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HOLE BORING THROUGH OVERDENSE PLASMAS USING MULTIPLE ULTRAHIGH INTENSITY LASER PULSES

N. Naumova[1], C. Labaune[2], T. Schlegel[3], V.T. Tikhonchuk[4], G. Mourou[1], I.V. Sokolov[5]

[1] *Laboratoire d'Optique Appliquée, ENSTA - Ecole Polytechnique - CNRS, Palaiseau, France*

[2] *Laboratoire pour l'Utilisation des Lasers Intenses and Institute Lasers and Plasmas, CNRS - CEA - Ecole Polytechnique - Université Pierre et Marie Curie, Palaiseau, France*

[3] *Technical University of Darmstadt - GSI, Darmstadt, Germany*

[4] *Centre Lasers Intenses et Applications, Université Bordeaux 1 - CEA - CNRS, Talence, France*

[5] *Space Physics Research Laboratory, University of Michigan, Ann Arbor, USA*

With the appearance of short-pulse lasers providing focal intensities larger than 10^{20} W/cm^2, the radiation pressure becomes a dominant effect in driving the particle motion in an ionized target. The electrons are pushed steadily by this force and ions can be accelerated in the strong electrostatic field forming a shock-like structure [1, 2, 3]. The use of circularly polarized laser light might further improve the efficiency of ponderomotive ion acceleration avoiding strong electron overheating and allow to obtain a quasi-monoenergetic ion bunch in an homogeneous medium by adjusting the laser pulse and plasma parameters [4, 5, 6].

Here, we discuss the effect of radiative ion acceleration for the first time in inhomogeneous overcritical plasmas with densities rising up to values about hundred electron critical densities. We show the possibility of creation of a hole in such plasmas by using laser pulses with intensities exceeding 10^{22} W/cm^2, which is much deeper and more stable than considered before [7]. The plasma parameters considered in this work correspond to typical values of the first stage of a fast ignitor fusion scenario, where the thermonuclear fuel is quasi-adiabatically compressed to densities of several hundred g/cm^3.

The key point of our proposal is to use the energy of ions directly accelerated by the laser in the outer layers of core to ignite the pre-compressed fuel. The plasma density and temperature profiles of the deuterium-tritium target at the stagnation moment of the pre-compression phase have been obtained in numerical simulations [8]. It corresponds to the baseline all-DT target of the HiPER project [9] that is expected to release ~ 10 MJ with the energy gain ~ 60. The electron density region $(1 - 100)\ n_c$ where the ion acceleration takes place, can be roughly approximated by an exponential profile with a scale length around 20 μm and the temperature of a few hundred eV.

Simulation results will be presented that clearly demonstrate that the interaction of an ultraintense laser pulse with a high-density plasma takes the form of a piston that drives an electrostatic shock in the plasma. The laser ponderomotive potential sweeps all electrons forward, so that the charge separation field forms a double layer where the ions are accelerated forward. The parameters of this double layer (electrostatic shock or piston) slowly evolve in time due to variations of the plasma density and the laser intensity. In front of the piston, the plasma is practically neutral - ions and electrons reflected from the piston are propagating in an unperturbed plasma with the same velocity [2, 3, 4, 5, 6].

The momentum conservation relation written in the reference frame of the piston, provides the following expression for the piston velocity $v_f = cB/(1+B)$, where the parameter $B = \sqrt{I/\rho c^3}$ is defined by the ratio of the laser intensity I to the plasma mass density ρ. The piston velocity characterizes also the reflection coefficient of the laser light in the laboratory frame, $R = (1 - v_f/c)/(1 + v_f/c)$, and the velocity of accelerated ions, $v_i = 2v_f/(1 + v_f^2/c^2)$.

In contrast to previous publications, we are considering here an inhomogeneous plasma with an exponential density profile corresponding to the compressed thermonuclear fusion target [12]. By integrating the equation for the piston coordinate, $dx_f/dt = v_f$, over the interval of densities, one finds the time needed to push the plasma, the laser pulse duration and the spectrum of accelerated ions. Energy spectra of accelerated ions and their characteristic energies are shown in Fig. 1. For laser intensities exceeding 10^{22} W/cm^2 they are in the range from a few tens of MeV to a few GeV.

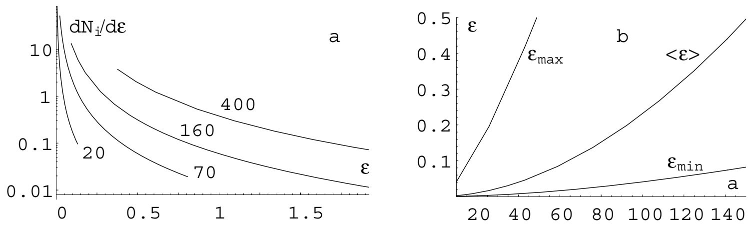

Figure 1: a) Energy distribution of accelerated ions for the plasma layer with density varying from 1 to 100 n_c for a circular polarization. The values of laser amplitude $a = eE_0/m_e\omega_0 c$ are given near the corresponding curves. The ion energy is normalized by $m_i c^2$. b) Dependence of the average, minimum and maximum ion energies on the dimensionless laser amplitude for the same conditions as shown in panel a.

The theoretical model of hole boring and ion acceleration in an inhomogeneous plasma using ultraintense laser pulses was confirmed in a series of one-dimensional (1D) and 2D simulations with fully relativistic electromagnetic particle-in-cell (PIC) code [10]. The code does not include the collisions between particles, but it accounts for the electron radiation losses, which can be important at high laser intensities [11]. The simulations show that for a laser pulse with the intensity 4×10^{22} W/cm^2 and a circular polarization, the plasma layer with the density exponentially rising from 5 to 100 n_c on the length of 60 laser wavelengths will be burned through after 250 periods and the laser pulse duration needed to create such a channel amounts to ~190 periods. Both numbers are in a good agreement with the model. The resulting laser fluence is equal to 20 GJ/cm^2, while 5.4 GJ/cm^2 (27%) is transferred in ions, ~ 1% of laser energy has been transformed to electrons and ~10% into high energy photons. An example of a channel formation for these laser and plasma parameters is shown in Fig. 2. The angular divergence of accelerated ions does not exceed 10°.

We emphasize the role of high energy photon emission by energetic electrons in the strong laser field. Although the radiation process increases energy losses, it appeared to play a positive role in the laser pulse channeling and ion acceleration, as it allows to maintain the electron thermal energy on a relatively low level and prevents the electron backward motion through the pulse region. Both effects tend to suppress the filamentation instability.

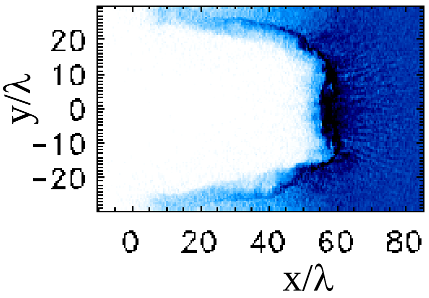

Figure 2: Density distribution in a plasma layer created by a laser pulse with a flat-top transverse laser intensity profile with a width of 20λ and exponential wings, $a = 100$, circular polarization. The instant of hole formation is 190 laser periods.

This mechanism of ion acceleration could be applied for the fast ignition of the thermonuclear fusion targets. Two laser pulses are needed: first for the hole boring and another for the ion acceleration. Assuming that the compressed fuel has a shape of a homogeneous sphere of the radius R and the density ρ, the scaling laws for the ignition energy, E_{ig}, the maximum pulse duration, and the hot spot radius, r_{ig}, were derived in Ref. [12]: $E_{ig} = 18(\rho_0/\rho)^{1.85}$ kJ and $r_{ig} = 20(\rho_0/\rho)^{0.97}\,\mu$m, where $\rho_0 = 300$ g/cm^3 is the reference density. This energy must be carried by fast ions with the stopping range of the order of the areal mass density in the compressed fuel, $\rho R \sim 1 - 1.5$ g/cm^2. Then the energy of fast ions carrying energy to the core is limited by the value of 60 MeV. In our presentation we will show that the laser pulse with intensity $\sim 2 \times 10^{22}$ W/cm^2 is sufficiently strong to evacuate most of the electrons and accelerate the ions to the correspondent energy in the density range from 70 to 200$\,n_c$ on the exponential density profile with the density scale length of 20$\,\mu$m. The ion energy flux of 3 GJ/cm^2 can be generated with a 0.75 ps laser pulse of a total flux ~ 15 GJ/cm^2. The total laser energy ~ 45 kJ is of the same order as in other schemes.

In addition, we estimate the laser energy required for for the hole creation in the undercritical plasma to provide the access for the laser pulse to the acceleration zone. Applying the intensity scalings from discussed above and confirmed in Ref. [13], we obtain an energy need of 20 kJ in a laser pulse with the intensity 10^{21} W/cm^2. The hole boring in the underdense plasma will take 3 ps and another 4 ps are necessary to reach the bottom of the acceleration zone, $n_e = 70\, n_c$.

The main advantage of this new approach to the fast ignition with two consequent laser pulses is that it does not need any additional target arrangements and can be applied for spherical targets, which are well adapted for the high repetition rate operation. However, it requires very intense laser pulses with a power of the order of 60 PW. Such power is supposed to be achieved in the second stage of the ELI project [14].

Acknowledgements

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