Interaction of the copper plasma jet with different media

T. Pisarczyk[1], A. Kasperczuk[1], T. Chodukowski[1], Z. Kalinowska[1], J. Ullschmied[2],
E. Krousky[3], M. Pfeifer[3], K. Rohlena[3], J. Skala[3], and P. Pisarczyk[4]

[1]*Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland*
[2]*Institute of Plasma Physics ASCR, v.v.i., Prague, Czech Republic*
[3]*Institute of Physics ASCR, v.v.i., Prague, Czech Republic*
[4]*Warsaw University of Technology, ICS, Warsaw, Poland*

Abstract

In this paper the interferometric investigations of interactions of copper plasma jet with different media, like He and Ar gases, plastic plasma and another Cu plasma jet, are presented. Experiments were carried out at the Prague Asterix Laser System (PALS). The laser provided a 250 ps pulse with an energy 100-200 J at the third harmonic frequency (λ=0.438 μm). The interactions of Cu plasma jet with above mentioned media were studied by means of a three-frame interferometric system.

1. Introduction

Collimated plasma outflows (jets) are a subject of great interest in the study of astrophysical phenomena [1], laser plasma interaction phenomena [2] and are of interest also for a new fast ignition concept [3]. Parameters of the jets produced experimentally in laboratories differ considerably from those observed in the Universe. Astrophysical jets are long, narrowly collimated structures emanating from young stellar objects, black holes, and active galactic nuclei. These exclusively astrophysical phenomena can be, however, simulated by artificially produced plasma jets, provided that certain their dimensionless parameters are comparable. High-power lasers can create conditions for studying physical processes taking place in astrophysical objects. The first attempts to generate jets relevant to astrophysical observation were presented in papers [4, 5]. Conically shaped targets made of different materials were irradiated there by five beams of the Nova laser with a pulse duration of 100 ps and an energy of each beam of 225 J or by six beams of the GEKKO-XII laser with the same pulse duration, but the total energy of 500 J. In 2006 we reported a simple method of plasma jet generation based on using a flat massive target with atomic number $Z\geq29$ ($Z=29$ corresponds to Cu) irradiated by a single partly defocused laser beam [6]. Further investigations of parameters of plasma jets produced this way have proved that such plasma jets could be used for different applications, including simulation of different astrophysical phenomena. Namely, using relatively low laser energy (a few tens Joules) the plasma jets reach supersonic velocities (above 5×10^7 cm/s), whereas their density above 10^{18} cm^{-3} is conserved even 20 ns. Our present interest is concentrated on interaction of the plasma jet with different media like gases (He and Ar), plastic plasma, and another Cu plasma jet. Experiments were carried out at the Prague Asterix Laser System (PALS). The laser provided a 250 ps pulse with an energy 100-200 J at the third harmonic frequency (λ=0.438 μm). For studying the plasma evolution a 3-frame interferometric system with automatic image processing was used.

2. Plasma jet interaction with ambient gases

Interactions of laser driven plasma jets with He and Ar gas puffs was investigated experimentally by means of three-frame interferometric/shadowgraphic system and three-frame X-ray pinhole camera [7, 8]. A defocused iodine laser beam interacting with massive planar Cu targets generated high-speed well-collimated plasma jets. The laser beam with an energy of 100 J was employed in two irradiation geometries: with an incidence normal to the target surface and, in order to minimize the heating of the ambient gas by the laser beam, with an oblique one (30° with respect to the target normal). Processes accompanying the interaction of the laser- produced plasma jet with ambient gas can be observed most distinctly in the case of Ar (Fig. 1), at the highest pressure used for this gas (10 bars).

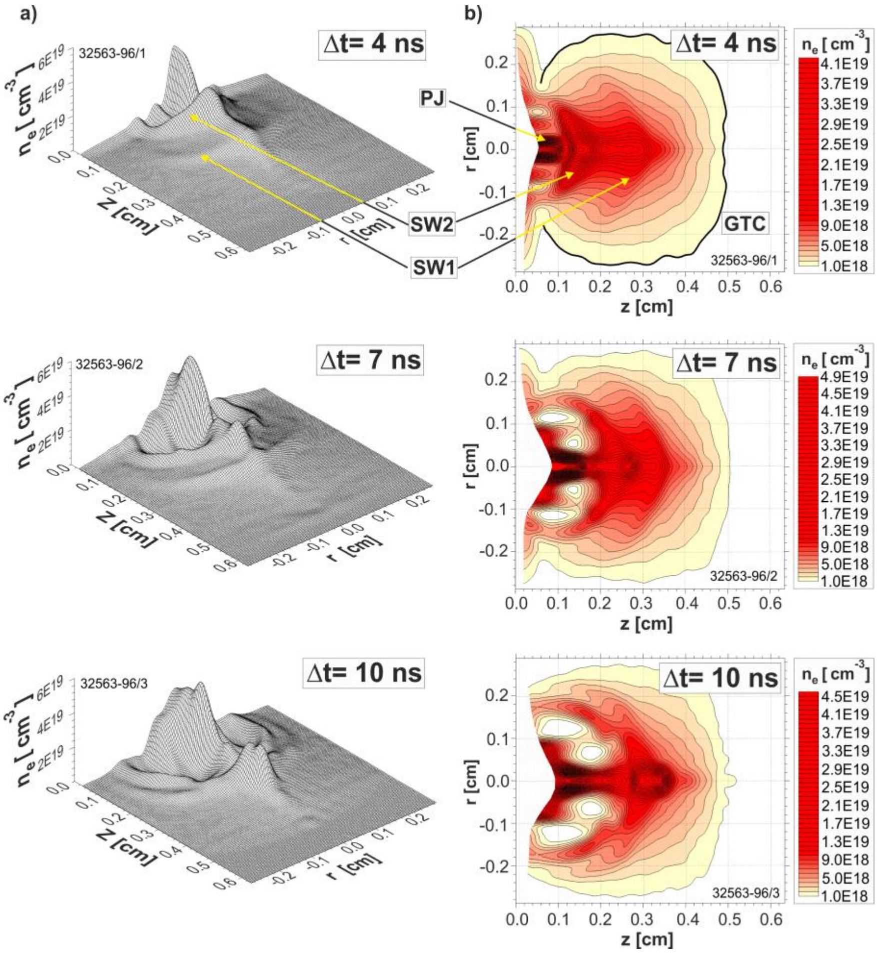

Fig. 1. Sequence of electron density distributions for *Ar* at pressure of 10 bars in spatial (a) and equidensitogram (b) form. GTC - gas target contour, PJ - plasma jet, SW1- the first shock wave, and SW2- the second shock wave

In the plasma jet-ambient gas interaction, the following three stages could be identified: (i) ablative plasma generation and preliminary ionization of the ambient gas, (ii) creation of the first shock wave in the ambient), and (iii) plasma jet forming and the second shock wave generation. These investigations have shown that the very easy method of plasma jet generation, unfolded by us recently at PALS, might open potential possibilities of plasma jet applications in original physical experiments. This work has also proved that plasma jets of interesting parameters can be produced at both normal and oblique incidence of the heating laser beam on the target. The possibility of the creation of plasma jets of high quality also at the oblique incidence allowed us to minimize the unwanted interaction of the heating laser beam with the gas target (impossible to avoid at normal angle of incidence). Thus, a much more reliable observation of processes accompanying the plasma jet-ambient gas interaction became accessible.

3. Plasma jet formation with different electron density configurations by mutual interaction of plasmas.

The experimental results reported have shown that axially symmetrical combinations of target materials with different atomic numbers allow creating of essentially different plasma configurations, like a high-quality plasma jet or a plasma pipe [9, 10, 11]. We took advantage of the fact that the lighter is the plasma, the higher is its pressure [12]. In parallel to interferometry a four-frame x-ray pinhole-camera with a pinhole of a diameter of 80 μm was used, registering soft x-ray plasma radiation in the range of 10-1000 eV. The exposure time of the x-ray camera was below 2 ns.

In the case of the plastic target with Cu insert (Fig. 2a) the Cu are essential improved. the Cu plasma jet produced inside the plastic plasma envelope is very narrow and has a velocity of about $8x10^7$ cm/s, that is almost twice greater in comparison with the velocity of pure Cu plasma jet [9].

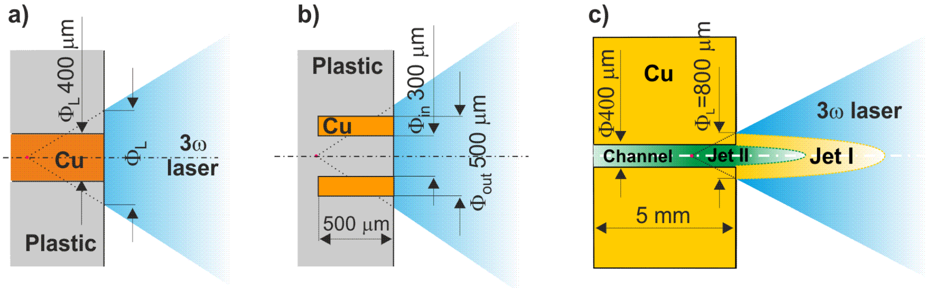

Fig. 2. The target types used in the experiments and schemes of their irradiation.

Our further investigations were aimed at creation of pipe-like Cu plasma streams [10]. For that reason the target with a tubular Cu insert shown in Fig. 2b was used. The results of our interferometric investigations are shown in Fig. 3a, in which sequences of interferograms and electron density distributions corresponding to them are presented.

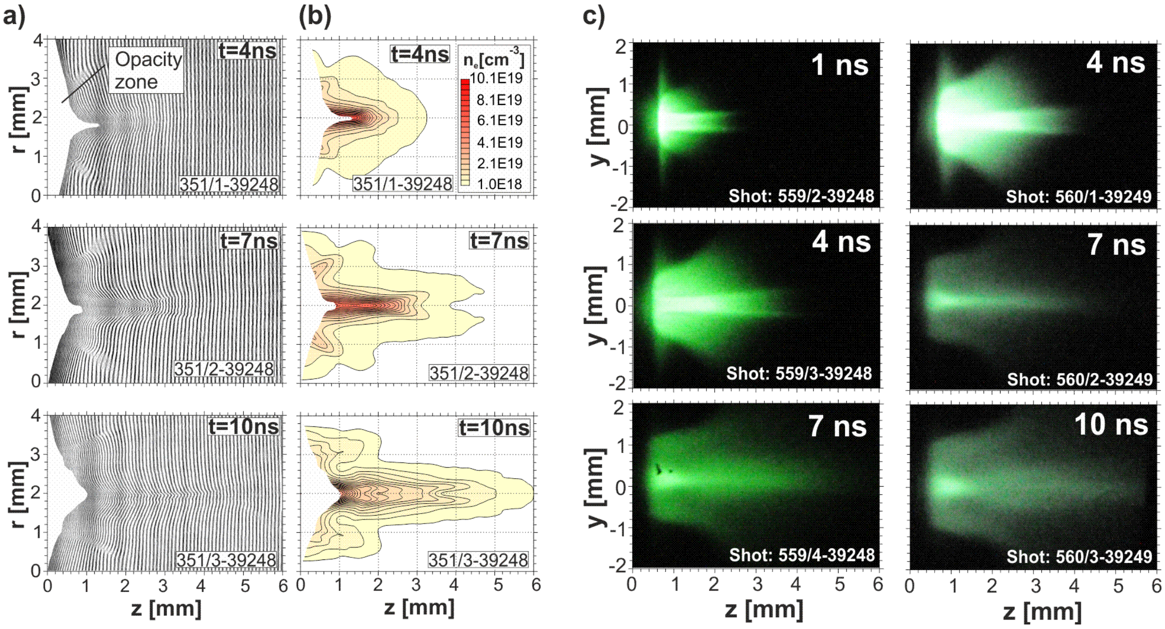

Fig. 3 The sequences of interferograms (a), electron density distributions (b) and x-ray images (c) showing the Cu plasma pipe formation for the plastic target with Cu tube insert. .

The three frames shown there correspond to three stages of the plasma stream evolution, i.e. the Cu plasma pipe creation, compression, and radial expansion. The Cu plasma position can be easily distinguished by the x-ray camera, since its x-ray radiation intensity is greater in comparison with that of the plastic plasma. A well-formed Cu plasma pipe is seen here just 1 ns after the laser action. At that instant the Cu plasma pipe length is about 1.8 mm. One can conclude that the plastic plasma leaving the pipe has a velocity considerably above $1x10^8$ cm/s. The initial Cu plasma configuration lives as long as 4-5 ns. Later on the Cu plasma pipe undergoes compression. Evidently, the plastic plasma pressure inside the Cu plasma pipe decreases faster than that in the outside. This can be due to the fast outflow of central plastic plasma, which breaks the initial pressure balance. Thus, until the Cu plasma pipe configuration becomes compressed, the Cu plasma serves as a nozzle for the central plastic plasma. The narrow plastic plasma stream at the Cu plasma nozzle mouth is well seen in Fig. 3b at 4 ns. At later times we observed radial Cu plasma expansion, which starts immediately after the compression stage. It can be ascribed to the reflected shock wave resulting from the strong Cu plasma compression at the axis.

The last experiment presented here shows the relatively simple way of creation of two independent plasma jets using the massive metallic target with cylindrical channel (Fig. 2c) [11]. Two successive jets were produced on a massive flat Cu target provided with a cylindrical channel 5 mm long and 400 μm in diameter. Since the focal spot diameter of the laser beam on the target surface was larger than that of the channel (800 μm), the annular irradiation of the target face resulted in creation of the first plasma jet, whereas the second jet was produced by action of the central part of laser beam on the channel wall.

This method can be useful for investigations of mutual interaction of two jets made of the same or different materials. It allows to study a mixing process of two plasmas. Besides, creation of desirable plasma stream configurations, starting from the plasma jet via a cylindrical pipe to end with the conically shaped plasma shell, seems to be of interest, too.

4. Conclusions

In this paper the investigations of interactions of copper plasma jet with different media, like He and Ar gases, plastic plasma and another Cu plasma jet, are presented. It was shown that the plasma jet produced by us is very useful for both physical investigations of its interaction with different media and practical applications. Axially symmetrical combination of target materials with different atomic numbers allows 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 possibility to shape the boundary between different laser-produced plasmas can be exploited in laboratory simulations of the interaction of astrophysical flows and streams. More complicated target structures, consisting of many inserts of different materials, would allow us to obtain even more sophisticated plasma configurations tailored for various scientific applications.

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References:

1. P. Velarde et al., *Laser and Particle Beams* **23,** 43-46(2005).
2. W. Hong et al., Laser Part. Beams 27, 19 – 26.
3. B. A. Remington, R. P. Drake, and D. D. Ryutov. Rev. Mod. Phys. 78, 755–807(2006)
4. D. R. Farley et al., *Phys. Rev. Lett*. **83**, 1982 (1999).
5. K. Shigemori et al., *Phys. Review E* **62**, 8838 (2000).
6. A. Kasperczuk, T. Pisarczyk et al. Phys. Plasmas **13**, 062704 (2006).
7. A. Kasperczuk, T. Pisarczyk et al., Laser Part. Beams **27**, 115 (2009).
8. Ph. Nicolai , V. Tikhonchuk, A. Kasperczuk, T. Pisarczyk, et al. Phys. Plasmas **13**, 062701(2006).
9. A. Kasperczuk, T. Pisarczyk et al., Plasma Phys. Control. Fusion **53**, 095003 (2011).
10. A. Kasperczuk, T. Pisarczyk et al., Phys. Plasmas **18**, 044503 (2011).
11. A. Kasperczuk, T. Pisarczyk et al., Laser Part. Beams **28**, 497 (2010).
12. T. Pisarczyk, A. Kasperczuk et al., Proceedings of 35th EPS Conference on Plasma Physics, Hersonissos, 9–13 June 2008, ECA Vol. 32, P-1.118 (2008).