Relativistic hole boring and fast ion ignition with ultra-intense laser pulses

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Abstract. An analytical model and numerical simulations demonstrate that pulses with intensities exceeding $10^{22}$ W/cm$^2$ may penetrate deeply into the plasma and accelerate efficiently ions in the forward direction. We propose a new scheme for fast ignition of precompressed DT fusion targets by using two laser pulses. The first pulse (or a sequence of several pulses) creates a channel with diameter $\sim 30 \mu m$ through the plasma corona up to the fuel density $\sim 1 \text{ g/cm}^3$. The second pulse with a higher intensity accelerates the deuterium and tritium ions at the head of this channel. The overall ignition energy is $\sim 100 \text{ kJ}$.

1. Introduction

The laser ponderomotive force may provide an efficient ion acceleration in bulk dense targets and evacuate a channel enabling further laser beam propagation. A quasi-stationary model of a laser piston predicts the general parameters of the acceleration process in one-dimensional geometry. The particle-in-cell (PIC) simulations confirm the estimated characteristics in a wide range of laser intensities and ion densities and show advantages of circularly polarized laser pulses compared to linear polarization. The characteristics of channel formation and the angular distribution of accelerated ions are found from two-dimensional PIC simulations. This model and integrated numerical simulations are used for design of a new scheme of ion fast ignition.

2. Quasi-stationary model of ponderomotive ion acceleration

A quasi-stationary model of a laser piston predicts general parameters of the acceleration process [1]. An expression for the instantaneous piston velocity follows from momentum conservation of the photon flux coming from the laser side and of the opposite plasma flow coming from the upstream region of the piston. Assuming a circular polarization of the laser light and neglecting the electron heating, this velocity, $v_f = \beta_f c$, is determined by the relation $\beta_f = B/(1 + B)$, where the dimensionless parameter $B = (I_{\text{las}}/\rho c^3)^{1/2}$. The ions are accelerated
in the thin double layer and they are propagating upstream with the velocity \( v_1 = 2\beta_f c/(1 + \beta_f^2) \) and with the energy \( \epsilon_1 = 2m_i c^2 B^2/(1 + 2B) \). In particular in the limit of a non relativistic piston, \( B \ll 1 \), \( v_1 \approx 2\nu_f \) and the ion energy obeys the asymptotic solution \( \epsilon_1 = 2m_i I_\text{las}/pc \).

Knowing the density dependence of the piston velocity and of the ion energy, one can describe also the acceleration process in an inhomogeneous plasma. For an exponential density increase in laser propagation direction with the scale length \( L \), we obtain analytical results for the ion fluence \( F_i \), the laser pulse duration \( \tau_{\text{las}} \) and the mean energy of accelerated ions:

\[
F_i \approx \frac{2I_{\text{las}} L}{c} \ln \frac{\rho_{\text{max}}}{\rho_{\text{min}}} , \quad \tau_{\text{las}} = 2L \sqrt{\frac{\rho_{\text{max}} c I_{\text{las}}}{I_{\text{las}}}} \left( 1 - \sqrt{\frac{\rho_{\text{min}}}{\rho_{\text{max}}}} \right) , \quad \langle \epsilon_i \rangle \approx \frac{2I_{\text{las}} m_i}{(\rho_{\text{max}} - \rho_{\text{min}}) c} \ln \frac{\rho_{\text{max}}}{\rho_{\text{min}}} . \tag{1}
\]

3. Numerical simulations of ion acceleration

One-dimensional PIC simulations [2] confirm the analytical predictions of the piston model. Two-dimensional [1, 3] and three-dimensional [4] PIC simulations of the ponderomotive ion acceleration with intense laser pulses provide an additional information about the angular divergence of the accelerated ions and the stability of the hole boring process. The mean divergence of the ion bunch depends on the laser beam intensity distribution, and for a flat top laser intensity profile accelerated ions are confined in a cone with the opening angle \( \Delta \theta \approx 6^\circ \). The plasma channel is formed with the velocity predicted by the piston model and the laser propagation in the channel is stable because almost no plasma has left behind the piston as it is shown in Fig. 1b. It was found from numerical simulations that the radiation losses from relativistic electrons entering the vacuum laser field behind the piston have a strong positive effect by maintaining escaped electrons in a close vicinity of the piston. This effect of electron cooling need to be accounted for laser intensities exceeding \( 10^{22} \) W/cm\(^2\).

4. Fast ignition with ponderomotively accelerated ions

The proposed ignition process proceeds in two stages. Similarly to the scheme of the electron fast ignition [5], the first laser pulse creates a channel through the plasma corona and the second pulse accelerates the deuterium and tritium ions in the bottom of this channel. The hole boring process can be also divided in two steps. For the hole boring of an underdense plasma one can utilize a laser pulse of an intensity \( \sim 10^{21} \) W/cm\(^2\) and, according to the scaling proposed in Ref. [6], a 1 mm hole can be produced in 3 ps with the laser power of 3.5 PW. The hole boring in the overdense plasma requires the intensities at least \( 3 \times 10^{21} \) W/cm\(^2\) and it may take more than 10 ps to create a channel to the densities about 1 g/cm\(^3\).
More intense laser pulses are needed for ignition. According to [7], the following scaling laws define the ignition energy $E_{ig}$, the hot spot radius $r_{ig}$ and the energy deposition time, $\tau_{ig}$, as functions of the fuel density $\rho$:

$$E_{ig} \approx 18(\rho_{ref}/\rho)^{1.85} \text{kJ}, \quad r_{ig} \approx 20(\rho_{ref}/\rho)^{0.97} \mu\text{m}, \quad \tau_{ig} \approx 21(\rho_{ref}/\rho)^{0.85} \text{ps}$$

where $\rho_{ref} = 300 \text{ g/cm}^3$. However these scalings were defined for a homogeneous sphere of fuel and for particles with a fixed range of $1.2 \text{ g/cm}^3$.

Knowing the ignition energy, $E_{ig}$, and the scale length of the plasma density profile, $L$, from Eqs. (1) we define the required laser power $P_{\text{las}} = \pi r_{\text{acc}}^2 I_{\text{las}}$ and the length of the acceleration zone $l_{\text{acc}} = L \ln(\rho_{\text{max}}/\rho_{\text{min}})$, assuming that the density ratio is chosen, $\rho_{\text{max}}/\rho_{\text{min}} \sim 4 - 6$. The radius of the acceleration zone, $r_{\text{acc}} = r_{ig} - \Delta \theta D$ is defined by the mean beam divergence $\Delta \theta$ and the distance $D$ between the acceleration zone and the dense fuel. The latter is found from the condition that the position of the acceleration zone is such that the range of accelerated ions is approximately $1 \text{ g/cm}^2$. This corresponds to the average energy of deuterium and tritium ions $\sim 10 \text{ MeV}$. This qualitative estimates provide a starting point for more detailed integrated numerical simulations. Three examples of fusion targets are explored: one of them is a relatively

small all-DT target designed for the HiPER project [8], other two targets of a larger size [9, 10] are more adapted for a future fusion energy plant. The integrated numerical simulations of the ignition and combustion processes were conducted with the radiation hydrodynamic codes CHIC [11] and DUED [12] combined with the modules of ballistic ion transport.

The baseline HIPER target [8] at the stagnation consists of a $25 \mu\text{m}$ thick shell of the mean density of $400 \text{ g/cm}^3$ with the mean radius of $50 \mu\text{m}$. This target requires $200 \text{ kJ}$ laser energy for compression. It was ignited with the laser pulse of intensity $I_{\text{las}} = 9.3 \times 10^{21} \text{ W/cm}^2$ focused in the spot of the radius of $r_{\text{acc}} = 23 \mu\text{m}$ at the density of $1 \text{ g/cm}^3$. The acceleration zone of a length $30 \mu\text{m}$ is located at the distance $D = 60 \mu\text{m}$ from the shell. In this example shown in Fig. 2, $20 \text{ kJ}$ (73%) of the ion energy is dumped to the dense shell and 23% is deposited along the ion path between the acceleration zone and the dense shell. The laser pulse power is $150 \text{ PW}$ and a corresponding laser energy is $350 \text{ kJ}$. The released fusion energy is $8.5 \text{ MJ}$, corresponding to the energy gain of about 15. The ignition process is not optimized because the shell is too thin and too much energy is lost for expansion of the heated region. According to Fig. 3a, the fusion reactions are stagnated at a low level first $20 \text{ ps}$ after the ion energy deposition, and the ignition occurs when the exploded part of the shell collides with the opposite, cold part. Targets with a thicker core and smaller hot spot need to be designed for fast ignition scheme. Two thicker
targets described in Refs. [9, 10] are more suited for the ion ignition. As it is shown in Fig. 3b, the fusion energy power grows continuously immediately after the energy deposition. Therefore, the reactions are ignited directly in the energy deposition zone. However, these targets require more laser energy for compression: 500 kJ for [10] and 1 MJ for [9]. The target of Ref. [10] requires 17 kJ of the ion energy for ignition and releases ~90 MJ, and the target [9] requires 12.7 kJ of the ion energy and released ≈200 MJ. According to the piston model, these targets require the ignition laser energy of 100 kJ and the power of 30 PW.

5. Conclusions

Laser ion acceleration by the ponderomotive pressure is an efficient process at high intensities, although a high contrast and circular polarization are needed. The model of a laser piston that predicts the ion energy spectrum in function of the laser and plasma parameters is confirmed with numerical PIC simulations. The process of channel formation is stabilized by the effect of electron radiation losses. The actual baseline HiPER target has a very thin shell at the stagnation time and it requires too much energy of the ignitor laser pulse, three times more than the energy estimated for the electron fast ignition. Such thin shell targets are not adapted for fast ignition. Thicker targets allow to reduce the ion ignition energy to the level of 100 kJ, and to obtain the energy gain more than 200. Future optimization of the ion fast ignition could be related to acceleration of ions with higher charge, such a carbon or oxygen. An experimental demonstration of the hole boring process is desirable for evaluation of reliability of this scheme.

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