Generation of Attosecond x-ray pulse using Coherent Relativistic Nonlinear Thomson Scattering

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1. Introduction

Relativistic plasma, a new regime in physics, has been opened due to the development in ultra-intense laser technology during the past decade [1,2]. Not only the fundamental aspect of relativistic plasma are attractive but also its potential application seems to be significant especially in the area of the generation of high energy particles such as electrons, ions, positrons, and γ-rays [3]. The generation of x-ray radiation with a pulse width of sub-femtoseconds presently draws much attention because such a radiation allows one to explore ultra-fast dynamics of electrons and nucleons.

Several schemes have been proposed and/or demonstrated to generate an ultra-short x-ray pulse: the relativistic Doppler shift of a backscattered laser pulse by a relativistic electron beam [4-6], the harmonic frequency upshift of a laser pulse by relativistic nonlinear motion of electrons [6-15], high order harmonic generation in the interaction of intense laser pulse with noble gases [16-19] and solids [20-21] The train of a few 100 attosecond pulses has been observed in the case of laser-noble gas interaction [17-19].

When a low-intensity laser pulse is irradiated on an electron, the electron undergoes a harmonic oscillatory motion and generates a dipole radiation with the same frequency as the incident laser pulse, which is called Thomson scattering. As the laser intensity increases, the oscillatory motion of the electron becomes relativistically nonlinear, which leads to the generation of harmonic radiations, referred to as Relativistic Nonlinear Thomson Scattered (RNTS) radiation. The motion of the electron begins to be relativistic as the following normalized vector potential approaches to unity:

$$a_o = 8.5\times 10^{-10}\lambda I^{1/2}, \qquad (1)$$

where λ is the laser wavelength in μm and I the laser intensity in W/cm^2

The RNTS radiation has been investigated in analytical ways [6-11]. Recently, indebted to the development of the ultra-intense laser pulse, experiments on RNTS radiation have been carried out by irradiating a laser pulse of 10^{18}-10^{20} W/cm^2 on gas jet targets [12-15]. A numerical study in the case of single electron has been attempted to characterize the RNTS radiation [10] and a subsequent study has shown that it has a potential to generate a few attosecond x-ray pulse [11].

The main property of RNTS radiation is believed to be incoherent. However to maintain the ultra-short characteristics of RNTS by a single electron, all the scattered radiations from a plasma should be coherently superposed, that is, the radiation intensity should increase quadratically on electron density. This motivation has led us to a condition for a coherent superposition of RNTS radiations from a plasma. The numerical simulations on this condition have been conducted and revealed that for an ultra-thin solid target, the characteristics of the RNTS radiation by single electron is indeed preserved at a specified direction and the RNTS radiation energy might exceed Bremsstrahlung radiation energy.

The simulation study has been extended to the nonlinear Compton scattering, which utilizes modulated high energy electron beam. In this case, any complex plasma dynamics can be avoided and the length of the electron beam can be increased by factor of 2 compared with an ultra-thin solid target.

2. Coherent RNTS Condition

To obtain the coherent RNTS condition, the following assumptions have been made; (1) Plane wave laser field, (2) no coulomb interaction between charged particles, thus neglecting ions, and (3) neglect of thermal velocity distributions of the electrons. With those assumptions, the radiation field of an electron at initial position of $\vec{x}_i = (x_i, y_i, z_i)$ can be calculated from that of an electron at origin initially, just considering the time delay between the electrons, Δt_i,

$$\Delta t_i = \Delta t_i^{'} - \frac{\hat{n}\cdot\vec{x}_i}{c}, \qquad (2)$$

where Δt_i' is the time delay of the laser pulse arriving at the electrons (c/ z_i) and $\hat{n}$ the unit directional vector of the radiation.

Since both pulse widths of the scattered radiation and the driving laser pulse are ultra-short, the phenomenon is very transient. Thus to keep the characteristics of the single electron's radiation, the time intervals between electrons should be comparable with the pulse width of the single electron's radiation, Δt^{s}_{FWHM} as

$$\Delta t_i \le \Delta t^{s}_{FWHM}. \qquad (3)$$

The peak radiation is directed to the direction of laser electric field ($\phi=0^o$) for a linearly polarized laser pulse and symmetric for a circularly polarized laser pulse. Thus insertion of $\phi=0^o$ to Eq. (2) leads to the following condition for the coherent radiation to a specified direction, θ

$$2\sin\xi\left(z\sin\xi - x\cos\xi\right) \le c\Delta t^{s}_{FWHM}, \qquad (4)$$

where $\theta=2\xi$. Above equation manifests that the RNTS from a group of electrons satisfying Eq. (3) can be coherently added to the specular direction as drawn in Fig. 1.

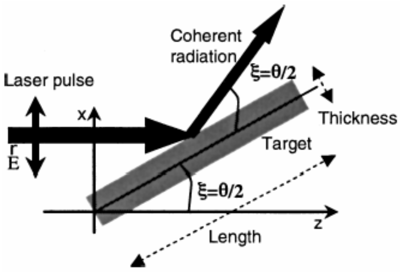

Figure 1 Schematic diagram for the target and the laser pulse for the coherent RNTS radiation.

3. Simulation Results

For the coherent condition proposed, an intense, attosecond pulse x-ray pulse has been numerically obtained. When the laser pulse of 20fs, 4×10^{19} W/cm^2 (a_o=4.3) irradiates on a 50 nm thick target, a 25 attosecond radiation with photon energy of a few tens eV has been generated (Fig 2). Since the coherent radiation appears to the specular direction of the laser pulse, it has very narrow angular distribution.

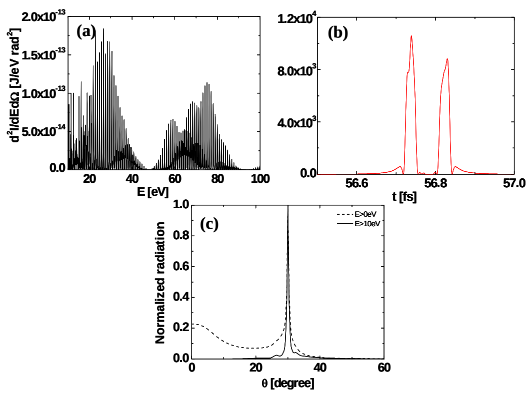

Figure 2 RNTS from 50 nm thick target irradiated by a 0.8 μm, 20 fs, 4×10^{19} W/cm^2 laser pulse. (a) Angular spectrum (b) peak angular power, and (c) angular distribution.

To observe the nonlinear Compton scattering, an electron which has an initial energy of 10 MeV is irradiated by an intense laser pulse of 10^{20} W/cm^2. Fig. 3 shows angular spectrum of the back-scattered radiation. With the laser intensity of 10^{17} W/cm^2 (Fig. 3(a)), the spectrum show just Doppler shifted monochromatic radiation. When the laser intensity enters a relativistic regime, 10^{20} W/cm^2, polychromatic spectrum is generated with maximum photon energy increased by factor of 10.

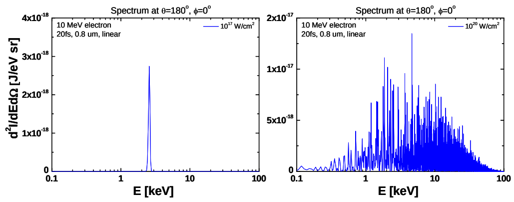

Figure 3 Compton scattered radiation (a) linear scattering and (b) nonlinear Compton scattering.

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