

Bright gamma-ray source from intense laser pulses obliquely incident on a plasma layer

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Generation of gamma-rays and hard X-rays is currently expected to be one of the most useful applications of high-intensity laser-matter interaction. The intensities that are required for that process are of the order of $10^{22} - 10^{23}$ W/cm² that are either available now or will be available in a few years. At such intensities, the target almost fully ionizes, electrons experience the strong laser field and accelerate up to very high energies (so their Lorentz factor can easily exceed several hundreds). In this case, the primary mechanism of energy loss by the electrons is synchrotron radiation. The radiation properties strongly depend on the interaction layout; particularly, it is demonstrated [1] that oblique incidence of the laser pulse onto a flat solid target can increase the gamma-ray generation efficiency (with respect to the case of normal incidence). In this work, we investigate the regime of oblique incidence in more detail; we find regions of parameters that correspond to the most efficient energy conversion from the laser pulse to hard photons.

We consider a *p*-polarized laser pulse of Gaussian-like shape with temporal length of 30 fs and dimensionless amplitude $a_0 = \frac{eE_0}{mc\omega} = 220$. This corresponds to laser pulse energy of 18 PW and peak intensity of 1.33×10^{23} W/cm². In our series of 3D PIC simulations, the laser pulse is obliquely incident onto a flat plasma slab (see Fig. 1) under angles in the range $0 - 84^\circ$. The target electron density varies between $25 n_{cr}$ and $200 n_{cr}$ for $\theta = 0 - 72^\circ$ and equals $200 n_{cr}$ for $\theta = 72 - 84^\circ$ ($n_{cr} = m\omega^2/(4\pi e^2)$ is the critical plasma density for a given laser frequency). The ion motion is included into simulation; ion charge-to-mass ratio is 0.25 of that for hydrogen.

If a laser pulse is normally incident onto an overdense flat target, a ponderomotive force pushes the electrons into the target until they are stopped by the charge separation field. Thus, a

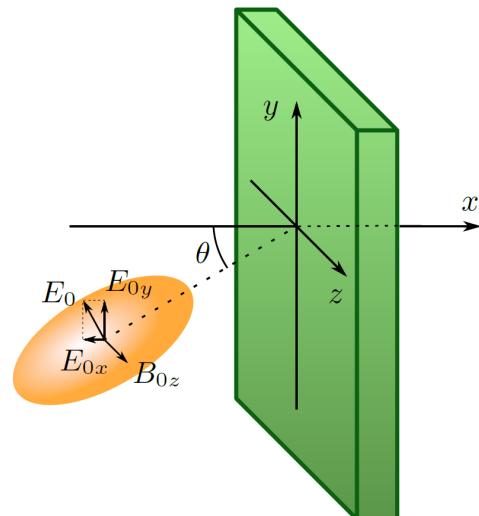


Figure 1: *Oblique incidence of a laser pulse onto a target.*

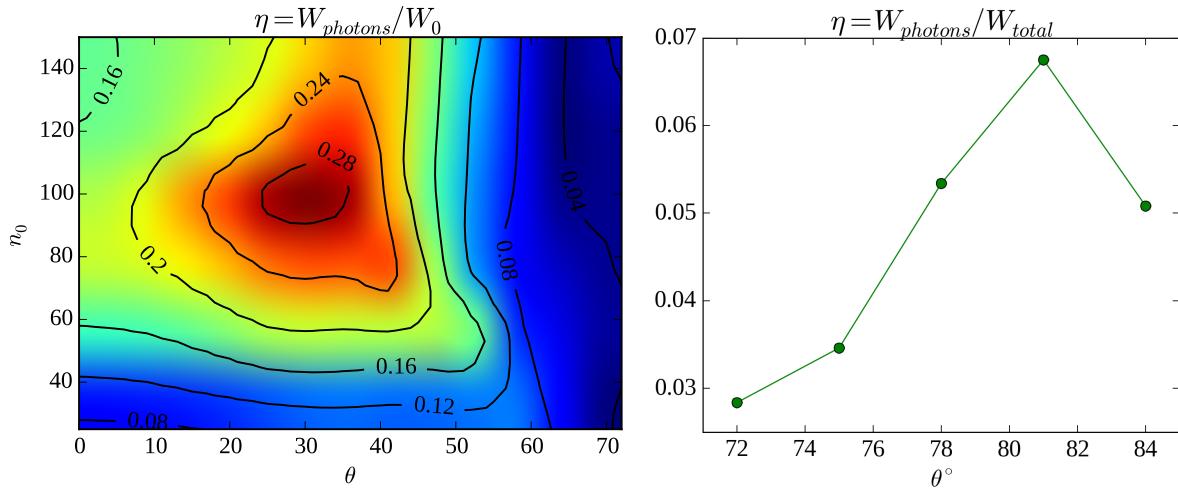


Figure 2: *Gamma-ray generation efficiency at different incidence angles θ : (left) efficiency map at different electron densities $n_0 = n_e/n_{cr}$ in the range 25-150 and $\theta = 0 - 72^\circ$; (right) efficiency at $n_0 = 200$ in the grazing incidence regime ($\theta = 72 - 84^\circ$). In both cases, the dimensionless laser field amplitude $a_0 = 220$.*

thin electron layer is formed near the plasma boundary, and its dynamics determines the properties of synchrotron radiation [2]. However, in the case of oblique incidence of a *p*-polarized laser pulse, there is the laser electric field component which is normal to the target surface (in our geometry it is E_x). It pulls the electrons from the target; so they are located not in the boundary layer but inside the strong electromagnetic field so they can gain more momentum [3]. Therefore, the gamma-ray radiation becomes stronger in the case of oblique incidence.

The results of our numerical simulations give the maximum gamma-ray generation efficiency $\eta = 29\%$ at optimal incidence angle $\theta = 30^\circ$ (Fig. 2, left) (we compute η as a fraction of hard photons energy in the whole energy at the end of a simulation). It also corresponds to results in [4]. The maximum efficiency is achieved at a certain electron density $n_e \approx 100 n_{cr}$. Note that the efficiency at $\theta = 29^\circ$ is more than 50% greater than in case of normal incidence.

Another series of our numerical experiments aimed to cover the region of high incidence angles $\theta > 72^\circ$. The simulations have been performed at $n_0 = 200$ (our test simulations at other electron densities showed that 200 is near the optimal density in this regime) and the same laser pulse amplitude ($a_0 = 220$). The gamma-ray generation efficiency in this series is shown in Fig. 2, right. The maximum η is about 7 % which is several times lower than at moderate θ values. However, the radiation pattern at high θ becomes very narrow (see Fig. 3) which points to a significant change in the electron dynamics. We are examining this regime in more detail below.

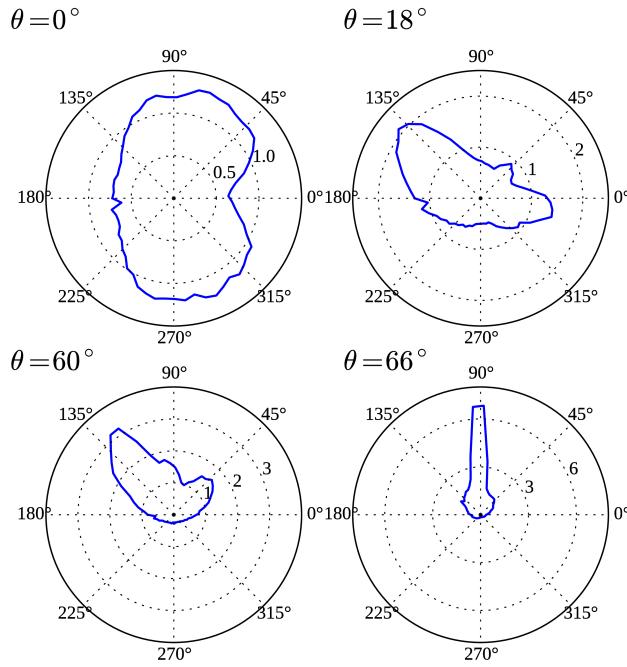


Figure 3: *Gamma-ray radiation pattern at different incidence angles θ .*

Regime of grazing incidence

When the incidence angle is greater than $60 - 65^\circ$, the laser-foil interaction properties become significantly different. This regime is often called "grazing incidence" which means that the angle between the laser pulse propagation direction and the target boundary is small. In this case, incident and reflected light interfere and provide a field structure that traps the electrons that are outside the target. Then these electrons can travel significant distances (several laser wavelengths) along the target surface and they gain much energy from the laser field. It means that the average p_y/p_x ratio of these electrons is much greater than unity. As a result, their synchrotron radiation becomes very focused in the direction of y -axis.

PIC simulations allow us to analyze the fields that act on the electrons and accelerate them. In Fig. 4, the field E_y (left), and E_x and B_z (right) can be seen. The interference of the incident and reflected waves results in the standing wave-like structure in the x direction; just near the surface, the E_y amplitude is high and the E_x and B_z amplitudes are low. Thus, the electron which is just near the surface mostly sees the E_y component of the laser field.

We can estimate the threshold of the grazing incidence regime. The phase speed of the wave traveling along the surface is $v_{ph} = c/\sin\theta$ which is greater than the speed of light. Taking electron speed $v \approx c$, we obtain its phase displacement φ after N laser field periods:

$$\varphi = \frac{2\pi}{\lambda_y} \left(\frac{c}{\sin\theta} - c \right) NT, \quad (1)$$

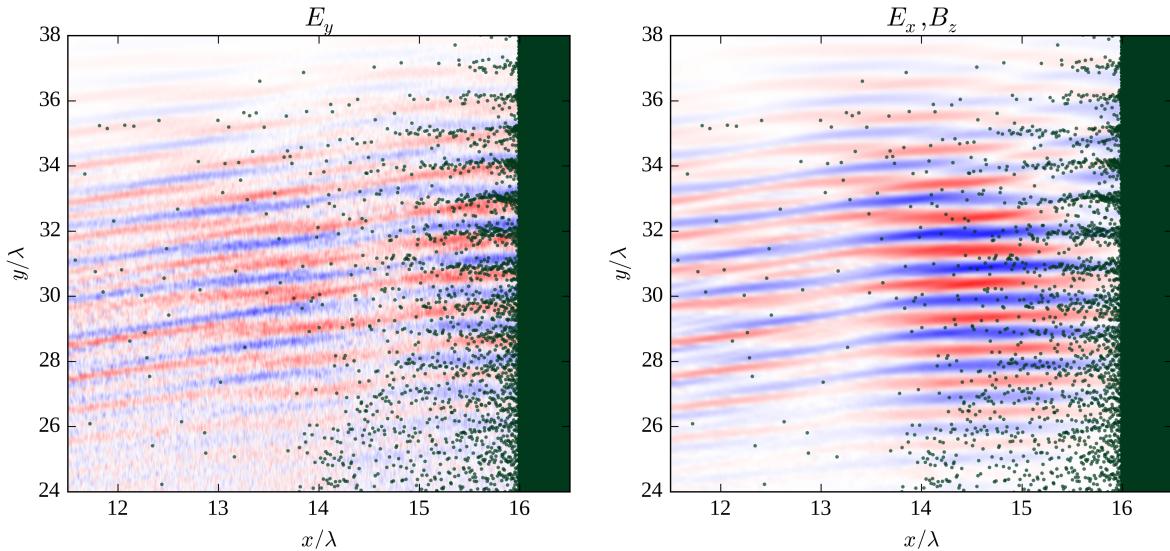


Figure 4: Structure of fields E_y (left) and E_x (right) in the grazing incidence regime ($\theta = 78^\circ$, $n_0 = 200$, $a_0 = 220$). Structure of field B_z is virtually the same as for E_x . Maximum amplitudes: $E_y^{max} = 96.4$ a.u., $E_x^{max} = 295.2$ a.u., $B_z^{max} = 306.1$ a.u. Dots show individual electrons in PIC simulations.

where $\lambda_y = \frac{\lambda}{\sin \theta}$ is the wavelength that is seen by an electron which travels in the y -direction. Taking into account that $\lambda = cT$, one can obtain that $\varphi = 2\pi N(1 - \sin \theta)$. For simplicity, we assume that the wave has accelerating and decelerating phases of the same length, so the phase displacement cannot be more than π for efficient acceleration. Therefore

$$N(\theta) = \frac{1}{2(1 - \sin \theta)}. \quad (2)$$

The function (2) is of the order of unity for small θ values, and begins to grow rapidly for $\theta \gtrsim 60^\circ$. This fact can explain the significant difference between the radiation patterns at $\theta = 60^\circ$ and $\theta = 66^\circ$ (see Fig. 3):

$$N(\theta = 60^\circ) = 3.73,$$

$$N(\theta = 66^\circ) = 5.78.$$

The more periods of laser field the electron can be in the proper phase, the more energy it gains. Thus, at high incidence angles the electrons can obtain very high p_y momentum values, and their radiation is directed into a narrow cone along the y axis.

References

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