THOMSON SCATTERING OF INTENSE FEMTOSECOND LASER FROM RELATIVISTIC PLASMA-ACCELERATED ELECTRON BUNCHES

N. Hafz*, C.B.Kim, G.H. Kim, H. Suk
Center for Advanced Accelerators, KERI, Seongju-Dong 28-1, Changwon, 641-120, Korea
Jongmin Lee
Advanced Photonics Research Institute, K-JIST, Oryong-dong 1, Buk-gu, Gwangju 500-712, Korea

Abstract

We propose a novel experimental scheme for a compact and tunable x-ray source capable of producing x-ray pulses as short as few tens of femtoseconds. It is based on the Thomson back scattering of a terawatt femtosecond laser from relativistic plasma-accelerated electrons. Here we present particle-in-cell simulations for the ultrashort e-beam generation from the laser-wakefield accelerator utilizing a plasma density transition and the basic characteristics of x-ray generation. A plan to perform the proposed experiment by using a 20 TW 40 fs laser system is presented.

INTRODUCTION

Sub-100 femtosocond (fs) x-rays is an important tool for ultrafast science because fs x-rays can be used to visualize the ultrafast phenomena and intermediate states, for example, in semiconductor surfaces and protein molecules. Thomson scattering is currently the most promising method for generating fs hard and soft x-rays [1], [2]. Ultrashort x-rays produced from the Thomson scattering have attractive properties such as, good directionality, high brightness, and wavelength tunability. A scheme for an ultrashort x-rays based on the scattering of intense laser pulse off a SM (self-modulated)- LWFA electron beam and optically-injected electrons has been proposed in Ref.[3, 4]. In this work, we propose the usage of the self-injected (SI) LWFA electron beams as an electron source instead of the SM-LWFA beams for performing the Thomson scattering. The SI-LWFA utilizing a sharp density transition can produce a relatively small energy-spread electron beams. Two-dimensional (2-D) simulation for the SI-LWFA is presented. We also present the x-ray generation characteristics based on the proposed scheme and a future experimental plan.

PRODUCTION OF FEMTOSECOND ELECTRON BEAMS

Now we study the trapping and acceleration of plasma electrons in the wake of an intense laser pulse when it crosses sharp density transition, $k_p l << 1$, where k_p and l are the wavenumber of the wake wave and the scale length of the density gradient, respectively [5],[10]. Two-dimensional particle-in-cell (PIC) simulations with OSIRIS code [6] were performed for this study. The simulation parameters are: 20 TW peak laser power with, pulse duration of 60 fs, wavelength λ of 800 nm, and beam diameter of 19 μm, respectively. The laser pulse propagates through a downward density transition, of which the density changes from $n_e^I = 5 \times 10^{18} cm^{-3}$ to $n_e^{II} = 3 \times 10^{18} cm^{-3}$ in the form of a step function. Figures 1 and 2 show the simulation results, in which the laser pulse is propagating to the right direction through the plasma. Figure 1 shows that a nonlinear laser wake wave is generated behind the laser pulse and a significant amount of background plasma electrons are self-injected into the acceleration phase of the first period in the wakefield when the wave passes the sharp density transition. Figure 2 shows the self-trapped electrons in the first period of the wake wave have an ultrashort duration of about 25 fs. Some of these elec-

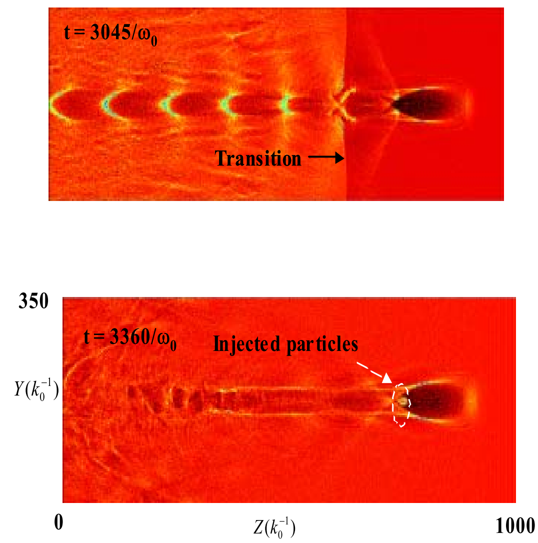

Figure 1: Position plots (y, z) of the plasma electrons at $t = 3045/\omega_0$ and, $t = 3360/\omega_0$ respectively, which corresponds to during and after the wake wave crosses the density transition. In the plots ω_0 and k_0 are the laser light frequency and wavenumber, respectively.

* nasr_hafz@yahoo.com

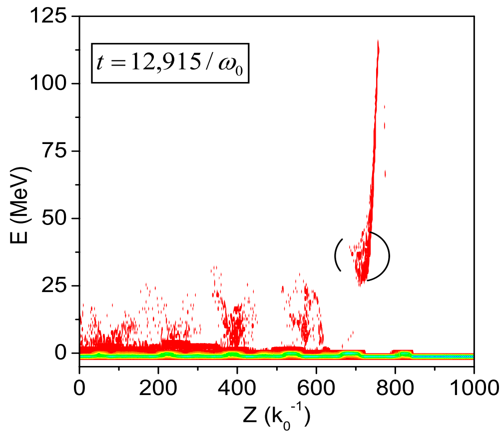

Figure 2: Background plasma-electrons energy ($E = cP_z$) versus z at $t = 12915/\omega_0$. Some electrons gained energies up to 115 MeV, however the majority of accelerated electrons having a rather narrow range between 30 and 50 MeV.

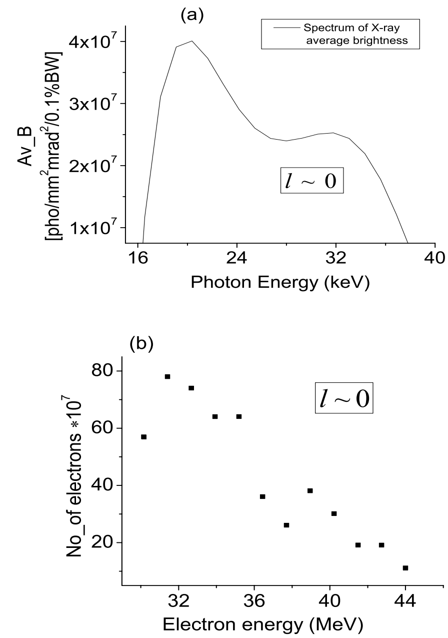

Figure 3: (a) Average brightness vs photon energies for an ultrashort x-rays emission via the Thomson scattering of a 0.5 TW laser from the electron bunch (produced in the 2-D simulation) with energy spectrum shown in (b)

trons gained energies up to 115 MeV over a distance of about 3 mm. The rms (root-mean-squared) energy spread of all trapped electrons produced at the density transition is 40%. The bunch (surrounded by circle) has rms energy spread of 15 %. The total number (following [7]) of electrons = 7.9$\times 10^9$, where 6 $\times 10^8$ electrons are inside the circle. After the beam is emitted from the plasma, its divergence angle and emittance are increased due to space charge force. In simulations, we found the e-beam radius $\sim r_b$= 10 μm after propagating 200 μm in vacuum, therefore the electron beam emittance is 20 $mm.mrad$.

FEMTOSECOND X-RAY CHARACTERISTICS

In this section, we present the x-ray emission characteristics when a tightly focused terawatt laser is backscattered from a counter-streaming relativistic electron bunch produced from the LWFA. Due to the large electron beam divergence, it is necessary that the interaction occurs just after the electron beam is emitted from the plasma, within 200 microns from the plasma, for example. The electron beam and laser beam parameters are summarized in Table.1 It is known from the theory of Thomson backscattering that only odd-harmonics are finite, but even harmonics vanish [8]. Furthermore, for modest power lasers $a_0^2 << 1$, only the fundamental harmonic (n =1) is significant, where a_0 is normalized vector potential of the laser beam. For an electron bunch with an energy spread of $\Delta E_{rms}/\bar{E}$ <<1 and for a narrow distribution in beam

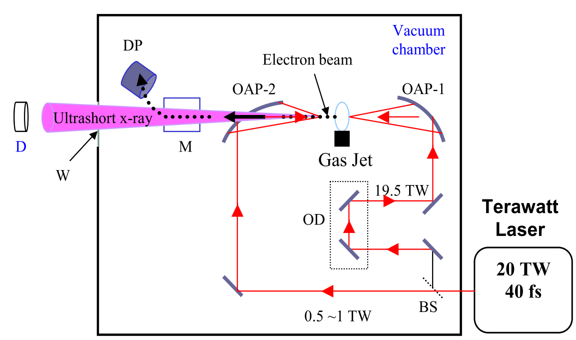

Figure 4: Schematic of a planned experiment for fs x-ray generation by the Thomson scattering. BS- beam splitter, DP- beam dump, D- detector, M- magnet, OD- optical delay, W- window.

angle with spread $\theta_b = \epsilon_n/\gamma_0 r_b << 1$, estimates for the x-ray flux and brightness were derived in Ref.[8]. Using the following formula, the average scattered photon energy is ~ 26 keV,

$$E_{photon}\,[keV] = \frac{0.019 E_b^2\,[MeV]}{(1 + a_0^2/2)\,\lambda\,[\mu m]}. \qquad (1)$$

Table 1: The laser and electron beam parameters at the IP.

Electron bunch produced from LWFA	Laser pulse
Average energy $E = 37MeV$	Power = 0.5 TW
rms Energy spread $\sim 15\%$	Pulse duration $\tau_L = 60fs$
Bunch length $\tau_b = 17fs$	λ= 800 nm
Beam charge $Q = 100pC$	Spot radius $r_0 = 5\mu m$
Bunch radius (at IP) $r_b = 10\mu m$	$a_0 = 0.7$

where E_b is the electron beam average energy. The x-ray wavelength can be tuned over a wide range of x-ray spectrum, from soft to hard x-ray simply by changing the main laser power. The peak photon flux within the cone $\theta_c \sim 1/\sqrt{L_0}\gamma_0 = 0.27\ mrad$ is F= 1×10^{19} photon/sec within a 0.1 % BW (bandwidth). We have assumed that the interaction length is equal to the laser pulse length $L = c\tau_L \sim 18\mu m$. The peak photon brightness is $B_{pk} = 6.25 \times 10^{17}$ photon/sec/$mm^2mrad^2/0.1\%BW$. The average brightness $Av_B = B_{pk}\tau_x f_{rep}$ versus the photon energies are shown in Fig. 3. A repetition rate of $f_{rep} = 10Hz$, an x-ray pulse duration of $\tau_x = 60fs$ and a collection angle of 1 $mrad$ were assumed.

FUTURE EXPERIMENT

An experiment for the Thomson back-scattering is planned in a collaboration between KERI and K-JIST, so the scheme shown in Fig. 4 is proposed. Tabletop 20 TW 40 fs Ti:sapphire laser system will be available at K-JIST soon [9]. The LWFA experiment will be performed and the e-beam generation will be characterized. Then the Thomson scattering experiment will be performed as briefly described here; a beam splitter will split the laser beam into two beams: 19 TW beam for electron beam generation and 1 TW beam for the x-ray generation. The synchronization between the 1 TW laser and the electron beam can be achieved by an optical delay. After the interaction, x-rays and electrons will pass through a small hole in the OAP-2.

REFERENCES

[1] R.W. Shoenlein et al., Science **274**, 236 (1996).

[2] W.P. Leemans et al., IEEE Jour, of Quant. Elec. **33**, 1925 (1997).

[3] E. Esarey et al., "Proceedings of the 21st ICFA Beam Dynamics Workshop on Laser-Beam Interactions, 11-15 June 2001, Stony Brook NY".

[4] P. Catravas et al., Meas. Sci. and Technol. **12**, 1828, (2001).

[5] H. Suk et al., to be published in J. Opt. Soc. Am. B.

[6] R. G. Hemker et al., "Proceedings of the 1999 PAC", edited by A. Luccio and W. MacKay (IEEE, New York, 3672, (1999).

[7] R. Hemker et al., Phys. Rev. E. **57**, 5920, (1998).

[8] E. Esarey et al., Phys. Rev. E., **48**, 3003, (1993).

[9] Do-Kyeong Ko and Jongmin Lee, " Korea Conference on Innovative Science and Technology-2003" FemtoScience and Technology-Future Implications. Nov. 2-5, 2003, Jeju, Korea.

[10] H. Suk et al, Phys. Rev. Lett., **86**, 1011 (2001).