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# A plasma focus device as a metallic plasma jet generator

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**Abstract**

This paper aims at a test of a plasma focus (PF) device as a metallic plasma jet generator. The experiment was carried out at the DPF-1000U device in which the inner electrode face was conically shaped. Deuterium ($D_2$) with the initial pressure of 0.9 Torr was used as a filling gas. In the experiment, a metallic plasma was ensured due to erosion of the inner electrode during a PF discharge. To create the metallic plasma jet, the eroded copper (Cu) plasma, swept by the deuterium plasma sheath, was accelerated axially and compressed to very small radius (about 1–2 mm). The Cu plasma jet achieved a velocity of $3 \times 10^7$ cm/s. To study processes of the plasma jet creation and propagation a 16-frame laser interferometer and a four-frame X-ray pinhole camera were used. Recorded images prove a successful adaptation of the PF device to the metallic plasma jet generator.

**Keywords:** Cu plasma jet; Deuterium plasma pressure; Plasma focus device; Plasma radiative cooling; Plasma sheath collapse

## 1. INTRODUCTION

Collimated plasma outflows (jets) attract the attention of high-energy density physics, laboratory astrophysics, material processing, and the like. Most attempts to generate laboratory jets were performed at laser facilities, e.g. NOVA and GEKKO XII (Farley *et al.*, 1999; Shigemori *et al.*, 2000), Omega (Coker *et al.*, 2007; Hartigan *et al.*, 2009), and PALS (Kasperczuk *et al.*, 2006, 2009). However, convergent plasma flows were generated also at the wire array Z-pinch (Lebedev *et al.*, 2002). Magnetically driven jets were produced there using radial or conical wire arrays, which consisted of a pair of concentric electrodes connected by thin metallic wires. A 1 MA current, rising over 240 ns, was applied to the array.

The plasma focus devices (PF) are usually used as thermonuclear facilities, in which deuterium ($D_2$) plays a role of working gas. Any impurity of deuterium, in particular impurities with great atomic number ($Z$), can lead to a certain degradation of the thermonuclear processes. Nevertheless, an erosion of material of the inner electrode traditionally causes a contamination of deuterium plasma. The impurities, as a by-product in the PF discharge, are mainly located in the vicinity of the inner electrode face. In the case of a flat face of the inner electrode, a plasma sheath radial motion (during the collapse stage) is finished on the PF axis where a plasma column is created. The nearly cylindrical configuration of the pinched plasma prevents an axial flow of the plasma. In consequence, the impurities are trapped in a region neighboring with the inner electrode face. Therefore in this case, the impurities only in a little degree influences on processes appearing in a farther part of the plasma column.

The paper is aimed at a test of adaptation of the PF device for a generator of cumulated streams (jets) of metallic plasma with the atomic number significantly greater than that of deuterium. Because, by contrast with deuterium, a copper (Cu) plasma resulting from the inner electrode erosion is characterized by relatively high $Z$ (29), thus it could be directly used for this aim. However, the use of that Cu plasma required: (*i*) an induction of its axial motion and, then, (*ii*) its collimation in order to obtain the jet-like configuration. The manners of doing them are presented in Section 3.

## 2. EXPERIMENTAL SETUP AND CONDITIONS

The investigations were performed with the use of the DPF-1000U device, which is equipped with Mather-type two coaxial electrodes 460 mm long. The inner electrode (anode) is a Cu tube 229 mm in diameter, while the outer

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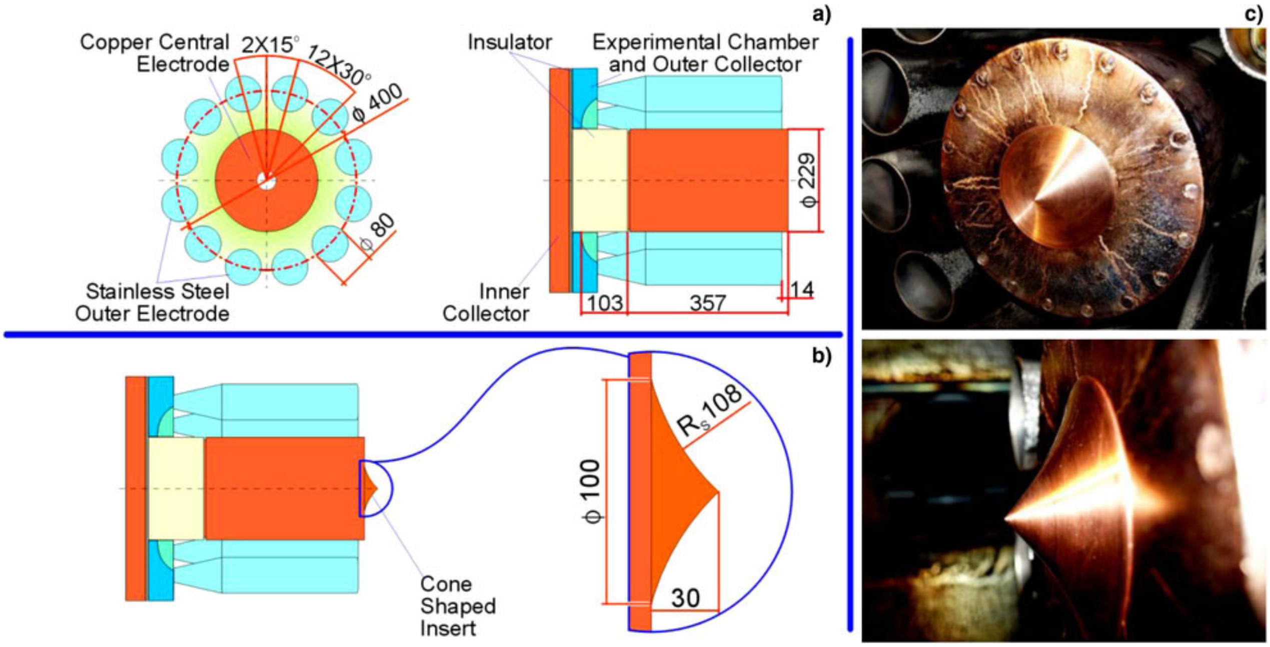


**Fig. 1.** The PF1000U device electrodes setup: (a) the traditional arrangement, (b) design details of the conical insert, and (c) a general view of the conically shaped inner electrode face.

one (cathode) is composed of twelve symmetrically distributed stainless-steel pipes, forming a cylinder with diameter of 400 mm (Fig. 1a). The electrodes are separated by an insulator with a length of 103 mm.

Usually, the inner electrode front is closed by a flat plate. However, in our experiment, a profile of the inner electrode face was changed. Namely, a Cu cone with diameter in base of 10 cm and height of 3 cm was centrally fixed to the face of the inner electrode. The PF1000U device electrodes setup and the cone profile are presented in Figure 1b and c.

Plasma-focus discharges were initiated at the initial deuterium pressure of 0.9 Torr by the application of a high-voltage pulse from the main condenser bank charged to 16 kV, which supplied the energy of about 170 kJ. The maximum current reached a value of 1.2 MA.

Two main diagnostics have been used in the experiment: a 16-frame laser interferometer (Zielińska *et al.,* 2011) and a four-frame X-ray camera.

The interferometric measurements were performed with a Nd:YLF laser operated at the second harmonics (527.5 nm). The laser pulse (lasting <1 ns) was split by a set of mirrors into 15 separated beams, which passed through a Mach–Zehnder interferometer. Those beams penetrated through the plasma region during a period of 210 ns.

The high-speed, four-frame soft X-ray camera (HS-4F-SXRC) was used to record plasma images in extreme UV and soft X-ray spectral ranges with nanosecond temporal and sub-millimeter spatial resolutions. This camera, developed by the ACS Laboratory, is a brand-new equipment based on four-sectors, gateable microchannel plate (MCP), which cooperates with a set of four pinholes. During the experiment the pinholes remained uncovered. It allowed recording plasma images within a relatively wide spectral range of 10–6200 eV.

The line-of-sight of both the diagnostics was oriented perpendicularly to the main axis of the PF1000U device with an angle of 45° between them (Fig. 2).

The instant of $t = 0$ is in Figures corresponds approximately to the Cu plasma jet start.

## 3. THE METALLIC PLASMA JET GENERATION – A WAY AND RESULTS

Our earlier investigations of the plasma sheath (PS) dynamics using the flat face of the inner electrode (Kasperczuk *et al.,* 2002) have shown that the axial velocity of the PS front-end during the collapse stage is roughly constant for any deuterium pressure. Meanwhile, the radial velocity of the plasma sheath part in the vicinity of the inner electrode face turns out to be a linear function of its position on the inner electrode front. The plasma sheath starts in the radial direction with the velocity equal to a half of the axial one, reaching its maximum value on the axis. At the deuterium pressure of 0.9 Torr, the final radial velocity of the plasma sheath reaches approximately the value of $3 \times 10^7$ cm/s.

As it was mentioned earlier, our intention was to use the eroded material (Cu) of the inner electrode for production of metallic plasma jets. However, the traditional flat geometry of the inner electrode face, proper for investigations of thermonuclear processes accompanying the PF discharge, could not be employed for our aim. In this case practically

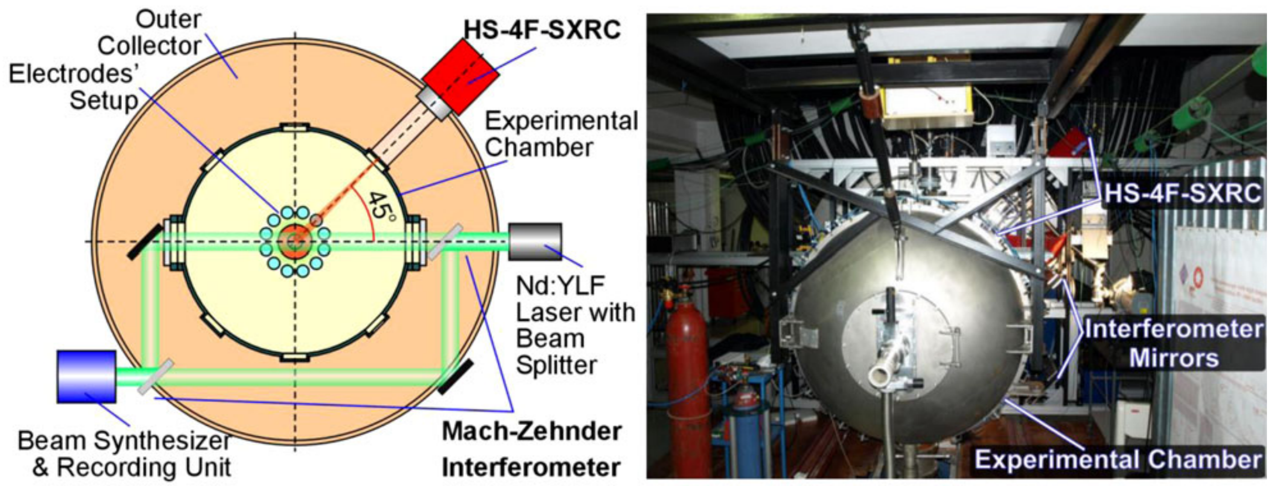


**Fig. 2.** The location of the high-speed frame imaging systems at the PF1000U experimental chamber.

an axial immobility of the plasma occurs. So, the essential question was how to force the fast axial plasma outflow. For this reason different geometries of the plasma sheath collapse were analyzed. It turned out that such the possibility could be given using the conically shaped inner electrode face. Then, the geometry of the plasma sheath collapse in the vicinity of the inner electrode becomes not cylindrical but conical, with significant axial velocity component during the collapse. For the test a Cu cone with a diameter in base of 10 cm and height of 3 cm was used.

A low radiation intensity of the plasma sheath in the soft X-ray range did not allow us to observe its propagation along the cone surface by means of the X-ray camera. For this reason the interferometric system was used. The sequence of six interferograms in Figure 3 has shown both the plasma sheath movement along the cone surface and the Cu plasma jet forming. The final plasma sheath velocity along the cone surface, estimated on the basis of the interferometric measurements, equals about $3 \times 10^7$ cm/s. Bearing in mind the final radial velocity of the plasma sheath in the case of the flat face of the inner electrode, equal to $3 \times 10^7$ cm/s, one can say that the transformation of the radial velocity of the plasma sheath in the axial one using the conically shaped face of the inner electrode appeared to be highly satisfactory.

The first phase of the process of Cu plasma jet creation lasts until the plasma sheath motion along the cone surface is over. The resulting conical-like geometry of the collapsing plasma sheath creates a plasma column with axially moving plasma as well as the strong pressure gradient along the axis

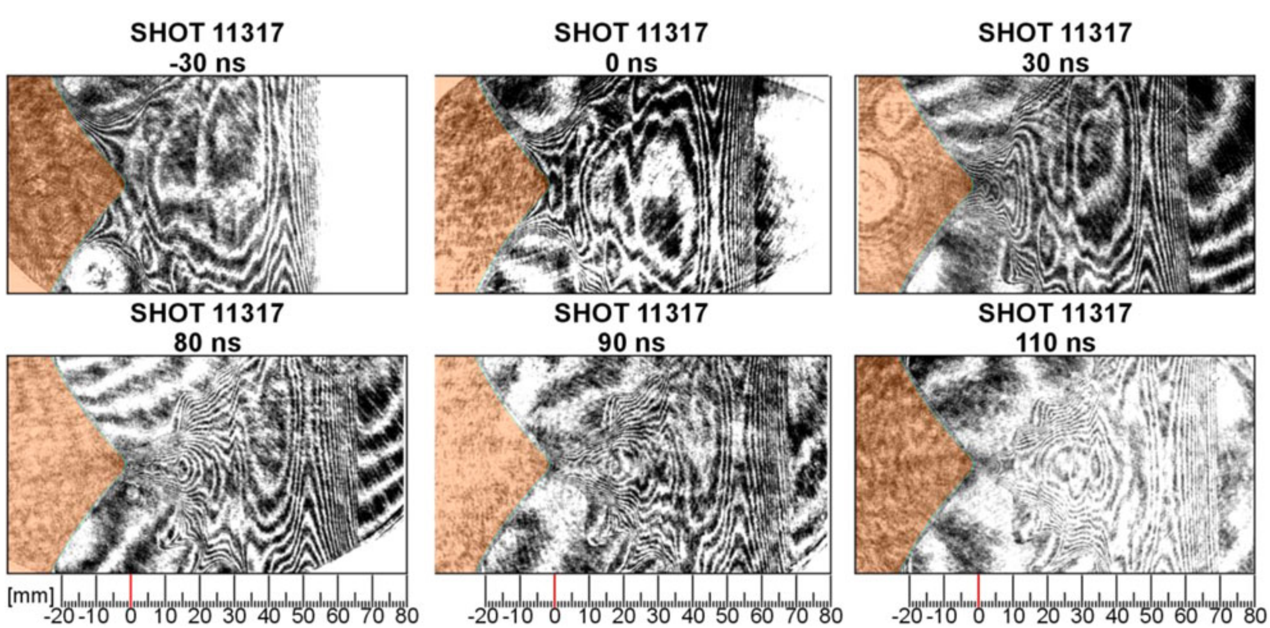


**Fig. 3.** Sequence of interferograms showing the plasma sheath movement along the cone surface and the Cu plasma jet forming.

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caused by successive pinch formation due to radial component of the sheath velocity. It allows us to start the second phase of this process, that is, the Cu plasma jet formation and propagation.

The exact mechanism of the evaporation of the Cu and its fast ionization is still to be investigated but we can already say that high temperature in the plasma sheath accelerated along the cone surface can be responsible for this process. A plasma temperature in the plasma sheath moving in the ambient deuterium gas can be estimated on the basis of the shock wave theory.

From the momentum conservation across the shock wave front (Zel'dovich & Raizer, 1996):

$$\rho_0 D u = (p_1 - p_0), \tag{1}$$

where $D$ is the velocity of the shock front, $u$ is the velocity of the gas behind the shock front, $\rho_0$ is the mass density of the ambient deuterium gas, $p_0$ and $p_1$ are pressure before and behind shock front.

As $p_1 \gg p_0$ and for perfect gas with $\gamma = 5/3$ $(\rho_1/\rho_0) = (\gamma + 1/\gamma - 1) = 4$ and $u = 3/4\,D$.

Hence,

$$\frac{3}{4}\rho_0 D^2 = p_1 = n_1(kT_\mathrm{i} + kT_\mathrm{e}) = \frac{4\rho_0}{m_\mathrm{D}}(kT_\mathrm{i} + kT_\mathrm{e}), \tag{2}$$

where $n_1$ is the plasma density; $T_\mathrm{i}$, $T_\mathrm{e}$ are ion and electron temperatures; $k$ the Boltzman constant, $m_\mathrm{D}$ the deuteron mass, and finally for $D = 3 \times 10^7$ cm/s:

$$(T_\mathrm{i} + T_\mathrm{e}) = \frac{3m_\mathrm{D}}{16k}D^2 \cong 350\,\mathrm{eV}. \tag{3}$$

In the shock front area, $T_\mathrm{i} \gg T_\mathrm{e}$ as the ion viscosity is a main dissipating mechanism that converts kinetic energy into the thermal one. Then, e–i collisions cause gradual equalization of both temperatures. Regardless details of thermal energy partition between electron and ion component in the plasma sheath, one can see that the surface of cone is exposed to a heavy thermal loads that, due to convergent nature of the collapse geometry, is focused at the cone tip area.

The suitable geometry of the plasma sheath collapse and the Cu plasma source existence allowed us to start the process of Cu plasma jet creation. However, the interferometric measurements turned out to be incorrect for detailed observation of the Cu plasma jet because of a small spatial resolution of interferograms. For this reason the X-ray camera proved to be appropriate.

The conical geometry and high dynamics of the PS collapse lead to generation of the fast deuterium plasma stream, the initial velocity of which amounts to above $4 \times 10^7$ cm/s (see Fig. 4). The X-ray radiation intensity of the Cu plasma is considerably higher as compared with that of the deuterium plasma; therefore the Cu plasma jet can be observed in the background of the deuterium plasma stream. The Cu plasma jet velocity is on the level of $3 \times 10^7$ cm/s. It is kept in the compression state for the whole length of its existence, conserving the diameter of 1–2 mm. It is demonstrated in Figure 4. The above results distinctly proved that the relatively thin deuterium plasma is able to compress the Cu plasma to a thread form. The Cu plasma jet exists above 250 ns and achieves a maximum length of 5 cm. Disintegration of the Cu plasma jet is induced by a development of MHD $m = 0$ instability (see Figure 5).

The Cu plasma compression by the relatively thin deuterium plasma requires an explanation. Let us discuss differences in plasma pressures related to plasmas with low and high

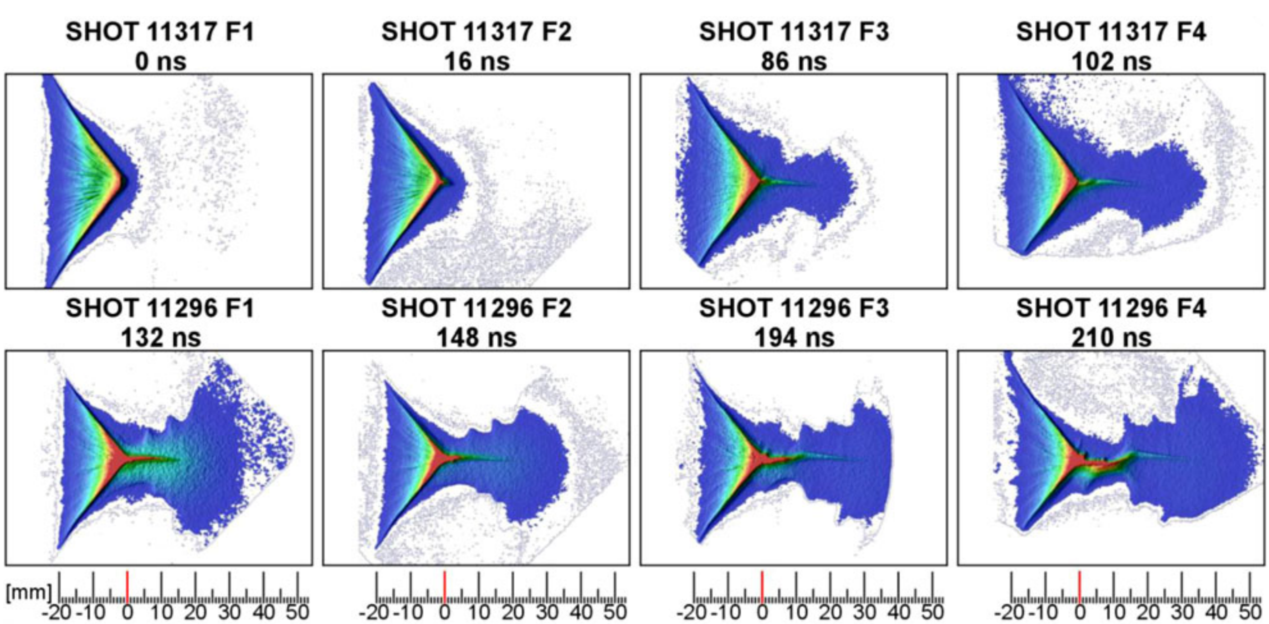


**Fig. 4.** Sequences of X-ray images of the Cu plasma jet creation and propagation.

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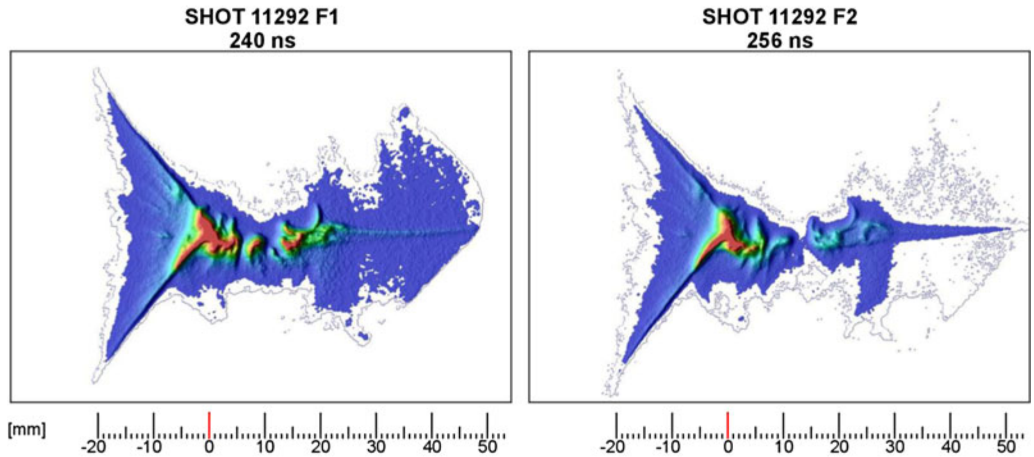


**Fig. 5.** The disintegration of the Cu plasma jet by a development of MHD $m = 0$ instability.

atomic numbers. Our earlier experiments at the PALS iodine laser facility, using target materials with atomic numbers in the range of 3.5–73, allowed us to come to the conclusion that the lighter is plasma, and the higher is its pressure (Kasperczuk *et al.,* 2011, 2014). Even relatively thin low-$Z$ plasma was able to compress high-$Z$ plasma to an electron density considerable larger in comparison with that of low-$Z$ plasma. It means that here an essential role plays differences in the plasma temperature, being considerably higher in the case of lower-$Z$ plasma. Recently, the investigations of an influence of different atomic number ablators on ablative plasma energy transfer into an inner massive target (Kasperczuk *et al.,* 2015) have shown that the electron temperature decreases strongly with the increasing $Z$ of ablators, even by 44% when the temperatures of plastic ($Z = 3.5$) and Ag (47) plasmas were compared. This temperature drop with the growing $Z$ results from a growth of the plasma self-radiation. In consequence, the higher radiation emission leads to much more effective radiative cooling of the higher-$Z$ plasma.

By analogy with the laser-produced plasma, the above conclusions can be referred to the plasma produced with the use of the PF device. In a final period of the collapse stage, the deuterium plasma temperature is on the level of several hundreds of eV. Thus at this time the Bremsstrahlung emission is a dominant factor. Because the power of the plasma Bremsstrahlung emission $P_{br} \sim Z_i^2 n_i n_e T_e^{1/2}$ (where $Z_i$ is the average ion charge, $n_i$ and $n_e$ are the plasma ion and electron densities, and $T_e$ is the electron temperature), in the case of the deuterium plasma a loss of plasma energy is negligible in comparison with that of the Cu plasma. Additionally, in the case of the Cu plasma a line emission increases the radiation loses. That is why the Cu plasma pressure drops radically and the deuterium plasma is capable of compress it to a very thin form.

## 4. CONCLUSIONS

In this work, we have demonstrated a simply way of production of metallic plasma jets by using the conically shaped face of the inner electrode of the PF device. Such modification of the inner electrode face allowed us to realize successfully both the Cu plasma acceleration and its compression. It was also shown that the relatively thin deuterium plasma envelope is able to compress the Cu plasma stream to a very small size. It was possible due to difference in pressures of deuterium and Cu plasmas.

A quality of the Cu plasma jet depends on its dimensions, velocity and mass. Dimensions of the Cu plasma jet under investigations are very promising because of its small diameter (1–2 mm) and large length (up to 5 cm). The Cu plasma jet velocity depends on the plasma pressure gradient along the axis at the collapse end and on the plasma sheath dynamics. Maybe, the former can be increased by an optimization of the cone shape and dimensions, whereas the latter is connected with the energy (voltage) of condenser bank and a filling gas pressure. Since in our experiment their optimum values were established, so a control of the plasma dynamics is greatly limited. Nevertheless, the Cu plasma jet velocity on the level of $3 \times 10^7$ cm/s seems to be full of interest for different applications. To increase the Cu plasma mass the cone top requires certain reconstruction. An elongated tip of the cone should be a source of larger amount of the Cu plasma.

Our investigation concerned only one cone material – Cu. It seems to be of interest to put the test of other cone materials, lighter and heavier than Cu, for example, Al (13) and Cd (48). It will allow us to compare processes acceleration and compression of metallic plasmas by the filling gas in dependence on their atomic number.

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## REFERENCES

Coker, R.F., Wilde, B.H., Foster, J.M., Blue, B.E., Rosen, P.A., Williams, R.J.R., Hartigan, P., Frank, A. & Back, C.A. (2007). Numerical simulations and astrophysical applications of laboratory jets at Omega. *Astrophys. Space Sci*. **307**, 57–62.

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. (1999). Stable dense plasma jets produced at laser power densities around $10^{14}$ W/cm$^2$. *Phys. Rev. Lett*. **83**, 1982–1985.

Hartigan, P., Foster, J.M., Wilde, B.H., Coker, R.F., Rosen, P.A., Hansen, J.F., Blue, B.E., Williams, R.J.R., Carver, R. & Frank, A. (2009). Laboratory experiments, numerical simulations, and astronomical observations of deflected supersonic jets: Application to HH110. *Astrophys. J*. **705**, 1073–1094.

Kasperczuk, A., Kumar, R., Miklaszewski, R., Paduch, M., Pisarczyk, T., Scholz, M., and Tomaszewski, K. (2002). Study of the plasma evolution in the PF-1000 device by means of optical diagnostics. *Phys. Scr*. **65**, 96–102.

Kasperczuk, A., Pisarczyk, T., Borodziuk, S., Ullschmied, J., Krousky, E., Masek, K., Rohlena, K., Skala, J. & Hora, H. (2006). Stable dense plasma jets produced at laser power densities around 1014 W/cm$^2$. *Phys. Plasmas* **13**, 1–8.

Kasperczuk, A., Pisarczyk, T., Demchenko, N.N., Gus'kov, S.Yu., Kalal, M., Ullschmied, J., Krousky, E., Masek, K., Pfeifer, M., Rohlena, K., Skala, J. & Pisarczyk, P. (2009). Experimental and theoretical investigations of mechanisms responsible for plasma jet formation at PALS. *Laser Part. Beams* **27**, 415–427.

Kasperczuk, A., Pisarczyk, T., Badziak, J., Borodziuk, S., Chodukowski, T., Gus'kov, S.Yu., Demchenko, N.N., Klir, D., Kravarik, J., Kubes, P., Rezac, K., Ullschmied, J., Krousky, E., Masek, K., Pfeifer, M., Rohlena, K., Skala, J. & Pisarczyk, P. (2011). Interaction of a laser-produced copper plasma with ambient plastic plasma. *Plasma Phys. Control. Fusion* **53**, 1–16.

Kasperczuk, A., Pisarczyk, T., Chodukowski, T., Kalinowska, Z., Gus'kov, S.Yu., Demchenko, N.N., Ullschmied, J., Krousky, E., Masek, Pfeifer, M., Skala, J. & Pisarczyk, P. (2014). Interactions of plastic plasma with different atomic number plasmas. *Phys. Scr. T* **161**, 1–4.

Kasperczuk, A., Pisarczyk, T., Chodukowski, T., Kalinowska, Z., Stepniewski, W., Jach, K., Swierczynski, R., Renner, O., Smid, M., Ullschmied, J., Cighardt, J., Klir, D., Kubes, P., Rezac, K., Krousky, E., Pfeifer, M. & Skala, J. (2015). Efficiency of ablative plasma energy transfer into a massive aluminum target using different atomic number ablators. *Laser Part. Beams* **33**, 379–386.

Lebedev, S.V., Chittenden, J.P., Beg, F.N., Bland, S.N., Ciardi, A., Ampleford, D., Hughes, S., Haines, M.G., Frank, A., Blackman, E.G. & Gardiner, T. (2002). Laboratory astrophysics and collimated stellar outflows: The production of radiatively cooled hypersonic plasma jets. *Astrophys. J*. **564**, 113–119.

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. (2000). Experiments on radiative collapse in laser-produced plasmas relevant to astrophysical jets. *Phys. Rev. E* **62**, 8838–8841.

Zel'dovich, Ya.B. & Raizer, Yu. P. (1996). *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, vol. I, New York and London: Academic Press.

Zielińska, E., Paduch, M. & Scholz, M. (2011). Sixteen-frame interferometer for a study of a pinch dynamics in PF-1000 device. *Contrib. Plasma Phys*. **51**, 279–283.