The Dependence of the Electron Temperature on the Discharge Voltage for Different Hall Thruster Configurations

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The dependence of the maximum electron temperature on the discharge voltage is studied for the Hall thruster configurations with different channel geometries. The electron temperature saturation is observed at high discharge voltage thruster operation. The level of temperature saturation for the boron nitride channel is much higher than the critical value for the space charge saturation sheath (SCS), estimated under the assumption of the Maxwellian electron energy distribution function. This result may support recent kinetic studies, which predict the existence of the kinetic regime of the SCS sheath in the collisionless thruster plasma.

Nomenclature

ν_{ew}	=	electron-wall collision frequency
Γ_{ew}	=	flux of primary electrons to the walls
n_e	=	plasma density
h	=	distance between the walls of the annular channel (channel width)
T_e	=	electron temperature
M_i	=	ion mass
δ	=	secondary electron emission coefficient of the wall material
Γ_{esec}	=	flux of secondary electrons from the wall
ε_w	=	energy loss at the wall per one electron
ϕ_w	=	voltage drop between the plasma and the wall

I. Introduction

High-Isp applications for the Earth orbiting and interplanetary space missions require operation of Hall thrusters at high discharge voltages. For conventional Hall thrusters (so-called stationary plasma thrusters[1,2] (SPT)) this requirement further intensifies scientific and technological challenges associated with the effective control of the plasma flow in these cross-field discharge devices. The plasma-wall interaction and magnetic insulation properties of the thruster discharge can be strongly affected by the discharge voltage. In high discharge voltage

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regimes, a strong secondary electron emission (SEE) from ceramic channel walls may increase the electron-wall collision frequency, leading to the increase in the power losses.[1-4]

In recent experiments at PPPL,[5,6] we studied macroscopic effects of the Joule heating and the electron-wall interaction on the plasma properties in a 2 kW Hall thruster. In this paper, we highlight several important results of the studies of high discharge voltage operation of a Hall thruster with different channel widths and magnetic field configurations. In addition, the wall material effects on the thruster discharge have been recently demonstrated.[7] The paper is organized as follows. Section II presents in brief the commonly accepted model of electron-wall interaction in Hall thrusters. In sections III and IV, we review the experimental setup and experimental results, respectively.

II. Electron-Wall Interaction

In a typical Hall thruster, the electron temperature is in the range 20-50 eV.[8,9] For the Maxwellian electron energy distribution function (EDF), the electron temperature within this range is sufficiently large to induce strong secondary electron emission (SEE) from ceramic channel walls.[10,11] In the commonly accepted model of the electron-wall interaction,[2-4,10,11] the electron-wall collision frequency and the electron energy loss at the walls for the Maxwellian electrons can be expressed as[3]

$$\nu_{ew} \equiv \frac{\Gamma_{ew}}{n_e h} \approx \frac{1}{h}\sqrt{\frac{T_e}{M_i}}\frac{1}{1-\delta(T_e)}, \quad (1)$$

$$\nu_{ew}\varepsilon_w = \frac{\tilde{\nu}}{h}\sqrt{\frac{T_e}{M_i}}\frac{1}{1-\delta(T_e)}\left(2T_e + \left(1-\delta(T_e)\right)e\,|\,\phi_w\,|\right), \quad (2)$$

respectively, where $\tilde{\nu}$ ~ 0.7-1.2 for typical thruster conditions.[3] Here, $\delta \equiv \Gamma_{esec}/\Gamma_{ew}$. The flux of primary electrons from the plasma to the floating wall is balanced by the flux of ions from the plasma and the flux of secondary electrons from the wall. When the SEE coefficient reaches approximately 1, the near-wall sheath becomes space charge saturated (SCS).[12] Any further increase of the secondary electron flux into the plasma is restricted by a potential minimum formed near the wall surface. Under such conditions, the channel wall acts as an extremely effective energy sink (Eq. (2)), which tends to limit the electron temperature.[2-4,11]

According to Eq. (1), the electron-wall collision frequency depends on the electron temperature, SEE properties of the channel wall material and the channel width. The electron temperature depends on the Joule heating, which can be controlled by the discharge voltage. We varied the parameters of Eq. (1) and compared the experimental results with simulations.

III. Experimental Setup

In these experiments a 2 kW laboratory Hall thruster with boron nitride (grade HP) channel walls was used as a benchmark thruster configuration (Fig. 1). The channel width of this thruster is 25 mm. The thruster, facility and diagnostics used in these experiments are described elsewhere.[5-7,9,13,14] In order to change the channel width two boron nitride spacers were added to the inner and outer channel walls of the wide channel (Fig. 1 b). With each spacer of 5 mm thick, the width of this channel became 15 mm. Because the magnetic field was fixed, the insertion of these ceramic spacers reduced the magnetic mirror ratio near the inner wall (Fig. 1b) from 2.1 to 1.5.[6] Therefore, when we refer to the channel narrowing it includes also the reduction of the mirror near the inner wall. In a separate set of experiments with different channel wall materials, we used the so-called segmented electrode Hall thruster.[15] The results of these particular experiments are described in detail in Refs. 7.

The thruster experiments took place in a 28 m^3 vacuum vessel equipped with cryogenic pumps. In each configuration, the thruster was operated at a constant xenon mass flow rate of about 2 mg/s and a fixed magnetic field. The background pressure did not exceed 6 µtorr. We used two different magnetic field topologies for each thruster configuration. The plasma potential, electron temperature, and plasma density were measured along the channel median by employing a fast movable setup with low disturbing shielded probes.[14] The plasma potential and electron temperature were deduced from the floating emissive and cold probe measurements, while the plasma density was measured with a biased cylindrical probe. The measurement procedure and analysis of physical uncertainties of the probe measurements are described in detail in our recent paper.[6]

In addition, the angular distribution of the ion flux from the thruster was measured with a 25-mm-diamete planar guarding sleeve probe[16] (often called "the Faraday probe" in thruster publications). The plume probe was placed at the distance of 700 mm from the channel exit and rotated ±90° relative to the thruster axis.[13] Both the probe and the sleeve were biased –30 V with respect to ground. In addition to the fast movable biased probe, the plasma density distribution was also computed from the plume measurements outside the channel exit and plasma potential measurements inside the channel.

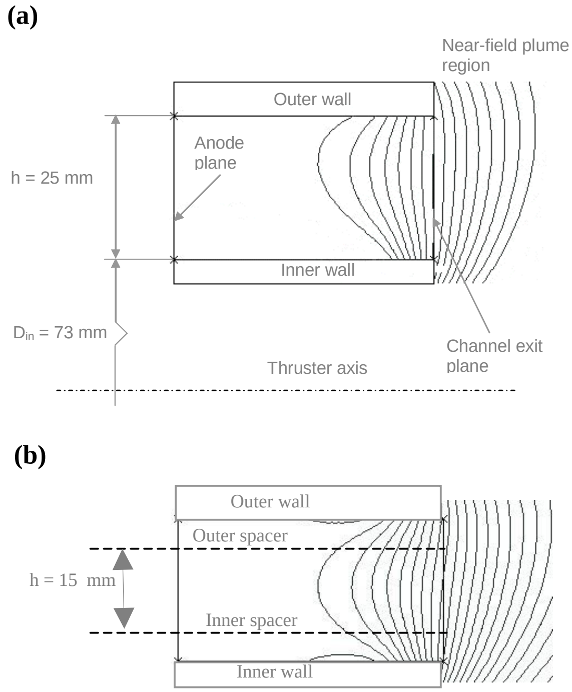

Figure 1. Schematic of the thruster channel with superimposed magnetic field lines for the benchmark thruster configuration[5,6] (a) and for the thruster configuration with two BN ceramic spacers[6] (b) .

IV. Experimental Results

A detail analysis of the V-I characteristics and plasma parameters measured for the thruster configurations used in these experiments is given in Refs. 5 and 6. Fig. 2 shows that the temperature dependence on the discharge voltage exhibits fairly similar general trends (Fig. 2a), including both transitional and steady state regimes[17]of the thruster operation with different channel widths. When the discharge voltage increases above 350-400 V, the maximum electron temperature saturates at approximately 50-60 eV.

The fluid models[2-4] predict the temperature saturation in the conventional Hall thrusters, when the near-wall sheaths approaches the space charge saturation. However, in the experiment, the temperature saturation exceeds the critical value for the SCS, estimated under the assumption of the Maxwellian electron EDF,[11] by a factor of about 3. In addition, the discharge voltage threshold appears to be almost two times higher than that predicted by the fluid model[3,4] for a different grade of boron nitride ceramic with a lower SEE than that for the grade HP boron nitride ceramic[11,18] used in our experiments. For the temperature saturation regime, by using the measured plasma parameters and exploiting the electron energy balance and Eq. (2), we obtained the experimental electron-wall collision frequency at the location of the maximum of the electron temperature. We compared this frequency with the theoretical frequency, given by Eq. (1). The comparison of these frequencies[7] (Fig. 2b) suggests that the experimental electron-wall frequency for high discharge voltages is much lower than the theoretical value obtained for space charge saturated sheath regime, but larger than the wall recombination frequency.

Without going into details of the disagreement between the experiment[5,6] and the theory,[2-4] we refer to a recent kinetic study of Sydorenko *et al.*,[19] which demonstrates the kinetic non-stationary regime of the SCS sheath in the collisionless thruster plasma with non-Maxwellian electrons. According to the PIC simulations,[19] the electron EDF in the thruster discharge is not only depleted at high energy, but also strongly anisotropic ($T_{e||}/T_{\perp} \sim 7$). More than that, secondary electrons emitted from the two opposite walls of the annular boron nitride channel can form counter-streaming beams.[19,20] When the beam electrons penetrate through the plasma bulk, they may gain enough energy (due to E×B motion) to induce the SEE from the wall.[19] In this case, the total flux of secondary electrons from the wall is[19] $\Gamma_{see} = \gamma_b \Gamma_b + \gamma_p \Gamma_p$, where γ_b and γ_p are the partial SEE coefficients due to the primary electron fluxes of the beam electrons, Γ_b, and the plasma bulk electrons, Γ_p, respectively. The effective total SEE coefficient, $\gamma_{see} \equiv \Gamma_{see} /(\Gamma_b + \Gamma_p)$ can be expressed as[19]

$$\langle \gamma \rangle = \frac{\gamma_p}{1+\alpha(\gamma_p - \gamma_b)} . \tag{3}$$

Here, $\alpha \equiv \Gamma_b / \Gamma_{see} < 1$ characterizes penetration of the electron beam through the plasma bulk. Under such conditions the sheath becomes space charge saturated when the effective coefficient $\langle\gamma\rangle$ approaches unity. It means that i) if $\langle\gamma\rangle$ <1, the SEE coefficient due to the plasma bulk electrons, γ_p, is no longer restricted to be less than unity and ii) the average energy of the plasma bulk electrons can be larger than the critical value required for the SCS sheath regime in the plasma without beams.[19] Note that using a macroscopic model, Ahedo *et al*.[20] obtained a similar conclusion with respect to $\gamma_p>1$. However, the model[20] assumes Maxwellian plasma electrons and does not consider the SEE due to the beam electrons, i.e., in Ref. 20, $\gamma_b = 0$. According to Ref. 19, a contribution of the beam electrons to the SEE is critical for precise understanding of plasma-wall interaction in Hall thrusters. It is important to emphasize that although a strong temperature anisotropy and beams of secondary electrons might explain the measured temperature saturation, these predictions require experimental verification.

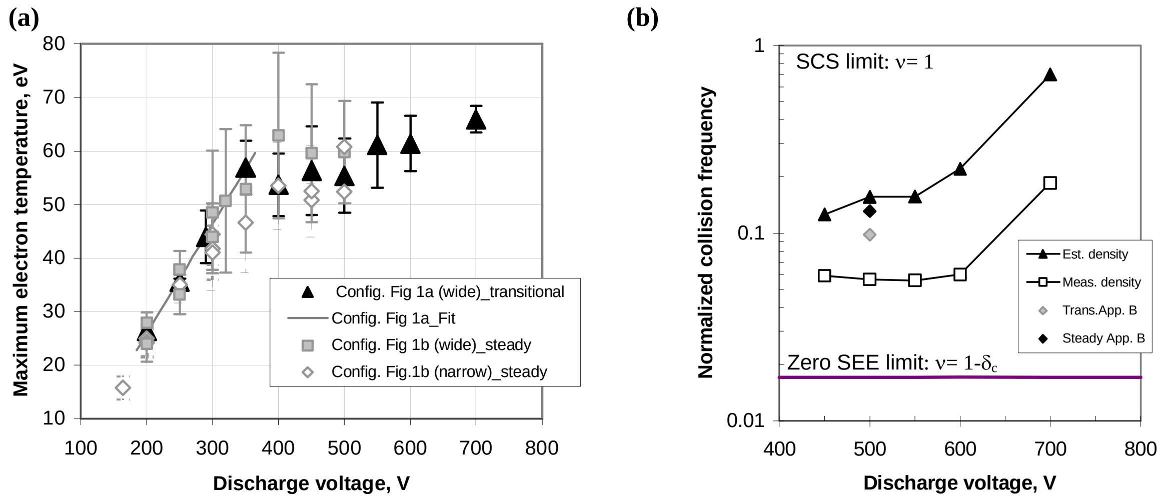

Figure 2. The dependence of the maximum electron temperature on the discharge voltage for different magnetic field and channel width configurations,[5,6] and for both steady state and transitional operating regimes (a). The frequency ratio[6] (the experimental electron-wall collision frequency to the theoretical frequency) obtained for the thruster configuration shown in Fig. 1a in transitional regime (lines with markers) and for the thruster configuration shown in Fig. 1b (markers only). Here, $\delta_c \approx 0.983$. For each thruster configuration, the magnetic field is not changed with the discharge voltage. The thruster channel is made of a grade HP boron nitride ceramic.

V. Conclusions

We reviewed the effects of the discharge voltage[5,6] and the channel width[5] on the electron temperature in Hall thrusters. The comparison of theoretical and experimental results demonstrates that the existing fluid models cannot quantitatively predict the dependence of the electron temperature on the discharge voltage and explain the electron temperature saturation obtained for the conventional Hall thruster with boron nitride channel walls. The experimental results may indirectly support recent kinetic studies,[19] which predict the kinetic regime of the SCS sheath in the collisionless thruster plasma with strongly anisotropic electron EDF and beams of secondary electrons.

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