On the Generation of Plasma Jets in the Kilojoule Plasma Focus Device

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Abstract—Laser–optic methods were used to study the properties of plasma jets generated in the KJ Plasma Focus device. Measurements of the plasma jet velocity were conducted immediately after its appearance. During the first 10 ns, the average velocity is about $5 \times 10^7$ cm/s, which corresponds to energy of 18 keV for the ions of nitrogen, which was the working gas of the PF setup. The jet density and velocity decrease manifold over distance of 2–3 cm from its generation point. The experiments confirm that the main reason of jet generation is the necking of the pinch. It was found that after the pinch decay, a new plasma column appears, which propagates in the axial direction.

Keywords: plasma focus, plasma jet, interferometry

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1. INTRODUCTION

Plasma focus (PF) is one of the first plasma electric discharge devices in which the ideas of controlled fusion were verified starting in the late 1950s [1]. At the same time as Filippov reported a record quantity of neutrons in these discharges, plasma jets propagating from anode to cathode were discovered [2]. Also at the same time, Mather discovered generation of neutrons in discharges of powerful plasma injectors, which are, in essence, plasma jet generators, during their operating on deuterium [3]. Despite their long history, the mechanisms of jet generation in PF remain unclear, despite the wide spectrum of their applications [4–7]. The theories of the origin of the jets in PF were dominated by Filippov’s hypothesis [2, 8, 9] of the so-called cumulative mechanism of their generation. The main source of plasma jet generation was considered to be the conical (noncylindrical) shape of the compressing plasma sheath. However, lately, this hypothesis was subjected to doubts. They were first published in [10], where it was noted that “flows of matter are present (in earlier works, this effect was explained by cumulation, which is not entirely correct), which are not connected to the dynamics of the current-carrying sheath along the axis.” Particular jet generation mechanisms were not considered in [10], and it was assumed that it was “probable that their nature is similar to astrophysical jets generated by stellar objects.” Axial flows of matter (in case of use working gas neon) with velocity $1.3 \times 10^7$ cm/s were recorded, and the authors were certain that their real maximum velocity was higher still at $2 \times 10^7$ cm/s. In experiments, and installation with energy content of several hundreds kilojoules and flat electrode geometry was used, and measurements were carried out using rapid image tubes.

In our work [11] that was carried out at the PF device with energy content of 4 kJ, we used the laser probing method and did not record the generation of the plasma jets either during the convergence of the conical current sheath, or during its compression, or at the pinching stage. The jet appeared later still, at the stage of pinch destruction. This scenario of jet creation agrees with the model of adiabatic compression of the plasma column [12].

Until now, in our experiments, the velocity of the jets was measured at some distance from their generation point, in the working gas, where the jet was already noticeably decelerated [11, 13]. The energy of ions in the jet was recorded at the level of 1 keV for nitrogen ions, but it was obvious that the initial jet velocity would have been substantially higher, if’t were recorded closer to the moment of its generation. In our previous experiments, we used the one-frame variant of laser probing of the discharge. The jet velocity was measured from the difference of positions of its front at known moments in time relative to the specific feature in different pulses. This method was justified given the relatively high repeatability (±10 ns) of the discharge dynamics. Closer to the specific feature, the error of determining the velocity approached 100%. Therefore, we chose the two-frame variant of interferometry in a in the same PF discharge pulse. For this, the probing laser ray was separated in two, one of
which was delayed relative to the other by the controlled difference in optical paths.

Another objective of this work was to trace the discharge evolution after the decay of the pinch and the appearance of the specific feature. Indeed, in our work [11] we determined that at this stage, a new plasma column is created, which rapidly grows upward and overtakes the shock wave. The effect of the new pinch on a sample placed at the discharge axis still has not been studied. Below, we present new results of the study of this plasma formation.

Note regarding the terminology: in our experiments, it would be more correct to call the plasma jet a plasma bunch due to its longitudinal and transverse dimensions being comparable, but the term “plasma jet,” which was introduced by Filippov [2] is more commonly used in literature. We will use both terms.

As is common, we will call the sharp jump on the derivative of the discharge current its specific feature, the skinned plasma current sheath of the discharge is referred to simply as the current sheath, and the neck in the plasma column that appears due to the development of the Rayleigh–Taylor instability we will call the neck.

2. DESCRIPTION OF EXPERIMENT

Experiments were carried out at the “Tulpan” PF-4 installation (Lebedev Physical Institute of the Russian Academy of Sciences) that is an electric discharge device of the plasma focus type with half-spherical electrode geometry. The diameter of the copper anode was of 30 mm and the diameter of the copper cathode was of 50 mm. The total capacity of the capacitor bank was $C = 48 \mu$F, the working voltage of 12 kV was not changed during all the pulses of the installation, the energy of the capacitive storage was of 3.5 kJ, the characteristic current raise time was of 3 $\mu$s, and the maximum discharge current at this voltage was of 0.3 MA. The working gas was nitrogen at a pressure of about 1 Torr.

The plasma was probed by the radiation of the second harmonic of a Nd:YAG laser with energy of about 100 mJ, pulse duration of 5 ns, and wavelength of 0.53 $\mu$m. The laser pulse was divided in two, one of which was delayed relative to the other by mirrors for intervals of 5, 18, and 46 ns of our choice. The interval between the passage of the first ray through plasma and the minimum of the specific feature on the current derivative was determined from the data of the photodiode and the magnetic probe using a Tektronix TDS 3054C oscilloscope with transmission band of 500 MHz.

The plasma focus device was built into one of the arms of a Mach–Zehnder interferometer. The interferograms were recorded by a Canon EOS 650D digital camera (in detail, see [10]). To separate the frames spatially on the CCD matrix of the camera, we installed quartz wedges in the focal plane of the Kaleinar-3B 2.8/150 long-focus lens (Fig. 1).

3. EXPERIMENTAL RESULTS

3.1. Jet Generation

Laser–optic measurements were carried out during the first and second half-periods of the discharge starting from the moment when the current sheath reached the anode's end. In the first half-period, it was found that this moment is ahead of the minimum of the specific feature of the current by 100–150 ns (point 1 in Fig. 2). This point is preceded by a slow linear decrease of the current derivative. Over interval 1–2, the rate of current decrease increases 20 times, which is explained by the sharp increase in the inductance of the conical part of the current sheath (Fig. 3). This shape of the sheath is observed until its closing near moment 2, when it becomes conical. During the entire convergence phase 1–2, no axial plasma ejections are observed. The sharp (additional 10–20 times) increase of the decay rate of the current derivative after moment 2 is accompanied by the radial deceleration of the plasma column and by it taking a cylindrical shape (Fig. 4). At this stage (2–3) as well, no axial flows of plasma were observed. Plasma formations that propagate in the axial direction were recorded after the decay of the pinch and after the minimum on the current derivative (Fig. 5). Current bunches with initial size about one millimeter and
density above \(10^{19}\ \text{cm}^{-3}\) were found that traveled upward along the axis (Fig. 1) from anode at a velocity higher than \(10^7\ \text{cm/s}\). These bunches gave rise to a bell-shaped shock wave that propagated in the working gas above the current sheath similar to [14–17]. With time, the bunches expanded and their density and velocity decreased (Fig. 6).

The jet velocity was calculated starting from the moment when the interference image was recorded relative to the time of the specific feature:

—**specific feature on the current derivative inside the time interval between frames.** The first frame indicated the position of necking. The distance traveled by the jet was calculated from this position to the leading edge of the jet in the second frame. The time of the jet travelling this distance was calculated from the minimum of the specific feature;

—**specific feature on the current derivative before the first frame.** The jet velocity was determined from the difference of positions of its leading and trailing edges in both frames.

The velocities determined by this method were tied to the middle of the mentioned time interval in the figures, i.e., these were the average values of velocities in the given time interval.

When calculating the velocity in the first case, we roughly estimated that the moment of current disruption and the moment of jet generation coincided with the minimum of the current derivative. This assumption is valid over relatively long time intervals, about tens of nanoseconds and longer. The real situation is, indeed, more complicated, which was described in detail in [18]. It is seen that the jet is born somewhat earlier than the disruption of the plasma column. The best agreement of both methods for calculating the jet velocity occurs under the assumption that the jet generation get ahead of the plasma column disruption by 2 ns.

The jet velocity measured by this method was about \(5 \times 10^7\ \text{cm/s}\) during the first 10 ns after its appearance, which corresponds to the kinetic energy of nitrogen ions equal to 18 keV.
For materials science studies carried out at our installation [5, 6], it is important to know the energy flux density carried by the plasma jet in whose path studied samples are placed at a distance of 3–8 cm from the anode. Let us estimate this density at the upper edge of the diagnostic port at the maximum distance of 3 cm that is still available for observation. In the graphs shown in Fig. 6, this distance corresponds
to time of 40–50 ns. In Fig. 5, the thickness of the current sheath is about 1 mm, the ion density in the sheath for the 3–4 degree of ionization (plasma temperature is comparable to the directed kinetic energy) is $10^{17} \text{ cm}^{-3}$, and each nitrogen ion at the speed of $10^7 \text{ cm/s}$ (Fig. 6) has kinetic energy about 1 keV $\approx 2 \times 10^{-16} \text{ J}$. A cube of such plasma with a millimeter-long side will have the energy about 0.02 J, and the corresponding energy flow intensity will be $2 \times 10^8 \text{ W/cm}^2$.

Note that in experiments in argon as the working gas, the bunch was much denser and more compact, its initial density exceeding $10^{19} \text{ cm}^{-3}$ [11]. In earlier experiments in the heavier gas xenon [13], it was seen that the jet was denser still and its leading edge was sharper.

### 3.2. Axial Growth of the Plasma Column

This stage of the discharge is well illustrated by interferograms together with the computer model whose basics are described in [19]. 200–300 ns after current disruption and pinch decay, the remaining plasma is once again compressed, and a new plasma column is created at the axis (Fig. 7). This process is not rigidly tied to the specific feature and can relatively widely (>100 ns) vary from pulse to pulse. The base of the column consists of cold plasma from the ions and atoms of the anode material (copper). Above the base is the plasma from the working gas ions. The top of the column penetrates into the cavity created by the shock wave.

The frames were taken in different pulses in the described time range. In some pulses, coupling of the column top with the leading edge of the shock wave is observed (right frame, Fig. 7) that is accompanied by new disruptions of the plasma column. The plasma column overtakes the shock wave because the latter is decelerated in the working gas, while the current sheath is pushed upward by the magnetic field of the discharge current. After the closing of the plasma column with the shock wave, a new current-carrying plasma formation is created, whose shape reminds a fountain. Below, we will call it a gushing pinch.

After ~300th ns, the shock wave and the plasma column top leave the observation field (Fig. 8, time dependence of the discharge shown in Fig. 9). Still, depending on the necking of the plasma column (shown by the arrow in Fig. 8), it decays and is reformed. The electron density of the plasma in the neck (Fig. 8, right frame) is about $3 \times 10^{19} \text{ cm}^{-3}$, its diameter is 0.3 mm, and the radial compression velocity is not high at $3 \times 10^6 \text{ cm/s}$. The base of the plasma column near the anode is two-layered, where the inner layer is composed of the ions of the anode material (copper) and the outer layer consists of the ions of the working gas. The copper ions are probably the result of the interaction of the electron beam and the plasma jet.

### 3.3. Short Overview of the Studies of Plasma Dynamics During the Second Half-Period

During the second half-period, when the polarity of the internal electrode is negative, the specific fea-
tures are observed rarely and they are never as sharp as in the first half-period (Fig. 12). Accordingly, we do not observe necks as thin as in the first half-period. This is probably connected to the changing composition of the working gas and, possibly, to the smaller current amplitude compared to the first half-period, since the current does not compress the neck of the pinch that generates the jet enough to disrupt it [11]. The characteristic dome of the shock wave was not found in any of the pulses. At the axis, plasma formations are seen that move upward together with the reverse current sheath but at an appreciably lower velocity than the bunches in the first half-period. For example, in Fig. 10, the velocity of such a fragment is $4 \times 10^6 \text{ cm/s}$ and its density is $\sim 4 \times 10^{18} \text{ cm}^{-3}$.

After the column disruption, the same as in the first half-period, a new column is created (Fig. 11, time dependence of the discharge in Fig. 12) with a few differences: the vapor and plasma from the anode material are not observed in the base of the column. This can be seen in the sharply defined shape of the anode (cf. Fig. 8 taken at similar time during the first half-period). Therefore, the plasma column is one-layered and it consists only of the ions of the working gas. The plasma density in the neck marked by the arrow is about $2 \times 10^{19} \text{ cm}^{-3}$, which is close to the value measured in the first half-period in this region. The current density at this moment is about half the maximum current, $\sim 150 \text{ kA}$.

4. DISCUSSION OF EXPERIMENTAL RESULTS

Note that the phase of the sharpening of the leading edge of the specific feature (the 2–3 region in Fig. 2) coincides with the phase of the radial deceleration of the current sheath. This means that during the deceleration and compression of the current sheath, its resistance, both active and inductive, increases. Even more obviously, this fact is described in [18], where the compression phase of the current sheath occurs at the same time as the minimum of the specific feature of the current. In our experiments, the specific feature is at the end of compression and start of pinch decay (Figs. 4, 5).

These experiments confirmed the conclusion of [11]: the axial plasma jets are already present during the cumulation stage of the current sheath. Let us explain this fact. We will separate this stage into the contraction phase of the current sheath and the compression phase of the sheath.

**Contraction phase.** After the current sheath reaches anode’s end, it acquires supersonic speed in the medium of weakly ionized working gas, which is either collected by it or passes through. The gas is compressible, and its thermal velocity is much lower than the velocity of the approaching sheath, so it is not reflected in the axial direction from the inclined surface of the conical current sheath. Therefore, there are
no substantial motions of matter and no cumulation. As is well said in [10]: “cumulation in its usual sense is possible for non-compressible matter, which plasma is not.”

**Compression phase.** Let us estimate the main parameters of the plasma column near the moment of the specific feature in the range –38...0 ns using the information shown in Figs. 3, 4 and the following general considerations:

— the discharge current is 300 kA;
— the radial velocity of current sheath contraction decreases from $10^7$ cm/s to zero;
— the radius of the plasma column is about 1 mm;
— the electron density determined from interferometry is about $10^{19}$ cm$^{-3}$;
— the temperature of the column calculated by Bennet’s relationship [1] is 300 eV;
— the average ion charge is $Z = 3$;
— the skin depth for classical conductivity [1] is of the order of 1 mm.

In this context, it is important that the skin depth is the same as the radius of the plasma column. The eigen magnetic field of the discharge inhibits the axial motion of the plasma that is frozen into it. Let us make a numerical estimate of the conditions under which the plasma of the pinch, through whose entire cross section a uniform current is flowing, is frozen into the magnetic field. The plasma is magnetized when its electrons make a complete rotation in the magnetic field between two collisions with ions [1], in other words, when the electron cyclotron frequency $\omega_{ce}$ exceeds the electron–ion collision frequency $v_{ei} = 1/\tau_{ei}$, i.e., $\omega_{ce}\tau_{ei} > 1$. By substituting $\tau_{ei} = 5 \times 10^4 T^{3/2}/(n_e Z^2)$, $\omega_{ce} = eB/mc$, and the magnetic field in the axial cross section $B = 0.2I/R$ [1], we get

$$\omega_{ce}\tau_{ei} \sim 2 \times 10^{11} T^{-3/2}/(n_e R Z^2),$$
where \( R \) is the pinch radius in cm; \( n_e \) is the electron density in cm\(^{-3}\), \( I \) is the discharge current in A, \( T \) is the plasma temperature in eV, \( m \) is electron mass, \( e \) is electron charge, and \( c \) is the speed of light. At the typical parameters for the compression phase (Fig. 4) (\( R = 0.1 \) cm, \( I = 300 \) kA, \( T = 100 \) eV, \( n = 10^{19} \) cm\(^{-3}\), and \( Z = 3 \)), \( \omega_{ce} \tau_{ei} = 10 \). During uniform current flow, the magnetic field is known to increase linearly from the axis. Therefore, only the plasma in a small region near the axis with size less than \( R/10 \) and, consequently, a volume less than \( 1/100 \) of the pinch volume remains unmagnetized (i.e., with \( \omega_{ce} \tau_{ei} < 1 \)), and crude estimates allow for plasma being magnetized in the entire volume of the plasma column during the compression phase. Thus, one can assume that the eigen magnetic field of the current flowing through the pinch will inhibit the propagation of axial plasma flows.

Consequently, axial jets are not observed during plasma sheath contraction for three possible reasons: the compressibility of the working gas, the supersonic motion of the sheath and the plasma being frozen into the magnetic field.

It is only close to the moment of current disruption that the reconnection of magnetic field lines helps with the creation of magneto-plasma formations [14] that can propagate in the axial direction.

The observed dynamics of plasma jet formation is close to the model of adiabatic compression of the plasma column that is described by Vikhrev, e.g., in [12]. Here, the process of plasma flowing out of the necks is the key mechanism of the compression and heating of the plasma column and the kinetic energy of the jet ions is comparable with the plasma temperature in the column, \( \sim 10 \) keV. In our experiments, we recorded the velocity of plasma bunches at the level of \( 5 \times 10^7 \) cm/s, which corresponds to kinetic energy of 18 keV.

After the first observed current disruption and generation of the shock wave, a new component of the axial plasma flow was observed. This is a rapidly growing plasma column of the discharge. Until now, it was assumed that the samples are only affected by the shock wave and the plasma jet [2, 10, 15]. The velocity of axial growth of the plasma column is in the range between the velocity of the shock wave, \( \sim 10^7 \) cm/s, and the axial velocity of the current sheath, \( \sim 5 \times 10^6 \) cm/s. The above-described measurements showed the presence of necks in the growing plasma column, where the plasma density was about \( 10^{19} \) cm\(^{-3}\). If one assumes that the entire current (300 kA) or at least its major part flows through this column, then the temperature in the neck should be of the order of 100 eV, the magnetic pressure \( 10^4 \sim 10^5 \) atm and a fraction of its energy can be deposited in the sample. The energy transfer mechanism has not yet been studied. Similar processes of column growth are also observed in the second half-period of the discharge.

The propagation of the gushing pinch and its necking lead to its separation into bunches with frozen in magnetic field. Similar plasma formations were observed in [14] at the powerful Mather focus. This mechanism probably also is the basis for the formation of glowing bunches observed at substantial distances in the megajoule Filippov Plasma focus [16, 17].

5. CONCLUSIONS

The initial velocity of the plasma jet generated in the kilojoule PF installation was measured. In the first 10 ns after its formation, the average velocity is about \( 5 \times 10^7 \) cm/s, which corresponds to kinetic energy about 18 keV for the nitrogen ions. The jet dynamics agrees with the model of adiabatic heating of the necks in plasma focus discharges [12] while the order of magnitude of the values agrees with experimental results.

Apparently, the studied samples placed in the materials science experiments [4–6] are not affected either by the shock wave that accompanies the plasma jet or the jet itself that rapidly loses velocity and density, but by the gushing pinch. Its dynamics is not yet well-studied.

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CONFLICT OF INTEREST

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