The Low-Energy Undulator Test Line: A SASE FEL Operating from 660 to 130 nm

S. G. Biedron for the LEUTL † and FEL Exotica†† Teams

†The LEUTL Team: S.G. Biedron♦, M. Borland, P. Den Hartog, R. Dejus, M. Erdmann, Z. Huang, K.-J. Kim, J. Lewellen, Y. Li, A. Lumpkin, O. Makarov, S.V. Milton, E. Moog, V. Sajaev, and G. Wiemerslage

Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439, USA

♦*and MAX-Laboratory, University of Lund, Sweden S-221 00*

††Recent work in exotic schemes has been performed by the following individuals; D. Attwood[1], S.G. Biedron [2,3], R. Bartolini[4], F. Ciocci[4], G. Dattoli[4], W.M. Fawley[1], G. Felici[4], H.P. Freund[5], J. Lewellen[2], Y. Li[2], S.V. Milton[2], H.-D. Nuhn[2], P.L. Ottaviani[6], A. Renieri[4], and J. Rocca[7]

[1]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

[2]*Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439, USA*

[3]*and MAX-Laboratory, University of Lund, Sweden S-221 00*

[4]*ENEA, Divisione Fisica Applicata, Centro Ricerche Frascati, C.P. 65, 00044 Frascati, Rome, Italy*

[5]*Science Applications International Corporation, McLean, VA 22102, USA*

[6]*ENEA, Divisione Fisica Applicata, Centro Ricerche E. Clementel, Via Don Fiammelli 2, Bologna, Italy*

[7]*Colorado State University, Fort Collins, CO 80523 USA*

PACS Codes: 41.60, 42.65.Ky, 52.59.-f

Keywords: Free-Electron Lasers, Harmonic Generation, Frequency Conversion, Intense Particle Beams and Radiation Sources

Abstract. There is a strong desire for short wavelength (down to 1 Å), short pulsewidth (<100 fs), high-brightness, transverse, and longitudinally coherent light pulses for use by the synchrotron radiation community. Much effort is ongoing worldwide to advance this desire both experimentally, in theory and design, and politically. One of the ongoing experimental efforts is the low-energy undulator test line (LEUTL) at the Advanced Photon Source (APS) at Argonne National Laboratory (ANL). This experiment is based upon the self-amplified spontaneous emission (SASE) process, a method to attain a next-generation light source. This presentation gives an overview concerning the history and results of next-generation light sources, the results of the LEUTL SASE FEL, and the description of the upcoming first user experiment on LEUTL. We will also briefly review exotic schemes for future, next-generation light sources based upon FELs including biharmonic undulators and the possibility of interfacing of traditional x-ray lasers with FELs.

WHAT ARE THE DESIRED CHARACTERISTICS OF A NEXT-GENERATION LIGHT SOURCE?

The synchrotron radiation sources of the past and present may be defined as follows. First-generation machines were electron synchrotrons and storage rings that were built for other purposes (e.g., high-energy and nuclear physics), but whose bending magnet radiation was parasitically used by synchrotron radiation "users." This radiation could cover many wavelength regimes due to the nature of the bending magnet emission. However, it had rather large photon source sizes as the electron beam emittance in these machines was large, and neither intended nor ideal for synchrotron radiation applications. The second-generation machines were dedicated machines for synchrotron radiation users and employed bending magnets as the primary source of synchrotron radiation. The beam emittances were designed by the machine builders to be relatively small in order to provide users with a smaller source size and higher brilliance. Third-generation machines are dedicated for synchrotron radiation users and were designed ab initio to accommodate many so-called insertion device magnets such as undulator and wiggler magnets. Undulator magnets have the feature that they generate relatively narrow spectral lines, and this enhances the overall photon brilliance.

Currently, the synchrotron radiation community employs many third-generation light sources, such as the Advanced Photon Source (APS) at Argonne National Laboratory (ANL), USA, the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, and SPring-8 in Harima Science Garden City, Japan. Such sources are capable of producing photons with energies of ~1-100 keV at peak spectral brightnesses of 1×10^{23} photons$\cdot$s$^{-1}\cdot$(0.1% bandwidth)$^{-1}\cdot$mm$^{-2}\cdot$mrad^{-2}. Although these short-wavelength, high-brightness machines have proven successful in discovering previously unobtainable structural information in a variety of scientific areas, the ability to obtain dynamical (temporal) information, particularly in relation to the biological sciences, is limited to time scales longer than ~10 ps. To obtain dynamical information at shorter time scales, one must produce and use x-rays in the 1-Å-wavelength regime with pulse lengths on the sub-ps timescale. It is also preferable that these pulses be fully coherent longitudinally in order to insure a narrow spectral bandwidth. Also, a diffraction-limited source with full transverse coherence is desirable. Finally, there is interest of peak radiation intensities and brightnesses many orders of magnitude higher than are available from contemporary machines. This will enhance spatial resolution and may even lead to the possibility of single molecule structure determination. Longer wavelength next-generation light sources are also important and desired by the scientific community; one example of which will be discussed below.

WAYS TO OBTAIN A NEXT-GENERATION LIGHT SOURCE

Numerous mechanisms to produce such high, peak-brightness photon pulses have been discussed [1], many belonging to the category of single-pass, high-gain free-electron lasers (FELs). However, for a number of reasons, oscillator (multiple-pass) and amplifier (referring to a one-undulator amplifier) FELs [2] alone are not well suited for these short wavelengths. The oscillator (multiple-pass) method is unsuitable for the x-ray (1-Å) regime, because mirrors of sufficient reflectivity are unavailable. In addition, such mirrors would be required to tolerate extreme power densities based on high peak- and average- powers. It is also the consensus that the storage-ring approach to the next-generation light source operating in the x-ray (1-Å) regime is unrealistic, as the necessary high electron bunch brightness and short pulse duration are presently unachievable in a storage ring [3].

The mechanisms of self-amplified spontaneous emission (SASE), amplifier, two-undulator harmonic-generation scheme (TUHGS), and high-gain harmonic generation (HGHG) FELs, as well as the nonlinear harmonics generated in each, belong to a genré of linear-accelerator-driven sources [1]. The SASE mechanism can provide the photon power and pulse duration required by the next-generation light source users. However, SASE is a random process that starts up from noise; therefore, its output is neither fully longitudinally coherent nor transform limited, and $\Delta\omega\Delta t > 1$, where $\Delta\omega$ is the frequency spread of the photon pulse and Δt is the pulse duration. An amplifier FEL requires a coherent (electromagnetic) input seed signal with a wavelength equal to that of the desired output radiation; however, this is presently unavailable in the 1-Å regime. The TUHGS and HGHG processes use a fully coherent seed at a subharmonic of the desired radiation output and can therefore generate a less noisy output photon pulse with full longitudinal coherence. The method of nonlinear harmonic generation provides the possibility of generating substantial photon powers at quite short wavelengths, while utilizing an electron bunch of lower energy and using one of the above methods. Finally, modular approaches to the next-generation light source provide the possibility of a coherent source in the x-ray regime based upon "stacked" or progressive modules of the above-described systems.

THE LOW-ENERGY UNDULATOR TEST LINE (LEUTL)

The low-energy undulator test line (LEUTL) of the APS is a test bed for the next generation of synchrotron light sources and is being configured to be an extreme ultraviolet user facility [4]. Its first experiment is an FEL based upon the SASE phenomenon and is currently tunable in wavelength from 660 to 130 nm. The repetition rate of the drive laser for the photocathode-rf gun is 6 Hz, which defines the repetition rate of the FEL. The FEL symbiotically (or epiphytically) shares with normal APS operations the injector (linear accelerator) necessary to produce the high-brightness beam required for high FEL gain. The APS linear accelerator has three electron guns: the photocathode-rf gun, used for LEUTL operation or storage-ring operation, and two thermionic-rf guns, used for storage-ring operation and for diagnostic check-out through the LEUTL line. The 2856-MHz APS linear accelerator is capable of accelerating electrons from the photocathode-rf gun to nearly 600 MeV [5,6], and incorporates a magnetic bunch compressor can compress the electron pulses down to a few hundred fs [7]. The chosen-energy electron beam is then transported through a transfer line from the linear accelerator to the LEUTL tunnel proper. There, a total of eight fixed-gap undulator devices, as well as various photon and electron beam diagnostics before the first and after every undulator thereafter, are employed by the FEL in the 50-m-long LEUTL hall. Each linearly-polarized undulator is 2.4 meters in length and uses ~160 permanent-magnet pole pieces to generate a undulator period of 3.3 cm. Beyond the LEUTL hall are additional diagnostics in an end-station area outside of the radiation enclosure. After first achieving "saturation" in September 2000 at both 530- and 385-nm wavelengths, we have been examining details of the FEL's performance such as z-resolved radiation spectra, nonlinear harmonic emission [8], and electron beam microbunching as evidenced by coherent transition radiation [9]. We have also recently pushed the FEL's operating wavelength down to 130 nm by increasing the electron beam energy. A typical peak power for FEL operation, for the case of 130 nm, is ~500 MW. The first LEUTL FEL user experiment will be installed in the next few months and will be discussed briefly in a later section. Results of this experiment are expected before December 2002. The LEUTL system is shown schematically in Figure 1.

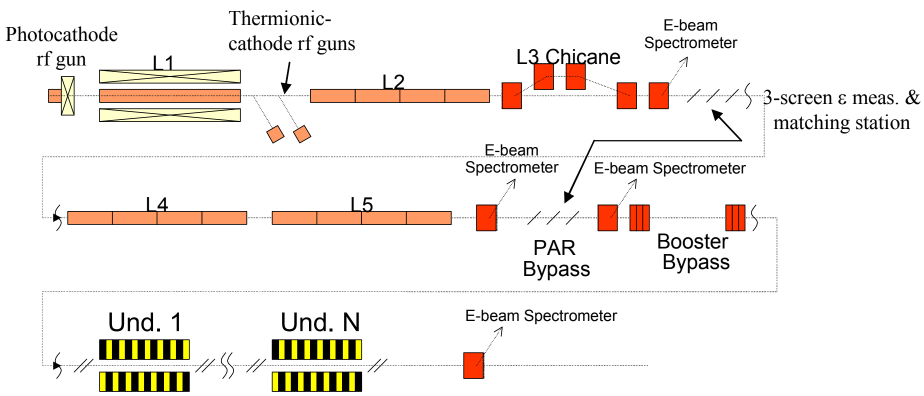

FIGURE 1. Schematic layout of the APS linac and undulator line of the LEUTL system.

LEUTL RESULTS

As described above, SASE devices have a random output component. It is therefore important to characterize the statistical fluctuations of the experimental data collected at the optical diagnostic located after each undulator [10]. Figure 2 shows one of the most basic LEUTL SASE measurements for an operational wavelength of 530 nm; optical energy as a function of distance along the LEUTL undulator line. The three lines represent the statistics of this system. The center line and square points indicate the 50th percentile of the optical energy, while the outlying lines represent the 25th and 75th percentiles of the optical intensity. These numbers are drawn from a sample size of 100 – 200 images per station. The nature of the intensity fluctuations clearly changes as the optical power saturates, as expected. In particular, the fluctuation becomes less and the 50th and 75th percentile lines become closer, as one would expect. After saturation, little additional power can be extracted, but the occasional "poor shot" can still result in a much lower than average intensity. This is also apparent in the statistics of the measured optical energy at each station. The crosses represent the normalized standard deviation of the output energy at each station. After saturation, the deviation dramatically decreases. The effects of electron beam jitter as well as SASE fluctuations affect this experimental data.

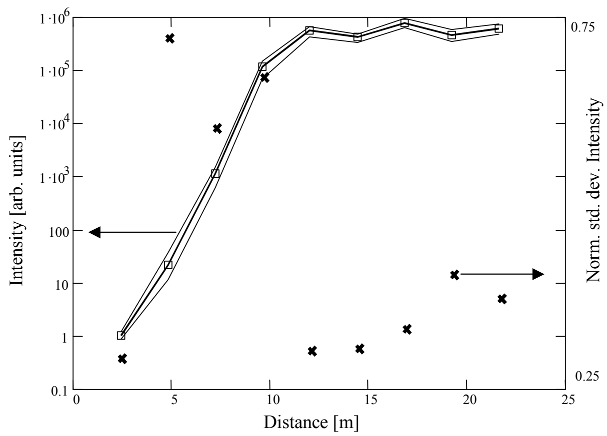

FIGURE 2. Measured optical intensity as a function of distance along the undulator line, normalized to the intensity at the first diagnostic station. The black crosses are the normalized standard deviations of the intensities measured at each diagnostic station. Electron beam properties are: peak current, 266 A; bunch length, 0.30 ps (rms); normalized emittance, 8.4 μm (rms); energy spread, 0.10% (rms). Theoretical gain length (power e-folding length) is 0.59 m, measured gain length is 0.57 m.

THE FIRST APS FEL USER EXPERIMENT

The first LEUTL user experiment is being led by Michael Pellin of the Chemistry Division at ANL [11]. This experiment will involve single photon ionization and resonant ionization to threshold (SPIRIT) and will use the high VUV pulse energy and tunable wavelength from LEUTL to uniquely study a few specific materials and systems. As an example, trace quantities of light elements (H, C, N, O) in semiconductors with 100 times lower detection limit than the current state-of-the-art can be investigated. In addition, LEUTL can facilitate the examination of organic molecules with minimal fragmentation to permit cell mapping by mass, polymer surface understanding, modified (carcinogenic) DNA mapping, and determination of photoionization thresholds. SPIRIT and LEUTL will also characterize the excited states of molecules, such as the cold wall desorption in accelerators and the sputtering of clusters. First results from SPIRIT are expected by December 2002. The setup of the SPIRIT experiment is shown in Figure 3.

EXOTIC NEXT-GENERATION LIGHT SOURCE CONCEPTS

A group of researchers has been meeting frequently since early 1998 to compare FEL simulation codes and discuss and develop exotic schemes to enhance the capabilities of next-generation light sources. Most recently we have discussed the possibility of enhancing the power of two wavelengths simultaneously using a bi-harmonic undulator [12] and the possibility of seeding with a soft x-ray FEL [13].

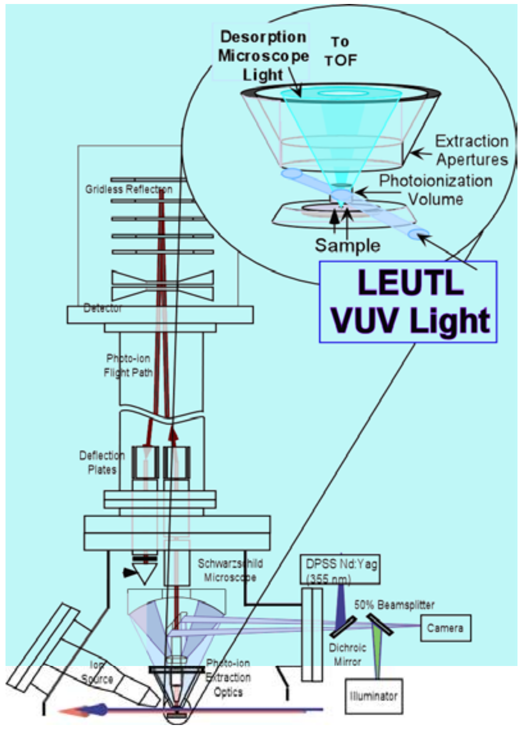

FIGURE 3. The SPIRIT experimental setup.

We performed a comparison of the high-gain FEL output from a biharmonic undulator, monoharmonic undulator, and two monoharmonic undulators in the TUHGS configuration. A biharmonic undulator has fields that are tuned such that the FEL emission is driven for a certain wavelength and a higher harmonic simultaneously. We examined three cases (monoharmonic, biharmonics, and TUHGS with monoharmonic undulators) and also a variation of the third case (TUHGS) by elongating the second undulator. The electron beam and undulator parameters of the cases can be examined in Table 1. In this presentation only the results of the code MEDUSA are shown (Table 2), although other cases were treated with other codes.

CONCLUSION

In summary, a next-generation light source would contain many of the following qualities, depending upon the needs of the users: tunable to ultrashort wavelengths, including the x-ray regime to 1.0 Å; full longitudinal coherence, full transverse coherence; ultra-short pulse durations (<100 fs); high peak powers; and as well as being as small and as cost effective as reasonably possible.

Table1: Electron beam and undulator parameters for the three cases.

Undulator type	Monoharmonic	Biharmonic	TUHGS
Electron beam energy (MeV)	935	1078	935
Normalized electron beam emittance (π mm mrad) [x,y]	1, 1	1, 1	1, 1
Electron beam peak current (A)	850	850	850
Energy spread (%)	0.05	0.05	0.05
Undulator(s) resonant wavelength	At fundamental only	At fundamental and third harmonic	First at fundamental only and second at third harmonic
Third harmonic undulator period (cm)	-na-	2.0	2.0
Peak magnetic field (kG)	1.767	1.767	First 1.767
Undulator period (cm)	6.0	6.0	6.0
Peak magnetic field (kG) of third harmonic undulator	-na-	5.301	Second 5.301
Fundamental wavelength (nm)	13.36	13.36	13.36
Third harmonic wavelength (nm)	4.45	4.45	4.45
Ninth harmonic wavelength (nm)	1.48	1.48	1.48

Table 2: Comparison of types of high-gain FELs

Type	Fundamental (14.45 nm)	Third (4.45 nm)	Ninth (1.48 nm)	Saturation z (m)	Energy (MeV)
Monoharmonic	398 MW	0.64 MW	50 kW	~60	935
Biharmonic (Perpendicular)	1270 MW	52 MW in y-pol.	5 kW	~60	1078
TUHGS (Undulator 1 ends at 63 m)	398 MW (z=63m)	0.424 MW (z=63m) 300 MW (z=84m)	0.373 MW (z=84m)	~80	935
TUHGS (Undulator 1 ends at 51 m)	11.8 MW (z=51m)	59.6 W (z=51m) 460 MW (z=74m)	0.15 MW (z=74m)	~74	935

Recently, there has been impressive progress made in the area of high-gain SASE FEL devices operating at wavelengths ranging from the near infrared to the far ultraviolet. The first experiment LEUTL [660-130 nm], the Tesla Test Facility (TTF) at DESY Hamburg [400-100 nm], and the Visible to Infrared SASE FEL (VISA) at Brookhaven National Laboratory (BNL) [840 nm] have demonstrated the single-pass, high-gain (SP HG) FEL using the SASE process to saturation [13-15]. In addition, a multistage method, the high-gain harmonic generation (HGHG) SP HG FEL was demonstrated [16] at BNL [5.3 microns] to saturation.

The LEUTL project was the first to demonstrate the SASE process to saturation in the tunable range from the visible to the VUV (660-130 nm). Currently, the first user experiment is being installed with the first results are expected by December 2002. Numerous beam and user proposals have been received and are currently under review.

Based upon theory and these recent experiments, a number of high-brightness, laser-like photon sources for users are being proposed. These light sources will operate from the ultraviolet to hard x-ray wavelength regimes and are based on the many methods of SP HG FELs. Some present proposals include LCLS-SLAC (0.15 nm, CDR prepared, first light 2008), TTF-2 (VUV user facility, 2004), TESLA/FEL DESY (0.1 nm, TDR complete), SCSS-SPring8 (> 2 nm, approved and funded), SDL-BNL (> 100 nm, reached saturation), SPARX-Italy (> 1 nm), and FERMI –Trieste.

ACKNOWLEDGMENTS

The work of S.G. Biedron, M. Borland, R. Dejus, M. Erdmann, Z. Huang, K-.J. Kim, J. Lewellen, Y. Li, A. Lumpkin, S.V. Milton, E. Moog, V. Sajaev, and G. Wiemerslage is supported at Argonne National Laboratory by the U.S. Department of Energy, Office of Basic Energy Sciences under Contract No. W-31-109-ENG-38. The activity and computational work for H. P. Freund is supported by Science Applications International Corporation's Advanced Technology Group under IR&D subproject 01-0060-73-0890-000. The activity of W.M. Fawley is supported at Lawrence Berkeley National Laboratory by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. The work of H.-D. Nuhn is supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Material Sciences, under contract No. DE-AC03-76SF00515. The work of R. Bartolini, F. Ciocci, G. Dattoli, G. Felici, P.L. Ottaviani, and A. Renieri is supported by ENEA the Italian Agency for New Technologies, Energy, and the Environment.

REFERENCES

1. See for example *Introduction to the Physics of FELs.* Laser Handbook, vol.6. Ed. W.B. Colson, C. Pellegrini, and A. Renieri. (Amsterdam:North Holland, 1990) and references 4-45 in S. G. Biedron, *Toward Creating a Coherent Next-Generation Light Source* (Alnarp, Sweden:Reproenheten, 2001).
2. See for example references 46-53 in in S. G. Biedron, *Toward Creating a Coherent Next-Generation Light Source* (Alnarp, Sweden:Reproenheten, 2001).
3. 10th ICFA, Workshop on 4th Generation Light Sources, ESRF, Grenoble, January 22-25, 1996.
4. S. V. Milton et al., originally published in Science Express as 10.1126/science.1059955 on May 17, 2001 and Science 292 (2001) 2037-2041.
5. S.V. Milton et al., Proc. SPIE **3614** (1999) 86.
6. S.G. Biedron, et al., “The Operation of the BNL Gun-IV Photocathode Gun at the Advanced Photon Source,” Proc. of the 1999 Particle Accelerator Conference (1999) pp. 2024-2026.
7. M. Borland, J. W. Lewellen, "Initial Characterization of Coherent Synchrotron Radiation Effects in the APS Bunch Compressor," Proceedings of the 2001 Particle Accelerator Conference, P. Lucas, S. Webber, 4, IEEE, (2001) pp. 2839-2841.
8. S.G. Biedron et al., "Measurements of Nonlinear Harmonic Generation at the Advanced Photon Source's SASE FEL," Nuclear Instruments and Methods in Physics Research A 483 (2002) 94.
9. A.H. Lumpkin et al., Phys. Rev. Lett. 88 (2002) 234801.
10. J.W. Lewellen et al., Nucl. Instrum. Methods A483 (2002) 40.
11. M. Pellin, private communication.
12. S.G. Biedron et al., Proc. SPIE 4632 (2002) 50-65.
13. S.G. Biedron et al., “Simulation of the fundamental and nonlinear harmonic output from an FEL amplifier with a soft x-ray seed laser,” Proceedings of 7th European Accelerator Conference (EPAC 2000), 26-30 June, Vienna (2000) 729.
14. V. Ayvazyan et al., Phys. Rev. Lett. 88 (2002) 104802.
15. A. Tremaine et al., Nucl. Instrum. Methods A483 (2002) 24.
16. L.-H. Yu et al., Science 289 (2000) 932.