The origin of plasma jets generated in Z-pinch discharges

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Abstract. The results of modeling in the framework of magnetic hydrodynamics (MHD) for the development of a plasma jet in Z-pinches are presented. It has been shown that plasma jet origin is associated with the development of MHD instability $m = 0$, but not with the conical current sheath structure. MHD modeling is also carried out for $\theta$-pinch systems where generation of plasma jets is much less effective. The corresponding analysis is presented.

1. Introduction

Z-pinch discharges are well known by generation of electron beams, neutrons, hard and soft x-ray emission, etc [1]. One of the most interesting features of Z-pinches is plasma jets spreading along the discharge axis. Despite of such phenomenon was numerously registered in laboratory experiments [2–4] there is no concrete information about his nature.

One of the main hypothesis assumes that plasma jets have cumulative origin similar to the one which takes place in cumulative shells [5]. The current sheath in Z-pinch has conical shape when comes to discharge axis, this shape looks very similar to conical hole mechanically fabricated in cumulative shells. So it was really a temptation to apply the theory of hollow charge explosions which considered the generation of cumulative jets to formation of plasma jets in Z-pinches. The relevance of study of plasma jets in Z-pinches is their unavoidable influence on plasma dynamics and also various applications of plasma jets in material science [6]. The other reason is generation of jets in astrophysical objects [7], where the presence of Z-pinch effect was found in [8].

In this paper, we present the results of numerical modeling of plasma jets generated in Z-pinches made in the frame of two-dimensional magnetic hydrodynamics (2D MHD). Z-pinch discharge is studied starting from the very beginning up to the end (plasma cooling). Modeling shows the development of current sheath with conical geometry when it comes to discharge axis, formation of hot dense plasma on discharge axis, generation of axial plasma jets. MHD modeling is also carried out for $\theta$-pinch systems where magnetic field has different geometry and generation of plasma jets was found much less effective. The analysis of results made it possible to put forward the idea on the origin of plasma jet generation.

2. Description of the model

Modeling of plasma jets generated in Z-pinch discharge is carried out within ideal 2D MHD model [9]. The core of the model is numerical code [10], which is able to predict plasma development.
in Z-pinches starting from initial breakdown with further generation of hot, dense plasma on discharge axis and ending with plasma decay. MHD equations for ionized plasma solved in the model are as follows:

\[
\frac{\partial n}{\partial t} + \text{div}(n\mathbf{V}) = 0, \tag{1}
\]

\[
\frac{\partial \mathbf{H}}{\partial t} - \text{rot}\{\mathbf{V}, \mathbf{H}\} = 0, \tag{2}
\]

\[
\frac{\partial (nV_{r,z})}{\partial t} + \text{div}(nV_{r,z}\mathbf{V}) = -\frac{2}{m_i}\text{grad}(nT)_{r,z} + \frac{1}{4\pi m_i}\text{[rot}\mathbf{H}, \mathbf{H}\]_{r,z}, \tag{3}
\]

\[
\frac{3}{2} \left( \frac{\partial (nT)}{\partial t} + \text{div}(nTV) \right) = -nT\text{div}\mathbf{V}, \tag{4}
\]

where \( n \) is the ion density; \( \mathbf{V} \) is the plasma velocity, consisting of radial and axial components, \( V_z \) and \( V_r \); \( \mathbf{H} \) is the magnetic field strength with azimuth \( H_\phi \), radial \( H_r \) and axial \( H_z \) components; \( t \) is time; \( r \) and \( z \) are the radial and axial coordinates; \( T \) is the plasma temperature (\( T_e = T_i = T \)); \( m_i \) is the ion mass.

System of MHD equations is closed by equations of electrical circuit and by the following boundary conditions: near wall velocity, temperature, plasma density are equal to zero, magnetic field on the electrode is zero, magnetic field on the isolator is \( H_\phi = \mu_0 I / (2\pi r_{isol}) \), where \( I \) is electric current, \( r_{isol} \) is radius of isolator. The following initial conditions are used: magnetic field and temperature are zero; electron density corresponds to the initial gas pressure.

Equations (1)–(4) are used to describe both discharges with a discharge current flowing thru a discharge chamber (Z-pinches) and the discharges created by magnetic coils (\( \theta \)-pinches). For \( \theta \)-pinches, the boundary condition for magnetic field on the isolator is \( \mathbf{H} = H_z\mathbf{i}_z = \mu_0 I / (2\pi r_{isol}\mathbf{i}_z) \), with \( \mathbf{i}_z \) standing for unit vector along \( z \).

3. Results of modeling and discussion

We carried out calculations for PF-4 machine (situated in the Lebedev Physical Institute RAS, Moscow), plasma focus of Mather type \cite{11, 12}. Simplified scheme of the machine is shown in figure 1.

Electrical parameters of the machine are as follows: initial voltage is 12 kV, inductance is 17 nH, battery capacity is 48 \( \mu \)F, battery energy is 3.6 kJ. The inner electrode, anode, has diameter 30 mm, anode length is 36 mm, the outer electrode, the cathode, consisted from eight
symmetrically mounted copper rods. Diagnostic chamber was filled by 2 Torr of neon. Plasma moves between rods and the discharge current flows through the rods.

This machine was chosen for our numerical study, because recent experiments have shown reproducible generation of high-speed plasma jets [11, 12]. Effective generation of plasma jets on PF-4 machine was found in case when electrical parameters were matched with working gas pressure and geometry of electrodes. In such optimized regime the moment of maximal plasma compression coincides with the peak of discharge current and optimal plasma parameters are achieved.

Results of numerical modeling are shown in figure 2. Figures 2(a–d) are devoted to dynamics of plasma electron density and distribution of magnetic field in Z-pinch, while figures 2(e–h) give dynamics of plasma electron density and distribution of magnetic field for \( \theta \)-pinch. At the initial stage of both the discharges current sheath is created near isolator surface (time < 0.1 \( \mu s \), shown in red in figure 1) and moves toward the discharge axis by ponderomotive force. The area between current sheath and isolator is filled by magnetic field [the bottom parts of figures 2(d) and 2(h)]. The typical thickness of current sheath is few millimeters and 99% of working gas is concentrated inside the current sheath. It is seen [compare figures 2(a) and 2(e), for example] that current sheath in Z-pinch is thinner, compared to that one in \( \theta \)-pinch. The front border of current sheath of the discharges is well pronounced, this is front of shock wave.

Conical geometry of current sheath is obviously seen at 0.8 \( \mu s < \text{time} < 1.1 \mu s \) [see figure 2(a, e)] for Z-pinch and \( \theta \)-pinch where the current sheath is coming out to anode end. Later, at the time > 1.2 \( \mu s \) [see figures 2(b, c) and 2(f, g)] conical geometry disappears and the current sheath becomes smoother. Figures 2(b) and 2(f) show the beginning of formation of hot and dense plasma on the discharge axis. The following plasma parameters are numerically calculated for plasma in figures 2(a) and 2(f): \( n_e = 2 \times 10^{18} \text{ cm}^{-3}, T_e = 150 \text{ eV} \) for Z-pinch, \( n_e = 3 \times 10^{17} \text{ cm}^{-3} \), \( T_e = 90 \text{ eV} \) for \( \theta \)-pinch. This is well known fact [9] that MHD \( m = 0 \) instability plays positive role in Z-pinch discharges: formation of hot and dense plasma occurs due to this instability. The simple picture of plasma dynamics led by MHD instability is as follows: while central plasma region is compressed in radial direction by magnetic field pressure plasma ends are opened and plasma starts to outflow in axial direction. The bubbles in the vicinity of axis region of current sheath [see figures 2(b) and 2(f)] testify to the very beginning of plasma outflow which is directly associated with jet generation. In the meantime plasma radius continues to decrease, plasma density and temperature increase.

In figure 2(c), plasma region is small circle-like spot, 1 mm in diameter, marked by red arrow, plasma jet is obviously formed and looks very narrow, less than 1 mm in diameter, according to numerical study jet moves in both cathode and anode directions. From figures 2(a) and 2(c), it follows that it took 0.25 \( \mu s \) to overcome 4 cm distance, so that velocity of plasma jet \( V = 4.7 \times 10^7 \text{ cm/s} \). Figure 2(c) corresponds to the moment of maximal plasma compression, when high temperature (\( T_e = 210 \text{ eV} \)) and density (\( N_e = 3 \times 10^{19} \text{ cm}^{-3} \)) plasma is created on the discharge axis. We note that such Z-pinch machines are usually called “plasma focus” machines since hot plasma is created in the area where current sheath is collapsed or focused.

In contrast, in the \( \theta \)-pinch in figure 2(g), there is no plasma jet, and the plasma region is less dense and larger. Plasma is not so hot in \( \theta \)-pinch since MHD instability is stabilized by longitudinal magnetic field of this system. However velocity of shock wave front in the vicinity of discharge axis is comparable to the velocity of plasma jet in figure 2(a, c).

Figure 2(d) shows that magnetic field in Z-pinch geometry is not homogeneous testifying to MHD instability. In addition it is strictly concentrated in the close vicinity of plasma jet finally contributing to her effective compression in radial direction. On contrary magnetic field in \( \theta \)-pinch system [see figure 2(h)] is mainly concentrated behind the current sheath. The crucial factor is that relatively high degree of homogeneity of magnetic field distribution in \( \theta \)-pinch leads to low level of MHD instability.
Figure 2. Dynamics of the electron plasma density (a–h) and the magnetic field (d, h) in the Z-pinch (a–d) and θ-pinch (e–h): gradation step is 1.4; tone panels are shown at the bottom (blue—the plasma density; yellow—the magnetic field). Diameter of central inner electrode (anode) is 30 mm. Time is calculated from applying voltage to electrodes: (a) 1.10, (b) 1.20, (c) 1.40, (d) 1.40, (e) 1.04, (f) 1.26, (g) 1.47 and (h) 1.47 µs.
According to the results presented above, origin of plasma jets cannot be explained by conical current sheath structure, the alleged main reason for plasma jet generation is MHD $m = 0$ instability.

4. Conclusion
We conclude:

- The current sheath is formed in both Z and $\theta$-pinches and moves with the same velocity to the discharge axis.
- At some instant time, current sheath has conical structure in both type of the discharges.
- Generation of jets in Z-pinch starts when conical current sheath structure is disappeared.
- The alleged main origin of generation of plasma jets in Z-pinch is MHD ($m = 0$) instability.

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