Plastic plasma influence on formation of laser-produced copper plasma jet

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Abstract :
This paper is aimed at investigations of interaction of axially symmetrical light (plastic - CH) plasma with heavy (Cu) plasma. It demonstrates that a relatively thin plastic plasma envelope can compress the Cu plasma and control the Cu-jet formation. The use of axially symmetrical composed targets consisting of both materials makes it possible to create different plasma stream configurations (very narrow jet, pipe, and cone). The experiment was carried out with the Prague Asterix Laser System (PALS) iodine laser. The laser provided a 250-ps pulse with energy of 130 J at the third harmonic frequency (λ_3 =0.438 μm). For measurements of the electron density evolution a three frame interferometric system was employed. Theoretical analysis of the experimental results allows us to conclude that difference in plasma pressure related to plasmas with low (CH) and high (Cu) atomic number results from essential differences in the plasma expansion features between these plasmas. The ratio of the pressures of plastic and copper plasmas was evaluated to be equal to 1.35.

1. Introduction

Supersonic laser-driven plasma jets are subjects of growing interest due to their importance for laboratory astrophysics [1-3], as well for inertial confinement fusion [4, 5]. Possibility to produce such plasma jets in laboratory would allow physicists to perform many original experiments. The first successful attempts to generate laboratory plasma jets by means of lasers, relevant to astrophysical observations, were described e.g. in Refs 6 and 7. In 2006 we reported a simple method of plasma jet generation based on using a flat massive target with atomic number Z≥29 (Z=29 corresponds to Cu) irradiated by a single partly defocused laser beam [8]. Our investigations of the plasma stream emitted from the joint of light and heavy target materials (Al-Cu or CH-Cu) [9] suggested that a low-Z plasma component could improve plasma jet parameters. This idea was connected with the observed peculiar behaviour of the jet-like structure in the vicinity of low-Z plasma. Namely, in that case the plasma jet is not propagating normally to the target surface but it is deflected to the side of the heavier material. The angles of jet deflection for Al-Cu and plastic-Cu joints were about 5^o and 10^o, respectively. It means that the lighter is the plasma the higher is its pressure. We supposed, therefore, that this plasma behaviour could allow us to get a plasma jet with better parameters (smaller diameter and higher plasma density) than those obtained hitherto. If the central cylindrical insert made of high-Z material (Cu) is fixed in a low-Z material (plastic), then the surrounding light plasma will compress the plasma jet produced from the insert. On the contrary, the plastic insert fixed in the centre of high-Z target should not allow to create a high-Z plasma jet due to higher pressure of the low-Z plasma located in the centre.

2. Experimental setup and conditions

Taking into consideration the above suggestions we used the following types of targets for the investigations: massive Cu target, plastic target with Cu insert diameter Φ_{in}=400 μm, and Cu targets with plastic inserts of diameters 200 μm or 400 μm. The target types used and their irradiation schemes are shown in Fig. 1.

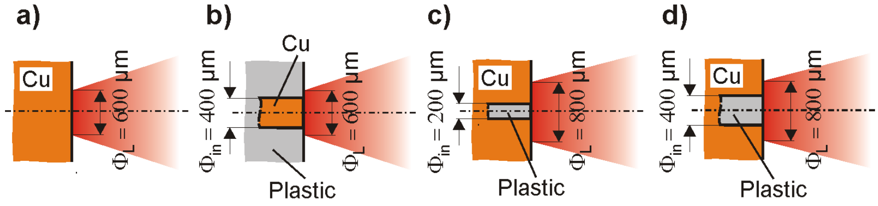

Fig. 1. Target types used in the experiment and the schemes of their irradiation.

The experiment was carried out with the use of the Prague Asterix Laser System (PALS) iodine laser facility. The plasma was generated by the third harmonic of the laser radiation used (λ=0.438 μm). The following laser parameters for target irradiation have been chosen: laser energy of 130 J, focal spot diameters (Φ_L) of 600 μm or 800 μm (the focal point being located inside the target), and a pulse duration of 250 ps (FWHM). The diameters of inserts as well as the focal spot diameters were chosen in such a manner for the mutual interaction of light and heavy plasmas to be clearly seen. The plasma expansion was studied by means of a 3-frame laser interferometric system with automatic image processing. The delay between the interferometric frames was set up to 3 ns.

3. Influence of the target type on the plasma stream configuration

The sequences of interferograms in Fig. 2 correspond to the above four different target types. In Fig. 2a the plasma jet created on a Cu target at Φ_L=600 μm is shown.

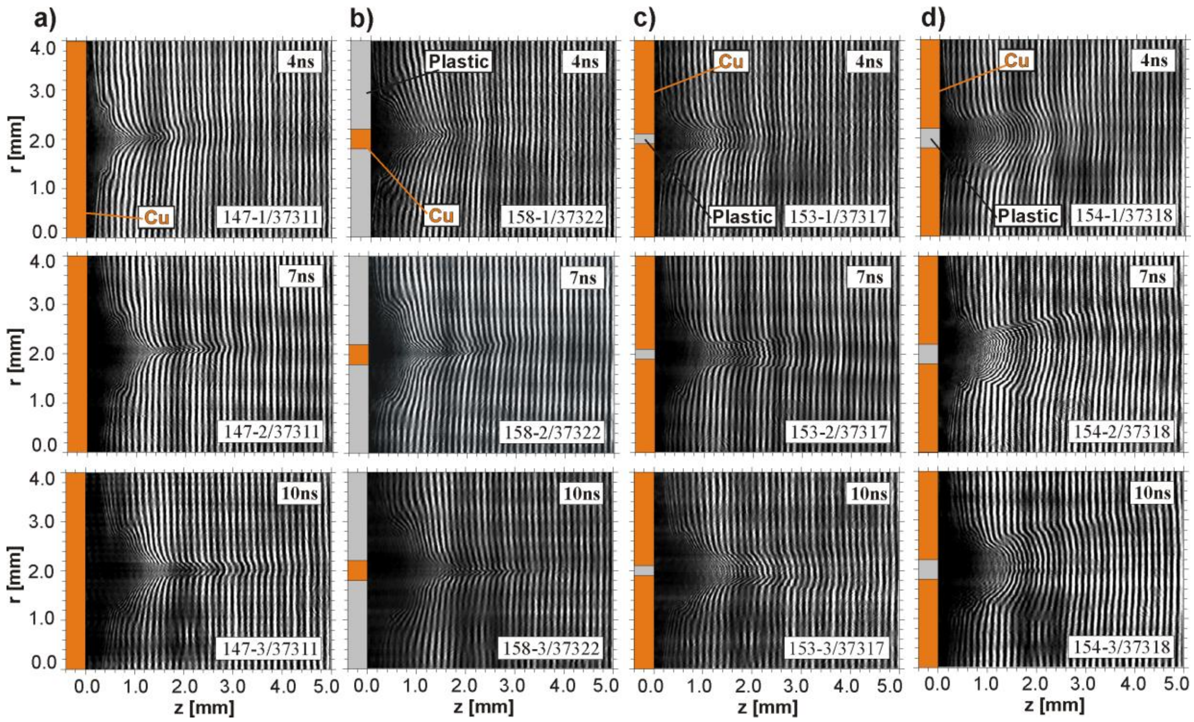

Fig. 2 The sequences of interferograms showing the plasma jet formation for the four different target types.

One can see there a well-formed jet, which is just slightly divergent even at 10 ns. The plasma jet top has a diameter of about 400 μm. By contrast, the plasma jet produced from the plastic target with 400-μm diameter Cu insert at the same target irradiation conditions has a very small diameter over its whole length (Fig. 2b). This diameter is at least twice smaller than that in the former case. The two lower sequences of interferograms show the Cu plasma jet transformation caused by the action of the internal plastic plasma on the Cu plasma stream. In order to suppress that very strong action, the focal spot diameter was set to 800 µm. It made it possible to increase the Cu plasma amount in comparison to that of the plastic. Additionally, in order to decrease further the ratio of the amounts of plastic and Cu plasmas the plastic insert diameter was also changed from 400 µm to 200 µm. Then, the ratios of the irradiated Cu target and plastic insert surfaces amounted to 3 and 15, respectively. These steps allowed us to demonstrate clearly the harmful influence of the internal plastic plasma on the creation of Cu plasma jet. It turned out that even a relatively small amount of plastic plasma created from the 200-µm diameter plastic insert is able to disturb the plasma jet formation process (see Fig. 2c). The plastic plasma pressure prevents the convergent motion of Cu plasma and its collision at the axis. If the plastic plasma amount is higher, which is the case for the plastic insert diameter of 400 µm (Fig. 2d), the plasma outflow becomes divergent.

In Fig. 3 the electron distributions of plasma streams at 10 ns for all the target types used are presented in forms of electron equidensitograms and spatial distributions. In the electron equidensitograms the outer plasma contour is determined by the electron equidensity line 10^{18} cm^{-3}, whereas the distance between adjacent lines is equal to $5x10^{18}$ cm^{-3}. In the case of Cu target (Fig. 3A-a) the plasma jet top is wide and rounded. On the contrary, the plasma jet for the plastic target with the 400-µm Cu insert (Fig. 3A-b) has a characteristic peaked form. One can also see here a large low-density plasma background in the ambient of the basic jet. It gives evidence that even a relatively thin plastic plasma layer is capable of compressing the Cu plasma to a density considerably higher than its own.

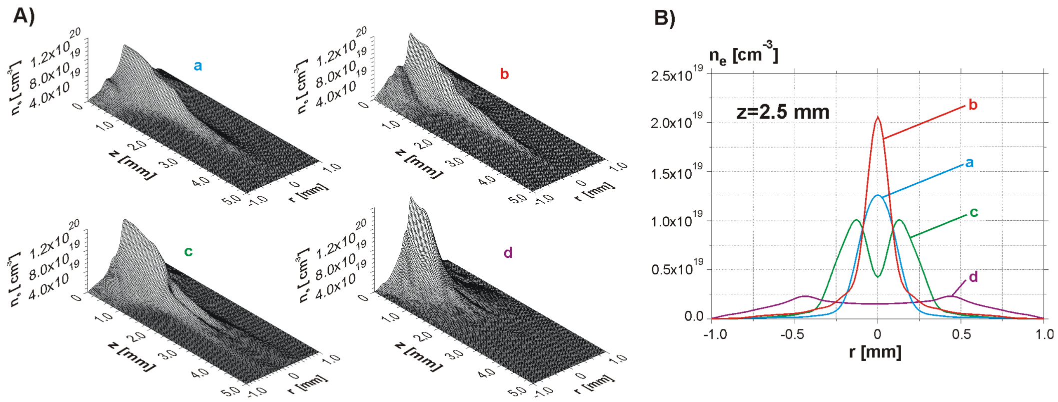

Fig. 3. The electron density profiles (A) and the radial electron density distributions of plasma jets at z=2.5 mm (B) at 10 ns corresponding to: a – pure Cu target, b – plastic target with 400-µm diameter Cu insert, c - Cu target with plastic insert of diameter 200 µm, and d– Cu target with plastic insert of diameter 400 µm.

The Cu plasma jet compression by the plastic plasma increases the jet electron density almost twice. It is seen in Fig. 3B, where the radial electron density distributions in the plasma streams cross-section at z=2.5 mm for all the considered above cases are plotted. Hence, we can conclude that the efficiency of action of the light plastic plasma on the heavier Cu plasma is very high. That is also clearly seen in the case of the last two target types. A relatively small amount of plastic plasma located inside the Cu plasma jet, corresponding to the plastic insert diameter of 200 µm, causes that the plasma stream configuration changes from a plasma jet-like to a cylindrical shell (see Fig. 3A-c). Further increase of the plastic plasma amount at the plastic insert diameter of 400 µm leads to a completely divergent Cu-plasma outflow, such as that seen in Fig. 3A-d. One can also see here a large low-density plasma background in the ambient of the basic jet. It gives evidence that even a relatively thin plastic plasma is capable of compressing the Cu plasma to a density considerably higher than its own. The Cu plasma jet compression by the plastic plasma increases the jet electron density almost twice. It is seen in Fig. 3B, where the radial electron density distributions in the

plasma streams cross-section at z=2.5 mm for all the considered above cases are plotted. The high efficiency of action of the light plastic plasma on the heavier Cu plasma is also clearly seen in the case of the last two target types. A relatively small amount of plastic plasma located inside the Cu plasma jet, corresponding to the plastic insert diameter of 200 μm, causes that the plasma stream configuration changes from a plasma jet-like to a cylindrical shell (see Fig. 3A-c). Further increase of the plastic plasma amount at the plastic insert diameter of 400 μm leads to a completely divergent Cu-plasma outflow, such as that seen in Fig. 3A-d. The depressions in the radial electron density distributions seen in the corresponding diagrams in Fig. 3B prove that the plastic plasma action lasts for a long time.

Our numerical simulations of the laser beam interaction with the separate planar Cu and plastic targets performed by using the two-dimensional hydrodynamic code ATLANT-HE have shown that under the conditions of relatively short pulse of the PALS laser, the Cu plasma expansion is approximately planar while that of the plastic plasma, which is significantly lighter, is almost spherical. The expansion regime is established, in reality, just during the period of laser pulse action. Therefore, we can evaluate the average pressures during the period of laser action in plastic and copper plasmas near the critical densities of 14.3 Mbar and 10.6 Mbar, respectively. The enhancement of pressure of 3.2 Mbar and the ratio of the pressures of plastic and copper plasmas can be estimated to 1.35.

4. Conclusions

In this work we have demonstrated a simple way how to improve plasma jets by using axially symmetrical target compositions consisting of materials with low and high atomic numbers. It was shown that relatively thin plastic plasma envelope is able to compress and control the Cu plasma stream, due to a considerably higher pressure of the light plasma. We have shown that axially symmetrical combination of target materials with different atomic numbers makes it possible to create essentially different plasma configurations, starting from a very thin plasma jet, over a pipe form of plasma stream, up to a divergent (conical) plasma shell. The technique of shaping the boundary between different laser-produced plasmas opens possibility of laboratory simulation of the interaction of astrophysical flows and streams. More complicated target compositions, consisting of many inserts of different materials, would allow us to obtain even more complicated plasma configurations, tailored for various scientific applications.

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