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# LABORATORY SIMULATION OF ASTROPHYSICAL JETS WITHIN FACILITIES OF PLASMA FOCUS TYPE

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A laboratory simulation of astrophysical processes is one of the intensively developed areas of plasma physics. A new series of experiments has been launched recently on the Plasma Focus type facility in NRC Kurchatov Institute. The main goal is to study the mechanisms of the jet stabilization, due to which it can propagate at distances much greater than their transverse dimensions. The experiments with stationary gas filling revealed regimes in which a narrowly collimated plasma jet was formed, the head of which was no wider than several centimeters at jet propagation distances of up to 100 cm. The PF-1000 (IFPiLM, Warsaw, Poland) and KPF-4 (SFTI, Sukhum, Abkhazia) experiments are aimed at creating profiled initial gas distributions to control the conditions of plasma jet propagation in the ambient plasma. Estimations of the dimensionless parameters, i.e. the Mach, Reynolds, and Peclet numbers which were achieved during the experiments, showed that the PF-facilities can be used for the YSO jets modelling. The future experiments, which can allow one to understand the nature of the stable plasma ejections observed in many astrophysical sources, are discussed.

*Keywords*: astrophysical jets, laboratory simulation

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## 1. Introduction

Laboratory simulation of astrophysical processes is one of the intensively developed areas of plasma physics. The obvious complexity of the theoretical simulation of the astrophysical objects is related to the absence of the targeted experiments, which allow one to observe the system response by varying the physical parameters. In recent decades, such experiments have been replaced by numerical simulation which yielded important results. At the same time, a lot of interesting astrophysical phenomena, including nonrelativistic ejections from the young stars, can be simulated in a laboratory experiment with observation of certain similarity laws.[1,2] Such an approach is reasonable since the MHD equations, which govern both the astrophysical plasma jets and the laboratory plasma flows, permit the spatial and temporal scaling.

Considerable progress in simulating the astrophysical processes has been achieved in recent decades due to the appearance of a whole group of new facilities with high energy density, which were developed within the framework of the program of inertial controlled fusion, in particular, the modern Z-pinch systems[3] and high-power lasers.[4] The obvious advantages of laboratory modeling are the ability to actively control the parameters of the experiment, high repeatability, and well-developed diagnostic base. In addition, it is possible to model the dynamics of the process and phenomena that are not available for direct observation. In particular, interesting results were obtained on a high-power laser in the LULI laboratory (Ecole Polytechnic), where it was shown that the superimposition of an external poloidal magnetic field can provide effective collimation of the plasma flow.[5] There are well-known studies of recent years on the Z-pinch installation MAGPIE (Imperial College London, Great Britain), which simulated some possible mechanisms of jet formation, the interaction of a supersonic, radiatively cooled plasma jet with an ambient medium and a number of other effects.[6,7]

Plasma Focus (PF) is a device, which operating principle is also based on the Z-pinch effect. At the same time, installations of this type have a number of preferences, which allow us to arrange the original experiments aimed at modeling the plasma outflows from young stellar objects (YSO). In this paper, we substantiate the applicability of these facilities for such modeling, list the main results obtained and formulate a program for further research.

## 2. Plasma Focus

PF is well known as a source of intense plasma flows, which are widely used in various fields of science and technology, such as radiation material science, modification of materials, etc. Plasma flow is formed in the stage of pinching, which lasts several hundred nanoseconds, in the pinch area with a diameter of approx. 1 cm and a length of (3-5) cm. Two most popular PF systems are known, which differ in the geometry of the discharge system: Filippov-type[8] and Mather-type[9] systems. The principal scheme of their operation is shown on Fig. 1.

After the preliminary pump-out, the chamber is filled with working gas (hydrogen, deuterium, helium, neon, argon, and their mixtures depending on the formulated tasks) under a pressure of a few Torr. When the spark gap switches on, a high voltage of power supply (condenser bank) is applied between the anode and the cathode, which leads to a breakdown of the working gas. The resulting plasma current-carring sheath (PCS) moves under the action of the Ampère force toward the discharge system axis, where the plasma pinch occurs. The pinching is accompanied by a drop in the discharge current, and accordingly the appearance of a sharp dip in its derivative.

In our opinion, the scheme of the experiment with PF has a number of advantages. First of all, there is the possibility to investigate the dynamics of the flow propagation in the ambient plasma at sufficiently large distances, more than two orders of magnitude greater than its initial transverse size. The presence of the ambient plasma in itself is an important factor that allows us simulating the interaction of the flow with the external environment. Moreover, the use of both stationary filling the working gas into the vacuum chamber and mode with gas-puffing and their combinations provides ample opportunities for the creation of various profiled gas distributions. This allows us modeling the density contrast effect (the ratio of the flow density to the density of the ambient plasma) on the jet dynamics. The use of various working gases, including strongly radiating, allows us investigating the role of radiation cooling in collimation and confinement of the jet. Finally, sufficiently large spatial dimensions of the flow (in comparison with the laser and Z-pinches experiment) made it possible to use magnetic probe techniques and allowed to investigate the distribution of magnetic fields.

We deliberately did not concentrate on the mechanisms of flow generation, because we understand that they can differ significantly from those in astrophysics. However, the formed jet propagates then in the interstellar gas, and it is quite accessible for the simulation. Therefore the main our goal is to study the mechanisms of the jet stabilization, due to which it can propagate at distances much greater than its transverse dimension.

A new series of experiments devoted to the astrophysical jets simulation has been launched recently on the PF-3 facility in NRC Kurchatov Institute.[10] The key difference of our experiments was the possibility of studying the process of propagation of jet plasma flows. For this PF-3 facility has been upgraded. A new

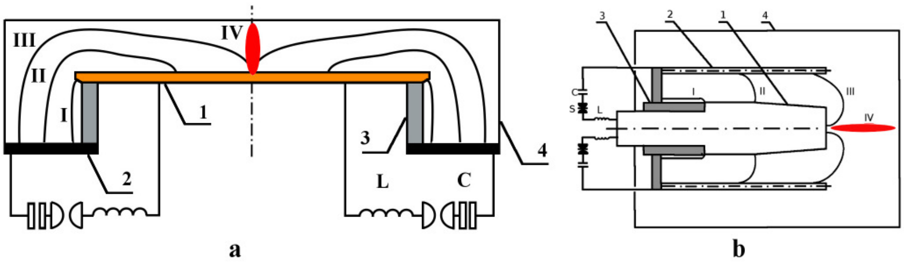


Fig. 1. Principal scheme of plasma focus operation: a) Filippov-type ($D/L \geq 1$), b) Mather-type ($D/L \ll 1$): 1 – anode, 2 – cathode, 3 – insulator, 4 – vacuum chamber, – power supply, L – external inductance, S – spark gap, I – break-down phase; II – run-down phase; III – dense plasma focus phase, IV — supersonic plasma outflow

three-section diagnostic drift chamber was designed, which allowed one to measure the jet and the ambient plasma parameters at distances of up to 100 cm from the plane of the anode, which was conventionally assumed to be the flow generation region (see Fig. 2).[11]

It was found that the compact plasma jets moving along the axis occur at the stage of the pinch decay and developing the MHD instabilities (Fig.3).[11–13] The initial jet velocity, determined from a series of successive snapshots in a frame mode, $V_0 \geq 10^7$ cm/s, regardless of the operating gas used. This velocity is close to the velocity of plasma outflows from young stars and exceeds the velocity of the PCS lifting in the axial direction under the action of Ampère forces. After a certain moment of time, the flow breaks away from the main current sheath and from the pinch and begins to live their lives, regardless of them.

One of the main obtained results is the finding the regimes with the formation

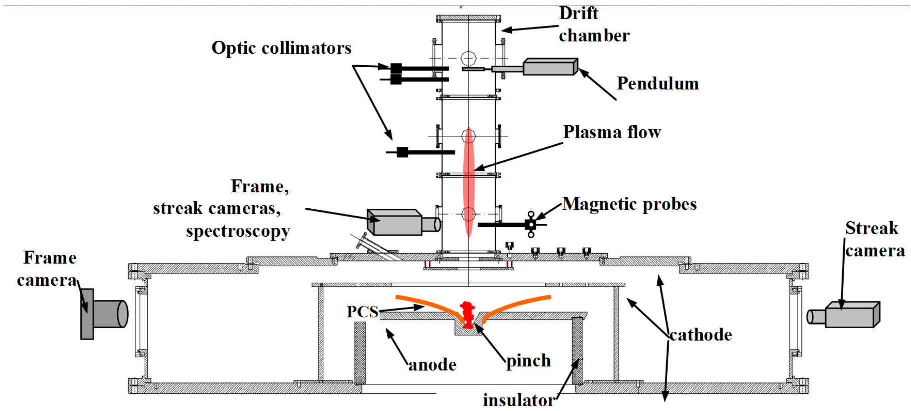


Fig. 2. Scheme of the PF-3 experiment

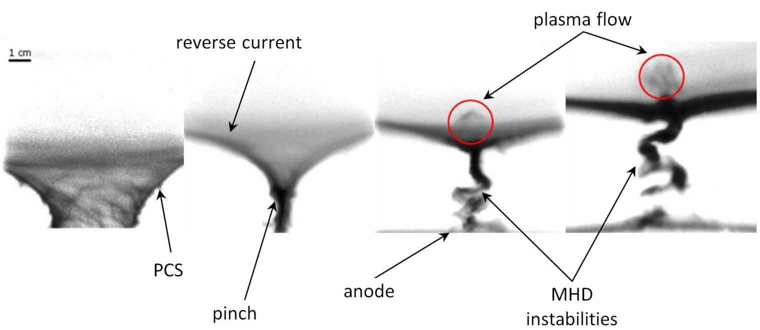


Fig. 3. Plasma-flow formation (from left to right): the stage of convergence of the plasma-current sheath to the axis, the pinch stage and the stages of the plasma flow formation. The pictures were obtained with optical frame cameras, exposure time is 12 ns

of plasma object, preserving its compact size when spread over large distances.[11,14] The transverse dimension of the flow head does not exceed a few cm at propagation distances more than 100 cm (Fig. 4).[13,15] This implies that there are mechanisms for stabilizing/confining the plasma flow, which was the subject of our further research.

First of all, it was necessary to make sure that the streams generated in the PF discharge could be used for modeling the jets from YSO. As is known, the key properties of astrophysical outflows are the presence of a regular longitudinal magnetic field, longitudinal electric current, as well as axial rotation. Finally, it was necessary to show the correspondence of the basic dimensionless parameters to the known scaling relations. To this end, a series of studies was carried out, including measurements of plasma parameters, flow velocity, magnetic fields, etc.

Measurements of density and temperature were performed using the spectral technique.[16–18] In the experiments with helium and neon, the flow density determined by the Stark broadening at the distance of 35 cm from the anode plane (the first section of the drift chamber) was $(2-4)\times10^{17}$ cm$^{-3}$, the electron plasma temperature of the jet was $(2-8)$ eV. The concentration of the ambient plasma was $\sim (2-4)\times10^{16}$ cm$^{-3}$. At a distance of 65 cm from the pinch, the concentration of the ambient neon plasma was outside the limits of spectral equipment registration: $N_{\mathrm{i}} < 10^{16}$ cm$^{-3}$. The maximum electron concentration in a jet is $(0.5-2)\times10^{17}$ cm$^{-3}$, which is lower than at a distance of 35 cm. However, the density reduction can be associated not only with the divergence of the flow, but also with a decrease in the degree of ionization due to plasma cooling (the electron temperature of the plasma jet at a distance of 65 cm is $T_{\mathrm{e}} \sim 1$ eV). The latter conclusion is confirmed by data from frame cameras, showing the weak divergence of the flow (Fig. 4).

As was already noted, the initial flow velocity in the laboratory experiment was similar to the velocity observed in the plasma outflows from YSO. The flow dynamics in different gases were studied using optical collimators, which record the radiation from a small solid angle along the diameter of the chamber.[11,19] The presence of the ambient plasma largely determines the evolution of the plasma jet when it moving along the system axis. The change in the flow velocity can be approximated by an

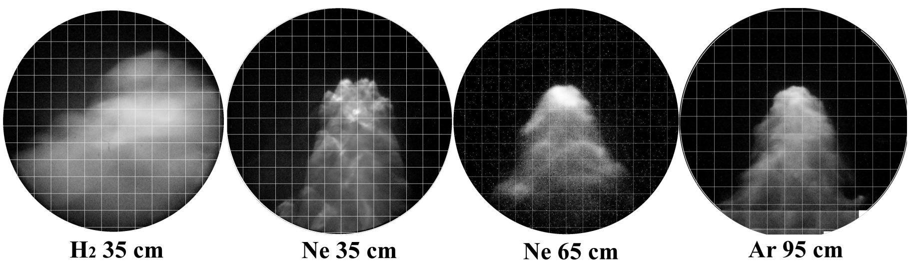


Fig. 4. Frame camera pictures of plasma flow front at different distances from the anode plane and at operation with different gases. Scale is 1 cm

expression $V = V_0 \exp(l/l_0)$, where $V_0$ is the initial velocity, $l_0$ is the braking length of the flow. It was shown that $l_0$ strongly depends on the working gas. At the same time, the initial velocity weakly depends on the type of the gas and corresponds well to the velocity determined by the frame cameras at the stage of the jet formation.

Finally, with the help of magnetic probes, the distribution of magnetic fields has been studied. Several modifications of magnetic probes are made for measurements: N-channel magnetic probe for measurements the radial distribution of the azimuthal component of the magnetic field and 4-channel ($B_z, B_r, B_\varphi$, optic) probe for measurements of three components of the magnetic fields and optical radiation of plasma (with photomultiplier). It was shown that the plasma flow moves with the frozen magnetic field of the order $(1-10)$ kG. Obtained radial distribution can be explained by the axial current in $(1-10)$ kA flowing in the zone near the axis with the radius of $(1-1.5)$ cm.

The estimations of key dimensionless parameters such as Mach number, Reynolds (both hydrodynamic and magnetic) and Peclet number made on the basis of the obtained data (Table 1) showed that the PF- type facilities really can be used to simulate the jets from YSO. This allowed us to proceed to the study of other properties of the outflows, which can be modelled with the help of PF installations.

Table 1. Key dimensionless parameters

| | YSO | | PF-3 (35 cm above the anode) |
|---|---|---|---|
| Peclet | $10^{11}$ | $> 1$, convective heat transfer | $> 10^7$ |
| Reynolds | $10^{13}$ | $\gg 1$, the viscosity is important | $10^4 - 10^5$ |
| Magnetic Reynolds | $10^{15}$ | $> 1$, magnetic field is frozen | $\sim 100$ |
| Mach ($V_{\rm jet}/V_{\rm cs}$) | $10 - 50$ | $> 1$, the jet is supersonic | $> 10$ (for Ne and Ar) |
| $\beta$ ($P_{\rm pl}/P_{\rm magn}$) | $\gg 1$ near source $\ll 1$ at 10 AU | | $\sim 0.35$ (for Ne and Ar) |
| density contrast ($n_{\rm jet}/n_{\rm amb}$) | $> 1$ | | $1 - 10$ |

First of all, the influence of ambient gas was investigated. For this purpose the experiments with different variants of gas-puff injection were performed on facilities PF-1000 (Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland) and KPF-4 Phoenix (Sukhum Physical Technical Institute, Sukhum, Abkhazia). On the PF-1000, after the initial filling the chamber with deuterium (0.9 Torr), there was applied an additional injection of a chosen gas (deuterium, helium, neon or their mixtures) along the electrode-axis, which influenced on the pinching, generation of plasma streams and their propagation through the ambient gas.[15,21] The plasma density was estimated from the Stark broadening at a distance of (27-57) cm from the end of the anode, which amounted to $(0.4-4.0)\times10^{17}$ cm$^{-3}$,[21] which is close to the values obtained on the PF-3 facility. The electron temperature was estimated as $3-5$ eV. At modes with gas-puffing, compact plasma structures were formed with dimensions of several cm (Fig. 5). Signals from magnetic probes showed that inside those plasma structures there were flowing some axial currents.[15] A complicated form of the plasma jet front might be caused by return currents which could flow at a plasma stream periphery.

In the KPF-4 device we realize the operational mode with the pulsed injection of the working gas with increased gas density near the insulator surface and low gas pressure in the region of the plasma jet propagation.[15] Thus, the necessary conditions are provided for the qualitative development of the discharge, on the one hand, and the possibility to change the "contrast" in the flow propagation area by changing the delay between the opening of the valve and the initiation of the discharge, on the other hand.[22] Note that in this case it was possible to simulate decreasing the density of the ambient plasma with a distance from the "central engine", which takes place in astrophysical sources. The experiments showed that in such a case, in contrary to that when the chamber is filled up to the stationary pressure, the plasma stream can propagate without considerable slowing down. In addition, measurements with magnetic probes indicate that the magnetic field is concentrated mainly in the region with weak luminosity in the optical range, in the so-called "magnetic bubbles".[23]

An important direction that can be developed in the scheme of the plasma-focus experiment is the study of mechanisms for stabilizing the plasma flow, allowing it to spread over long distances while maintaining compact transverse dimensions. First of all, the analysis of the results obtained in experiments with various gases shows the significant effect of the radiation cooling. Compact plasma formations at a large distance from the flow generation area were obtained in experiments with argon or

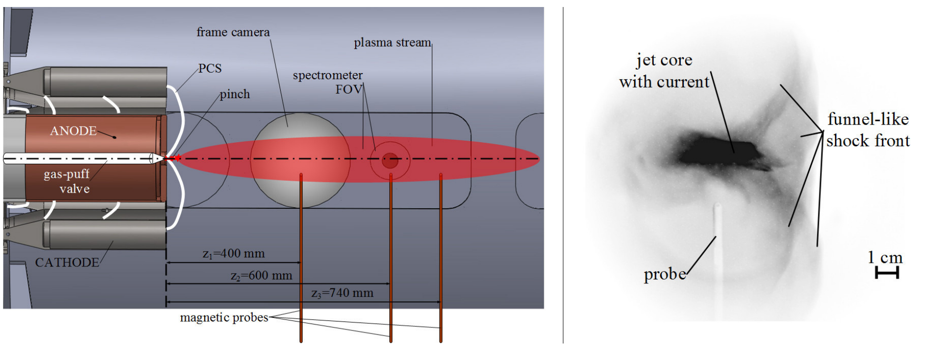


Fig. 5. a) Scheme of the PF-1000U experiment with the use of the additional gas injection. b) Frame picture of a plasma flow at a distance of 40 cm from the anode outlet at the initial deuterium pressure of 1.2 hPa and the additional injection of a mixture of deuterium (75%) and neon (25%).[15]

neon at PF-3 facility (Fig. 4), either with additional neon injection into the pinching area on the PF-1000 facility (Fig. 5).

Finally, another significant result is the fact that the observed radial distribution of the azimuthal magnetic field corresponds well to the longitudinal current of $\sim 10$ kA flowing in the axial zone, in the core of the flow.[13,20,24] It is shown that the field distribution has the form $B \propto r$ in the region $r < R_{\rm core}$ and $B \sim 1/r$ in the region $r > R_{\rm core}$ (Fig.6), which is well consistent with the known theoretical models. Two important conclusions can be drawn from this. First, the estimates show that the magnetic field created by this current can be sufficient to ensure the Bennett equilibrium of the plasma. In this case, the stable-state duration of the jet should be determined by the time of decay of the currents circulating in the plasma. Second, if the axial current is present, it should be closed on the periphery.

In particular, from the results of experiments at the PF-3 facility it follows that the radius of the reverse current at a distance of 35 cm from the anode is $< 10$ cm [24]. The study of the distribution of the reverse current depending on the parameters of the experiment is one of the main immediate tasks.

## 3. Conclusion

Thus, it was shown that the plasma focus in the stage of the pinch formation creates a plasma flow propagating along the facility axis with the velocities large than 100 km/s, i.e., with velocities close to the one observed in the real jets from young stars. It is important that the flow is supersonic as in real jets. The values of the main dimensionless parameters achieved in the experiments allow us to consider the PF-type facilities as an effective tool for simulation physical processes in the jets of young stars. We obtain the conditions when the plasma flow remains compact propagating over distances far exceeding its transverse size. This fact indicates the excess of the longitudinal jet velocity over the transverse velocity of its expansion. This opens the possibility of modeling and studying the mechanisms of stabilization.

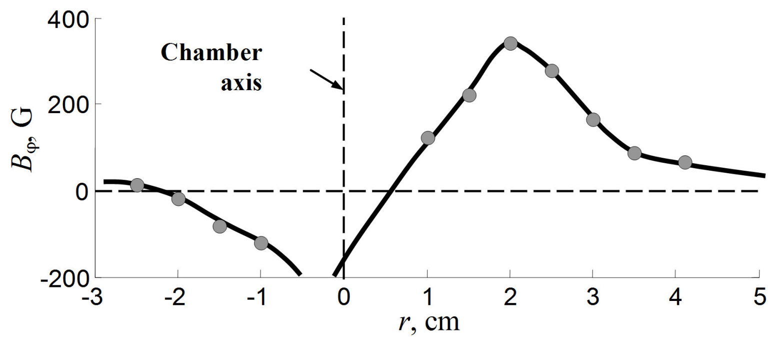


Fig. 6. Radial distribution of the azimuthal magnetic field in the plasma jet on PF-3 facility at a height of $z = 35$ cm from the anode plane.

It also was found that many other properties of the experimental flows corresponds to the main characteristics of young stars jets, for example, the presence of a longitudinal current determining the predominance of the toroidal magnetic field. However, the nature of the magnetic field distribution, in particular, the detected rotation of the induction vector,[19, 20] in the conditions of the magnetic field frozen in the plasma may indicate both the rotation of the flow as a whole, and the presence of spiral current structures. Therefore, the question of rotation of the plasma flows requires additional studies.

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