Adaptation of plasma focus type facilities for laboratory simulation of astrophysical jets

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Introduction. Laboratory simulation of astrophysical processes is one of the most rapidly progressing research areas [1]. Powerful lasers [2], Z-pinches [3] and other facilities are used for laboratory simulation. Recently, a new series of experiments has been launched in the NRC "Kurchatov Institute" [4] to simulate some of the most striking phenomena in the Universe - astrophysical jets. The facility of plasma focus type, being one of the Z-pinch modifications, is used as an experimental stand. The main goal is to study the mechanisms of the astrophysical jet stabilization, due of which they can propagate along the axis of the accretion disk rotation at distances much greater than their transverse dimensions.

Experimental setup. To solve this problem the Filippov-type PF-3 facility was upgraded. A new diagnostic drift chamber was designed to measure the jet and the ambient plasma parameters at the distances up to 100 cm from the place of jet generation (fig. 1). The manifold set of diagnostic tools was used including streak and frame cameras, light collimators, multi-component magnetic probes, laser diagnostics set on the base of nanosecond Nd3+:YAP laser, ballistic pendulum, calorimeter, spectral diagnostics, etc.

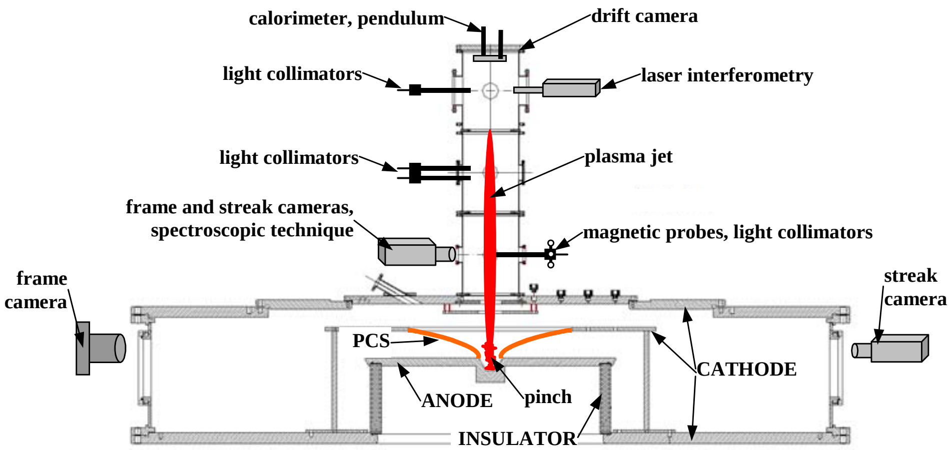

Fig. 1. Experimental setup

Experiments were done at the power supply energy W=290-560 kJ and the discharge current 1 – 2 MA. H_2, D_2, He, Ne, Ar, Xe and their mixtures at a pressure 1 – 4 Torr were used as a working gases.

Experimental results. The stage of the plasma jet formation was studied with the high speed photo recorders. The compact plasma jets moving along the axis occur at the stage of the pinch decay and developing the MHD instabilities (fig. 2a). The initial jet velocity, $V_0 \geq 10^7$ cm/s, exceeds the velocity of the current-carrying plasma sheath in the axial direction and weakly depends on the kind of the working gas.

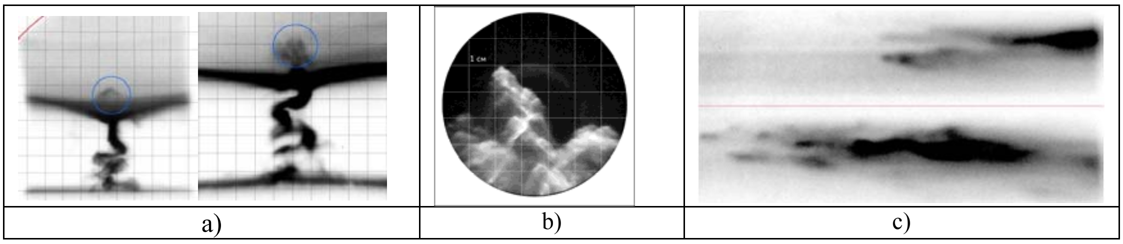

Fig.2. (a) – Frame camera pictures of the pinch at the stage of jet formation. The scale is 1 cm/div. Frame exposure is 12 ns, time interval between frames is 150 ns. b) - Frame camera picture of the plasma jet at the distance of 35 cm from anode plane. Frame exposure is 12 ns, the scale is 1 cm/div. c) – Streak-camera images of the plasma jet at the slits orientation along the anode plane. The distance between the slits is 4 cm, the sweep duration is 3 μs. The photos were obtained in the discharges in neon.

Frame and streak cameras show preserving the compactness of plasma objects at their propagation over distances much greater than their cross-sectional dimensions. It evidences that the longitudinal velocity of the jet is much greater than the lateral velocity of its expansion. The jet structure consists of separate plasma objects (fig. 2 b, c). Such structures is clearly seen also on the signals of the light collimators, which record the time of arrival of the strongly radiating objects in a certain area of observation (Fig. 3). If use two collimated channels separated by a short distance (16 mm), one can estimate the instantaneous velocity of plasma jet in the point of observation. In some cases, individual peaks on the signal of collimator correlate well with the dips on the current derivative signal.

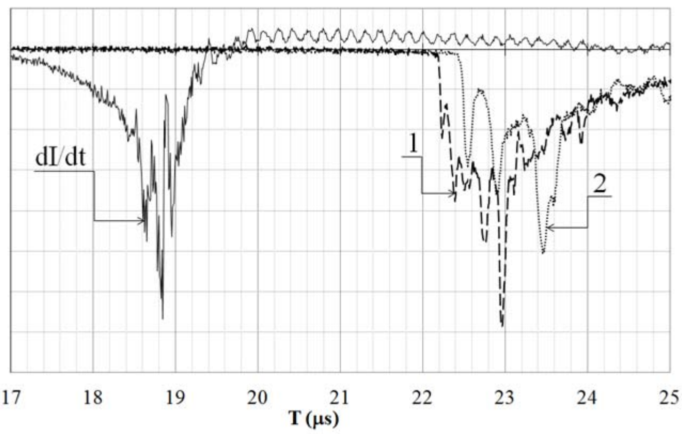

Fig. 3. Signals of discharge current derivative, dI/dt, and optical double collimator (1, 2). The distance between the axis of the two collimator channels is 16 mm. The distance from the anode plane is 35 cm.

In this experimental scheme we used a stationary gas filling. That means that plasma jet propagates in the plasma with finite density arising during ionization of the ambient gas by the emission of the pinch. Therefore information about the parameters of both plasma jet and ambient plasma is key in the study of the jet dynamics. To study the plasma parameters, the diagnostic set including the spectrograph with high resolution in combination with a time-analyzing streak camera was developed. The helium was selected as a working gas. The studies were done at the distance 35 cm from the anode plane. The plasma electron temperature, T≈ 3 – 8 eV, was determined from the ratio of the intensities of the two lines, one of which (λ1 = 5876 Å) belongs to the neutral helium, and the second one (λ2 = 4686 Å) – to the hydrogen-like ion. The plasma concentration estimated from the Stark broadening of the lines of helium due to the electric fields of various nature varies in time and space from 10^{14} to $2\cdot10^{17}$ cm^{-3}.

The presence of the ambient plasma largely determines the evolution of the plasma jet when it moving along the system axis. The plasma jet deceleration was studied with the double optic collimators. It was shown that the jet velocity at different distances from the point of generation is given by the expression $V = V_0 e^{-l/l_0}$, where V_0 is the initial jet velocity, l_0 is the distance at which the jet velocity decreases in e times. l_0 is strongly depend on the variety of working gas, which is associated with different degrees of ionization of background gas by the pinch emission. At the same time, the initial velocity is weakly depend on the kind of gas and corresponds well the velocity determined by the frame cameras at the stage of the jet formation.

The presence of the complex configurations of captured magnetic field in the plasma jet was shown by the multi-channel magnetic probes (Fig. 4). The radial distribution of the azimuthal magnetic field at a distance of 35 cm from the point of generation was built. An example of such distribution for the shot in neon as a working gas in the certain instant of time is shown in Fig. 4b. Such distribution can be explained by the axial current flowing in the region near the axis with the radius 1 – 1.5 cm and closing on the periphery of the plasma jet. Temporal behavior of the signals of various components of the magnetic field, in particular, polarity reversal in some cases (Fig.4a), indicates a possible rotation of the magnetic field induction vector (Fig. 4c). Some evidence of the jet rotation was also obtained with streak cameras. The elucidation of the role of the detected magnetic field configurations in ensuring the jet stability is one of the main directions of our research.

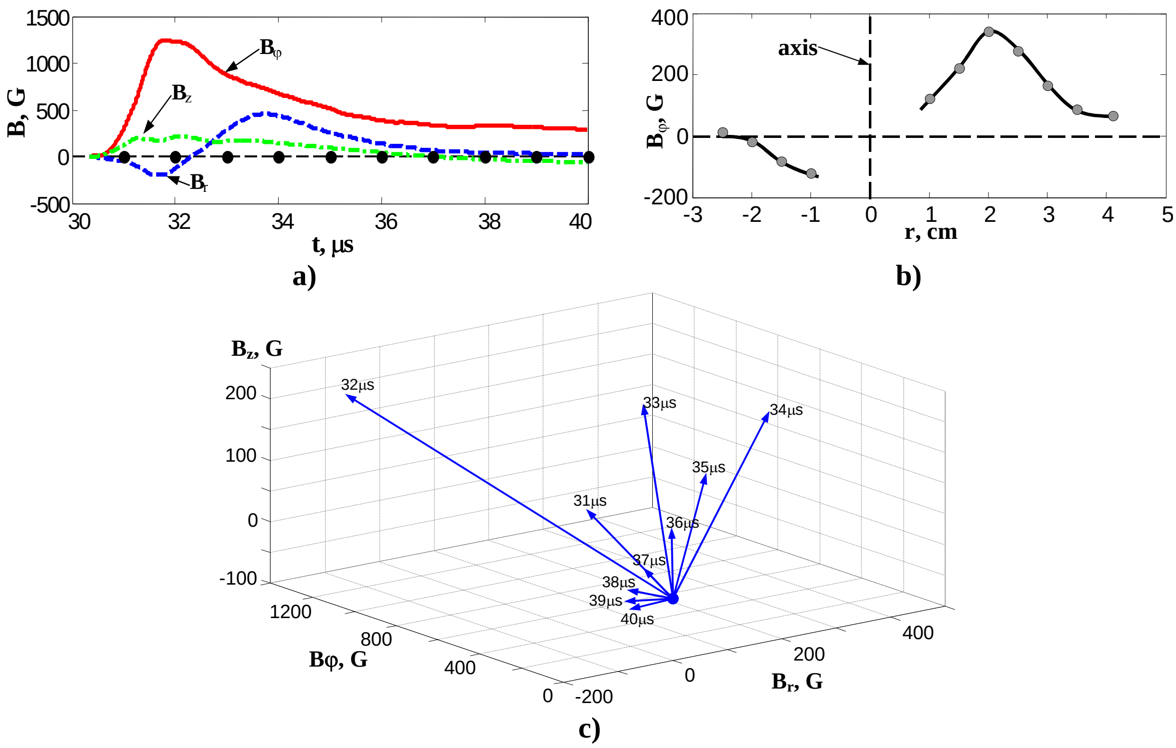

Fig. 4. a) Time dependences: B_φ, B_z, B_r – azimuthal, axial and radial component of the magnetic field induction; b) radial distribution of the azimuthal component of the magnetic field induction, $B_\varphi(r_{i,j},t_i)$; c) direction and value of the sum vector $\vec{B} = \vec{B}_r + \vec{B}_\varphi + \vec{B}_z$, reconstructed for shot on Fig. 4a. The measurements were done at the distance 35 cm from the anode plane. a), c) – shot in H_2, b) – shot in neon.

Conclusion. The developed experimental stand allows to study the propagation of the plasma jets in the ambient medium to long distances. The experimental scheme and wide possibilities to change the conditions of the experiment allows us to analyze the influence of different factors, such as radiative cooling, the captured magnetic field, hydrodynamic effects, etc. on the collimation and stability of the plasma jet. Achieved parameters of the plasma jet, such as its velocity, $V \geq 10^7$ cm/s, the Mach number, $M \geq 1$, the Reynolds number, $R = 10^4$ - 10^5, the contrast (ratio of the jet density to the density of ambient plasma), K=1-10, the plasma temperature, T= 3 – 8 eV, seems very prospective in the simulation the plasma jets in the young stellar objects known as the objects 'Herbig-Haro'.

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