Influence of magnetic field and density of environment on collimation of laboratory jet

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Abstract. In this work a numerical simulation of the propagation of a plasma bunch in the experimental plasma focus facility was carried out to determine the parameters influencing on the value of an opening angle. Both the experiment and the numerical simulations are supposed to have the same dimensionless parameters as astrophysical jets. The dependence of the jet opening angle on the magnitude of the magnetic field and the ratio of the densities of the jet itself and the surrounding plasma was investigated. Due to the obtained results, it became possible to determine the dominant factor responsible for jet collimation.

1. Introduction

An astrophysical jets are plasma outflows emitted as a beam along the axis of rotation of a central massive object. Collimated outflows have been detected in such compact objects as active galactic nuclei, microquasars, pulsars, young stars and even brown dwarfs [1]. The fact that such process occurs in so many different objects, having different spatial and energetic scales, tells us about a resembling nature of the formation and propagation mechanisms of jets.

The construction of theoretical models is difficult due to the lack of data obtained from astrophysical observations. In this regard attempts to recreate astrophysical condition using laboratory experiments [2, 3, 4] are getting important. Those experiments allow to reach dimensionless parameters of plasma, which are near to astrophysical parameters of jets of young stars. At the same time, within the framework of laboratory modeling, we may speak only about reproducing of propagation of astrophysical jets, but not about their producing, because the gravitational force, playing a key role in formation of outflows, cannot be reconstructed.

At the moment, the phenomenon of self-collimation of elements of jet emissions has already been considered [5, 6]. But so far the structure of the first departing bunch has not been studied in more detail. It also remains open to the question of what affects the collimation of a jet to a greater degree: the magnitude of the toroidal magnetic field or of environmental resistance. The toroidal magnetic field compresses the plasma clot due to the so-called pinch effect, while the plasma surrounding the supersonic jet promotes to flow of the substance of the jet into the shock wave, destroying the clot. The aim of this work is to identify such a dominant parameter.
The investigation of the laboratory jets allow us the unique chance to study large scale astrophysical processes «in vitro» usually having a detail picture of the process. Therefore this work focused on the investigation of jets, produced by PF-3 facility. PF-3 is Filippov-type plasma focus facility, it is known as a source of intensive plasma flows. Recently the wide cycle experiments were undertaken on studies of plasma flow parameters [7, 8, 9]. These experiments show that PF-3 facility may be effectively used for laboratory modeling astrophysical jets.

2. The opening angle determination

As it has been shown in [6] Reynolds number, magnetic Reynolds number and Peclet number are much greater than one for both astrophysical and laboratory jets. It means that the flow may be describe in frames of ideal hydrodynamics by these equations:

$$\frac{\partial \rho}{\partial t} = -\text{div} \, \rho \mathbf{v},$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v}, \nabla) \mathbf{v} = -\nabla p - \frac{1}{4\pi} \mathbf{H} \times \text{rot} \mathbf{H},$$

$$\frac{\partial \mathbf{H}}{\partial t} = \text{rot} (\mathbf{v} \times \mathbf{H}),$$

$$\text{div} \mathbf{H} = 0,$$

$$\frac{\partial e}{\partial t} = -\text{div} \left( \mathbf{v} \left( e + p + \frac{\mathbf{H}^2}{8\pi} \right) - \frac{\mathbf{H} (\mathbf{v} \cdot \mathbf{H})}{4\pi} \right) + S,$$

$$p = (\gamma - 1) \left( e - \frac{\rho \mathbf{v}^2}{2} - \frac{\mathbf{H}^2}{8\pi} \right),$$

where $e = \rho e + \rho \mathbf{v}^2/2 + \mathbf{H}^2/8\pi$ is full internal energy, $S$ is a rate of volume cooling of laboratory plasma, calculated with PrOpacEOS program [10].

For solving these equations we have used our own Godunov type scheme in two dimensions cylindrical coordinates with the well proven solver HLLD [11]. We performed the calculations supposing that the working gas is argon. As initial conditions we chose cylindrical shape of the jet with 2 cm radius and 2 cm height. Temperature of the ambient plasma have been taken as 1 eV, concentration is $2.5 \cdot 10^{16} \text{cm}^{-3}$. In case of this choice of thermodynamic values all observed parameters are achieved after several steps of calculation. Magnetic field has been taken like measured: it grows from zero to jet border linearly and decrease from jet border like $r^{-1}$ [9].

The simulation process was launched at different values of the initial parameters. The initial value of the magnetic field $B$ and the ratio of the density of the bunch to the density of the environment was varied. The ratio of densities varied from 1 to 11 with 0.5 step and the magnetic field from 1 to 10 kG with step of 0.5 kG. After that, a point corresponding to the maximum value of the radial component of the density gradient was being found. Knowing the coordinates of this point, we determined the values of the opening angle. The figure 1 shows a diagram showing the values of the opening angle at jet flying 50 cm. The typical dynamic of jet propagation with values: $B = 4.5 \text{kGs}$ $n_{jet}/n_{ambient} = 10$ is presented at figure 2.

From this diagram it can be seen that the key parameter affecting jet collimation is the value of the ratio of densities. There is also a clear line of separation between areas with large and small angles, which indicates the presence of values of the magnetic field critical for collimation and the ratio of densities. Thick lines indicate the areas in which the angles correspond to the experimental values, as well as the areas of possible values of the ratio of densities and magnetic field. You can see that there is only one area that satisfies both conditions: $B = 3.5 - 4.5 \text{kGs}$ and $n_{jet}/n_{ambient} = 5 - 5.5$. 


3. Conclusions
In this paper, a diagram for the opening angles of the laboratory jets was constructed. From the diagram it can be directly seen that the main parameter affecting the collimation of a jet is the ratio of the concentrations between the spreading clot and its environment. A comparison was made with the available experimental data from the PF-3 installation. In the future, to more accurately determine the parameters, it is planned to increase the size of the calculated grid for the angle chart.
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