

Calculation and Analysis of Electrophysical Processes in a High-Power Plasma Accelerator with an Intrinsic Magnetic Field

A. M. Zhukeshov^{a, *}, A. U. Amrenova^a, A. T. Gabdullina^a,
Zh. M. Moldabekov^a, and B. M. Useinov^{a, b}

^aNational Nanotechnology Laboratory of Open Type, Almaty, 050012 Kazakhstan

^bNorth Kazakhstan State University, Petropavlovsk, 150000 Kazakhstan

*e-mail: azhukeshov@gmail.com

Received January 6, 2018; in final form, September 17, 2018

Abstract—We have considered basic theoretical models describing various aspects of the formation and acceleration of plasma in pulsed accelerators. The discharge current, magnetic field, and plasma bunch velocity have been determined experimentally at different initial gas pressures in the accelerator chamber. We have considered the correspondence of some theoretical models of plasma acceleration to experimental data obtained in a KPU-30 coaxial accelerator. It is shown that the formation of the plasma in the coaxial accelerator depends on the plasma density, and acceleration processes at densities higher and lower than a certain transient density value on the order of 10^{11} – 10^{12} cm⁻³ are different. At a density higher than this critical value, the plasma is accelerated by a magnetic force. At the same time, at a low plasma density, plasma can be accelerated by an internal electric field.

DOI: 10.1134/S1063784219030277

INTRODUCTION

Pulsed plasma accelerators are not only instruments used in applied problems but are objects of investigation themselves. The principle of plasma acceleration in these devices is based on the law of interaction of a magnetic field with current, which was discovered by Ampere and is known as the electrodynamic law. The main advantage of the electrodynamic method of plasma acceleration is the possibility to overcome the difficulties associated with beam defocusing under the action of space charge forces. The quasi-neutrality of plasma makes it possible in principle to obtain several accelerated particles in a pulse. Calculations show that their velocity can attain values of 10^6 m/s and higher. Thermalization of directed energy of such beams must lead to the formation of plasma with a deuterium stagnation temperature of ~ 10 keV. Therefore, this method makes it possible to obtain high-temperature plasma flows and can in principle be used for designing fusion reactors. The plasma beam parameters (particle energy exceeding 10 keV and a density of 10^{18} cm⁻³) required for thermonuclear fusion can be obtained when the energy in the storage ring is on the order of 100 MJ, which has not been attained in experiments yet. However, on account of the plasma beam defocusing effect, the requirements to the initial plasma flux density can be

lowered. Moreover, using focusing, additional conditions for acceleration of particles with a special electromagnetic field configuration can be created.

The experimental aspects of the operation of pulsed plasma accelerators were described in detail and analyzed in 1960–1970 in the United States and Soviet Union [1–4]. It was shown that for attaining a beam velocity of $\sim 10^6$ m/s at a fixed energy of capacitive storage rings, the density of particles in the beam must be lowered. In these conditions, the discharge passed to the turbulent state. At the same time, in experiments on acceleration of relatively high-density bunches, a compact plasma shell with a low (10^4 m/s) velocity was formed in the accelerator. Its evolution can be described by comparatively simple equations [5]. The interest in pulsed plasma accelerators has increased significantly again in recent years in view of their technological potentialities [6–8]. Modern investigations of plasma accelerators were associated with the use of so-called transformers, which ensured their operation in a quasi-stationary regime [9].

Despite all advances in experiments, a unified theoretical model that would describe the entire variety of processes in plasma accelerators has not been developed yet. However, in recent years, due to achievements in the development of plasma accelerators, the possibility of plasma acceleration by electric fields has

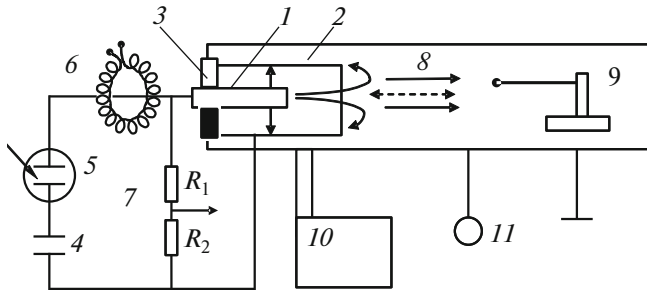


Fig. 1. Schematic diagram of the KPU-30 plasma gun and experimental technique: (1) cathode; (2) anode; (3) insulator; (4) capacitor bank; (5) switch; (6) Rogowski loop located on the cathode bus; (7) Ohmic divider; (8) plasma bunch; (9) magnetic probe; (10) vacuum pump; and (11) manometer.

appeared. The phenomenon undoubtedly plays a role in coaxial guns of the Marshal type. Therefore, it becomes necessary to compare available models with the recently obtained experimental data for developing better approaches. The dynamics of the formation of plasma bunches must be considered meticulously, and the process must be analyzed for determining possible mechanisms of ion acceleration under the action of electric fields.

1. EXPERIMENTAL SETUP

In this work, the results of theoretical calculations are compared with the experimental data obtained in recent years by the authors on the KPU-30 coaxial accelerator [10–13]. The schematic diagram of the experimental setup is shown in Fig. 1. The electrode system of this accelerator consists of copper coaxial cylinders 1 and 2, which play the role of the cathode or the anode depending on the discharge time. The diameters of the inner and outer electrodes are 90 and 26 mm, respectively, and their lengths are 450 and 400 mm. The storage system of the KPU-30 includes capacitor bank 4 of capacitance 69 μF with a working voltage of 10–30 kV. The high voltage is switched using controllable vacuum discharger 5. The discharger consists of two massive steel circular disks separated by an organic glass insulator. The breakdown of the vacuum gap occurs at triggering of the initiating spark discharge of about 5 J; for this purpose, three igniter electrodes are installed over the disk perimeter. The vacuum chamber of the accelerator is prepared in the form of a tube 16 cm in diameter and 105 cm in length. To preclude turbulent effects and nonuniformity of gas injection, the continuous filling regime was used in the KPU-30 accelerator. Prior to each shot, the chamber was evacuated by pump 10 to the limiting residual vacuum (10^{-3} Torr) and then gas (air) was puffed to attain the working pressure. This method allowed us to accurately control the plasma density and ultimately ensured the high repeatability of experiments. All

experiments were carried out at a fixed pressure of puffed gas (0.05, 0.1, 0.5, and 1 Torr).

The current was measured by Rogowski loop 6 embracing the inner electrode with 2450 turns. If the loop embraces N current buses (their total number being M), the expression for calculating the current is

$$I = \frac{2450 V_{\text{osc}}}{0.5} \frac{M}{N}. \quad (1)$$

For ratio 16 : 7 of the numbers of wires, the coefficient in expression (1) for the current is 11 200 V_{osc} . Other loops of a smaller size with 580 turns, which were installed at a certain distance from one another, were used for measuring the flow velocity in the accelerator chamber.

The voltage was measured using Ohmic divider 7. To ensure a division factor of about 1 : 10 000, we used nominal resistors with $R_1 = 510 \text{ k}\Omega$ and $R_2 = 50 \Omega$. Voltage pulses from the divider were fed to oscilloscopes via screened coaxial cables with matched impedances. The magnetic field in the electrodes was measured by magnetic probe 9. All pulsed signals were recorded on the digital storage oscilloscope with a transmission band of 300 MHz.

2. RESULTS AND DISCUSSION

In any plasma unit, the dynamics of processes is determined by the electromagnetic field configuration. Block models describing fundamental feature of the processes give the main idea of the plasma acceleration mechanisms in coaxial accelerators. One such simple model is the Artsimovich one-component model of the magnetoelectric railotron [3, 4]. In this model (Fig. 2a), we consider a circuit consisting of a source of emf $\mathcal{E}$, which accelerates the plasma bridge having current J with velocity v in the presence of external magnetic field H . Calculations show that the plasma bridge in this model performs pulsations with average velocity

$$u_E = \frac{c\mathcal{E}}{Hl},$$

coinciding with the electric drift velocity, where c is the speed of light and l is the distance traversed by the bridge.

The maximum velocity of the plasma bridge in such a circuit is attained over a rather short time after the beginning of motion, which is determined by the ratio of the electric and magnetic energies. If we take into account the Ohmic resistance of the plasma in the given circuit, oscillations will attenuate, and the bridge will move after a certain time with velocity u_E . Numerical calculations based on this model were given in our earlier publication [11], where the maximum velocity was found to be about 96 km/s, which was attained a few microseconds after the beginning of acceleration.

Let us consider the experimental results obtained on the KPU-30 device in comparison with the results of calculations based on this theory. Figure 3 shows typical curves of the discharge current and voltage across the electrode of the accelerator for the initial gas pressure of 0.1–0.05 Torr in the chamber. The data on the discharge current and voltage were obtained with the help of a Rogowski loop and a purely Ohmic divider.

It can be seen that the discharge current in the accelerator is a periodically damped signal. The half-period is almost independent of the initial pressure in the chamber. The current period increases insignificantly by 1–2 μs , while the current amplitude decreases exponentially with a decrement of $\sim 10^5$. The existence of rapidly damped oscillations at the beginning of the sweep can be due to the signal of reflection from the ends of the cable, which is typical of such measurements. In addition, the current increases very rapidly at the beginning of the discharge, attaining an amplitude of 500 kA after 3 μs . In this case, the current rise rate is 1.7×10^{11} A/s. The discharge current depends on the voltage almost linearly, indicating the absence of current slip as a result of the Hall effect, which is characteristic of plasma accelerators.

We measured the maximal plasma flow velocities at different initial pressures in the chamber (5, 0.1, and 0.05 Torr). According to the results, the maximal velocity was 3.3 ± 0.3 cm/ μs for a pressure of 5 Torr, 5.7 ± 0.3 cm/ μs at 0.1 Torr, and 4.8 ± 0.3 cm/ μs at 0.05 Torr. In order of magnitude, these velocities coincide with the estimates obtained in the electrodynamic model; however, these values are almost independent of pressure (Fig. 4).

Let us now consider the pattern of a magnetic field inside the electrode system. The oscillograms obtained using magnetic probes at a pressure of 0.05 Torr without integration and after it are shown in Figs. 5 and 6, respectively. At a low pressure of 0.05 Torr, the probe registers high-frequency oscillations of the magnetic field derivative; it is possible to get rid of these oscillations by connecting an integrating circuit with a time constant of 10–20 μs (Fig. 6). At the same time, no such oscillations were observed at a high pressure (5 Torr). We obtained experimentally a series of oscillograms for determining the magnetic field amplitude along the coaxial axis. Using magnetic probes, we obtained $B_\phi(z)$ oscillograms for different positions of the probe at the middle between coaxial electrodes at distances of 2 to 40 cm from the beginning of the outer electrode. The discharges were initiated at the same voltage (20 kV) across the capacitors and at pressures of 20 kV and pressures of 0.1 and 1 Torr.

Figures 7 and 8 show the amplitudes of the magnetic field and average velocity of the current layer in the interelectrode space at different distances from the end of the outer electrode. The average velocity was determined from the probe signals at adjacent points

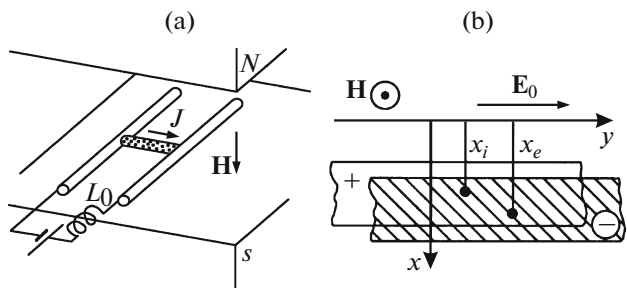


Fig. 2. Schematic diagram of (a) railotron and (b) double-block model of a plasma accelerator according to Morozov.

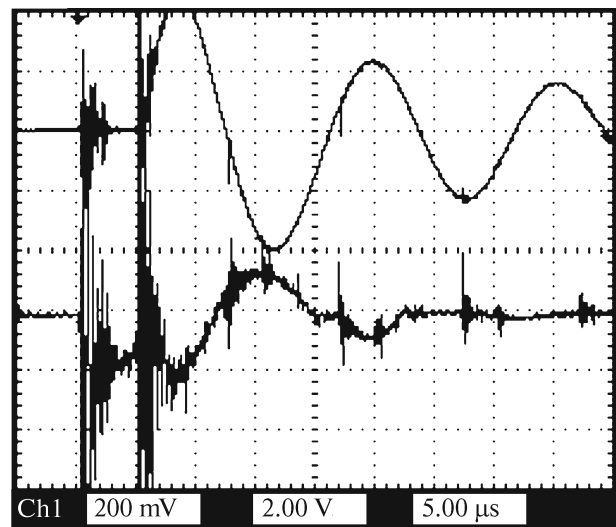


Fig. 3. Current (112 kA/mark) and voltage (20 kV/mark) oscillograms at a pressure of 0.1 Torr.

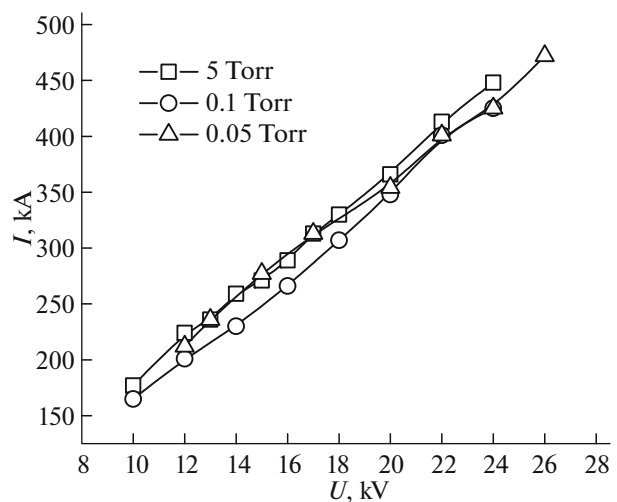


Fig. 4. Dependence of the discharge current amplitude on the voltage at different pressures in the accelerator chamber.

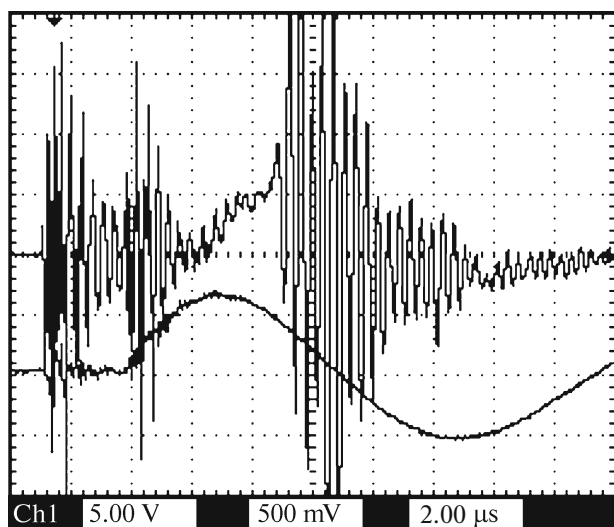


Fig. 5. Oscilloscope of the magnetic field derivative at a pressure of 0.05 Torr and of the discharge current (bottom).

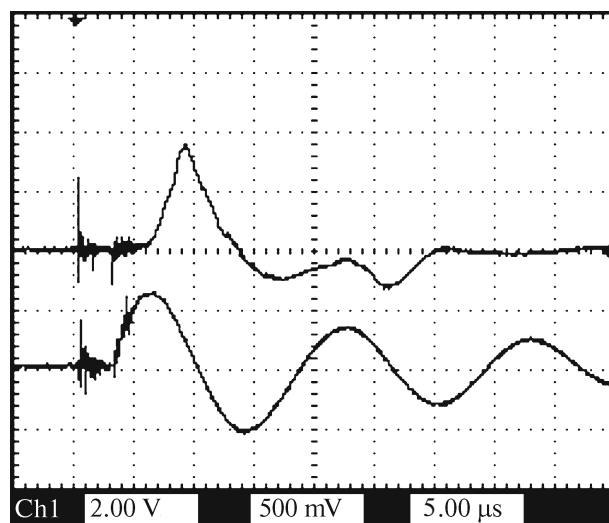


Fig. 6. Oscilloscope of (top) magnetic field and (bottom) discharge current.

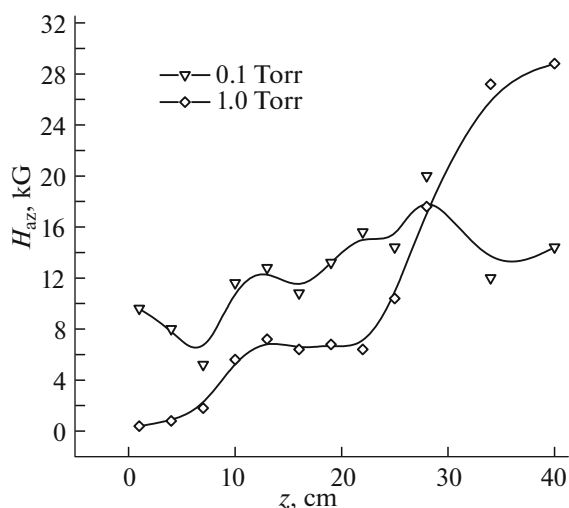


Fig. 7. Dependence of the magnetic field on the distance in the interelectrode space at pressures of 0.1 and 1 Torr.

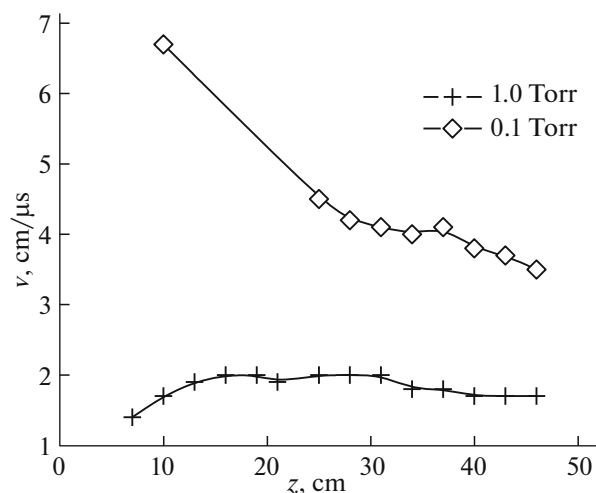


Fig. 8. Dependence of the average velocity on the distance from the electrode end at pressures of 1 and 0.1 Torr.

located on the coaxial axis and separated by 2 cm from one another. It can be seen that the mode of formation of the plasma at the low initial pressure differs significantly from that at the high pressure. At the high pressure, the magnetic field performs slow pulsations, and the plasma velocity reaches a certain value and then remains unchanged, which is generally in conformity with the railotron model. However, at a pressure of 0.1 Torr, the velocity of the current layer at the start is 3–4 times higher than that at 1 Torr. Therefore, in spite of the fact that the magnetic field amplitude at the accelerator exit is smaller at the low pressure, the plasma velocity is higher. This in no way matches the model

of a one-component plasma with a constant drift velocity.

Therefore, the main macroscopic parameters of the plasma such as the flow velocity, discharge current amplitude, and magnetic field are in agreement with the calculated values obtained using the one-component model. However, the emerging magnetic field oscillations under the low working gas pressure and the sharp increase in the flow velocity cannot be explained proceeding from this theory.

In the previous model, the plasma bunch being accelerated was represented as a current bridge with an invariable shape. However, a plasma always consists of

at least two components that move consistently with each other. Therefore, we must also consider the two-component model proposed by Morozov [14], which makes it possible not only to describe the plasma system as a whole, but also reveals the fundamental role of quasi-neutrality. The schematic diagram of the block model and the arrangement of field vectors were shown above in Fig. 2b. This diagram can be described by the following system of equations:

$$\begin{aligned} M \frac{dV_{ix}}{dt} &= eE_x + \frac{e}{c} B_0 V_{iy}; & M \frac{dV_{iy}}{dt} &= eE_0 - \frac{e}{c} B_0 V_{ix}; \\ m \frac{dV_{ex}}{dt} &= -eE_x - \frac{eB_0}{c} V_{ey}; & m \frac{dV_{ey}}{dt} &= -eE_0 - \frac{eB_0}{c} V_{ex}; \\ E_x &= 4\pi en_0(x_e - x_i), \end{aligned} \quad (2)$$

where M and m are the masses of an ion and an electron, respectively, and V_i and V_e are the velocities of the centers of mass of the ion and electron blocks.

System (2) is the projection of the Lorentz force in the Cartesian system of coordinates for the ion and electron plasma components separately. The last equation in system (2) considers the quasi-neutrality of the plasma. In the given diagram, the x direction coincides with the direction of motion of the plasma. The numerical solution of this system of linear equations was performed in the MathCAD7 medium considering the following initial conditions: the discharge voltage is 20 kV, the magnetic field is 2 T, and the initial velocity of particles is zero. We analyzed the dependence of the particle trajectory on concentration n corresponding to the working pressure in the range 0.05–0.5 Torr.

At a very low plasma density ($n \rightarrow 0$), i.e., when quasi-neutrality is not realized, the Larmor radii are obviously large for ions and small for electrons. For this reason, on account of the size of the interelectrode space (width of about 2 cm and length of about 40 cm), ions move almost vertically (in the y direction), while electrons move in the horizontal (x) direction, and these particles move practically independently from one another. Figure 9 shows the electron trajectories at different concentrations. At a concentration lower than 10^{12} cm^{-3} , motion of electrons occurs, like in the previous case, over the cycloid along the x axis. Upon an increase in the concentration, electrons are displaced along the y axis (i.e., produce a radial current), and acceleration occurs under the action of the Ampère force. Calculations show that there exists a concentration threshold on the order of 10^{12} cm^{-3} , at which ions are accelerated along the x axis due to the action of the space charge of electrons.

Therefore, electrons produce in this case current in the interelectrode space, while ions are the “purely inertial” component of the system. In such a case, space charge fluctuations must lead to Langmuir oscillations of appreciable amplitude, which were observed above upon magnetic field variation (see

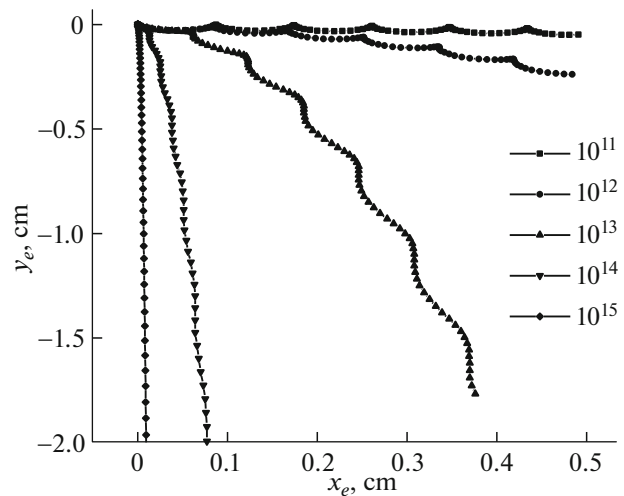


Fig. 9. Electron trajectories at different concentrations.

Fig. 5). The amplitude of these oscillations must increase with decreasing plasma density right to the instant when quasi-neutrality is violated, and we cannot speak of the plasma as such any longer.

CONCLUSIONS

Thus, the theoretical models considered here describe the main aspects of plasma formation in pulsed guns quite satisfactorily. The one-component and electrodynamic model analogous to it give only order-of-magnitude estimates of the discharge current and the bunch velocity at the initial stage, but cannot take into account the motion of the plasma over a long period. The two-component model correctly describes the main phenomena in the plasma but can be used only for describing individual stages of occurring processes. It was shown in this study that the plasma formation in a coaxial accelerator depends on the plasma density, and processes of acceleration at pressures above or below a certain transition value of density on the order of 10^{11} – 10^{12} cm^{-3} . At a density higher than this critical value, the radial electron current prevails in the plasma flow. The main accelerating force is obviously the Ampère force acting on the radial current. In this case, the velocity of the flow is lower due to the current slip over the anode because the force exerted by the magnetic field on the side of the outer electrode is significant. For a density lower than the critical value, the diffuse plasma distribution is formed, and the space charge density begins to oscillate at this instant; in this case, plasma is accelerated under the action of the electric field of the electron space charge. The instantaneous flow velocity attains thereby a higher value, but bunch deceleration can also occur for a nonoptimal length of the central electrode.

Our results make it possible to use the peculiarities of plasma accelerator operation in two different

regimes for solving various problems of science and engineering. For example, if dense bunches of relatively cold plasma are required for filling the volume and subsequent heating (e.g., in tokamaks), the high-pressure regime is applicable. If, however, a very fast particle beam is required (e.g., in material sputtering technology), the regime with a low initial pressure in the chamber can be used. Finally, the regime with continuous filling makes it possible to obtain bunches with almost identical parameters after each shot, which is very important for solving technological problems.

ACKNOWLEDGMENTS

This study was supported by the Ministry of Education and Science of the Kazakhstan Republic (grant no. BR05236730) under the program “Analysis of Fundamental Problems in the Physics of Plasma and Plasma-Like Media.”

REFERENCES

1. I. Marshall, *Phys. Fluids* **3**, 34 (1960).
2. Ph. Hart, *Phys. Fluids* **5**, 38 (1962).
3. *Plasma Accelerators*, Ed. by L. A. Artsimovich (Mashinostroenie, Moscow, 1973).
4. *Physics and Application of Plasma Accelerators*, Ed. by A. I. Morozov (Nauka i Tekhnika, Minsk, 1974).
5. V. I. Tereshin, F. N. Bandura, A. V. Bovda, et al., *Rev. Sci. Instrum.* **73**, 831 (2002).
6. J. M. Piekoszewski, *Phys. Status Solidi A* **67**, 163 (1981).
7. D. E. Potter, *Phys. Fluids* **14**, 1911 (1971).
8. V. M. Astashinskii, V. A. Man'kovskii, L. Ya. Min'ko, and A. I. Morozov, *Fiz. Plazmy* **18**, 90 (1992).
9. A. M. Zhukeshov, F. B. Baimbetov, A. U. Amrenova, and A. T. Gabdullina, *J. Eng. Thermophys.* **16**, 40 (2007).
10. F. B. Baimbetov, A. M. Zhukeshov, and A. U. Amrenova, *Tech. Phys. Lett.* **33**, 77 (2007).
11. A. M. Zhukeshov, *Plasma Deices Oper.* **17**, 73 (2009).
12. A. Zhukeshov, *J. Phys.: Conf. Ser.* **63**, 012014 (2007).
13. A. M. Zhukeshov, A. U. Amrenova, A. T. Gabdullina, and B. M. Ibraev, *Am. J. Phys. Appl.* **1**, 5 (2013).
14. A. I. Morozov, *Introduction to Plasma Dynamics* (Fizmatlit, Moscow, 2006), Chap. 1, pp. 79–80.

Translated by N. Wadhwa