Laboratory simulations of astrophysical jets: results from experiments at the PF-3, PF-1000U, and KPF-4 facilities

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Abstract. Results are presented from laboratory simulations of plasma jets emitted by young stellar objects carried out at the plasma focus facilities. The experiments were performed at three facilities: the PF-3, PF-1000U and KPF-4. The operation modes were realized enabling the formation of narrow plasma jets which can propagate over long distances. The main parameters of plasma jets and background plasma were determined. In order to control the ratio of a jet density to that of background plasma, some special operation modes with pulsed injection of the working gas were used.

1. Introduction

Laboratory simulations of astrophysical phenomena are one of the priority directions in the scientific research [1]. Substantial progress in modelling the astrophysical jets has been achieved using high-power lasers [2] and Z-pinch facilities [3]. Recent studies have shown that the plasma focus (PF) facilities can be successfully used for modelling plasma jets emitted by young stellar objects (YSO). It was shown that plasma jets generated during the PF discharges can propagate over distances which are considerably larger than the transversal dimensions of these jets [4]. A plasma jet with a density of \( \geq 2 \times 10^{17} \text{ cm}^{-3} \) and a temperature of a few electron-volts can propagate through background plasma with a density of \( \geq 2 \times 10^{16} \text{ cm}^{-3} \) [5-6]. It was also shown that, in this case, an axial current appears which generates the toroidal magnetic field confining the plasma jet [7-8]. Problem of stability is one of the important issues in studies of plasma jet dynamics.

Currently, an international scientific collaboration is being developed which involves studies at three large PF facilities, notably, the PF-3 facility at the NRC “Kurchatov Institute” in Moscow (Russia), the PF-1000U facility at the IFPiLM in Warsaw (Poland), and the KPF-4 facility at the SUE “SFTI” in Sukhum (Abkhazia). The paper presents a short review of the main results, which were recently obtained at these facilities.
2. The PF-3 facility

At the PF-3 facility, at the stationary filling of the experimental chamber with the working gas, the modes of operation with the formation of narrow plasma jets were obtained (see Fig. 1). Generally, such modes are achieved using heavy and strongly-radiating gases. In the course of propagation over a distance of about 100 cm, the transversal dimensions of a plasma jet head do not exceed several centimetres (see Fig. 1a). The observed radial distribution of the toroidal magnetic field is consistent with the distribution generated by an axial current of about 3-10 kA, which flows in the paraxial region with a radius of 1-2 cm (see Fig. 1b).

![Figure 1](image-url)

**Figure 1.** a) Schematic of the PF-3 facility and images of the plasma jet taken in the stage of jet formation (bottom) and at a distance of 95 cm from the anode surface (top); the exposure was 12 ns. b) Radial distribution of the toroidal magnetic field at a distance of 35 cm from the anode end.

At a periphery of the plasma stream one can observe magnetic field structures induced by a flow of return currents. In spite of a strong damping of the magnetic field in the course of the jet propagation, for the PF discharges in neon, the plasma jet head remains compact which can be due to the radiative cooling of plasma.

3. The PF-1000U facility

The experiments at the PF-1000U facility, as well as at the KPF-4 facility, were mainly aimed to create different initial distributions of the working gas density. This makes it possible to manage changes in the conditions of the plasma jet propagation in the background plasma.

The PF-1000U facility, which is the Mather-type facility, can operate in the modes with additional puffing of the working gas into the paraxial region of the discharge. The experimental setup is shown in Fig. 2.

The experiments were carried out at discharge energy of 170 kJ, and at the stationary filling of deuterium with an initial pressure of 1.2 hPa. To produce higher gas density in the pinch region, different gases were used for the additional gas puffing: deuterium, helium, neon and their mixtures. Gases were injected through a pulsed valve which was opened about 2 ms before the discharge initiation.
Figure 2. Setup of the PF-1000U experiment performed with the additional gas puffing.

The plasma jet structure was studied at a distance of 40 cm from the anode end using an optical single-frame camera with an exposure of 10 ns. It was observed that the plasma jet structure considerably differed for discharges with the stationary and combined (stationary + additional) gas puffing (see Fig. 3). In the second case, the compact plasma structures with dimensions of several centimetres formed. Signals of the magnetic probes showed that the axial current flowed through these plasma structures. A complicated funnel-like shape of the shock front might be caused by the reverse currents at a plasma jet periphery.

![Diagram](image)

Figure 3. Frame images of a plasma jet taken at a distance of 40 cm from the anode end: a) the stationary filling of deuterium at the initial pressure of 1.2 hPa; b) the combined filling of deuterium at the initial pressure of 1.2 hPa with the additional injection of a gas mixture (deuterium (75%) and neon (25%)). The magnetic probe which recorded the azimuthal magnetic field is also seen in the images.

The magnetic field damping due to the dissipation of the axial current was observed in the course of propagation of the plasma jet along the axis. In the case of the stationary deuterium filling, only the shock wave front is seen in the image. However, the magnetic probe recorded the appearance of the
magnetic field behind the front of the shock wave, which is induced by the axial current. Evidently, the plasma parameters achieved in this case were insufficient for the visualization of the jet core.

The plasma density at a distance of 57 cm from the anode end was estimated from the Stark broadening of spectral lines. It occurred to be $(0.4 - 3.7) \times 10^{17} \text{ cm}^{-3}$ and depended on the initial gas distribution and delay time between the spectrum registration and the plasma jet generation. The electron temperature of the jet plasma amounted to about 5 eV, and the density of background plasma was about $1.5 \times 10^{15} \text{ cm}^{-3}$ [6].

4. The KPF-4 facility

The KPF-4 facility can operate in the mode with the pulsed injection of the working gas, which differs from that used at the PF-1000U facility, because it provides an increased gas density near the insulator surface. The working gas is puffed using a fast valve equipped with 36 nozzles, which are distributed symmetrically around the cathode disk and directed towards the insulator surface. The gas is puffed after preliminary pumping the experimental chamber down to the pressure of about $10^{-2} \text{ hPa}$. Measurements performed using electrodynamic pressure sensors showed that the optimal time delay between triggering the gas valve and the discharge initiation is 5-6 ms. At this delay time, the pressure near the insulator and in the acceleration channel amounts to $\geq 1 \text{ hPa}$, which is sufficient for the development of the discharge, although the gas pressure in the region of the plasma jet propagation is low (much lower than 1 hPa). Thus, at some distance from the anode end, the conditions of high “density contrast” are achieved (i.e. the ratio of the plasma jet density to the background gas density increases). In these experiments as opposed to the experiments with stationary filling of the vacuum chamber, the plasma jet propagated without considerable deceleration (see Fig. 4).

Figure 4. Deceleration of the plasma jet in the KPF-4 facility operating under various conditions: at the stationary pressure and with additional gas puffing.

In experiments on localization of the magnetic field inside the plasma jet, a comparison between the magnetic probe signals and optical streak images was performed. It was shown that the magnetic field captured by the plasma jet is localized in the regions with weak optical emission from plasma, i.e., in the so-called “magnetic bubbles”.

5. Conclusions

In the experiments performed at three PF facilities with different configurations and systems of the working gas supply, we observed the similar processes of plasma jet generation in a wide range of
experimental conditions. In laboratory experiments, plasma jets with velocities up to \(10^7\) cm/s and the Mach numbers of M = 2–10 were observed. These parameters are comparable to those of the astrophysical jets. The obtained data made it possible to compare the main dimensionless parameters. The hydrodynamic and magnetic Reynolds numbers achieved in the experiments, as well as the Péclet numbers, are much higher than 1, similarly to these parameters of the astrophysical jets. It may be the reason for using the PF facilities for laboratory simulations of astrophysical jets, because the MHD equations (which describe laboratory and astrophysical plasma jets) can be scaled up in space and time.

An important feature of the described experimental systems is the possibility of studying stability of the plasma jets in the course of their propagation over large distances at different parameters of background plasma.

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