Plasma acceleration from radio-frequency discharge in dielectric capillary

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A capacitive rf discharge was demonstrated in a dielectric capillary for generation of quasineutral plasma flow with energies of several tens of eV. A potential gradient at the open end of the capillary and high-temperature electrons in the capillary discharge promote the ion acceleration. The plasma flow was generated from a ceramic capillary with inner diameter of ~0.8 mm and a length of ~10 mm, at a gas flow rate of 2–10 SCCM (SCCM denotes cubic centimeter per minute at STP) and input power of 15–20 W. The ion energy spectrum consists of high-energy accelerated ions and a low-energy tail formed due to ionization in the acceleration region. The relatively wide plume angle of ~65° indicates that the acceleration region is placed outside the capillary and has a convex shape. Estimated total efficiency at 2 SCCM Xe flow rate and 15 W input power reaches 2%–3%. This approach may be attractive for micropropulsion applications due to its simplicity, low weight and small dimensions of the source, and the absence of a cathode neutralizer. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2214127]

Electric propulsion devices for spacecraft with masses of several tens of kilograms are in increasing demand. These devices should provide thrust up to 1 mN and specific impulse of about 10^3 s with power consumption of only a few tens of watts. The size and weight of such minithrusters should be minimized. Conventional steady-state thrusters such as Hall and ion, however, cannot be scaled down easily in power, weight, and dimensions. Saturation and thermal load on the magnetic system limit miniaturization of the Hall thrusters.[1] New concepts of low power cylindrical Hall thruster with 2.6 cm channel can operate at the power of 50 W and higher with an efficiency of about 30%.[2] A miniature ion thruster was also recently developed with dimensions of several centimeters and with the efficiency in the same range.[3] Yet the further miniaturization of the Hall and ion thrusters together with the decreasing power consumption below 50 W is not straightforward and might occur only at the expense of significant decrease of the efficiency and the lifetime. For example, a conventional design Hall thruster with a subcentimeter channel had only an efficiency of ~6% at 100 W consumed power.[4] Pulsing propulsion devices such as pulsed plasma thrusters (PPTs) do have advantages in this power range. Indeed, the PPT is a simple, small, lightweight thruster, which does not have long on/off cycle and does not require a cathode neutralizer.[5] However, the PPT cannot be used for some missions, where steady acceleration without broadband electromagnetic noise is required.[6] The present work suggests a steady-state cathodeless plasma thruster, which would have all the advantages of PPT operating at 10–20 W input power and with reasonable efficiency.

Steady-state supersonic flow of quasineutral plasma can be generated in systems with potential gradients generated by effects, such as nonuniform magnetic fields, electric currents, and density gradients, and may be accompanied by the formation of double layers.[7] Momentum impartment in configurations with double layers was recently treated theoretically by Fruchtman.[8] Configurations with divergent magnetic fields[9–11] are promising for large-scale propulsion application, but appear unavoidably bulky for micropropulsion. However, observations of a current-free double layer in helicon discharges, by Charles and Boswell,[12,13] revealed physical principles, which might be used for small plasma accelerators. If the discharge is created in a dielectric chamber and has an open-end configuration, the conservation of the total flux leads to a corresponding increase of the wall potential to sustain the voltage drop due to plasma expansion.[14]

Potential drop in the expansion region depends on electron temperature in the upstream discharge. Presence of nonnegligible fraction of high-temperature electrons in the upstream discharge is required for the generation of an energetic plasma flow. One of the possible configurations, which might satisfy this condition, is a capacitive rf discharge in a dielectric capillary. In the capacitive discharge, the plasma acquires a positive potential with respect to the rf electrodes of about a third of the applied rf voltage amplitude.[15] This positive space charge confines low-temperature electrons in an open-ended capillary, similar to hollow cathodes.[16] High-temperature electrons may appear in such a discharge due to acceleration of secondary electrons in the sheath, as it appears, for instance, in some regimes in Hall thrusters.[17] This effect should be more pronounced in discharges with higher surface-to-volume ratio, i.e., in a capillary. The flow would be then neutralized by fast electrons, which pass the potential drop.

Accelerated plasma flows in capillary discharges were already observed in the collisional expansion at high background pressure.[18,19] In the present letter, we report experimental study of the formation of accelerated plasma flow from a capacitive rf discharge in a ceramic capillary opened into vacuum.

The capillary was fed by Ar through a molybdenum tube with an inner diameter of 0.6 mm and the length of 18 mm,

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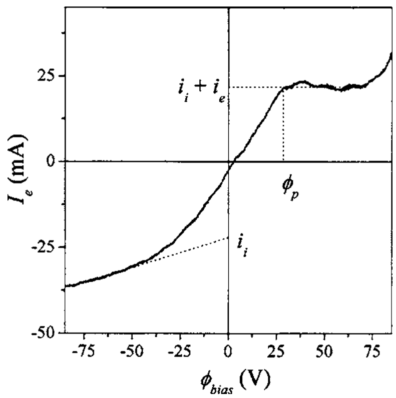

FIG. 1. Typical characteristic of the planar collector placed perpendicularly to the plasma flow. U_{rf}=230 V, Γ_0=10 SCCM Ar.

which played the role of a potential electrode. The ground electrode was a ring made of copper foil with a width of 2 mm, glued on the outer surface of the capillary near the open end. Ar mass flow rate varied from 2 to 10 SCCM, so the pressure at the entrance of the feeding tube, measured by a MKS capacitive nanometer, was changed from 7 to 18 Torr. Assuming the tube entrance as a stagnation point, and assuming viscous flow in a cylindrical pipe with an open end, the neutral pressure in the discharge region then changes from a few torrs at the entrance of the capillary to a few hundreds of millitorrs at the open end.[20] The discharge was powered by a rf source with frequency of 2 MHz. The amplitude of the rf voltage on the discharge was $U_{rf} \sim 210-230$ V and depended on the mass flow rate and the discharge power, which varied in the range of 15–20 W. At gas pressures of about hundreds of millitorrs, the discharge plasma inside the capillary may acquire a potential up to $V_p \sim 0.85 U_{rf}$.[11] For hot electrons with energy of about $eV_p > 120$ eV, the mean free path for momentum transfer collisions in Ar will be $\lambda_m \geq 6$ mm at the room temperature. Hot electrons will pass the capillary with at least one collision if $l_c \geq \lambda_m$. Anticipating higher temperatures of the capillary and correspondingly higher λ_m, the length of the capillary was chosen $l_c \sim 10$ mm. Diameter of the capillary $d_c \sim 0.8-1$ mm is smaller than the skin depth in plasma with density $\leq 10^{13}$ cm^{-3}, the highest expected plasma density in the discharge.

The capillary was mounted in a coaxial aluminum shroud to reduce the electromagnetic noise and improve the coupling with the rf power source. The capillary was placed in a vacuum chamber with a set of diagnostics built for study of low power cylindrical Hall thruster.[21] General information about the plasma flow were obtained from the characteristic of a planar collector, placed normally to the flow direction. The collector was placed at 9 cm from the capillary and collected about of 80% of the flow. Bias potential of the collector changed from -85 to $+85$ V. Typical characteristics, measured at the mass flow rate of Γ_0=10 SCCM of Ar, are shown in Fig. 1. In flowing plasma, with energetic ion beam and cold comoving electrons, planar probes have two well-distinguishable steps of electron and ion parts of the probe characteristic, which are separated by a part of nearly constant current.[22] The observed characteristic, indeed, has two steps, with a first knee at the 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 slope of the electron part of the characteristic indicates the presence of a directed electron flow with an energy of about 20 eV. At the bias potential $\varphi_{bias} > 80$ V, ion characteristic appears. In the range of $30\text{ V} < \varphi_{bias} < 80$ V, the probe current is almost flat, which means the absence of significant amount of low energy ions in the flow.

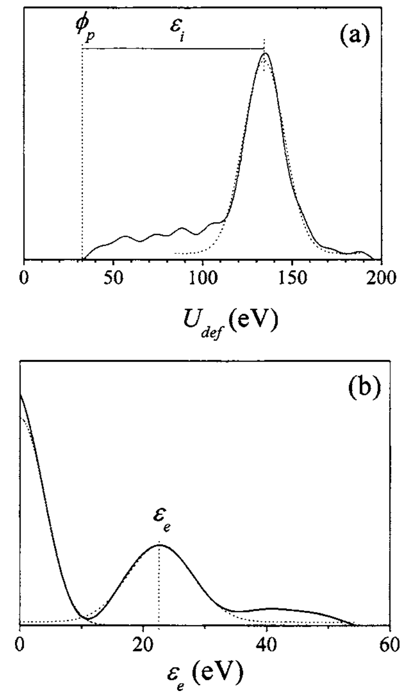

FIG. 2. (a) Ion energy distribution as measured by 45° energy analyzer. The dashed line shows Gaussian fit with $\langle\varepsilon_i\rangle$=134 eV and FWHM of 23 eV. (b) Electron velocity distribution. The dashed line shows Gaussian fit with $\langle\varepsilon_e\rangle$=22.8 eV and FWHM of 10.6 eV. The low energy part is fitted by Druyvesteyn-type function $\sim\exp(-k\varepsilon_e^2)$. U_{rf}=230 V, Γ_0=10 SCCM Ar.

The ion energy distribution was measured by a two-plate electrostatic energy analyzer.[23] 45° 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. 2(a). The observed distribution has a narrow peak with a median energy from 110 to 135 eV, depending on the dimensions of the capillary. In order to obtain the real energy distribution, the observed distribution should be shifted about φ_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 flow, therefore, was about 80–105 eV. In the range of ion energies lower than 70 eV, where 45° energy analyzer has low sensitivity, the spectrum was measured by four-grid retarding potential analyzer. These measurements revealed the presence of ions with energies higher than φ_p [see Fig. 2(a)], which indicates additional ionization in the downstream region.

Electron energy distribution function (EEDF) was deduced from the second derivative of the characteristic of a small planar probe.[24] Carbon probe with a diameter of 4 mm and a guarding sleeve was placed at 12.6 cm from the capillary normally to the flow direction. Typical EEDF measured at Γ_0=10 SCCM Ar and U_{rf}=230 V is shown in Fig. 2(b). The EEDF has well-pronounced beam with the mean energy of $\varepsilon_e \approx 23$ eV, which corresponds to Ar ion energies of ~ 100 eV in the current-compensated flow: $\varepsilon_i \approx 4.7\varepsilon_e$.

As illustrated in Fig. 2(b), the measured shape of the low-energy part of EEDF can be fitted well by a Druyvesteyn distribution. Electron fraction with Druyvesteyn distribution

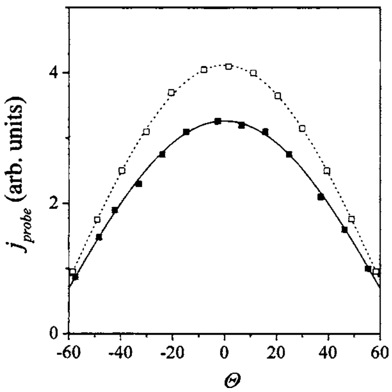

FIG. 3. Angular distribution of the ion saturation current, measured by a planar probe with a guarding sleeve: $B=0$ (solid line), $B=200$ G (dashed line). $U_{rf}=220$ V, $\Gamma_0=8$ SCCM Ar.

is typical for ionization in the presence of collisions and electric fields. Appearance of such a fraction in EEDF is another indirect evidence of additional ionization in the downstream region close to the exit plane of the capillary, where neutral density is still high and the potential gradient is formed.

Plume divergence is one of the important parameters of plasma propulsion devices. The divergence was measured by a carbon planar probe with a guarding sleeve, mounted on a rotating arm at 140 mm from the capillary. The probe was rotated from −90° to +90° in the vertical plane. Bias potential of the probe was set to −45 V to collect the ion saturation current. Typical plume divergence is shown in Fig. 3. The distribution appears to be wide, which is insignificant dependence on the mass flow rate. It may indicate that the acceleration region has a convex shape and, indeed, is formed outside the capillary. 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 corresponding 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 thereby improves the thermal stability of the discharge.

Measured electron and ion energy distributions, as well as the angular distribution of the plasma flow, might indicate correctness of the initial assumptions regarding formation of 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.

In summary, these experiments show that it is feasible to apply a capacitive rf discharge in a dielectric capillary for generation of quasineutral plasma flow with energies of several tens of eV without an additional cathode neutralizer. The experimental prototype of the capillary, together with the outer shroud, had an outer diameter of 8.5 mm and a length of 25 mm, which is significantly smaller than the dimensions of the smallest Hall and ion microthrusters.[2–5] In the tested range of the gas flow rate of 2–10 SCCM, the discharge power varied from 15 to 20 W. Estimations of the thrust, based on the measured total ion current and taking into account actual plume divergence, yield ~0.3 mN at 2 SCCM of Xe flow rate and 15 W power to ~0.4 mN at 10 SCCM and 20 W. The propellant utilization is about 20% at 2 SCCM but drops fast to 5%–8% at higher flow rate. The low propellant utilization is caused, presumably, by excessive ion losses on the capillary walls. In spite of the low propellant utilization, the estimated total efficiency of the laboratory prototype reaches 2%–3% at 2 SCCM. By way of comparison, a miniaturized conventional Hall thruster,[2] still being larger and heavier, showed comparable efficiency only at 100 W. Thus, the rf discharge in a dielectric capillary, if optimized through design and materials, might be attractive as a miniature, lightweight steady-state thruster with total power consumption of 10–20 W.

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