Dynamics of axial plasma jets in neon and argon plasma focus discharges

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Abstract. Axial plasma jets at the final stage of plasma focus discharge filled by neon or argon were studied by the method of shearing interferometry. It was found that neon plasma is more stable than argon one and jets in neon are stronger than in argon. The velocity of current sheath, taken from experiment, is $V_{sh} = (2–3) \times 10^6$ cm/s, while the velocity of cumulative jet is $V_j = (3–4) \times 10^7$ cm/s. These features are supported by theoretical interpretation given in the frame of 2D MHD model.

1. Introduction
This paper aims to study the properties of plasma jets, generated in plasma focus discharge [1, 2]. At the present time the plasma jets are widely used to create new promising materials with attractive physical properties [3–7]. Most studies of the plasma focus emphasize the dense pinch itself: the early stage of current-plasma sheath motion to the axis (CPS) receives more attention while the disassembly stage after the pinch is most often ignored. However, in these latter stages there occurs a very important process: the formation of powerful high-speed plasma jets moving in the axial direction. The formation of jets is conceptually explained by the non-cylindrical shape of CPS. The properties of the jet depend on such parameters as gas pressure and element composition, the geometry of electrodes and other parameters. This paper is devoted to the investigation of plasma jet dynamics by the method of differential interferometry. Two-dimensional computer simulations with a simple magneto-hydrodynamics (MHD) model show features that are similar to the experimental observations.

2. Experiment
Measurements are done on a “Tulip” machine, plasma focus discharge of Mather type [1] with the discharge current 200 kA, the charging voltage 12 kV, the initial pressure of the working gas (argon or neon) $P = 2–3$ Torr. The electrode system is shown in figure 1, where no1 is the anode, no2 is cathode, no3 is an isolator. In this type of discharges, the breakdown happens along the isolator and current sheath accelerated by Lorentz force moves towards the
discharge axis. Eventually, current sheath comes to the top of the anode, where hot and dense plasma \( N_e \approx 10^{18} - 10^{20} \text{ cm}^{-3}, T_e \approx 100 - 500 \text{ eV} \) is created near the discharge axis at the time of maximal compression \( t_0 \). At this time plasma radius is small enough and the pressure of poloidal magnetic field of discharge current is so large, that plasma starts to outflow in axis direction, creating so-called plasma jets.

The axial plasma jets were studied with optical methods based on a second harmonics of YAG-laser. Its energy per pulse is 100 mJ, time duration 3–4 ns, and the beam is typically expended to the diameter 50–60 mm. Figure 2 shows time integrated typical pinhole images, taken after Be filter. The difference is vividly seen between a) and b) images: in the former case, it is plasma column, in the latter-three small plasma regions situated close to each other. The explanation for this difference is as follows: higher radiation losses of argon discharge lead to the formation of instabilities according to radiative collapse phenomena. So, plasma in neon discharges is more stable than plasma in argon one.

Figure 3 shows a set up for an interferometric measurements in which Mach-Zehnder interferometer formed by mirrors M1-M4, which has the plasma in its 2 meter long bottom leg. Interferograms are registered by “Videoscan” system (K1) synchronized with the laser beam. Other measurements are carried out with a compact shearing interferometer (mirrors M7-M10) and corresponding interferograms are registered by camera Canon EOS 7D (K2). The main results were cross checked by Mach-Zehnder device.

Results of our study are shown in figure 4 for neon discharges with initial gas pressure \( P = 24 \text{ Torr} \). The axial movement of current sheath is registered within different delay time \( t = -\infty \) to 40 ns) with respect to the moment of maximal compression \( t_0 \). The appearance of plasma jet happens at about \( t = 20 \text{ ns} \), where the bubble-like structure is vividly seen at the top of current sheath with its further propagation in axial direction, see frame \( t = 40 \text{ ns} \). The velocity of current sheath, calculated from those images, is \( V_{sh} = (2-3) \cdot 10^6 \text{ cm/s} \), while the velocity of cumulative jet is \( V_j = (3-4) \cdot 10^7 \text{ cm/s} \).

The velocity of current sheath is shown to be almost same for the argon discharge. However, in the contrast with the neon discharges we have never registered so pronounced plasma jets in argon discharges.

### 3. Results of numerical calculations

The dynamics of plasma jet is likewise studied by solving the ideal 2D MHD equations:

\[
\frac{\partial n}{\partial t} + \text{div} (n \mathbf{V}) = 0,
\]
Figure 4. Dynamics of plasma jet in neon discharge, $P = 2$ Torr, $I = 200$ kA, $U = 12$ kV. Arrow 1 shows current sheath, arrow 2 shows the front of plasma jet. Time is given from the moment of maximal compression $t_0$. Exposure time is 3 ns, frames $t = 60$ ns and $t = 0$ are given to demonstrate the reproducibility of the positions of current sheath and the jet in different discharges.

\[
\frac{\partial n V_r}{\partial t} + \frac{n V_r V_r}{r} + \frac{\partial n V_r V_z}{\partial z} = -2 \frac{\partial}{\partial r} (n T) + \frac{1}{4 \pi m_i} \frac{\partial B_\theta}{\partial z} B_\theta, \tag{3}
\]

\[
\frac{3}{2} \left( \frac{\partial n T}{\partial t} + \text{div} (n T V) \right) = -n T \text{div} V, \tag{5}
\]

where $n, B_\theta, T, m_i$ and $V$ are the plasma electron density, azimuthal magnetic field, electron temperature and flow velocity respectively. The equations were solved with the following initial and boundary conditions: zero velocity on all surfaces, magnetic field is zero in the electrodes and equal to $2I/r_c$ in the insulator, the plasma density is fixed at 0.0001 of initial density in the layer closest to insulator. With this boundary conditions the MHD evolution produces the hot and dense plasma on the discharge axis, where the strength of azimuthal magnetic field of the discharge current at time $t_0$ is so high that its pressure is main factor responsible for the formation of axial plasma jet.

So we studied the behavior of plasma jets numerically for the case of column-like plasma (single-pincher) and twin-pincher case. Figure 5 shows the results of those calculations. Plasma jets no1 and no2 on the right side of figure 5 interact with each other, leading to the radial jets no3 and no4. Finally total plasma outflow in axial direction is decreased.

Figure 6 shows time evolution of $\int n V ds$ number of particles flowing through the pinch cross section (non-dimensional values). The dashed line corresponds to column-like plasma or single pinch, while solid line—to the plasma consisted from double point-like regions, or twin pinch. It
Figure 5. Plasma jets, shown for column-like plasma and point-like plasma with a twin structure.

Figure 6. Plasma jets, shown for column-like plasma and point-like plasma with a twin structure.

is seen that number of jet particles in the former case exceeds those of the latter case. This fact is main reason that plasma jets are less visible in argon discharges compared to those in neon one.

It should likewise be noted that MHD modeling predicts almost same velocities: $V_{sh} = (2–3) \cdot 10^6 \text{ cm/s}$ and $V_j = (3–4) \cdot 10^7 \text{ cm/s}$ and a very recognizable bubble-like shape of cumulative jet.

4. Summary
The formation of supersonic jets in plasma focus discharge is studied by shearing interferometry approach. It is shown that column-like plasma generates jets more effectively compared to the plasma, consisted from two point-like sources. Experimental results are supported by numerical modeling carried out within 2D MHG model.

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References
[1] Eliseev S P, Nikulin V Ya and Silin P V 2008 Problems of Atomic Science and Technology 6 216
[2] Baronova E O, Bashutin O A, Vikhrev V V, Vovchenko E D, Dodulad E I, Eliseev S P, Krauz V I, Mironenko-Marenkov A D, Nikulin V Ya, Raevskii I F, Savelov A S, Sarantsev S A, Silin P V, Stepanenko A M, Kakutina Yu A and Dushina L A 2012 Plasma Physics Reports 38 751

[3] Mikhailova G V, Antonova L I, Borovitskaya I V, Krokhin O N, Majorov A N, Mikhailov B A, Nikulin V Ya, Silin P V, Troitskiy A 2013 Physica Status Solidi (C) Current Topics in Solid State Physics 10 689

[4] Didyk A Y, Ivanov L I, Krokhin O N, Nikulin V Ya, Maiorov A N 2012 Doklady Physics 57 7

[5] Kolokol’tsev V N, Borovitskaya I V, Ivanov L I, Lyakhovitskii M M, Paramonova V V, Nikulin V Ya 2011 Inorganic Materials: Applied Research 2 167

[6] Ivanov L I, Dedyurin A I, Borovitskaya I V, Krokhin O N, Nikulin V Ya, Peregudova E N, Oginov A V, Tikhomirov A A 2009 The European Physical Journal D - Atomic, Molecular and Optical Physics B 1 1

[7] Nikulin V Ya, Ivanov L I, Mikhailova G N, Mikhailov B P, Troitskii A V, Antonova L K, Borovitskaja I V, Gorskikh P V, Peregudova E N, Pokrovskij S V, Rudnev I A 2011 Acta Technica 56 T238