DESIGN STUDIES FOR A VUV-SOFT X-RAY FEL FACILITY AT LBNL*

J.N. Corlett#, K.M. Baptiste, J.M. Byrd, P. Denes, R.W. Falcone, J. Feng, M. Graves, J. Kirz, D. Li, H.A. Padmore, C. Papadopoulos, G. Penn, J. Qiang, D.S. Robin, R. Ryne, F. Sannibale, R.W. Schoenlein, J.W. Staples, C. Steier, T. Vecchione, M. Venturini, W. Wan, R. Wells, R. Wilcox, J. Wurtele, LBNL, Berkeley, CA94720, U.S.A.
A. Charman, E. Kur, UCB, Berkeley, CA 94720, U.S.A.
A.A. Zholents, ANL, Argonne, IL 60439, U.S.A.

Abstract

Recent reports have identified the scientific requirements for a future soft x-ray light source and a high-repetition-rate FEL facility responsive to them is being studied at LBNL: the Next Generation Light Source (NGLS). The facility is based on a CW superconducting linear accelerator with beam supplied by a high-brightness, high-repetition-rate photocathode electron gun, and on an array of FELs to which the beam is distributed, each operating at high repetition rate and with even pulse spacing. Dependent on the experimental requirements, the individual FELs may be configured for either SASE, HGHG, EEHG, or oscillator mode of operation, and will produce high peak and average brightness x-rays with a flexible pulse format ranging from sub-femtoseconds to hundreds of femtoseconds. We are developing a design concept for a 10-beamline, coherent, soft x-ray FEL array powered by a 2.4 GeV superconducting accelerator operating with a 1 MHz bunch repetition rate. Electron bunches are fanned out through a spreader, distributing beams to an array of 10 independently configurable FEL beamlines with nominal bunch rates up to 100 kHz. Additionally, one beamline could be configured to operate at higher repetition rate.

INTRODUCTION

Several recent reports have identified the scientific requirements for a future soft X-ray light source [1, 2, 3], and a high-repetition-rate free-electron laser (FEL) facility responsive to them is being studied at Lawrence Berkeley National Laboratory (LBNL) [4]. The facility is based on a continuous-wave (CW) superconducting linear accelerator with beam supplied by a high-brightness, high-repetition-rate photocathode electron gun operating in CW mode, and on an array of FELs to which the accelerated beam is distributed, each operating at high repetition rate and with even pulse spacing. Dependent on the experimental requirements, the individual FELs may be configured for either self-amplified spontaneous emission (SASE), seeded high-gain harmonic generation (HGHG), echo-enabled harmonic generation (EEHG), or oscillator mode of operation, and will produce high peak and average brightness x-rays with a flexible pulse format ranging from sub-femtoseconds to hundreds of femtoseconds. This new light source would serve a broad community of scientists in many areas of research, similar to existing utilization of storage ring based light sources.

A NEXT GENERATION LIGHT SOURCE

The LBNL design concept for a NGLS is a 10-beamline, coherent, soft x-ray FEL array powered by a 2.4 GeV superconducting accelerator operating with a 1 MHz bunch repetition rate. Up to 1 nC electron bunches are fanned out through a spreader, distributing beams to an array of 10 independently configurable undulators and FEL beamlines with nominal bunch rates up to 100 kHz. A schematic of the accelerator layout is shown in Figure 1. The FELs may be seeded by optical lasers to control the X-ray output characteristics or may use SASE techniques, including generation of low-charge, high-brightness bunches with intrinsically short duration. Users specify the wavelength, pulse duration, and polarization, so that the 10 simultaneously operating beamlines can be individually optimized for specific experiments, including broad spectral coverage and multiple beam capability. The spectral range is from 10 eV to 1 keV, with harmonics to approximately 5 keV at reduced intensity. The beams are also synchronized with optical lasers or IR and THz sources for pump–probe experiments. Three principal modes of operation are proposed: ultrashort pulse (300 as–10 fs), short pulse (10 fs–100 fs), and high spectral resolution (requiring pulses from 100–500 fs). The spectral bandwidth in each mode is anticipated to approach fundamental transform limits. Other features include the capability to achieve high peak power (~1 GW) for nonlinear optics, control of peak power to reduce sample damage, and high average power (~1–10 W) for low-scattering-rate experiments. With 10 beamlines, the facility will be capable of serving ~2000 users per year. Figure 1 shows a schematic of the facility layout.

Electron Beam Delivery Systems

We have developed a baseline design for the accelerator part of the machine capable of delivering a 2.4 GeV beam with the required 6D brightness $\hat{B}_{6D} = 2I/(\varepsilon_{\perp}^{2}\sigma_{E})$. In the proposed design acceleration is provided by twenty 1.3 GHz TESLA-type superconducting rf modules operating in CW mode with 13.5 MeV/m average gradient. During compression, acceleration, and transport, a number of effects can degrade beam quality and spoil brightness, including transverse and longitudinal space charge, longitudinal wake fields, and coherent synchrotron radiation. We have investigated these effects extensively focusing primarily on what we believe is the

*Work supported by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231
#jncorlett@lbl.gov

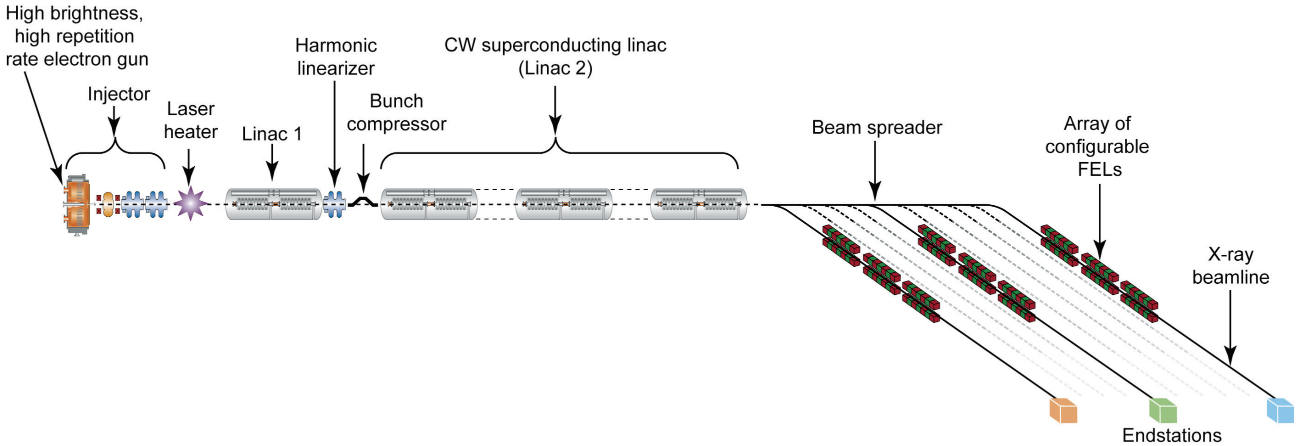

Figure 1: Schematic layout of the NGLS

most challenging mode of operation employing long (~500 fs), high-charge (~0.8 nC) bunches. Assuming a 60-70 A beam peak current at the exit of the injector, results of our studies [5] show that the required 1 kA peak current at the FEL beamlines can be obtained by magnetic compression through a single chicane while preserving a small transverse emittance (≤1 μm) and uncorrelated energy spread ($\sigma_E \approx 100$ keV).

One of the most delicate issues of beam dynamics is control of the microbunching instability, which could degrade longitudinal phase-space beam quality and prevent successful operation of a seeded FEL. High resolution macroparticle simulations [6] indicate that a laser heater arranged to generate a 5 keV energy spread allows the electron beam to maintain a reasonably smooth density profile through the end of the spreader while keeping the slice uncorrelated energy spread in the beam core below 100 keV.

FEL Design

A number of techniques have been developed for controlling FEL output, including the use of electron beams that are ultrabright, ultrashort-pulse, optically manipulated, or seeded [7]. A leading technique for a seeded FEL in our project is EEHG [8]. Recent studies [9] indicate that using this technique, one can reach X-ray wavelengths in the range of a few 100 eV beginning with an optical seed by performing two relatively simple acts of electron-beam manipulation using laser beams.

We continue to explore optical manipulation techniques that can provide exquisite control of the X-ray pulse, allowing novel and powerful experimentation opportunities. One approach we have developed [10] is to prepare pairs of attosecond-scale pulses at two different colors with a precisely controlled variable time delay to do stimulated X-ray Raman spectroscopy to address this need [11].

The high electron-bunch repetition rate in the NGLS offers an excellent opportunity for precision electron-beam diagnostics and use of broadband feedback loops. Simulating a wide variety of jitter sources, we find that feedback systems can reduce electron-bunch arrival-time jitter from 60 to 20 fs, and the electron-bunch energy jitter from 250 to 90 keV, which will greatly enhance seeded FEL and pump-probe capabilities.

Photocathode Design

A high repetition rate requires high quantum efficiency (QE) photocathodes that ideally operate in the optical or IR regimes [12]. We are investigating the use of the alkali antimonides, specifically K_2CsSb, as the basis for a high-rep-rate cathode. This material was used previously in photoinjectors, specifically in the Los Alamos–Boeing FEL [13], and achieved good performance at high average current. It was found to be efficient and reproducible in manufacture, but suffered from oxygen and water contamination that reduced QE over time. However, a 30-hr lifetime was achieved in an improved gun design with improved vacuum. The VHF gun design under development at LBNL (see below), with its high conductance and large pumping capacity, is designed to provide much better vacuum than existing rf guns and should give commensurately longer cathode lifetimes.

The great advantage of the alkali antimonides is that second harmonic light from a Yb (thin disk or fiber) laser can be used, greatly reducing laser complexity. We have produced films on a Mo substrate and measured QE of 7% at 532 nm (peak of 25% QE at 400 nm), and plan to demonstrate high average current and low transverse momentum. This work is carried out in a lab dedicated to photocathode production and characterization. The latter consists of measurements of QE as a function of energy, reflectivity, scattering, and angle-resolved photoemission for momentum measurements. While we believe that K_2CsSb is the ideal material, it is unproven under our precise conditions of QE and emittance, and so we also plan to investigate Cs_2Te as a backup option. This material, although now proven to achieve high QE and long lifetime, requires significantly higher laser power due to its UV threshold.

VHF Photo-gun

To meet the needs of a future high-repetition-rate FEL facility, LBNL is developing a VHF CW laser photocathode rf gun using a room-temperature copper cavity. The gun is designed to achieve three main goals—production of the high-brightness beam required by the FEL, compatibility with high-QE photocathodes requiring extremely low vacuum pressures, and the capability to operate at a high repetition rate with optimal performance. The choice of a CW VHF cavity operating at room temperature is expected to meet all the performance requirements simultaneously, based on preliminary beam dynamics studies [14]. The use of mature and robust VHF cavity technology overcomes the reliability challenges of other techniques while accommodating a variety of cathode materials and allowing a high accelerating gradient at the cathode at high repetition rate [15,16,17].

The core of such a gun is a normal-conducting cavity resonating at approximately 187 MHz. The frequency choice is compatible with both 1.3 and 1.5 GHz superconducting linac technologies, the most probable candidates for the main linac. Because of the low frequency, the structure is relatively large and the power density on the walls is small and compatible with CW operation using conventional water-cooling. Additionally, the long wavelength allows for the large high-conductance vacuum ports necessary for achieving the desired vacuum pressure. Most of the cavity is made of solid OFHC copper externally supported by stainless steel flanges. Cooling channels are machined into areas of highest heat load, and cooling tubes are provided for other areas. The vacuum system is designed to achieve a pressure into the low 10^{-11} Torr range when operating at the nominal power.

The VHF cavity is currently under construction, and the VHF tetrode power supply is being procured from a commercial vendor. Preparation of the shielded area for housing the photoinjector has started, and initial rf conditioning followed by tests of gradient and vacuum conditions are planned for summer and fall 2010.

Timing and Synchronization Systems

LBNL staff are developing timing distribution systems for synchronization of rf plants and/or lasers in short-pulse FEL facilities [18,19,20]. We have installed and are developing a timing system that will synchronize pulsed lasers to the electron-bunch arrival time in the LCLS, and another system that will deliver a stable rf reference to the low-level rf system in the FERMI@elettra FEL at Sincrotrone Trieste. The scheme used for both systems is to modulate S-band rf (~3 GHz) onto a single-frequency, wavelength-stabilized laser signal delivered over fiber optics and to receive the rf on a photodiode. Changes in fiber length are monitored by an interferometer that uses the same laser signal and provides information to a digital phase shifter at the receiver. The received rf is digitized and numerically phase shifted in proportion to the interferometer data on fiber length. This phase-shifted signal can be compared with a local oscillator or with a pickup from an accelerating cavity to generate an error signal for control [21]. All components are standard fiber telecom, microwave, and digital parts.

Tests have been made of a dual-channel transmitter/receiver set with different fiber lengths in the two channels. The relative rms temporal stability over 60 hours was 19.4 fs with 2.2 km in one channel and 2 m in the other. With 200 m in one channel and 2 m in the other, the rms stability over 20 h was 8.4 fs. Specifications are 50 fs rms for FERMI@Elettra and 100 fs for LCLS, both requiring about 200-m fiber runs, so we are able to meet these with some margin.

REFERENCES

[1] http://www.sc.doe.gov/bes/reports/list.html

[2] http://www.als.lbl.gov/als/publications/genpubs.html

[3] https://hpcrd.lbl.gov/sxls/home.html

[4] J. Corlett et al., "Design Studies for a VUV–Soft X-ray Free-Electron Laser Array", *Synchrotron Radiation News* **22**, No. 5, 25 (2009).

[5] E. Kur, *et al., LBNL Report* LBNL-2670E (2009).

[6] J. Qiang *et al., Phys. Rev. ST Accel. Beams* **12**, 100702 (2009).

[7] W.A. Barletta, et al., *Nucl. Instr. and Meth. A* (2010), doi:10.1016/j.nima.2010.02.274 (in press)

[8] G. Stupakov, *Phys. Rev. Lett.* **102**, 074801 (2009).

[9] D. Xiang and G. Stupakov, *Proc. PAC09*, paper WE5RFP028 (2009).

[10] A. Zholents and G. Penn, *Nucl. Instrum. Methods Phys. Res., Sect. A* **612**, 2, (January 2010)

[11] I. V. Schweigert and S. Mukamel, *Phys. Rev. A* **76**, 01250 (2007).

[12] D.H. Dowell,et al., *Nucl. Instrum. Methods Phys. Res., Sect. A* (2010), doi:10.1016/j.nima.2010.03.104 (in press)

[13] D. H. Dowell et al., *Nucl. Instrum. Methods Phys. Res., Sect. A* **356**, 167 (1995).

[14] K. Baptiste et al., *Nucl. Instrum. Methods Phys. Res., Sect. A* **599**, 9 (2009).

[15] J. Staples et al., *Proc. EPAC04*, paper MOPKF069 (2004).

[16] J. Staples et al., "VHF-band photoinjector," CBP Tech. Note 366 (October 2006).

[17] K. Baptiste et al., *Proc. PAC09*, paper MO6RFP077 (2009).

[18] R. B. Wilcox et al., *Proc. PAC05*, paper RPAT075 (2005).

[19] R. B. Wilcox and J. W. Staples, *Proc. PAC07*, paper FROAC05 (2007).

[20] R. B. Wilcox and J. W. Staples, *Proc. CLEO 2007*, paper CThHH4 (2007).

[21] J. W. Staples et al., *Proc. LINAC08*, paper THP118 (2008).