Coherent attosecond radiation from the interaction of high power femtosecond laser with nonotube arrays

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An isolated attosecond pulse generation from the interaction of high-power femtosecond laser pulse with carbon nanotube array was demonstrated by two-dimensional particle-in-cell (PIC) simulations. The radiations are based on the relativistic nonlinear Thomson scattering (RNTS) [1, 2], and a mirror reflection condition [3] is necessary for coherent radiation. The coherence of the radiation is essential to get an attosecond pulse, and it can be achieved with a nanotube array target and a sharply increasing laser pulse. (Fig. 1) With the combination of these two method, it is possible to generate a coherent attosecond radiation even with a high density target material.

When a single electron interacts with an relativistically high power laser pulse, it radiates attosecond X-ray pulse train by the RNTS. However, electron source is not a single electron but a mass of electrons like an electron bunch, solid target or plasma. In these cases, even though each electron radiates attosecond pulse, whole of the electrons radiates much longer pulse. A method to keep coherence between radiations is required to generate attosecond pulse in actual experiment.

In this study, mirror reflection condition was used as an coherent condition. (Fig. 1) In the

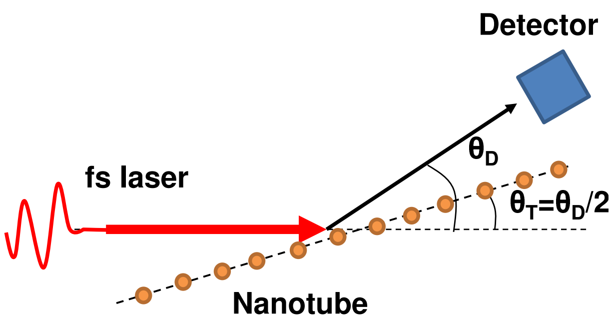

Figure 1: The schematic diagram of the interaction of sharply increasing laser pulse and the nanotube array. The mirror reflection coherent condition is obtained when the angles satisfy the relation $\theta_T = \theta_D/2$.

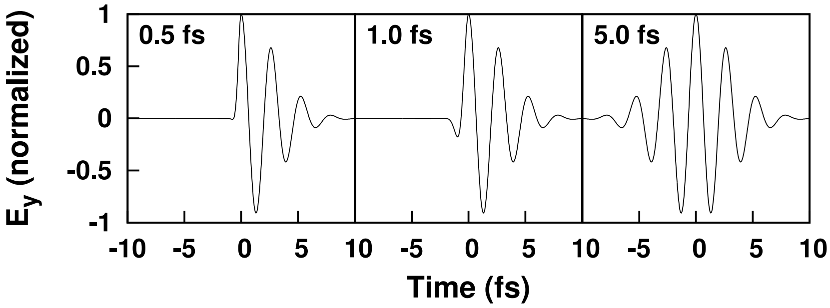

Figure 2: Sharply increasing laser pulse. The field shape is expressed in Eq. (1)

mirror reflection condition a thin flat solid target interacts with laser and the detecting angle from the target plane is the same as the laser incident angle from the target plane. Then, the summation of optical path from the start to the interaction of the laser and the path from the radiation to detection of attosecond pulse is the same for all radiations when the thickness of the target is ignored. However, the thickness of the target (i.e. thickness of whole electrons) is inceased the coherence is also broken. In the RNTS the electrons are accelerated to the direction of the laser propagation, the electrons move far from ions. The repulsive Coulomb force between electrons are very strong and very fast expansion occurs.

To keep the thin thickness and the coherence at the radiation, sharply increasing laser pulse and nanotube array target were proposed. When a solid target interact with laser field the target begin to expand with the front part of the laser pulse but the strong radiation is generated with the strongest part of the laser pulse. The sharply increasing laser pulse decreases the time interval between the begin of expansion and the strong radiation. In this study, the sharply increasing laser pulse was expressed as

$$E_y = \exp\left[-2\ln 2\frac{(t-x/c)^2}{\tau^2}\right]\cos(\omega t - kx) \tag{1}$$

$\tau = \tau_1$ for $t \leq 0$ and $\tau = \tau_2$ for $t > 0$. c is speed of light, $\omega = 2\pi c/\lambda$ and $k = 2\pi/\lambda$. τ_2 was fixed to 5 fs and τ_1 was varied from 0.5 fs to 5 fs. The rear part of the laser pulse was barely affected to the coherence because the coherence was already broken when electrons interact with the rear part. The nantube array target decreases the Coulomb force on the surface of the target. A thin film and a nanotube array of the same thickness and the same charge density have similar surface electric field initially. However, when the expansion begins, the thin film has constant electric field but the electric field of the nanotube target decreases and is proportional to the inverse of the diameter.

The far field calculation is essential to consider interference and coherence. However, far field was considered in only a few of the studies on the radiation from laser interaction with overdense

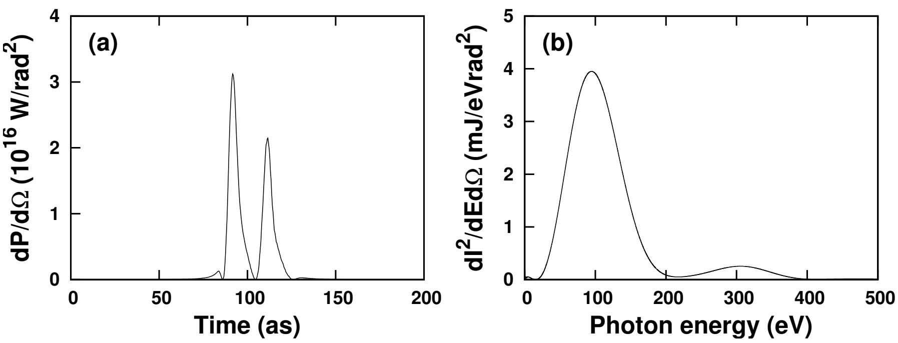

Figure 3: (a) The temporal structure and (b) the spectrum of the attosecond pulse radiation.

plasma because the calculation of the far field with the PIC code itself [i.e. finite-difference time-domain (FDTD) method] is difficult to do. To calculate the far-field with the FDTD method very long calculation window and long calculation time is required. [4] Espacialy. in the RNTS the wavelength of the radiation is very short, so very fine grid should be used. [5] In this study the radiated field from the dynamics of the macro particles of the electrons, which was calculated in the PIC code, were calculated with Liénard-Wiechert potential.

$$\vec{E}(t') = \frac{e}{c}\left[\frac{\hat{n}\times\{(\hat{n}-\vec{\beta})\times\dot{\vec{\beta}}\}}{(1-\vec{\beta}\cdot\hat{n})^3 R}\right] \tag{2}$$

when t' is retarded time, $\hat{n}$ is unit vector of direction from the electron to the detector, and R is distance from the electron to the detector. $\dot{\vec{\beta}} = d\vec{\beta}/dt$ [6]. Radiated fields from all macro particles of electrons were added in detector's frame [7] and were converted to the actual radiation considering number ratio between macro particles and actual electrons of the targets. By this method the far-field can be calculated directly with smaller computing power and higher accuracy than FDTD mathod.

In the simulation the nanotubes shown in Fig. 1 are aligned in z-diraction. The diameter of the nanotube is 5 nm and they are aligned regularly with the period of 25 nm in the range of 4 μm. The angle between the nanotube array and the laser propagation direction is θ_T. The sharply increasing laser pulse propagates in x-direction and polarized in y-direction. The electron density is $10n_{cr}$, where n_{cr} is the critical density corresponding to the wavelength of the laser, 800 nm. The peak intensity of the laser is 1.0×10^{20} W/cm^2 ($a = 6.8$). The beam waist of the laser beam is 16 μm and focused on the center of the nanotube array.

Fig. 3 shows the result. The full-width at half-maximum (FWHM) of the radiated pulse is 24 as, and the peak angular intensity is 3.1×10^{16} W/rad^2. The peak spectral angular energy is 4.0 mJ/(eV rad^2) and the average photon energy is 120 eV. When the detector covers the angular cross section of 1 μrad^2, the peak power is 31 GW and the total pulse energy is 0.37

μJ.

In this study, the attosecond X-ray pulse from the RNTS interaction between nanotube array target and high intensity femtosecond laser was demonstrated with the series of the 2-dimensional PIC simulations and the Liénard-Wiechert potential calculations. To get the short pulse length, high photon energy and high intensity the coherence of the radiation is important. As a coherence condition the mirror reflection condition was adopted and the thickness of the target should be thin at the radiating time in the condition. The nanotube array target instead of the thin film target and the sharply increasing laser pulse instead of normal Gaussian laser pulse proposed to enhance the coherence and were verified.

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