Laser acceleration and collimation of dense plasma using laser-induced cavity pressure

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Abstract

A novel efficient scheme of acceleration and collimation of dense plasma is proposed and examined. In this scheme, a target placed in a cavity at the entrance of a guiding channel is irradiated by a laser beam introduced into the cavity through a hole and accelerated along the channel by the pressure created and accumulated in the cavity by the hot plasma expanding from the target and the cavity walls. Using 1.315-μm, 0.3-ns laser pulse of energy up to 200J and a thin CH target, it was shown that the forward accelerated dense plasma projectile produced from the target can be effectively guided and collimated in the 2-mm cylindrical guiding channel and the energetic efficiency of acceleration in this scheme is an order of magnitude higher than in the case of conventional ablative acceleration.

1. Introduction

The ablative acceleration (AA) driven by the pressure of expanding plasma produced by a laser or X-ray radiation is commonly applied to accelerate and compress fusion targets [1, 2] and has also been proposed to be used to accelerate a macroparticle to hypervelocity to ignite the fuel in the impact fast ignition (IFI) fusion scheme [3] as well as for other, non-fusion applications [4]. The energetic efficiency of acceleration, \( \eta_{\text{acc}} \), defined as the ratio of kinetic energy of the accelerated target to energy of radiation used for the acceleration, is limited by two factors: the absorption coefficient of radiation in the plasma, \( \eta_{\text{abs}} \), and the hydrodynamic efficiency, \( \eta_{\text{h}} \) (the ratio of the target kinetic energy to the absorbed energy). Even for a short-wavelength radiation (e.g. a 3ω beam of Nd:glass laser), for which these coefficients can be relatively high (\( \eta_{\text{abs}} \approx 70 – 80\% \), \( \eta_{\text{h}} \approx 10 – 20\% \) [1, 2]), the efficiency \( \eta_{\text{acc}} = \eta_{\text{abs}} \eta_{\text{h}} \) is rather low: \( \eta_{\text{acc}} \approx 7 – 16\% \). One of the important consequences of the low energetic efficiency of acceleration is very high laser energy required for high-gain laser fusion [1, 2].

In this paper, a novel highly efficient scheme of acceleration and collimation of dense plasma, referred to as laser-induced cavity pressure acceleration (LICPA), is proposed. The experimental results demonstrating that the energetic efficiency of acceleration in the LICPA scheme can be significantly higher than that in the AA scheme are presented.

2. Results

In the proposed scheme (Fig. 1), a projectile placed in a cavity at the entrance of the guiding channel is irradiated by a laser beam through a small hole in the cavity wall and accelerated along the channel by the pressure produced and accumulated in the cavity by the hot plasma expanding from the irradiated part of the projectile (from the ablator) and from the
cavity walls. An important part of the scheme (not considered in previously proposed schemes using the cavity pressure [5, 6]) is the guiding channel, which plays a role similar to that of a barrel in a conventional cannon. In particular, it prevents an “escape” of the pressure from the cavity (which allows for acceleration of the projectile for a long time) and, moreover, it makes it possible to collimate and compress the accelerated plasma.

Fig. 1. A scheme of laser-driven accelerator using LICPA (see the text).

The experiment aimed to demonstrate efficient acceleration and collimation of dense plasma in the proposed scheme was performed at the PALS laser facility in Prague. Both the cavity and the channel of the accelerator were hollowed-out in the massive Al cylinder and their length \( L_c, L_{Ch} \) and diameters \( d_c, d_{Ch} \) were equal to: \( L_c = 0.1 \text{mm}, L_{Ch} = 2 \text{mm}, d_c = d_{Ch} = 0.3 \text{mm} \) (Fig. 2). The diameter of the hole in the cavity wall was \( d_{hole} = 0.18 \text{mm} \) and the thickness of this wall was 0.1mm. A 10-\( \mu \text{m} \) polystyrene (CH) foil placed at the channel entrance was irradiated by a 1.315\( \mu \text{m} \), 0.3-ns laser pulse of energy up to 200 J and intensity up to \( 10^{15} \text{W/cm}^2 \) injected into the cavity through the hole. The parameters of the forward-accelerated part of the foil (actually – the dense CH plasma), playing the role of a projectile, were measured either in configuration M or N. In the configuration M, the massive Al target was placed at the output of the channel (see Fig. 2) and the volume of the crater produced in the target was assumed to be a measure of energy deposited in the target by forward moving dense plasma. In the configuration N (without the massive target) three-frame interferometry and ion diagnostic (ion charge collector) were used to estimated the velocity and temperature of plasma at the channel output. The results of the measurements performed in the LICPA scheme, in particular, the measurements of the crater volume and depth, were compared to the ones obtained for the AA scheme (CH foil accelerated in the channel without the use of the cavity).

Fig. 2. The volume and depth of craters produced in the Al target by high-density plasma driven by LICPA or ablative acceleration (AA) as a function of laser energy (intensity)
A quantitative comparison of the volume and depth of craters produced in the LICPA scheme and in the AA scheme is presented in Fig. 2. The laser intensity values marked in the figures were calculated assuming that all laser energy (focused to $d_L^2 \approx 0.5 \, d_{\text{hole}}$) was injected into the cavity through the hole in the LICPA scheme. The volume of the craters produced in the Al target by high-density plasma accelerated in the LICPA scheme is more than 30 times greater than that for the AA scheme. The crater volume for the LICPA scheme increases approximately linearly with an increase in laser energy and the saturation, seen in the plot for the AA scheme, does not appear in the considered energy range. As the crater volume is a measure of the energy deposited in the target and, indirectly, a measure of the kinetic energy of the forward-accelerated plasma, these results demonstrate that the energetic efficiency of acceleration ($\eta_{\text{acc}}$) in the LICPA scheme is significantly (an order of magnitude) higher than in the case of ablative acceleration. Also, the energy fluence of the plasma accelerated in the LICPA scheme is remarkably higher than that in the AA scheme, which results in a few times greater crater depth.

It should be underlined that, as it results from our measurements, using a guiding channel in the LICPA scheme is of key importance for production of a fast and dense plasma bunch since it ensures both efficient acceleration and collimation of the plasma. We have observed that in the case of employing LICPA without the channel, a very shallow crater or no crater was produced in the Al target placed at distances from the CH foil comparable to the channel length (1 or 2mm). It indicates that in such a case the energy accumulated in the cavity is finally dispersed in a large angle like in the case of using AA for the foil acceleration in free space [7].

The three-frame interferometry using the $2\omega$ PALS laser beam reveals that, at laser energy $\sim 130$ J, the forward-accelerated plasma covers the distance of 2 mm in $\sim 10 - 15$ ns in the channel, which means that the average plasma velocity in the channel is $<v> \sim (1.5 - 2) \times 10^7$ cm/s. This velocity was found to be comparable to the velocity of a plasma jet of relatively low electron density ($\sim 10^{18} - 10^{20}$ cm$^{-3}$) observed at the channel output in the AA scheme [7]. However, contrary to the AA case, such a plasma jet was not recorded in the LICPA scheme. As it results from our numerical simulations using 1D HYDES code, a plausible reason for this difference is the significantly higher density of plasma in the LICPA scheme caused by additional plasma compression by the pressure accumulated in the cavity.

3. Conclusion

In conclusion, a novel efficient scheme of high-density plasma acceleration and collimation using laser-induced cavity pressure has been proposed and demonstrated. Due to higher hydrodynamic efficiency and higher absorption of laser radiation in the cavity, the energetic efficiency of acceleration in this scheme can be an order of magnitude greater than in the case of the conventional ablative acceleration using the “rocket effect”. The proposed LICPA accelerator has a potential to be highly useful for fusion-related applications (e.g., for IFI fusion) as well as for other fields of research such as high energy-density physics, laboratory astrophysics or material processing.

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