EVALUATION OF FEMTOSECOND X-RAYS PRODUCED BY INVERSE COMPTON SCATTERING UNDER LINEAR AND NONLINEAR INTERACTIONS BETWEEN A LOW EMITTANCE ELECTRON BEAM AND AN INTENSE POLARIZED LASER LIGHT

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Abstract

The mechanisms of inverse Compton scatterings under linear and nonlinear interactions are discussed theoretically and used to evaluate characters of femtosecond (fs) X-rays produced by collision between a low emittance electron beam and an intense polarized laser light. In the evaluation, we start from the differential cross section of the inverse Compton scattering under the linear interaction, and calculate the effects of the interaction angle and the laser light polarization on the production of the fs X-rays. The energy and emission angular distributions of the produced fs X-rays are evaluated under the linear and nonlinear interactions between the electron beam and laser light.

1 INTRODUCTION

A bright femtosecond (fs) X-ray pulse source, as a typical practical tool to control the photonic and electronic states in a fs region, expected to contribute to the new foundations of industrial technology and science of near future.

It is well known that the pulse X-rays are produced by means of a synchrotron radiation (SRs)[1]. SRs produce X-rays with the pulse length of a few tens of picosecond (ps) and furthermore very-high-energy (>5 GeV) storage rings are required to produce X-rays at higher energies (>10 keV). However, the recent rapid development of fs pulse lasers makes a laser Compton process with a low emittance pulse electron (e^-) beam to generate fs X-ray pulses realistically.

In the laser Compton process, which is called inverse Compton scattering, the laser photons scatter with the e^-'s and the X-rays are mostly emitted along the e^- direction. The shorter pulse length of X-rays is generated by means of the inverse Compton scattering at 90-degree between a fs pulse laser and a tightly focused e^- pulse beam. A high brightness X-rays are generally produced under linear interactions between a low emittance e^- beam and laser lights, in which an e^- interacts with a single laser photon. For an intense laser pulse, nonlinear interactions in which an e^- scatters simultaneously with two or more laser photons may occurs. High energy X-rays are generated and the emission angular distribution of the X-rays is spread throughout the beam direction in the nonlinear interactions. However, the generated X-rays are not easily controllable for applications.

2 GENERATION OF FEMTOSECOND X-RAY PULSES

Figure 1 shows schematically a generation of the fs X-ray pulse by the inverse Compton scattering between a low emittance e^- pulse beam and a fs laser pulse light. The fs laser light pulse meets the e^- pulse in the transverse direction. The ultrashort interaction times, which produce the fs X-ray pulses, are achieved by focusing the e^- beam and the laser light beam into a few tens of micron meter. A ps e^- pulse beam and an intense fs pulse laser, as given in Table 1 and 2 respectively, are used for the fs X-ray generation. The produced X-rays are separated by bending the e^-'s after the interactions.

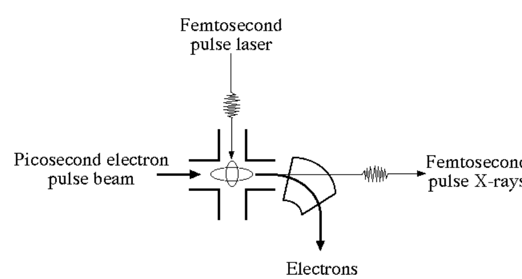

Figure 1: A schematic illustration of the fs X-ray generation by the inverse Compton scattering between a low emittance e^- beam and an intense fs laser light.

We assume that both the e^- and laser light pulses satisfy the Gaussian distribution. The pulse length of the X-rays can be thus evaluated as following formalism by considering that the laser pulse meets the e^- pulse at the transverse direction with a maximum overlapping volume,

$$\sigma_x = \frac{\sigma_{el}}{c} \frac{\sqrt{\sigma_{et}^2 + \sigma_{ll}^2 + \sigma_{lt}^2}}{\sqrt{\sigma_{et}^2 + \sigma_{et}^2 + \sigma_{ll}^2 + \sigma_{lt}^2}} \qquad (1)$$

where $\sigma_{el}(\sigma_{et})$ represents the pulse length (beam size) of the e^-'s, $\sigma_{ll}(\sigma_{lt})$ the pulse length (beam size) of the laser lights, and c the velocity of light. Equation 1 shows that the shorter pulse of the X-rays is achieved by the shorter pulses of both the e^- beam and the laser lights.

Table 1: Specifications of the e^- pulse beam

Energy	150 MeV
Charge / pulse	1.6 nC
Pulse length	0.5 ps
Beam size	50 μm
Polarization	unpolarized

Table 2: Specifications of the laser pulse light

Wavelength	1 μm
Energy / pulse	0.5 J
Pulse length	100 fs
Beam size	50 μm
Polarization	linearly polarized

3 LINEAR INVERSE COMPTON SCATTERING

To simplify the calculation, we only consider the polarizations of the e^- beam and the laser lights before the scattering, *i.e.* the initial e^- polarization and the initial laser light polarization interfere in the interaction between the e^- beam and the laser light. Therefore, the differential cross section of the linear inverse Compton scattering in an e^- rest frame can be thus described by the Lipps and Tolhoek theory[2] as follows,

$$\frac{d\sigma}{d\cos\theta} = \pi r_0^2 \left(\frac{E_2}{E_1}\right)^2 \left\{ \frac{E_1}{E_2} + \frac{E_2}{E_1} - \sin^2\theta + P_l \sin^2\theta - P_e P_c \left(\frac{E_1}{E_2} - \frac{E_2}{E_1}\right)\cos\theta \right\} \quad (2)$$

where E_1 and E_2 represent respectively the energies of the laser photon and X-ray photon in the e^- rest frame, θ the emission angle of the X-ray in the e^- rest frame, r_0 the classical e^- radius, P_e the spin polarization of e^-'s which P_e=+1(-1)assumed to be parallel (antiparallel) to the direction of the e^-' motion, P_l and P_c the linear and circular polarizations of the laser lights, respectively. We give P_l =1 and P_l = 0 for the linearly polarized laser lights which the polarization directions are parallel and perpendicular to the scattering plane, respectively.

Figure 2 shows the total photon number in the X-ray pulse produced under the linearly polarized laser lights and the different interaction angle between the e^- and laser light pulses. In the calculation, the parameters of the e^- beam and the laser light are given in Tables 1 and 2, respectively. An intense X-ray source is achieved by using a linearly polarized laser. In the presented system, the e^- beam is unpolarized, resulting in a same value of the cross section of the linear inverse Compton scattering for the circularly polarized laser lights and the unpolarized laser lights.

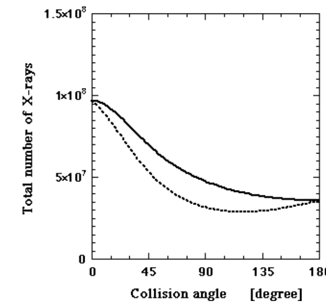

Figure 2: Total number of X-ray photons produced by linearly polarized lasers under the different interaction angles. The solid (dashed) line represents the polarization direction is parallel (perpendicular) to the scattering plane.

Figure 3 gives the energies of the X-ray photons produced in the 90-degree linear inverse Compton scattering with various e^- energies. The X-rays with energy of 214 keV are obtained by using the 150 MeV e^- beam and the 1 μm fs laser light in the presented system.

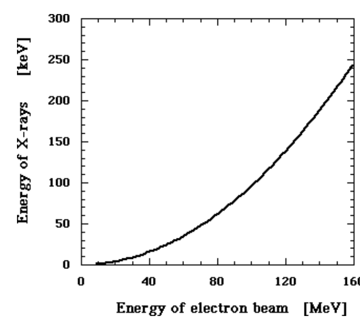

Figure 3: Energy of the X-ray photons vs energy of e^- beam.

Using Eq. 1, we evaluate the pulse length of X-rays generated by different pulse length and focused beam size of laser lights and e^- beam, as shown in Fig. 4. The more shorter X-ray pulse are observed using the short pulse length and small focused beam size of the e^- beam and the laser light, *i.e.* a 100 fs pulse X-rays are calculated using a 0.5 ps pulse e^- beam and a 50 fs pulse laser light beam with the focused beam size of 20 μm.

Using Eq. 2, we also calculate the energy and emission angular distributions of X-rays under the linear inverse Compton scattering at 90-degree, as shown in Fig. 5. The total number of the X-ray photons in Fig. 5 is normalised to be $4.7\text{x}10^7$ photons per one pulse. Both distributions of energy and emission angle have sharp peaks at 214 keV and 180-degree (the direction of the e^- beam direction), respectively. Finally, the characters of the produced X-ray beam is obtained and given in Table 3.

Table 3: Characters of the produced fs X-ray pulses

Wavelength	$5.8\text{x}10^{-3}$ nm(214keV)
Pulse length	228 fs
Intensity	$3\text{x}10^7$photons/pulse
Collection angle	5 mrad

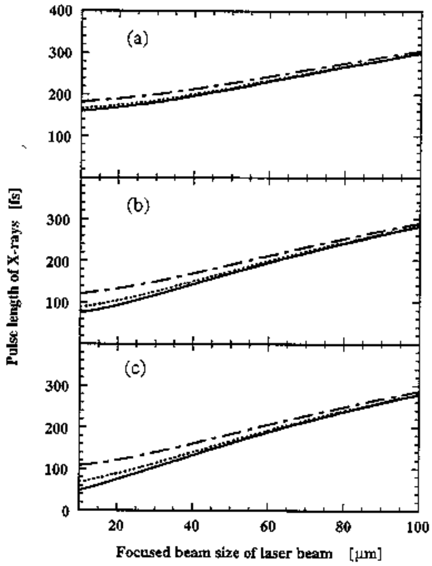

Figure 4: Pulse length of the X-rays produced by 10 (solid line), 50 (dashed line) and 100 fs (solid-dashed line) pulse laser. The e^- beams with the focused beam size of 50 (a), 20 (b) and 10 μm (c) are used in the calculation.

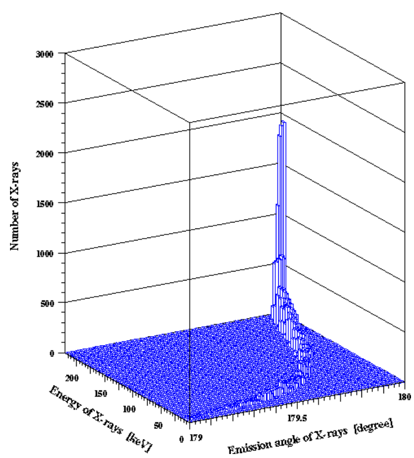

Figure 5: Energy and angular distributions of the X-rays produced under the linear inverse Compton scattering.

4 NONLINEAR INVERSE COMPTON SCATTERING

The nonlinear inverse Compton scattering on the fs X-ray production can be described with the classical theory of synchrotron radiations, *i.e.* the X-rays are emitted from the e^-'s by the radiation when the e^-'s travel in a laser field. The energy spectrum of the X-rays emitted by a single e^- in the laser field during the interaction time T is

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2\omega^2}{4\pi^2 c}\left|\int_{-T/2}^{+T/2} dt[\mathbf{n}\times(\mathbf{n}\times\beta)]\times e^{i\omega(t-\mathbf{n}\cdot\mathbf{r}/c)}\right|^2 \quad (3)$$

calculated from the Lienard-Wiechert potentials[3], where $\mathbf{r}(t)$ represents an arbitrary orbit of the e^-'s in the laser field, $\mathbf{n}$ a unit vector pointing in the direction of observation. $\beta=\boldsymbol{v}/c$, $\boldsymbol{v}$ the velocity vector of the e^-, and ω the energy of the emitted X-rays. All quantities in Eq. 3 are defined in the laboratory frame.

Figure 6 gives the angular distributions of X-rays emitted by a single e^- under the nonlinear interactions with the harmonic numbers of m=2, 3 and 4. The angular distributions of the X-rays emitted in the nonlinear interactions are spread throughout the beam e^- direction. Comparing with the linear interaction, the higher energy X-rays are generated in the nonlinear interactions with the harmonic numbers of two and more than two. Therefore, the nonlinear interactions are required to be avoided for the generation of high brightness fs X-rays.

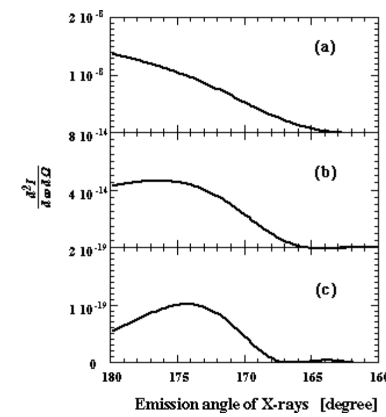

Figure 6: Angular distributions of the X-rays emitted by the nonlinear Compton scattering with the harmonic number of m=2(a), 3(b) and 4(c).

5 CONCLUSION

The inverse Compton scatterings under the linear and nonlinear interactions between a low emittance e^- beam and a fs laser light have been described for the generation of the high brightness fs pulse X-rays. The dependence of the polarization and the interaction angle have bean discussed. The energy and angular distributions of the X-rays are evaluated under the linear and nonlinear interactions. Finally, a 228 fs X-ray beam is achievable in the presented system, in which the effect of the nonlinear interaction is negligible. The pulse length of the X-rays is expected to be 100fs by focusing the beam sizes of the e^-'s and laser lights to be 20 μm.

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