

Theoretical investigation of the ultra-intense laser interaction with plasma mirrors in radiation pressure dominant regime

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Abstract. At laser intensity in the range $\sim 10^{22}$ - 10^{23} W/cm², the radiation pressure starts to play a key role in the interaction of an intense electromagnetic wave with a dense plasma foil. Depending upon the incident laser intensity, polarization of the incident beam and also on the density of the thin plasma layer the mirror motion may be assumed to be uniform, accelerated, or oscillatory. A solid dense plasma slab, accelerated in the radiation pressure dominant (RPD) regime, can efficiently reflect a counter-propagating relativistically strong source pulse consisting of up-shifted frequency and high harmonics. In this RPD regime we present our numerical results for the frequency and brightness of the reflected radiation from a uniformly moving plasma mirror. Our numerical results show that for the appropriate laser and plasma parameters in the case $2\gamma < (n_e \lambda_s^3)^{1/6}$ there are approximately 8.03×10^{42} photons / (mm² - mrad² - sec. - 0.1% bandwidth) in the energy range ~ 10 keV. In the case when $2\gamma > (n_e \lambda_s^3)^{1/6}$ for the same parameters and $a_d = 300$, $\lambda_d = 0.8 \mu\text{m}$, the brightness is found to be 3.27×10^{34} photons / (mm² - mrad² - sec. - 0.1% bandwidth) in the energy range ~ 100 keV.

1. Introduction

With the availability of a new range of laser intensities by the development of CPA (chirped pulse amplification) technique has revived interest in high harmonic generation (HHG) from plasmas [1]. The ultra-short and relativistically strong laser pulses provided by CPA turn a solid target almost immediately into overdense plasma [2]. Because of the huge radiation pressure associated with laser intensities $\sim 10^{22}$ - 10^{23} W/cm², combined with ponderomotive force and Coulomb attraction of ions, the plasma electron fluid moves with relativistic velocity and acts as relativistically moving mirror [3]. Depending upon the incident laser intensity, polarization of the incident beam and also on the density of the thin plasma layer the mirror motion may be assumed to be uniform, accelerated, or oscillatory [4]. In the case if an accelerated dense thin plasma slab meets a counter-propagating intense laser pulse, the reflected laser pulse is compressed in the longitudinal direction, intensified, and its frequency is Doppler-upshifted by a factor of $4\gamma^2$ [5]. This phenomenon is of great interest for developing compact sources of coherent radiation in the ultraviolet and X-ray range of photo energies [6]. X-ray sources have a broad range of applications from single-molecule imaging to medicine, oncological hadron therapy [7] and they are required in material science and for the investigation of fundamental science problems such as in nonlinear quantum electrodynamics (QED) [4]. In the present paper we consider analytically and numerically the interaction of a uniformly moving plasma mirror with a counter-propagating intense plane electromagnetic wave (source wave) at normal/oblique incidence. In this paper we give our numerical results of the brightness of a source. The numerical results of the spectral brightness of the reflected radiation from a uniformly moving



plasma mirror as a function of the photon energy are obtained under the assumption $2\gamma < (n_e \lambda_s^3)^{1/6}$ and also in the opposite case when $2\gamma > (n_e \lambda_s^3)^{1/6}$.

2. Reflection of electromagnetic wave from an uniformly moving thin plasma foil

An electromagnetic wave incident on an infinitely thin plasma foil, representing a mirror moving along x -axis represented by the coordinate $X_M(t)$, satisfies the wave equation [4,8]

$$\frac{\partial^2 A}{\partial t^2} - c^2 \frac{\partial^2 A}{\partial x^2} + \frac{4\pi e^2 n_e l \delta(x - X_M(t))}{m_e \gamma} A = 0, \quad (1)$$

where A is the vector potential, n_e is initial electron density, l is thickness of plasma slab, m_e is the mass of electron and $\gamma = [1 - \dot{X}_M^2 c^{-2}]^{-1/2}$. Introducing the dimensionless variables $\bar{x} = kx$, $\bar{t} = ckt$ and new variables $\xi = (\bar{x} - \bar{t})/2$, $\eta = (\bar{x} + \bar{t})/2$, equation (1) becomes

$$\frac{\partial^2 A}{\partial \eta \partial \xi} = 2n_e l \frac{e^2}{m_e c^2} \left(\frac{2\pi}{k} \right) \frac{\delta(\psi(\xi, \eta))}{\gamma(\xi, \eta)} A, \quad (2)$$

where $\psi(\xi, \eta) = (\eta + \xi - X_M(\eta - \xi))$. Solution of equation (2) with proper boundary conditions at the plasma interface can be written in the form of two differential equations [9]

$$a'_1(\xi) = \chi(a_1(\xi) + a_0 e^{2i\eta_0(\xi)})F(\xi, \eta_0(\xi)), \quad (3)$$

$$2ia_0 e^{2i\eta_0(\xi)} - a'_2(\eta) = \frac{\chi}{F(\xi_0(\eta), \eta)} a_2(\eta). \quad (4)$$

Here a_0 , $a_1(\xi)$ and $a_2(\eta)$ are the incident, reflected and transmitted wave amplitudes respectively, plasma density parameter $\chi = 2n_e l r_e \lambda$, $\lambda = (2\pi/k)$, r_e is the classical radius of electron and $F = \left[\frac{1 + X'_M(\eta - \xi)}{1 - X'_M(\eta - \xi)} \right]^{1/2}$. Solution of the equation (3) for the uniformly moving mirror gives the reflected wave amplitude [8, 9]

$$a_1 = -a_0 \frac{\chi}{\chi + 2iF_0} \exp(-2iF_0^2 \xi). \quad (5)$$

The expression for the reflection coefficient is given by $R = |a_1/a_0|^2 = \chi^2 / (\chi^2 + 4F_0^2)$. (6)

Similarly transmission coefficient can be calculated by the relation $R + T = 1$, where $n_e = 480 n_{cr} = 5.4 \times 10^{23} \text{ cm}^{-3} \times (1 \mu\text{m} / \lambda)^2$, $l = 0.01 \lambda$, $r_e = 2.8 \times 10^{-13} \text{ cm}$, $\lambda = 0.8 \mu\text{m}$, $F_0 = (1 + \beta_M / 1 - \beta_M)^{1/2}$. The frequency of a reflected wave depends on the incidence angle and the mirror velocity as

$$\omega_r = \omega_0 \frac{1 + 2\beta_M \cos \theta_0 + \beta_M^2}{1 - \beta_M^2}. \quad (7)$$

Depending on whether the wave and mirror are co-propagating ($\beta_M < 0$) or counter-propagating ($\beta_M > 0$) in the lab-frame, we have either the frequency downshift or frequency upshift. In the simplest configuration of normal incidence of the wave on the mirror ($\theta_0 = 0$), then

$\omega_r = \omega_0 (1 + \beta_M / 1 - \beta_M) = \omega_0 (1 + \beta_M)^2 \gamma^2$, where $\gamma = (1 - \beta_M^2)^{-1/2}$. In the ultra-relativistic limit $\gamma \gg 1$, the reflected wave frequency is higher by a factor $\approx 4\gamma^2$.

3. Spectral brightness

A light beam from a finite source can be characterized by its beam divergence $\Delta\Omega$, source size (usually surface area A), spectral power density $P(\nu)$ (watts per hertz of bandwidth). From these parameters it is useful to determine the "spectral brightness β_ν " of the source, which is defined as the

power flow per unit area, per unit band width, and steradian namely $\beta_\nu = P_\nu / A \Delta \Omega \Delta \nu$. If dS denotes the elemental surface area of the source, the power dP emitted by dS into the solid angle $d\Omega$ around a direction making the angle θ with respect to the surface, can be written as $dP = B \cos \theta dS d\Omega$, where B is the brightness.

For mirror velocities greater than some critical value $(2\gamma) > (n_e \lambda_s^3)^{1/6}$, the wavelength of the reflected light from the moving mirror in the frame of the mirror becomes shorter due to relativistic Doppler effect. In this case the scattering of light from the plasma mirror electrons is incoherent and corresponding brightness [4] is given by $B \approx a_d \varepsilon_s (\hbar \omega_r)^2 r_e \lambda_s^2 / 8\pi^4 \hbar^3 c^2 \lambda_d^3$, where ε_s is source pulse energy, a_d is the dimensionless vector potential of driver pulse, λ_s is the source pulse wavelength and λ_d is the wavelength of driver pulse. The coherent scattering occurs when the condition $(2\gamma) < (n_e \lambda_s^3)^{1/6}$ is satisfied [4] and corresponding brightness is given by $B \approx \varepsilon_s (\hbar \omega_r)^3 \lambda_s / 4\pi^5 \hbar^4 c^3$. In both the cases one can get bright high frequency radiation source.

4. Results and discussions

Figure 1 shows the variation of the frequency of the reflected wave (ω_r / ω_0) when the counter-propagating laser pulse from the source meets the plasma mirror at an angle θ for a given mirror velocity $\beta_M = 0.999$.

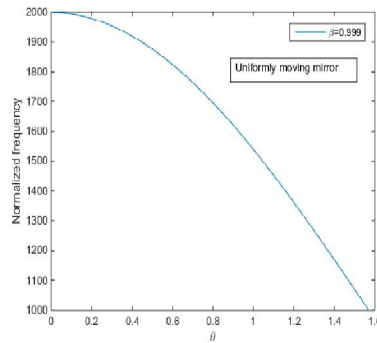


Figure 1. Figure showing the variation of normalized frequency of the reflected radiation versus incidence angle of the mirror.

Figure (2) shows the variation of brightness of the reflected radiation versus energy of the reflected photon in the case when $2\gamma < (n_e \lambda_s^3)^{1/6}$ for different values of source pulse energy ε_s . From this figure we see that in the coherent interaction for the parameter $\lambda_s = \lambda = 0.8 \mu m$, maximum brightness corresponding to 10 keV photon energy is approximately 4.82×10^{42} photons / (mm² - mrad² - sec. - 0.1% bandwidth) for $\varepsilon_s = 6$ J, 6.43×10^{42} photons / (mm² - mrad² - sec. - 0.1% bandwidth) for $\varepsilon_s = 8$ J, 8.03×10^{42} photons / (mm² - mrad² - sec. - 0.1% bandwidth) for $\varepsilon_s = 10$ J, and 9.64×10^{42} photons / (mm² - mrad² - sec. - 0.1% bandwidth) for $\varepsilon_s = 12$ J. This energy of the reflected photon is corresponding to the energy of hard X-ray source. Figure (3) shows the variation of brightness of the reflected radiation versus energy of the reflected photon in the case when $2\gamma > (n_e \lambda_s^3)^{1/6}$ for different values of source pulse energy ε_s . In this case when the mirror is moving uniformly, the reflection of the photons are incoherent. From this figure we see that in the incoherent interaction using parameters $\lambda_s = \lambda_d = 0.8 \mu m$, $a_d = 300$, and $r_e = 2.8 \times 10^{-13}$ cm maximum brightness corresponding to 100 keV photon energy is approximately 1.96×10^{34} photons / (mm² - mrad² - sec. - 0.1% bandwidth)

for $\varepsilon_s = 6$ J, 2.62×10^{34} photons / (mm² - mrad² - sec. - 0.1% bandwidth) for $\varepsilon_s = 8$ J, 3.27×10^{34} photons / (mm² - mrad² - sec. - 0.1% bandwidth) for $\varepsilon_s = 10$ J, and 3.93×10^{34} photons / (mm² - mrad² - sec. - 0.1% bandwidth) for $\varepsilon_s = 12$ J. This energy of the reflected photon is corresponding to the energy of gamma- ray.

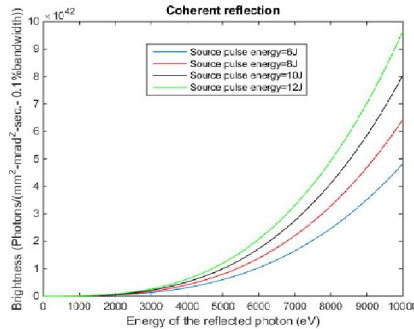


Figure 2. Variation of brightness of the reflected radiation versus energy of the reflected photon in the case

$2\gamma \langle n_e \lambda_s^3 \rangle^{1/6}$ when mirror is moving uniformly for different values of source pulse energy $\varepsilon_s = 6$ J, 8 J, 10 J, 12 J

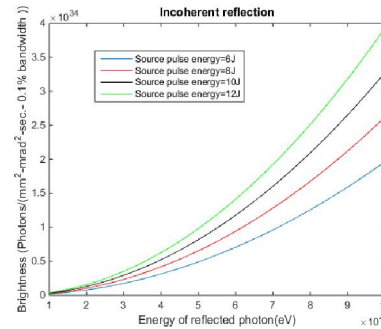


Figure 3. Variation of brightness of the reflected radiation versus energy of the reflected photon in the case

$2\gamma \langle n_e \lambda_s^3 \rangle^{1/6}$ when mirror is moving uniformly for different values of source pulse energy $\varepsilon_s = 6$ J, 8 J, 10 J, 12 J

5. Conclusions

A solid dense plasma slab, accelerated in the RPD regime, can efficiently reflect a counter-propagating relativistically strong source pulse consisting of up-shifted frequency and high harmonics. This reflected source pulse is chirped due to mirror acceleration. Our numerical results for brightness show that when the plasma mirror velocities are greater than some threshold then the distance between electrons in the slab becomes longer than the incident wavelength so the reflection from plasma slab is not coherent. In effect, one can develop a compact source of high-brightness X-rays and short gamma rays.

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