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Mathematical Simulation of a Low-Pressure Capacitive RF Discharge in an External Radial Magnetic Field Using the KARAT Code

I. I. Zadiriev[a]*, A. A. Rukhadze[a], E. A. Kral'kina[b], K. V. Vavilin[b], V. B. Pavlov[b], and V. P. Tarakanov[c,d]

[a] *Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, Moscow, 119991 Russia*
[b] *Lomonosov Moscow State University, GSP-1, 119991 Moscow*
[c] *Joint Institute for Low Temperatures, Russian Academy of Sciences, Izhorskaya ul. 13/19, Moscow, 125412 Russia*
[d] *National Research Nuclear University MEPhI, Kashirskoe sh. 31, Moscow, 115409 Russia*
**e-mail: iizadiriev@gmail.com*

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Abstract—A high-frequency capacitive discharge is simulated in the geometry of a plasma accelerator with closed electron drift. It has been shown that, in such a discharge, as in a dc discharge, an azimuthal electron drift takes place and a potential drop is formed at the discharge channel exit, which leads to the emergence of an accelerated ion beam from the channel.

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INTRODUCTION

Vast scientific information has been globally accumulated on dc discharge in a magnetic field with a predominant radial component. Apart from the fact that such discharge has been the object of intense fundamental studies during several last decades, it has found practical application as the working process in Hall-effect electric thrusters [1, 2]. Despite the more than the 40-year history of application, some fundamental questions remain the subjects of active investigation and discussion [3]. This primarily concerns the mechanisms of current transport from the cathode to the anode across magnetic field and the physical reasons of many types of oscillations emerging in the discharge [1, 4].

The main physical idea behind the working process of the Hall thruster is the organization of the azimuthal electron drift in crossed longitudinal electric and radial magnetic fields [3]. The electric field in the channel near its exit appears due to the cathode potential drop. The plasma in the channel is maintained due to ionization of the gas by electrons emitted from the cathode. In accordance with the prevailing patterns of physical processes occurring in the discharge, a considerable contribution to the electron transport from the cathode to the anode comes not only from the collision of electrons with other plasma particles, but also from processes associated with near-wall conduction [1], the emergence of drift instability, and the generation of secondary electrons in collisions of electrons and ions with the channel walls [4–6].

It is known that, in a capacitive high-frequency (rf) discharge, space charge layers in which quasi-stationary electric fields are induced are formed near the electrodes [7]. It can be proposed that the presence of the radial magnetic field will lead to the azimuthal drift of electrons in the regions of localization of the space-charge layers. At the same time, the rf discharge does not require metallic electrodes to be in contact with the plasma or the emitting cathode layer to be sustained. This eliminates the difficulties associated with the correct description of electron transport in the discharge channel and solves the problem of the redeposition of metal due to electrode sputtering. These considerations stimulate the analysis of the possibility of using a capacitive rf discharge with a radial magnetic field as the working process in electric propulsion and ion sources. In this study, we solve this problem using mathematical simulation.

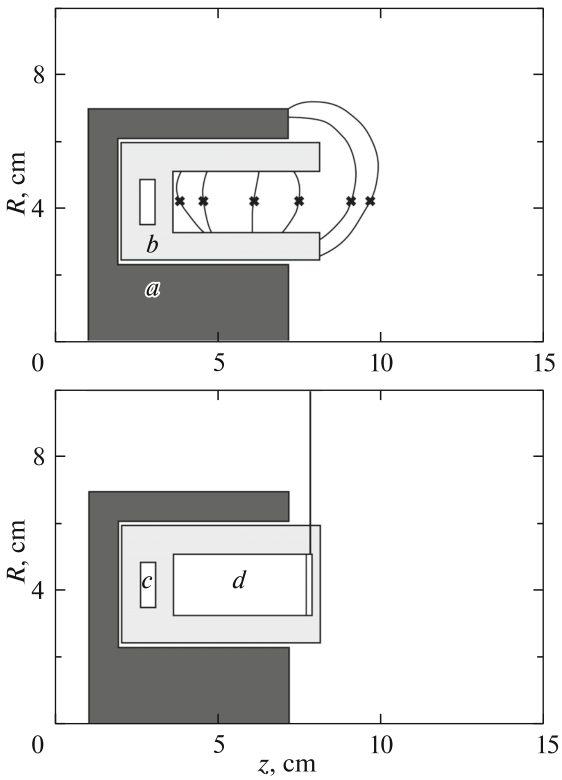

Fig. 1. (top) Basic geometry of the simulated region with the magnetic field lines passing through the points marked by crosses and (bottom) the arrangement of the electrodes in the case of the closed channel. Notation: (*a*) conducting shell; (*b*) dielectric channel; (*c*) active electrode; and (*d*) grounded electrode.

1. CALCULATION TECHNIQUE

Numerical simulation of physical processes in a capacitive rf discharge in an external radial magnetic field was performed using the 2D axisymmetric nonrelativistic version of the KARAT code [8] in which the time-dependent Maxwell equations are solved with various constitutive equations. In this study, the plasma is simulated by the particle-in-cell (PiC) method taking into account all components of particle velocities. The applicability conditions for the computational algorithm are as follows: the grid pitch is much smaller than the minimal size of any geometrical object being simulated as well as the Debye length of the plasma; the time step is much shorter than any characteristic time of the system (including the period of Langmuir oscillations, the period of rotation in the magnetic field, and the mean free time of particles), and both the cell and the Debye sphere contains several tens of PiC particles. These requirements are met in the results reported here. Since the time when the code was written [8], comparison with the available analytic and experimental results and with the numerical results obtained by other groups has been performed.

The computational domain was a cylinder 15 cm in length and 10 cm in radius. The geometry of the plasma source was close to the geometry of a Hall thruster [1] (Fig. 1). Here, we consider three cases. In the first case, the discharge channel was closed by electrodes at the ends. An rf voltage was applied to the left electrode and the right electrode was grounded. In the second case, the right electrode was brought by parallel translation beyond the channel. In the third case, the right electrode was displaced to the computation domain boundary so that its surface did not cover the exit of the channel. We calculated the field of the toroidal active electrode to which a harmonic rf voltage with a frequency of 12.5 MHz and an amplitude in the range of 0.5–2.0 kV was applied. At the initial instant, we specified in the computational domain a density of neutral xenon atoms with a constant concentration in the channel and an order-of-magnitude lower concentration outside the channel, as well as the initial plasma that consisted of ions and electrons with a concentration of 10^{10} cm^{-3}. During numerical simulation, we considered the dynamics of charged plasma particles in the applied and intrinsic self-consistent electric fields. For collisions of electrons with the surfaces of the grounded electrode of the dielectric channel, we simulated secondary electron emission using the simplest model with a constant secondary ion–electron emissivity $\gamma = 0.1$. In the bulk, we simulated elastic and ionizing collisions of electrons with xenon atoms with concentrations ranging from 3×10^{13} to 3×10^{14} cm^{-3}. The relevant collision cross sections were borrowed from [9]. The electron–ion pairs formed as a result of ionization were included in the simulation thus conducted for an increased plasma density. A current of 0.01, 0.1, and 1 A that corresponds to the thermoemission current was emitted from the grounded electrode. The magnetic field induction was in the range of 50–200 G. To reduce the computer time, we assumed that ion mass M is equal to 2000 electron masses m.

As a rule, the calculated evolution time of the system was 8 μs. As a result of simulation, we recorded the final parameters of the numerical system in the case when the plasma concentration in the discharge channel averaged over a period of rf oscillations attained the steady-state value on the time interval being simulated. Otherwise, the concentration either dropped to zero, i.e., the initial plasma spread, and the discharge was assumed to be extinguished in these conditions, or the concentration reached a value on the order of 10^{12} cm^{-3}, and the computer time required to calculate such a system in the given numerical model was too long (in view of the required reduction of the grid pitch and the time step).

The computational model described above was tested for a dc glow discharge in a cylindrical vessel with planar electrodes at its ends and for a capacitive rf discharge in the same geometry (the frequency of the

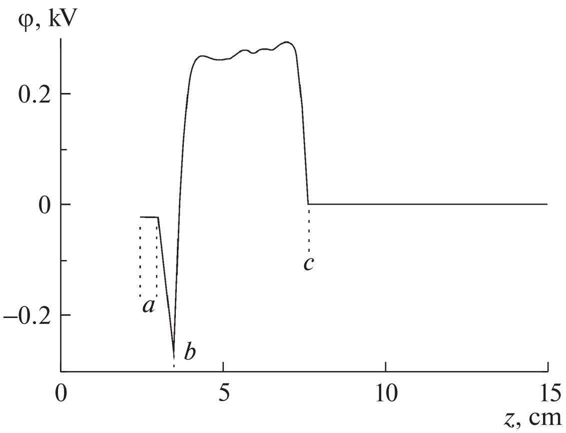

Fig. 2. Instantaneous potential distribution in a closed discharge channel ($R = 4.25$ cm).

voltage across the electrodes was 12.5 MHz), after which the results were compared with the experimental data obtained earlier. It was found that the simulation correctly reproduced the qualitative structure of the near-electrode layers and the central regions of the rf discharge plasma and the dc discharge plasma. However, the ion concentration in the entire discharge turned out to be 1.5 times lower than the experimental value, which can be explained by the artificial reduction of the ion mass to 2000 electron masses. In the cases when this reduction was not performed, the concentration approximately corresponded to the experimental value (to within 10% of its magnitude). The secondary ion–electron emissivity $\gamma = 0.1$ was selected for the best matching of the results of the simulation and experimental data.

2. RESULTS OF CALCULATIONS

The numerical simulation has shown that the main properties of a capacitive rf discharge are preserved in the presence of a radial magnetic field. Figure 2 shows the instantaneous distribution of the plasma potential over the channel length. It can be seen that its form is typical of a capacitive discharge, including the space charge layers in which a substantial potential drop is observed are formed near the electrodes, while the region at the center of the channel is characterized by the almost constant value of the potential.

Figure 3 shows the time dependence of the rf electric field components near the active and grounded electrodes. It can be seen that, first, the longitudinal rf field near electrodes varies inharmonically and, second, it has a constant (in time) component ensuring the quasi-stationary potential drop at the electrodes.

Figures 4 and 5 show the distributions of the concentration and kinetic energy of electrons and ions along the channel axis. It can be seen that the plasma is formed in the central part of the channel, where the

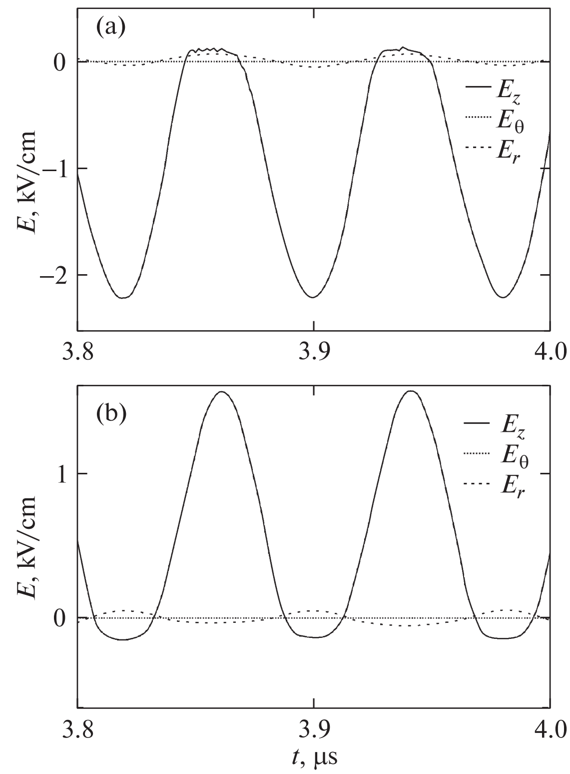

Fig. 3. Time dependence of the electric field components near the active (a) and grounded (b) electrodes.

potential drop is insignificant. The mean electron energy in the region of near-electrode layers of the space charge is substantially higher than in the central region. Electrons generated in it as a result of the ion–electron emission and accelerated by near-electrode fields in the direction to the plasma possess the highest energy near the active electrode. The kinetic energy of electrons emitted from the grounded electrode is also high in the vicinity of this electrode. Ions are in turn accelerated by quasi-stationary fields in the direction from the plasma to the electrodes. This makes it possible to obtain an accelerated ion beam at the open exit of the channel.

The presence of a radial magnetic field manifests in the emergence of the azimuthal electron drift in the near-electrode regions (Fig. 6). It should be noted that electrons emitted from the surface of the grounded electrode that drift along the azimuth in crossed $\mathbf{E} \times \mathbf{B}$ fields are localized near this electrode because their propagation to the bulk of the plasma is limited by the radial magnetic field. In the discharge geometry in which the right electrode is removed from the channel, emitted electrons do not enter the channel because these particles are confined by the radial magnetic field outside the channel (Fig. 7).

It should be emphasized that emissions from one of the electrodes are not necessary for sustaining a capacitive rf discharge in an external magnetic field.

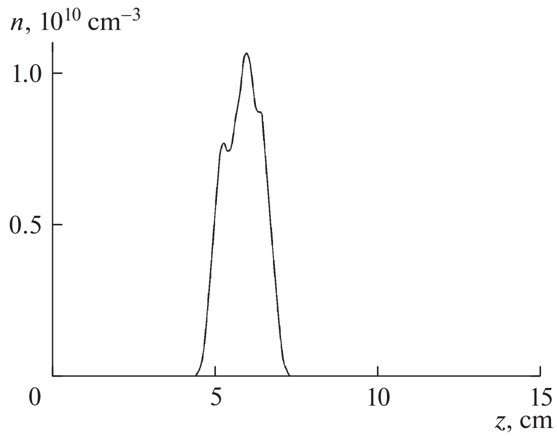

Fig. 4. Ion density distribution along the discharge channel.

The discharge is sustained due to the dissipation of the energy of rf fields as a result of collisionless, as well as collisional mechanisms [7]. The enhancement of electron emissions from the earthed electrode is generally accompanied by an increase in the plasma density and the narrowing of near-electrode space-charge layers. However, the increase in the emission current simultaneously lowers the near-electrode potential at the grounded electrode, which is connected with the partial compensation for the space charge of positive ions by emitted electrons.

Calculations have shown that an increase in the external magnetic field induction is accompanied by an increase in the plasma density; however, in this case, the ion energy decreases (Fig. 8). The increase in the atomic concentration and the amplitude of the rf voltage applied to the electrodes leads to an increase in the plasma density, while an increase in the rf voltage leads to an increase in the ion energy at the exit of the discharge channel.

The results of mathematical simulation described above were partly verified later in experiments [10] in which the ion flow formed in a capacitive rf discharge in a radial magnetic field was investigated. In the entire range of discharge powers analyzed in [10], the rf voltage amplitude almost remained unchanged and amounted to approximately 450 V, which differs substantially from the result of numerical simulation in which the concentration of the initial plasma at the amplitudes of the voltage at the active electrode lower than 700 V did not attain the steady-state value and uniformly decreased to zero, i.e., the discharge being simulated was suppressed. However, all dependences of the parameters of the ion flux (its density and aver-

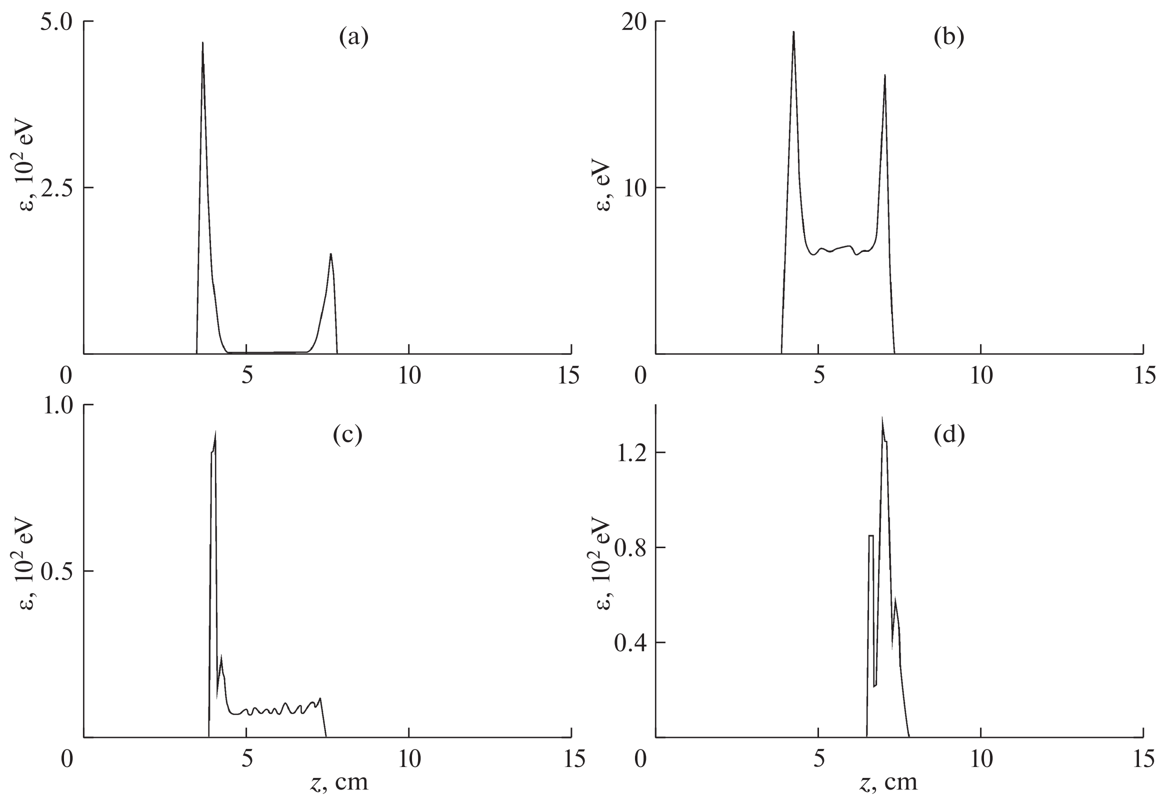

Fig. 5. Distributions of the kinetic energies of particles of different species: ions (a), electrons generated by ionization of neutral gas (b), electrons generated during ion–electron emission near the active electrode (c), and electrons emitted from the earthed electrode (d).

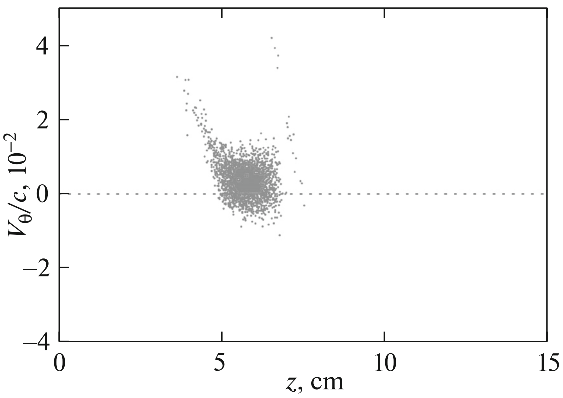

Fig. 6. Instantaneous distribution of the azimuthal velocity of electrons (coarse particles) along the discharge channel.

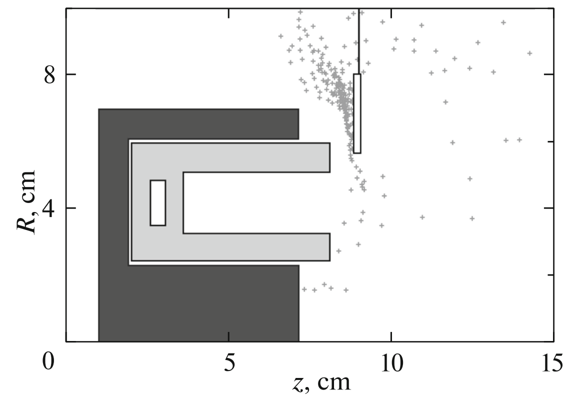

Fig. 7. Localization of electrons emitted from the earthed electrode in the case of an open channel.

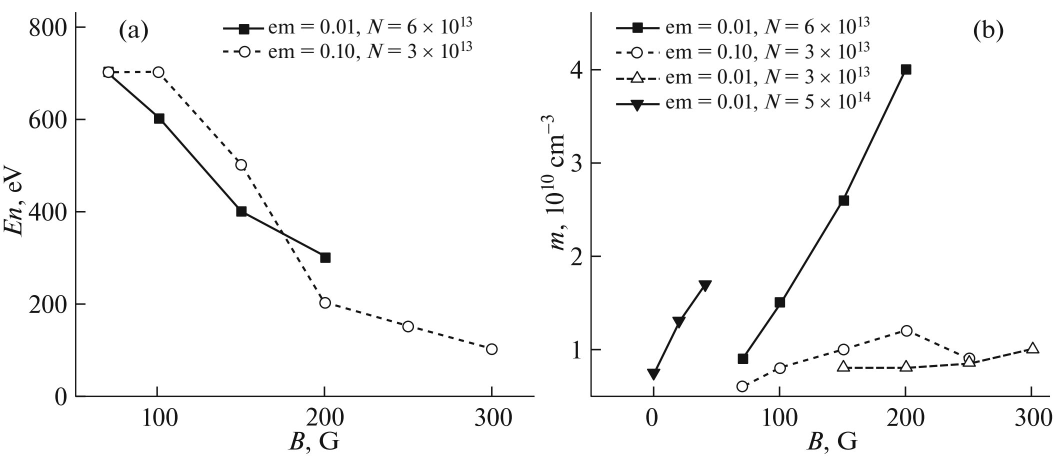

Fig. 8. Dependences of the energy of ions moving to the active electrode (a) and plasma concentration (b) on the external magnetic field induction; em indicates the emission current from the earthed electrode (in A); N is the concentration of the neutral gas in the discharge channel (in cm^{-3}).

age energy) on the external discharge parameters turned out to be qualitatively similar. In particular, in both cases, the mean energy of ions leaving the discharge channel was approximately equal to half the amplitude of the discharge voltage, and the ion flux density increased with the magnetic field at the channel exit.

CONCLUSIONS

Our calculations have shown that near-electrode potential drops appear in the vicinity of the electrodes of a capacitive rf discharge in a radial external magnetic field, the potential drop at the earthed electrode increasing upon a decrease in the emission current. The presence of a longitudinal electric field and a radial magnetic field leads to azimuthal drift of electrons. An increase in the voltage applied to the electrodes, the atomic density, and the magnetic field causes an increase in the electron density in the channel. The potential drop averaged over the period of electric field oscillations, which appears near the channel exit, is accelerating for ions leaving the discharge channel, which manifests in the formation of an ion beam at the exit of the plasma source.

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