

Pair and γ -photon production from a thin foil confined by two laser pulses

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Electron-positron and γ -photon production by high-intensity laser pulses is investigated for a special target geometry, in which two pulses irradiate a very thin foil ($10\text{--}100\text{ nm} < \text{skin depth}$) with same intensity from opposite sides. A stationary solution is derived describing foil compression between the two pulses. Circular polarization is chosen such that all electrons and positrons rotate in the plane of the foil. We discuss the laser and target parameters required in order to optimize the γ photon and pair production rate. We find a γ -photon intensity of $7 \times 10^{27}/\text{sr s}$ and a positron density of $5 \times 10^{22}/\text{cm}^3$ when using two 330 fs , $7 \times 10^{21}\text{ W/cm}^2$ laser pulses.

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I. INTRODUCTION

For laser intensities exceeding $10^{18}\text{ W/cm}^2 \times (\lambda/\mu\text{m})^2$ [1], electrons of irradiated targets move relativistically in the laser field. They are heated up to multi-MeV temperatures [2–4], and a large fraction is accelerated in laser direction [5–11]. For kinetic electron energies of $E > 2m_e c^2$, electron-positron pairs are produced via direct electron-ion collision [12,13] and the two-step process, involving emission of γ photons followed by pair production [14–18]. Other nuclear reactions, such as nuclear fission and neutron production, are also possible [15,16,18–20]. Shkolnikov *et al.* estimated 10^7 positrons per shot for a terawatt (TW), 200 fs laser pulse, producing electrons which then propagate into a high- Z material and produce pairs via the two-step process [14]. This process has been demonstrated experimentally [15,17].

Liang *et al.* [13] have suggested another method to produce pairs. A foil is heated by two linearly polarized laser pulses from opposite sides. The characteristic kinetic energy is roughly given by [2]

$$E_{hot} = m_e c^2 (\sqrt{1 + I\lambda^2/1.4} - 1), \quad (1)$$

with laser intensity I in units of 10^{18} W/cm^2 and laser wavelength λ in μm ; m_e is the electron mass and c the velocity of light. From this one finds $E_{hot} > 2m_e c^2$ for $I\lambda^2 > 1.2 \times 10^{19}\text{ (W/cm}^2)\mu\text{m}^2$. When $E_{hot} > 2m_e c^2$, pairs can be produced via direct electron-ion collisions. Because the cross section is very small, high plasma density and long confinement times are important for this process.

We mention that pair production was also considered for underdense plasmas [12] or for a plasma channel. In this context, the number of relativistic electrons can be high, because the laser pulse can propagate a long distance. However, the density is limited by the critical density $n_c = 1.1 \times 10^{21}\text{ cm}^{-3}$ for laser pulses of wavelength $1\mu\text{m}$. Therefore, one needs long plasma channels to obtain sufficient production rates.

In the present paper, we follow the proposal of Liang, but use two circularly polarized laser pulses illuminating a very thin foil, for example, a gold foil 10 nm thick. The polarization of the counterpropagating pulses is chosen such that

their electric vectors rotate in the same direction. In this case, there is no fast oscillating interference pattern, and the light pressure varies with time just as the envelope of the pulse. It leads to a quasistationary situation with a self-consistent density profile in which light pressure is balanced by thermal electron pressure inside the foil, and electron motion is dominated by circular motion in the plane of the foil with kinetic energy

$$E_{kin} = m_e c^2 (\sqrt{1 + a^2} - 1), \quad (2)$$

involving the normalized vector potential $a = eA/m_e c^2$ of laser field. This configuration produces the most gentle form of beam target interaction, in which electron heating is reduced to a minimum. Because of low electron temperature, high electron density is obtained. When applying laser intensities of a few 10^{19} W/cm^2 , the kinetic energy of the electrons exceeds $E_{kin} = 2m_e c^2$, and pair production sets in.

The efficiency of γ photon production due to bremsstrahlung [21] inside the foil increases with plasma density. Since electrons are not strongly heated in the present configuration and do not propagate, the emission of γ photons is concentrated in space time in the laser interaction volume. However, not much two-step pair production occurs in this volume, because typically $\mu r \ll 1$, where μ is the coefficient for pair production and r the volume size. To make the $(\gamma, e^+ e^-)$ process efficient, one has to place sufficient high- Z material around the interaction volume. In the following, we discuss the various cross sections in Sec. II, the model for stationary foil compression in Sec. III, and the results from both analytical treatment and corresponding one-dimensional particle-in-cell (1D-PIC) simulations in Sec. IV [2,4,22]. The simulations are based on the 1D-PIC code LPIC++ [23].

II. CROSS SECTIONS

For in-flight $e^+ e^-$ annihilation into two photons [24], the cross section is

$$\sigma_{an}(Z, \gamma) = \frac{Z\pi r_0^2}{\gamma + 1} \left[\frac{\gamma^2 + 4\gamma + 1}{\gamma^2 - 1} \ln(\gamma + \sqrt{\gamma^2 - 1}) - \frac{\gamma + 3}{\sqrt{\gamma^2 - 1}} \right], \quad (3)$$

where $r_0 = 2.8179 \times 10^{-13}$ cm is the classical electron radius, γ is Lorentz factor of the positron. In this paper, we have $\gamma = \sqrt{1 + a^2}$, recalling that electron momentum is related to the laser field by $a = p/m_e c$ in the present context. For $\gamma = 3$, $\sigma_{an} = 1.7 \times 10^{-25} Z$ cm². Usually the annihilation rate is low due to the low positron density. The cross section for e^+e^- production from direct electron-ion collision [12,13] is

$$\sigma_{ei} = 5 \times 10^{-33} Z^2 (\gamma - 3)^{3.6} \text{ cm}^2, \quad (4)$$

in the electron energy region of $E < 7$ MeV; for $E > 7$ MeV one has

$$\sigma_{ei} = 1.6 \times 10^{-30} Z^2 (\ln \gamma)^3 \text{ cm}^2. \quad (5)$$

In the limit of low annihilation rate, the pair density grows according to

$$\dot{n}_+ = (n_+ + n_e) n_i c \sigma_{ei}, \quad (6)$$

where n_e and n_i are density of electron and ion, respectively. The equation can be integrated to give the pair growth history,

$$n_+(z, t) = \frac{1}{2} Z n_i(z) \{ \exp[\Gamma(z)t] - 1 \}, \quad (7)$$

where z is the space coordinate and the pair growth rate is

$$\Gamma(z) = 2 n_i(z) c \sigma_{ei}(z). \quad (8)$$

When $\Gamma t \ll 1$, $n_+ = n_e n_i \sigma_{ei} c t$. The total number of positrons produced from the foil per area is

$$\mathcal{N}_+ = \int n_+ dz. \quad (9)$$

Liang *et al.* [13] estimate that a 1 ps, 1.4×10^{20} W/cm² laser pulse focused to a 10 μm radius spot on a thin gold foil 3.5 μm thick and with an electron density of $n_e/n_c = 30$ may heat 7.3×10^{12} electrons, i.e., 20% of all electrons, to energies much higher than 1 MeV. The temperature of this hot electron component is $T_e = 10$ MeV. The pair creation rate from direct electron-ion collisions then is $\Gamma = 2 c n_i \sigma = (6 \times 10^{10}) \times (4.2 \times 10^{20}) \times (2.8 \times 10^{-25}) = 7 \times 10^6/\text{s}$ and the total pair number per shot amounts to

$$\begin{aligned} \mathcal{N}_{pair} &= \frac{1}{2} \mathcal{N}_-(\Gamma t) = 0.5 \times (7.3 \times 10^{12}) \times (7 \times 10^{-6}) \\ &= 2.6 \times 10^7, \end{aligned} \quad (10)$$

or 2.9×10^7 per kJ of laser energy. In the paper of Liang *et al.*, a much higher pair production rate was obtained. It seems that they used solid density to calculate the pair production rate. If all the foil is heated to 10 MeV, it is impossible to maintain a solid density because of the great thermal pressure, as we will see below. When a thick foil is used so that in the middle of the foil it is still cold while the laser pulses are on, then only some energetic electrons go through the foil, and the efficiency of pair production is similar to the

case where a solid target is illuminated by a single laser pulse; we cannot reproduce the pair density of 0.1% of the target electron density reported in Ref. [13].

In the two-step process, first γ photons are generated due to the bremsstrahlung of the relativistic electrons. The cross section of bremsstrahlung for γ photons of energy larger than E_0 [14] is

$$\sigma_\gamma = 1.1 \times 10^{-26} Z^2 \left[0.83 \left(\frac{E_0}{E_{kin}} - 1 \right) - \ln \frac{E_0}{E_{kin}} \right] \text{ cm}^2, \quad (11)$$

where E_{kin} is the kinetic energy of the incident electron. In order to produce pairs, the energy of the γ photons must be larger than the threshold $E_0 = 1.022$ MeV. The cross section for pair production is $\sigma_{pair} = \sigma_0 \bar{p} Z^2$, where $\sigma_0 = 5.8 \times 10^{-28} \text{ cm}^{-2}$. For $m_e c^2 \ll h\nu \ll 137 m_e c^2 Z^{-1/3}$, it is approximately [25]

$$\sigma_{pair} = \sigma_0 Z^2 \left[\frac{28}{9} \ln \frac{2h\nu}{m_e c^2} - \frac{218}{27} \right]. \quad (12)$$

In addition to the process of pair production, photoionization and Compton scattering occurs. The total linear attenuation coefficient is about $\mu = 0.5 \text{ cm}^{-1}$ for lead in the energy range of interest [25].

Energetic electrons can be generated in both underdense and overdense plasmas and are typically emitted in the direction of the laser pulse [9,10,26]. These electrons will then propagate into high- Z material. The number of the bremsstrahlung γ photons at the position z is

$$\mathcal{N}_\gamma(z) = \mathcal{N}_- \int_0^z n_0 \sigma_\gamma dz = \mathcal{N}_- n_0 \sigma_\gamma z, \quad (13)$$

where \mathcal{N}_- is the number of energetic electrons emitted from the laser-plasma interaction region, n_0 is the atom density of the high- Z material. The total number of positrons produced is

$$\begin{aligned} \mathcal{N}_+ &= \int_0^l \mathcal{N}_\gamma(z) n_0 \sigma_{pair} dz \\ &= \mathcal{N}_- \sigma_\gamma \sigma_{pair} n_0^2 l^2 / 2 \\ &= \frac{1}{2} \mathcal{N}_- (\sigma_\gamma n_0 l) (\sigma_{pair} n_0 l). \end{aligned} \quad (14)$$

This equation is valid when the length of the high- Z material is $l \ll R$ and μ^{-1} , where R is the stopping distance of the energetic electron and μ the absorption coefficient of the γ photons. It is clear that the propagation distance in high- Z material is very important for pair production in the two-step process.

In the experiment of Gahn *et al.* [9], the total number of energetic electrons of temperature 3 MeV emitted from laser plasma interaction is about 2×10^{10} for a 200 fs, 250 mJ laser pulse with peak intensity of $4 \times 10^{18} \text{ W/cm}^2$. For 1 kJ laser energy, we extrapolate a number of 8×10^{13} . A $l = 2$ mm

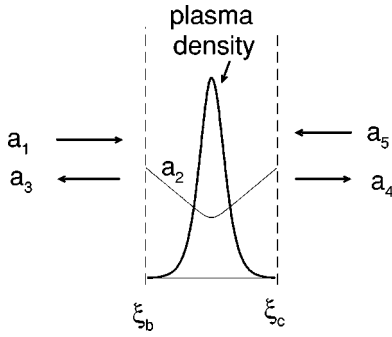


FIG. 1. Schematic drawing of plasma density with positions ξ_b, ξ_c , where boundary conditions are used, and a_1, a_2, a_3, a_4, a_5 defining wave amplitudes.

thick lead ($Z=82$) of atom density $n_0=3.3 \times 10^{22} \text{ cm}^{-3}$ can be used to produce γ photons and then pairs. We suppose the Lorentz factor of the electrons to be $\gamma=6$. The conversion factor from energetic electron to γ photon is $K_{e\gamma}=\sigma_\gamma n_0 l=(4.6 \times 10^{-27} Z^2) \times (3.3 \times 10^{22}) \times 0.2=0.2$. The factor from γ photon to pair is $K_{\gamma, pair}=\sigma_{pair} n_0 l=0.008$. Here we use $\sigma_{pair}=2. \times 10^{-28} Z^2$ for a photon energy of 2 MeV [25]. Therefore, the pair number per shot is about $\mathcal{N}_{pair}=\frac{1}{2} \mathcal{N}_- K_{e\gamma} K_{\gamma, pair}=1.6 \times 10^7$ or 6.4×10^{10} per kJ of laser energy. In the following, we discuss pair production in a thin foil confined between two circularly polarized laser pulses.

III. FOIL COMPRESSED BY LASER PULSES

We consider a thin foil illuminated by two circularly polarized laser pulses from opposite sides, as sketched in Fig. 1. This configuration has been studied in detail in Ref. [27]. Thin foils illuminated by a single laser pulse have been studied in a number of papers [28–32]. In Ref. [27], it was supposed that ions are fixed and electrons are cold [33–36]. It was found that the light pressure strongly compresses the electrons inside the foil. Here we suppose that the laser pulse is long enough for ions to follow electron motion within the thin foil. As a model, we set the electron density equal to the ion density so that the electrostatic field is zero. We try to obtain a one-dimensional (1D) stationary solution of this problem, where the ponderomotive force of the laser field is balanced by thermal electron pressure. Fermi pressure is neglected. A very thin foil is assumed, say a 10 nm thick gold foil or a 50 nm aluminum foil, which is ionized by the laser pulses.

It is well known that the normalized thermal pressure is

$$E_T = \frac{3}{2} T_e N_e, \quad (15)$$

where the electron density N_e normalized to the critical density n_c , electron temperature T_e normalized to $m_e c^2$. Because the ponderomotive force is balanced by the thermal force, we have

$$N_e \frac{\partial \gamma}{\partial \xi} = -\frac{\partial E_T}{\partial \xi} = -\frac{3}{2} T_e \frac{\partial N_e}{\partial \xi}, \quad (16)$$

where $\gamma=(1+a^2)^{1/2}$, $a=eA/m_e c^2$, and $\xi=\omega_L z/c$; ω_L is the frequency of laser. We easily obtain the solution

$$N_e = N_0 \exp(-2\gamma/3T_e). \quad (17)$$

Following the method in Ref. [27], we take the field $a=a(\xi)e^{i\omega_L t+i\theta(\xi)}$ inside the foil with real amplitude $a(\xi)$ and real phase $\theta(\xi)$. Because the ion density is the same as the electron density at each position, we obtain

$$\frac{\gamma}{a} \frac{\partial^2 a}{\partial \xi^2} - \frac{\gamma M^2}{a^4} + \gamma = N_e, \quad (18)$$

$$M = -\frac{\partial \theta}{\partial \xi} (\gamma^2 - 1), \quad (19)$$

$$W = \frac{\gamma^2}{2a^2} \left(\frac{\partial \gamma}{\partial \xi} \right)^2 + \frac{M^2}{2a^2} + \frac{1}{2} \gamma^2 + \frac{3}{2} T_e N_e, \quad (20)$$

where M and W are constants with respect to ξ . At positions ξ_b and ξ_c , where the electron density is very low, the incident laser pulses and the outgoing laser pulses propagate just as in vacuum. From continuity of transverse electric and magnetic field at left and right boundary, one finds ten equations relating amplitudes and phases; they have been derived as Eqs. (8) to (18) in Ref. [27] and are not given explicitly here. In addition, one finds

$$W = 2a_1^2 + 1/2 - M + (3/2)T_e N_e(\xi_b). \quad (21)$$

Now the task is to obtain the two constants M and W , the space-dependent laser field, and the electron density by using the amplitudes a_1, a_5 , the relative phase ϕ_{51} , the electron temperature, and the foil density per area. In practice, we suppose M to be given and also a_2 at some arbitrary position; we choose the point where the electron density is for example $N_e=0.1$. From Eq. (21), we then get W . We rewrite Eq. (20) as

$$\frac{\partial a}{\partial \xi} = \pm (2W - M^2/a^2 - a^2 - 1 - 3T_e N_e)^{1/2}. \quad (22)$$

Using Eqs. (17) and (22), we obtain laser field and electron density as a function of space and thereby the foil density per area. At the same time, $\phi_{51}=\phi_{5c}-\phi_{1b}$ can be obtained. Strictly speaking, ϕ_{51} is not the exact phase difference between the two incident laser pulses for the foil, because for $M \neq 0$ the density distribution is asymmetric. However, because the foil is very thin, we neglect this phase difference. In conclusion, we have derived ϕ_{51} and foil density per area from M and a_b . For $M=0$, $\phi_{51}=0$ or $\phi_{51}=\pi$. It means that M, W , and all other quantities can be obtained by inversion.

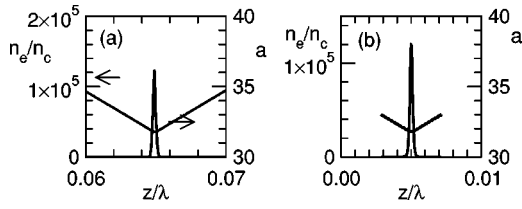


FIG. 2. Electron density distribution n_e/n_c and laser field a as a function of foil depth Z/λ . Two circularly polarized laser pulses of amplitude $a=50$ and phase $\phi_{51}=0$ illuminate the foil from opposite sides. The electron density of the foil per area is 3.3×10^{18} /cm². (a) Simulation result at peak of laser pulses. (b) Analytical results.

IV. RESULTS

First we give results for a thin gold foil with areal density of 3.3×10^{18} cm⁻² ($3000 n_c \times 10$ nm), illuminated by two 330 fs circularly polarized laser pulses of intensity 6.8×10^{21} W/cm² and having amplitudes $a_1 = a_5 = 50(\hat{x} \sin \omega t + \hat{y} \cos \omega t) \sin(\omega t/400)$ in the time interval $0 < \omega t < 400\pi$. The initial relative phase between the two laser pulses is zero. In the PIC simulation, performed in parallel to the analytic analysis, the foil is initially located at $0.06 < z/\lambda < 0.07$ with a uniform density $n_e/n_c = 3000$. Therefore, in Fig. (2) and Fig. (3) the location of electron density differs from the analytic result in which the foil is initially located at $0 < z/\lambda < 0.01$. We use $q/e = 1$ and $m_i/m_e = 4580$ for completely ionized gold. The initial electron temperature is supposed to be $T_e = 9.2 \times 10^{-3} m_e c^2$ (460 eV). Heating due to ionization and collisions are not included in the PIC code. Nevertheless, the plasma is compressed by the light pressure and heated by the work done by the light pressure. It is interesting that, when neglecting heating by light pressure, the electron temperature becomes lower than the initial temperature. This is due to the relativistic increase in mass, supposing that thermal momentum and thermal energy are initially P_{T0} and $P_{T0}^2/2m_e$. After laser pulse incidence, the electrons rotate relativistically in the laser field with Lorentz factor γ . Because the thermal momentum is constant, thermal energy becomes $P_{T0}^2/2m_e \gamma$.

In Fig. 2(a), we show electron and ion density and the laser field, as obtained from the 1D-PIC simulation. It is seen that the foil is strongly compressed due to the large light pressure. Also the laser field inside the foil is very large ($a = 32$); this is because the thickness of foil is smaller than the skin depth. The analytical result is given in Fig. 2(b). The temperature used in the analytical calculation is $T_e = 0.025 m_e c^2$ (13 keV), which is taken from the PIC simulation. First we consider the one-step process to produce pairs.

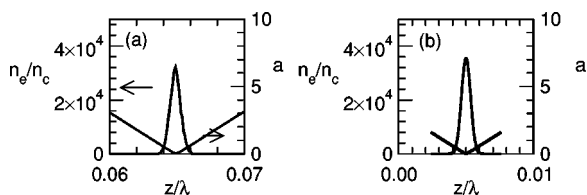


FIG. 3. Same as Fig. 2, but for $\phi_{51} = \pi$.

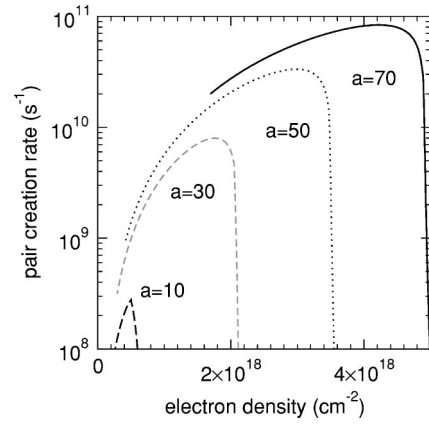


FIG. 4. Pair creation rate as a function of foil density for different laser amplitudes.

We use Eq. (8) to calculate the growth rate and find 2.9×10^{10} s⁻¹ at the peak of laser pulse. For two 330 fs laser pulses with a focal radius of 10 μ m, we obtain 5×10^{10} positrons per shot or 3.6×10^9 per kJ laser energy. The positron density is 0.5% of the electron density, i.e., 5×10^{22} /cm³ in the middle of the foil.

One should notice that $\phi_{51} = 0$ does not correspond to a stable point [27]. Fortunately, however, the foil can stay for several hundred femtoseconds in this position before moving appreciably. It is important that one has $\phi_{51} = 0$ initially. Otherwise, the foil would oscillate quickly. Although $\phi_{51} = \pi$ is a stable point, it would not be a good choice. As we see in Fig. 3, the plasma density is much lower in this case than in Fig. 2, and the laser field in the foil is $a < 1$. Therefore, pair production would be strongly degraded. The analytical results again give a good agreement to the PIC simulation for an electron temperature of $T_e = 0.024 m_e c^2$. The thickness of the foil is also crucial for pair production. For a foil much thicker than the skin depth, one would have $M \approx 0$ for any ϕ_{51} . From Eq. (20) and (21), we find that the largest electron density in the middle of the foil is

$$N_e(\max) = \frac{4}{3} a_1^2 / T_e. \quad (23)$$

This implies high plasma density for low temperature. On the other hand, the laser field a is too small even near the surface of the foil. In order to check this point, we have performed a simulation using a foil with an electron density of 3.3×10^{19} /cm² ($3000 n_c \times 0.1 \mu$ m), ten times larger than before. In this case, we find the laser field to be $a < 3$ inside the foil, too low for pair production. From the PIC simulation, we find also that the electron temperature $T_e = 0.15 m_e c^2$ is much higher than in the case of the thin foil that gives $T_e = 0.025 m_e c^2$. This is due to the fact that most electrons are no longer relativistic.

In Fig. 4 we plot the rate of pair production as a function of foil density. We suppose that the electron temperature is $T_e = 0.025 m_e c^2$. We find that the increase of the pair creation rate is faster than the increase of laser intensity. From Fig. 4, we find that proper choice of foil thickness is also important. Pair production is low for either too thick or too thin foils,

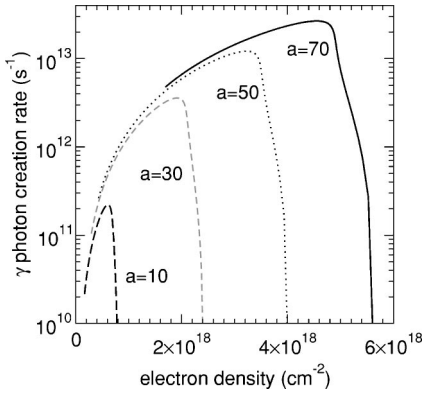


FIG. 5. Creation rate of γ photons of energy larger than 1 MeV as a function of foil density for different laser amplitudes.

because it gives a low pair creation rate and low pair creation number. It is also easier for the thin foil to oscillate.

Now we consider the two-step process. For the case of Fig. 2, the production rate of bremsstrahlung γ photons inside the foil with energy larger than 1.022 MeV is $1.2 \times 10^{13} \text{ s}^{-1}$, which is obtained with the help of Eq. (11). The γ photon intensity is $4 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, because the foil density is $3.3 \times 10^{18} \text{ cm}^{-2}$. Therefore, even if the γ photons radiate uniformly in space, the radiation intensity can reach $1.0 \times 10^{25} \text{ (sr s)}^{-1}$ for a focus radius of $10 \mu\text{m}$. At 1 m distance, it is $1 \times 10^{21} \text{ (cm}^2 \text{ s)}^{-1}$. We plot the γ photon creation rate as a function of foil density in Fig. 5. The γ photon creation rate has a similar behavior as the pair creation rate inside the foil.

We use the approximate function [37,38]

$$f(u) = C(ue^{-au} + due^{-3au}) \quad (24)$$

to calculate the angular distribution, where $u = (\gamma - 1)\theta$, $C = 9a^2/(9 + d)$, $a = 0.625$, and $d = 0.13[0.8 + (1.3/Z)][100 + (1/E)]\{1 + [k/\gamma - 1]\}$. Here k is the photon energy. For the case of $\gamma = 32$, we plot the angular distribution in Fig. 6. We find that the peak in the angular radiation spectrum is at about $\pm 1^\circ$ out of the target plane and most of the energy is radiated into the region of $\pm 3^\circ$. Therefore, the solid angle is about $2\pi(1 - \cos \theta) \approx 4\pi/730$, and the radiation intensity is 730 times stronger than estimated above.

Even if the γ photons move exactly in transverse direction, it takes only about 30 fs for them to move a distance $10 \mu\text{m}$ which is the radius of laser focus. Because the foil is very thin (1 nm after compression), γ photons easily move out. For the case of Fig. (5), a γ photon propagates only about $0.6 \mu\text{m}$ before it moves out. Therefore, pair production due to the two-step process inside the foil is much smaller than outside the focus supposing it is surrounded by high- Z material.

For 2 mm thick lead, the (γ, e^+e^-) production factor is $K_{\gamma, \text{pair}} = \sigma_{\text{pair}} n_0 l = 0.1$. Here $\sigma_{\text{pair}} = 2.6 \times 10^{-27} Z^2 \text{ cm}^{-2}$ is used for γ photons of energy 15 MeV [25]. Therefore, the pair production rate is $\Gamma_{\text{pair}} = \Gamma_{\gamma} K_{\gamma, \text{pair}} = 1.2 \times 10^{12} \text{ s}^{-1}$ and, for a 330 fs laser pulse, we have $1.3 \times 10^{19} \text{ cm}^{-2}$ pos-

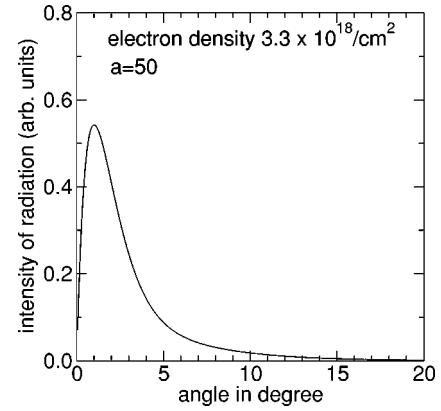


FIG. 6. Angular distribution of γ photons for the case in Fig. 2.

itrons per shot or 1.5×10^{11} per kJ laser energy. In this way we can obtain higher pair production than in the one-step process ($3.2 \times 10^{16} \text{ cm}^{-2}$ per shot). If we use μ^{-1} instead of 2 mm to calculate pair production, it will be ten times higher.

V. CONCLUSIONS

In conclusion, we have obtained stationary analytical solutions for intense electromagnetic waves of circular polarization shining from opposite sides on a thin foil. Both electron and ion motion is considered. Ultrathin foils illuminated by two intense circularly polarized laser pulses of zero phase difference are considered to produce γ photons and electron-positron pairs. We find γ photon intensities of $7 \times 10^{27} \text{ (sr s)}^{-1}$ and positron densities of $5 \times 10^{22} \text{ cm}^{-3}$ by using 330 fs laser pulses of amplitude $a = 50$.

The large positron population should lead to an ultrashort ultrabright flash of 511 keV annihilation radiation. The time structure of this flash depends on how a quasineutral e^+e^- cloud may expand and separate from the dense production volume. The results presented here are based on one-dimensional treatment; effects of instabilities possibly occurring in real three-dimensional space have not been investigated. The 1D-PIC simulations seem to confirm that electron heating is low under the irradiation conditions considered. The neglect of collisions may be justified in view of the relativistic electron energies, but could play a role in the startup phase of irradiation. In this context, prepulse suppression is a crucial issue. Experimental verification of the present results, therefore, appears to be very demanding; it requires high-contrast-ratio laser pulses and two-sided irradiation of very thin foils with high precision. Exploratory experiments are now under preparation at the Rutherford laboratory [39].

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