Peculiarities of laser-driven acceleration of a flat projectile up to "thermonuclear" velocities

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Abstract. Theoretical and numerical results on laser-driven acceleration of flat foil to ultrahigh velocity of the order of 1000 km/s, which corresponds to an achievement of thermonuclear temperatures due to an inelastic impact, are reported. The comparison with experiments performed on the Gekko/HIPER laser, where a laser-driven projectile achieved the record-breaking velocity is presented. The laser pulse and foil parameters responsible for acceleration of the projectile up to “thermonuclear” velocities in a dense state have been determined.

1. Introduction

The interest to impact ignition has considerably increased at the present day due to elaboration of fast ignition ICF concept [1,2]. The impact by laser-accelerated projectile [3,4] is an effective method to ignite the preliminarily compressed ICF-target, along with the action of fast electron or ion beams. Such an approach was developed to “impact fast ignition” concept [5,6] being actively studied now. The record projectile velocity was achieved in Gekko/HIPER experiments [6] destined to study impact fast ignition. Here the 14-20 \textmu m thickness CH (50\%C, 50\%H) or CHBr (50\%C, 47\%H, 3\%Br) foils were irradiated by third harmonic of Nd-laser radiation ($\lambda=0.35$ \textmu m) at the pulse intensity, $I=410^{14}$ W/cm$^2$ and duration, 2.5 ns. The foil velocities of 600-700 km/s were measured. The foil density was not measured. The problem of laser-driven impact ignition is more complicated, as compared to one-dimensional acceleration of a flat foil. To minimize undesirable two-dimensional effects, as well as to solve some other problems, in particular, to increase the final projectile density, the impact fast ignition scheme [5,6] assumes the acceleration of a spherical layer along a conical channel.

The paper is devoted to a theoretical investigation of flat foil acceleration up to ultrahigh velocities of the order of 1000 km/s. The research was made in 1D-approximation to define ultimate possibilities of laser-driven acceleration of a projectile in a dense state. The comparison with the results of Gekko/HIPER experiments is presented.

2. Target and laser parameters necessary to achieve thermonuclear velocities

The investigation is performed of a low-entropy laser-driven acceleration of light-element target irradiated by laser radiation, when $I\lambda^2$-parameter is not higher than 510$^{14}$ Wcm$^{-1}$\textmu m$^2$. Then, the laser light is effectively absorbed by inverse Bremsstrahlung mechanism, the ablation density is close to the
critical plasma density, the most effective laser coupling with a blow-off plasma and minimal heating of unablated part of the target are provided. Under these conditions, the rocket model gives the following solution for the final velocity of a plane foil \( u \) (measured in the units of thermonuclear velocity, 1000 km/s) and thickness \( \delta \) of unablated foil (normalized to initial foil thickness, \( \Delta_0 \)):

\[
u = 0.83(\lambda^2)^{1/3} \ln \delta^{-1}, \quad \delta = 1 - 1.97(\lambda^2)^{1/3} \Delta_0^{-1} - 1.73\lambda^{-2} \quad (1)
\]

In Eqs. (1) are supposed that the blow off plasma is fully ionized, the adiabatic exponent is equal to 5/3 and the intensity \( I \), pulse duration \( \tau \), the initial foil density \( \rho_0 \), wavelength \( \lambda \) together with foil thickness \( \Delta_0 \) are measured in the units of \( 10^{17} \) W/cm\(^2\), ns, g/cm\(^2\) and \( \mu \)m, respectively. For \( \delta = 1/5 \), which corresponds to a maximal hydrodynamic efficiency of plane acceleration (\( \eta = 0.41 \)), Eqs. (1) show that the ultimate velocity achievable at low-entropy acceleration actually conforms to the thermonuclear velocity, and lies within the range of \((1.1-1.5) \times 10^4\) Wcm\(^{-2}\)\(/\mu m^2\). Such a velocity corresponds to impact-produced temperature of deuterium-tritium fuel equal to 10–20 keV.

To find the laser and foil parameters, which correspond to the certain final velocity, one should add to the Eqs. (1) the requirement of plane expansion of the blow-off plasma \( \tau R_o/c_s \), where \( R_o \) is the laser beam radius and \( c_s \) is the plasma sound velocity at the ablation boundary:

\[c_a = [2(\gamma - 1)/(\gamma + 1)]^{1/3} (1/\rho_0^{1/3}) (2)
\]

Then, the choice of \( \delta = 1/5 \) and sign of equality in the plane expansion requirement leads to

\[\Delta_0 \rho_0 \approx 0.45 \left( \frac{\lambda^2 - 4/3}{u^{2/3}} \right)^{1/3} \left( \frac{\lambda^2}{u} \right)^{1/3}, \quad \tau \approx 0.22 \left( \frac{\lambda^2}{u} \right)^{1/3} \left( \frac{\lambda^2}{u} \right)^{1/3}, \quad R_o \approx 48 \left( \frac{\lambda^2}{u} \right)^{1/3} \left( \frac{\lambda^2}{u} \right)^{1/3} \quad (3)
\]

For the fixed energy, each of those parameters decreases with the final velocity increase, and the pulse duration increases most strongly. The pulse duration and beam radius increase with the wavelength, while the target thickness, on the contrary, decreases. The wavelength influence on the final state of accelerated foil is ambiguous. According to Eqs. (1), the final velocity increases with the growth of wavelength because the sound velocity increases with the decrease in critical density (see Eq. (2)). On the other hand, with the increase of the wavelength the processes responsible for the reduction of the final projectile density due to a thermal expansion become more evident. That is the heating of unablated foil by electron heat conductivity and shock waves. The thermal expansion is insignificant when the time \( t \approx \Delta_0/c_s \), \( c_s \) is the sound velocity in unablated foil) is longer than the laser pulse duration \( \tau \). For shock-heating \( c = \gamma (\gamma + 1)^{1/2}(\rho_0/\rho)^{1/2}c_s \), where \( \gamma \), is the adiabatic exponent behind the wave front. Then, the requirement that the final foil density is higher than the initial one is

\[\tau \geq 410^{-2} \Delta_0 \rho_0^{1/2} \lambda^{1/2}(\lambda^2)^{-1/3} \quad (4)
\]

According to Eqs. (1) and (3), in order to reach the velocity of polystyrene foil of 1000 km/s at the final density not less than the initial one (\( \rho_0 = 1 g/cm^3 \)) under the action of \( 10^4 \) J pulse of the third Nd-laser-harmonic radiation the parameters should be taken as \( \tau \approx 1.2 \) ns, \( R_o \approx 380 \mu m \) and \( \Delta_0 \approx 27 \mu m \) (\( 1 \approx 210^{14} \) W/cm\(^2\)). The Gekko/HIPER experiment conditions are close to optimal for reaching the thermonuclear velocities. However, according to Eq. (4), to conserve the final foil density larger than the initial one, the pulse duration should be less than that used in the experiment, namely, \( \tau = (0.8-1) \) ns.

Now consider the Rayleigh-Taylor instability effect on foil acceleration by using the well-known formula for an increment of a perturbation growth at a linear stage of instability evolution [7]

\[\Gamma = \Gamma_0 - \beta k \frac{D_m}{m}, \quad \Gamma_0 = \left[ A \frac{m}{m_a} g / \left( 1 + k \frac{L_m}{a} \right) \right]^{1/2} \quad (5)
\]

In these expressions, \( k_m \) is the unstable wavenumber; \( g \approx \mu / \tau \), the acceleration; \( L \approx \kappa \tau \), the density gradient scale length at the ablation front; \( A \), the Atwood number \( (A = (\rho_0 - \rho_a)/(\rho_a + \rho_0)/2) \), since \( \rho_0 < \rho_a \); the velocity of evaporation wave \( D \approx \eta \rho_0/\rho_a \) and \( c_s \) is given by Eq. (2); the constant \( \beta \approx 3 \). For the most dangerous (with respect to foil destruction) mode, \( k_m = 2\pi/\Delta \), and hence, \( k_m L_m >> 1 \). So, Eqs. (5) gives the following increment for the dangerous mode
\[ \Gamma = \left( \frac{u}{c_a} \right)^{1/2} \tau - 6 \pi \rho_a c_a / \rho_0 \Delta. \] (6)

Equation (6) shows that under acceleration of a flat foil up to the velocities not higher than the sound velocity of the ablated matter the relation \( \tau < \Gamma^{-1} \) is always valid, and the instability influence on plane foil acceleration is small. The influence becomes stronger under "supersonic" acceleration of the foil, when \( u > c_a \). Introduce Eqs. (1) and (2) into Eq. (6), and assume (as was made earlier) that \( \delta = 1/5, \gamma = 5/3 \). Then, from Eq. (6) one can see that the requirement \( \tau < \Gamma^{-1} \) is fulfilled if

\[ \tau > 2.21 \times 10^{-7} \rho_0 \Delta_0 \sqrt{I_\lambda^2} (I_\lambda^2)^{-1/3} \]

At \( I_\lambda = 10^{14} \text{ Wcm}^2 \mu \text{m} \) and \( \lambda = 1.06 \mu \text{m} \) the pulse duration should exceed 0.7 ns for 30 \( \mu \text{m} \) thick CH-foil, and 2.2 ns for 100 \( \mu \text{m} \) foil thickness. For the third harmonic (\( \lambda = 0.35 \mu \text{m} \)) the limit value of laser pulse duration becomes smaller: \( \tau > 0.08 \) ns for foil thickness of 30 \( \mu \text{m} \), and \( \tau > 0.23 \) ns for foil thickness of 100 \( \mu \text{m} \). So, for the third harmonic the condition of stable acceleration is valid for the laser and foil parameters corresponding to the foil acceleration to thermonuclear velocity in a dense state.

3. Numerical simulations of laser-driven acceleration of a plane projectile.

Here the results from two sets of numerical simulations are discussed. The first group of simulations was performed by 1D Diana-code, and was aimed to the modeling of Gekko/HIPER experiments. The second group of simulations was performed by 1D Rapid-code, and was aimed to define the laser and target parameters for dense-state projectile acceleration up to thermonuclear velocities. In both codes the main physical processes typical for the inertial thermonuclear fusion were taken into account, namely, the electron and ion heat conductivity, the two-temperature state, the laser radiation absorption by the inverse Bremsstrahlung mechanism, the ionization and real equations of state. In addition, the Rapid-code takes into account the resonance mechanism of laser light absorption.

**Figure 1.** The foil position versus the time for the case when the initial foil thickness is 20 \( \mu \text{m} \).

**Figure 2.** The space-distribution of the foil density in the different moments of time for the case when the initial foil thickness is 20 \( \mu \text{m} \).

Figures 1 and 2 show the results of Diana-code simulation performed for the polystyrene foil of the thickness of 20 \( \mu \text{m} \) irradiated by Gekko/HIPER laser pulse. Figure 1 shows the temporal evolution of the foil position. The variation of maximal density versus the foil position is indicated. The density in the color scale is given in g/cm\(^3\). The velocity of the accelerated foil reaches 800 km/s, which is close to the experimental results. To the end of a laser pulse the hydrodynamic efficiency and the fraction of
unablated mass are, respectively, 0.24, and 0.51. In the analyzed simulations the energy losses due to thermal emission are small, and constitute (1-2)% of the deposited laser energy. Figure 2 illustrates the density profiles for the time moments $t=0.0, 1.2, 2.0, 2.4,$ and $2.8$ ns in respect to the spatial coordinate. At the moment $t=2.4$ ns the maximum density equals $0.1$ g/cm$^3$. It should be noted that the foil of $20$ μm thickness is not burnt through. The final foil density is higher than the critical density. The simulations made for a thinner foil ($\lambda=14$ μm) and the same pulse parameters showed that such a foil is burnt through before the pulse ends. The foil velocity reaches approximately $1000$ km/s.

Table 1 lists the results of Rapid-code simulations for the mass-averaged velocity $u_{av}(t^*)$ of the accelerated foil at the moment $t^*$ when the maximal density of the accelerated foil $\rho_{max}$ becomes equal to the initial foil density. The foil velocity increases with the growth of the initial foil thickness and laser radiation intensity. The laser radiation absorption is close to $100\%$ due to a short wavelength of laser light. 2D-effects decrease the absorption down to $75$-80\%.

| $I$, W/cm$^2$ | $\Delta_0 = 15\mu m$ | $\Delta_0 = 30\mu m$ | $\Delta_0 = 60\mu m$ |
|--------------|----------------------|----------------------|----------------------|
|              | $u_{av}(t^*)$, cm/s  | $t^*$, ns            | $u_{av}(t^*)$, cm/s  | $t^*$, ns            | $u_{av}(t^*)$, cm/s  | $t^*$, ns            |
| $10^4$       | $3.59\times10^7$     | 28                   | $4.25\times10^7$     | 76                   | $4.9\times10^7$     | 200                  |
| $10^5$       | $4.40\times10^7$     | 4.6                  | $5.32\times10^7$     | 13                   | $6.36\times10^7$    | 36                   |
| $10^6$       | $4.41\times10^7$     | 0.64                 | $5.59\times10^7$     | 1.77                 | $6.89\times10^7$    | 5.1                  |

For the foil thickness of $\Delta_0 = 60$ μm the simulations were made with the linearly growing laser pulse: $I=(t/5ns)\times210^7$ W/cm$^2$ ($\lambda=0.35$ μm). The simulations showed that at $t=5$ ns the foil velocity is almost the same as for a constant pulse, $u_{av}=6.85\times10^7$ cm/s. The maximum density of the foil reaches $8$ g/cm$^3$ that is higher than for a constant pulse ($3.6$ g/cm$^3$) and turns to be high up to the moment $t$.

4. Conclusion.

The thermonuclear velocity of a flat projectile can be reached under low-entropy laser-driven acceleration. The velocity of $1000$ km/s of dense plastic foil can be reached at high laser light absorption and hydrodynamic efficiencies of 70-80% and 20%, respectively. The requirement on conservation of high projectile’s density at the end of acceleration process leads to the upper limit of laser pulse duration. The laser pulse profiling increases the final foil density. Although the foil velocity grows with the wavelength growth, it is more preferable to make use of the third harmonic of Nd-laser radiation. This is stipulated by the fact that under the decrease of laser wavelength the role of stimulated plasma processes becomes smaller and the absorption efficiency enhances, the hydrodynamic stability of foil acceleration grows, and the foil density decreases more slowly. The choice of shorter wavelength should be combined with the necessity to use the higher intensity the smaller is the wavelength, so that $I\lambda^{-2}$ parameter does not exceed $510^{15}$ Wcm$^{-2}$μm$^{-2}$.

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