SCALING OF PLASMA-FOCUSED RADIATION DISCHARGES FROM AN EROSION-TYPE MAGNETOPLASMA COMPRESSOR

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Radiation plasma dynamic discharges (PDD) from an erosion-type magnetoplasma compressor (MPC) represent the basic elements of various promising plasma systems of practical importance [1-3]. For a number of applications it is essential that we have a significant increase in the energy-evolving characteristics of such discharges (up to 10^{10}-10^{11} W, 10^6-10^7 J). The extreme difficulty in carrying out multiparametric experimental optimization in this area makes exceedingly urgent preliminary theoretical optimization. A substantial number of studies ([4-7], etc.) has been devoted to the study of such processes in these discharges, and the study program in [8-12] is directed toward that end. A serious drawback here is the inadequate degree to which one of the main operational processes has been subjected to study, namely, plasma formation through erosion, as a consequence of which in numerical models the plasma mass flow $\rho_p v_p$ had to be specified from experimentation or by means of semiempirical relationships reliable only within this particular region of energy release ($P = 10^7$-10^9 watts, $W = 10^2$-10^6 J), and for a specific geometry and working fluids. The present study represents a stage along the path toward the solution of such problems.

1. Mechanism of Plasma Formation. The MPC of the erosion type represents a system of axisymmetric electrodes between which a high-current (10^4-10^7 A) discharge is established. The plasma is formed on the erosion of the interelectrode disk, it is accelerated by the intrinsic magnetic fields within the current layer at the dielectric, and it is decelerated in the magnetic focusing at the axis of symmetry, forming the plasma focus (PF), where it emits a portion of its internal energy [7, 6, 13]. Earlier, for P = 0.05-1 GW it had been established that the erosion of a solid dielectric in the PDD of the MPC is associated with the gradient discharge flux [14], and the decomposition of the dielectric is associated with complex nonequilibrium chemical reactions [15]. At the very beginning of the discharge the role of heat transfer into the depth of the wall may be significant, and this leads to a retardation of the onset for the erosion yield of mass relative to the onset of the discharge [16]. On the basis of the data from [6, 17] semiempirical relationships have been derived in [12] for the instantaneous mass flow $\rho_p v_p$. Comparison of the calculations from [12] with experimental data from [18] demonstrated the possibility of extrapolating these relationships to 4-5 GW.

Analysis of the time relationships for the plasma flow velocities during the course of the main discharge stage indicate the inertia of plasma formation relative to energy release, and a relatively small time error $t_* \le 0.1 t_{1/2}$ ($t_{1/2}$ is the half period) leads to substantial scattering of mass in terms of velocity, and a pronounced dependence on time for the temperature and the emittance of the principal radiation zone, i.e., the plasma focus [8, 12].

Vapor ionization (that is, the formation of plasma itself) occurs in the narrow virtually locally uniform layer at the boundary between the plasma and the dielectric or its vapors. It can be demonstrated that the processes in this layer are defined by the linear current density i, A/m (or by the magnetic-field difference ΔB) and the flow of radiation S_0 absorbed in the layer. In the MPC discharges involving hydrogen, deuterium, etc., plasma formation is associated with ohmic heating [19, 20], i.e., it depends on the value of i. In analogy with erosion systems, the mass yield is usually associated with the current strength [4, 8, 12]. We are confronted with yet another series of unresolved questions, such as, for example, the unclear reasons behind the inertia in plasma formation in the main discharge stage (the heating of the dielectric [16] plays no role in this stage, while the ionization reaction time [15] is substantially smaller than t_*), still unknown are the quantitative relationships governing the formation of the radial distribution of $\rho_p v_p$, etc.

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The emittance at the focus of the MPC, however, is several orders of magnitude greater than in other zones [6, 8]; vacuum ultraviolet (VUV) predominates, the vapors are impenetrable to this radiation, and the plasma flow is semitransparent [8, 21]. It is therefore natural to assume that in the radiation MPC discharges the formation of the plasma is associated with the ionizing radiation wave (RW) in which the dielectric vapors absorb the light flux S_0 from the plasma focus, i.e., to assume the above-cited locally uniform layer values of i and S_0 that the ionization depends exclusively on S_0. Then, moving away from the extremely complex [15, 16] but less energy-consuming than the ionization of the vaporization processes (yielding, moreover, a plasma flow $\rho_p v_p$ not directly required for the calculations, but rather a vapor flow $\rho_V v_V \geq \rho_p v_p$), we come up with the following local instantaneous flow of mass

$$\rho_p v_p = \rho_0 v_0 = S_0 m_i h_{i0}^{-1}, \quad (1)$$

where ρ is the density; v is the velocity; m_i is the mass of the average ion; h_{i0} is the change in enthalpy in the RW per single ion; $h_{i0} \gtrsim I_i$, I_i is the energy of atomic ionization; the subscript 0 here and throughout denotes the parameters of the accelerated plasma flow.

We will demonstrate that such an approach is both qualitatively and quantitatively truly reflective of the unique features encountered in the formation of plasma in PDD of the erosion type and that it is possible to rely on the creation of numerical models, based on this approach, capable of solving the above-formulated problems.

On the basis of (1) we derive a true estimate of the plasma mass. Indeed, having integrated (1) over the surface and over time, we find $M_\Sigma' = m_i W \eta_\ell \eta_d / (h_{i0}(1 - \eta_d))$ (W is the energy released, η_ℓ is the light efficiency, η_d represents that portion of the radiation incident on the dielectric); on the other hand, $M_\Sigma'' \bar{v}_0^2/2 = W\eta_k$ (η_k is the kinetic efficiency, and $\bar{v}_0$ is the average velocity of the plasma). For the data from [6, 8] (η_ℓ = 12%, η_d = 0.3, η_k = 0.8, m_i = 16.7 uamu, $I_i \simeq$ 15 eV, $\bar{v}_0 = 5\cdot 10^4$ m/sec) we find that $M_\Sigma' = 5\cdot 10^{-6}$ kg $\simeq M_\Sigma'' = 6\cdot 10^{-6}$ kg.

The concept of plasma formation under the action of radiation from a plasma focus correspond to the experimental profiles of erosion mass yield. Thus, Fig. 1 shows the radial distribution for the mass yield $m' = \int \rho_p v_p 2\pi r dr$ integral in the azimuthal direction from the surface of the interelectrode dielectric insert: the calculation is carried out under the assumption that: 1) the illumination is provided by a source situated in the zone of flow deceleration, focused at an angle of 30° (the source in the PF); 2) the flow of light from the discharge plasma is uniform; 3) the light flux is proportional to ohmic heating, i.e., i; 4) the approximation m' = const, used in [8]; 5, 6, 7) the experiments in [17] in the case of an external cylindrical electrode have been carried out for energies of 1, 2, and 3 kJ, respectively. We can see that curve 1 coincides with [17], while 2 and 3 do not. Moreover, it follows from the plasma-forming disk profile shown in Fig. 2 that if a portion of the dielectric surface is shaded, for example by the internal electrode, the intensity of the erosion there will diminish markedly (1, initial shape of the dielectric; 2, its final shape after a series of discharges; 3, the radiation zone of the plasma focus; the dielectric is made of polyformaldehyde; the discharge energy is 10 kJ; the current may be as high as 0.3 MA). (The experimental data in Fig. 2 were given to us by A. S. Kamrukov, P. A. Ovchinnikov, and I. I. Telenkov.)

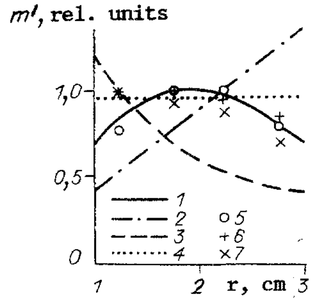

Fig. 1

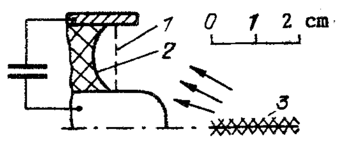

Fig. 2

Also well described is the inertia of plasma formation, associated simply with the time required for the plasma to pass from the acceleration zone to the radiation zone of the focus. Indeed, this time of passage $t_0 = v_0 d_F$ (d_F represents the distance from the dielectric to the focus) for the data from [6, 8] ($v_0 = 5 \cdot 10^4$ m/sec, d_F = 3-5 cm) is approximately equal to the inertia parameter $t_* \approx 1$ μsec, derived in [12] for the same conditions.

Thus, we have on hand a fully sufficient number of arguments in favor of the proposed hypothesis.

2. Similarity of Plasma Flows in MPC Discharges. Using the methods from the theory of dimensionality and similarity let us analyze the computational system of equations for the numerical modeling of the PDD of the MPC [8]:

$$\partial\rho/\partial t + \operatorname{div}(\rho \mathbf{v}) = 0,\ \rho d\mathbf{v}/dt = -\operatorname{grad} p + [\mathbf{j}, \mathbf{B}],$$
$$\mathbf{j} = (1/\mu_0) \operatorname{rot} \mathbf{B},\ \rho d\varepsilon/dt = -p \operatorname{div} \mathbf{v} - \mathbf{q}. \tag{2}$$

Here p is the pressure; $\mathbf{j}$ is the current density; $\mathbf{B}$ is the induction of the magnetic field; t is time; μ_0 is the magnetic constant; ε is the internal energy; $\mathbf{q}$ is the radiation term. Such an analysis shows that two quasisteady regimes are similar if the Mach number M, the Alfvén number β, the effective adiabatic exponent γ, and the radiation criterion $\Omega t = (q_x t_x)/(\rho_x \varepsilon_x)$ are equal, in addition to the geometric similarity of the boundary (the subscript x denotes the characteristic values of the parameters). The term similarity is here understood to refer to the coincidence of distribution in the dimensionless values of the functions (ρ/ρ_x, $\varepsilon/\varepsilon_x$, v/v_x, etc.) in the space of dimensionless coordinates (i.e., referred to the characteristic dimension L). Similarity allows us to construct a numerical model, describing the configuration of various discharge zones and the basic operational processes by means of a system of dimensionless coefficients C_i for each regime, and then making use of the constancy of the values of C_i in the transition to other similarity regimes characterized by other linear scales of L or energy release power P.

Results from the numerical simulation of erosion-type PDD in MPC in a vacuum, in a rather detailed formulation [8], show that such similarity is satisfied with significant variations in the values of the criteria M_0 and β_0: with a change in M_0 by a factor of 2, and by a factor of 4 in β_0 (all other conditions being equal) the characteristic dimensions of the zones, the differences in the quantities in the focus region, and other parameters characterizing the configuration of the flow and the working processes, remained constant with an accuracy up to 10-30% [8]. The weak dependence of the flow on these criteria is associated with the fact that for the discharges being examined here $\beta_0 \gg 1$ and $M_0 \gg 1$ [6] are characteristic. The values of γ for plasma-forming substances in an MPC for characteristic plasma temperatures of T_x = 2-7 eV change within limits of 5-15% [21], γ virtually does not disrupt similarity. For the criterion $\Omega_F t_F$, determining the light efficiency of the discharge, one should not expect preservation of these values; however, this criterion affects only the focus zone [8]: only $\Omega_F t_F$ is not small in comparison to unity, and no gasdynamic perturbation is propagated upstream along the supersonic flow (the subscript F here and below denotes the parameters of the plasma focus). Thus, if in this simplified model we take into consideration the effect of $\Omega_F t_F$ at least in first approximation, we might hope for adequate reliability in the description of the basic trends.

3. Numerical Model of the Discharge. Let us construct such a model for regimes similar to the one studied in [8]. According to [8], the element of plasma mass formed at the point having the radial coordinates $r_0 = C_1 L$ is accelerated to v_0 and in the time $t_0 = d_F/v_0$ moves virtually inertially ($d_F = C_2 L$ is the distance to the focus); in the compression zone this velocity drops off to $v_F = C_3 v_0$. The pressure here is determined by the actuated velocity head $p_F = \rho_{0F} v_0^2(1 - C_3)$ ($\rho_{0F} = \rho_0 r_0/r_F$, $r_F = C_4 L$ is the radial dimension of the focus), while the internal energy immediately following deceleration is defined by the enthalpy h_F, $\varepsilon_F = h_F/\gamma_F = (1 - C_3^2)v_0^2/(2\gamma_F)$. The velocity head of the flow immediately beyond the acceleration zone is equal to the magnetic pressure ahead of that zone (as a result of the conservation of momentum for this zone): $\rho_0 v_0^2 = B^2/(2\mu_0)$, $B = \mu_0 I/(2\pi r_0)$, I is the current strength of the discharge. The relationship between I and P sets the resistance of the MPC as an element of the discharge circuit, $R = P/I^2$, on the whole exhibiting an active component associated with the plasmadynamic nature of the energy release and proportional to the velocity level of the plasma [8, 12]: $R = C_5 v_0/\mu_0$. The plasma-forming radiation flow S_0 at the point r_0 at the instant of time t, required for the closure of the model with

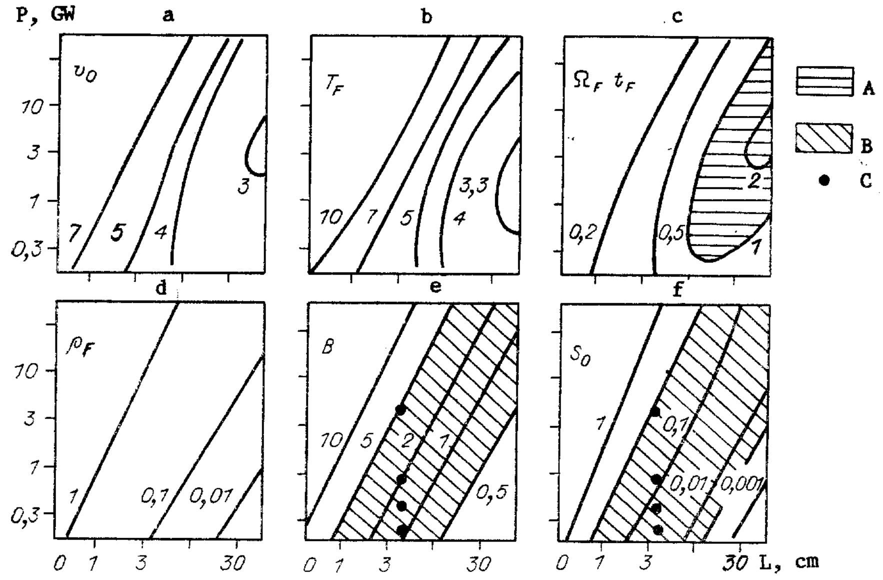

Fig. 3

the aid of (1), is calculated as $S_0(t) = E_F(t)\eta_r/(4\pi d_F^2)$, where $E_F(t) = (1 - C_3^2)C_6P(t - \Delta t)/r_F$ is the kinetic energy of the flow, transformed per unit time to the internal energy of the focus; C_6 is the fraction (in terms of kinetic energy) of those flow tubes which pass through the focus; $P(t - \Delta t)$ represents the electrical power; $\Delta t \simeq t_0$. The efficiency η_r of transition from internal energy to radiation is determined on the basis of the equation of energy from system (2), which with consideration of the approximate constancy of Ω_F, v_F, and p_F at an effective focal length of $z_F = C_7L$ [8] assumes the form $d(\rho\varepsilon)/dt = -\Omega_F(\rho\varepsilon)$, from which $\eta_r = \int q dt/(\rho_F\varepsilon_F) = 1 - \exp(-\Omega_F t_F)$, $t_F = z_F/v_F$ [i.e., the light efficiency $\eta_\ell = (1 - C_3^2)C_6(1 - \exp(-\Omega_F t_F))/\gamma_F$). In calculating q_F we take into consideration the reabsorption of radiation both within the compression zone itself and in the plasma flow. The resulting expression which correctly accounts for the contribution of the frequency ranges with large ($\tau_{nF} \gg 1$) and small ($\tau_{nF} \ll 1$) optical focal density is written as follows:

$$q_F = \sum_n (1 - \exp(-\tau_{nF}))\, 2\pi J_{np}(T_F)\exp(-\tau_{n0})/r_F,$$
$$\tau_{nF} = 2r_F\varkappa_n'(\rho_F,\ T_F),\ \tau_{n0} = d_F\varkappa_n'(\rho_0,\ T_0).$$

Here $\sum_n$ denotes summation over groups of quanta; κ_n' represents the group coefficient of absorption; J_{np} represents the integrals of the Planck function for radiation intensity; T, temperature. For a fluorocarbon plasma the function $p = p(\rho, T)$, $\varepsilon = \varepsilon(\rho, T)$ is given in accordance with the data from [21]; for electrogeometry similar to [6, 8], $C_1 = 0.32$ (for L equal to the radius of the external electrode); $C_2 = C_3 = 0.7$, $C_4 = 0.05$, $C_5 = 0.11$, $C_6 = 0.6$, $C_7 = 0.37$.

The cited relationships together with (1) make it possible to determine the main characteristics of the discharge and the parameters of the plasma on the basis of the given values of the scale L and the power P of the energy release (the latter may be calculated from the Kirchhoff equation for the discharge circuit) without any experimental data with respect to regime, i.e., these relationships represent a numerical model whose only empirical parameter is $T_0 \simeq 1.6$ eV, and as demonstrated below, constant over a broad range of parameters. This model is valid for regimes in which the proposed approach to the description of plasma formation is applicable, while the values of M_0 and β_0 differ from the basis values by factors of less than 2 and 4.

4. Analysis of Calculations and Comparison with Experiment. The computational results based on the model described here for quasisteady discharges are shown in Figs. 3 and 4. The range of regimes encompasses the region of energy release and the linear dimensions which exceed, by an order or two, those experimentally studied. Figure 3 shows the theoretical values of the characteristic parameters for the quasisteady MPC discharges for various P and L (electrodes with an end-face geometry such that the diameters are 2L and L/2, and the plasma-forming dielectric is made of Teflon): a) the velocity of the plasma in front

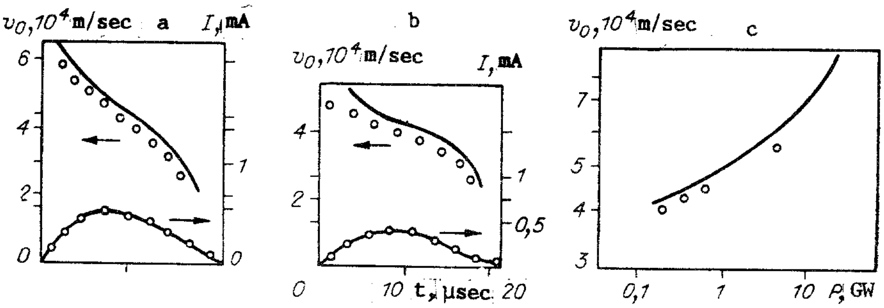

Fig. 4

of the focus (10^4 m/sec); b) the temperature at the focus (eV); c) the radiation factor; d) the density of the plasma at the focus (kg/m^3); e) the induction of the magnetic field at the dielectric (3.5 T); f) the light flux out of the plasma at the boundary with the dielectric vapors (10^7 W/cm^2). A identifies the region of regimes with the greatest $\Omega_F t_F$; B identifies the regimes in which the model has been validated; C represents the regimes studied experimentally in [6, 18]. Figure 4 shows a comparison of the theoretical (curves) and the experimental (points) from [6, 18] for the relationships between the discharge current and the velocity of the plasma flow as functions of time (a, for the initial voltage of 5 kV to the capacitive storage; b, 3 kV) as well as functions of the energy release power at maximum current (c).

For the greater portion of these regimes the theoretical values of M_0 fall within limits of $(0.65\text{-}1.2)M_{B0}$, while β_0 – $(0.5\text{-}1.6)\beta_{B0}$; M_{B0}, β_{B0} represent the values of M_0, β_0 in the basis regime,* i.e., the approximate similarity of flow configuration in the region shown in Fig. 3 must be maintained. For regimes corresponding to those investigated in [6, 18], the theoretical values of M_0 vary within limits of ±12%, while for β_0 they vary within limits of ±25% (similarity for these must be satisfied with great accuracy). The comparison of the computational results with the experimental data may then point to the reliability with which the processes of plasma formation are described, since the description of the remaining basic working processes have been rather well validated. Such a comparison has been undertaken in Fig. 4 for the velocity of the plasma flow, i.e., a reliably measured parameter directly associated with the plasma flow rate. For the case in which $0.1 < P < 4.3$ GW we have achieved good qualitative and quantitative agreement. In the given case this corresponds to approximate constancy of the level of velocities as P increases, i.e., proportionality of flow rate and power (such a result is nontrivial, since the emittance of the plasma at the focus increases more rapidly than the linear law, and compensation occurs primarily owing to the narrowing of the transparency band for the plasma flow, with the increase in its optical thickness a result of an elevation in the density level). Thus, the approach proposed for the description of the plasma formation properly reflects the relationship between the plasma flow rate and the power for the case in which L = 4 cm = const within limits of $0.1 < P < 4.3$ GW.

The rapid rise in the velocities (or the sharp reduction in the flows of mass, referred to the power of the energy released) outside of the indicated power range for the given scale (see Fig. 3) is associated with the reduction in the light flows coming in from the focus: with small P, due to the low emittance, and for large P due to the nontransparency of the plasma flows. In the former case, no growth in v_0 is noted in the experiments, other processes arise primarily in the plasma formation, and the proposed approach is not suitable. No experimental data are at hand for high powers, and the question as to the suitability of this approach remains open.

According to calculations, along the line PL^{-2} = const with an accuracy of ≈15% the levels of the magnetic fields and flows of light to the boundary between the plasma and the dielectric are maintained (the boundary conditions for the locally uniform plasma-forming layer). From this we conclude that if the description of this layer is applicable to any regime, it will then be suitable also for the entire family of similar regimes with

*The basic regime according to which values of M_{B0} and β_{B0} are determined corresponds to the maximum energy evolved in the discharge that has been studied in greatest detail, namely: P_B = 0.8 GW and L_B = 4 cm [6, 8].

PL^{-2} = idem. The approach proposed for the description of plasma formation, based on the concept of the heating of the plasma in radiation waves and on the constancy of T_0 can be utilized for a rather broad range of regimes, including the region of energy release where the power is greater by an order for two of that achieved experimentally, and for many of these regimes the conditions of flow similarity are satisfied, i.e., the suitability of the model is validated here.

Hence it follows that within the limits of the indicated range of parameters, in accordance with the calculations, the level of velocities and temperatures changes relatively slightly, the density of the plasma and pressure rise monotonically with an increase in power when L = const and change only slightly along the PL^{-2} = const curves. The scaling which provides for retention of the levels of such local plasma-flow parameters as velocity, density, temperature, magnetic-field induction, current density, pressure, the absorption factor, the radiant flux, and others, is achieved on satisfaction of the condition PL^{-2} = const, and the experimental execution of powerful discharges may, to a considerable extent, be accomplished in regimes similar in terms to PL^{-2} with a moderate energy release. Of considerable interest is the study of regimes with $PL^{-2} \geq 10^{12}$ W/m^2 which have not been studied: the effectiveness of discharges exhibiting the end-face geometry dealt with here under these regimes can be substantially greater than the theoretical, owing to an increase in the luminescent body, the heating of the plasma flow by current and by radiation, etc. Let us note that such regimes can be achieved with a moderate power of $\approx 0.5 \cdot 10^9$ W for an MPC exhibiting dimensions of 2L < 1.5 cm.

Given the identical MPC construction, the values of the radiation criterion $\Omega_F t_F$ (consequently, and of the light efficiency) exhibit a power maximum whose position, as the MPC scales increase, shifts into the region of large energy releases. Among these regimes with PL^{-2} = idem the more effective system is the one with large electrode dimensions, since the mass element, although having the same emittance, must remain for a longer period of time in the high-pressure zone and more fully emit its internal energy. It is significant that among regimes with high electrical power there are such whose light efficiency is in no way lower than that achieved experimentally with moderate energy release [6], but in fact exceed these significantly. The specific values of the parameters relate to the specific shape of the electrodes and the fluorocarbon plasma; however, one should expect preservation of the qualitative form of the relationships and on transition to other geometric relationships and working substances (in particular, the thermodynamic functions and the relationships of the optical properties in the VUV for the characteristic plasma-forming substances of the MPC are close to one another [21-22]).

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LITERATURE CITED

1. A. I. Morozov, Physical Fundamentals of Electroreactive Space Engines [in Russian], Vol. 1, Atomizdat, Moscow (1978).
2. A. S. Kamrukov, N. P. Kozlov, and Yu. S. Protasov, "Generators of laser and powerful thermal emissions, based on high-current plasmadynamic discharges," in: Plasma Accelerators and Ion Injectors [in Russian], Nauka, Moscow (1984).
3. A. S. Kamrukov, N. P. Kozlov, and Yu. S. Protasov, "Plasmadynamic sources of a continuous spectrum," Dokl. Akad. Nauk SSSR, 239, No. 4 (1978).
4. Yu. A. Alekseev and M. N. Kazeev, "Numerical modeling of two-dimensional flows in pulsed plasma accelerators," Fiz. Plazmy, 7, No. 5 (1981).
5. I. S. Gushchin, Yu. P. Popov, and V. V. Savichev, "The calculation of nonsteady plasma acceleration with consideration of dielectric ablation," Fiz. Plazmy, 2, No. 5 (1976).
6. A. S. Kamrukov, N. P. Kozlov, and Yu. S. Protasov, "The dynamics and radiation of open (vacuum) plasmadynamic discharges of the 'plasma focus' type," Teplofiz. Vys. Temp., 20, No. 2 (1982).
7. L. A. Artsimovich, S. Yu. Luk'yanov, N. M. Podgornyi, and S. A. Chuvatin, "Electromagnetic acceleration of plasma clusters," Zh. Éksp. Teor. Fiz., 22, No. 7 (1957).
8. N. V. Ardelyan, A. S. Kamrukov, N. P. Kozlov, et al., "Numerical modeling of radiation plasmadynamic discharges from an erosion-type magnetoplasma compressor," Dokl. Akad. Nauk SSSR, 292, No. 3 (1987).

9. N. V. Ardelyan, A. S. Kamrukov, N. P. Koslov, et al., "Magnetogasdynamic effect on interaction with gas of erosion plasma flows from a magnetoplasma compressor," Dokl. Akad. Nauk SSSR, 292, No. 1 (1987).
10. A. S. Kamrukov, N. P. Kozlov, Yu. S. Protasov, and S. N. Chubashev, "Radiation-gas-dynamic processes in cumulative plasmadynamic MPC discharges," Zh. Teor. Fiz., 55, No. 3 (1985).
11. A. S. Kamrukov, N. P. Kozlov, Yu. S. Protasov, and S. N. Chubashev, "The nature of micrononuniformities of radiation plasma flows," Pis'ma Zh. Tekh. Fiz., 11, No. 23 (1985).
12. A. S. Kamrukov, N. P. Kozlov, Yu. S. Protasov, and S. N. Chubashev, "Calculating the parameters of the plasma flow of a pulsed erosion plasma accelerator," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1984).
13. K. V. Brushlinskii, N. I. Gerlakh, and A. I. Morozov, "The influence of finite conductivity on steady self-compressed plasma flows," Dokl. Akad. Nauk SSSR, 180, No. 6 (1968).
14. V. Ya. Gubarev, N. P. Kozlov, L. V. Leskov, and Yu. S. Protasov, "Determining the heat flow from a plasma to a dielectric in pulsed erosion accelerators," in: Plasma Accelerators [in Russian], Mashinostroenie, Moscow (1973).
15. Yu. A. Alekseev and M. N. Kazeev, "Pulsed vaporization of an insulator in plasma accelerators, with erosion," Preprint No. 3000, Akad. Nauk SSSR, IAÉ, Moscow (1978).
16. V. V. Savichev, "Calculating the velocity of dielectric mass entrainment in a pulsed discharge," in: Problems in the Physics of Low-Temperature Plasma [in Russian], Nauka i Tekhnika, Minsk (1970).
17. L. V. Leskov, M. Z. Mukhoyan, and V. V. Savichev, "An investigation into the pulsed electromagnetic source of erosion plasma," ibid.
18. V. V. Vladimirov, I. I. Divnov, A. S. Kamrukov, et al., "The magnetoplasma compressor with a magnetic explosive generator of energy," Zh. Tekh. Fiz., 50, No. 7 (1980).
19. K. V. Brushlinskii and A. I. Morozov, "Calculating the two-dimensional flow of a plasma in channels," in: Problems in the Theory of the Plasma [in Russian], Issue 8, Atomizdat, Moscow (1974).
20. S. I. Ananin and T. A. Lepshei, "Numerical modeling of the dynamics of compression plasma flows by the large-particle method," Dokl. Akad. Nauk BSSR, 27, No. 8 (1983).
21. A. S. Kamrukov, N. P. Kozlov, Yu. S. Protasov, and S. N. Chubashev, "Optical and thermodynamic properties of a fluorocarbon plasma," Teplofiz. Vys. Temp., 24, No. 1 (1986).
22. A. S. Kamrukov, N. P. Kozlov, Yu. S. Protasov, and S. N. Chubashev, "Optical and thermodynamic properties of a polyformaldehyde plasma," Zh. Prikl. Spektrosk., 43, No. 6 (1985).