CONTROL OF THE COMPRESSION ZONE POSITION IN PLASMA STREAMS GENERATED BY MPC

D.G Solyakov[1], Y.E. Volkova[2], T.M. Cherednychenko[1], M.S. Ladygina[1], A.K. Marchenko[1], Yu.V. Petrov[1], V.V. Chebotarev[1], V.A. Makhlaj[1], V.V. Staltsov[1], D.V. Yeliseyev[1]

[1]National Science Center "Kharkov Institute of Physics and Technology", Institute of Plasma Physics, Kharkiv, Ukraine;
[2]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine

E-mail: solyakov@ipp.kharkov.ua

This paper is devoted to the investigation of magnetohydrodynamic characteristics of plasma streams generated by a magnetoplasma compressor (MPC) and control mechanisms of a compression zone position. Nitrogen, helium, and argon were used as working gases. The measurement results of electric currents spatial distributions in the plasma streams identified that for helium (P = 10 Torr) both toroidal vortices and magnetic field displacement from the near-axis region are observed, then, the electric current direction reverses. Similar spatial structure of the electric currents was observed for helium with the initial pressure of 2 Torr. However, in this case, the electric current direction changes much earlier. The electric currents flow from 20 cm to 30 cm from the central electrode of MPC accelerating channel in the modes with nitrogen (P = 0.6 and P = 0.3 Torr). There are current vortices and a sizable magnetic field displacement at a distance of a 6 cm to 18 cm from the MPC output. The duration of a plasma stream generation is about two times less for helium than for the modes of operation with other gases.

PACS: 52.40.Hf; 52.70

INTRODUCTION

Numerous studies of self-compressed high-density plasma streams explore the fundamentals of plasma physics. That is due to prospects for the development of lithography oriented applications and investigations of plasma-surface interaction [1-8]. To implement all of the possible applications it is required to provide significant mitigation of a electrodes surface erosion which is caused by a high-temperature plasma in the compression zone region [1-2]. MPC as a source of extreme ultraviolet radiation is in urgent need of reducing these adverse effects. Information on the process of the compression zone formation is essential for finding the ways to control the compression zone spatial position, which is the crucial issue that remains unsolved [1-8].

A vast majority of the previous theoretical and experimental investigations established that parameters of the compressed plasma streams and the position of the compression zone are values that strongly influenced by the distribution of the electromagnetic forces [1-5]. Two main mechanisms of the compression zone creation were analyzed earlier in the plasma streams generated by the MPC facility, namely, ballistic mechanism and electromagnetic mechanism [5-8]. In studies on the distributions of the plasma stream parameters along the vacuum channel, the ruling mechanism of the compression zone formation is discussed in detail [5-8]. The results obtained in [5] revealed that having been decelerated in the compression zone the plasma streams gain acceleration at the output from the compression region. It has been suggested that, at first, the plasma stream kinetic energy converts into the thermal energy of the compression region. Then it converts both into the kinetic energy of the plasma streams and the energy of the current vortices [5-7].

Therefore, the main aim of the current studies is to analyze the mechanisms of the compression zone formation and control of its spatial position. In that connection, we explore the control mechanisms by means of changing the initial conditions of the MPC operation that strongly affect the magnetohydrodynamic characteristics of the plasma streams.

1. EXPERIMENTAL DEVICE AND DIAGNOSTICS

All experiments were conducted with the MPC compact geometry [1-2; 5-7]. The MPC accelerating channel consists of two coaxial copper electrodes: a cylindrical rod-type anode with an outer diameter of 8 cm and a conical solid cathode with an outer diameter of 3 cm. The shape of the MPC channel (Fig. 1) was constructed in accordance with the ideal single-fluid magnetohydrodynamic model for profiled channels [5]. This model predicts the compression mode of operation if the following criteria for a profiled accelerating channel are met, namely, the average radius and width of the MPC channel should decrease along the axis [4]. The MPC is installed into the vacuum chamber with a diameter of 40 and a length of 200 cm [5].

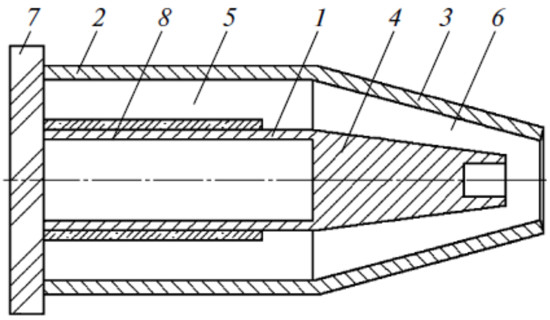

Fig. 1. Scheme of the MPC accelerating channel: 1 – cylindrical part of the cathode; 2 – cylindrical part of the anode; 3 – conical part of the anode; 4 – conical part of the cathode; 5 – cylindrical part of the channel; 6 – channel; 7 – end insulator; 8 – longitudinal insulator

The distributions of electric currents in plasma streams were measured using a set of magnetic probes in the different modes of MPC operation with residual gas. Each probe is a small shielded multi-layer cylindrical coil, 5 mm in diameter with a length of about5 mm encased in a ceramic [6]. Nitrogen, argon, and helium were used as working gases. Spatial distributions of plasma density with high resolution were obtained in plasma stream and in compression region using the Stark broadening of spectral lines [8]. The velocity of a front edge of a plasma stream was measured by the time-of-flight method between two electric probes. The average statistical error of the probe measurements was up to 10…15 %. Present experiments were performed at a voltage up to 20 kV, the maximum value of discharge current was 400 kA.

2. RESULTS AND DISCUSSION

2.1. SPACE-TIME DISTRIBUTIONS OF THE ELECTRIC CURRENTS IN PLASMA STREAMS GENERATED BY MPC

The space-time distributions of the electric currents were retrieved by measuring an intrinsic magnetic field of plasma streams for different initial conditions of the MPC operation [5-8]. The earlier studies showed that a magnetic field displacement indicates the compression zone formation in that region [5-7]. It is noticeable that there are neither toroidal vortices of electric currents in plasma streams nor displacement of a magnetic field from the axial part of a plasma stream till 10 μs of discharge for helium (P = 10 Torr). Starting from 13 μs both toroidal vortices and magnetic field displacement are observed, then, the change of electric current direction occurs at 20 μs (Fig. 2). There are similar spatial configurations of electric currents for the regime of operation with helium under initial of 2 Torr, but in this case, current direction changes earlier. These results are in a good agreement with the previous findings [1-2; 5-7].

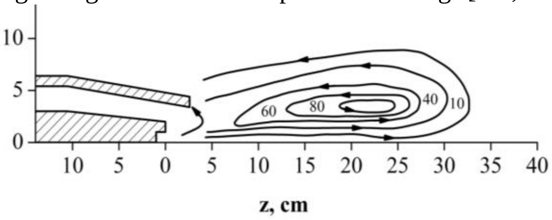

Fig. 2. Spatial distribution of the electric currents in the plasma stream for helium with the initial pressure P = 10 Torr. Discharge time t = 20 μs

There are several possible explanations for the results with a change in current direction. For example, current sheet formation [9] is considered to be the possible explanation of the discharge stages when the change in current direction occurs.

We obtained that for the mode of operation with nitrogen (P = 0.3 Torr) electric currents expand from 25 to 30 cm from the central electrode. We can observe various types of electric current spatial configurations in the plasma streams generated by MPC. The current vortices move further down the vacuum chamber starting from 10 μs, while the magnetic field displacement from the near-axis region becomes substantially increased. Figs. 3, 4 and 5 demonstrate the behavior of the electric current spatial distribution for three time moments. In the following figures, the numbers near the current isolines indicate the value of a current in kiloampere and arrows point its direction.

Slightly higher values of the nitrogen pressure (P = 0.6 Torr) lead to an enormous increase in magnetic field displacement which locates at a distance of a 7 to 20 cm from the MPC output (Figs. 6 and Fig. 7). Current vortices appear from 10 μs of the discharge and grow to a length of a 32 cm from the MPC output.

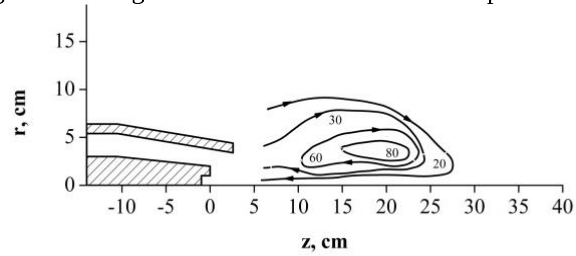

Fig. 3. Spatial distribution of the electric currents in the plasma stream for nitrogen with the initial pressure P = 0.3 Torr. Discharge time t = 10 μs

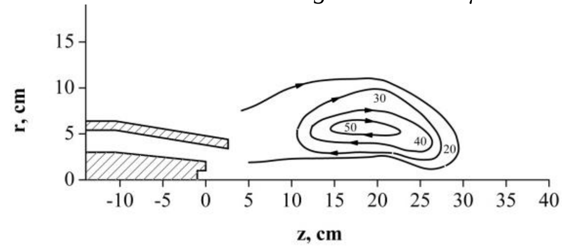

Fig. 4. Spatial distribution of the electric currents in the plasma stream for nitrogen with the initial pressure P = 0.3 Torr. Discharge time t = 12 μs

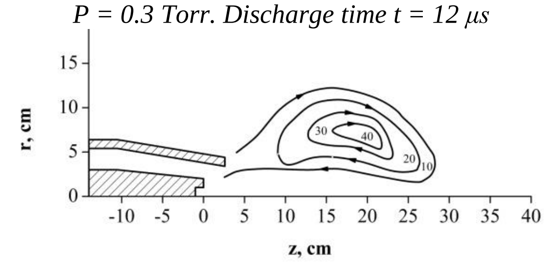

Fig. 5. Spatial distribution of the electric currents in the plasma stream for nitrogen with the initial pressure P = 0.3 Torr. Discharge time t = 14 μs

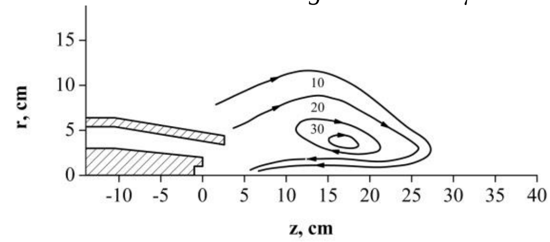

Fig. 6. Spatial distribution of the electric currents in the plasma stream for nitrogen with the initial pressure P = 0.6 Torr. Discharge time t = 13 μs

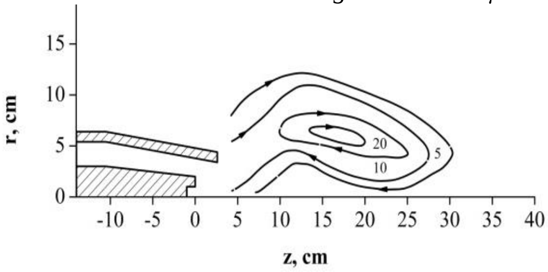

Fig. 7. Spatial distribution of the electric currents in the plasma stream for nitrogen with the initial pressure P = 0.6 Torr. Discharge time t = 15 μs

The vortices with the opposite current direction appear from 17 μs as illustrated in Fig. 8. The total value of current in plasma streams outside of the MPC channel is up to 120 kA.

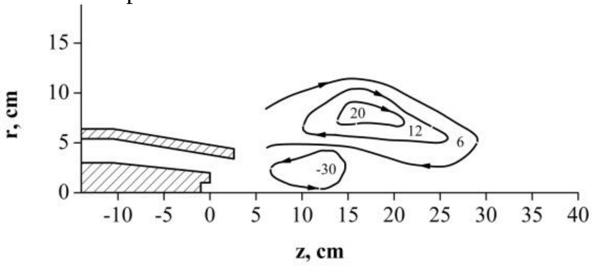

Fig. 8. Spatial distribution of the electric currents in the plasma stream for nitrogen with the initial pressure P = 0.6 Torr. Discharge time t = 17 μs

2.2. DENSITY MEASUREMENTS

For helium under initial pressure P = 10 Torr, the maximum value of a plasma electron density is located closer to the electrodes at a distance of 5…6 cm [8], as seen in Fig. 9. The maximum value of plasma density achieved n = (3…5) × 10^{18} cm^{-3} has been measured for the initial pressure P = 1 Torr of argon at a distance of 7…8 cm from the electrode ends [8]. When the initial concentration of working gas increases 10 times, the plasma density in the compression zone decreases 3…5 times [8]. For modes with nitrogen and argon, the maximum density is shifted forward from the electrode surface.

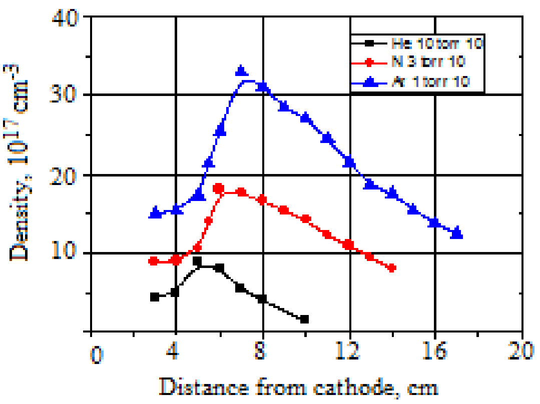

Fig. 9. Plasma density in the compression zone as a function of a distance from the MPC cathode

2.3. VELOCITY MEASUREMENTS

We measured the velocity of a front edge of the plasma stream for nitrogen (P = 3 Torr) and helium (P = 2 and P = 10 Torr) by changing the distance between the two electric probes. The first electric probe was at 7 cm from the MPC output. In the beginning, the second one was at a distance of 11 cm from the MPC output thus the length between the probes was 4 cm. Further, we changed the position of the second electrical probe to 21 cm from the MPC output, so the distance between the probes was 14 cm.

We found that for helium the duration of the plasma stream generation (the width on a half-height of the velocity curve) is 1.5…2.5 times fewer compared to other regimes. As Fig. 10 indicates, the value of the maximum velocity for nitrogen stands out as the highest one. The plasma stream velocity for considered modes of operation varies between 3×10^6 and 7.2×10^6 cm/s.

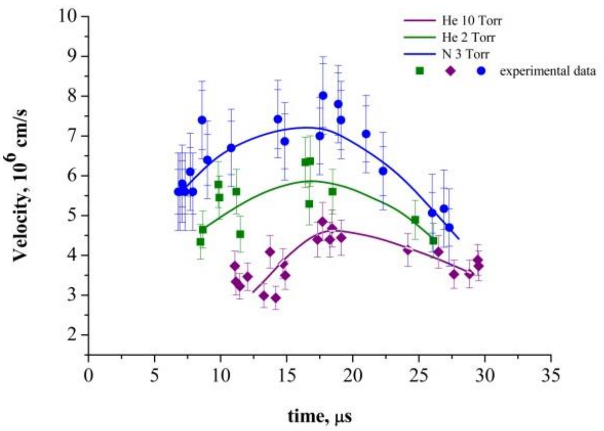

Fig. 10. Velocity of plasma stream vs discharge time. The curves correspond to the operation modes for helium with P = 10 Torr, helium with P = 2 Torr, and nitrogen with P = 3 Torr, respectively

CONCLUSIONS

These results are consistent with other investigations on electric currents distribution in the plasma streams of MPC [1-2; 5-8]: for helium, currents are closer to the MPC output, in contrast with the argon modes. There are current vortices and further magnetic field displacement from the near-axis region at a distance of 6…18 cm from the central electrode output for modes with nitrogen (P = 0.6 Torr and P = 0.3 Torr). Currents expand from 10 to 35 cm from the MPC output that depends on the MPC mode of operation. The modes with nitrogen and argon turned out to have maximum densities shifted forward from the electrode surface and a considerable magnetic field displacement from the near-axis region. The velocity measurements revealed that for helium the duration of the plasma stream generation decreases for 1.5…2.5 times in comparison with other modes. Previously it was shown that distributions of electric currents in plasma streams possess a complex spatial structure (toroidal and fan-shaped current configurations) [5-7].

In general, therefore, the results show the striking differences in current spatial distributions between the modes with nitrogen, argon, and helium. This research confirms previous findings and contributes to our understanding of how distributions of electric currents can influence the control mechanism of the compression zone spatial position.

Findings of the current study can be put into a broader context by using the information on local MHD characteristics to define unknown parameters of plasma streams [10, p. 78-102]. Furthermore, future research should concentrate on taking into account the processes that lie behind the change in the current direction in the plasma stream.

ACKNOWLEDGEMENTS

This work has been supported by National Academy of Sciences of Belarus the project № 08-01-18 and the Targeted Program of NAS of Ukraine on Plasma Physics the project № П-5/24-2018.

REFERENCES

1. A.K. Marchenko, et al. Diagnostics of plasma streams and plasma-surface interaction of essentially different duration of plasma pulses // *Prob. At. Sci. Techn.* 2016, № 6(106), p. 125-128.
2. I.E. Garkusha et. al. EUV radiation from pinching discharges of magnetoplasma compressor type and its dependence on the dynamics of compression zone formation // *Phys. Scr.* 2014, v. 161, p. 014037.
3. A.I. Morozov, A.K. Vinogradova. Stationary compressed streams // *Physics and applications of plasma accelerator*s. 1974, p. 103-141 (in Russian).
4. A.I. Morozov and L.S. Solov'ev. // *Reviews of Plasma Physics. / Ed. by M. A. Leontovich*. Moscow: "Atomizdat", 1974; New York: "Consultants Bureau", 1980, v. 8 (in Russian).
5. D.G. Solyakov, et al. Formation of a compression zone in the plasma stream generated by MPC // *Plasma Physics.* 2013, v. 39, p. 1099-1106 (in Russian).
6. M.S. Ladygina, et al. Dynamics of self-compressed argon and helium plasma streamsin the MPC facility // *Phys. Scr.* 2016, v. 91, p. 074006.
7. T.M. Cherednychenko, et al. Local MHD characteristics of the plasma stream generated by MPC// *Acta Polytechn*. 2013, v. 53 (2), p. 131-133.
8. Y.E. Volkova et al. Compression zone formation in plasma streams, generated by MPC // *Proceedings of IEEE Young Scientists Forum*, Lviv, October 17-21 2017, p. 134.
9. A.G. Frank, N.P. Kyrie. Experimental investigations of magnetic structure and plasma dynamics in current sheets (a review) // *Advances in Physical Sciences.* 2015, v. 3, №5.
10. P.E. Kovrov, A.P. Shubin. High-current coaxial plasma accelerator in quasistationary mode // *Physics and applications of plasma accelerator*s. 1974, p. 78-102 (in Russian).

Article received 15.10.2018

УПРАВЛЕНИЕ ПОЛОЖЕНИЕМ ЗОНЫ КОМПРЕССИИ В ПЛАЗМЕННЫХ ПОТОКАХ, ГЕНЕРИРУЕМЫХ МПК

Д.Г. Соляков, Ю.Е. Волкова, Т.Н. Чередниченко, М.С. Ладыгина, А.К. Марченко, Ю.В. Петров, В.В. Чеботарёв, В.А. Махлай, В.В. Стальцов, Д.В. Елисеев

Целью этой статьи является исследование магнитогидродинамических характеристик плазменных потоков, генерируемых магнитоплазменным компрессором (МПК), и механизмов управления положением зоны компрессии. В качестве рабочих газов использовались азот, аргон и гелий. Было обнаружено, что для гелия (P = 10 Торр) наблюдаются как тороидальные токовые вихри, так и вытеснение магнитного поля из приосевой области, с дальнейшей сменой направления протекания тока. Подобная пространственная структура электрических токов была получена и для гелия с начальным давлением 2 Торр. Однако, в этом случае, направление протекания тока меняется значительно раньше. В режимах работы с азотом при остаточном давлении (P = 0.6 и P = 0.3 Торр) токи распространяются на расстояния от 20 см до 30 см от центрального электрода ускорительного канала МПК. Происходит развитие токовых вихрей, с дальнейшим вытеснением магнитного поля из приосевой области на расстоянии от 6 см до 18 см от выхода МПК. Также было установлено, что для режимов работы с гелием время генерации плазменного потока почти в два раза меньше, в сравнении с режимами работы на других газах.

КЕРУВАННЯ ПОЛОЖЕННЯМ ЗОНИ КОМПРЕСІЇ У ПЛАЗМОВИХ ПОТОКАХ, ЩО ГЕНЕРУЮТЬСЯ МПК

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

Метою статті є дослідження магнітогідродинамічних характеристик плазмових потоків, що генеруються магнітоплазмовим компресором (МПК), та механізмів керування положенням зони компресії. У якості робочих газів було використано азот, аргон та гелій. Результати вимірювання просторового розподілу електричних струмів у плазмовому потоці продемонстрували, що для гелію (P = 10 Торр) спостерігаються як тороїдальні вихори струму, так і витіснення магнітного поля із приосьової області, з подальшою зміною напрямку протікання струму. Подібну просторову структуру електричних струмів було отримано і для гелію з початковим тиском 2 Торр. Проте, у цьому випадку, напрямок протікання струму змінюється значно раніше. У режимах роботи з азотом на залишковому газі (P = 0.6 та P = 0.3 Торр) струми розповсюджується на відстані від 20 см до 30 см від центрального електроду прискорювального каналу МПК. Розвиваються вихори струму із подальшим витісненням магнітного із приосьової області на відстані від 6 см до 18 см від виходу МПК. Також виявлено, що для режимів роботи з гелієм час генерації плазмового потоку майже у два рази менше, порівняно з режимами роботи на інших газах.