Optica Applicata, Vol. XXXVII, No. 1–2, 2007

Plasma jet generation by flyer disk collision with massive target

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In this paper, results from experiments with Al flyer targets (disks with a diameter of 300 μm and a thickness of 6 μm) accelerated at first to high velocities by PALS iodine laser pulses (with an energy of 130 J, pulse duration of 400 ps, a wavelength of 1.315 μm, and laser spot diameter of 250 μm), subsequently creating craters after their collisions with massive Al targets (placed at a distance of the order of 200 μm) are presented. To measure the plasma density evolution a three frame interferometric system was employed. The experimental results demonstrate that the flyer disk–massive target collision generates an axial plasma jet corresponding to a flat shock wave propagating in a massive target. This form of the shock wave was deduced from a crater trapezoidal shape which was reconstructed by means of crater replica technique.

Keywords: ablative acceleration, plasma jet, flyer disk, interferometry, macroparticle, double target, linear electron density, crater, shock wave.

1. Introduction

The approach with using macroscopic particles for producing controlled thermonuclear power was already suggested a few tens of years ago (*e.g.*, [1]). In this method, macroparticles, accelerated to high velocity (10^8–10^9 cm/s), collide either with other particles or a target, and their kinetic energy is converted into thermal energy inertially confined to a small region for a short period of time. The suggestion that an ablatively accelerated thin foil may achieve high velocity which cannot be obtained in any other way was formulated in paper [2].

The flyer impact configuration plays now an important role in the study of problems related to inertial confinement fusion. In this project, the flyer at first acquires considerable kinetic energy as a result of its interaction with the driver. Then the flyer impact is used to ignite a laser compressed cold fuel. However, in the opinion of CARUSO and PAIS [3], realization of this concept requires the development of entirely new drivers specialized for ignition at energy levels of 10 to 50 kJ. Certain progress in this subject was achieved by MURAKAMI *et al.* [4]. They have proposed using a hollow conical target, which is stuck to the spherical pellet. Both the results of the two-dimensional hydrodynamic simulation of such a scheme and the preliminary experimental result are very promising.

Our earlier investigations of the flyer targets [5–8] were focused on determination of the macroparticle acceleration and the crater creation efficiency depending on: i) the macroparticle type (the extracted foil fragment or prefabricated disk), and ii) the laser beam wavelength (the first or third harmonic of the iodine laser). Attention was also paid to the delay in the flyer target getting under way with respect to the laser pulse action, final velocity achieved for different target thicknesses and/or wavelength and so on. In this paper, the new possibility of the flyer technique, *i.e.*, its use for a plasma jet generation, is presented.

The formation, propagation and stability of plasma jets are fundamental issues in the astrophysical context. The attempts to generate jets relevant to astrophysical observations are presented in papers [9, 10]. 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. The jet-like structures were formed by collision of ablated flows at the axis of conical targets.

Recently, we have demonstrated a simple method of the jet production by interaction of a relatively low energy laser pulse with metallic massive planar targets [11]. A successful realization of plasma jet generation required a target material with atomic number greater than that of aluminium, a short wavelength, and a focal spot radius relatively large.

To accomplish this paper some modifications of experimental conditions, in comparison with our earlier papers devoted to the flyer target–massive target interaction, were required. Firstly, in this experiment our attention was focused on the flyer disk impact effects observed in a long period after the collision had occurred, *i.e.*, up to about 17 ns after the impact. In our previous experiments, the interferometric observations were finished directly after the flyer target impact. Secondly, unlike in our previous measurements, where plasma generated from the massive target outside the flyer target was screened by the disk supporting foil, a new target construction employed made it possible to visualize the plasma generation and subsequent expansion across the whole massive target surface.

To study the temporal and spatial behaviors of the plasma expansion a three-frame interferometric system was used. Additionally, a crater replica technology and an optical microscopy were applied to determine the crater profiles and dimensions.

2. Experimental set-up

The experimental investigation was carried out on the PALS iodine laser facility. Its optical scheme is depicted in Fig. 1.

The laser provided a 400 ps (FWHM) pulse with the energy of 130 J at the first harmonic ($\lambda_1 = 1.315$ μm). A full laser beam diameter at the target chamber entrance window was about 290 mm. Inside the chamber it was focused by means an aspherical lens with a focal length of 627 mm reaching the focal spot radius of 250 μm on the target (the focal point was located inside the target). Intensity distributions across the laser beam cross-section were recorded in each laser shot by the CCD camera. One example of such typical intensity distribution corresponding to the above laser energy is shown in Fig. 2, clearly proving a very high homogeneity of the intensity distribution across the whole cross-section of the laser beam. To avoid diffraction effects, which could disturb the laser beam intensity distribution on the target surface, retransmission of the beam on the target through the soft diaphragm placed in the laser system, as well as a proper space beam filtration were used.

To study the plasma expansion and flyer disk acceleration, a 3-frame interferometric system with automatic image processing was employed. Each of the interferometric channels was equipped with its own independent interferometer of the folding wave type. The diagnostic beam was obtained as a part of the main laser beam subsequently

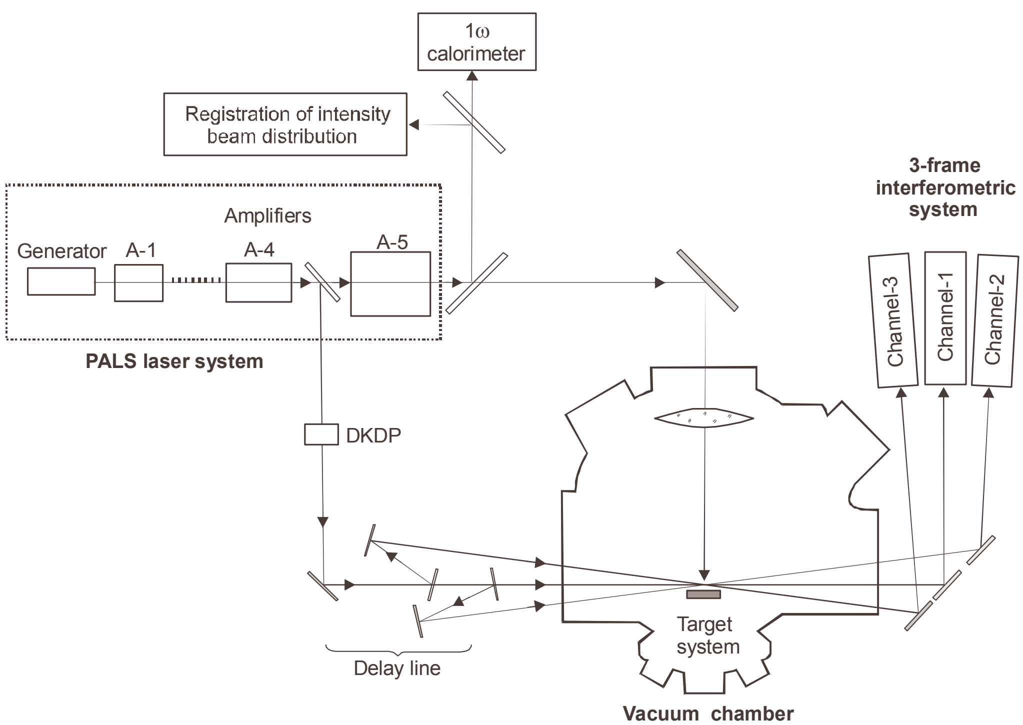

Fig. 1. Experimental set-up.

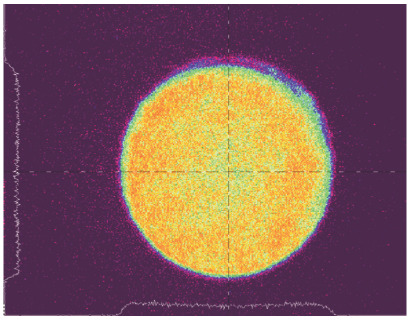

Fig. 2. Typical intensity distribution in the laser beam cross-section.

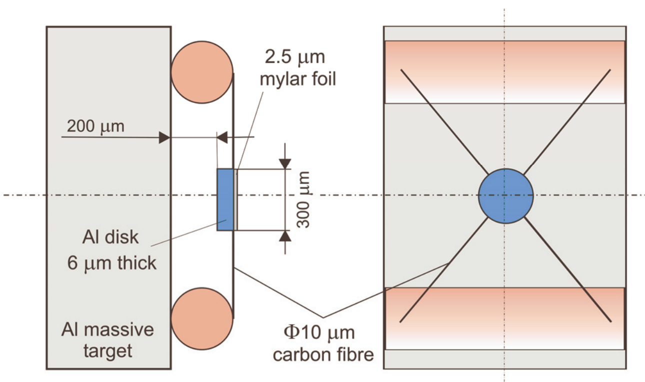

Fig. 3. Construction of the double target.

converted to the third harmonic. The delay between the frames was 3 ns, thus the interferometric measurement during a single shot covered a period of 6 ns only. Due to a high reproducibility of the plasma expansion at different laser shots under the same target irradiation conditions sequences from different shots allowed sewing them together. That way our observation period could be extended. The maximum possible delay of the interferometric measurement related to the heating laser pulse reached 23 ns.

In these experiments, the Al double targets consisting of a 6 μm thick flyer disk placed in front of the slab at a distance of 200 μm were employed. Unlike in our previous experiments the disks were fixed by 10 μm carbon fibres (see Fig. 3).

3. Experimental results

In Figure 4, a typical profile of the craters obtained by the impact of the disk is shown. Contrary to a hemispherical form of the laser beam produced crater [11], the disk produced crater shapes are like a trapezium, the shorter side of which constitutes the crater bottom.

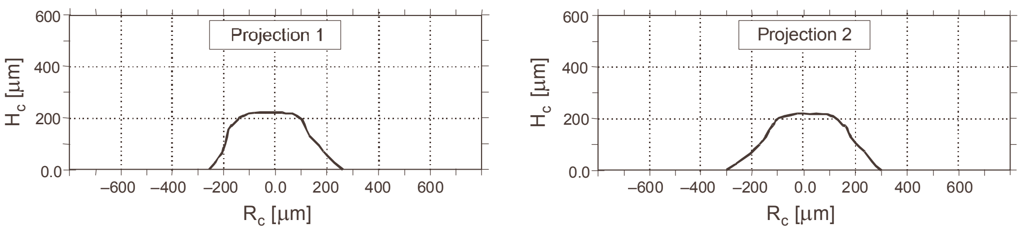

Fig. 4. Shapes and dimensions of the crater (in two mutually perpendicular projections) produced by the flyer disk, where: R_c and H_c are the radius and the depth of the crater, respectively.

One of the most important problems connected with the crater creation by very fast macroparticles is determination of their velocities at an instant of the impact. A detailed investigation of the disk motion performed earlier [11], has shown that the disks start moving about 2 ns after the laser action. The disk velocity corresponding to the disk thickness of 6 μm is equal to $(6 \pm 0.2) \times 10^6$ cm/s.

Taking into account both the disk motion delay and the measured disk velocity one can conclude that the disk should reach the distance of 200 μm after about 6 ns after the laser beam action. Therefore, the sequence of the first three electron isodensitograms for Δt = 2, 5, and 8 ns (see Fig. 5) should rather well illustrate the first stage of the phenomena under investigation, starting from the laser beam action, and finishing with the disk impact. The presented electron density distributions start from the original disk surface position, denoted here as $z = 0$.

Although the disk impact occurs after about 6 ns of the laser action, its consequences can be observed after the next several ns. The dominating wide central part of the plasma stream, seen at 8 ns, corresponds still to the ablative plasma induced by the laser action. Participation of the lateral plasma at this instant is relatively small and corresponds likely to an interaction of X-ray radiation from plasma with the massive target surface. At some later time the picture of the plasma outflow is unlike. The central plasma participation decreases at the expense of the lateral one. This means that in the period of 8–11 ns the ablative plasma disappears and, at a time, a new kind of the plasma starts. This plasma results from the disk impact. Although the disk reached the massive target a few ns earlier, consequences of the disk impact are postponed by a couple of ns. This corresponds to our earlier numerical modeling of the crater formation by the flyer foil which has shown [11], that the post-impact stage begins when the flyer foil is already completely decomposed. The sequence of subsequent electron isodensitograms and spatial distributions of the electron density in Fig. 6 shows the evolution of the disk-produced plasma. The plasma as a whole consists of two parts: i) the axial stream with the radius of about 250 μm and ii) the lateral plasma, of the radius of above 1.5 mm. To reach the distance of 1.5 mm the lateral plasma had to start earlier than the axial one which reached at the same time moment (11 ns) only 0.8 mm of the distance. This is connected with the fact that the lateral plasma originates from the disk edge where the plasma outflow is not limited whereas the axial component can expand after the disk disappearance. The electron

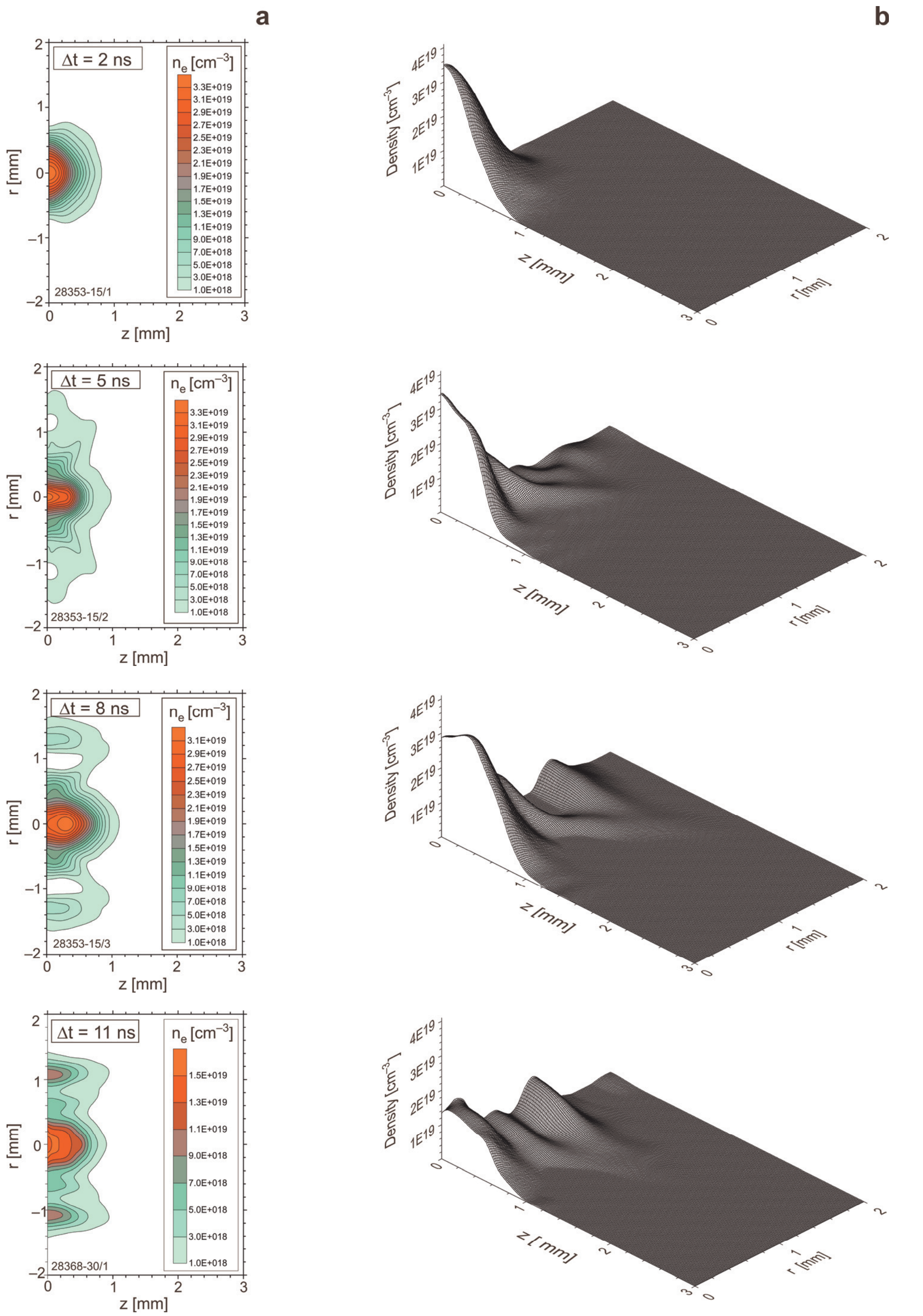

Fig. 5. A sequence of electron isodensitograms (**a**) and electron density distributions (**b**) corresponds to the appearance and decay of ablative plasma.

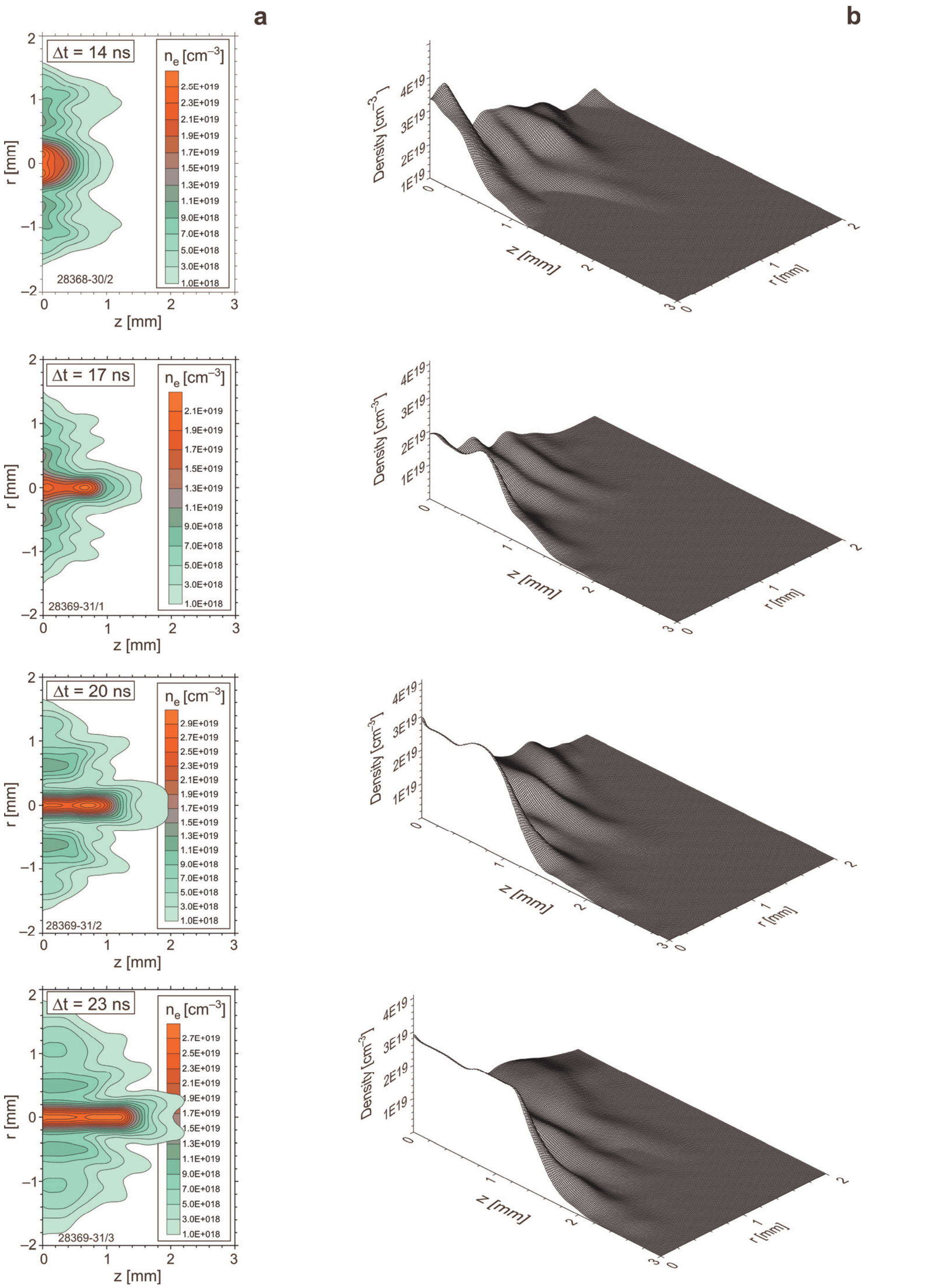

Fig. 6. A sequence of electron isodensitograms (**a**) and electron density distributions (**b**) corresponds to the post-impact stage.

density of the lateral plasma exceeds 10^{19} cm^{-3}, thus at the beginning of the post-impact stage the participation of this plasma as a whole reaches 90%. At a later time the role of the axial plasma should grow and one can suppose that in due time the axial plasma will dominate. Although our period of observation was too short to prove this, the trapezoidal crater with the bottom diameter corresponding to that of the axial stream indicates that this conclusion is sound.

Velocities of the axial plasma streams (determined at relatively high density levels of $n_e > 10^{19}$ cm^{-3}) reach 10^7 cm/s. The maximum electron density in the plasma stream is close to 3×10^{19} cm^{-3}.

Taking into account the actual plasma stream diameter being equal to about 500 μm, the linear electron density distributions in the stream at different instants were computed (the linear electron density informs about the number of electrons in any cross-section of plasma stream per cm). Diagrams presented in Fig. 7 illustrate the stream linear electron density distributions along the axis. One can see that the plasma uniformly fills the propagation channel reaching the linear electron density of 3×10^{16} cm^{-1}. If this process is continued for a long period of time, it seems that this plasma stream can reach a length of a few mm.

4. Discussion of the experimental data and conclusions

Ablative acceleration of the flyer disk is seemingly a very simple action. Meanwhile, apart from technological problems with preparation of targets of very high quality to ensure reproducibility of the phenomenon under investigation in different shots, of major importance is the choice of complementary diagnostics for such an investigation. A combination of the interferometric measurements with the crater replica technique made it possible to get a very rich experimental material for subsequent analyses and interpretations.

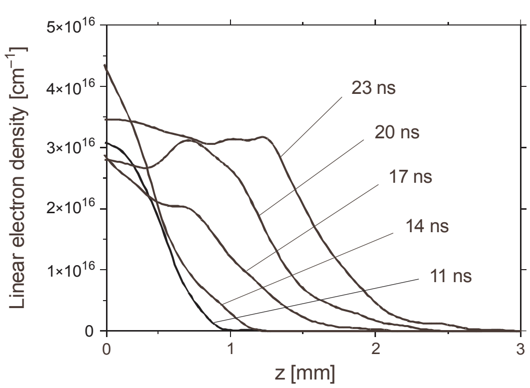

Fig. 7. Diagrams of the linear electron density of the axial plasma stream at different instants of its propagation.

In this work, we have studied the formation of the plasma jet using the collision of the flyer disk with the massive target. In spite of many complex physical processes accompanying acceleration and impact of the disk, continuation of the flyer target experiments may provide relevant information for the inertial confinement fusion and for the astrophysics. Additionally, applications of the flyer disk impact in different technological projects seem to be very prospective.

Of course, our experiment has a preliminary character and only shows the new way for the plasma jet production. However, in our opinion, optimization of both disk parameters and disk irradiation conditions can improve the plasma jet characteristics a lot.

Acknowledgements – The work was supported in part by the Association EURATOM-IPPLM (contract No. FU06-CT-2006-00430), by the Ministry of Scientific Research and Information Technology in Poland (project No. 3 T10B 024 273), and by the Ministry of Schools, Youth and Sports of the Czech Republic (project No. LC528).

References

[1] Harrison E.R., *Alternative approach to the problem of producing controlled thermonuclear power*, Physical Review Letters **11**(12), 1963, pp. 535–7.

[2] Borodziuk S., Kostecki J.L., *Studies of hypervelocity impact problem by means of laser-target experiments – a new approach*, Laser and Particle Beams **8**(1–2), 1990, pp. 241–5.

[3] Caruso A., Pais V.A., *The ignition of dense DT fuel by injected triggers*, Nuclear Fusions **36**(6), 1996, pp. 745–57.

[4] Murakami M., Nagatomo H., Sakaiya T., Azech H., Fuijoka S., Shiraga H., Nakai M., Shigemori K., Saito H., Obenschain M., Karasik M., Gardner J., Bates J., Colombant D., Weaver J., Aglitsiy Y., *Towards realization of hyper-velocities for impact fast ignition*, Plasma Physics and Controlled Fusion **47**(12B), 2005, pp. B815–22.

[5] Pisarczyk T., Borodziuk S., Demchenko N.N., Gus'kov S.Yu., Kalal M, Kasperczuk A., Kondrashov V.N., Limpouch J., Pisarczyk P., Rohlena K., Rozanov V.B., Skala J., Ullschmied J., *Energy transfer and shock wave generation at the collision of laser-driven macroparticle*, Proceedings of 28th ECLIM, Roma, 6–10 September 2004, pp. 465–9.

[6] Kasperczuk A., Borodziuk S., Demchenko N.N., Gus'kov S.Yu., Kalal M., Kondrashov V.N., Kralikova B., Krousky E, Limpouch J, Masek K., Pfeifer M., Pisarczyk P., Pisarczyk T., Rohlena K., Rozanov V.B., Skala J., Ullschmied J., *Investigation of crater creation efficiency by means of single and double targets in the PALS experiment*, 31st EPS Conference on Plasma Physics, London, 28 June–2 July 2004, ECA, Vol. 28G, p. 5.067.

[7] Borodziuk S., Demchenko N.N., Gus'kov S.Yu., Jungwirth K., Kalal M., Kasperczuk A., Kondrashov V.N., Kralikova B., Krousky E., Limpouch J., Masek K., Pisarczyk P., Pisarczyk T., Pfeifer M., Rohlena K., Rozanov V.B., Skala J., Ullschmied J., *High power laser interaction with single and double layer targets*, Optica Applicata **35**(2), 2005, pp. 241–62.

[8] Pisarczyk T., Borodziuk S., Kasperczuk A., Demchenko N.N., Gus'kov S.Yu., Kalal M., Kondrashov V.N., Kralikova B., Krousky E., Limpouch J., Masek K., Pfeifer M., Pisarczyk P., Rohlena K., Rozanov V.B., Skala J., Ullschmied J., *Experimental and theoretical investigations of the crater formation process by means of double-target technique*, 31st EPS Conference on Plasma Physics, London, 28 June–2 July 2004, ECA, Vol. 28G, p. 5.066.

[9] Farley D.R., Estabrook K.G., Glendinning S.G., Glenzer S.H., Remington B.A., Shigemori K., Stone J.M., Wallance R.J., Zimmerman G.B., Harte J.A., *Radiative jet experiments of astrophysical interest using intense lasers*, Physical Review Letters **83**(10), 1999, pp. 1982–5.

[10] Shigemori K., Kodama R., Farley D.R., Koase T., Estabrook K.G., Remington B.A., Ryutov D.D., Ochi Y., Azechi H., Stone J., Turner N., *Experiments on radiative collapse in laser-produced plasmas relevant to astrophysical jets*, Physical Review E **62**(6), 2000, pp. 8838–41.

[11] Kasperczuk A., Pisarczyk T., Borodziuk S., Ullschmied J., Krousky E., Masek K., Rohlena K., Skala J., Hora H., *Stable dense plasma jets produced at laser power densities around 10^{14} W/cm^2*, Physics of Plasmas **13**(6), 2006, p. 062704.

Received July 30, 2006