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EXPERIMENTAL STUDY OF CURRENT-SHEET-LIKE STRUCTURE IN PINCHING PLASMA FLOWS WITH ELECTRIC AND MAGNETIC PROBES

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The formation of the current-sheet-like structure under the influence of the external magnetic field in pinching plasma flows generated by the magnetoplasma compressor has been studied. A set of magnetic and electric probes were used to measure the self-generated magnetic field, electron temperature, and electric field locally with sufficiently high temporal and spatial resolution. The data obtained from the probe measurements were used to plot the spatial distributions of electric current and drift velocity in the plasma stream to identify the patterns of plasma flow. In the presence of external magnetic field, the current density, electron temperature, and the ion saturation current reach a peak in close proximity to the sheet. Measurements indicate the outflow of two electron jets of different temperatures from the layer.

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INTRODUCTION

Quasistationary pinching plasma flows have many applications in science and technology [1, 2], including plasma-surface interaction, new generation lithography, electric propulsion, etc. In theory, it is possible to reach high density and temperature values in compression zone forms in a self-compressed plasma stream generated by a magnetoplasma compressor (MPC). The plasma density in the compression zone can be up to $10^{18}…10^{19}$ cm^{-3} and temperature up to a few kiloelectronvolt. In previous experiments [2-4], plasma streams with a plasma density of 10^{18} cm^{-3} and temperature of a hundred electronvolt were obtained.

Self-compressed plasma flow has a rather complex structure: local compression region, toroidal current vortices, return currents, etc. The sets of concentric vortices and enclosed toroidal current structures have been observed in different regimes of the MPC operation. The spatial structures of the electric current in the case with no axial magnetic field contain current vortices near the axis, as opposed to the case with the magnetic field [3]. The current isolines are expelled or "pushed out" from the center of the plasma stream. This effect is associated with a formation of a compression zone in the region. The additional axial magnetic field affects the structure of the plasma flow ejected from the accelerator, although it is applied only inside the channel and its magnitude is negligible in the plasma volume measurements were conducted [3]. The imposed magnetic field might enhance the formation of the current-sheet-like structure during later stages of the MPC discharge, which has become a subject of study for the first time. Current sheets are the sites of the onset and evolution of magnetic reconnection [5-9], which is a naturally occurring fundamental process in the space sciences, allowing for the release of energy stored in magnetic fields. They play central role in explosive phenomena such as flares, jets, and coronal mass ejections (CMEs) [9]. Magnetic reconnection is also important in the heating of quasi-static corona and less explosive events. Such structures resembling the current sheet has been observed in previous MPC experiments without external magnetic field [4], although their nature has not been fully understood and no sufficient evidence of their specific features was found. Therefore, such an interesting finding requires further comprehensive investigation. Laboratory experiments have, for example the Magnetic Reconnection Experiment [10], play an important role in understanding the physics of magnetic reconnection. However, any diagnostic in these experiments needs to be able to resolve small scales. This is an extremely challenging task for laboratory diagnostics.

An intricate structure of the MPC flow also requires local diagnostics to measure plasma parameters in each specific plasma layer. Considering the presence of the external magnetic field, this task becomes even more critical. Since the spectroscopic methods are not appropriate for local measurements, we apply a set of magnetic and double electric probes [3, 4] to measure plasma parameters locally. Probes have proven to be reliable diagnostic tools among the contact methods used to measure plasma parameters with sufficiently high temporal and spatial resolution in various devices, including tokamaks and stellarators [11-14]. Double electric probes designed specifically for the temperature measurements allowed us to obtain the data in different layers of the plasma stream [11-15]. It is also possible to use them in case of a bi-Maxwellian EEDF with well-separated temperatures [13, 15] which can be extracted by straight-line fits on the semi-logarithmic discharge-voltage characteristic.

In this paper, we report our recent experimental results of the local measurements of the plasma parameters near the region of the current sheet formation.

This paper is structured as follows: the first section describes the experimental setup and diagnostics system. The second section is devoted to our experimental results. The last section summarizes the main findings.

1. EXPERIMENTAL DEVICE AND DIAGNOSTICS

Experiments were performed in the magnetoplasma compressor (MPC) device [2-4, 15]. The accelerating channel of the MPC used in the present experiments consists of two coaxial electrodes made of copper. An external electrode (anode) is formed by a solid cylindrical part and a conical part consisting of 12 rods inclined at 7.5 degrees to the axis of the channel. The cylindrical part is 12 cm in diameter and 14.5 cm in length. Each rod of the conical part of the anode is 14.7 cm in length and 1 cm in diameter. Following a similar shape, an internal electrode (cathode) consists of cylindrical and conical parts. A solid part of the cathode is 20.8 cm in length and 6 cm in diameter. A 12 cm-long conical part with an outlet diameter of 3 cm has an opening at its outlet, serving a purpose of a divertor for impurities from the main plasma flow.

A system of capacitor banks triggered by a vacuum spark gap is used to supply the MPC discharge. Its total capacitance is 90 μF, with a maximum voltage reaching up to 30 kV.

The MPC is installed inside a solenoid that produces an axial magnetic field of up to 0.4 T inside the accelerating channel. The inner diameter and the total length of the solenoid are 15 and 17 cm, respectively [4]. Fig. 1 shows a general view of the entire accelerating system, including the solenoid with the MPC accelerating channel inside. The MPC device operates in a regime with residual gas at different pressures. The complete system of the MPC with the solenoid is installed inside the vacuum vessel of 2 m in length and 40 cm in diameter.

The diagnostic system includes a Rogowski coil for discharge current measurements, voltage dividers, a set of local magnetic and electric probes.

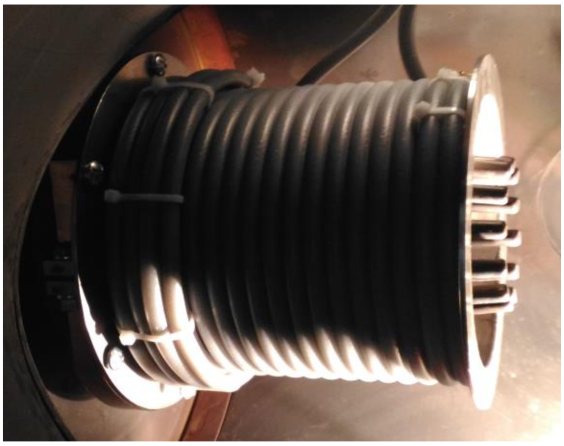

Fig. 1. MPC accelerating channel with a solenoid

A number of double electric probes were used for local electron temperature measurements. Fig. 2 presents the general view of the double electric probe.

Fig. 2. Double probe general view

The results of the double electric probe measurements strongly depend on their mode of operation. According to the literature [11, 12, 14], in the conditions typical for the MPC discharge, the double probe is expected to work in the diffusion regime. As it has been shown [12], in this mode of probe operation, the ion saturation current does not depend on the probe diameter and can be written as

$$I_i = j_i \cdot S_p = \frac{1}{4} \cdot e \cdot n \cdot \overline{v_i} \cdot \frac{\lambda_{i,a}}{R_p} \cdot S_p = I_i^{Langmuir} \cdot \lambda_{i,a},$$

where S_p – area of the probe electrodes; j_i – density of the ion saturation current; n – density; v_i – ion velocity; $\lambda_{i,a}$ – the free path length; $I_i^{Langmuir}$ – Langmuir's ion saturation current. Therefore, Langmuir's theory can be applied for measurements of the lower level of electron temperature, although the reduction ration still remains unknown [15]. This has been confirmed in our studies with the probe consisting of the pins of different diameters of the working part [15], also used in the current experiments. The probe pins are made of molybdenum wire. The non-working area is shielded with a cylindrical ceramic tube. The diameter of the working part is 1 mm, and the length is 3 mm. The measuring circuit is isolated from the MPC electrodes and plasma by a sensitive Rogowski coil. An isolated capacitor bank of 0.05 F and the maximum voltage of up to 100 V powers the probe.

The electric probe of a different design was applied in order to conduct measurements of the electric field in plasma. The radial component of the electric field can be measured by dividing the potential difference over the distance between the pins location. The probe is made of two molybdenum cylindrical electrodes of the same size, approximately 1 mm in diameter, separated radially by 1 cm from each other. Each of the electrodes is protected with a ceramic tube. The distance between the ceramic tubes is about 6 mm. The measuring circuit of the probe includes a voltage divider and a 10 kV isolation transformer. The picture of the electric probe used for the measurements of the radial component of the electric field is shown in the Fig. 3. These measurements were used for the calculations of the drift velocities described in more detail in the next section of this paper.

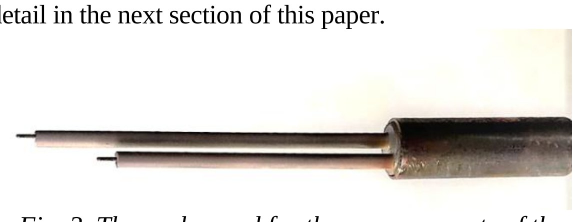

Fig. 3. The probe used for the measurements of the electric field radial component

Magnetic probes are an inexpensive and reliable tool to measure the magnetic fields in plasma and perform an indirect determination of the plasma current through the application of Ampere's law [4]. Each probe is a small inductive cylindrical coil protected by a ceramic case (diameter of 4 mm, length of 5 mm). The signal from the probe is integrated using analog RC integrators. Considering the axial symmetry of the plasma stream, the self-generated magnetic field at different distances from the MPC outlet and different radii. During the discharge, one probe was introduced into the plasma flow and oriented in a way that the self-magnetic field passes through the loops of the coil. In order to keep track of the variation of the signals, several shots were made at each point of measurements. Compared with the magnitude of the self-generated azimuthal magnetic field *Bφ*, the magnitude of the external axial B_z and radial B_r components were negligible outside the accelerating channel. The average error of the probe measurements accounted for up to 15 %.

Experiments have been carried out in the MPC facility under the following experimental conditions: the residual working gas – Helium at a pressure of 2 Torr; the discharge current I_d = 400 kA; the magnitude of the external longitudinal magnetic field (B_z) inside the MPC channel of 0 and 0.24 T.

2. EXPERIMENTAL RESULTS AND DISCUSSION

The typical waveforms of the discharge current, the azimuthal component of the self-magnetic field ($B_φ$) in the plasma stream, and the radial component of the electric field (E_r) are shown in Fig. 4. The signals are obtained for the external field magnitude of 0.4 T, at the distance of 3 cm from the cathode and at the radius of 1 cm.

The half-period of the discharge current is 10 µs. The duration of the signals of the self-magnetic field and radial component of the electric field correspond to the discharge duration. The electric probe field changes its polarity during the second half-period of the discharge.

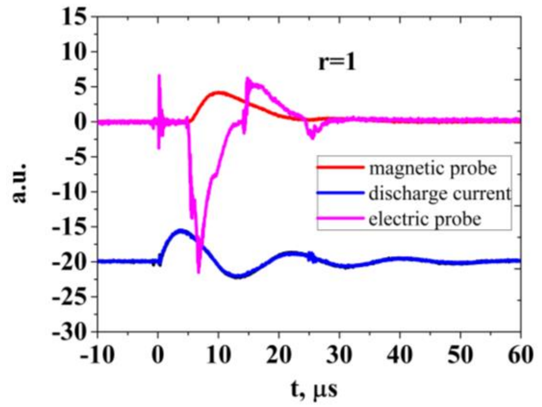

Fig. 4. Waveforms of the discharge current, self-magnetic field $H_φ$, and radial component of electric field E_r. External magnetic field is 0.4 T

During our experiments dedicated to the external B-field influence on the plasma stream structure, we studied the two-dimensional distributions of the electric current isolines in plasma streams (Fig. 5). Fig. 6 illustrates the axial distributions of the current density and the azimuthal component of the self-generated magnetic field at the distance of 1 cm from the plasma stream core.

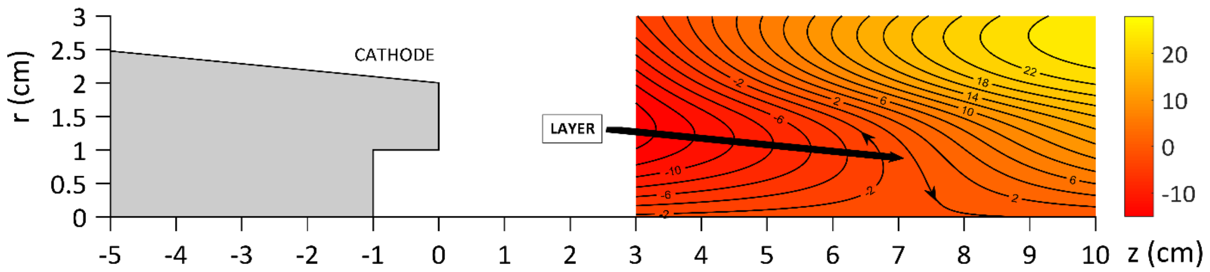

Fig. 5. Two-dimensional distributions of the electric current with the external B-field of 0.24 T at 16 µs of the discharge. The black arrows indicate the direction of the current flow

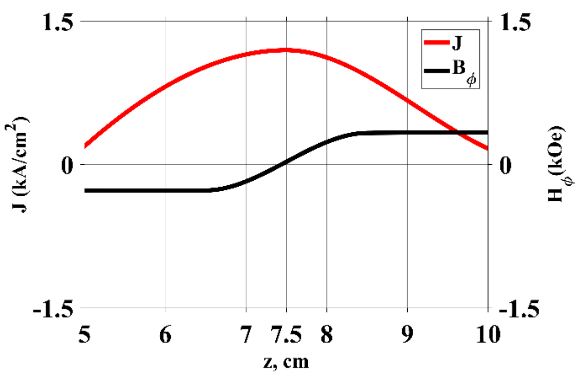

Fig. 6. The ion saturation current and two temperatures measured near the layer of the current sheet

We have found that at the later stages of the discharge (corresponding to the second half-period of the discharge current), namely at the moment of 16 µs, the number of current vortices is fewer, although the magnitude moderately increases and the layers containing the reverse current appear near the MPC outlet. It is worth noting that the magnitude of the current of the reverse polarity increases closer to the accelerator's outlet. However, in the vicinity of the plasma stream center, the layer separated by oppositely directed current isolines is observed between 6 and 8 cm. The current isolines separating the layer are of 2 and -2 kA. It is clearly seen that the self-magnetic field passes through zero at the distance of 7.5 cm from the cathode (see Fig. 6). At the same location, the current density reaches a peak of approximately 1.5 kA/cm^2. It is an important result since the hallmark of reconnection is that the current density is expected to become large at its location [16].

The local electron temperature can be determined from the current-voltage characteristic of the double electric probe measured at different spatial positions inside the vacuum chamber during the discharge. We measured the I-V curves of the double probe with a step of the biasing probe voltage of 2…4 V from point to point in space. The statistical spread of the probe signals did not exceed 10%. Special attention was paid to the probe electrode cleanness performed with a glow discharge or a high-voltage (up to 100 V) short discharge after two consecutive working shots.

The I-V curve for the 16 µs plotted semi-logarithmically contained two linear regions in the transition region, which implies the presence of groups of electrons with different temperatures. As it is shown in Fig. 7, the second temperature increases near the region where the layer containing the current-sheet-like structure is detected. Noteworthy, the first temperature remains quite low, reaching about 20 eV at the distance of 3 cm and gradually decreasing further. More importantly, the ion saturation current reaches a maximum in the same region. Since the ion saturation current of the double probe is directly proportional to the plasma density, it allows us to suggest that the plasma density increases at the same location, as well.

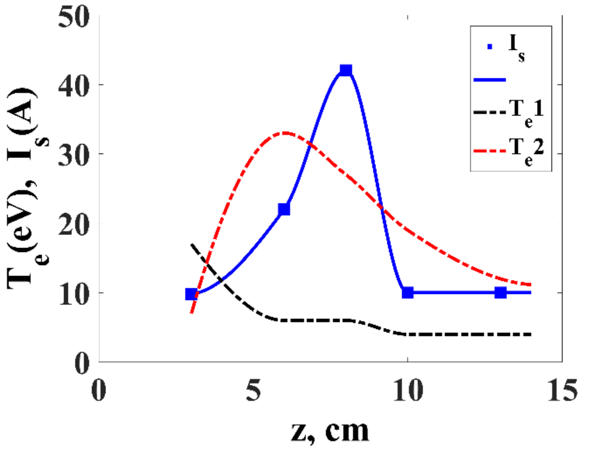

Fig. 7. The ion saturation current and two temperatures measured near the plasma layer with the current sheet

All these observations can be interpreted as an indication of the generation of two electron jets of different temperatures taking place near the region of the current sheet structure formation.

Nevertheless, for further consideration, it is important to take into account the distribution of the drift velocity. As for its measurements, it is crucial to look in detail at the specific region, namely at radii of 1 cm and 0.5 cm where the current sheet forms. The drift velocity was calculated using the measurements of the azimuthal component of the self-generated magnetic field and radial component of the electric field. The radial distributions of the radial component were used for the calculations of the electric potential and longitudinal component of the electric field. Fig. 8 shows the axial distribution of the radial component of the drift velocity measured at the radius of 1 cm with and without external magnetic field of 0.24 T. When no magnetic field is applied inside the accelerating channel, the radial drift velocity is 10×10^6 cm/s, as opposed to the case with the magnetic field, when it reverses direction and reaches as high as 40×10^6 cm/s. In this particular case, the radial velocity is directed out of the layer and towards the center of the plasma stream.

Let us take a closer look at the case with the magnetic field and the longitudinal component of the drift velocity illustrated in Fig. 9. The velocity changes direction at smaller radii (0.5 cm), whereas at 1 cm, its direction coincides with the plasma stream propagation. The longitudinal drift velocity reaches nearly 225×10^6 cm/s at the distance of 8 cm from the cathode, which is presumably a boundary layer of the current-sheet-like structure. Since the formation of the layer surrounded by oppositely directed current isolines takes place between 6 and 8 cm from the cathode, this result, along with the temperature measurements, lends support for the suggestion that there is a generation of two jets of electrons of different temperatures out flowing of the stream in opposite directions.

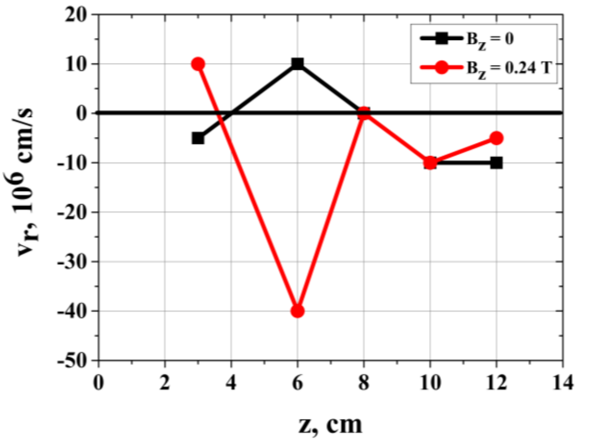

Fig. 8. The radial component of the drift velocity vs. distance from the cathode measured at 1 cm from the center of the stream

Unfortunately, it is significantly difficult to determine the thickness of the layer experimentally in the scope of the current study. Nonetheless, the findings imply that it might be located at approximately 7...7.5 cm from the cathode, while the electron jets outflow is observed at the distance of 6 and 8 cm.

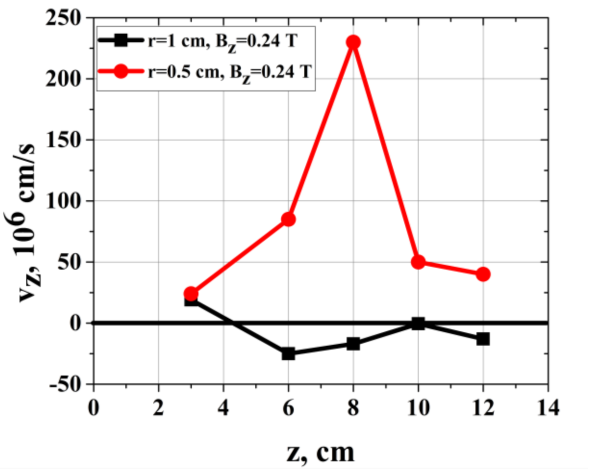

Fig. 9. The longitudinal component of the drift velocity vs. distance from the cathode measured at two radii

CONCLUSIONS

A current-sheet-like structure has been detected in self-compressed plasma streams generated during the MPC discharge in the external magnetic field. With the aim to study the local parameters of the current-sheet-structure formed in the MPC plasma stream, we applied electric and magnetic probes. Two-dimensional distributions of the electric current isolines in the plasma stream show the moment of the sheet formation during the second half-period of the discharge current. It has been found that the self-magnetic field passes through zero in its location. Two groups of electrons with different temperatures appear in the vicinity of the layer. Also, the current density, the second electron temperature, and the ion saturation current reach a peak in the close proximity to the sheet. The reversed direction of the drift velocity near the center of the plasma stream might be explained by the outflow of two electron jets of different temperatures from the layer. This finding makes it possible to model complex astrophysical phenomena in a laboratory plasma.

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ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ СТРУКТУРИ ТИПУ СТРУМОВИЙ ШАР У САМОСТИСНЕНИХ ПОТОКАХ ПЛАЗМИ ІЗ ЗАСТОСУВАННЯМ ЕЛЕКТРИЧНИХ ТА МАГНІТНИХ ЗОНДІВ

Ю.Є. Волкова, Д.Г. Соляков, А.К. Марченко, М.С. Ладигіна, Ю.В. Петров, В.В. Чеботарьов, Т.М. Меренкова, В.О. Махлай, Д.В. Єлісєєв, В.В. Стальцов

Досліджено формування структури типу струмовий шар під впливом зовнішнього магнітного поля в самостиснених потоках плазми, що генеруються магнітоплазмовим компресором. Магнітні та електричні зонди використовувалися для локального вимірювання власного магнітного поля, електронної температури й електричного поля з достатньо високою часовою і просторовою роздільною здатністю. Дані, які отримані в результаті зондових вимірювань, були використані для побудови просторових розподілів електричного струму та швидкості дрейфу в потоці плазми для виявлення особливостей потоку плазми. За присутності зовнішнього магнітного поля густина електричного струму, електронна температура та іонний струм насичення досягають максимуму в безпосередній близькості від шару. Вимірювання свідчать про витік із шару двох електронних пучків із різними температурами.