files from POISSON, MAFIA, and SUPERFISH [16] to accurately describe the field distributions in the accelerator. The electron beam parameters are: 20 MeV final energy, 200 to 300 A peak for 10 ps, and a 90% normalized emittance of less than 15 π mm-mrad. Only those electrons in the middle 75% of the pulse in time contribute to the FEL interaction (the temporal wings do not interact). The

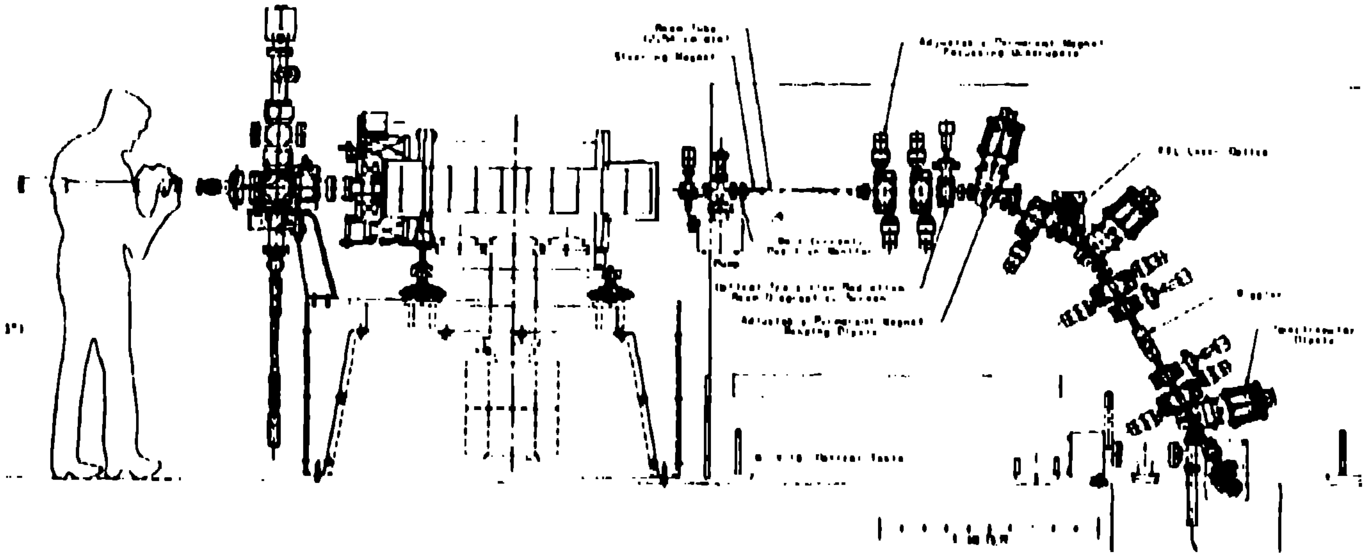

Figure 9. Schematic of the AFEL experiment, showing linac, beamline, and FEL resonator.

To be finished, just a line drawing of major components of an XUV FEL

Figure 10. Schematic of a XUV FEL based on the AFEL system design.

emittance of just the middle 75% of the pulse is less than 8 π mm-mrad. The accelerator is 1.2 m long giving a true gradient of 18 MV/m. The calculated gain (with the FEL code FELEX) for the 3rd harmonic of a 3 mm period pulsed wire wiggler is greater than 50% at 390 nm. Accelerator operation is scheduled to begin in the first half of 1992.

Based on the AFEL system, an XUV FEL was designed [17]. The XUV FEL schematic is shown in Fig. 10. The base line design for a 60 nm machine is: 90 MeV final energy, 1 nC micropulse charge, 0.13 A average current, and 160 A peak current. The accelerator is driven by four Thomson CSF 2022E 20-MW 1300-MHz klystrons operated at 60 Hz with a 0.3% duty factor. The overall accelerator length is 5 m. The pulsed wire wiggler has a period of 2.6 mm and is 22 cm long. The optical resonator uses multifaceted reflector optics and is approximately 4 m long. The calculated output power is 100 W at 60 nm.

VI. REFERENCES

[1] Numerous workshops have been held on XUV applications. For detailed information consult the following: *Los Alamos Workshop on Applications of Free-Electron Lasers*, Deacon, D. A. G. and De Angelis, A., eds., Nucl. Instr. and Methods in Phys. Res., A239, pp. 371-443; *Los Alamos Workshop on Appplications of Coherent Extreme-Ultraviolet Radiation*, Newnam, B. E., ed., LANL report DRP/DEW-FEL-86:19, 1986; *Report from the NSLS Workshop*, E. D. Johnson and J. B. Hastings, Eds., BNL report 45439, 1990.

[2] B. E. Newnam, "Development of Free-Electron Lasers for XUV Projection Lithography," *SPIE Conf. on Free Electron Lasers and Appl.*, 1227, 1990.

[3] J. S. Fraser and R. L. Sheffield., "High-Brightness Injectors for RF-Driven Free-Electron Lasers," *J. Quantum Electron.*, QE-23, pp. 1489-1496, 1987.

[4] K. Batchelor, H. Kirk J. Sheehan, M. Woodle, and K. McDonald, *Proc. Europ. Part. Accel. Conf.*, Rome, Italy, 1988.

[5] R. L. Sheffield, J. H. Booske, B. Danely, K. Halbach, B. Jackson, J. Slater, A. Toor, P. Walstrom, and R. W. Warren, "Workshop Results on Small-Period Wiggler Designs," LANL Report LA-UR-89-2851, 1989.

[6] D. R. Cline, "Development of a Compact X-ray Linear Light Source and FEL at UCLA," *Proc. of the 11th Int. Free Electron Conf.*, Nucl. Instr. and Methods, A296, pp. 814-821, 1990.

[7] K. Batchelor, I. Ben-zvi, R. Fernow, J. Gallardo, H. Kirk, C. Pellegrini, and A. Van Steenbergen, "A Microwiggler Free-Electron Laser at the Brookhaven Accelerator Test Facility," Nucl. Instr. and Methods in Phys. Res., A296, pp. 239-243, 1990.

[8] B. E. Newnam, "Free-Electron Laser sources of Extreme-Ultraviolet Radiation and their Vacuum Requirements," *Proc. of the 2nd Int. Conf. on Vacuum Design of Advanced Synchrotron Light Sources*, AIP Conf. Proc., November 13-15, 1990.

[9] B. E. Newman, "Multifacet Metal Mirror Design for Soft X-Ray and Extreme-Ultraviolet Free-Electron Laser Resonators," *Laser Induced Damage in Optical Materials: 1985*, H. E. Bennett, A. H. Guenther, D. Milam, and B. E. Newnam, Eds., NBS Spec. Publ. 746, pp. 261-269, 1988.

[10] BNL uv fel ref

[11] A. M. Sessler et. al., Phys. Rev. Lett. 58, pp. 2439, 1987; M. Allen et al., *Proc. Eur. Particle Accelerator Conf.*, 1988.

[12] H. Wiedemann, Int. Conf. on Insertion Devices for Synchrotron Sources, Proc. SPIE 582, pp. 156-162, 1986; J. E. La Sala, D. A. G. Deacon, and J. M. J. Madey, "Performance of an XUV FEL Oscillator on the Stanford Storage Ring,", Nucl. Instr. and Methods in Phys. Res., A250, pp. 262-273,1986.

[13] N. Marquardt, *Proc. 1989 Part. Accel. Conf.*, 2, pp. 780-782, 1989; D. Nolle, F. Brinker, M. Negrazus, D. Schirmer, and K. Wille, "DELTA, A New Storage-Ring-FEL Facility at the University of Dortmund," Nucl. Instr. and Methods in Phys. Res. A296, pp. 263-269, 1990.

[14] R. L. Sheffield, "Photocathode RF Guns," *Physics of Particle Accelerators*, AIP Conf. Proc. 184, Vol. 2, pp. 1500-1531, 1989.

[15] R. W. Warren, D. W. Feldman, and D. Preston, "High-Field Pulsed Microwigglers," Nucl. Instr. and Methods in Phys. Rev. Res., to be publ., 1990.

[16] For further information on these codes, see *Computer Codes for Particle Accelerator Design and Analysis: A Compendium*, H. S. Deaven and K. C. D. Chan, eds., publ. by Los Alamos Accelerator Code Group, Report LA-UR-90-1766, 1990.

[17] Private communication with Richard Cooper, Los Alamos National Laboratory.