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Plasma acceleration from rf discharge in dielectric capillary

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Plasma acceleration from rf discharge in dielectric capillary was demonstrated. Observed plasma flow had ion energies of ~100 eV and electron energies of ~20 eV. The discharge was powered by a MHz-range rf generator and fed by Ar. Experimental results indicate possible validity of assumptions about formation of a potential difference at the open end of the capillary and presence of hot electron fraction in the capillary discharge. Simplicity and small dimensions of the source are attractive for micro-propulsion applications.

52.50.Dg, 52.75.Di, 52.80.Pi

Electric propulsion devices for spacecrafts with masses of several tens to one hundred kilograms are in an increasing demand. These devices should provide thrust up to 1 mN and specific impulse of about 10^3 s at the total power consumption of a few tens of W. Miniature ion engines are developed for power range of about 50 W with the efficiency of 30-55%.[1] New concepts of low power cylindrical Hall thruster also possess reasonably high performance at 50-100 W.[2] However, further attempts to scale down the total power did not lead yet to correspondent scaling down in mass and size of Hall and ion thrusters. There are also physical limitations, which cause, for instance, decrease of efficiency in Hall thruster. Pulsing propulsion devices like Pulsed Plasma Thrusters (PPT), where ions are accelerated in quasineutral plasma by $j\times B$ force, have obvious advantages in this range of parameters: they are simple in design, small, light, short in on/off cycle, and does not require cathode-neutralizers.[3] However, the idea of steady-state micro-propulsion device, which would have all mentioned advantages of PPTs, remains attractive.

Steady-state supersonic flows in quasineutral plasma can be generated in various configurations, where potential gradients may be inspired by effects like nonuniform magnetic fields, electric currents, and density gradients, and may accompany by formation of double layers (DL).[4] Configurations with divergent magnetic fields,[5,6,7] are promising for large-scale propulsion applications but seem unavoidably bulky for micropropulsion. However, observations of a current-free DL in helicon discharges by Charles and Boswell,[8,9] revealed physical principles, which should be attractive for small and simple plasma accelerators. If the discharge is created in a dielectric cylindrical chamber and has an open-end configuration to let the plasma to expand out of the source, conservation of the total flux leads to correspondent increase of the wall potential to sustain the voltage drop due to plasma expansion.[10] In this situation, current-free DL appears in the expansion region, with the potential drop determined by the electron temperature in the upstream discharge and the density gradient in the expansion region.

If the explanation suggested by Charles and Boswell is correct, one should expect an appearance of potential gradients in other configurations, where density gradient is well pronounced. There is, however, another requirement for the generation of a neutral plasma flow, namely presence of an electron fraction in the upstream discharge, which would be able to pass the potential difference and neutralize the accelerated ions by charge and current. One of the possible configurations, which might satisfy both conditions, is a capacitive rf discharge in a dielectric capillary. Indeed, in capacitive discharges, plasma acquires a positive potential in respect to the rf electrodes of about third of the applied rf voltage amplitude.[11] This positive space charge may confine a fraction of hot electrons, similarly to hollow cathodes.[12] Hot electrons, in their turn, may appear due to acceleration of secondary electrons, which are emitted from the ceramic walls, in the sheath.[13] If the DL will play a role of the second, virtual rf electrode at the open end, a part of the hot electron fraction may penetrate the potential barrier of the DL and compensate the ion flux. Evidences of formation of accelerated plasma flows in capillary discharges were already observed at higher pressures.[14,15]

These assumptions were attempted to find an experimental proof on a discharge, initiated in an open-ended ceramic capillary. The capillary had a diameter d_c = 0.8 - 1 mm and a length l_c = 6 - 10 mm. The capillary was fed by Ar through a molybdenum tube with an inner diameter of 0.6 mm and the length of 18 mm. Dimensions of the capillary have been chosen from the following consideration. Ar mass flow rate was varied from 2 to 10 sccm. Pressure at the entrance of the feeding tube, measured by an MKS capacitive manometer, changed from 7 to18 Torr, respectively. Assuming the tube entrance as a stagnation point, in approximation of viscous flow in a cylindrical pipe with an open end, estimated neutral pressure in the discharge region changes from a few Torr at the entrance of the capillary to a few hundreds of mTorr at the open end.[16] The discharge was powered by an rf source with a frequency of 2 MHz. Amplitude of the rf voltage on the discharge was $U_{rf} \sim 210 – 230$ V and depended insignificantly on the mass flow rate and the discharge power, which varied in the range of 15 – 20 W. For gas pressures of about hundreds of mTorr, the discharge plasma inside the capillary may acquire a potential up to $V_p \sim 0.85U_{rf}$.[11] For hot electrons with energy of about $eV_p > 120$ eV, mean free path for momentum transfer collisions in Ar will be $\lambda_m > 6$ mm, and hot electrons will pass the capillary without collisions if $\lambda_m > l_c$. Notice that these estimations are made for the room temperature. At higher temperatures, λ_m will be higher. Skin depth $\delta \sim d_c = 1$ mm corresponds to the plasma density of 2.8×10^{13} cm^{-3}, which is higher that expected plasma density in the discharge.

Capillary was placed in a setup built for study of low-power cylindrical Hall thruster.[17] General information about the plasma flow was obtained from the characteristic of a planar collector, placed normally to the flow direction. In flowing plasma with energetic ion beam and cold co-moving electrons, electron and ion parts of a planar probe characteristic should be separated.[18] At high negative bias on the probe, all electrons are repelled and the probe is collecting the ion saturation current. With the increase of the probe bias, electrons are collected by the probe, forming the electron part of the characteristic. At the probe bias higher than the plasma potential, both electron and ion currents are in saturation. From this point, probe current remains constant until the probe bias becomes high enough to repel ions. Electron saturation is reached when the ion beam is totally repelled by high positive potential of the probe. Thus, the probe characteristic has two well-distinguishable steps, which are separated by part with nearly constant current.

For rough estimations of the flow total currents, we measured the characteristic of a cup-like collector, placed at 9 cm from the source and collected of about 80% of the flow. Bias potential of the collector changed from -85 to +85 V. Typical characteristic, measured at the mass flow rate of Γ_0 = 10 sccm of Ar, is shown in Fig. 1. The observed characteristic, indeed, has two steps, which are separated at the bias potential higher than plasma potential $\varphi_p \sim 30$ V. Total ion current in the flow at these conditions was about $i_{i,sat} \approx 22$ mA. The electron part of the characteristic has a slight slope, which indicates the presence of a directed electron flow with the energy of about 20 eV. At the bias potential $\varphi_{bias} > 80$ V, ions characteristic appears. In the range of 30 V $< \varphi_{bias} <$ 80 V, the probe current is almost flat, which indicates absence of significant amount of low energy ions in the flow.

Ion energy distribution has been measured by a two-plate electrostatic energy analyzer.[19] 45-degree energy analyzer had 3% energy resolution in the range of 70 – 500 eV. The measured distribution at 11.6 cm from the source is shown in Fig. 2a. Observed distribution was narrow peak which, depending on the dimensions of the capillary, had a median energy of 110-135 eV. In order to get the real position of the energy distribution, one should take into account the shift of the observed distribution to about V_p due to additional ion acceleration in the sheath between the plasma and the grounded aperture of the energy analyzer. Average ion energy in the accelerated plasma flow, therefore, was, about 80-105 eV. Absence of significant amount of ions with energies lower than 70 eV, where 45-degree energy analyzer has low sensitivity, was confirmed by 4-grid RPA. There are, however, ions with energies from about V_p and up, which indicates presence of additional ionization downstream the acceleration region.

Electron energy distribution function (EEDF) has been deduced from the second derivative of the characteristic of a small planar probe.[20] The probe was made of carbon had a guarding sleeve, and was placed at 12.6 cm from the source. For Γ_0 = 10 sccm of Ar and U_{rf} = 230 V, measured EEDF is shown in Fig. 2b. It has well-pronounced beam with the mean energy of $\varepsilon_e \approx 23$ eV correspond to Ar ion energies of ~100 eV in current-compensated flow: $\varepsilon_i = 4.7\varepsilon_e$.

Shape of the low-energy part of EEDF is fitted well by a Druyvesteyn distribution. Electron fraction with Druyvesteyn distribution is typical for ionization in presence of collisions and electric fields. According to the suggested scenario, it might correspond to additional ionization in the region at the vicinity of the capillary exit, where neutral density is still high and the potential gradient is expected. Presence of the low-energy ions (See Fig. 2a) supports this assumption.

Angular distribution of the ion current in the flow was measured by a planar probe mounted on a rotating arm. The probe had a bias of -45 V to collect the ion saturation current. Typical angular distribution is shown in Fig. 3. The distribution appears to be wide, which insignificant dependence on the mass flow rate. It may indicate that the acceleration region, indeed, is formed outside the capillary and has a convex shape.

Application of an axial magnetic field with $B_z \sim 200$ G improves slightly the directness of the flow (see dashed curve in Fig. 3), with correspondent increase of the total ion current. Axial magnetic field does not affect much the discharge voltage and current. However, it decreases the temperature of the capillary and improves by this the thermal stability of the discharge.

Measured electron and ion energy distributions, as well as angular distribution of the plasma flow, might indicate correctness of the initial assumptions regarding formation of the significant potential gradient at the exit of the capillary. Another indirect proof was obtained by placing a floating filament in this region. Electron emission from the filament should cancel out the positive space charge and consequently destroy the potential gradient. Indeed, the peak of accelerated ions in the ion energy distribution disappeared when the filament was heated up. Potential of the cold floating filament was about 100 V and dropped to 17-20 V when heated up.

The described experiments show feasibility to generate a quasi-neutral plasma flow with energies of several tens of eVs out of capacitive rf discharge in a ceramic capillary. Simplicity of the design, small size, and absence of cathode-neutralizer make the demonstrated physical principle attractive for steady-state gas-fed propulsion devices. Additional study is required, however, for understanding the formation of the accelerating potential drop.

Figures captions

Fig. 1. Typical characteristic of the planar collector placed perpendicularly to the plasma flow. U_{rf} = 230 V, Γ_0 = 10 sccm Ar.

Fig. 2. (a) Ion energy distribution as measured by 45-degree energy analyzer. Dashed line shows Gaussian fit with $<\varepsilon_i>$ = 134 eV and FWHM of 23 eV. (b) Electron velocity distribution. Dashed line shows Gaussian fit with $<\varepsilon_e>$ = 22.8 eV and FWHM of 10.6 eV. Low energy part is fitted by Druyvesteyn-type function ~exp($-k\varepsilon_e^2$). U_{rf} = 230 V, Γ_0 = 10 sccm Ar.

Fig. 3. Angular distribution of the ion saturation current, measured by a planar probe with a guarding sleeve: B = 0 (solid line), B = 200 G (dashed line). U_{rf} = 220 V, Γ_0 = 8 sccm Ar.

Figures

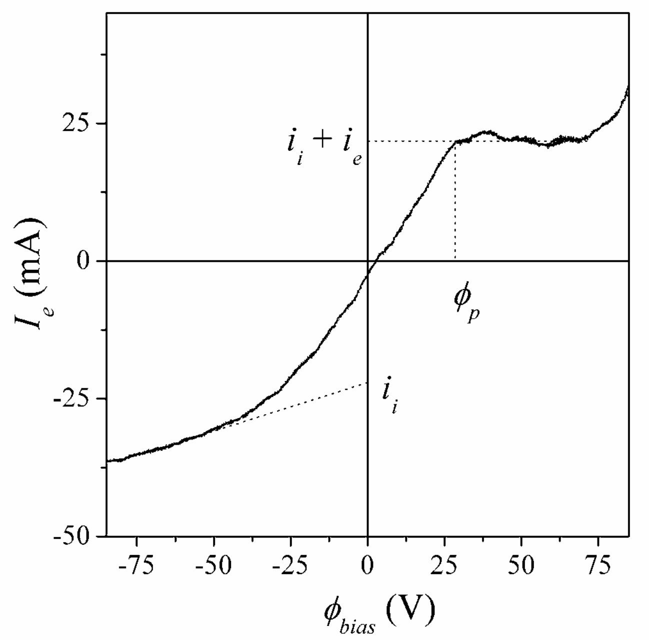

Figure 1. A. Dunaevsky *et al.*, “Plasma acceleration from rf discharge in dielectric capillary”

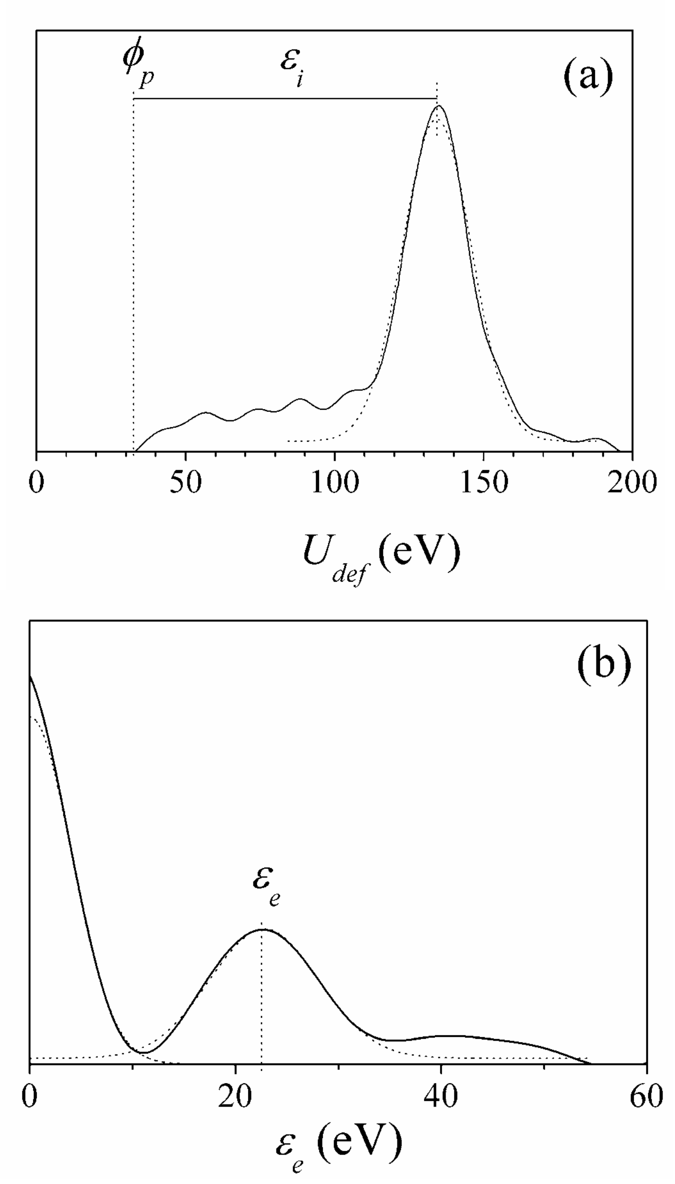

Figure 2. A. Dunaevsky *et al.*, “Plasma acceleration from rf discharge in dielectric capillary”

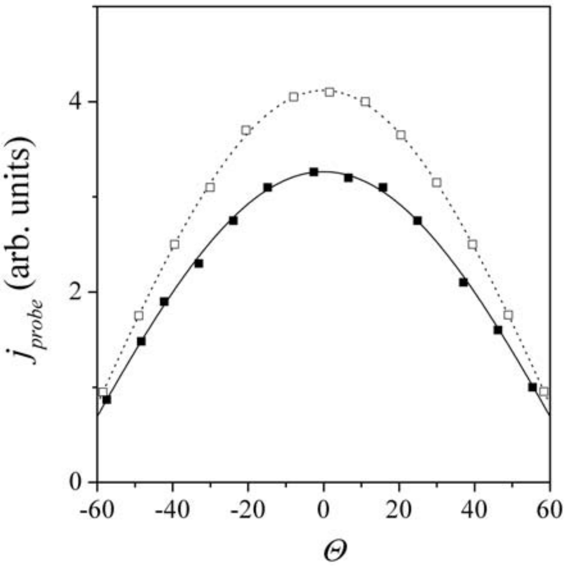

Figure 3. A. Dunaevsky *et al.*, “Plasma acceleration from rf discharge in dielectric capillary”

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