COHERENT THOMSON SCATTERING RADIATION GENERATED BY USING PEHG

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Abstract

Electron beam is density modulated by the phase-merging effect to obtain ultra-short longitudinal structures in the phase space. Coherent radiations are then generated by the coherent Thomson scattering between the phase-merged beam and a long wavelength laser pulse.

INTRODUCTION

It is able to generate intense short wavelength radiation by the Thomson scattering between relativistic electron beam and an incident high-field laser beam. In the case of back-scattering, the radiation wavelength is expressed by [1]

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

where the dimensionless vector potential a_L of the incident laser can be expressed as

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

Equation 1 has the similar form with the radiation wavelength of undulator radiation except for a Doppler-shift factor of $4\gamma^2$ rather than $2\gamma^2$. Usually the wavelength of incident laser is much shorter than undulator period length. Therefore, to obtain radiation with same wavelength, it requires much lower electron beam energy than that of the undulator radiation. However, the radiation of Thomson scattering is usually incoherent.

If the electron bunch has longitudinal structure shorter than the radiation wavelength, coherent Thomson scattering radiation can be generated. Several methods to obtain such a longitudinal structure have been discussed previously [2–4]. In this paper, we propose to use the phase-merging effect method realized by transverse gradient undulator (TGU), which is referred as PEHG in FEL [5–7], to modulate the electron bunch and generate short longitudinal phase space structures. Then a long wavelength laser in THz region [8] is used as laser undulator to generate coherent Thomson scattering radiation with such a beam.

LASER-BEAM INTERACTION IN UNDULATOR

The Hamiltonian of laser-beam interaction in a planar undulator is expressed as follows

$$H = (1+\delta) - \sqrt{(1+\delta)^2 - (\boldsymbol{p} - \frac{\boldsymbol{a}}{\gamma})^2 - \frac{1}{\gamma^2}}, \tag{3}$$

where $a_x = \hat{a}_u \cos k_u s + \hat{a}_L \cos k_L z$.

The equations of electron motion are expressed by

$$\begin{aligned}
x' &= \left(p_x - \frac{a_x}{\gamma}\right)\frac{1}{p_s},\\
p_x' &= \frac{1}{\gamma p_s}\left(p_x - \frac{a_x}{\gamma}\right)\frac{da_x}{dx}\\
z' &= -\frac{\left(p_x - \frac{a_x}{\gamma}\right)^2 + p_y^2 + \frac{1}{\gamma^2}}{p_s(p_s + 1 + \delta)},\\
\delta' &= \frac{1}{\gamma p_s}\left(p_x - \frac{a_x}{\gamma}\right)\frac{da_x}{dz}\\
p_s &= \sqrt{(1+\delta)^2 - (\boldsymbol{p} - \frac{\boldsymbol{a}}{\gamma})^2 - \frac{1}{\gamma^2}}
\end{aligned} \tag{4}$$

Equation 4 can be solved numerically by, for example, Runge-Kutta integration. The radiation emitted by an electron can be calculated by the Heaviside-Feynman expression

$$\boldsymbol{E}_i(\boldsymbol{x}_0, t) = \frac{e}{4\pi\varepsilon_0}\left[\frac{\boldsymbol{R}_i}{R_i^3} + \frac{R_i}{c}\frac{d}{dt}\frac{\boldsymbol{R}_i}{R_i^3} + \frac{1}{c^2}\frac{d^2}{dt^2}\frac{\boldsymbol{R}_i}{R_i}\right] \tag{5}$$

Here "i" denotes the i-th electron and $\boldsymbol{R}_i$ is the vector between observation point $\boldsymbol{x}_o$ and the election position $\boldsymbol{x}_i$. Then the total radiation field can be calculated using the superposition principle. A numerical simulation code using this method has been developed by K. Ohmi [2] and will be used in this work.

DENSITY MODULATION BY PEHG

Basic Principle of PEHG

In traditional HGHG [9, 10], the harmonic components contained in the density modulated bunch are measured by the bunching factor

$$b_n =< e^{-in\theta_j} >= e^{-\frac{1}{2}n^2\sigma_\gamma^2(\frac{d\theta}{d\gamma})^2} J_n(n\Delta\gamma\frac{d\theta}{d\gamma}). \tag{6}$$

As is seen in Eq. 6, the bunching factor reduces exponentially with the harmonic number increases due to the none-zero energy spread σ_γ. The performance of density modulation of traditional HGHG is restricted so that it is hard to obtain sufficiently short longitudinal structures in the phase space.

PEHG [5, 7] was proposed to improve the harmonic number of traditional HGHG by replacing the modulator undulator with a TGU with transverse field gradient α. Meanwhile, a dog-leg section with a dispersion strength η is put

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in the front stream of the TGU to provide the transverse-longitudinal coupling. The principle equation inside the TGU is shown in Eq. 7,

$$\frac{\gamma' - \gamma'_0}{\gamma - \gamma_0} = 1 - \frac{2\pi N_u \Delta\gamma}{\gamma_0}\left(\frac{\alpha\eta {K_0}^2}{K_0^2 + 2} - 1\right). \tag{7}$$

By choosing the values of transverse gradient α of TGU and the dispersion strength η of the dog-leg properly, one can make the right hand side of Eq. 7 becomes zero. The electrons with the same energy merge to the same phase during the energy modulation process. After passing through the dispersion section with proper value of R_{56}, ultra-short longitudinal structures are obtained inside the electron bunch.

Density Modulation

We assume an 100 MeV electron beam of an Energy Recovery Linac (ERL). Firstly, only 1-D simulations are carried out, i.e., assumeing the transverse emittance is neglectable. The simulation parameters are shown in Table 1.

Table 1: Simulation Parameters

TGU modulator		
Period length	λ_u	2 cm
Period number	N_u	15
Central Undulator strength	K_0	2.0316
Electron beam		
Central beam energy	E_0	100 MeV
Beam energy spread	σ_E	30 keV
Seeding laser		
Wavelength	λ_s	800 nm
Vector potential	a_s	3.7761×10^{-5}
Max. energy modulation	$\Delta\gamma$	180 keV

From Eq. 7, the optimized value of $\alpha\eta$ is

$$(\alpha\eta)_{opt} = \left(\frac{\gamma_0}{2\pi N_u \Delta\gamma} + 1\right)\frac{K_0^2 + 2}{K_0^2}. \tag{8}$$

With the parameters in Table 1, Eq. 8 gives the theoretical optimized value of $\alpha\eta \approx 10.24$. In actually, 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. In this simulation, the values of $\alpha\eta$ and R_{56} are optimized for the 40th harmonic of the seeding laser. The 3-D plot of the bunching factor optimization result is shown Fig. 1.

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

The longitudinal phase space modulated by a traditional HGHG with the similar parameters is also shown as a comparison (with a slight slippage to distinguish the two longitudinal phase space). It shows an obvious phase-merging

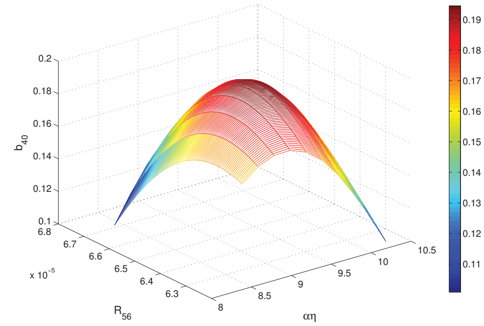
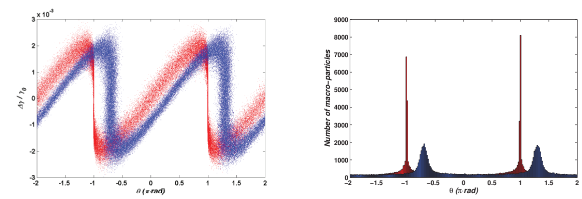


Figure 1: Optimization of the 40th harmonic of the seeding laser



(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): Particle distribution.

phenomenon around the phase $\theta = \pm\pi$ in the PEHG modulated phase space. Although there is also a broadening effect on other phase, the particle distribution shown in Fig. 2(b) indicates that most particles are concentrated near the phase $\theta = \pm\pi$. The length of this ultra-short longitudinal structure is less than 20 nm.

COHERENT THOMSON SCATTERING

The modulated bunch are used to collide with an incident laser pulse to generate coherent Thomson scattering radiation. For simplicity, only the head-on collision case (back-scattering) is considered. The incident laser has a wavelength $\lambda_L = 2$ mm, dimensionless vector potential $a_L \approx 1.0314$ and pulse length $\sigma_L = 2\lambda_L$. The electric field of the scattered radiation observed on the direction of electron motion (i.e., $\theta = 0$) is shown in Fig. 3. A single pulse length is about 600 atto-seconds. The radiation spectrum is shown in Fig. 4. The amplitude of radiation with phase-merged beam is significantly enhanced compared with the amplitude with out phase-merging, almost three order of magnitude. Since the dimensionless vector potential of incident laser is larger than 1, some higher harmonic components appears due to the non-linear effect of Thomson scattering. However, because of the coherence of the fundamental mode and incoherence of higher harmonics, the fundamental mode has much higher amplitude than the higher harmonics.

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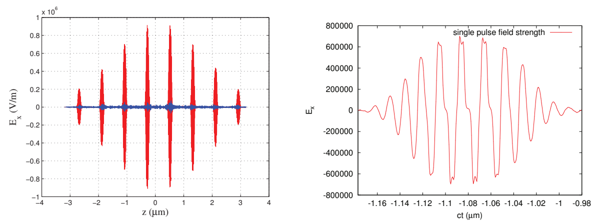


Figure 3: Electrical field strength distribution of the scattering radiation.

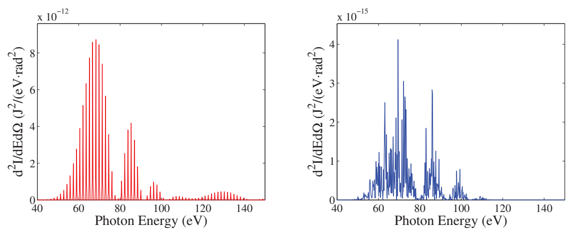
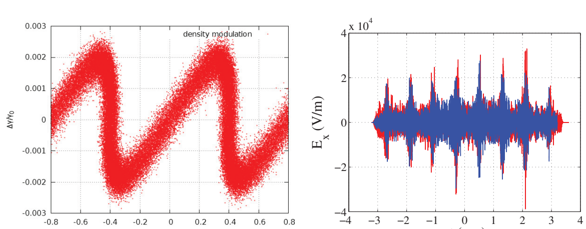


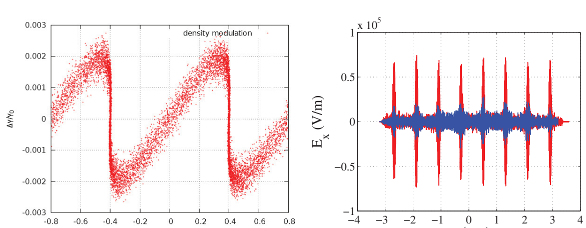
Figure 4: Spectrum of the scattered radiation.

INFLUENCE OF THE INITIAL TRANSVERSE EMITTANCE

In the simulation above, we assume the electron beam has a extremely small transverse emittance, i.e., in 1-D scene. We can get a set of ultra-short electron slices to generate coherent Thomson scattering radiation. However, in 3-D case, the effect of the initial transverse emittance which acts as a equivalent energy spread should be considered. The correlation between electron energy and it's transverse position after the dog-leg is smeared by the initial transverse distribution. In order to counteract this effect, the dispersion strength of dog-leg should be enlarged to provide a stronger transverse-longitudinal coupling and improve the resolution in TGU.



(a) η = 0.2 m, α = 46 m^{-1}



(b) η = 2.0 m, α = 4.6 m^{-1}

Figure 5: 3-D simulation with the transverse emittance ε_x = 1mm·mrad

In Fig. 5, the results of 3-D simulation with initial transverse emittance ε_x = 1 mm·mrad are shown. By increasing the dispersion strength η, coherent radiation can still be obtained after Thomson scattering. We should also notice that because the longitudinal charge density also reduces because of a longer bunch length after the stronger dispersion, the amplitude of electric field is one order of magnitude lower than the 1-D result. Even though, it is still much stronger than the radiation without PEHG modulation.

SUMMARY

We have studied the coherent Thomson scattering radiation emitted by the head-on collision of the density modulated electron bunch and a long-wavelength laser pulse. Electron bunch is density modulated using the phase-merging effect in a TGU to generate ultra-short longitudinal structures (shorter than 20 nm) in the phase space and then scattering with an incident laser with 2 mm wavelength. The scattered radiation is significantly improved compared with the case using beam without phase-merging. Transverse emittance could be a possible limitation to this method. However, by increasing the dispersion strength of dog-leg, coherent radiation can still be obtained.

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