Status of the LBL experiment on femtosecond X-ray generation through 90° Thomson scattering *

W. Leemans, S. Chattopadhyay, M. Conde, E. Glover, K.- J. Kim, R. Schoenlein, and C. V. Shank
Lawrence Berkeley Laboratory
1 Cyclotron Road, Berkeley, CA 94720 USA

Abstract

A status report on the generation of femtosecond X-ray pulses through 90° Thomson scattering is presented. The experiment involves a relativistic electron beam (tunable from 25 - 50 MeV) with a bunch length of 10 ps containing 1 -2 nC, and a ultrashort pulse (50 - 200 fs), high power (4 TW) 0.8 μm Ti:Al_2O_3 laser system. Both beams are focussed down to about a 50 μm waist size and intersect at 90°. The laser field acts as an electromagnetic undulator for the relativistic electron beam generating radiation upshifted by 2 γ^2 and a pulse length given by the transit time of the laser beam across the electron beam. For a 50 MeV electron beam we expect 10^5 photons at 0.4 Å (10% bandwidth) in a cone angle of 6 mrad in a 170 fs pulse.

I. INTRODUCTION

A scientific frontier of utmost importance to studies of all ultrafast phenomena and of immediate relevance to basic and industrial apllications in surface, material, chemical and biological sciences, is the generation and use of femtosecond x-ray pulses. Such a source will allow direct measurements of the structure of materials on a time scale comparable to a vibrational period, i.e time resolve atomic motion. This will provide valuable information about the properties of novel materials as well as important chemical and biological reactions occurring on ultrafast time scales.

Our goal is to develop and test a technically feasible concept and the associated technology for the production of ultrashort x-ray pulses with a performance reach to the regime of 1 Å, 30 fs and 10^{12} photons/s, which we believe will have wide-scale scientific and industrial utility. The proposed approach consists of generating femtosecond x-ray pulses via right angle Thomson scattering [1] a near-infrared, terawatt femtosecond laser against a moderate energy (30 - 50 MeV) tightly focussed electron beam.

The interaction of laser beams and relativistic electron beams has also gained great importance for high energy physics : γ - γ colliders will rely on high power lasers scattering off relativistic electron beams; laser based diagnostics have been proposed and developed [2] to determine the transverse and longitudinal properties of electron beams at the final focus in high energy colliders.

II. LASER UNDULATORS

Using a laser beam as an electromagnetic undulator has been proposed in the early 60's by Milburn and Arutyunian and V.A. Tumanian [3]. Subsequently experiments on synchrotrons [4], linacs [5] and storage rings [6] were reported. In those original experiments the photon flux was typically extremely low. The availability of chirped pulse amplification (CPA) [7] based compact terawatt lasers renewed the interest in the use of lasers as undulators and spawned lots of theoretical work on laser undulator based light sources (backscatter geometry) and non-linear Thomson scattering [8]. In the backscattering geometry the pulse length is determined by the longer of the laser or electron pulse (typically the latter). Femtosecond x-ray pulses can be generated by using femtosecond laser pulses and colliding them with a relativistic electron beam at 90°.[1] In this geometry the x-ray pulse length is determined by the longer of the laser pulse and the transit time of the laser beam across the electron beam waist. The generic set-up is shown in Fig. 1.

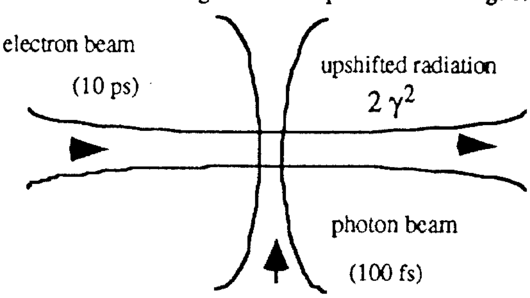

Figure 1: A generic lay-out of the 90° x-ray generation experiment. The laser beam is upshifted by $2\gamma^2$ and propagates in the direction of the electron beam.

X-ray sources based on the interaction of terawatt laser pulse with solids have recently demonstrated high efficiency in the sub-keV region.[9] However, the efficiency rapidly decreases for higher energy x-ray radiation and plasma dynamics may prevent femtosecond pulse lengths. Harmonic generation in gases [10] has been shown to produce highly directional and coherent light with duration on the order of the incident pulse. The shortest wavelength generated to date is however is on the order of 100 Å with efficiencies on the order of 10^{-11}. Third generation light sources such as ALS [11] generate high brightness, high power, tunable x-ray radiation but pulse lengths are typically 30 - 40 ps.

III. ORTHOGONAL THOMSON SCATTERING

3.1 Theoretical properties

An estimate of the laser and electron beam requirements can be made using a simple Thomson scattering model :

$$\#\text{X-rays /pulse} = \frac{\#\text{incident photons/pulse}}{\text{cm}^2} \cdot \sigma_T \cdot n_e \cdot \frac{\sigma_L}{\sigma_e},$$

* This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

where σ_T is the Thomson cross-section. For typical electron beam parameters (1 nC/bunch, bunch length σ_e about 10 ps) and laser beam parameters (pulse length σ_L of 150 fs, 150 mJ/pulse) and matching the transverse electron beam size (i.e. transit time) to the laser pulse length we estimate to produce 10^5 x-rays per pulse. We next determine the properties of the scattered radiation.

The frequency of the upshifted radiation can easily be calculated from energy and momentum conservation:

$$\omega_r = \frac{\gamma_{eff}\,\omega_o}{\gamma_{eff}(1-\beta\cos\theta) + \frac{\hbar\omega_o}{mc^2}(1-\sin\theta)} \qquad (2)$$

and

$$\gamma_{eff} = \frac{\gamma}{\sqrt{1+K^2/2}} \qquad (3)$$

Here β and γ are the normalized velocity and Lorentz factor, K the wiggler strength, θ the angle of observation, ω_o the incident laser frequency, c the speed of light, m the electron rest mass. The wiggler strength is given by

$$K = \frac{25.6}{c[cm/s]}\sqrt{I[W/cm^2]}\,\lambda[\mu m] \qquad (4)$$

where I is the incident laser intensity and λ the wavelength. In our experiment the Compton shift can be neglected and θ and K are small so that Eqn. (2) reduces to

$$\omega_r \cong \frac{2\gamma^2\omega_o}{1+K^2/2+\gamma^2\theta^2} \qquad (5).$$

The number of photons per pulse, taking into account the proper Gaussian temporal and spatial profiles of both the electron and laser beam can be found from:[1]

$$\Delta n = \pi\alpha K^2 N_{eff} n_e \frac{\Delta\lambda}{\lambda}\frac{\sigma_w\sqrt{\sigma_w^2+\sigma_L^2}}{\sqrt{(\sigma_x^2+\sigma_w^2)(\sigma_z^2+\sigma_x^2+\sigma_w^2+\sigma_L^2)}} \qquad (6)$$

Here N_{eff} is the effective number of undulator periods with which the electron beam interacts:

$$N_{eff} = \frac{2\sqrt{\pi}}{\lambda_L}\frac{\sigma_w\sigma_L}{\sqrt{\sigma_w^2+\sigma_L^2}} \qquad (7).$$

The x-ray pulse duration is then given by (for $\sigma_z >> \sigma_x$)

$$\tau_x = \frac{\sqrt{\sigma_x^2+\sigma_w^2+\sigma_L^2}}{\sqrt{1+\frac{(\sigma_x^2+\sigma_w^2+\sigma_L^2)}{\sigma_z^2}}} \qquad (8)$$

with σ_x, σ_z the transverse and longitudinal electron beam sizes and σ_w , σ_L the laser transverse and longitudinal laser beam sizes (microns). Further simplication of Eqn.(6) leads to

$$\Delta n = 113\frac{\Delta\lambda}{\lambda}J n_e\frac{\lambda_L}{\sqrt{(\sigma_x^2+\sigma_w^2)(\sigma_z^2+\sigma_x^2+\sigma_w^2+\sigma_L^2)}} \qquad (9)$$

where J is the laser energy in Joules. The number of photons/electron within a given bandwidth is therefore independent of γ whereas the energy efficiency increases with γ.

The spectral width within a cone of half angle θ is

$$\frac{\Delta\omega}{\omega} \cong \gamma^2\theta^2 \qquad (10)$$

Bandwidth broadening is caused by a variety of mechanisms:

(a) finite interaction length broadening $\left.\frac{\Delta\omega}{\omega}\right|_i \cong \frac{1}{N_{eff}}$

(b) energy spread broadening $\left.\frac{\Delta\omega}{\omega}\right|_E \cong 2\frac{\Delta\gamma}{\gamma}$

(c) finite emittance broadening $\left.\frac{\Delta\omega}{\omega}\right|_\varepsilon \cong \gamma^2\theta^2 = \frac{\varepsilon_n^2}{\sigma_x^2}$ and

(d) laser bandwidth broadening $\left.\frac{\Delta\omega}{\omega}\right|_{\sigma_L} \cong \frac{\Delta\omega_o}{\omega_o} = \frac{4\ln 2\lambda_L}{2\pi\sigma_L}$.

Here ε_n is the normalized emittance. The total broadening is then

$$\left.\frac{\Delta\omega}{\omega}\right|_T = \sqrt{\left(\left.\frac{\Delta\omega}{\omega}\right|_i\right)^2+\left(\left.\frac{\Delta\omega}{\omega}\right|_E\right)^2+\left(\left.\frac{\Delta\omega}{\omega}\right|_\varepsilon\right)^2+\left(\left.\frac{\Delta\omega}{\omega}\right|_{\sigma_L}\right)^2} \qquad (11)$$

3.2 Experimental parameters

The current experiment at LBL involves the use of a 30 - 50 MeV electron beam and a terawatt Ti:Al_2O_3 laser system in the Beam Test Facility (BTF)..

The BTF, operated under the auspices of the Center for Beam Physics in support of its experimental R&D program, has recently been constructed. The details of the design of the transport line have been reported previously [12]. The commissioning phase of the line is nearing completion. The ALS linac parameters are given in Table 1. The lay-out of the BTF-line is shown in Fig. 2

Maximum Energy	50 MeV
Charge	1-2 nC/bunch
Bunch Length (σ_z)	10-15 ps
Emittance rms (unnorm)	0.3 mm-mrad
# bunches/macropulse @ 125 MHz	1 - 10 (max 100)
Macropulse rep. rate	1 - 10 Hz

Table 1: ALS Linac parameters

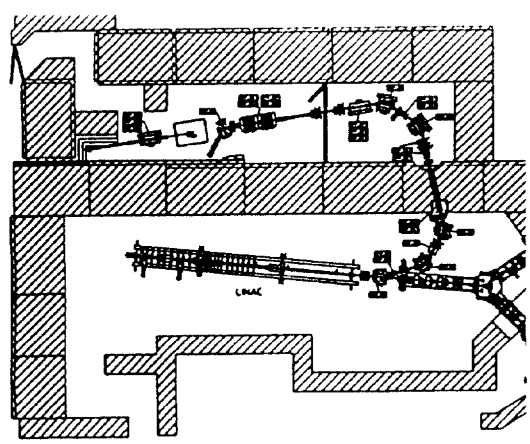

Figure 2: CAD lay-out of the BTF-line

The line has been designed to allow a variety of experiments to be carried out. A wide range of diagnostics have been built and implemented to allow full characterization of the electron beam. These include integrating current transformers for charge measurement, high bandwidth beam position monitors, fluorescent screens for transverse beam analysis and an optical transition radiation (OTR) diagnostic system [13]. The OTR system allows single bunch measurement of beam emittance, energy, charge and bunch length.

The electron beam will be focussed down to a spot size of 35 μm using a telescope consisting of two quadrupole triplets. The large bore (6") of the final magnet allows for small f-number focussing and reduces Bremsstrahlung production by beam halo scraping against the beam pipe. A 60° H-magnet separates the particle and photon beams after the interaction point.

The main laser system parameters are listed in Table 2. The passively Kerr lens modelocked $Ti:Al_2O_3$ laser oscillator operates at 62.5 MHz (8^{th} subharmonic of the ALS 500 MHz linac masterclock frequency). We have achieved RF locking of the laser oscillator to a 500 MHz RF clock with timing jitter performance better than 2 ps.

Wavelength	0.8 μm
Energy/pulse	175 mJ
Pulse length	50 - 200 fs
Repetition rate	10 Hz
Timing jitter with RF	< 2 ps

Table 2: Laser system parameters

The x-ray source parameters are given in Table 3. The parameters have been calculated using Eqns. (5) and (7) through (11) with electron and laser beam parameters from Tables 1 and 2.

Wavelength (Å)	0.4 (1.2)
Pulse length (fs)	200
# photons (10 % bandwidth)	1.3×10^5
Full angle cone (mrad)	6 (11)
Bandwidth (%)	80 %
Brightness photons/(s $mm^2 mrad^2$ 0.1 % bandwidth)	1.7×10^{19}

Table 3: x-ray source parameters. The wavelength and cone angle values refer to electron beam energies of 50 MeV and 30 MeV respectively.

The laser and e-beam alignment tolerances put tight constraints on the shot-to-shot movement of the beam in the transverse and longitudinal directions. The effect of current ripple in the supplies powering the bend magnets and the quadrupoles on the beam dynamics has been studied previously and requires current stability of a part in 10^4. [12]

3.3 X-ray diagnostics

A variety of x-ray diagnostics will be implemented to measure wavelength, beam size and divergence, pulse length and polarization.

A 75 μm Be-foil isolates the beam line high vacuum from the x-ray diagnostic systems. Detailed calculations have been performed to estimate the required amount of shielding to reduce the background x-ray level, caused by the close proximity of the beam dump to the x-ray diagnostic, below 10 photons/cm^2 (total spectrum). Spatial filtering with a tapered lead cone pointing at the laser electron beam interaction volume will reduce the number of Bremsstrahlung x-rays co-propagating with the beam.

Spatial properties of the X-ray beam (spot size and divergence) will be measured using a slow scan CCD camera looking at a P-11 phosphor screen. The photon energy will be determined by using Si(Li) detectors and operating an X-ray CCD camera in a single photon regime. For initial pulse length measurements the transit time will be lengthened by changing the horizontal focussing strength of the quadrupoles, allowing the use of a diamond photodiode as well as an X-ray streak camera. A coincidence technique between the X-ray pulse and an optical pulse in a gas jet will be used to measure shorter pulse durations. In the absence of the laser, photo electrons will be produced in a Kr gas jet by x-rays with energy about 500 eV higher than the K-shell energy of Kr-gas (14.3 keV). If the laser pulse arrives simultaneously with the x-ray pulse, the x-ray photo electrons will acquire an additional drift velocity component whose magnitude and direction depends on the phase and amplitude of the laser field at which the photo electron is born and the relative polarization of the laser with respect to the x-rays. The temporal overlap between the two pulses will therefore determine the emitted x-ray photo electron spectrum.

VI. Summary

A status report has been given of the planned orthogonal Thomson scattering experiment at the BTF. Based on simple scaling laws we have calculated that about 10^5 x-ray photons will be produced. Both the electron beam line and the laser system have been completed. Integration of both systems is planned to occur during the summer of '94.

VII. Acknowledgments

The authors wish to thank the ALS personnel for their outstanding efforts in the construction of the Beam Test Facility, and M. de Loos, R. Govil and B. vander Geer for their help during BTF commissioning.

VIII. References

[1] K.- J. Kim et al., NIMA 341, 351 (1994).
[2] T. Shintake, NIMA 453 (1992).
[3] R. H. Milburn, Phys. Rev. Lett. 10, 75 (1963); F. R. Arutyunian and V.A. Tumanian, Phys. Lett. 4, 176 (1963).
[4] O. F. Kulikov et al., Phys. Lett. 13, 344 (1964); C. Bemporad et al., Phys. Rev. 138, B1546 (1965).
[5] C. K. Sinclair et al., IEEE Trans. Nucl. Sci. NS-16, 1065 (1969)
[6] L. Federici et al., Nuovo Cim. B59, 247 (1980); Yamazaki et al., IEEE Trans. Nucl. Sci. NS-32, 3406 (1985).
[7] G. Mourou and D. Umstadter, Phys. Fluids B4, 2315 (1994) and many references therein.
[8] E. Esarey et al., Phys. Rev E 48, 3003 (1993) and many references therein.
[9] M. M. Murnane et al., Science 251, 531 (1991).
[10] A. l'Huillier and P. Balcou, Phys. Rev. Lett. 70, 774 (1993).
[11] "1-2 GeV Synchrotron Radiation Source", Conceptual Design Report, LBL-PUB 5172 Rev., 1986.
[12] W. Leemans et al., Proc. 1993 Part. Accel Conf, 83 (1993).
[13] M. de Loos et al., these proceedings