Plasma Sources as Thrusters

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Abstract: The use of electrode-less plasma sources as thrusters is attractive. The simplicity and the lack of erosion that accompanies current-driven sources are potentially important advantages. We show that the efficiency of such a plasma thruster without an additional acceleration is likely to be low. This is because of the high cost of ionization and because of losses at the back-wall sheath. We then discuss possible improvement that may result from the excitation of a double layer at the exit of the plasma source. Finally, we show that ion-neutral collisions enhance the thrust for a specified accelerating power.

Nomenclature

η	=	total efficiency
η_m	=	propellant utilization
ε_c	=	cost of ionization
T	=	electron temperature
m	=	ion (and neutral) mass
m_e	=	electron mass
e	=	the elementary charge
E	=	the electric field
n	=	the plasma density

I. Introduction

Plasma sources are attractive for the use as plasma thrusters, especially when they are electrode-less. [1-8] The simplicity and the lack of erosion that accompanies current-driven sources are potentially important advantages. Often such plasma sources are only the first stage of the thruster, while in the second stage an accelerating mechanism is considered. [1] The use of plasma sources with an open end as thrusters, where the force is due to the plasma pressure only, is also considered. [2-8] We draw the attention here, however, to possible disadvantages of such plasma sources and to the challenge of turning them into practical thrusters. In Section II we briefly present our previous analysis[9] of the efficiency of plasma sources as thrusters.

The recently discovered double layer in a helicon discharge is also being considered for electric propulsion. In the double layer itself no net momentum is delivered to the plasma. [10] We discuss in Section III certain aspects of the double layer in the context of propulsion.

Propellant saving is a major motivation of electric propulsion. However, we note that for specified power, the thrust is larger when ions collide with neutrals, delivering some of their momentum to neutrals during the acceleration. [11] We discuss this issue in Section IV.

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II. Plasma Thruster Efficiency

A plasma source in which plasma flows outwards through an open end is a natural configuration to use a plasma source as a thruster.[9] It should be clear that the thrust in such plasma sources is simply due to the plasma pressure. We have recently analyzed the efficiency of such a plasma source. Numerical calculations are shown for an argon plasma source of common parameters. It is shown in Fig. 1 that even when the propellant utilization reaches unity, the total efficiency is low. The sources of the low efficiency are the high cost of energy production and sheath losses at the backwall. The cost of ionization is several tens of eV for an electron-ion pair. If the ions only acquire the sound speed, the kinetic energy they gain is small relative to the energy spent on ionization and excitation. The energy cost is high because the electron temperature is a few eV only, lower than in the Hall thruster, for example. The sheath potential reduces the efficiency further. The wall sheath is a sink of energy that does not contribute to the thrust. The analysis is detailed in Ref. 7.

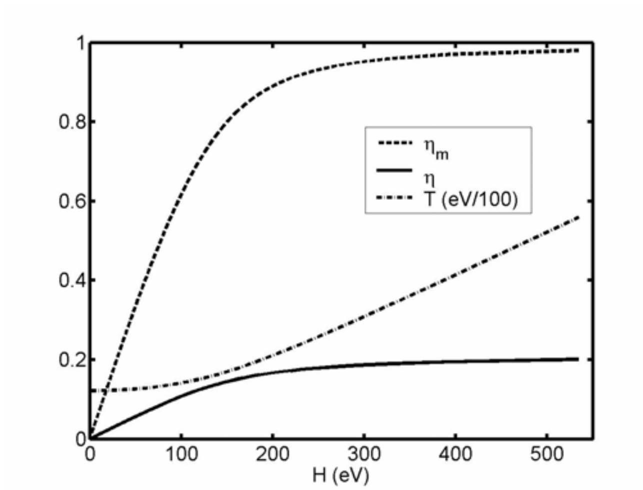

Figure 1. The propellant utilization, the efficiency, and the electron temperature, as functions of the energy deposited per particle.[7]

The analysis in Ref. 7 was for a collisionless beam of neutrals, flowing with an identical velocity, for simplicity, and being ionized while moving ballistically. The generated plasma flows either towards the backwall or towards the exit. The plasma that impinges on the backwall exerts the force on the wall, accompanied by energy losses.

The expression for the losses, derived in Ref. 7, exhibits these ionization and sheath losses, which result in the low total efficiency. The expression for the efficiency is

$$\eta = \frac{\eta_m}{\varepsilon_c/T + 2 + 0.25[1 + \ln(m/2\pi m_e)]}. \quad (1)$$

The first term in the denominator exhibits the ionization cost, while the last term expresses the sheath losses at the backwall. This expression has been derived for collisionless plasma. We note that lateral wall losses have been neglected. Taking those losses into account would make the efficiency even lower.

III. Double Layer Thruster

Recently, it has been discovered that a double layer (DL) is sometimes excited at the exit of a helicon source.[8,9] Accelerated by the DL, a supersonic ion beam exits the helicon source with a potentially high thrust. The helicon DL has been suggested as a thruster with a potentially high specific impulse, and hopefully, a higher efficiency. We have recently examined the momentum balance across the double layer.[10] We have shown that the net force exerted on the plasma in the double layer is zero. The force exerted on the ions towards the exit is balanced by the force exerted on the electrons in the opposite direction.

This vanishing of the net force is easily understood once one recognizes that this electric force is an internal force of the plasma due to charge separation inside the plasma. A net electric force on the plasma is exerted when some of the charges that generate the electric field are located outside the plasma, on an electrode, for example. The force is not zero also if the DL is along a divergent magnetic field. The net force is then due to the magnetic field pressure.[10] However, since the DL is very narrow, this contribution of the magnetic field pressure within this nozzle geometry is small.

The DL configuration is different from that of the Hall thruster in which a net force is exerted on the plasma by the magnetic field pressure. The same-size electric force acts on the ions and on the electrons, but the electric force on the electrons is balance by the magnetic force on them. As a result, a net force is exerted on the plasma by the electromagnetic forces. The plasma in turn exerts the same-size force on the coils, which is the force exerted on the satellite.

The DL does not therefore directly exert a net force on the plasma and therefore a net force is not directly exerted on the satellite. The plasma exerts a force on the satellite only at the backwall. We need to find out whether the DL increases the plasma pressure upstream, so that the force on the backwall increases. An investigation of the modification of the plasma pressure by the DL is important in the research in this exciting subject. The possible presence in the upstream plasma of electron beams and reflected such beams [8] could help in clarifying this issue.

In summary, the DL does not exert force on the plasma. In addition, since it is current free, no electromagnetic energy is deposited in it. With no momentum and no energy, it seems that the DL does is to manipulate the particle distribution functions, so that they exert a larger force on the backwall.

IV. Enhanced electric force due to ion-neutral collisions

When plasma flow carries momentum, some momentum is also delivered to neutrals. We have recently built and characterized a plasma source of a cylindrical geometry with an applied axial magnetic field in order to generate a radially outward ion flow.[11] A photograph of the radial plasma source and its schematic, are shown in Fig. 2. Since the radial flow is azimuthally symmetric, no net thrust is expected. Nevertheless, measuring the force by a balance force meter that we developed allowed us to examine the radial force exerted in a asymmetrical plasma source. We have shown that the thrust for a given deposited power is larger when ions collide with neutrals during the acceleration.

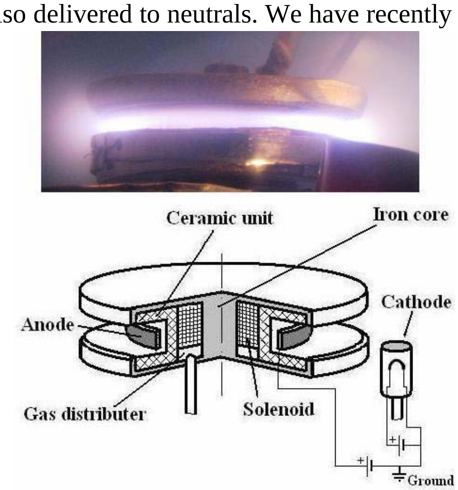

Figure 2. The Radial Plasma Source

The electric field exerts force on the ions. Part of the momentum gained by the ions is delivered to neutrals through ion-neutral collisions. Since ions are slowed by collisions their transit time in the acceleration region is larger. They feel the electric force for a longer period of time; therefore the total electric force exerted on the ion flow becomes larger. The electric power is delivered to a larger mass and the momentum gained for the same energy is larger. For a simple case of a constant electric field the force on an ion flow turns out to be

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

Here a is the length of the acceleration region, λ is the ion-neutral mean free-path, and Γ_i is the ion flux. This is an enhanced force relative to the force when ion-neutral collisions are absent. In that collisionless case the force is $F_{T0} = 2\pi b \int_{r_0}^{r_1} neE r dr = \Gamma_i eE\tau_0 = m\Gamma_i v_0$. Here $v_0 = \sqrt{2eV_a/m}$, b is the distance between the discs, τ_0 and τ_1 are the transit time of an ion in the absence and in the presence of collisions, their expressions are easily found from the equations above.

The force measured has been found to be larger than the maximal force that the ions, upon gaining the full voltage, could exert. Employing Eq. (2) we were able to explain the increase of force as resulting from ion collisions with neutrals.

Further study is required to better understand the thrust delivered by collisional plasma, especially in a configuration suitable for propulsion.

V. Conclusions

Various aspects of the use of plasma sources as thrusters have been discussed. The inherent low efficiency has been shown. The possibility of increasing the efficiency by use of the double layer in the exit of a plasma source has been discussed. It has been mentioned that the source of the thrust increase in such a configuration is not yet understood. Finally, it has been shown that the thrust for given power is increased when ions collide with neutrals.

Acknowledgments

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