Study of Momentum and Energy of Plasma Flow Generated in Plasma Focus Discharge

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Abstract—The paper is devoted to the study of the plasma flows generated in the plasma focus discharge at the PF-3 facility at its propagation in the ambient medium up to distances of ~100 cm and, in particular, the study of the dynamics of such important parameters as velocity, total energy, and momentum. Momentum and energy measurements were made using a ballistic pendulum, which could be used simultaneously in the calorimeter mode. Optical collimators are used to measure the flow velocity. It is shown that, in experiments with argon at a distance of 65 cm, the energy density of the incident flow of ≥10 J/cm² is observed. The total number of particles in the flow and the total mass of the flow are calculated.

Keywords: plasma focus, plasma flow, plasma diagnostics, calorimetry, laboratory simulation

INTRODUCTION

One of the important features of plasma focus (PF) systems is the generation of intense plasma flows, which was discovered at the early stages of research [1]. However, in connection with the initial orientation of research on the problem of Controlled Fusion, the study of this phenomenon was given insufficient attention. At the same time, the outflow of plasma from the pinch zone can have a significant impact on the pinch dynamics and the final emission characteristics of the PF. In addition, the practical application of these flows is actively growing. In particular, they are used to study the interaction of plasma with the surface [2, 3] and for modification of structural materials in order to give them new properties, including the production of nanocoatings [4–7] and a number of other applications. Obviously, the requirements for plasma flows when used in various fields of science and technology may vary significantly depending on the tasks. However, the flows generation mechanisms and their parameters are not well understood, making it difficult to optimize plasma flows in order to increase the efficiency of various practical applications.

One of the interesting fields of application of these flows is the laboratory simulation of a wide range of phenomena in the Universe. In particular, plasma flows at the PF-3 facility at the National Research Center Kurchatov Institute were used to simulate the interaction of the solar wind with the Earth’s magnetosphere [8]. The results of recent experiments [9–15] showed that they are also an effective tool for laboratory simulation of one of the variants of astrophysical jets—outflows of young stellar objects (YSO). In experiments on the facilities PF-3 [9–12, 14, 15], PF-1000 (Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland) [13, 14], and KPF-4 (SNPO SFTI, Sukhumi, Abkhazia) [14, 15], it was demonstrated that compact plasma formations can extend over considerable distances from the place of generation (~1 m), significantly exceeding their transverse dimensions. To determine the nature of the jet emission, the relation between the electromagnetic field energy flux density and the kinetic energy density of particles is essential. To estimate this relationship, data on the energy characteristics of the flow are necessary.

In addition, in contrast to direct astrophysical observations and mainly steady-state theoretical models based on them, in laboratory simulation, it is possible to study the dynamics of the formation and propagation of a plasma flow in the background plasma. In the Universe, the ratio of the plasma flow density to the density of the background plasma (the so-called “contrast”) can vary within fairly wide limits. The interaction of the flow with the background plasma leads to the appearance of a number of effects, such as the formation of a head shock wave and the development of hydrodynamic instabilities. In particular, the flow can be inhibited and its energy dissipated.
The main goal of this work was to measure the energy and momentum of the plasma flow during its propagation in various gases.

**SCHEME OF EXPERIMENT**

The experiments were performed on a PF-3 facility, representing a plasma focus with a Filippov-type electrode geometry. Within the laboratory simulation program, the facility was upgraded: a three-section drift chamber was manufactured, which allows the studies of the plasma flow dynamics up to 100 cm from the anode (Fig. 1). Each section has a set of diagnostic windows designed for various diagnostics, and the interchangeability of sections makes it possible to study the flow parameters at a distance of 35, 65 and 95 cm (central cross sections of each window). One of the sections is designed for measurements using a ballistic pendulum. Figure 1 shows an example of the possible location of diagnostic equipment.

A detector based on the spring pendulum principle (Figs. 2 and 3) was manufactured to measure the plasma flow momentum. The dimensions of our detector were selected on the basis of the design features of the corresponding section of the drift chamber. When the spring bend angle is $90^\circ$ between its ends, the period of free oscillations was $\sim1.2$ s. The developed design makes it possible to change the sen-
sitivity of the pendulum by more than a factor of 30 by changing the thickness and material of the disk and, respectively, its mass and selecting the appropriate spring.

The ballistic pendulum calorimeter was installed in the section of the transient-time chamber with a window of 100 mm through a vacuum gate. On the opposite diagnostic port, behind a glass with a diameter of 100 mm, there is a camera recording the movements of the pendulum. For a more accurate measurement of the amplitude of oscillations two lamps are fixed on the disk of the pendulum, which also give a clear spatial scale (Fig. 4).

In the perpendicular direction, there are two ports with vacuum slide gates with diameter 50 mm, through which optic radiation was recorded by light collimators and shooting was taken with a frame camera. One of the ports was also used to illuminate the pendulum when tuning it.

The pendulum was calibrated using test bodies. A copper target disk with a diameter of 8.6 cm and a thickness of 0.9 cm was used. The total mass of the oscillating unit of the pendulum was 660 g. A plasticine ball weighing 10 g, freely falling from a height of 13 cm, was used as the test body. The ball velocity when it touched the pendulum was

$$V = (2ah)^{1/2} = 160 \text{ cm/s},$$

and the momentum was

$$P = mV = 1600 \text{ g cm/s}.$$ To measure the amplitude of oscillations of the pendulum, video recording was used with a Canon EOS 650D camera at a frequency of 60 frames per second followed by a shooting sheet. The resulting calibration sensitivity for the completely inelastic interaction was $2.2 \times 10^3 \text{ g/s}$.

The flow energy was measured by the same detector in the calorimeter mode. To this end, a thin (0.5 mm) copper disk $6$ (see Fig. 2) with a copper-constantan thermocouple is attached to the main disk of the ballistic pendulum, the pins of which are held inside the supporting rod $5$ (see Fig. 2) made as a tube and brought out through a vacuum-tight connector. The receiving disk was fastened with screws and nuts in front of the main disk of the pendulum at a distance of 4 mm from it. Mounting nuts were fabricated of stainless steel in order to reduce heat leakage from the receiving disk. The measuring thermocouple is formed by a copper receiving disk, galvanically connected to a pendulum and a constantan conductor, connected at one end to the center of the calorimeter (on the reverse side of the receiving disk) and at the other to the output connector. An M95 magnetoelectric microammeter was used to measure the EMF of the thermocouple.

Estimates of the cooling time of the receiving disk of the calorimeter, taking into account the thermal conductivity of the working gases and fastening elements, showed that it is large enough (~11 s for argon and ~8.5 s for hydrogen) for reading the microammeter. The output signal was recorded a few seconds after the discharge, so the electrical interference also did not affect the accuracy of the measurements. The problem of the temperature equalization on the receiving disk does not matter much, because the cross section of the plasma bunch is comparable with the size of the receiving disk.

The experiments were carried out at a charging voltage of 7–10 kV and a discharge energy accordingly of 220–450 kJ.

### Table 1. Section 2 (65 cm). Argon, 1.9 Torr

| $U$, kV | $\Delta T$, K | $E, J$ (therm.) | $2A$, cm | $P$, kg cm/s | $E, J$ (mech.) |
|---------|--------------|----------------|---------|--------------|----------------|
| 8       | 26           | 225            | 9.6     | 10.5         | 500            |
| 8       | 29           | 250            | 11.2    | 12.3         | 615            |
| 9       | 53           | 460            | 12.0    | 13.2         | 660            |
| 9       | 48           | 416            | 12.9    | 14.2         | 710            |
| 10      | 53           | 460            | 14.1    | 15.5         | 775            |

### Table 2. Section 2 (65 cm). H$_2$, 3 Torr

| $U$, kV | $\Delta T$, K | $E, J$ (therm.) | $2A$, cm | $P$, kg cm/s | $E, J$ (mech.) |
|---------|--------------|----------------|---------|--------------|----------------|
| 9       | 16.4         | 142            | 1.7     | 1.9          | 243            |
| 9       | 16.1         | 140            | 1.7     | 1.9          | 243            |
| 9       | 20.8         | 180            | 2.4     | 2.6          | 343            |
| 10      | 16.7         | 145            | 1.8     | 2.0          | 260            |

### Table 3. Section 3 (95 cm). Argon, 1.6 Torr

| $U$, kV | $\Delta T$, K | $E, J$ (therm.) | $2A$, cm | $P$, kg cm/s | $E, J$ (mech.) |
|---------|--------------|----------------|---------|--------------|----------------|
| 7       | 10           | 87             | 4.7     | 5.2          | 103            |
| 8       | 12           | 104            | 4.7     | 5.2          | 103            |
| 9       | 13           | 113            | 6.7     | 7.4          | 147            |
| 10      | 14           | 122            | 6.0     | 6.6          | 132            |
| 10      | 17           | 148            | 7.4     | 8.2          | 163            |

### Table 4. Section 3 (95 cm). Hydrogen, 2.4 Torr

| $U$, kV | $\Delta T$, K | $E, J$ (therm.) | $2A$, cm | $P$, kg cm/s | $E, J$ (mech.) |
|---------|--------------|----------------|---------|--------------|----------------|
| 7       | 8.5          | 74             | 1.08    | 1.2          | 96             |
| 7       | 6.5          | 57             | 0.84    | 0.9          | 72             |
| 8       | 11           | 96             | 1.06    | 1.2          | 92             |
| 9       | 12           | 104            | 1.45    | 1.6          | 128            |
| 10      | 15           | 130            | 1.34    | 1.5          | 116            |
| 10      | 10           | 87             | 1.18    | 1.3          | 104            |
MEASUREMENT RESULTS

Measurements of the energy and momentum were carried out in two sections of the drift chamber at distances of 65 and 95 cm from the anode plane. The plasma flow energy was estimated in two ways: by the absorbed heat in the calorimeter mode and by calculation from the measured momentum of the plasma flow and its velocity. The momentum of the flow was determined by the magnitude (range) of the deviations of the light bulbs from the equilibrium position. To protect the camera’s matrix from the radiation of the plasma flow, a 1 : 36 diaphragm and filters were used. In this case, only filaments of the incandescent bulbs were recorded, which also increased the accuracy of measuring the amplitude of oscillations. Then a shooting sheet of recording was made and the frames with the maximum deviation were selected (Fig. 5). Since it is difficult to accurately determine the equilibrium position, we measured exactly the range of oscillations. With undamped or weakly damped oscillations, the span almost corresponds to twice the amplitude, the value of which we used in estimating the value of the momentum. Control measurements made with the use of the valve protecting the pendulum from the flow showed that the measurement error caused by the vibration of the facility during the discharge does not exceed 10%.

Several experimental series were conducted in different conditions. The measurement results are shown in Tables 1—4, where \( U \) is the charging voltage of the power source, \( \Delta T \) is the thermocouple reading of the calorimeter, \( E \) (therm.) is the energy measured by the calorimeter, \( A \) is the amplitude of oscillations of the ballistic pendulum, \( P \) is the value of the momentum, and \( E \) (mech.) is the energy of a plasma bunch calculated according to the ballistic pendulum and light collimator data.

Light collimators were used to measure the plasma flow velocity [15]. The collimator consists of two tubes with a length of 38 and a diameter of 1.1 cm. The distance between the axes of the tubes is 1.6 cm. A collimating diaphragm is installed at the inlet and outlet of each tube, as well as inside the tubes. The solid angle of each channel is such that, in the center of the chamber, a region with a diameter of ~3 mm is observed. The outgoing light with the help of two plastic light guides is transmitted to the input of two FEU-30 photomultiplier tubes. Since the centers of channels are separated by 1.6 cm, the time shift between the appearance of signals from each channel make it possible to accurately measure the velocity in this region. For example, it follows from the waveforms shown in Fig. 6 that the delay in the appearance of signals of two collimators is 630 ns, which corresponds to the flow velocity of \( \sim 2.5 \times 10^6 \) cm/s.

The flow velocity depends on the distance traveled by the flow in the drift chamber, on the working gas used, on the discharge energy, and on a number of other factors. Since simultaneous measurements with a light collimator and a ballistic pendulum in one discharge are difficult because of flow perturbations as a
result of its collision with the target disk and the appearance of reflected flows, the velocity was measured in a separate series of experiments. In further evaluations, we used the average (typical) velocity obtained under identical experimental conditions. In our case, these velocities were $2.6 \times 10^6 \pm 20\%$ cm/s and $1.6 \times 10^6 \pm 20\%$ cm/s for hydrogen and $1.0 \times 10^6 \pm 20\%$ cm/s and $0.4 \times 10^6 \pm 20\%$ cm/s for argon in the second and third sections, respectively.

As already noted, the plasma flow energy was estimated in two ways: by the absorbed heat in the calorimeter mode and by calculation from the measured plasma flow momentum and its velocity. There is a difference in the measurement results. So, for experiments with argon, the maximum energy determined by the absorbed heat in the second section (65 cm from the anode plane) was 460 J, and the kinetic energy calculated from the momentum and velocity of the plasma flow was 710 J.

It should be noted here that, in the case of argon, the total energy of the flow is actually determined by the kinetic energy, since the velocity of the flow along the axis considerably exceeds the thermal expansion rate, which results in maintaining the compactness of the flow at large distances (several centimeters in diameter at a distance of up to 100 cm from the anode, Fig. 7). We do not have data on the temperature of the argon or hydrogen plasma at these distances, but measurements made in neon at a distance of 65 cm [16] give values of ~1 eV. It is logical to assume that the argon plasma temperature will be at least no higher than this value. In this case, the directional velocity is several times higher than the thermal one. In the case of hydrogen, the situation is not so unambiguous; however, given the higher directional velocity of hydrogen ions, it can be assumed that, in this case, the kinetic energy prevails over the thermal energy. Thus, the fact that the total energy measured by the calorimeter is less than that calculated from the indications of the ballistic pendulum can be explained by the fact that, on one hand, the calorimeter is not an absolutely black body and gives underestimated values. On the other hand, the ballistic pendulum gives an overestimation, since the impact of the jet is not completely inelastic. In the experiment, reflected flows are observed in the third section, albeit with lower velocities. So, in the example shown in Fig. 8, the time delay of the appearance of the signal from the second collimator with respect to the first one is $\tau_1 = 0.95 \mu s$, which corresponds to the flow velocity of $1.7 \times 10^6$ cm/s. Later we see the appearance of signals from the reflected flow: the signal from the second collimator is ahead of the signal from the first by 1.5 $\mu$s, which corresponds to the velocity of the reflected flow of $1.1 \times 10^6$ cm/s. It should be noted that this decrease in velocity can be due to the inelastic nature of the interaction and the flow deceleration along the span from the observation point (95 cm) to the upper flange of the chamber (110 cm) and back. Since, as already noted, measuring the velocity of both direct and reflected flow directly in the interaction with the pendulum is impossible and, moreover, we do not know the coefficient of “sticking” and the contribution of recycling and other physical processes that affect the
elasticiety of the interaction, its more accurate quantitative analysis is difficult.

It should also be noted that the estimation of the kinetic energy is made by the value of the velocity of the flow front, and not by the average velocity of the particles. It is quite reasonable to assume that the particles of the flow have different velocities, which causes a relatively large length of the bunch. Unfortunately, it is not possible to determine the velocity distribution of particles in the flow within this work. At the same time, the results of previous studies using optical recorders, light collimators, and magnetic probes indicate that the bunch retains its compactness even at large distances. It can be seen in Fig. 8 that the duration of the glow of the main part of the flow, even for the reflected flow, increases slightly. In addition, the use of maximum values of velocity leads to an overestimated value of energy, which does not contradict the previously made conclusion about the estimation of energy from above by this method. 

Fig. 7. Frame camera pictures of the plasma flow in hydrogen (a) and argon (b) at a height of 65 cm and in argon at a height of 95 cm from the anode surface (c) (cell scale of 1 cm).

Fig. 8. Signals of the derivative of the discharge current (—) and of two channels of the light collimator (—, —). Hydrogen discharge, 4.0 Torr, \( U = 10 \) kV, third section (95 cm).

 Apparently, it can be stated that the real value of the flow energy has an intermediate value. For the maximum recorded energy, it is possible to take the value of \( \approx 620 \pm 180 \) J. This energy flow is recorded by a detector with a diameter of 8.6 cm and an area of 58 cm\(^2\). This size is comparable to the lateral flow size observed in the photographs taken with the frame camera (see Fig. 7). Thus, in experiments with argon at a distance of 65 cm, the energy density of the incident flow of \( \geq 10 \) J/cm\(^2\) is observed.

The energy flux density in hydrogen is several times smaller, since, as shown by previous measurements, the particle velocity for argon and hydrogen differs slightly with a large difference in the mass of the flow [15]. The flow energy increases with the discharge energy.

Similar measurements were performed in the third section. The energy content of the flow decreased significantly, which was due to the deceleration of the flow when it interacted with the background plasma. This especially affected the energy of the argon plasma flow, since, as was shown earlier [15], the argon inhibition length is much shorter, especially at large distances.

Using the obtained data on the magnitude of the momentum, one can determine the total mass of the flow. So, for the measured argon flow momentum in the second section of \( \approx 10^4 \) g cm/s at the velocity of \( \approx 10^6 \) cm/s, the total mass arriving at the detector is \( \approx 10^{-2} \) g, which corresponds to the number of particles of \( \approx 1.5 \times 10^{20} \). For a detector with an area of \( \approx 58 \) cm\(^2\), the linear density will be correspondingly \( \approx 2.5 \times 10^{18} \) particles/cm\(^2\). Estimated from the pulse duration of the light collimator, taking into account the plasma velocity, the flow length is \( \geq 10 \) cm, which makes it possible to estimate its density as \( \leq 2.5 \times 10^{17} \). This value corresponds well to the plasma density measured previously by spectroscopic methods at a distance of 35 cm (first section) at the discharge in neon of \( (2–4) \times 10^{17} \) cm\(^{-3}\) [16, 17]. In the second section, the density
was slightly lower \((0.5-2) \times 10^{17} \text{ cm}^{-3}\). It should be noted that the plasma density is determined by the spectral method, while in our calculations the total particle density is estimated. From this, we can conclude that the density of particles in the plasma flow changes insignificantly, which indicates a small divergence of the flow up to a distance of \(~100 \text{ cm}\), which is also confirmed by photographing of the flow using the frame camera (see Fig. 8).

**CONCLUSIONS**

The measurements of energy and pulse allowed us to determine the main energy characteristics of the plasma flow generated in the plasma focus discharge at the PF-3 facility. It is shown that, upon a discharge in argon at a distance of 65 cm from the place of generation, it is possible to obtain flows with energy density \(\geq 10 \text{ J/cm}^2\). The use of two methods for estimating the total energy of the flow showed similar values, which increases the reliability of the results obtained. The flux density estimates made also fit the spectroscopic measurements well. The obtained data can be used both in laboratory simulation of astrophysical jets and to estimate the possible effect of the plasma flow on structural materials in radiation materials science.

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