41. Interaction of intense femtosecond laser pulses with high-*Z* solids

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A plasma irradiated by an intense very short pulse laser can be an ultimate high brightness source of incoherent inner-shell X-ray emission of 1-30 keV. The recently developed 100 TW, 20 fs laser facility in JAERI can make considerable enhancement here. To show this a hybrid model combining hydrodynamics and collisional particle-in-cell simulations is applied. Effect of laser prepulse on the interaction of an intense s-polarized femtosecond, ~20/40 fs, laser pulse with high-Z solid targets is studied. A new absorption mechanism originating from the interaction of the laser pulse with plasma waves excited by the relativistic component of the Lorentz force is found to increase the absorption rate over 30% even for a very short laser pulse. The obtained hot electron temperature exceeds 0.5-1 MeV at optimal conditions for absorption. Results of the simulation for lower laser pulse intensities are in good agreement with the experimental measurements of the hot electron energy distribution.

Keywords: Short-pulse laser, PIC simulation, Overdense plasma, Hot electron distribution, Relativistic resonance absorption, Kα emission

1. Introduction

Solids of high-Z matter irradiated by an intense very short (<100 fs) pulse laser can be an ultimate high brightness source of Kα emission of 1-30 keV [1-7]. Recently developed 100 TW, 20 fs laser facility in JAERI can make considerable enhancement here so that the study interaction of a relativistically intense ultra short laser pulse with a solid target becomes very important. In contrast to first calculations made for laser intensity ~10^{19} W/cm^2 [8-10] showing very low absorption efficiency of solid targets, only a few percents for a normally incident femtosecond pulse lasers, in this paper we demonstrate via particle-in-cell simulation, conforming to a direct solution of the Fokker-Planck equation [11], the way of increasing the absorption efficiency over 30% via using a laser prepulse. This becomes possible due to the non-linear resonance interaction of a nonuniform density plasma with a pulse laser of relativistic intensity, $eE/mc\omega > 1$.

The effective heating of plasma electrons by a normally incidence laser pulse of relativistic intensity via the $\boldsymbol{v}\times\boldsymbol{B}$ force at twice the laser frequency force has been shown in [12] through 2D PIC simulation. An uniform plasma slab at $4N_{\rm cr}$ density has been considered and the absorption efficiency near 30%

has been numerically obtained. Actually, the motion of a relativistic electron in an overdense plasma has a set of resonance ranging near 2ω and ω, all of the resonance effect on the absorption process. The effect of $\boldsymbol{v}\times\boldsymbol{B}$ force on the absorption of a short laser pulse may occur at low laser intensities as well. We make calculations for moderate laser intensity and show a good agreement of our results with previous experimental ones of Ref.[7].

2. Interaction of a short laser pulse with an overdence plasma

The electron motion in the electromagnetic plane wave

$$E_Y = A\cos(\omega t + kx), \qquad H_Z = A\cos(\omega t + kx)$$

irradiating the plasma can be found in the laboratory reference frame. Assuming the acting force due to plasma electrostatic field in the following form

$$F_x = -m\omega_{pl}^2 x$$

where x is the electron coordinate, ω_{nl} the plasma frequency, one can find

$$\begin{cases} u_Y = \tilde{A}\sin(\tau + \tilde{x}) + u_Y^0 & , \\ \dot{u}_X = -\alpha^2\tilde{x} - \frac{1}{2}\tilde{A}^2\sin(2\tau + 2\tilde{x})/\gamma, & \\ \gamma = \sqrt{1 + u_X^2 + \tilde{A}^2\sin^2(\tau + \tilde{x})} & , \\ \dot{\tilde{x}} = u_X/\gamma & , \end{cases} \qquad (1)$$

where

$$\tilde{A} = eA/mc\omega, \vec{p} = mc\vec{u}, \tau = \omega t, \tilde{x} = \omega x/c,$$

$\alpha = \omega_{pl}/\omega$, A is the amplitude of the electromagnetic wave, u^0 the initial momentum of the electron. The x-component of the momentum can be express in the form of implicit equation

$$u_X = \frac{1 + u_Y^2 - \left(\gamma_0 - u_X^0 - \alpha^2[\tilde{x}^2/2 - \int \tilde{x}\,d\tau]\right)^2}{2(\gamma_0 - u_X^0 - \alpha^2[\tilde{x}^2/2 - \int \tilde{x}\,d\tau])} \qquad (2)$$

with γ_0 the initial energy of the electron. According to Eq.(2) the resonance condition appears at $\omega_{pl} = 2\omega$ if $A \sim 1$. With increase of the wave amplitude the resonance condition shifts to ω. At very high laser intensity the set of resonance covers interval $[\omega, 2\omega]$. These conditions determine the optimal density gradient which obviously must increase with A.

Results of the simulation of interaction of a 20 fs laser pulse with an Al slab target is shown in Fig.1. At low intensity we observe no resonance interaction in small density gradient scale region L~0.1-0.3λ.The resonance interaction appears at laser intensity $I\lambda^2 > 2\times10^{18}$ Wμm^2/cm^2. Initially, the absorption efficiency is maximal at the density gradient correspondent to the resonance at 2ω while, with the laser intensity, the density gradient increases to that determined by the resonance condition at $\omega_{pl} = \omega$. The temporal evolution of the electron distribution function is presented in Fig.2. Without the resonance condition the temperature of hot electrons is quite low, about 100 keV. Due to the resonance condition the temperature of hot electrons at the optimal density gradient considerably increases and can exceed 1 MeV at laser parameters achieved by JAERI facility.

To verify the model for the short laser pulse plasma interaction we perform the simulation of the electron distribution function at conditions of the experiment [7] where moderate laser intensity was applied. To include the effect of the laser prepulse we make the hydrodynamic calculation using HYADES code. The parameters of a Cu plasma after 8 ns prepulse of 10^{11} W/cm^2 intensity are shown in Fig.3. These parameters are used for further PIC simulation. The distribution function for s-polarized and p-polarized laser pulses are shown in Fig.4 and Fig.5. The electron distribution function for the p-polarized laser pulse is completely agree with the experimental one. The dependence of intensity of Kα emission with the energy of the laser pulse shown in Fig.6 is determined by electron energy cut-off and agree well with the measured.

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Figure captions

Fig.1 The dependence of the absorption efficiency on the density gradient for a 20 fs laser pulse of relativistic intensity in Al solids, λ=800 nm.

Fig.2 The temporal evolution of the electron distribution function at the optimal density gradient in Al slab targets.

Fig.3 Parameters of a Cu plasma after irradiation by the laser prepulse of 8 ns duration and 10^{11} W/cm^2 intensity [7].

Fig.4 The electron distribution function with s-polarized laser pulse of 42 fs duration and intensity of 10^{17} W/cm^2 (see also Ref. [7]).

Fig.5 The electron distribution function with the p-polarized laser pulse.

Fig.6 The calculated dependence of Cu Kα output with the energy of the laser pulse and the results of measurements [7].

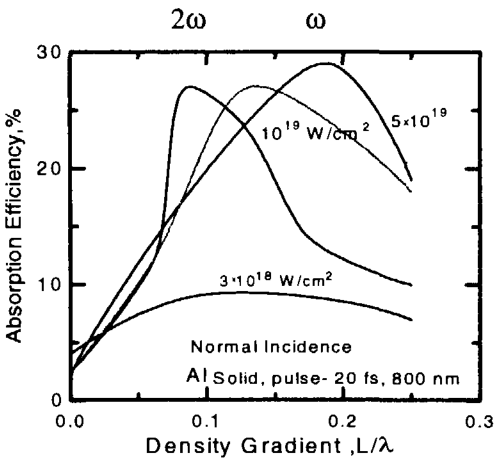

Fig.1

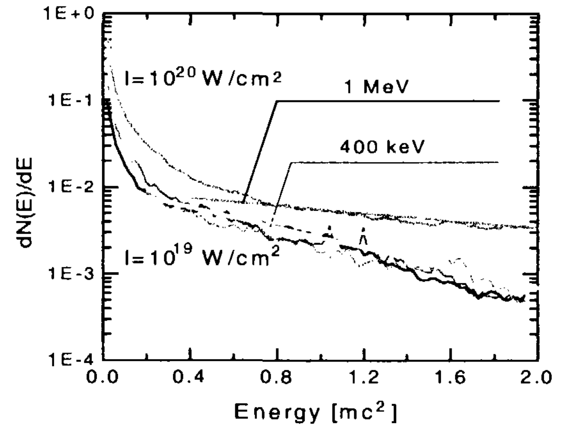

Fig.2

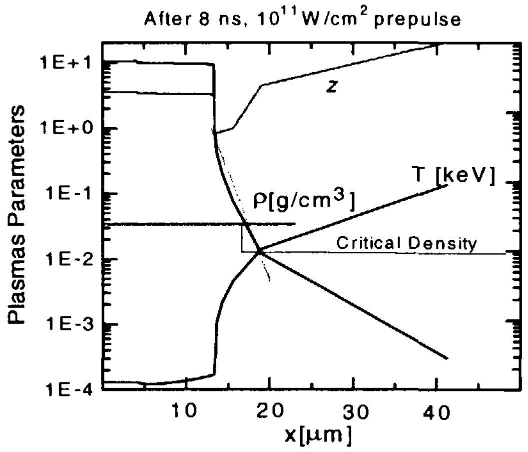

Fig.3

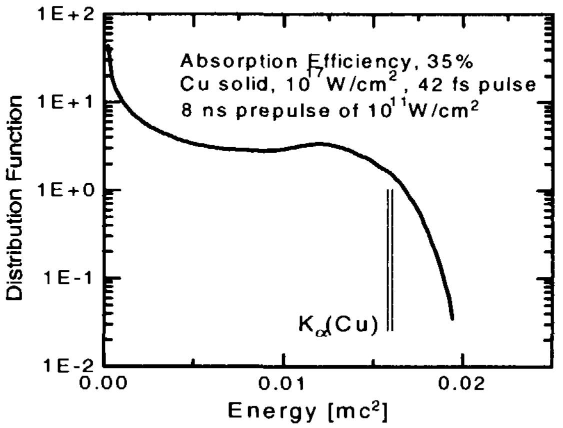

Fig.4

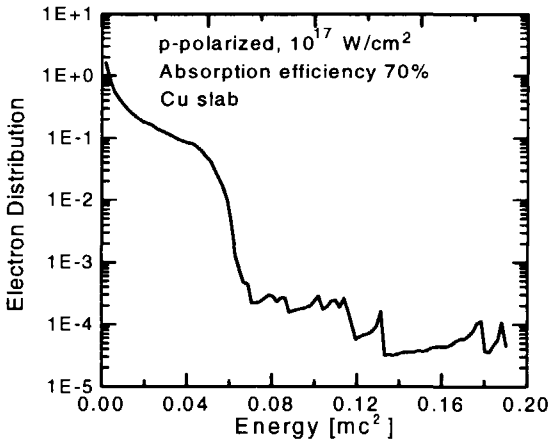

Fig.5

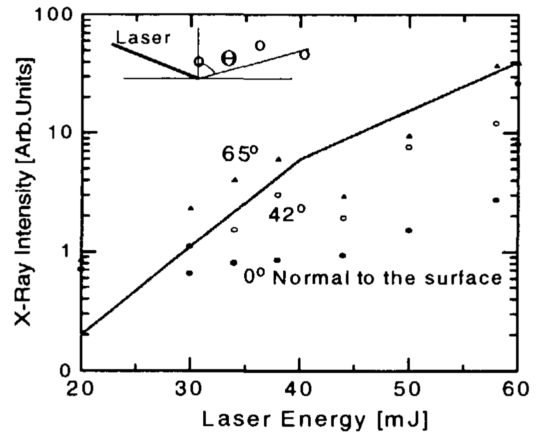

Fig.6