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COHERENT THOMSON SCATTERING RADIATION GENERATED BY USING PEHG

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Abstract

The density modulation method of the newly proposed PEHG is used to generate ultra-short electron longitudinal structures for the bunch of a 100MeV ERL. Coherent Thomson scattering radiation in EUV range can be emitted by the scattering of such a modulated bunch with a long wavelength laser.

INTRODUCTION

Thomson scattering of an intense laser by relativistic electrons has thus drawn a considerable attention by its possibility of generating short wavelength radiations with relatively lower beam energy. In the recent years, several Thomson scattering light sources have been builted and some new methods of improving the performance of Thomson scattering light sources have been proposed. However, because of the bunch length is usually much longer than the radiation wavelength in these cases, the scattered radiation is mostly incoherent. In order to generate coherent Thomson scattering radiation, electron bunches with ultra-thin longitudinal structures, whose length is compariable or even shorter than the wavelength of scattered radiation, should be obtained first. In order to get such a ultra-thin longitudinal structure in electron bunches, several methods have been proposed previously [1, 2]. In this paper, we are referring a newly proposed bunch longitudinal density modulation method which is called Phase-merging Enhanced Harmonic Generation (PEHG) [3–5] to generate the ultra-thin bunch slices. By colliding with a long wavelength laser pulse generated by ERL beam, coherent and ultra-short pulse radiation is emitted through coherent Thomson scattering.

THOMSON SCATTERING

When a relativistic electron beam collides with an intense laser beam propagates along the inverse direction, the electrons start to oscillate driven by the Lorentz force of the laser electromagnetic field and generate intense and highly concentrated radiation along the direction of electrons propagate. This laser-electron collision process is so called Thomson scattering. The strength of the incident laser is described by the dimensionless vector potential, which can be expressed by the parameters of laser as

$$a_L = \frac{eE_L}{m_e c\omega_L} = 0.85 \times 10^{-9} \lambda_L[\mu m] I_0^{1/2} [W/cm^2] \tag{1}$$

where E_L, ω_L are the electrical field and the angular frequency of the incident laser. The radiation wavelength of Thomson scattering is quite similar to the undulator radiation thus it is also called *laser undulator radiation*. Considering the scenario of backscattering, the radiation wavelength is

$$\lambda_r = \frac{\lambda_L}{4\gamma^2}(1 + \frac{a_L^2}{2} + \gamma^2\theta^2) \tag{2}$$

where θ is the radiation angle and λ_L is the wavelength of the incident laser. Because of λ_L is usually much smaller than the traditional undulator period, one can generate radiation with similar wavelength but much smaller γ.

DENSITY MODULATION BY PEHG

Basic Principle of PEHG

PEHG was first proposed as an alternated harmonic generation method to the traditional HGHG [7, 8]. The performance of traditional HGHG method is restricted by the existence of initial energy spread of the electron bunch. As is shown in Eq. 3,

$$b_n = < e^{-in\theta_j} > = e^{-\frac{1}{2}n^2\sigma_\gamma^2(\frac{d\theta}{d\gamma})^2} J_n(n\Delta\gamma\frac{d\theta}{d\gamma}). \tag{3}$$

where $\frac{d\theta}{d\gamma} = 2\pi R_{56}/\lambda_s\gamma_0$, λ_s is the wavelength of seeding laser, γ_0 is the Lorentz factor of electron beam, σ_γ is the initial energy spread, $\Delta\gamma = \frac{k_s a_u F_B}{\gamma_0} a_s N_u \lambda_u$ with $F_B = J_0(\xi) - J_1(\xi)$ and $\xi = a_u^2/2/(1 + a_u^2/2)$, is the maximum energy modulation. The bunching factor drops exponentially with the harmonic increases due to the none-zero σ_γ in the exponential term. Because the bunching factor is the Fourier expansion of the longitudinal distribution, this also indicates the length of the longitudinal structure in the phase space is restricted.

In PEHG, the traditional modulator undulator is replaced by a *Transverse Gradient Undulator (TGU)* with transverse field gradient α and a dog-leg section is put in the front stream of the TGU to provide a dispersion η. The dog-leg acts a function of transverse-longitudinal coupling to establish a correlation between transverse position with energy. Then the electron bunch passes through the TGU and this correlation alternated to the correlation between electron energy and different undulator parameter. The principle equation inside the TGU is shown in Eq. (4) [3],

$$\frac{\gamma' - \gamma_0'}{\gamma - \gamma_0} = 1 - \frac{2\pi N_u \Delta\gamma}{\gamma_0}(\frac{\alpha\eta {K_0}^2}{K_0^2 + 2} - 1). \tag{4}$$

where γ_0' and γ' are the Lorentz factor of an reference electron and an arbitrary electron which have the same phase at the exit of the dog-leg; γ_0 and γ are the corresponding

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Lorentz factor at the entrance of the TGU, N_u and K_0 are the period number and the central undulator parameter respectively. By properly choosing the transverse gradient α of TGU and the dispersion strength η of the dog-leg to make the right side of Eq. (4) becomes zero. It indicates that the electrons with the same energy are merging to the same phase during the energy modulation process. After passing through the dispersion section with proper value of R_{56}, ultra-thin longitudinal structures are obtained inside the electron bunch. The optimized value of $\alpha\eta$ can be derived from Eq. (4),

$$(\alpha\eta)_{opt} = (\frac{\gamma_0}{2\pi N_u \Delta\gamma} + 1)\frac{K_0^2 + 2}{K_0^2}. \tag{5}$$

Ultra-thin Longitudinal Structure Generated by PEHG

Considering an ERL with electron energy of 100 MeV, we simulate the phase space evolution under the manipulation method of PEHG. The detailed parameters for simulation is shown in Table 1.

Table 1: Simulation Parameters

TGU modulator		
Period length	λ_u	2 cm
Period number	N_u	15
Undulator strength	a_u	2.0316
Seeding laser		
Wavelength	λ_s	800 nm
Vector potential	a_s	3.7761×10^{-5}
Max. energy modulation amplitude	$\Delta\gamma$	180 keV
Electron beam		
Central beam energy	E_0	100 MeV
Beam energy spread	σ_E	30 keV
Bunch charge	I_{pk}	77 pC
Bunch length	l_b	1 ps

With the parameters described above, Eq. (5) gives the theoretical value of optimized $\alpha\eta \approx 10.24$. However, in actually, because of the dispersion of undulator, the optimized value of $\alpha\eta$ is slightly different with the theoretical value. Meanwhile, the R_{56} value of the dispersion section should also be optimized to achieve a better rotation inside the longitudinal phase space. Figure 1 shows the optimization of $\alpha\eta$ and R_{56} in the form of bunching factor of the 40th harmonic of the seeding laser.

From Fig. 1, the optimized value of $\alpha\eta \approx 9.2$ and $R_{56} \approx 6.425 \times 10^{-5}$. With these parameters, the longitudinal phase space after the density modulation of PEHG is shown in Fig. 2(a).

As a comparison, the longitudinal phase space modulated by HGHG is also shown in the same figure (with a slight slippage to distinguish the two longitudinal phase space). As is shown in Fig. 2, the longitudinal phase merging is significantly enhanced in PEHG, so that most electrons are concentrated to a set of extremely short slices. The bunching

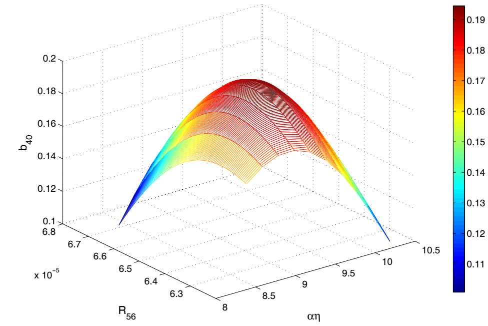
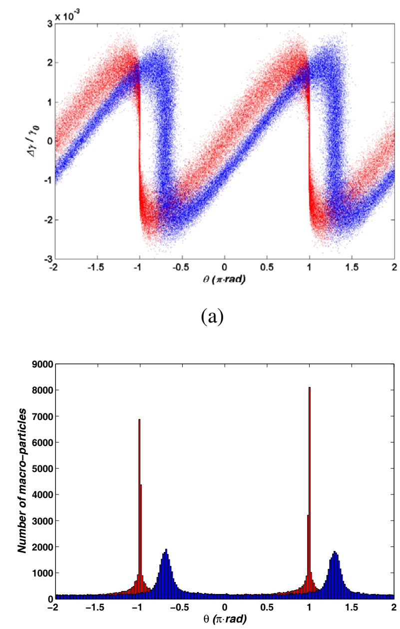


Figure 1: Optimization of the 40th harmonic of the seeding laser



(a)

(b)

Figure 2: Longitudinal phase space after dispersion section. PEHG in red and HGHG in blue for comparison. 2(a): Longitudinal phase space; 2(b): Histogram of the particle distribution;

factor of the PEHG modulated bunch does not drops so quickly with the harmonic number increases.

COHERENT THOMSON SCATTERING USING MODULATED BUNCH

By the density modulation of PEHG mechanism we get the ultra-short longitudinal structure of about 20nm in the electron bunch. The modulated bunch are used to collision with a incident laser pulse to generate coherent Thomson scattering radiation. For simplicity, we just consider the head-on collision case and observe the radiation on the same direction of electron bunch propagates (i.e., $\varphi = 180°$ and $\theta = 0°$). The incident laser with the wavelength $\lambda_L = 2mm$, which is in the THz range. This incident laser can be

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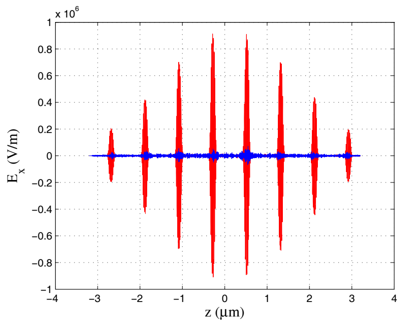
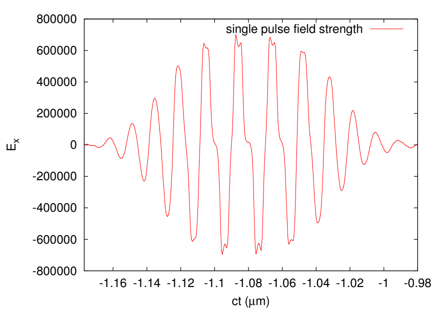
obtained by collecting the CSR radiation of ERL beams at the bending magnet using optical cavity [6]. The scattering radiation wavelength at $\theta = 0$ direction is $\lambda_r = 20\mathrm{nm}$ to be comparable with the length of the longitudinal structure in the PEHG modulated bunch. This radiation wavelength requires a dimensionless vector potential of the incident laser $a_L \approx 1.0314$.

Figure 3 shows the electric field strength distribution of the total radiation (Fig. 3(a)) and a single pulse (Fig. 3(b)). The electric field of scattering radiation is enhanced due to the coherence and shows a distinct pulse structure. A single pulse length is about 600 atto-seconds.



(a)



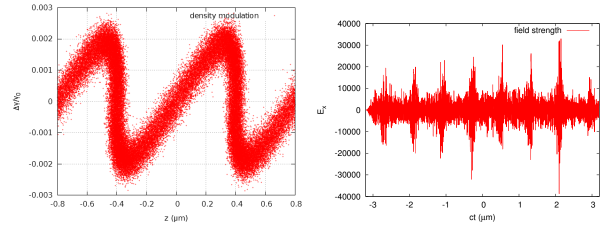
(b)

Figure 3: Electrical field strength distribution of the scattering radiation.

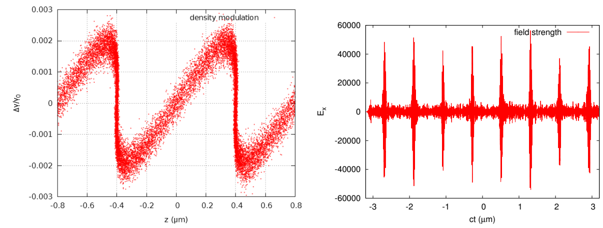
INFLUENCE OF INITIAL TRANSVERSE EMITTANCE

In the discussion above, we assume the electron beam has a extramely small transverse emittance so that in 1D scene we can get a set of ultra-short electron slices to generate coherent Thomson scattering radiation. However, the existence of the initial emittance, witch will smear the transverse dispersion of dog-leg, acts actually as an equivalent energy spread. To counteract this effect, we need to enlarge the dog-leg dispersion while keeping the value of $\alpha\eta$. Figure 4 shows the results of the enlarged η.

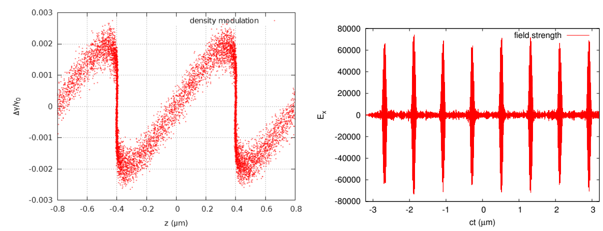
With the increase of the dog-leg dispersion, the phase-merging is enhanced and the longitudinal bunching can be improved. With sufficiently strong η, coherent Thomson scattering can still be observed. However, we can also find



(a) $\eta = 0.2$, $\alpha = 46$



(b) $\eta = 1.0$, $\alpha = 9.2$



(c) $\eta = 2.0$, $\alpha = 4.6$

Figure 4: Considering the transverse emittance $\varepsilon_x = 1mm \cdot mrad$, the longitudinal phase space after density modulation and the electrical field distribution of the radiation after Thomson scattering.

that because of the electrons are dispersed to the transverse direction stronger, the longitudinal charge density of the modulated bunch are significantly reduced. Therefore, the radiation strength becomes smaller than the ideal case. That could be a underlying restriction for the application of this method.

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