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 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 built and some new methods of improving the performance of Thomson scattering light sources have also 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 comparable or even shorter than the wavelength of scattered radiation, is considered to 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

\[ a_L = \frac{eE_L}{m_ec\omega_L} = 0.85 \times 10^{-9} \lambda_L [\mu m] V_0^2 [W/cm^2] \]

where \( E_L \), \( \omega_L \) 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

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

where \( \theta \) is the radiation angle and \( \lambda_L \) is the wavelength of the incident laser. Because of \( a_L \) is usually much smaller than the traditional undulator period, one can generate radiation with similar wavelength but much smaller \( \gamma \).

DENSITY MODULATION BY PEHG

Basic Principle of PEHG

PEHG was first proposed as an alternate 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,

\[ b_n = e^{-i\eta_0} = e^{-\frac{i}{2}\sigma_\gamma^2 J_1(n\Delta \gamma^2 \frac{d\theta}{dy})} \]

where \( \frac{d\theta}{dy} = 2\pi R S/L \lambda_s \gamma_0 \), \( \lambda_s \) is the wavelength of seeding laser, \( \gamma_0 \) is the Lorentz factor of electron beam, \( \sigma_\gamma \) is the initial energy spread, \( \Delta \gamma = \frac{\gamma_0 a_u F_B}{\gamma_0 a_u N_u \lambda_u} \) 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 \( \sigma_\gamma \) 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 of \( \alpha \) and a dog-leg section is put in the front stream of the TGU to provide a dispersion \( \eta \). The dog-leg acts as 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 is altered to the correlation between electron energy and different undulator parameter. The principle equation inside the TGU is shown in Eq. (4) [3],

\[ \frac{\gamma' - \gamma_0'}{\gamma - \gamma_0} = 1 - 2\pi N_u \Delta \gamma a_u^2 K_0^2 \frac{K_0^2 + 2}{\gamma_0^2} - 1 \]

where \( \gamma_0' \) and \( \gamma' \) are the Lorentz factor of an reference electron and an arbitrary electron which have the same phase at the exit of the dog-leg; \( \gamma_0 \) and \( \gamma \) 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 $\alpha$ of TGU and the dispersion strength $\eta$ 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),

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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGU modulator</td>
<td></td>
</tr>
<tr>
<td>Period length $\lambda_u$</td>
<td>2 cm</td>
</tr>
<tr>
<td>Period number $N_u$</td>
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<tr>
<td>Undulator strength $\alpha_u$</td>
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</tr>
<tr>
<td>Seeding laser</td>
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</tr>
<tr>
<td>Wavelength $\lambda_s$</td>
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</tr>
<tr>
<td>Vector potential $\alpha_s$</td>
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<tr>
<td>Max. energy modulation amplitude $\Delta \gamma$</td>
<td>180 keV</td>
</tr>
<tr>
<td>Electron beam</td>
<td></td>
</tr>
<tr>
<td>Central beam energy $E_0$</td>
<td>100 MeV</td>
</tr>
<tr>
<td>Beam energy spread $\sigma_E$</td>
<td>30 keV</td>
</tr>
<tr>
<td>Bunch charge $I_{pk}$</td>
<td>77 pC</td>
</tr>
<tr>
<td>Bunch length $l_b$</td>
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</tr>
</tbody>
</table>

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 $R_{56} \approx 3.425 \times 10^{-5}$. 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 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 an 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., $\varphi = 180^\circ$ and $\theta = 0^\circ$). The incident laser with the wavelength $\lambda_L = 2mm$, which is in the THz range. This incident laser can be
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 $\lambda_r = 20\text{nm}$ 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 $600\text{ attoseconds}$.

Figure 4: Considering the transverse emittance $\varepsilon_x = 1\text{mm} \cdot \text{mrad}$, 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.

**REFERENCES**