PARTICLE BEAMS FROM LASER-IRRADIATED SOLIDS AT ULTRAHIGH INTENSITIES

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Laser-solid interactions at the intensity range $10^{23}\ldots10^{26}$ W cm^{-2} and the plasma density about 10^{24} cm^{-3} are studied by means of numerical simulations. This range of parameters is extremely important for various laser applications such as fast ignition, gamma-ray generation and ion acceleration, and will be reached by the next generation of intense laser facilities. An overview of the interaction regimes is given.

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INTRODUCTION

Generation of high-energy particles in laser-matter interactions attracts a lot of attention for many years. The interest to this topic has been warmed up recently by plans on construction of extremely intense laser facilities such as ELI [1] and XCELS [2]. A plenty of novel effects are expected to be observed at the corresponding intensity level, among them efficient ion acceleration [3], electron acceleration [4, 5], gamma-ray generation [6, 7], domination of radiation reaction [8] and production of electron-positron pairs [9 - 12]. In order to observe these effects some certain conditions should be met. For instance, efficient ion generation implies utilization of a quite wide supergaussian laser beam [3] and prolific production of electron-positron pairs also requires special field configuration [12]. However, some traits of these phenomena can reveal itself in quite simple experimental setups.

In this paper normal incidence of an extremely intense laser pulse on a solid-density foil is investigated by means of 3D numerical simulations. The simulations utilize particle-in-cell (PIC) and Monte Carlo (MC) techniques and take into account ion motion, photon emission (that readily lets to describe radiation reaction) and electron-positron pair production via decay of hard photons in strong laser-plasma fields.

Despite the considered problem statement is elementary, the interference of key effects leads to challenging laser-plasma dynamics. A number of specific intensity levels can be highlighted. Namely, at relativistic, but low intensities the foil reflects the laser pulse that slightly heats foil electrons; at higher intensities ions are accelerated to relativistic velocities. Then gamma-ray generation becomes efficient, at the same time ion motion significantly affects photon emission and the resulting radiation pattern. Finally, at intensity level about $10^{25}\ldots10^{26}$ W cm^{-2} prolific generation of electron-positron plasma and generation of hard photons become dominating. In this case ion acceleration is highly inefficient, however, collimated gamma-ray beams as well as a big number of ultrarelativistic electrons and positrons are produced.

Since relativistic ions, ultrarelativistic electrons, positrons and hard photons have sufficiently different energy transport characteristics, the efficiency of laser-based fast ignition schemes should strongly depend on the laser-matter interaction regime.

1. KEY INTENSITY LEVELS

The key effects of laser-matter interaction in the considered range of parameters are the following: ion acceleration, radiation losses and pair production. In order to estimate the intensity levels in which the corresponding effects become important, we adopt the following assumptions. First, the electric field normal to the foil surface is supposed to be the order of the incident field. Second, the Lorentz factor of the laser-irradiated electrons is estimated as $a_0 = eE_0 / mc\omega$, where E_0 is the amplitude of the laser field, c is the speed of light, $e > 0$ and m are the magnitude of the electron charge and the electron mass, respectively. Third, we assume that the angle between the force acting on the electrons and the electron velocity is about unity. We also neglect here the effect of the reflected field gain [13].

The above mentioned assumptions lead to the following values of the key intensity levels:

$$I_{RL} = 1.6\times10^{23}\lambda^{-4/3}[\mu\text{m}]\,\text{W/cm}^2;$$

$$I_{RPA} = 2.3\times10^{23}\lambda^{-2}[\mu\text{m}]\,\text{W/cm}^2;$$

$$I_{Oe+e-} = 1.1\times10^{24}\,\text{W/cm}^2;$$

$$I_{Ae+e-} = 2.5\times10^{25}\lambda^{-1}[\mu\text{m}]\,\text{W/cm}^2.$$

Where I_{RL} is the intensity level corresponds to significant radiation losses, I_{RPA} is the radiation-pressure-acceleration regime, I_{Oe+e-} is the occasional e^+e^--pair production and I_{Ae+e-} is the abundant e^+e^--pair production, respectively, $\lambda[\mu\text{m}]$ is the laser wavelength in micrometers. The significance of the radiation losses means that the electrons emit a substantial portion of their energy during the motion that can noticeably cools the plasma electrons. Radiation pressure acceleration regime (laser-piston regime) is a regime of laser-foil interaction that is characterized by co-directional motion of the laser pulse and the irradiated piece of the foil [3]. In this regime ions quickly becomes relativistic and ion acceleration can be very efficient. The intensity levels for occasional and abundant e^+e^--pair production [14] was estimated in the framework of the electromagnetic cascade model in rotating electric field [9]. Here occasional pair production means that only a small fraction of plasma electrons emits photons that are capable to decay and produce pairs, otherwise, abundant pair production means that intense electromagnetic cascade is developing, hence, a substantial fraction of the electrons emits hard photons that decay and produce next generation of electrons and positrons, that can also be accelerated and emit hard photons.

2. RESULTS OF NUMERICAL SIMULATIONS

The results of 3D PIC+MC simulations of the normal incidence of the laser pulses with different intensities on a fully ionized Ti foil (the corresponding unperturbed electron density is $1.25 \cdot 10^{24}$ cm^{-3}) are shown in Figs. 1-5. The duration of the laser pulses is 9 fs, and their radius is 3 µm, the laser wavelength is 1 µm. The dependency of the energy of the emitted hard photons, the electron energy, the ion energy and the positron energy on initial laser pulse intensity is depicted in Fig. 1.

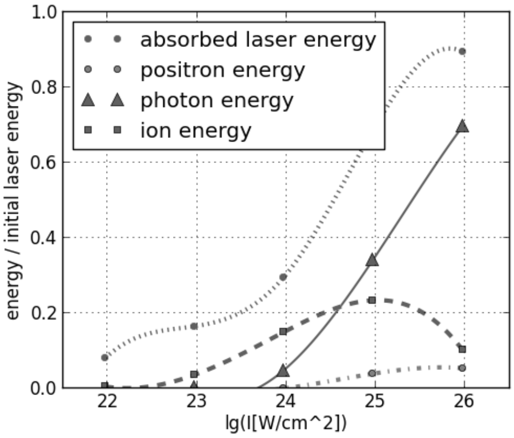

Fig. 1. The absorbed laser energy (dotted line), the fraction of absorbed laser energy transmitted into the gamma-ray energy (solid line), into the ion energy (dashed line) and the positron energy (dash-dotted line) obtained in numerical simulation of normal incidence of a laser pulse on a Ti foil (see text for details)

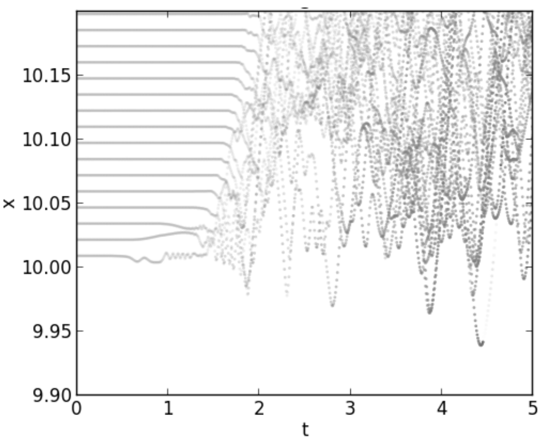

Fig. 2. The trajectories of test foil electrons lying initially on the laser pulse axis; t is the current time normalized on the laser period and x is the coordinate directed into the foil and normalized on the laser wavelength

It should be mentioned that the intensity levels computed in Sec. 2 agree reasonably with the dependencies in Fig. 1. Namely, significant part of absorbed laser energy goes to the ion energy at intensities higher than $2 \cdot 10^{23}$ W cm^{-2}; the threshold intensity for positron production is about 10^{24} W cm^{-2}. The efficiently of the ion acceleration abruptly falls at intensities higher than 10^{25} W cm^{-2}, that is explained by abundant e+e- plasma generation (see Sec. 4) and agrees fairly good with the value of I_{Ae+e-} from Sec. 2.

Nevertheless, the portion of absorbed laser energy that is converted into gamma-ray energy dominates over the electron energy at intensities higher than 2.10^{24} W cm^{-3} that looks contradictory to the value of I_{RL} from Sec. 2. The explanation of this discrepancy lies possibly in the closeness of I_{RL} and I_{RPA} values, as well as in some features of electron heating. The trajectories of the test foil electrons shown in Fig. 2 clearly demonstrates that at moderate intensity ($3 \cdot 10^{23}$ W cm^{-2}) the electrons interacts with strong laser field only on a shot time interval and are injected into the foil. This process leads to efficient conversion of laser energy into electron energy, however, electrons have no time to gain high energy and emit it in hard photons.

3. HIGH-INTENSITY LIMIT

The energy density of the laser field, the electron density and the positron density in successive time instances are shown in Figs. 3-4 for the initial laser intensity 10^{26} W cm^{-2} and other parameters the same as in Sec. 3. The laser pulse is spaced initially from the foil by 5 laser wavelengths.

It is seen from Fig. 3 that the laser pulse significantly pushes plasma electrons. This leads to the generation of strong longitudinal (in the direction of the laser pulse propagation) electric field that accelerates ions up to relativistic velocities in a time less than the laser period. Hence, ions and electrons move co-directionally with the laser pulse. Electrons, however, moves along the complicated trajectories and only in the average move together with the ions and the laser pulse. Hence, since the electron trajectories are bended, electrons emit hard photons that decay in the laser-plasma field and produce positrons.

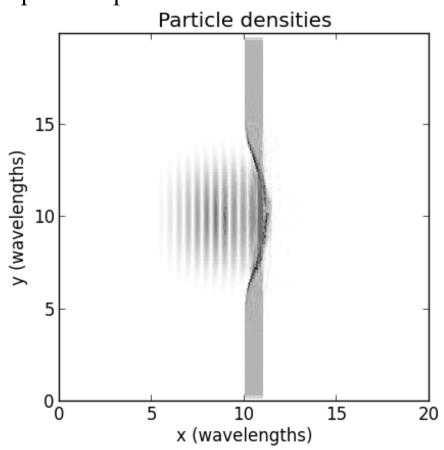

Fig. 3. The laser energy density, the electron density and the positron density at the time instance normalized on laser period t=4. See text for details

In Fig. 4 the final stage of laser-plasma interaction in high-intensity limit is shown. The bulb of electron-positron plasma is generated and the number of electron-positron pairs becomes much greater than the number of the accelerated ions, because of this ion acceleration becomes inefficient (see Fig. 1). Despite of abundant production of electron-positron pairs, gamma-ray emission remains the dominating process at high-intensity limit.

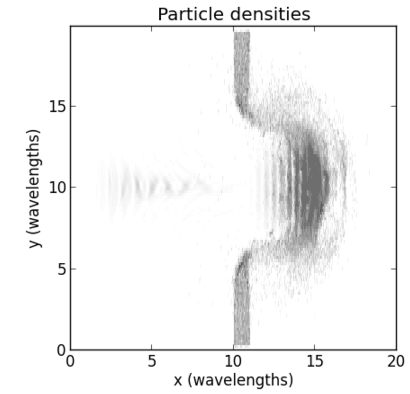

Fig. 4. The laser energy density, the electron density and the positron density at the time instance normalized on laser period t=12. See text for details

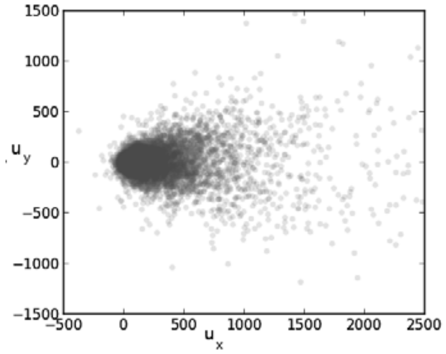

Fig. 5. The gamma-ray distribution in the phasespace u_x-u_y at the final stage of the laser-foil interaction depicted in Fig. 4. Here u_x and u_y are the longitudinal and transverse photon momenta, respectively, normalized on mc

CONCLUSIONS

Results of 3D numerical simulations of normal incidence of laser pulses on a plasma slab (foil) reveal a number of specific interaction regimes. The characteristic intensity levels that correspond to these regimes are estimated and compared with the results of numerical simulations. It is shown that up to intensity 10^{25} W cm^{-2} ion acceleration remains efficient, and at higher intensities emission of gamma-rays and production of electron-positron pairs in a co-propagated with a laser pulse bulb of particles becomes the dominating process. The considered regimes of laser-plasma interaction could be important for future laser-based positron and gamma-ray sources, as well as for fast ignition experiments.

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ГЕНЕРАЦИЯ ПУЧКОВ ЧАСТИЦ ПРИ ВЗАИМОДЕЙСТВИИ ЛАЗЕРНОГО ИЗЛУЧЕНИЯ СВЕРХВЫСОКОЙ ИНТЕНСИВНОСТИ С ТВЕРДОТЕЛЬНЫМИ МИШЕНЯМИ

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С использованием численного моделирования рассмотрено взаимодействие лазерных импульсов интенсивностью $10^{23}…10^{26}$ Вт·см$^{-2}$ с плазменным слоем плотностью 10^{24} см$^{-3}$. Рассмотренная область параметров чрезвычайно важна для будущих приложений сверхмощных лазерных систем, например, для схем «быстрого поджига», для генерации гамма-квантов, позитронов и ускоренных ионов. Дан обзор различных режимов взаимодействия, отвечающих различным значениям интенсивности лазерного поля.

ГЕНЕРАЦІЯ ПУЧКІВ ЧАСТИНОК ПРИ ВЗАЄМОДІЇ ЛАЗЕРНОГО ВИПРОМІНЮВАННЯ НАДВИСОКОЇ ІНТЕНСИВНОСТІ З ТВЕРДОТІЛЬНИМИ МІШЕНЯМИ

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З використанням чисельного моделювання розглянуто взаємодію лазерних імпульсів інтенсивністю $10^{23}…10^{26}$ Вт·см$^{-2}$ з плазмовим шаром густиною 10^{24} см$^{-3}$. Розглянута область параметрів надзвичайно важлива для майбутніх застосувань надпотужних лазерних систем, наприклад, для схем «швидкого підпалу», для генерації гама-квантів, позитронів та прискорених іонів. Наведено огляд різних режимів взаємодії, що відповідають різним значенням інтенсивності лазерного поля.