doi: 10.15407/ujpe62.04.0306

T.M. CHEREDNYCHENKO,[1] I.E. GARKUSHA,[1] V.O. MAKHLAI,[1] D.G. SOLYAKOV,[1]
YU.V. PETROV,[1] V.V. CHEBOTAREV,[1] M.S. LADYGINA,[1] A.K. MARCHENKO,[1]
V.V. STALTSOV,[1] D.V. YELISYEYEV,[1] V.M. ASTASHYNSKI,[2] S.I. ANANIN[2]

[1] Institute of Plasma Physics of the NSC KIPT
(1, Akademichna Str., Kharkiv 61108, Ukraine; e-mail: cherednichenko@kipt.kharkov.ua)
[2] O.V. Lykov Heat and Mass Transfer Institute of the NAS of Belorus
(Minsk, Belorus)

PACS 52.30.Cv; 52.50.Dg

CREATION OF A COMPRESSION ZONE IN THE PLASMA STEAM MPC UNDER DIFFERENT INITIAL CONDITIONS

The analysis of fundamental properties of the compression zone in the self-compressed plasma streams generated by a magnetoplasma compressor (MPC) is carried out. The main attention is attended to the research of the dependences of basic plasma parameters in a compressed plasma stream depending on the initial conditions. It has been shown experimentally that the reduction of the initial concentration of a working gas leads to an increase of the plasma density in the compression zone. The detailed studies of the spatial distributions of currents in the plasma flows are fulfilled for different initial concentrations of a substance in the accelerating channel of MPC. Under the experiment conditions, it is found that a decrease of the initial concentration of a working gas leads to the displacement of the currents from the compression zone.

Keywords: plasma dynamics, magnetoplasma compressor, compression zone.

1. Introduction

The studies of self-compressed high density plasma streams are of interest from the point of view of the fundamental principles of plasma physics and for a further development of the experimental technology in this field [1–15]. The main attention was paid to the research of common features of the formation and the dynamics of a compression area in plasma streams generated by plasmadynamic compression systems. For many years, a large number of research groups carried out the studies of this problem [2–7]. A magnetoplasma compressor (MPC) is a plasmadynamic system with stable compression zone. The basic laws of motion of the plasma stream outside the MPC channel were studied in previous experiments. The comparison of experimentally measured parameters of a plasma stream and theoretical estimates of their values was done for identical experimental conditions [9, 12, 15]. It is known [1, 15] that the density and the temperature of a compressed plasma stream strongly depend on the initial conditions at the entrance of the accelerating channel. It should be noted that a large number of experimental, theoretical, and numerical studies of plasma flows have been fulfilled for profiled channels. However, the clear criteria of selecting the initial conditions and geometry of an accelerating channel have not yet formulated for getting the compressed streams with parameters close to the theoretical limit for a compression area. Therefore, the main objective of this work was

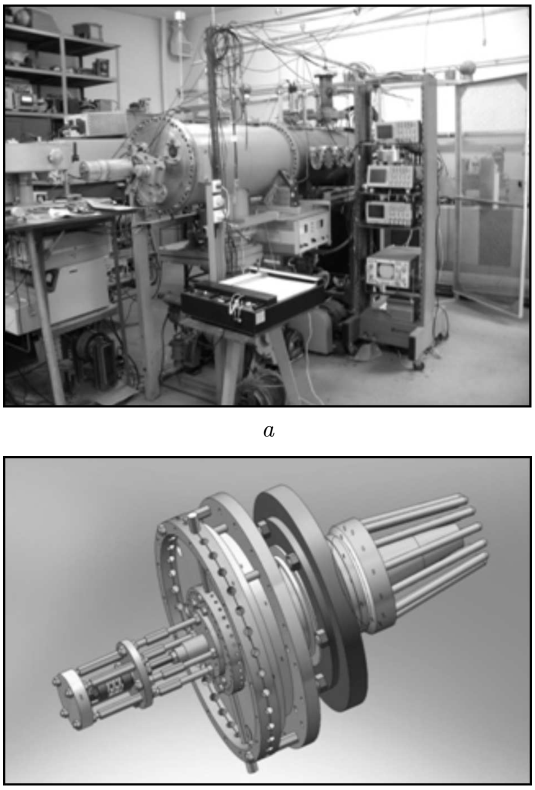
---

the study of the influence of the initial experimental conditions on the formation of compressed areas and parameters of a generated plasma stream.

2. Experimental Set-Up and Diagnostic Techniques

Experiments were carried out on the MPC facility (Fig. 1, *a*). For the realization of the compression of a plasma stream, the geometry of channels of plasmadynamic devices must satisfy some specific conditions [8, 10, 12]. For example, the average width and radius of the accelerating channel must decrease. The MPC accelerating channel [1, 8–14] (Fig. 1, *b*) is formed by copper coaxial electrodes. The outer electrode is the anode and the inner one is the cathode. The anode consists of two sections: the solid cylindrical section 120 mm in diameter and 145 mm in length and the conical rod section 147 mm in length with an output diameter of 75 mm. The solid cathode consists of the cylindrical section 208 mm in length and 60 mm in diameter and the conical section with an output diameter of 30 mm and a length of 120 mm. The anode and cathode are separated by a ring insulator with an inner diameter of 42 mm and a thickness of 20 mm. The MPC was placed in a vacuum chamber of 45 cm in diameter and 200 cm in length. The MPC discharge was supplied from a capacitor bank with a total capacitance of 90 μF and a maximum voltage of 30 kV.

Experiments were fulfilled in the mode of operation with a residual gas. Before each discharge, the vacuum chamber was filled by working gases at different pressures. As working gases, helium and argon were used. The choice of these gases was determined by the difference of their atomic weights equal to 10. At an essential change of the initial pressure in the vacuum chamber (e.g., by working with helium at a pressure of 10 Torr and argon at a pressure of 1 Torr), the effect of the initial concentration on the formation of a compressed zone and on the parameters of generated flows could be studied under an invariable integral mass flow rate. The diagnostic system of an MPC experimental stand includes Rogowski coils, frequency-compensated voltage dividers, magnetic and electrical probes, local mobile calorimeters, and a complex for the spectroscopic diagnosis. The plasma density was determined from the Stark broadening of spectral lines HeII 4685 Å, and ArII 4806 Å. Measurements were carried out along the axis of the plasma stream with a time resolution of about 0.5–0.6 ms. The spatial distributions of the intrinsic magnetic field in a plasma stream were measured by a set of magnetic probes with a maximum diameter of 4 mm. The location of probes allows measuring the radial distributions of the intrinsic magnetic field at different distances from the MPC section. Thus, we have obtained the two-dimensional distribution of the magnetic field $H_\varphi(r, z)$ in the plasma stream. The average statistical error of probe measurements was 10–15 %. From the experimentally obtained spatial distributions of the magnetic field with regard for the axial symmetry, we calculated the spatial distributions of electric currents in the flow, i.e., the lines with the same current $I(r, z) = 5rH_\varphi(r, z) = \text{const}$.



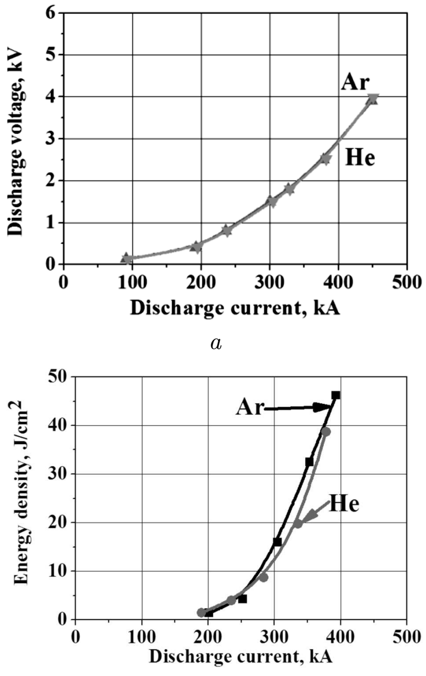
a

b

Fig. 1. General view of MPC (*a*) and the electrode system of an accelerator (*b*)

3. Experimental Results

All experiments were carried out under the follow initial conditions: pressures in a vacuum chamber



a

b

Fig. 2. VAC discharge (*a*) and the energy density in a stream (*b*)

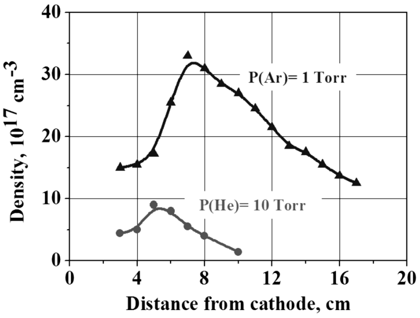
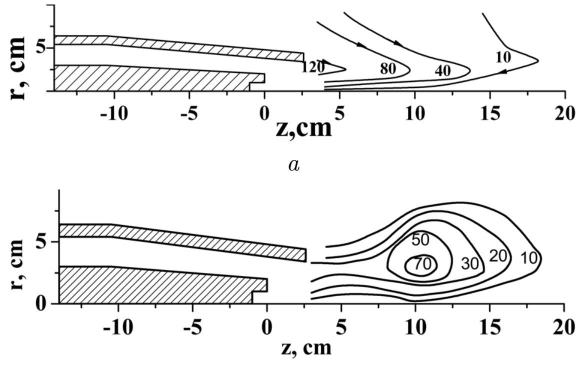


Fig. 3. Time dependence of the electron density of a plasma stream along the axis, when working with helium (10 Torr) and argon (1 Torr)

were 1 Torr for argon and 10 Torr for helium. The voltage of a capacitor bank was 20 kV. The maximum value of discharge current was 450 kA in the MPC channel and does not depend on the sort of a working gas (Fig. 2, *a*). The dependences of the energy density on the discharge current in the accelerating channel measured at a distance of 30 cm from the MPC output are shown in Fig. 2, *b*. We can see that the dependences of the voltage on electrodes and the energy density in the axial part of a plasma stream on the discharge current are almost the same for these two operating regimes. The discharge voltage and the plasma stream velocity depend on the discharge current and the mass flow rate of a working gas as $U_p \approx \frac{J_p^3}{\dot{m}}$ and $V \approx \frac{J_p^2}{\dot{m}}$ [2, 5], respectively. This indicates that the velocity of a plasma stream is not changed at the transition from helium to argon at different initial pressures, i.e., under a constant integral mass flow rate. The dependence of the maximum value of plasma density in a compression zone on the initial conditions (such as the initial concentration of a working gas, initial temperature, and discharge current in the MPC channel) can be calculated, by using the Bernoulli equation $\left(\frac{v^2}{2} + \int \frac{d\rho}{\rho} + \frac{H^2}{4\pi\rho} = \frac{H_0^2}{4\pi\rho_0}\right)$ [9–12]. The density in the compression zone $n = n_0\left[(\gamma - 1)\left(\frac{C_{A0}^2}{C_{T0}^2}\right)\right]^{\frac{1}{\gamma-1}}$, where $C_{A_0}^2 \sim \frac{H_0^2}{M_i n_0}$ and $C_{T_0}^2 \sim \frac{T_0}{M_i}$ are the Alfven and heat velocity in the accelerating channel, respectively, n_0 is the initial concentration of a working gas, H is the intrinsic magnetic field of a plasma stream, v is the stream velocity, and ρ is the density. At the adiabatic compression ($\gamma = 5/3$), the maximum plasma density in the compression zone depends on the initial concentration of a working gas as $n \sim \frac{H_0^3}{\sqrt{n_0}T_0^{3/2}}$, H_0 is the value of intrinsic magnetic field at the input of the MPC channel, and T_0 is the intial gas temperature.



a

b

Fig. 4. Lines of equal current (in kA) occurring in a plasma stream of MPC at working with helium (*a*) and argon (*b*)

The comparison of measurements of the density along the stream axis for helium and argon are shown in Fig. 3. It is obtained that the maximum plasma density in a compression zone is 9×10^{17} cm^{-3} at the initial pressure of helium equal to 10 Torr. When the atomic weight of a working gas is increased (argon) at the simultaneous decrease of the initial pressure down to 1 Torr, the initial concentration reduces by 10 times. In this case, the plasma density in the compression area is enhanced by a factor of 3.6 as compared with the helium and reaches 3.3×10^{18} cm^{-3}. The average length of the compression zone increases by 1.5–2 times. We have studied the spatial current distributions in plasma streams in order to analyze the dynamics of formation of a compression zone. The results of measurements at $t = 10$ μs correspond to the end of the first half-period of the discharge current are presented in Fig. 4. No clear formation of a compression zone is registered, when helium is used (Fig. 4, *a*). There are no toroidal vortices of the electric current in a plasma stream that is attributed to a strong compression of plasma [15]. No displacement of the current from the axial part of a plasma stream near the MPC output was observed. Currents expand to 15–17 cm from MPC. The total value of current in a plasma stream outside of the MPC channel is up to 120 kA. Before the end of the first half-period of the discharge current, a fan-like distribution of the current rises and expands to 17–18 cm from the MPC output with the use of argon, i.e. at a change of the initial concentration of the working gas. The displacement of the magnetic field and an increase of the plasma stream density are observed near the axis at a distance of 6–8 cm from the central electrode output. Thus, the spatial distributions of currents and the Ampere forces, as well as the dynamics of formation of a compression zone, depend on the initial concentration of a working gas and do not depend on the mass flow rate.

4. Conclusions

Features of the formation of a compression zone of the plasma stream outside the MPC channel under various initial conditions have been studied at a constant integral mass flow in the accelerating channel. It was possible due to the application of working gases with different atomic masses: an initial pressure of Helium – 10 Torr and Argon – 1 Torr were chosen. Simultaneous changes of kind and pressure of working gas allow keeping the mass flow rate without changes although the initial concentration changed essentially. Thus, it is possible to study the dependences of the compression zone formation and plasma stream parameters on the initial concentration of a working gas. It was shown that the integral discharge characteristics (VAC) and the energy density of the near axial part of a plasma flow do not change under changing the initial concentration of the working gas at constant values of the mass flow.

Spatial distributions of the current in plasma have been studied under different initial concentrations of a working gas in the MPC channel. It is found that a decrease of the initial concentration leads to a considerable change of the spatial distributions of currents in the plasma streams. In particular, we have observed the generation of toroidal current vortices and a displacement of the current out of the axial zone. As a result, the spatial distribution of Ampere forces in the stream has significantly changed. This leads to a partial braking of the plasma stream and to its compression toward the axis of the system [10].

It is experimentally obtained that a reduction of the initial concentration of the working gas at the invariable discharge current and integrated mass flow rate leads to an increase of the plasma density in the compression zone. In particular, when the initial concentration decreases by one order, the density increases by 3.6 times. This can be explained by a change of the distribution of electromagnetic forces in the plasma stream. The obtained results agree well with theoretical estimations based on the Bernoulli equation.

This work has been performed in the frame of research programs of the NAS of Ukraine and the NAS of Belarus, project 11-02-15.

1. O.I. Morozov. *Introduction to Plasma Dynamics* (Fizmalit, 2006) (in Russian).
2. Yu.V. Skvortsov, V.S. Komel'kov, S.S. Tserevitynov *et al.* The structure of magnetic fields in a plasma jet with intrinsic currents. *JTF*, **34** (6), 965 (1964) (in Russian).
3. A.K. Vinogradova, O.I. Morozov. *Physics and Applications of Plasma Accelerators*, edited by A.I. Morozov (Nauka i tekhnika, 1974), p. 103 (in Russian).
4. V.V. Sidnev, Yu.V. Skvortzov, V.G. Solovyeva *et al. Proc. of the XV Conf. on Phenomena in Ionized Gases* (Minsk, 1981), p. 903.
5. G.A. Diakonov, V.B. Tikhonov. Experimental studies of the influence of the geometry of an accelerating channel and the external magnetic field on modes of a plasma flow in a coaxial quasisteady plasma accelerator of the P-50A type. *Phys. Plasm.* **20(6)**, 533 (1994) (in Russian).

6. A.M. Kozlov. Study of the near-electrode processes in quasi-steady plasma accelerators with impenetrable electrodes. *Plasma Phys. Rep.* **38** (1), 12 (2012) [DOI: 10.1134/S1063780X11120051].
7. K.V. Bryshlinskyy, A.M. Zabrov, A.M. Kozlov, A.I. Morozov, V.V. Savel'ev. Numerical modeling of plasma flows in a coaxial quasisteady plasma accelerator. *Phys. Plasm.* **16** (2), 147 (1990) (in Russian).
8. O.I. Morozov, L.S. Solov'ev. *Questions of Plasma Theory*, edited by M.A. Leontovich (Gosatomizdat, 1974), p. 3 (in Russian).
9. I.E. Garkusha, V.V. Chebotarev, D.G. Solaykov, Yu.V. Petrov, M.S. Ladygina, A.K. Marchenko, V.V. Staltsov, D.V. Yelisyeyev. Compression zone of a magnetoplasma compressor as a source of extreme UV radiation. *Plasma Phys. Rep.* **38**, 110 (2012) [DOI: 10.1134/S1063780X12010047].
10. A.K. Marchenko, M.S. Ladygina, I.E. Garkusha, Yu.V. Petrov, D.G. Solyakov, T.N. Cherednichenko, V.A. Makhlaj, V.V. Chebotarev, V.V. Staltsov, D.V. Yelisyeyev, V.I. Krauz. Compression zone formation in the plasma streams generated by MPC facility operating the gases with sufficiently different masses. *Problems of Atomic Science and Technology* No. 6 (94), 83 (2014).
11. A.I. Morozov. The acceleration of a plasma by a magnetic field. *Zh. Eksp. Teor. Fiz.* **32**, 305 (1957).
12. V.V. Chebotarev, I.E. Garkusha, V.S. Ladygina, A.K. Marchenko, Yu.V. Petrov, D.G. Solyakov, V.I. Tereshin, S.A. Trubchaninov, A.V. Tsarenko, A. Hassanein. Investigation of pinching discharges in MPC device operating with nitrogen and xenon gases. *Czech. J. Phys.* **56**, 335 (2006) [DOI: 10.1007/s10582-006-0219-y].
13. D.G. Solyakov. High-power plasma dynamic systems of quasi-stationary type in IPP KIPT: Results and prospects. *Problems of Atomic Science and Technology* No. 1 (95), 104 (2015).
14. V.V. Chebotarev, T.N. Cherednychenko, D.V. Eliseev, I.E. Garkusha, A.N. Kozlov, N.V. Kulik, M.S. Ladygina, A.K. Marchenko, Ya.I. Morgal, Yu.V. Petrov, D.G. Solyakov, V.V. Staltsov. MHD characteristics of compression zone in plasma stream generated by MPC. *Problems of Atomic Science and Technology* No. 6 (82), 123 (2012).
15. T.M. Cherednychenko, I.E. Garkusha, V.V. Chebotarev, D.G. Solyakov, Yu.V. Petrov, M.S. Ladygina, D.V. Eliseev, A.A. Chuvilo. Local magnetohydrodynamic characteristics of the plasma stream generated by MPC. *Acta Polytechn.* **53** (2), 131 (2013).
16. D.G. Solyakov, Yu.V. Petrov, I.E. Garkusha, V.V. Chebotarev, M.S. Ladygina, T.N. Cherednichenko, Ya.I. Morgal', N.V. Kulik, V.V. Stal'tsov, D.V. Eliseev. Formation of the compression zone in a plasma flow generated by a magnetoplasma compressor. *Plasma Phys. Rep.* **39**, 986 (2013) [DOI: 10.1134/S1063780X13110081].

Received 20.11.15

Т.М. Чередниченко, І.Є. Гаркуша,
В.О. Махлай, Д.Г. Соляков, Ю.В. Петров, В.В. Чеботарев,
М.С. Ладигіна, А.К. Марченко, В.В. Стальцов,
Д.В. Єлисеев, В.М. Асташинський, С.І. Ананін

ФОРМУВАННЯ ОБЛАСТІ КОМПРЕСІЇ В ПЛАЗМОВОМУ ПОТОЦІ МПК ЗА РІЗНИХ ПОЧАТКОВИХ УМОВ

Резюме

Проаналізовані властивості зони компресії у самостиснених плазмових потоках, які генеруються магнітоплазмовим компресором (МПК). Основна увага приділялася виявленню залежностей основних параметрів плазми в потоках плазми, що стискаються, від початкових умов. Експериментально показано, що зменшення початкової концентрації робочого газу веде до збільшення густини плазми в зоні компресії. Проведено детальне дослідження просторових розподілів струмів, що протікають в плазмових потоках, за різних початкових концентрацій робочої речовини в каналі МПК. Встановлено, що зменшення початкової концентрації, в рамках даних експериментів, веде до витіснення струму із зони компресії.