Interaction of super intense laser pulses with thin foil: Doppler transformation of coherent light into X-ray and gamma-ray bands

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Abstract

The formation of relativistic electron mirror produced via ionization of thin solid target by ultraintense femtosecond laser pulse is considered with the help of computer simulations. It is shown that the reflection of weak counter-propagating wave from such a mirror can produce the coherent radiation in x-ray and gamma-ray bands. The spectrum of up-conversed radiation is investigated.

1 Introduction

Production of coherent short wavelength electromagnetic radiation in X-ray and gamma-ray bands attracts great attention during last decades [1,2]. Different physical mechanisms have been considered as candidates for practical implementation of this process: generation in free-electron lasers [3-5], X-ray and γ-ray lasing [1,2,6-8], high optical harmonics generation in gases [9,10] and solids [11-13], and others. Most of the schemes imply the use of the powerful lasers as part of the system so the investigations received large impetus last years due to experimental realization of ultraintense femtosecond laser pulses [14]. In this paper we consider the Doppler up-conversion of laser light into the X-ray or γ-ray bands with the help of relativistic electron mirror produced during interaction of high intensity ultrashort optical pulse with thin solid target in vacuum.

The idea for generation of high frequency coherent electromagnetic radiation by Doppler transformation of the incident wave was proposed by Landecker [15]. Actually when the light reflects from relativistic mirror its frequency and amplitude increase by the factor $(1 + v/c)/(1 - v/c)$, where $v$ is the velocity of the mirror and $c$ is the light velocity. So for $v/c \approx 1$ the
frequency increase can be very large. Additional benefit of such scheme is its tunability because the frequency of resulting radiation depends on the velocity of the mirror which can be simply adjusted. The only problem is how to produce such a relativistic mirror. Obviously it have to be pure electronic because ordinary neutral matter cannot be accelerated to ultrarelativistic velocities in laboratory. The breakthrough in this problem became possible due to experimental realization of femtosecond laser pulses of very high intensity. During interaction of this pulse with thin foil the electrons of the latter can be accelerated to ultrarelativistic velocities keeping the initial geometrical form of the foil and constituting the required relativistic mirror.

Acceleration of electron bunch produced by ionization of thin solid target with femtosecond laser pulse was considered in details in [16]. Here in section 1 we reproduce only the results which are important for the problem of light up-conversion, in section 2 the process of light reflection from relativistic electron mirror will be considered.

2 Formation of relativistic electron mirror

Let the medium is uniform in directions perpendicular to $Oz$ axis. Then it can be modeled by a set of parallel planes (electron sheets) with constant surface density of electrons. Each plane is supposed to have infinite dimensions in $x$ and $y$ directions. If the movement of each plane is without rotations and deformations then all variables depend only on coordinate $z$ and time $t$ and the 1D3V model can be used for the system: the movement of the planes can be described by three components of velocity $\beta_x = V_x/c, \beta_y = V_y/c, \beta_z = V_z/c$ and one coordinate $Z$ [17]. In present paper the analytical-numerical variant of 1D3V model is used which reduces to the system of ordinary differential equations with delay.

Charge density and current are described by the following formulas for the electron sheet ($\sigma$ is a surface charge density)

$$\rho(z, t) = \sigma \delta(z - Z(t)) \quad j(z, t) = \sigma v(t) \delta(z - Z(t))$$ (1)

where $Z(t)$ is $z$ coordinate of a sheet. Then the solutions of Maxwell equations for the radiation fields of the medium at coordinate $z$ and time $t$ can be obtained with the help of Green function and have the form [18]
\[ E_z(z, t) = 2\pi \sigma \text{sign}(z - Z(t')) \]
\[ E_\perp(z, t) = -2\pi \sigma \frac{\beta_\perp(t')}{1 - \beta_z(t')\text{sign}(z - Z(t'))} \]
\[ H(z, t) = 2\pi \sigma \text{sign}(z - Z(t')) \frac{[\beta_\perp(t'), e_z]}{1 - \beta_z(t')\text{sign}(z - Z(t'))} \]

where \( E_\perp = E_{xe}e_x + E_{ye}e_y, v_\perp = v_xe_x + v_ye_y, \beta = v/c \) and \( t' \) - is a retarded time: \( c(t - t') = |z - Z(t')| \). The resulting radiation field \( E_s, H_s \) for the thin charged layer is the sum of radiation fields of all electron sheets (note that the retarded time \( t' \) is different for different sheets). Interaction of each electron sheet with the radiation field of the layer results in appearance of self-action viscous force \( F_s = eE_s + e[\beta, H_s] \), which modifies the dynamics of the sheet. This force is analogous to the Dirac force acting on the moving electron.

The equations of motion for the electrons in the sheets have now the following form

\[ \frac{dp}{dt} = eE + e[\beta, H] + F_s, \]

where \( e \) is the charge of the electron, \( p \) is relativistic momentum of electrons, \( E \) and \( H \) are the external fields (it is supposed that these fields support the geometry of electron medium). It is worth to mention that the radiation reaction force \( F_s \) have not only the transverse component but the longitudinal component as well the last having essentially nonlinear character. For infinitely thin electron sheet the self action force is

\[ F_{s\perp} = -2\pi \sigma e\beta_\perp, \quad F_{sz} = -2\pi \sigma e\beta_\perp^2 \beta_z/(1 - \beta_z^2), \]

Let now consider the ultraintense plane electromagnetic wave with frequency \( \omega \) falling normally at the layer (wave vector \( k \) is parallel to the \( Oz \) axis) so that an acceleration parameter of the wave \( \alpha_0 = eE_0/(m\omega c) \gg 1 \), where \( m \) is the mass of an electron, \( E_0 \) is the amplitude of the wave field. Then the electrons of the layer will accelerate in the \( z \) direction to ultrarelativistic velocities just by the first half wave keeping initial geometry of the bunch [16].

Account for the layer radiation friction force give some interesting features to the motion of the electrons inside the layer. First of all an additional
accelerating force emerges which constitutes the mean value of the Lorentz force. Actually in this situation the mean Lorentz force is nonzero due to the extra phase shift between the electromagnetic wave and the electrons’ velocities arising from the action of radiation friction force (scattering of incident wave). At fig. 1 the light pressure force acting on the electron layer is presented for the motion in the given field (fig. 1a, $\alpha = 0$) and with account of the radiation losses (fig. 1b, $\alpha = 0.1$), where the parameter $\alpha = 2\pi \sigma e/(m\omega c)$ characterizes the electron density of the bunch. The amplitude of the external wave is not large $\alpha_0 = 2$ besides the coulomb interaction of the electrons is omitted. Fig. 1 demonstrates that the mean Lorentz force is not equal to zero: the deviation of the line to the up is larger than to the down. Besides the increasing period of the force corresponds to the increasing longitudinal velocity of the electron layer so that the effective interaction time of the layer with each half wave is also increasing. For the motion in the given field the frequency of Lorentz force and the mean velocity of electron layer are constants.

Another peculiarity due to account of the radiation friction force is the emergence of the bunching forces which compress the layer in the $z$ direction and support its initial geometry [16]. These forces slow down the electron sheets with velocities larger than the mean velocity of the layer and accelerate the delaying sheets (fig. 2). At fig. 2a the bunching effect of the radiation friction force is not taken into account and the coulomb forces tear the layer during very short time. At fig. 2b the coulomb forces and the bunching forces are taken into account simultaneously so the layer is stable for considerably longer time. The stability of the layer geometry depends on the value of accelerating parameter $\alpha_0$, initial thickness of the layer and a value of electron density inside the bunch. Such bunching forces can compensate partially the coulomb spread of the layer along the $z$ direction (increase of the bunch thickness) and appear to be in a sense analogous to the magnetic attraction forces between two parallel currents formed by the moving charges.

One has to account for an action of an ion background of the target for proper simulation of the process of interaction between electromagnetic wave and dense plasma layer in the 1D3V model [16]. Actually this model is adequate in case when the distance between the electron and ion layers is considerably smaller than the transverse dimensions of the layers. In our simulations below the ion background is supposed to be motionless producing only the Coulomb force acting on the electron layer.

The initial thickness of the target used in simulations is $l = 10^{-2}\mu$ and
considerably smaller than the wavelength of the incident radiation which is \( \lambda = 1 \mu \). The targets with such thickness can be easily obtained experimentally [20] besides the front of ultraintense laser pulse squeezes the electron layer in the \( z \) direction making it thickness considerably smaller than initial thickness of the target [16,21].

At fig. 3 the results of computer simulations for the process of electron layer acceleration are presented (the parameter \( \alpha = 1 \) in the fig. 3a and \( \alpha = 0.001 \) in the fig. 3b). At the upper plots the dependence of transverse momenta \( p_y \) for some electron sheets of the bunch on dimensionless laboratory time \( \omega t \) are presented and at the lower plots the longitudinal momenta \( p_z \) are shown. The acceleration parameter \( \alpha_0 = 100 \). So all electron sheets of the layer can in principle move synchronously during acceleration by the first half cycle of electromagnetic wave constituting the relativistic electron mirror. For other half cycles of the incident laser pulse the bunch can be destroyed for large parameter \( \alpha \) by the coulomb forces however for small \( \alpha \) values the bunch can be stable during several half cycles that in laboratory frame can correspond to the time of several hundreds of femtosecond. So in the process of interaction of ultraintense femtosecond laser pulse with thin solid target the relativistic electron mirror can be formed allowing to realize the up-conversion of light into X-ray and gamma-ray bands.

3 Up-conversion of counter propagating wave

Let now consider the simulation of the wave transformation for weak counter-propagating wave with an amplitude \( E_1 (\alpha_1 = eE_1/(m\omega c)) \) and frequency \( \omega_0 \) (for simplicity we suppose that the frequencies of accelerating and counter-propagating waves are equal). At fig. 4a the frequency transformation factor \( f_v = (1 + \beta_z)/(1 - \beta_z) \) is presented. The plot of \( p_y \) in the presence of counter propagating wave is shown at fig. 4b. The parameter \( \alpha_1 = 1 \), the front of this pulse have a delay with respect to accelerating pulse for the electrons can achieve high energy and become ultra relativistic. The zoom of electron oscillations at the top of fig. 4b is presented at fig. 4c. It is worth to mention that all electron sheets move practically along one trajectory so the dependencies of \( p_y \) on time for different sheets are coincide.

At fig. 5a the reflected radiation of the counter-propagating wave is presented for \( \alpha = 0.1 \), \( \alpha_0 = 100 \) and \( \alpha_1 = 1 \). Due to the time dependence of transformation factor \( f_v \) the frequency of reflected wave have to be altering
being small at the beginning of the acceleration process then largest at the
top of the first half wave and small again at the end of the first half wave.

At fig. 5b the zoom of the reflected field is shown (sample 2). The devi-
ation of the radiation field from sinusoidal form results from high harmonics
generating during the reflection of the counter-propagating wave from rela-
tivistic electron bunch and partially from the simulation numerical errors.

At fig. 5c the spectra of the samples of equal length at the slope (1)
and at the top (2) of the first half wave of accelerating pulse are presented
(the amplitude and the frequency of the reflected wave are normalized to the
amplitude and the frequency of the incident accelerating wave). The carrying
frequencies in two cases are different due to the different transformation factor
\( f_v \) (cf. fig. 4a), besides the spectral bandwidth for sample 1 is larger than
for sample 2 because of the faster change of frequency at the slope.

The amplitude of the reflected wave depends on the values of parameters \( \alpha \)
and \( \alpha_0 \). For smaller value of parameter \( \alpha \) the amplitude of the reflected wave
is smaller because of the lower electron density in the bunch and correspond-
ingly low value of reflection coefficient. On the other hand the frequency
transformation coefficient is larger for small \( \alpha \) value the parameter \( \alpha_0 \) being
constant because of smaller radiation friction (cf. fig. 3).

For \( \alpha_0 = 30 \) that can be realized in modern experiments the maximum
frequency transformation factor \( f_v \) can be about \( 4\alpha_0^2 \approx 2000 \) so the reflection
of incident wave with wavelength \( \lambda = 200nm \) can give the coherent radiation
from the X-ray band. For petawatt lasers the acceleration parameter \( \alpha_0 \) can
be about \( 100 \div 200 \) so the reflected coherent radiation can be already in the
\( \gamma \)-ray band.

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Captions for the figures

Fig. 1. Force acting on the electron sheet for $\alpha_0 = 2$ in the given field (a, $\alpha = 0$) and in account of radiation losses (b, $\alpha = 0.1$).

Fig. 2. Longitudinal momenta $p_z$ for several electron sheets ($\alpha_0 = 100$, $\alpha = 1$) with accounting of the coulomb forces only (a) and the radiation friction forces and the coulomb forces (b).

Fig. 3. Transverse $p_y$ and longitudinal $p_z$ momenta for several electron sheets for acceleration of the electron layer in vacuum by the intense electromagnetic wave ($\alpha_0 = 100$): $\alpha = 1$ for fig. 3a and $\alpha = 0.001$ for fig. 3b. The thickness of the layer in the $z$ direction is considerably smaller than $\lambda$ for both cases.

Fig. 4. Frequency transformation factor (a), transverse momentum (b) and the zoom of electron momentum oscillations (c) for the small counter-propagating wave falling at the electron mirror. The trajectories of all electron sheets practically coincide. The counter-propagating wave strikes the electron mirror at $\omega t = 1570$.

Fig. 5. The reflected field (a), zoom of the field (b) and the spectra (c) of two samples 1 and 2 from different regions of the accelerating curve.
Fig. 1a

Fig. 1b
Fig. 2a

Fig. 2b
\( \frac{(1+\beta z)}{(1-\beta z)} \)
Fig. 4c

$P_y/(mc^2)$ vs $\omega t$
Fig. 5a

\[ \frac{E}{E_0} \]

\[ \omega_t \]

Points 1 and 2 on the curve.
$E(\omega)/E_0$ vs $\omega/\omega_0$ for various $\omega_0$ values.