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# Research of plasma accelerator KPU-30

**Abstract**

In this paper presented the results of experimental study of pulsed plasma accelerator with coaxial geometry of electrodes, working in continuously filling mode at different initial pressure of working gas. The discharge current and plasma flow speed values is determined at gas density in range 0.05-5 Torr. It was shown anomalous plasma resistance at the initial moment of discharge, then the voltage in the first quarter of the discharge period was greater than the initial value . The magnetic field distribution between electrodes was obtained by magnetic probes and Rogowski belt (for outside of electrodes). It is shown, that the distribution of magnet field along axial direction of accelerator at low and medium vacuum has a significant influence on the process of plasma propagation, and at low density achievement maximal parameters of plasma flow, too.

***Key words:*** Acceleration process, high-power plasma, magnetic probes, coaxial plasma accelerator CPA-30, oscillogram.

## Introduction

Pulsed plasma accelerators are used to obtain high-power plasma flows. Such flows are widely used in science and technology. Of particular interest is the use of hot plasma streams for processing of materials [1-3]. On the experimental side of these accelerators work fairly thoroughly investigated, but so far there is no single theoretical model that describes the diversity of processes occurring in them. Therefore, you need to compare the experimental data for compliance with the existing theoretical models describing the dynamics of the formation of plasmoids and the acceleration process.

Earlier on the basis of probe studies, the authors found that formed in the pulsed plasma accelerator CPA-30 streams have a velocity of $10^5$ m/sec, and may consist of individual bunches, following one another [4]. In subsequent experiments we observed such phenomena as the emission current for the electrodes, as well as features on the curves of current and voltage of the energy [5]. However, the question of the structure of the plasma formation is not fully understood. For plasma separation flow into its components is possible only at low densities, when the Debye radius becomes comparable to the size of the system. In any plasma installation process dynamics determines the configuration of electromagnetic fields. Therefore, you must determine the presence and distribution of the magnetic field in the coaxial line and the current in the plasma flow and magnetic probes are in principle well suited [6]. In this paper we investigate the dynamics of the formation of plasmoids in a pulsed coaxial accelerator with magnetic probes.

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Work pulsed plasma accelerators has been thoroughly investigated by pulsed gas inlet through a fast valve, however, the regime with a constant initial pressure of the gas, called "mode with a solid content", little studied. By varying the pressure of working gas, we can adjust the plasma density, and investigate the dynamics of the formation of plasmoids with different densities.

## Installation and measurement technique

The experiments were performed on a coaxial plasma accelerator CPA-30. The installation consists of the working chamber with coaxial electrodes made of copper (diameter 24 mm anode, cathode diameter 90 mm), batteries, high voltage capacitors 70 μF electro-valves controlled by a vacuum gap, the charging system and ignition system pumping and gas inlet and diagnostic devices. The length of the outer electrode of the accelerator is 60 cm, inner -45 cm discharge voltage varies in the range of U=10-30 kV. Stored energy storage W = 5-32 kJ. The amplitude of the discharge current of 500 kA, the current period of 14 ms. Used mode of operation of the accelerator at a constant pressure inside the discharge chamber in the range (0,05-5) ± 20% Torr. The working gas was air.

The experimental setup is shown in Figure 1. The distribution of the magnetic field and the current was measured with magnetic probes and Rogowski loop. To measure the high voltages used a combined resistive and capacitive voltage divider with division ratio of 1:10,000. The signals were studied using a digital oscilloscope with a bandwidth of 200 MHz. Before each discharge chamber was evacuated to a pressure of $10^{-3}$ Torr. After that, depending on the task, the chamber pressure rose to values in the range of 0.05-5 Torr.

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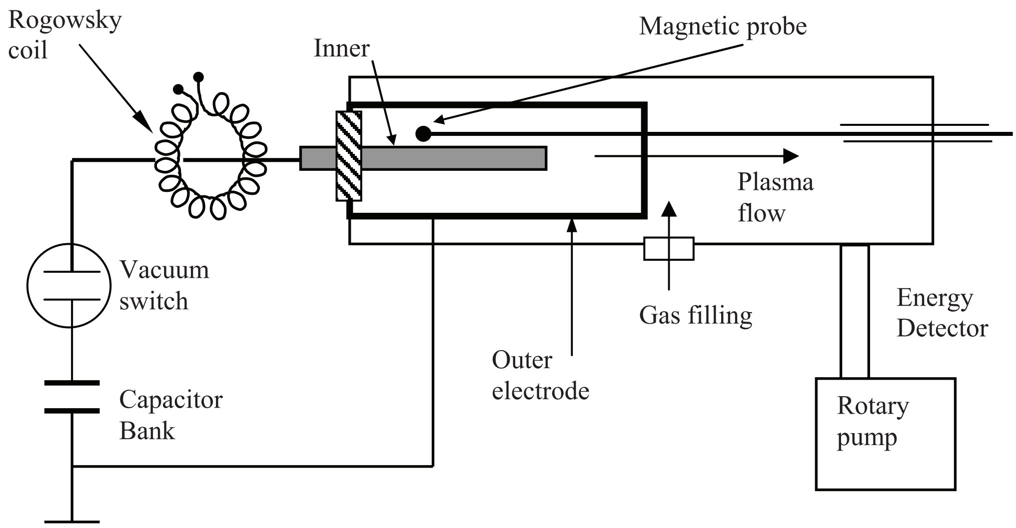



**Figure 1 –** Scheme of experiments on the CPU-30

**The experimental results**

Typical current waveforms at pressures of 0.1 and 0.05 Torr are shown in Figure 2. As can be seen from the figures, the discharge current in the accelerator is aperiodic damped signal. The number of half cycles is almost independent of the initial pressure in the chamber. The period of the current increases slightly by 1-2 ms, the current amplitude decreases exponentially with a decrement of ~$10^5$. The presence of rapidly damped oscillation at the beginning of the sweep can be attributed to the reflection signal from the cable ends, which is typical for such measurements. Figure 2 (bottom) also shows the voltage waveforms at various pressures. Attention is drawn to the following features of these curves. First, the line voltage is strongly indented, which is caused by impulse noise. At the current curves in the initial moment of time, you can also notice the presence of rapid oscillations, but since the Rogowski coil has a large self-inductance irregularity is manifested not so much. In addition, it is clear that at the beginning of the discharge current increases very rapidly, reaching 500 kA for a time of 3 ms. In this case, the rate of current rise will be $1.7 \cdot 10^{11}$ A/sec. Second, the voltage in the first quarter of the discharge is greater than the initial value and then decreases. Such behavior, apparently, to the effect described in the literature as anomalous plasma resistance at the initial moment of the discharge [7]. In this case, the total resistance of the plasma dominates its ohmic resistance. As a result, the voltage across the discharge gap increases.

Current-voltage characteristics of the accelerator is constructed as the dependence of the amplitude of the external discharge current of the voltage. Experimental data on the accelerator, the CPA-30 by using the continuous mode of operation are shown in Figure 3. As can be seen, the current-voltage characteristics of the discharge currents in the range 150-500 kA are virtually linear, and almost the same at any pressure within the discharge chamber of the accelerator.

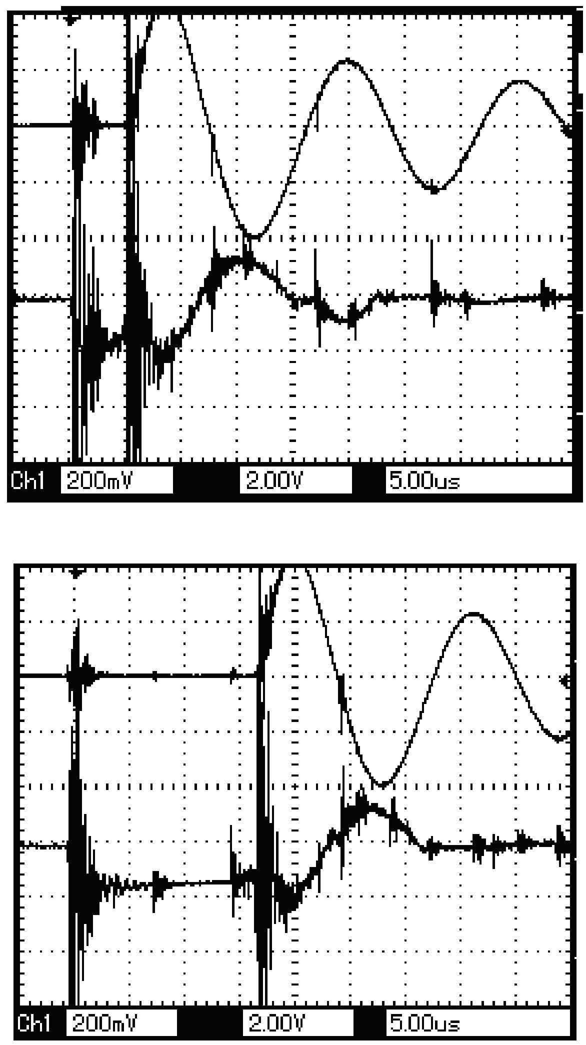



**Figure 2 –** Current waveforms (top) and voltage (bottom) at 15 kV. The pressure in the chamber on the top -0.1 Torr, bottom-0.05 Torr

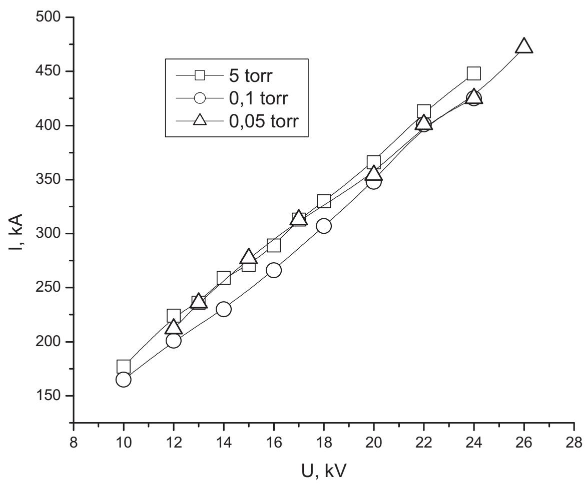
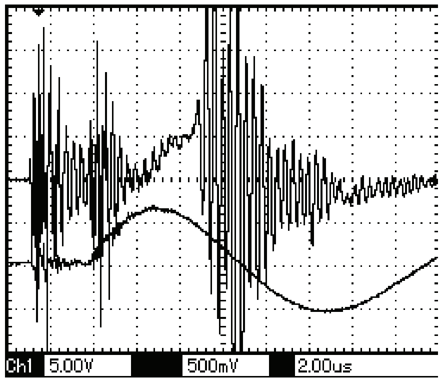



**Figure 3 –** CVC of the accelerator CPA-30 at three different pressures

The magnetic field distribution inside the interelectrode space was removed from the magnetic probes and Rogowski loop (for a slice of the electrode). Oscillograms of the magnetic probes, taken at a distance of 26 cm from the edge of the outer electrode are shown in Figure 1. By lowering the pressure sensor detects high-frequency oscillations of the magnetic field. These oscillations are a broadband signal in the range of 5.2 MHz, to get rid of vibrations can be achieved by integrating network connection with the integration constant for more than 3 ms.

With the help of magnetic probes were obtained by waveform *B(t)* for different positions of the probe in the middle between the cylindrical electrodes at a distance of 1 cm to 40 cm from the edge of the outer electrode. Discharges made under the same conditions: the voltage across the capacitor 20 kV and a pressure of 0.1 and 1 Torr. The results showed good reproducibility of the signal from discharge to discharge. Next, we consider a series of waveforms of the magnetic field along the axial axis at various distances from the edge of the outer electrode, shown in Figure 5.

From the oscillograms that the magnetic field moves forward in the axial axis of the exit of the electrode. The average velocity of the front signal was 2.5 cm/μsec. Rate of rise of the front is about 1 microsecond, so the thickness of the current sheet, on which passes the discharge current of 2-3 cm at a pressure of 1 Torr, the average front velocity signal was 2.3 cm/μsec, which is almost equal to the rate at 0.1 Torr. Rate of rise of the front was about 2 microseconds, so the thickness of the current sheet, on which is the discharge current, was 4-5 cm Thus, the speed of the current layer is weakly dependent on pressure. Of interest to determine the rate in another way, namely by two belts installed at a distance from each other. Results of experimental measurements are shown in Table 1 and Figure 5.



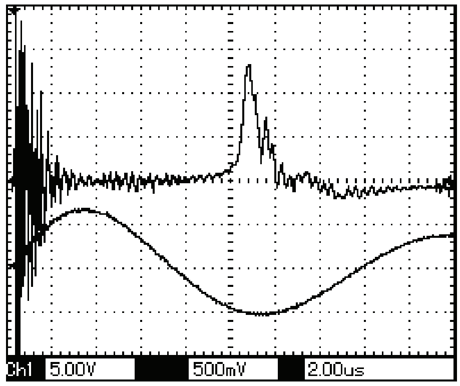




**Figure 4 –** The signals from the magnetic probe without integration at a pressure of 0.1 Torr (top) and 1 Torr (bottom)

In accordance with Figure 6, the voltage dependence of the rate of non-linear. The maximum flow rate at a voltage of 26 kV was (5,6 ± 0,3) cm/μsec. In addition, there is also no noticeable difference in flow rate and pressure.

Next, Figure 7 shows a plot of the amplitude of the magnetic field in the interelectrode space. The amplitude of the magnetic field along the electrodes behave uniquely. If at a pressure of 1 Torr, it is the same order of magnitude at the beginning and at the outlet (on the graph on the left) electrode, at 0.1 Torr. Follow, amplitude reduced from 30 kGauss to near zero.

**Conclusion**

Thus, in this study using magnetic probes investigated the magnetic field distribution along the electrodes of the accelerator CPA. It is established that the magnetic field moves in a direction to the outlet of the electrodes. The average flow rate is practically independent of the initial gas pressure in the chamber of the accelerator, at least within the limits of 0.1-1 Torr. This result can be explained by the fact that according to Spitzer charged particle concentration in plasma is determined by the degree of ionization. In this case, at sufficiently high voltage to the discharge, achieved full ionization of the gas, and in this case, the discharge current and flow rate does not depend on pressure.

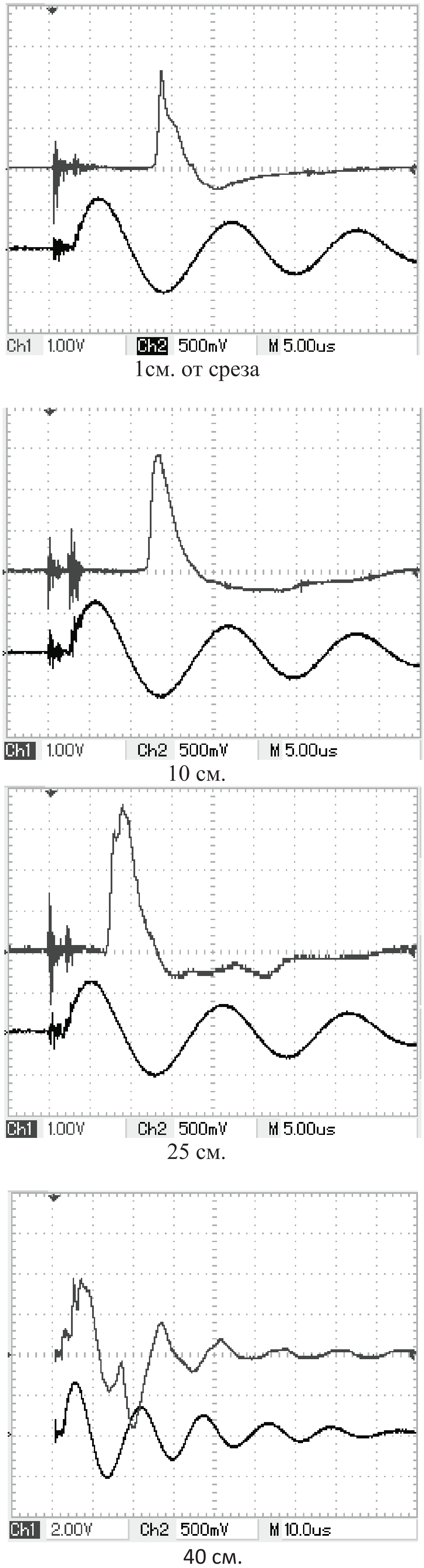



**Figure 5 –** Oscillograms of the magnetic field at 0.1 Torr

**Table 1 –** The results of experimental measurements of flow rate based on Rogowski coil at 17 cm

| $U_{зар.}$, kV | $V\cdot 10^6$, cm/sec | | |
|---|---|---|---|
| | 0,05 Torr | 0,1 Torr | 5 Torr |
| 12 | 1,8 ± 0,5 | | |
| 14 | 1,7 | | |
| 16 | 2,1 | | |
| 18 | 3,1 | | |
| 20 | 3,4 | 3,4 | 3,2 |
| 22 | 4,2 | 3,4 | |
| 24 | 4,8 | 4,8 | |
| 26 | 5,0 | 5,6 | |

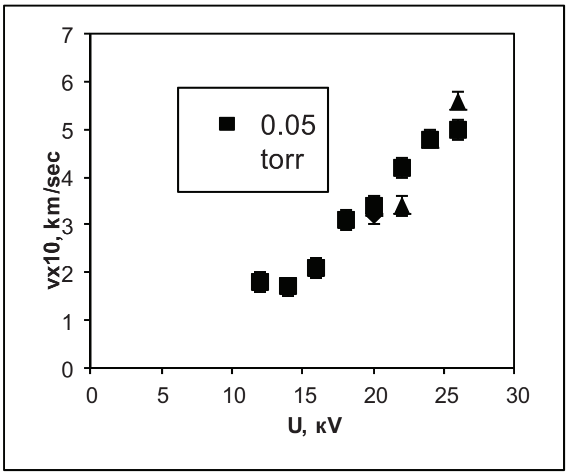



**Figure 6 –** The dependence of the flow rate of the voltage at different pressures

Voltage dependence of the rate of non-linear and is described by a power law. These results are evidence that this accelerator main force of the movement is electro-Ampere force [8], since in this case, the flow rate

$$\upsilon \sim J^2 t^n .$$

Analysis of experimental data suggests the magnitude of the initial pressure in the chamber has a significant influence on the dynamics of the magnetic field inside the electrode space. At lower pressures the electromagnetic energy is proportional to the magnetic field is realized in the initial stage of acceleration. High pressure is evenly distributed along the length of the accelerator. In this case, the acceleration of the magnetic force is the ampere. At the same time, at a pressure below 0.1 Torr in the accelerator, there are significant oscillations in the magnetic field, but they tend to decay with increasing pressure. We can assume that in this case is formed in the accelerator instability associated with

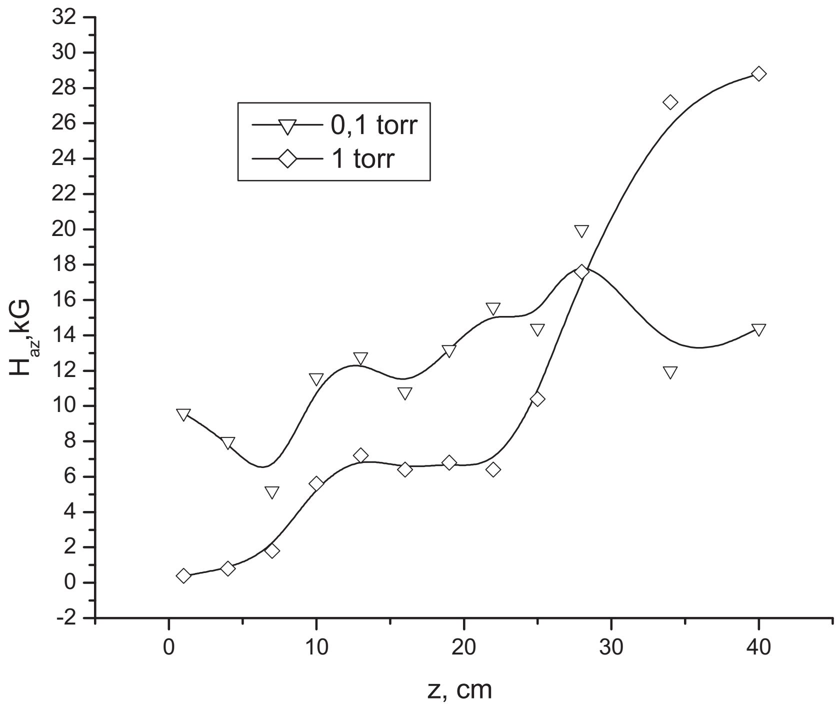



**Figure 7 –** The dependence of the magnetic field in the interelectrode space at pressures of 0.1 and 1 Torr

anomalous plasma resistance, the formation of structures such as filaments [8], which leads to an increase in voltage across the electrodes at the beginning of the discharge. Further development of the instability leads to a buildup of large amplitude oscillations. As noted above, in some cases, the observed phenomenon is an accelerator for the removal of the current section of the electrodes, and you should assume that the reason for this is the occurrence of oscillations. However, the appearance of oscillations does not fit into the framework of the electrodynamic acceleration model, but perhaps an explanation of the Hall effect in accelerators [9]. The presence of slip along the current electrodes can be determined by detailed measurements of the current lines that may be made the subject of further research.

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