*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, O-4.24 (2004)*

Laser induced fusion in a boron-hydrogen mixture

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The yield of alpha-particles in nuclear fusion reaction between ^{11}B nuclei and protons ($p + {}^{11}B \to 3\alpha$) in solid mixture induced by *p*-polarized inclined picosecond laser pulses with high laser contrast is derived analytically.

The ionization, stopping, and thermalization of hydrogen and boron beams, injected, respectively, in boron and hydrogen plasmas, were studied in [1]. The evolution of the charge state populations of the neutral beams is described considering the various ionization, excitation, and charge exchange channels.

We suggest here another mechanism for realization of this fusion reaction which takes place at the interaction of super-intense picosecond laser pulse with a solid target consisting of the boron – hydrogen mixture

The effect of the significant increase of the electron heating occurs at the inclined fall of the *p*-polarized laser beam upon the solid target. In this case there is the nonzero component of the laser electric field strength $F\sin\theta$ which is normal to the target surface. Then free electrons inside plasma oscillate in the normal direction to its surface and go out plasma into vacuum and back periodically (with the frequency of the laser field). When an electron is in the vacuum it can acquire the kinetic energy from the laser field which is of the order of the electron oscillating energy. Thus, an electron can return back into plasma with the kinetic energy which is much greater than its initial energy. In other words, an electron can really absorb a large amount of laser photons in the presence of the third body: the sharp surface between plasma and vacuum that provides the non-adiabaticity of the absorption process. Of course, an electron can also emit laser photons, but the probability of induced absorption is always larger than the probability of induced emission, independent on the type of the third body. For example, this fact is well known for the process of induced inverse bremsstrahlung where the third body is an atomic ion [2]. This heating mechanism (so called "vacuum heating") was suggested by F. Brunel [3]. It accelerates the heating of both electrons and atomic ions in plasma irradiated by super-intense laser field of picosecond duration because of common motion of the plasma surface.

Of course, the amount of the acquired energy depends on the phase of laser field at which the ejection of the electron into vacuum begins. F. Brunel [3] carried out the uniform averaging over this phase. He obtained the averaged energy which is acquired by an electron during one laser cycle. Of course, only a small part of free electrons are ejected from the plasma to vacuum during the laser cycle. When some amount of electrons is ejected, the quasi-static electric field appears which is directed oppositely to the external laser field. The ejection stops when the total compensation of both electric fields takes place. The average electron kinetic energy at the vacuum heating is found to be

$$E = 0.9U_p \sin^2 \theta$$

Here $U_p = F^2(t)/4\omega^2$ is the average electron ponderomotive energy in the external laser field, $F(t)$ is the envelope of laser field strength, and θ is the angle between the wave vector of laser radiation and the normal to the target surface, ω is the laser frequency (atomic units are used). Thus, the conclusion can be made that the kinetic energy of electrons heated in the process of the vacuum heating is of the order of its oscillating energy, i.e. it is much greater than at the heating due to induced inverse bremsstrahlung.

The depth of the heated region in the target is $l(t) = \dfrac{F(t)\sin\theta}{\omega_p^2}$.

The heated electrons move together with nuclei having the speed of plasma ionic sound $V = \sqrt{T_e / M}$ (here M is the mass of the nucleus and T_e is an electron temperature). Hence, the nuclear kinetic energy is equal to $MV^2/2 = T_e/2$. The nuclear temperature T_n is then derived knowing the electron temperature: $T_n = T_e/3$. When the peak laser intensity is $2 \cdot 10^{18}$ W/cm², one obtains $T_n = 33$ keV.

When electrons are heated to high temperatures, they can, in principle, separate from plasma ions. In PIC simulations such charge displacement creates an electrostatic sheath, which eventually accelerates the ions. Laser hole boring into overdense plasma with a pulse of 10^{20} W/cm² (and higher) takes place due to strong light pressure [4]. The ions are pulled by the charge of the electrons and pushed by the other ions' unshielded charges. This was first shown with gas jet targets [5] and then later with thin solid density films [6]. However, this phenomenon can be simply described as the macroscopic ambipolar diffusion in plasma, when both electrons and atomic ions are moving together with the speed of the plasma ionic sound, since plasmas try always to restore their neutrality.

Our goal is to derive the yield of alpha-particles in the nuclear fusion reaction p + ^{11}B $\rightarrow$ 3α which is practically unknown in laser fusion experiments. The rate of this nuclear reaction at the nuclear temperature T_n = 33 keV is equal to $\langle \sigma V \rangle$ = 6·10^{-19} cm^3/s.

We consider here the case of the equal mass part of the polyethylene $(CH_2)_n$ and boron matter in the mixture for fusion reaction having in mind our future experiments. We derive the yield of alpha particles N_α according to the relation

$$N_\alpha = \frac{3\sqrt{\pi}}{4} \langle \sigma V \rangle n_p r^2 \tau \, F_0 \sin\theta.$$

Here r is the radius of the laser beam, the Gaussian envelope of the laser pulse for the electric field strength is of the form

$$F(t) = F_0 \exp\left(-t^2/\tau^2\right).$$

n_p is the number density of protons.

Substituting the values of r = 5 μm, τ = 1.5 ps, $\langle \sigma V \rangle$ = 6·10^{-19} cm^3/s, the number density of protons n_p = 7.6·10^{22} cm^{-3} in boron – polyethylene $(CH_2)_n$ mixture and the peak laser intensity $I = 2 \cdot 10^{18}$ W/cm², one obtains finally N_α = 4000.

Obviously, the vacuum heating is absent when the laser light propagates normal to the target surface (or when the laser field is *s*-polarized at the inclined falling). However, laser hole boring into overdense plasma with a pulse of 10^{20} W/cm² (and higher) takes place due to strong light pressure [4]. Then electrons can be ejected by the laser field into the vacuum hole; electrons acquire the kinetic energy of some MeV because of the vacuum heating.

It should be noted also that in the case of picosecond (and longer) laser pulses the ponderomotive force of the laser pulse pushes the plasma electrons radially out of the focal spot. As a result an electron acquires the ponderomotive energy. But this heating mechanism is effective only in an underdense plasma [7]. In the case of an overdense plasma this energy is diminished by $(\omega_p/\omega)^2 >> 1$ times. The stationary channel formed by high intensity lasers in overdense plasmas was studied in [8]. This channel is formed by a balance between the laser ponderomotive force and the space-charge electrostatic field produced by expelled electrons (the atomic ions remain stationary during the ultrashort pulse duration).

Relativistic electron drift along the propagation of laser radiation produced by a magnetic part of laser field remains after the end of the laser pulse, unlike the relativistic drift of a free electron in an underdense plasma. As a result the penetration depth is much larger than the classical skin depth. The conclusion has been made [9] that the drift velocity is a non-relativistic quantity even at the peak laser intensity of 10^{21} W/cm^2. The time at which an electron penetrates into field-free matter from the skin layer is much less than the pulse duration. Thus, the electron drift does not increase the effective electron temperature produced by vacuum heating.

We considered here the non-relativistic acceleration of electrons. In the case of ultra-intense laser pulses (>10^{19} W/cm^2) with high contrast relativistic vacuum heating occurs even at the normal fall of laser light on the solid target [10]. The magnetic part of the Lorentz force pushes electrons in the normal direction to the target surface. Thus, electrons can complete half of their figure-eight orbits, on the vacuum side. During this motion electrons gain relativistic ponderomotive energy from the laser field and then return to the plasma side. They move through the overdense region without the laser field to pull them back. Of course, such a simple picture is realized when light encounters a sharp interface between vacuum and solid density. We should have in mind that the relativistic mass shift diminishes the plasma frequency, i.e. increases the critical density to higher values. This effect induces transparency of solid targets by intense pulses.

We conclude that the vacuum heating mechanism provides large fusion yield in boron-hydrogen mixture irradiated by a super-intense *p*-polarized picosecond laser pulse.

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