High-ion dynamics in the acceleration of protons by high-power lasers with double-layer targets

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Abstract

The acceleration of light ions (protons) through interaction of high-power laser pulse with a double-layer target is theoretically related to the production of heavy ion (protons) due to the physical characteristics of a heavy-ion layer (electronic mass ratio and effective charge state of the ions). In one theoretical model, the hydrodynamic equations for both electrons and heavy-ion species are solved and the two-particle approximation for the light ions (protons) is applied. The heavy ion motion is found to modify the longitudinal electric field distribution, thus changing the acceleration conditions for the protons.

The target structure

The target consists of 0.1 µm thick high-density (n_e = 6.4 × 10^{20} cm^{-3}) heavy-ion foil with a 0.10 µm thick low-density (n_e = 2.8 × 10^{19} cm^{-3}) hydrogen layer located along the target surface with a dimension of 33.5 nm and width (distance) of 24 and 140 (FWHH), respectively, which corresponds to approximately 0.05 TW laser pulse. Several types of targets with different electron-to-proton mass ratio and ionization state have been investigated.

The change of the substrate is considered to be a parameter in this work.

1D hydrodynamic model

We switch from the Euler variables (x, t) to those of the Lagrange variables (x_i, t), where x_i is the electron fluid element coordinate at t = 0. The two sets of coordinates are related through the following expression:

\[ x_i(t) = x + L_i(t) \]

(1)

where L_i(t) is the displacement of the electron fluid element from its initial position x_i at t = 0. The two variables can be solved iteratively.

The momentum in general is a function of the initial electron momentum 0 and given by the following expression:

\[ p_i(t) = \left(1 + \frac{\gamma v_i}{c}\right) p_i(0) \]

(2)

where \( \gamma \) is the Lorentz factor, which is the change of the particle's energy due to the electric field of the light pulse, \( v_i \) is the initial electron velocity, and \( p_i(0) \) is the initial electron momentum.

1D PIC simulation results

A 2D PIC numerical simulation code was used to model the interaction of a high-power laser pulse with a double-layer target. The calculations were performed in a box of 240 × 125 simulations in a box of 200 ions and 200 protons. The laser pulse is Gaussian in shape with length (duration) and width (Gaussian time) of 100 fs and 200 fs, respectively, which corresponds to approximately 0.05 TW laser pulse. Several types of targets with different electron-to-proton mass ratios and ionization state have been investigated.

The solution of Eqs. (2 a–2 e) is given by the following expression:

\[ \tilde{E}(x_i, t) = -4\pi e Z_i n_e 2 \frac{e^{2}}{m_e \omega^2_{pe}^2 \Delta} \left(1 + \frac{\gamma v_i}{c}\right) \delta(x_i - x_{i0}) \delta(t - t_{i0}) \]

(3a)

The solution of Eq. (2 x) is given by the following expression:

\[ \tilde{p}(x_i, t) = \frac{e}{m_e} \left(1 + \frac{\gamma v_i}{c}\right) p_i(0) \delta(x_i - x_{i0}) \delta(t - t_{i0}) \]

(3b)

and decreases afterward. Eventually the electron fluid element returns to the target, and we can observe the following behavior.

The general dynamic of the electron component can be described by the oscillations around the target. The time to return the period of oscillation depends on the initial position x_i of the fluid element. Electrons that initially are closest to the boundary of the plasma slab (\( x_i - x_{i0} \)) have longer return times.

1D PIC simulations

Conclusions

We analyzed on quantitatively well the role of the heavy ions in the acceleration of the electron component.

The electron acceleration is found to be more efficient for lower values of the structural parameter \( \gamma = Z_{i0}/n_{i0} \). Up to 50% difference in the maximum power energy was observed for the lowest substrate mass that made platinum, but otherwise the same ionization state (Z_i = 4).

With the help of a simplified 1D hydrodynamic model, we obtain the electron field profile at the front of the expanding electron slab (Fig. 8) and find an increase in the electron field strength in the region behind the surface of the target. 2D PIC simulation of the interaction confirm the analytical results obtained from the 1D hydrodynamic model.

The 2D PIC of the electrons, revealed by the hydrodynamic model, may partially explain the electron acceleration of the ion slab, thus somewhat enriching the proton acceleration.