Proceedings of International Conference on "Recent Innovations in Engineering, Technology
& Science for Sustainable Development (RIETSSD-2026)"
Career Point International Journal of Research (CPIJR)
©2022 CPIJR | Special Issue | ISSN : 2583-1895
Conference Paper | DOI: https://doi.org/10.5281/zenodo.20694920

Study of Ultra-Intense Laser Interaction with Oscillating Plasma Mirrors in the Radiation Pressure Dominated Regime

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Abstract*:* At laser intensities on the order of 10^{22}–10^{23} W/cm^2, radiation pressure becomes the dominant mechanism governing the interaction between an ultra-intense electromagnetic wave and a dense plasma foil. The dynamical response of the plasma mirror depends sensitively on the incident laser intensity, the polarization of the electromagnetic field, and the density of the thin plasma layer; under appropriate conditions, the mirror motion may be treated as oscillatory. A solid, high-density plasma slab accelerated in the radiation-pressure-dominated (RPD) regime can efficiently reflect a counter-propagating, relativistically intense source pulse, leading to significant frequency up-shifting and the generation of high-order harmonics. Within this RPD framework, we present analytical and numerical investigations of the frequency spectrum, reflectivity, and brightness of radiation reflected from an oscillating plasma mirror.

Keywords: laser-plasma interaction, Radiation pressure dominant regime, plasma mirror, coherent radiation, X-ray generation

I. 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 ~ 10^{22} - 10^{23} W/cm^2, 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 [4-6]. 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 $4\gamma^2$ [7]. This phenomenon is of great interest for developing compact sources of coherent radiation in the ultraviolet and X-ray range of photo energies [8, 9]. X-ray sources have a broad range of applications from single-molecule imaging to medicine, oncological hadron therapy [10] and they are required in material science and for the investigation of fundamental science problems such as in nonlinear quantum electrodynamics (QED) and relativistic astrophysics [11].

In the present paper we consider analytically and numerically the interaction of a oscillating plasma mirror with a counter-propagating intense plane electromagnetic wave (source wave) at normal/oblique incidence . The role of the mirror is played by a high density plasma slab which is accelerated as a whole by an ultra-intense laser pulse (the driver) in the RPD regime [12-14].

In this paper we present our numerical results of frequency up-shift of the reflected wave as a result of the interaction of the counter-propagating intense laser pulse with a oscillating plasma mirror. The role of the plasma mirror is played by a high density plasma slab which is accelerated as a whole by an ultra-intense laser pulse (the driver) in the RPD regime [4, 16]. In the case of oscillating mirror the change in the frequency and amplitude of reflected laser pulse occurs due to double Doppler effect [17-18].

The paper is organized as follows: In section 2 of the paper we review the basic equations of intense laser-thin foil interaction. Expressions for the frequency and amplitude of the reflected wave from an oscillating plasma mirror are derived. Section3 of the paper deals with the brightness of the reflected radiations. Numerical results and discussion are given in section 4. Conclusions are drawn in the last section.

II. OSCILLATING MIRROR

We consider a thin electron layer oscillating under the action of a linearly polarized electromagnetic wave with the electric field in the y-direction:

$$E_y = E_0 \cos\left(\Omega v\right). \tag{1}$$

The source pulse is reflected from the electron layer which forms the mirror. To describe the electron layer motion, we use the results of an exact solution of the problem of the electric charge dynamics in the field of an electromagnetic wave as [19]:

$$x = \frac{e^2 c E_0^2}{8\gamma^2 \Omega^3} \sin 2\eta, \qquad y = \frac{c e E_0}{\gamma \Omega^2} \cos\eta, \quad z = 0,$$

$$t = v + \frac{e^2 E_0^2}{8\gamma^2 \Omega^3} \sin 2\eta, \quad \text{and} \quad \gamma^2 = m_e^2 c^2 + \frac{e^2 E_0^2}{2\Omega^2}.$$

(2)

Here, normalized amplitude of the wave is $a_0 = \frac{e E_0}{m_e \Omega c}$, e is the electron charge, m_e is the mass of the electron, and $\eta = \Omega v$. Using these solutions, we can calculate the phase $\psi_r(u) = \omega_0 \left(2t(u) - u\right)$ and frequency $\omega_r = \omega_0 \frac{1+\beta}{1-\beta} = 1 + \frac{a_0^2 \cos 2\eta}{\left(2 + a_0^2\right)}$ of the reflected wave. The electric field of the reflected wave will be given by $\frac{E_r}{E_0} = \frac{\omega_r}{\omega_0} \cos\left(\psi_r(t)\right)$.

The oscillating mirror model describes the case when the laser pulse interacts with the electron layer oscillating with the amplitude comparable to the laser wavelength. As a result the reflected wave frequency spectrum is enriched with high order harmonic: $\omega_0 / 4\gamma^2 < \omega_r < 4\gamma^2 \omega_0$. In the coordinate space the reflected wave packet comprises attosecond pulse. The electromagnetic pulse width for optimal conditions scales as $\delta t = \frac{1}{\omega_r a_0}$ [20]. The reflection coefficient in terms of the reflected photon number scales as $\sim \gamma^{-3}$ [4]. Taking into account the volume change where the reflected laser pulse is localized, the intensity of the reflected electromagnetic wave is given by $I_r \approx 32 I_0 \left(D_0 / \lambda_0\right)^2 \gamma^3$, where D_0 is the reflected beam diameter [4].

III. BRIGHTNESS CHARACTERISTICS OF THE REFLECTED RADIATION

Brightness of a source is defined by the light energy emerging from a portion of an illuminated surface of a solid. 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. Considering a diffraction-limited laser beam of power P, with a circular cross section of diameter D and with a divergence θ_d, then $P = 2\pi S \int_0^{\theta_d} B\cos\theta \sin\theta\, d\theta = \frac{1}{2}\pi B S\left[1 - \cos 2\theta_d\right]$, where the beam cross-section is given by $S = \pi D^2/4$. Since θ_d is small, we can express $P \approx \pi B S \theta_d^2$, where angle of diffraction $\theta_d = \beta\lambda/D$, and β=1.22 for diffraction due to a circular aperture. This reduces to $B = \left(2/(\pi\beta\lambda)\right)^2 P$.

For mirror velocities greater than some critical values $(2\gamma) > \left(n_e\lambda_s^3\right)^{1/6}$, the wavelength of the reflected light from the moving mirror in the frame of the mirror becomes shorter due to relativistic Doppler effect. Here, n_e is the electron density, and λ_s is the wavelength of the source laser pulse. So the scattering of light from the plasma mirror is incoherent. The intensity of the reflected wave is proportional to the number of electrons. The coherent scattering occurs when the condition $(2\gamma) < \left(n_e\lambda_s^3\right)^{1/6}$ is satisfied [4]. In both the above cases one can get bright high frequency radiation source.

The expression for the brightness for the case of coherent reflection, i.e., when $(2\gamma) < \left(n_e\lambda_s^3\right)^{1/6}$ is given by $B_M \approx \frac{\varepsilon_s(\hbar\omega_r)^3\lambda_s}{4\pi^5\hbar^4c^3}$, and in the case when γ is very large, i.e., $(2\gamma) > \left(n_e\lambda_s^3\right)^{1/6}$ then the interaction becomes incoherent and corresponding brightness is given by $B_T \approx \frac{a_d\,\varepsilon_s(\hbar\omega_r)^2 r_e\lambda_s^2}{8\pi^4\hbar^3c^2\lambda_d^3}$, where $\hbar\omega_r$ is the energy of the reflected photon, ε_s is source pulse energy, a_d is the dimensionless vector potential of driver pulse, r_e is the classical radius of the electron, and λ_d is the wavelength of the driver pulse [4].

IV. RESULTS AND DISCUSSIONS

Numerical results are obtained by making use of MATLAB software for the following set of parameters of the laser pulse and thin dense plasma foil; source pulse wavelength $\lambda_s = 800 nm$, driver pulse wavelength $\lambda_d = 800 nm$, driver laser pulse amplitude $a_d = 300$ which is corresponds to $I \approx 10^{23} W/cm^2$.

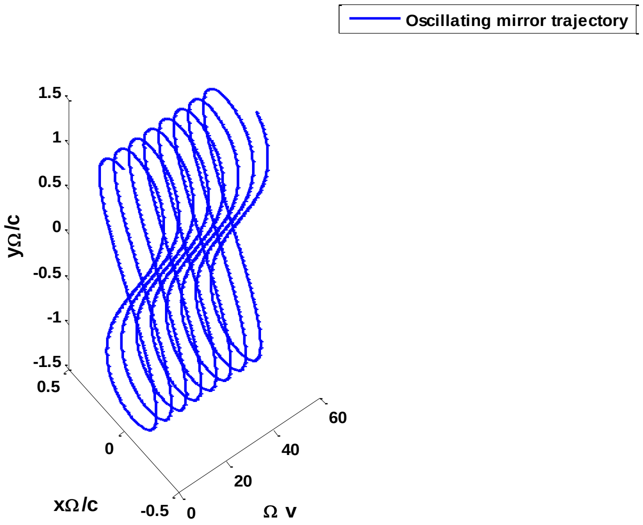

Fig. 1 Trajectory of the oscillating mirror for $a_0 = 10$.

Fig. 1 shows the trajectory of an electron in the field of linearly polarized electromagnetic wave in case of oscillating mirror. Fig. 2 shows the variation of brightness of the reflected radiation with energy of the reflected photons in the case when $2\gamma < \left(n_e \lambda_s^3\right)^{1/6}$ for different values of source pulse energy ε_s. From this figure we see that in the case of coherent interaction for the parameters $\lambda_s = \lambda = 0.8 \mu m$, n_e = 480 n_{cr} = 5.4×10^{23} cm^{-3} $\times$ $(1 \mu m / \lambda)^2$, maximum brightness corresponding to 10 keV photon energy is found to be ~ 4.82 $\times 10^{42}$ photons / (mm^2 - mrad^2 - sec. - 0.1% bandwidth) for the source pulse energy ε_s = 6 J, 6.43 $\times 10^{42}$ photons / (mm^2 - mrad^2 - sec. - 0.1% bandwidth) for ε_s = 8 J, 8.03 $\times 10^{42}$ photons / (mm^2 - mrad^2 - sec. - 0.1% bandwidth) for ε_s = 10 J, and 9.64 $\times 10^{42}$ photons / (mm^2 - mrad^2 - sec. - 0.1% bandwidth) for ε_s = 12 J. This energy of the reflected photon is corresponding to the energy of hard X-ray source.

Fig. 3 shows the variation of brightness of the reflected radiation with energy of the reflected photon in the case when $2\gamma > \left(n_e \lambda_s^3\right)^{1/6}$ 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 and corresponding scattering is Thomson scattering. From this figure we see that in the case of incoherent interaction using parameters $\lambda_s = \lambda_d = 0.8\mu m$, n_e = 480 n_{cr} = $5.4\times10^{23}\text{cm}^{-3}\times\left(1\mu m/\lambda\right)^2$, $a_d = 300$, maximum brightness corresponding to 100 keV photon energy is found to be ~ 1.96×10^{34} photons / (mm^2 - mrad^2 - sec.- 0.1% bandwidth) for ε_s = 6 J, 2.62×10^{34} photons / (mm^2 - mrad^2 - sec.-0.1% bandwidth) for ε_s = 8 J, 3.27×10^{34} photons / (mm^2 - mrad^2 - sec. - 0.1% bandwidth) for ε_s = 10 J, and 3.93×10^{34} photons / (mm^2 - mrad^2 - sec. - 0.1% bandwidth) for ε_s = 12 J. This energy of the reflected photon is corresponding to the energy of gamma- ray.

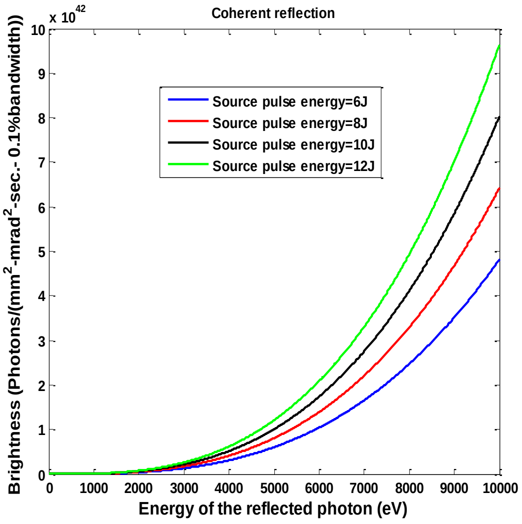

Fig. 2 Variation of brightness of the reflected radiation with energy of the reflected photon for coherent interaction for the source pulse energy ε_s =6J, 8J, 10J, 12J.

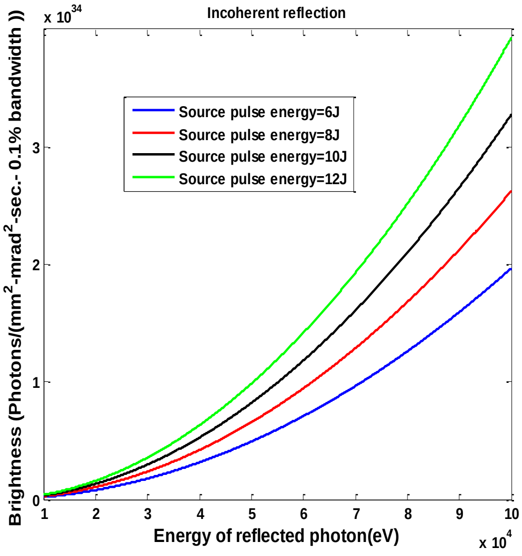

Fig. 3 Variation of brightness of the reflected radiation with energy of the reflected photon for incoherent interaction for the source pulse energy ε_s =6J, 8J, 10J, 12J.

V. CONCLUSIONS

A dense plasma foil moving with ultra-relativistic velocity can efficiently reflect a counter-propagating relativistic laser pulse. The frequency of the reflected radiation is Doppler upshifted by a factor of $4\gamma^2$. Numerical results for brightness show that when the plasma mirror velocities are greater than a threshold value, the distance between the electrons in the plasma slab becomes longer than the incident wavelength resulting in the incoherent reflection of the laser pulse. Using this technique one can develop a compact source of high-bright X-rays and short gamma rays which have tremendous applications.

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