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FEATURES OF ENHANCED PLASMA COMPRESSION UNDER EXTERNAL MAGNETIC FIELD

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The impact of an external longitudinal magnetic field on a self-compressed quasi-stationary plasma flow generated by a high-current magnetoplasma compressor is studied. The additional magnetic field of 0.24 T was applied to the plasma discharge. A significant enhancement of flow compression when an external longitudinal magnetic field is applied was found. The magnetic field also influences the process of current vortices formation, which is linked to the conversion of kinetic energy into magnetic field energy. The formation of fewer vortices in the presence of the magnetic field suggests more efficient compression and potentially higher plasma parameters in the compression zone.

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INTRODUCTION

High-current plasmadynamic systems, such as QSPAs (quasi-stationary plasma accelerators) and MPCs (magnetoplasma compressors), generate quasistationary compressed plasma flows with broad scientific and technological applications. Compressed plasma flows are generated using an MPC, where the balance between electromagnetic forces, gas-dynamic pressure, and thermal effects defines the compression process [1]. Compressed plasma flows can be used in various applications, such as plasma etching, deposition, the development of plasma sources for lithography, as well as for the simulation of the conditions in the ITER divertor [2–4]. Additionally, these flows can contribute to the study of magnetic reconnection, a fundamental process in both laboratory and astrophysical plasmas [5, 6].

Previous studies have shown that such systems can produce plasma flows with parameters nearing the theoretical limits achievable under certain experimental conditions [1]. The achievement of maximum plasma parameters critically depends on the specific arrangement of the plasma flow within the accelerating channel, particularly in the proximity of its electrodes [1–4]. Studies revealed a concerning depletion of charge carriers near the anode. This localized scarcity of charge carriers induced a critical operational state within the plasmadynamic system, aptly termed a "current crisis". This "current crisis" precipitated a cascade of detrimental effects, ultimately degrading the overall quality and performance of the plasma flow [1].

The "current crisis" in quasistationary systems mirrors the challenges encountered in pulsed plasma thrusters and magnetoplasmadynamic thrusters (MPDT). Similarly, their efficiency is limited by the onset of severe voltage fluctuations and anode damage when a certain critical current is exceeded [7, 8]. These parallels underscore the importance of maintaining adequate charge carrier density throughout acceleration to ensure optimal performance. Any disruption in the delicate balance of charge carriers can lead to operational instabilities and compromised performance, emphasizing the need for careful design and control strategies to mitigate such issues. To reduce the "current crisis" effect at high discharge currents, the electrode system was improved, and a transition to ion current transfer was achieved [1]. However, this effect could not be eliminated, and further increases in discharge current remain problematic [1]. Applying an external longitudinal magnetic field, similar to applied-field MPDTs [7], can enhance discharge characteristics and improve plasma flow parameters [9–12].

Thus, understanding the behavior of compressed plasma flows in external magnetic fields is crucial for optimizing plasmadynamic devices. Accurate measurement of plasma parameters in compressed flows is necessary for characterizing their properties.

This paper investigates the impact of an external longitudinal magnetic field on a self-compressed quasistationary plasma flow generated by a high-current plasmadynamic system, focusing on the spatial distribution of the electromagnetic forces, electric potential, and current within the flow. These distributions provide insights into the fundamental behavior of plasma in magnetic fields, including compression, acceleration, and confinement.

1. EXPERIMENTAL FACILITY

The experiments were conducted in the magnetoplasma compressor facility described elsewhere [1, 2, 4, 11, 12]. The MPC is contained within a vacuum chamber with a diameter of 45 cm. The length of the chamber is 2 m. A turbomolecular pump with a flow rate of 500 l/s and a fore vacuum pump are used to reach a pressure of 10^{-5} Torr in the chamber. Before each pulse, the vacuum chamber is filled with residual working gas to a certain pressure. The diagnostic system of the MPC facility includes a Rogowski coil for measuring the discharge current, frequency-compensated voltage dividers for measuring the discharge voltage, magnetic and electric probes of various designs, moving calorimeters, spectroscopic diagnostics, and high-speed registration complexes.

Magnetic probes were used to measure the magnetic field in the plasma flow at different distances from the outlet of the MPC and different radii, taking into account the axial symmetry of the flow. The probes are attached to a plexiglass flange and are inserted into the vacuum chamber through special Teflon vacuum seals, installed into the chamber's diagnostic ports. This allows the probes to be inserted and removed, as well as moved along the chamber or rotated for better access to different areas of the plasma flow. During the discharge, one probe was introduced into the plasma flow and oriented so that a self-magnetic field passed through the turns of the probe coil. The measurement of the radial distribution of the azimuthal component of the self-magnetic field was performed for several cross-sections.

Electric probes were used to measure the radial component of the electric field. The device with such an electric probe uses a conceptually simple technique of measuring the potential difference between two electrodes in the plasma. The value of the radial component of the electric field can be obtained by dividing the measured potential difference by the distance between the probe electrodes. Such an electric probe consists of two cylindrical molybdenum electrodes of the same size (approximately 1 mm in diameter), placed at a distance of 1 cm from each other in the radial direction. Each of the electrodes has a protective ceramic tube, the gap between the tubes is approximately 6 mm. The measuring circuit of the electric probe consists of a voltage divider and a separation transformer (10 kV) with a volume coil.

For the experimental study of the influence of the external longitudinal magnetic field on the compressive plasma flows, a specially-made solenoid was installed on the discharge channel of the MPC [11, 12]. The magnetic field signal duration is 250 μs. The value of the external magnetic field inside the MPC discharge channel ranges from 0 to 0.4 T. The experiments were conducted at the external magnetic field of 0.24 T. The plasma discharge occurred when the magnetic field reached its maximum. The magnetic field did not change during the plasma discharge.

2. EXPERIMENTAL RESULTS

Fig. 1 shows the spatial distributions of the electric potential in the plasma for 10 μs of the discharge with and without an external magnetic field of 0.24 T. The output of the cathode is chosen as the zero reference point of the horizontal axis. The potential lines bend to the axis of the system, and a closed structure of enclosed equipotentials is also formed, which is characteristic of plasmadynamic systems of this type [1, 13]. When an external magnetic field is applied, the structure of the enclosed equipotentials is shifted to a greater distance from the MPC output, and the maximum value increases from $\varphi = 2500$ V to $\varphi = 3500$ V. This value is greater than the voltage on the electrodes at the moment of maximum current. Without a magnetic field, a structure with a positive potential value is observed at distances far from the channel. Similar results were also obtained for QSPA P-50 [13].

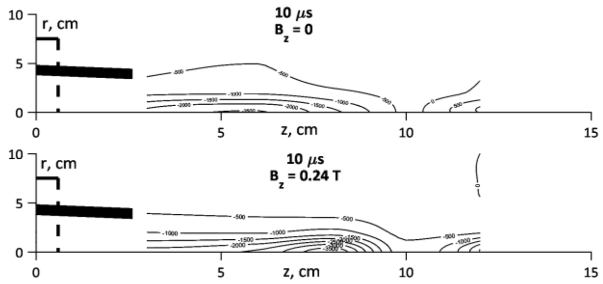

Fig. 1. Two-dimensional distribution of the electric potential φ without an external magnetic field (top) and with a field of 0.24 T (bottom). Potential values are given in volts. The discharge time is 10 μs

Since plasma acceleration and flow compression occur under the influence of *J×B* force, its spatial distribution in the plasma flow was obtained (Fig. 2). The magnitude and direction of the electromagnetic force depend on the density of the electric current and its self-magnetic field in the stream. In the figure, the vectors show only the direction of the force and do not reflect its magnitude. In both modes of operation of the MPC, both with and without a magnetic field application, in the axial zone at radii r < 3 cm at a distance of 5 to 10 cm from the cathode, the radial component of the electromagnetic force is directed towards the axis of the flow, whereas the longitudinal component is against the direction of the flow propagation.

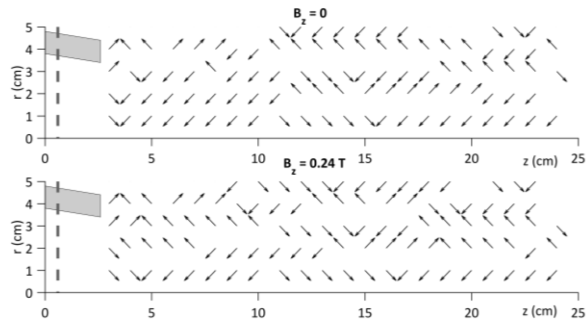

Fig. 2. Spatial distribution of J×B force in a plasma flow without an external magnetic field (top) and with a field of 0.24 T (bottom). The discharge time is 10 μs

This distribution indicates that the plasma flow is decelerated before the compression zone. At a distance > 10 cm, the direction of the longitudinal component of the force coincides with the direction of the flow, which indicates its acceleration after the compression zone. At radii over 1 cm, the radial component is mostly directed toward the wall of the vacuum chamber, which is associated with the movement of plasma to the periphery of the flow.

For a more accurate comparison of the compression characteristics of the flow of the two modes of operation, the ratio of the radial components of $J \times B$ force at a radius of r = 1 cm is plotted (Fig. 3).

As can be seen in the obtained distribution, the radial component of the electromagnetic force in the case with a magnetic field is 3–4 times greater at a distance of 8 to 11 cm from the cathode, which indicates compression of the flow in this region and is confirmed by the previously obtained "displacement" of the current isoline on current distributions [10]. This result indicates the improvement of the compression properties of the flow with an external magnetic field in the discharge channel

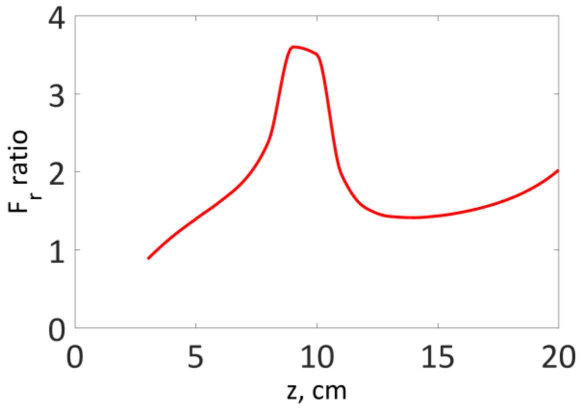

Fig. 3. Comparison of the radial component of $J \times B$ force in the case with a magnetic field with the radial component without it at a radius of r = 1 cm. The discharge time is 10 µs

Two-dimensional distributions of the electric current were obtained using the data from the measurements of the self-magnetic field outside the discharge channel of the MPC, taking into account the experimentally verified axial symmetry. Since measurements at radii smaller than 1 cm are difficult, the data for the axial region of the flow were extrapolated where necessary, considering the axial symmetry of the flow and assuming that the magnetic field on the axis of the flow is zero.

Figs. 4 and 5 show the distributions of the electric current for 12 and 14 µs of the discharge. In the case without a magnetic field, the number of toroidal current vortices decreases slightly, the magnitude of the stream currents decreases significantly, and is 20…45 kA near the outlet of the discharge channel.

It is worth noting that a decrease in the magnitude of the currents is observed in both cases in the second half-period of the discharge. This indicates that part of the magnetic field energy concentrated in the current vortices has been converted into the thermal energy of the compression zone. Also, in both cases, a slight "displacement" of the current isolines from the axial region is observed, while the displacement zone is larger in the case of a magnetic field. This indicates an increase in the size of the compression zone.

In the case of a magnetic field, the number of vortices behind the compression zone is significantly smaller. The formation of current vortices is considered to be the result of the conversion of a portion of the kinetic energy of the flow into the energy of the magnetic field [1], which, possibly, leads to a deterioration of the compression parameters. Conversely, a smaller number of vortices likely indicates a more efficient compression mode, and therefore the plasma parameters in the compression zone increase.

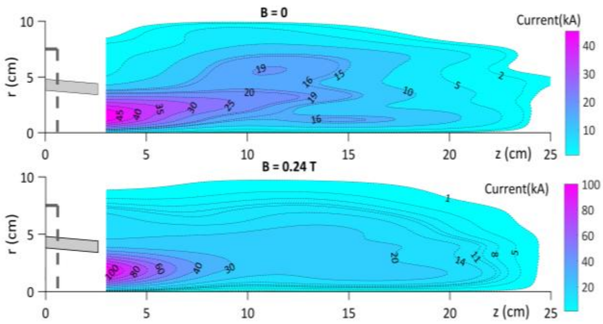

Fig. 4. Two-dimensional distribution of electric current without an external magnetic field (top) and with a field of 0.24 T (bottom). The moment of discharge is 12 µs

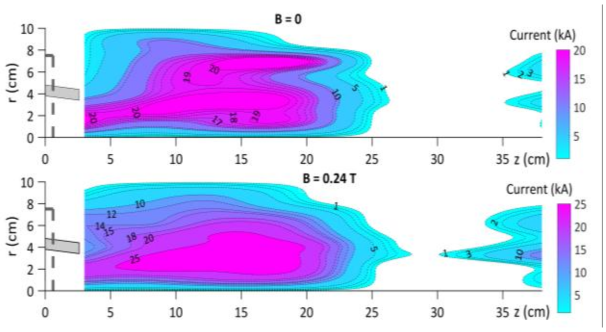

Fig. 5. Two-dimensional distribution of electric current without an external magnetic field (top) and with a field of 0.24 T (bottom). The moment of discharge is 14 µs

Both in the case with a magnetic field in the channel and without it, the kinetic energy of the flow is converted into thermal energy of the compression zone and the energy of the magnetic field concentrated in the current vortices. Therefore, since there are fewer current vortices in the case of a magnetic field, a larger fraction of the kinetic energy is converted into the thermal energy of the compression zone, and the compression is more pronounced.

CONCLUSIONS

The application of an external longitudinal magnetic field significantly affects the characteristics of the compressed plasma flow generated by a high-current plasmadynamic system. The enhancement of the compression properties of the flow evidenced by the "displacement" of the current isolines in current distributions and a notable increase in the radial component of the electromagnetic force is a key observation.

Furthermore, applying a magnetic field influences the formation of current vortices, leading to fewer of them being observed. This also suggests a more efficient compression mode and potentially leads to an increase in plasma parameters within the compression zone.

These findings highlight the complex ways in which an external magnetic field can influence plasma flow dynamics. The magnetic field not only enhances the compression of the plasma flow but also affects the energy conversion processes within the system. These insights contribute to a deeper understanding of plasma behavior in magnetic fields and have implications for the design and optimization of such devices for various applications.

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ОСОБЛИВОСТІ ПІДВИЩЕНОГО СТИСНЕННЯ ПЛАЗМИ У ЗОВНІШНЬОМУ МАГНІТНОМУ ПОЛІ

Ю.Є. Волкова, І.Є. Гаркуша, В.О. Махлай, Д.Г. Соляков, С.С. Геращенко, Ю.В. Петров, Д.В. Єлісєєв, П.Б. Шевчук, Ю.В. Сіромолот, М.В. Кулик, С.І. Лебедєв, М.М. Аксьонов, Д.Л. Греков, Т.М. Меренкова

Досліджено вплив зовнішнього поздовжнього магнітного поля на самостиснутий квазістаціонарний потік плазми, що створюється сильнострумовим магнітоплазмовим компресором. До плазмового розряду прикладалося додаткове магнітне поле величиною 0,24 Тл. Виявлено значне посилення компресії потоку під час застосування зовнішнього поздовжнього магнітного поля. Магнітне поле також впливає на процес формування вихорів струму, що пов'язаний з перетворенням кінетичної енергії в енергію магнітного поля. Утворення меншої кількості вихорів у присутності магнітного поля свідчить про більш ефективну компресію та потенційно вищі параметри плазми в зоні стиснення.