Study of plasma jets in plasma focus using the snow-plough model

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Abstract. Development of plasma jets (PJ) generated in plasma focus machine is investigated numerically by the snow-plough model. It is shown that axial speed of PJ, \( V = 5 \times 10^7 \text{ cm/s} \), few times exceeds the speed of thermal plasma expansion. It means that long distance transportation of plasma jets can be achieved. Results of calculations are in good agreement with experimental data obtained by interferometry.

1. Introduction

The collapse of conical shells was studied by the theory of hollow-charge explosions [1], in which the formation of a cumulative jet involving a certain amount of compressed substance was considered. A breakdown factor of cumulative shells associated with high pressure (up to few tons per squared cm) was shown to be more than ten times higher compared to traditional one. In plasma experiments, the purely hydrodynamic effect, which takes place in solid explosives, is replaced with the magneto-hydrodynamics (MHD) effect, which allows one to achieve much higher temperatures and jet velocities [2]. Current sheath (CS) in plasma focus discharges (PFD) moves along the discharge axis due to ponderomotive force and radial speed of CS achieves \( 5 \times 10^7 \text{ cm/s} \). At the compression stage dense (\( N_e \) from \( 10^{18} \) to \( 10^{21} \text{ cm}^{-3} \)) and hot (\( T_e \) from 100 to 1000 eV) plasma is created and plasma jets are generated moving along the discharge axis [3–6].

The important applications of high speed plasma jets are: acceleration of macro particles, simulation of meteorite showers, investigation of plasma-surface interaction [7,8], modification of constructional materials with the aim to impart new properties to them including the deposition of nanocoatings [9,10], laboratory modeling of astrophysical phenomena, such as the excitation of shock waves with above 3 Mach numbers during the interaction of the solar wind with the magnetic field of the Earth [11]. It was also shown that fast plasma outflow leads to the development of MHD instabilities (\( m = 0 \)), promoting the generation of high temperature plasma, which is a source of high power neutron and x-ray emission [12]. So investigation of generation of plasma jets (PJ) is important for thermonuclear fusion.

Numerical modeling of PJ development which predicts optimal conditions for their generation might decrease the cost of corresponding experiments. Development of PJ was studied by MHD
2. Description of the model

The simplest description of plasma dynamics in Z-pinches was suggested by Rosenbluth [14], and then by Braginski and Migdal [15]. They constructed one-dimensional model which assumes that plasma sheath created near the isolator moves along the anode fully scooping in working gas. Discharge current is concentrated inside the thin current sheath which moves due to ponderomotive force. It was assumed that CS thickness is small compared to the radius of CS, gas velocity inside CS is constant and each element of current sheath can be described by same coordinate and speed. Such a model was named “the snow-plough model”. Practice has shown that one-dimensional models well describe the time and speed of current sheath compression in cylindrical Z-pinches (CZP). To describe CS motion in PFD the two-dimensional snow-plough model (TDSP) was suggested in [16]. Results of numerical study of current sheath motion made within TDSP is given in [17–19]. Discharge chamber is divided into two areas, the first one is filled with working gas, and the second one is filled by magnetic field. The value of magnetic field, $H$, at distance $R$ from discharge axis is determined by current $I$, flowing through Z-pinch: $H = 2I/(cR)$. The interaction of discharge current and magnetic field leads to the corresponding pressure $p = H^2/(8\pi)$.

The two-dimensional CS motion can be described in a one-dimensional non-stationary model by introducing the coordinate $\lambda$ (figure 1), directed along the current shell in the plane $(R, Z)$, where $\lambda = 0$ on the anode, $\lambda = 1$ at the cathode; $R(\lambda, t)$ is vector in $(R, Z)$ plane, which determines the position of small part of CS with coordinate $\lambda$ at the time $t$. This vector at $t = \text{const}$ describes the shape of current sheath, while at $\lambda t = \text{const}$—describes the trajectory of this small part. In the frame of the snow-plough model the change of mass of small part of current sheath with the length $\Delta \lambda$ is described as $\partial M/\partial t = c_m R |\partial R/\partial \lambda| V_n \Delta \lambda$ where $M$ is mass of small part of current sheath, $V_n$ is velocity component normal to current sheath, $c_m$ is capture coefficient which is equal to unit.
A numerical study of the dynamics of CS with the TDSP model, however, does not take into account plasma pressure. That is why calculated CS crosses discharge axis. To avoid such effect the following approximation is used in our model: if the CS to axis distance is less than 0.1 cm then radial speed is zero, while the distance itself is kept as 0.1 cm. Such an approximation made it possible to calculate CS dynamics even after the generation of hot plasma on the axis. Experiments have shown that 0.1 cm is close to minimal plasma size, so at this distance plasma pressure is balanced by magnetic field pressure, radial plasma velocity is equal to zero and the energy of magnetic field is transformed into axial plasma motion.

3. Results of modeling

Axial plasma jets were calculated for the PF-4 (Tulip) machine, which is a Mather type plasma focus. The pressure of working gas, Ne, is 2.3 Torr. Diameter of inner electrode is 30 mm, the cathode is copper cylinder with diameter 50 mm. Total capacity is 48 $\mu$F, working voltage is 12 kV, energy at 12 kV is 3.6 kJ, current rise time is 2.5 $\mu$s, total current is 250 kA [20].

In figure 2, position of current sheath (black lines 1–6) is shown for different time moments. Time distance between two lines is 20 ns. Position 1 corresponds to the time moment when current sheath touches discharge axis. Plasma is compressed in radial direction by magnetic field pressure. Numerical study shows the “bubble” in the central part of the current sheath, which is associated with plasma jet. It is seen in figure 2 that plasma jets start to be generated along the discharge axis (the “bubbles” on black lines 3–6). Jet speed in axial direction, $V = 5 \times 10^7$ cm/s, few times exceeds $U = 3 \times 10^6$ cm/s, the typical speed of thermal motion. The relation between axial and radial speed increases with time from zero to 4, so that transportation of plasma jets along the discharge axis is effective enough. We note that plasma jets move in both directions: to the cathode and to the anode. This effect is due to fast radial plasma compression by magnetic field with further interruption of radial movement at the moment of maximal plasma compression. Plasma density is increased on the “bubble” boundary which was further confirmed by interferometry study described in section 4.

Figure 2. PJ dynamics taken from the snow-plough model: 1 and 6—positions of current sheath at different time moments; time distance between 1 and 6 is 100 ns. Central horizontal line is the discharge axis.
4. Experimental set up and diagnostic equipment

The experiments were carried out upon the PF-4 machine. The scheme of the PF-4 is shown in figure 3. PF-4 is equipped by Zehnder interferometer, which is aimed to study plasma with high density gradient. Diagnostic assembly of PF-4 is equipped by shearing (Bates) interferometer, fabricated in Kurchatov institute [21]. This interferometer has variable sensitivity and able to study plasma with high electron density gradients. A second harmonic of YAG laser with energy 100 mJ and with duration time 4 ns was used as a light source. Interferograms were registered by digital camera conjugated with computer. The laser beam was synchronized with the discharge triggering system so that information on plasma dynamics at different stages of plasma development could be obtained. Optical scheme including both interferometers and two registration channels is given in figure 4. Dividing mirror M5 (reflects 40%) and reflecting mirror M6 (reflects 100%) are used to direct radiation to Bates interferometer (mirrors M7–M10).

It was previously shown [22] that at the moment of maximal compression plasma radiates soft x-ray emission in the vicinity 1 keV belonging to helium-like (NeIX) and hydrogen-like (NeX) ions, diameter of plasma region is 1 mm, height of plasma column is 10 mm, in maximal compression stage plasma life time is up to 40 ns, plasma electron temperature is up to 200 eV, plasma electron density \( N_e \) is from \( 10^{16} \) to \( 10^{19} \) cm\(^{-3}\). To study the time development of current sheath numerous series of shearing interferograms were registered (figure 4) with different delay with respect to the time of maximal plasma compression. The main results are discussed in section 5.

In such experiments, a high temporal resolution is ensured, since interferograms were recorded with an exposure time of 4 ns. Each interferogram was taken at particular time moment of different discharge keeping the same initial conditions. In such experiments the general plasma behavior is well reproducible for the initial, middle and final stages of the discharge even for the higher current PF machines [23, 24].

5. Results of interferometry measurements in compression stage

Figure 5(a) \((t = -90 \text{ ns})\) shows the first sign of CS at the anode (time is measured from the moment of maximal compression). Figure 5(b) corresponds to CS half rise at \( t = -60 \text{ ns} \). Next one, figure 5(c), \( t = -20 \text{ ns} \), shows the further movement of CS to the discharge axis. For \( t = 0 \),
Figure 4. Optical scheme of interferometric measurements on PF-4: 1—plasma source; 2—YAG laser; K1 and K2—detectors; M1–M4—mirrors of Mach–Zehnder; M5 and M6—dividing and reflecting mirrors; M7–M10—mirrors of shearing interferometer.

Figure 5. Shearing interferograms taken on PF-4 in different time moments, time is calculated from the moment of maximal compression: (a) $t = -90$, (b) $-60$, (c) $-20$, (d) 0, (e) 20 and (f) 40 ns.

Figure 5(d), the main part of CS is collapsed at the anode, producing high temperature plasma (the moment of maximal compression). For $t = 20$ ns, figure 5(e), CS leaves the anode surface, a small bubble is appeared in the central part of the sheath, which moves in both anode and cathode directions. The bubble becomes even more visible in figure 5(f) at $t = 40$ ns. Calculated speed of “bubble” boundary in the direction from the anode to cathode is $V = 5 \times 10^7$ cm/s, while the speed, taken from experiment is $V = 3 \times 10^7$ cm/s. Velocity of main part of CS is bit less: $V = 5 \times 10^6$ cm/s. We mention, that results of calculations are well matched with
experiments, confirming general behavior of CS in the initial, middle and final stages of the discharge.

6. Conclusion
Numerical code is created for the snow-plough model, which is used to calculate the development of plasma current sheath for PF-4 “Tulip" machine. Results of modeling testify that high speed plasma jets are generated moving along the discharge axis. The behavior of calculated current sheath and plasma jets are supported by results of experiment. Plasma jet velocity estimated in experiment is well matched with the one calculated within the snow-plough model. Our results have shown that the snow-plough model is effectively used to search optimal conditions for plasma jet generation in the machines of considered class.

References
[1] Birkhoff G, MacDougall D, Pugt E and Taylor G 1948 J. Appl. Phys. 19 563–82
[2] Filippov N V 1983 Plasma Phys. Rep. 9 14–6
[3] Filippov N V, Filippova T J and Vinogradov V P 1962 Nucl. Fusion 2 577–81
[4] Mather J W 1965 Phys. Fluids 8 366–70
[5] Vikhrev V V, Ivanov V V and Rozanova G A 1989 Sov. J. Plasma Phys. 15 77–81
[6] Krauz V I et al 2014 Phys. Scr. T161 16–23
[7] Borowiecki M N, De Chiara P K and Dubrovsky A A 2001 Nucleonica 46 117–21
[8] Demina E V, Pimenov E V and Maslyaev S A 2010 Fiziko-Khimicheskaya Obrabotka Materialov 23 51–9
[9] Ivanov L I, Krokhin O N and Dedyurin A I 2004 Perspekt. Mater. 21 31–8
[10] Mikhaslov B P et al 2012 Perspekt. Mater. 442 56–9
[11] Mourenas D N et al 2003 Phys. Plasmas 10 605–10
[12] Vikhrev V V 1977 Plasma Phys. Rep. 3 981–6
[13] Baronova E O et al 2012 Plasma Phys. Rep. 38 751–60
[14] Rosenbluth M M 1958 Dynamics of Compressed Gas. Magnitohydrodynamics (Moscow: Atomizdat) pp 3–8
[15] Braginski S I and Migdal A B 1958 Fizika Plasmy i Problemy Upravlyayemykh Termoyadernykh Reaktii vol 2 (Moscow: Izdatelstvo AN SSSR) pp 20–34
[16] Basque G C, Jolas A A and Watteau J P 1968 Phys. Fluids 11 1384–8
[17] Vikhrev V V and Braginskiy S I 1980 Voprosy Teorii Plasmy vol 10 (Moscow: Atomizdat) pp 243–58
[18] Vikhrev V V 1973 Prikladnaya Matematika i Tekhnicheskaya Fizika 2 160–5
[19] Vikhrev V V and Korolev V D 2007 Plasma Phys. Rep. 33 397–423
[20] Eiseve S P, Nikulin V Ya and Silin P V 2008 Probl. At. Sci. Technol. (6) 216–8
[21] Baronova E O, Vinogradov V P, Krauz V I, Myalton V V, Stepanenko A M and Stepanenko M M 2011 Plasma Phys. Rep. 37 1001–10
[22] Baronova E O, Bashutin O A and Vovchenko E A 2011 All-Russian Conf. on Diagnostics of High Temperature Plasma (Zvenigorod) (Moscow: Nauka) pp 51–65
[23] Polukhin S N, Gurey A E, Nikulin V Ya, Peregodova E N, Silin P V and Kharrasov A M 2016 Yadernaya Fizika i Inzhinirinng 7 458–61
[24] Polukhin S N, Djamankulov A M, Gurey A E, Nikulin V Ya, Peregodova E N and Silin P V 2016 Plasma Phys. Rep. 42 1080–6