Enhancement of electric force by ion-neutral collisions

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The measured force exerted on an ion flow by an electric field is found to be larger than the electric force that can be exerted if the ions are collisionless. In addition, the increase of the gas pressure is found to result in an *increase* of the electric force despite a simultaneous *decrease* of the deposited electric power. Employing a simple model, we argue that these experimental findings result from the electric force being felt by the ions for a longer time, their residence time in the acceleration region is increased due to their slowing-down collisions with neutrals. © *2009 American Institute of Physics*. [doi:10.1063/1.3257694]

The force exerted by a flowing plasma is an important characteristic for applications such as surface treatment and electric propulsion. We have recently reported measurements of the force exerted on a wall by a flow out of a radial plasma source (RPS).[1] Part of that force results from the electric force exerted on, and imparts momentum to, the ions in the mixed ion-neutral flow. We show here that the electric force exerted on the ions, as deduced from the measured force exerted by the flow, is larger than the maximal force that can be exerted on the ions if they are collisionless. The exerted force *increases* despite the *decrease* in deposited power, as the gas flow rate increases. By examining the dependence of the measured force on the gas flow rate, we demonstrate that this force being larger can be explained by ion-neutral collisions, as suggested in our preliminary study.[1] Thus, one can increase the force exerted on plasma ions in specified applied voltage and power, by operating at a larger gas pressure.

Figure 1 is a schematic and a photograph of the RPS in operation. The RPS has some similarity to other plasma devices in which plasma is accelerated radially by an electric field across an axial magnetic field.[2–6] As described in detail in Ref. 1, the RPS consists of a ceramic unit, a molybdenum anode, a magnetic field generating solenoid, an iron core, a gas distributor, and a cathode employed for neutralizing the ion flow. An argon gas is injected through the gas distributor in the anode. A voltage that is applied between the anode and the cathode ignites a discharge and accelerates the plasma ions radially outward across the axial magnetic field.

In the experiments, we specified the discharge current, the magnetic field intensity and the gas flow rate. We measured during the RPS operation the radial ion current, I_i, the plasma potential, V_B, and the force exerted by the flow, F_1, all at the same position at a distance of 70 mm from the axis of symmetry of the RPS. We also measured at the same position the force, denoted by F_2, exerted by the gas flow immediately after the RPS discharge is turned off. The radial ion current, I_i, the ion current flowing radially outward onto the side of a Langmuir probe facing the RPS, was deduced from measurements of ion saturation currents into the Langmuir probe.[1] The plasma potential, V_B, was deduced from measurements employing an emissive probe. The forces F_1 and F_2 were measured by use of an upgraded version of the balance force-meter (BFM) described in,[1] a detailed description of which will be given elsewhere. In addition, we measured the voltage between the anode and the cathode, V_d, and the pressure in the chamber P_r at a distance 50 cm from the RPS. Figure 2 shows V_d, I_i, and P_r versus the gas flow rate that varies from 11–100 SCCM (SCCM denotes standard cubic centimeters per minute) during the RPS operation. All the measurements shown in this letter are for constant discharge current (1.90 A) and magnetic field intensity (160 G is the maximal field at the center plane in the core gap).

Figure 3 shows, denoted by triangles, $F=F_1-F_2$, the net force exerted on the BFM due to the acceleration of the ion flow by the electric field, versus the gas flow rate. The net force is thus obtained by subtracting the force by the neutral gas flow that is present even in the absence of the accelerating electric field, F_2, from the force F_1. Also shown in Fig. 3, denoted by diamonds, is F_{cl}, the maximal force that can be exerted by the plasma ions accelerated by the electric field, if they are collisionless. This maximal force is calculated as

$$F_{cl} = m\Gamma_F v_0. \tag{1}$$

Here m is the ion (or neutral) mass, e the elementary charge, and $\Gamma_F=(S_F/S_i)I_i/e$ is the radially outward ion flux onto the BFM (S_F and S_i are the RPS-facing areas of the BFM and of the Langmuir probe, respectively). Also, $v_0=\sqrt{2eV_a/m}$, $V_a=V_d-V_B$ being the potential difference between the anode and the BFM. The plasma potential at the location of the measurements, V_B, remains constant (at a value of 25 ± 1 V)

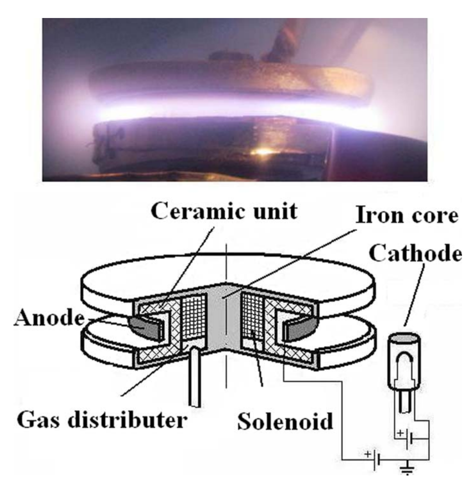

FIG. 1. (Color online) The RPS in operation (top) and a schematic (bottom).

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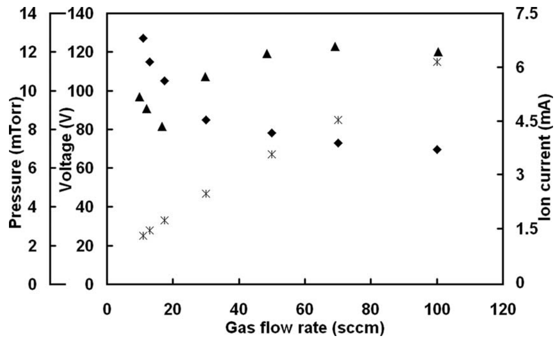

FIG. 2. The discharge voltage V_d (diamond), the ion current I_i (triangle), and the pressure in the vacuum chamber P_r (flake) vs the gas flow rate Γ_N.

with respect to the cathode when the gas flow rate varies. It is seen in the figure that the measured net force, F, is larger than that maximal force, F_{cl}, especially for the higher gas flow rates. Moreover, the measured net force increases even though this calculated maximal force and the total deposited power decrease when the gas flow rate increase (due to the decrease of V_d while the discharge current is fixed).

In order to explain this disparity, we turn to estimating the electric force on the plasma ions in the presence of ion-neutral collisions. The radial force per unit volume exerted on the ions is $F_i = neE - \nu mnv$ while the radial force exerted on the neutrals is $F_N = \nu mnv$. Here, E is the radial electric field, v and n are the radial velocity and density of the ions, and ν is the ion-neutral collision frequency. The net force per unit volume exerted on the ion and neutral flow is the electric force $F_i + F_N = neE$. The total net force along the acceleration zone (the total electric force) on the flow is

$$F_T = 2\pi b \int_{r_0}^{r_1} r(F_i + F_N)dr = 2\pi b \int_{r_0}^{r_1} neErdr. \quad (2)$$

Here r_0 and r_1 are the inner and outer radial boundaries and b is the (assumed constant) width of the acceleration zone. It is clear from this expression that collisions enhance the exerted force by slowing down the ions, so that their density is higher. Differently stated, the slowed ions spend a longer time in the acceleration zone, as we shortly show, and the electric force exerted on the ion flow becomes thus larger.

We now estimate the exerted electric force. For simplicity, we assume that all the ionization occurs near the peak of the potential, at the neighborhood of the anode, so that all ions are accelerated by the full voltage drop along the acceleration zone. This assumption is reasonable, since ionization is expected to occur mainly by electrons that acquired energy through climbing the electric potential. Ionization by electrons not at the peak of the potential, results in a smaller force than that we calculate. Therefore, our calculation provides an upper bound on the electric force. The ion momentum equation, when ionization is negligible, is $v dv/dr = eE/m - \nu v$. We assume in the subsequent analysis that the electric field is constant along the acceleration region so that $V_a = Ea, a \equiv r_1 - r_0$. If the ion velocity is larger than the neutral thermal velocity, we may write[7] $\nu = \sigma N v$, in which σ is the ion-neutral (assumed constant) collision cross-section and N is the neutral density, also assumed uniform. Integrating the momentum equation with this expression for the collision frequency, we obtain the ion velocity as $v^2(r) = v_0^2(\lambda/2a)\{1 - \exp[-2(r - r_0)/\lambda]\}$, where $\lambda \equiv 1/\sigma N$ is the ion mean free path. The condition that the final ion velocity $v(r_1)$ is larger than the neutral thermal velocity v_T turns out to be $\lambda/(2a) \geqslant (v_T/v_0)^2$, which indeed holds for the flow in the RPS, even for the higher gas pressure. Writing the ion density as $n = \Gamma_i/(2\pi r b v)$, where Γ_i is the radial ion flux constant along the acceleration zone, we find the total electric force to be

$$F_{T1} = 2\pi b \int_{r_0}^{r_1} neErdr = \Gamma_i eE\tau_1$$
$$= m\Gamma_i v_0 \left(\frac{\lambda}{8a}\right)^{1/2} \ln \frac{1 + \sqrt{1 - \exp(-2a/\lambda)}}{1 - \sqrt{1 - \exp(-2a/\lambda)}}. \quad (3)$$

Here $\tau_1 = (2a/v_0)\sqrt{\lambda/8a}\ln[(1 + \sqrt{1 - \exp(-2a/\lambda)})/(1 - \sqrt{1 - \exp(-2a/\lambda)})]$ is the ion residence time in the acceleration zone, increased by collisions with neutrals from its collisionless value $\tau_0 = 2a/v_0$, making the force on the flow larger. This expression for the force is reduced in the collisionless limit, at $2a/\lambda \ll 1$, to $m\Gamma_i v_0$, and at the collisional limit, $2a/\lambda \gg 1$, to $m\Gamma_i v_0\sqrt{a/2\lambda}$ (see Ref. 1).

Employing the expression in Eq. (3), we express the net force expected to be exerted on the BFM as $F_{th} = F_{T1}\Gamma_F/\Gamma_i$. For the calculation of F_{th}, we evaluate Γ_F and V_a as described above, using the measured I_i, V_d, and V_B. We also need to evaluate the value of a/λ. We assume that the acceleration zone is located where the magnetic field is strong, between $r_0 = 3$ cm and $r_1 = 4$ cm, so that $a = 1$ cm. The neutral density in the acceleration region is expected to be larger than in the chamber and therefore cannot be deduced from the measured pressure in the chamber, shown in Fig. 2. Rather, we estimate the density of the gas that flows radially outward as $N = \Gamma_N/(2\pi r b v_N)$. Here Γ_N is the gas flow rate and v_N is the gas flow velocity. We take $b = 0.5$ cm and assume that inside the acceleration region, at $r = 4$ cm, the gas flow velocity is $v_N = 37$ m/s. The neutral density thus calculated that we take as uniform in the acceleration zone, increases linearly with the gas flow rate, and is about 1.5–2.5 times the neutral density deduced from the measured pressure shown in Fig. 2. The value of the ion-neutral collision cross-section is approximated, according to Ref. 8, as $\sigma = 8 \times 10^{-19}$ m^2 and the ratio a/λ turns out to vary from 0.8 to 7.6 as the gas flow rate is varied from 11 to 100 SCCM.

The force F_{th}, calculated according to the description above, is shown in Fig. 3. It is found to increase with the increase of the gas flow rate, as does the measured net force

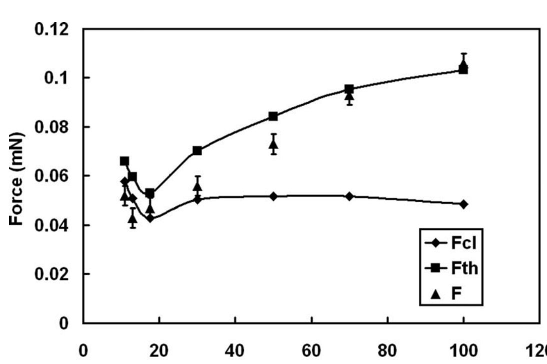

FIG. 3. The force F_{cl} calculated according to Eq. (1), the force F_{th} calculated according to $F_{th} = F_{T1}\Gamma_F/\Gamma_i$, and the measured net force F vs the gas flow rate Γ_N.

F, in contrast to the force if the ion flow is collisionless, F_{cl}, and to the total power deposited which both decrease with the increase of the gas flow rate. The calculated F_{th}, obtained with a reasonable estimate of a/λ turns to be equal or somewhat larger than the measured net force F, which is expected, since we assumed that the ionization is at the peak of the potential only. Thus, we have shown that these are ion-neutral collisions in the acceleration zone that significantly enhance the electric force on the ion flow.

We note that the force enhancement is expected also when the ion velocity is smaller than the neutral thermal velocity, so that the ion-neutral collision frequency is $\nu=\sigma N v_T$.[7] Solving the ion momentum equation, we find that in this case the ion velocity satisfies $(v_T v/v_0^2)(2a/\lambda)+\ln[1-(v_T v/v_0^2)(2a/\lambda)]=2(v_T^2/v_0^2)a(r_0-r)/\lambda^2$, and the total electric force is $F_{T2}=2\pi b\int_{r_0}^{r_1} neE r dr=-m\Gamma_i(v_0^2/v_T)\lambda/(2a)\ln[1-(v_T v/v_0^2)(2a/\lambda)]$. At the collisional limit, when $2(v_T^2/v_0^2)a^2/\lambda^2 \gg 1$, the maximal ion velocity is expressed as $v=(v_0^2/v_T)(\lambda/2a)\{1-\exp[-(2v_T^2 a^2/\lambda^2 v_0^2)-1]\}$ and the electric force becomes $m\Gamma_i v_T a/\lambda$ which is $(v_T/v_0)(a/\lambda)$ larger than in the collisionless case. The force then can also be written as $\Gamma_i eE\tau_2$, where the residence time is $\tau_2=\tau_0(v_T/v_0)(a/\lambda)$. The regime of validity is $v \ll v_T$ which holds if $(v_0^2/v_T^2)(\lambda/2a)\ll 1$.

The net electric force exerted on the whole quasineutral plasma is zero. The electric force exerted on the electrons is equal in size and opposite in direction to the electric force exerted on the ions. The radially inward momentum gained by the electrons is delivered to the RPS (Ref. 9) mostly through the coils that generate the magnetic force that balances the electric force on the electrons. The momentum gained by the electrons is also delivered to the RPS by the neutrals that acquire some of that radially inward momentum through collisions with the electrons. However, because of its radially inward direction, this momentum acquired by the neutrals does not affect the force measured by the BFM.

Energy balance and efficiency, which are of major importance for electric propulsion, depend on the rate of ionization and on the plasma impedance that have not been discussed here. We note though that the ratio F_T/P (F_T is the total force exerted on the BFM and P is the discharge power), which is important for electric propulsion, increases when the gas flow rate increases, reflecting the force enhancement described here.

In the present configuration, because of the azimuthal symmetry, no net momentum is delivered to the RPS due to the radial acceleration. Additional testing of the force increase due to ion-neutral collisions will be considered, in a plasma source of a configuration that is directly applicable to electric propulsion. In addition, the ion and the neutral heat fluxes will be measured employing methods recently developed.[10]

In summary, we have presented force measurements that show that ion-neutral collisions enhance the electric force exerted on the plasma ions. We note that if ions collide with neutrals after they have been accelerated then the total momentum of ions and neutrals is the same as without collisions. However, if ions collide *while they are being accelerated by the electric field*, the total momentum gained by the flow is enhanced. Putting it differently, the force and the imparted momentum are increased because, for a given deposited power, the force is exerted on a larger mass, as happens here through plasma collisions.

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[1] G. Makrinich and A. Fruchtman, Phys. Plasmas **16**, 043507 (2009).
[2] I. I. Beilis, R. L. Boxman, S. Goldsmith, and V. L. Paperny, Appl. Phys. Lett. **75**, 2734 (1999).
[3] A. Goncharov and I. Brown, IEEE Trans. Plasma Sci. **32**, 80 (2004).
[4] I. Levchenko, M. Romanov, M. Keidar, and I. I. Beilis, Appl. Phys. Lett. **85**, 2202 (2004).
[5] G. A. Pozdnyakov, Tech. Phys. Lett. **33**, 474 (2007).
[6] M. Rondanini, C. Cavallotti, D. Ricci, D. Chrastina, G. Isella, T. Moiseev, and H. von Kanel, J. Appl. Phys. **104**, 013304 (2008).
[7] V. A. Godyak, *Soviet Radio Frequency Discharge Research* (Delphic Associates, Falls Church, 1986); A. Fruchtman, G. Makrinich, and J. Ashkenazy, Plasma Sources Sci. Technol. **14**, 152 (2005).
[8] M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing* (Wiley, New York, 1994).
[9] A. Fruchtman, Phys. Rev. Lett. **96**, 065002 (2006).
[10] H. Kersten, E. Stoffels, W. W. Stoffels, M. Otte, C. Csambal, H. Deutsch, and R. Hippler, J. Appl. Phys. **87**, 3637 (2000); G. Makrinich and A. Fruchtman, *ibid.* **100**, 093302 (2006).