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Application of laser-induced double ablation of plasma for enhanced macroparticle acceleration

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Abstract. The objective of the studies was to demonstrate that using laser-induced double plasma ablation (created by the laser light and the X-rays from a high-Z dopant introduced to a low-Z target) it is possible to increase significantly the kinetic energy of a macroparticle accelerated by a laser. In the experiments, the high-intensity (10^{14} – 10^{15}W/cm^2), high-energy (up to 120J) sub-ns 3ω beam of the PALS laser interacted with various (with and without high-Z dopant) thin foil targets. The laser-driven foil (the “macroparticle”) collided with a massive (Al) target producing crater, the volume of which was a measure of the foil kinetic energy released to the foil. Parameters of the accelerated foil and the ablated plasma were determined using three-frame interferometry, ion diagnostics, soft and hard X-ray diagnostics as well as the measurements of the crater dimensions. The results of investigations for low-Z foil targets; for undoped (homogenous) and for ones with high-Z dopants, were compared. It was found that the X-ray yield from the foil target with high-Z dopant is a few times higher than that from the undoped target and the ablating plasma flow is faster and more collimated. It results in an increase in kinetic energy of the accelerated foil (the crater volume is up to 80% larger) provided that the foil is sufficiently thick (20μm). Higher increase in the kinetic energy seems to be possible when using foils with a higher amount of a high-Z dopant and the foil thickness is well matched to the laser beam parameters.

1. Introduction

Impact fast ignition of inertial fusion requires that a macroparticle of sufficiently high density and mass is accelerated by laser-induced plasma ablation to velocities above 108 cm/s [1, 2]. The main obstacle in achieving such macroparticle velocities (which has never been attained before) is the Rayleigh-Taylor (RT) instability [3], which prevents the macroparticles from stable acceleration and it can destroy them before colliding with the precompressed DT fuel. One of the possible ways to suppress the RT instability and, as a result, to increase the macroparticle parameters is using laser-induced double plasma ablation (created by the laser light and the X-rays from a high-Z dopant introduced to a low-Z target) [4, 5]. It has been demonstrated recently that a plastic thin foil disc (a macroparticle) doped with a small amount (~ 3% weight) of high-Z atoms (Br) and irradiated by 0.35 -μm, 2.5-ns, 10^{14} W/cm^2 laser pulse could be accelerated to a record velocity of 6×10^7 cm/s [2], which was remarkably higher than that for an undoped disc. However, it was not confirmed that the densities of the accelerated discs were similar for both cases and, that the kinetic energy of the high-Z doped disc was also higher. This paper reports the results of the experiment in which the effect of a high-Z dopant on characteristics of accelerated macroparticle and ablating plasma was studied in detail.

2. Apparatus and methods Introduction

In the experiment, the high-intensity (10^{14} – 10^{15} W/cm^2), high-energy (up to 120 J) 0.3-ns pulse of the 0.44μm PALS laser beam [6] interacted with various (with and without high-Z dopant) thin foil targets. The laser-driven foil (the "macroparticle") collided with a massive (Al) target producing a crater, the volume of which was a measure of the foil kinetic energy. The parameters of the accelerated foil and the ablating plasma were determined using three-frame interferometry [7], ion diagnostics [8], soft and hard X-ray diagnostics [9] as well as the measurements of the crater dimensions (Figure 1).

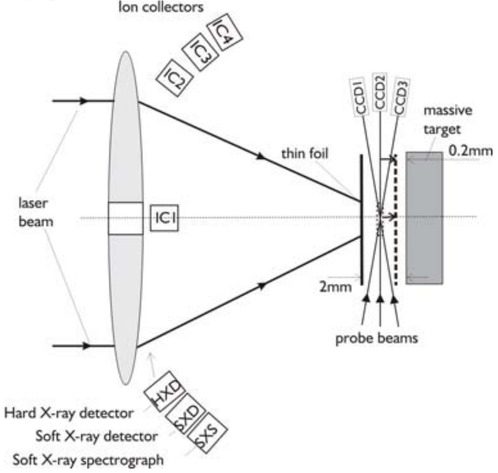

Figure 1. Simplified scheme of the experimental set-up (out of scale). The PALS laser beam irradiates a thin foil. Characteristics of ion and X-ray emission from the produced plasma are measured with the use of ion collectors (IC), hard and soft X-ray detectors, and a soft X-ray spectrograph. The velocity of the flying foil and the evolution of the ablating plasma are measured by the three-frame interferometric system.

The crater dimensions were measured for the Al target placed at distances of 0.2 mm and 2 mm from the initial foil position. The results of the investigations for two sets of foil targets were compared. In the first one the hydrogenated plastic (CH or OCT) targets, 10 μm or 20 μm thick, with a high-Z dopant (2 % of Cu in OCT or 3 % of Br in CH) were used. In the second one the plastic targets without the high-Z dopant were applied.

Figure 2 illustrates the evolution of ablating plasma from 10 μm thick undoped (CH-10) and Br-doped (CH(Br)-10) plastic foils irradiated perpendicularly to the foil surface by the 3ω laser beam of energy ~ 120 J and the beam diameter on the target d_L = 300 μm (the laser focus was behind the target). The two-dimensional (r, z) distributions in the figure are plasma electron isodensitograms – derived from the three-frame interferometry - recorded at three different times after irradiation of the target by the laser pulse (t = 0). Just below the isodensitograms, the corresponding spatial distributions of electron density are placed. It can be seen that in the case of CH(Br)-10 target the ablating plasma flow is more collimated and the plasma density is higher, especially at a late phase of plasma ablation (t = 8 ns). Qualitatively similar behavior of the ablating plasma was observed for 20 μm thick targets. However, the recorded plasma density at the late phase for CH(Br)-20 target was twice as high as for CH(Br)-10 and, moreover, the plasma flow velocity for CH(Br)-20 was higher than that for CH-20.

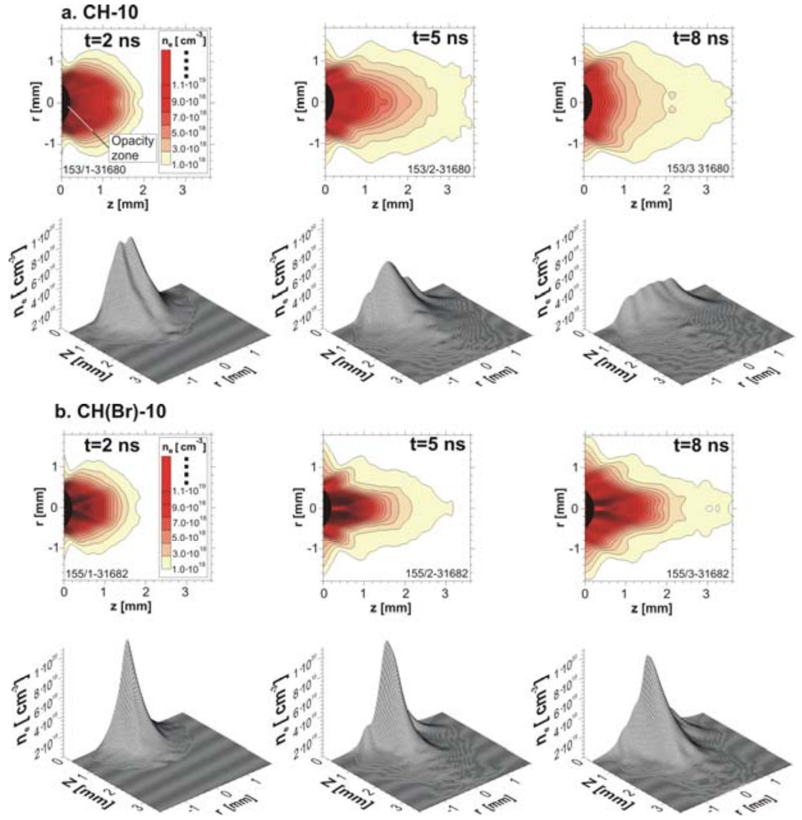

Figure 2. Evolution of ablating plasma from undoped (a) and Br-doped (b) CH foils of the thickness 10μm. $E_L \approx 120$J, $d_L \approx 300$μm, $I_L \approx 5 \times 10^{14}$W/cm^2.

3. Results and discussion

Ion diagnostics give similar differences in the ablating plasma flows from CH and CH(Br) targets, than those revealed by interferometry. In the case of CH(Br) targets the angular distribution of ion emission was narrower than for CH targets and maximum ion emission was usually recorded along the target normal, as opposite to the undoped target for which the distinct maximum was always outside the target normal. Significant differences were also observed in X-ray emissions from the two kinds of employed targets. In spite of small amount of high-Z dopand, the X-ray yields for both Br-doped and Cu-doped targets were several times higher than those for the undoped ones. In order to obtain information about the shape and dimensions of craters produced in the collision of the flyer foil with the Al target, the craters replica were made of cellulose acetate [10]. Figure 3 illustrates the replicas of craters produced in the Al target by CH(Br)-20 and CH-20 foils at the distance of 0.2 mm from the initial foil position. The crater produced by the CH(Br)-20 foil is larger and its volume is about twice as large as that for the undoped foil. Even larger differences in the crater volumes produced by high-Z doped and undoped foils were observed at longer distances (2 mm) from the laser-foil interaction region. It should be noted, however, that these differences were significant only for the thicker, 20-μm foils and they were quite small (within the experimental error) for 10 μm foils.

In general, a larger crater volume is a result of more energy deposited to the massive target which, in turn, depends on the kinetic energy and density of the flyer foil at the moment of the foil-target collision. Foil velocity measurements, performed on the basis of the shadowgrams recorded for t = 2 ns, 5 ns and 8 ns, show that the velocities of doped foils (up to ~ 2×10^7 cm/s) are only slightly higher

(~ 10 – 20 %) than for undoped foils. Thus, the possible differences in kinetic energies of the foils do not explain significant differences in the crater volumes. The more important reason seems to be the higher density of the doped foil at the late phase of acceleration.

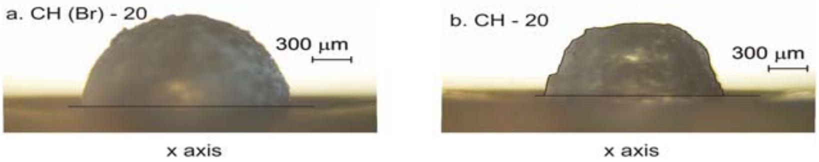

Figure 3. Replica of craters produced in the Al target by CH (Br)-20 (a) and CH-20 (b) foils accelerated by a laser pulse. $E_L \approx 120J$, $d_L \approx 300\mu m$, $I_L \approx 5 \times 10^{14} W/cm^2$.

In conclusion, it has been found that the ablating plasma flow from the high-Z doped foil target moves faster and more collimated and the plasma has a higher density than in the case of undoped target. It results in higher kinetic energy and/or density of the flyer foil at the late phase of acceleration (at the moment of the foil-massive target collision) in case the foil is sufficiently thick. The observed increase in the flyer foil performance is likely caused by additional plasma ablation created deep in the foil by X-ray radiation, which is measured to be significantly more intense in the case of high-Z doped target. Even larger increase seems to be possible with this method when using foils with a higher amount of a high-Z dopant and the foil thickness is well matched to the laser beam parameters.

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