Controlling Ion Acceleration Region in Hall thrusters

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The channel width is shown to have a significant effect on the plasma potential distribution in a Hall thruster. In the discharge voltage range of 200-500V, the channel narrowing significantly reduces the electric field inside the thruster channel and causes the accelerating voltage drop to be established mainly in the near-field plasma plume. An enhanced anomalous cross-field mobility is suggested as an explanation to the reduced electric field measured inside a narrow channel. Having a larger potential drop in the near field plasma plume may have advantages with respect to erosion of the thruster channel.

I. Introduction

In conventional Hall thrusters,[1,2] the electric field distribution is controlled mainly by the magnetic field profile along a ceramic thruster channel. However, the ion beam divergence is large, leading to erosion of the channel walls and making difficult the integration of the thruster with a satellite.[3,4] The magnetic field lines curvature and electron pressure are among the factors, which can contribute to the beam divergence in Hall thrusters.[5] A relatively long (~ 2 cm) ion acceleration region with a large voltage drop is usually located partially inside and partially outside the channel exit,[6-9] where the fringing magnetic field can lead to defocusing of the ion beam.[3,5] In order to improve the ion beam focusing, the magnetic field topology with a zero field region was proposed and implemented in a number of advanced Hall thrusters.[1,10] Control of the plasma flow is also possible with segmented electrodes placed along the thruster channel.[11] For a 1 kW segmented electrode Hall thruster, the plume narrowing effect of segmented electrodes[11]was attributed to the reduced voltage drop measured outside the channel exit[12] For a given discharge voltage, the accelerating voltage drop inside the channel with segmented electrodes is increased, which may lead to erosion of the electrodes due to the ion-induced sputtering. In addition to a possible lifetime issue, the erosion of electrodes can cause a conductive coating on the ceramic part of the thruster channel. Such a coating may significantly alter thruster operation, including an increase of the discharge current and instability of the discharge, leading to a degradation of thruster performance. Appropriate sputtering resistant materials are therefore important, especially for high specific impulse applications, which require a high discharge voltage operation of the Hall thruster. In recent experiments with a 2 kW Hall thruster, we demonstrated durability of segmented electrodes made of a low sputtering carbon fiber velvet material.[13] This novel material has exceptional sputtering resistant properties with respect to the backflow of contamination, which is much less than that from graphite and carbon composite

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materials. Because of a low density of the velvet material, a critical challenge for thruster applications is, however, to minimize the wear rate of the velvet electrodes. A polycrystalline diamond can be another potential material for the thruster channel walls[14] and segmented electrodes, provided that films of this material can be made thick enough to last for an adequate time.

A different approach to the problem of the channel wall erosion is to place the ion acceleration region with a large voltage drop outside the channel exit.[3,8,15] A possible advantage of this approach is that the ions which strike the walls and cause the erosion are now less energetic. However, in this case, the ion acceleration occurs in the fringing magnetic field where the plasma flow is subjected to divergence because of defocusing equipotential surfaces.[3,5] Kapulkin *et al.*[15] proposed the outside electric field Hall thruster, in which the anode is placed at the channel exit. For effective ionization of Xenon gas, the thruster was operated in a two stage configuration. In a recent paper,[8] we showed that the placement of the acceleration region outside the channel exit can be also achieved by the channel narrowing. In this paper, we highlight key results of this study for a high discharge voltage operation of a 2 kW Hall thruster with two different channel widths. In section II, we briefly describe the experimental setup. Experimental results are reviewed in Section III, and conclusions are presented in Sec. IV.

II. Experimental Setup

A 2 kW Hall thruster (Fig. 1) was operated in a 28 m^3 vacuum vessel equipped with cryogenic pumps. The background pressure did not exceed 6 µtorr. The thruster, facility and diagnostics used in these experiments are described elsewhere.[16-18] The thruster channel is made of a grade HP boron nitride ceramic. The effective channel length taken from the anode to the channel exit is 46 mm. The channel width is measured between the inner and outer channel walls. In one thruster geometry, the channel has the outer diameter of 123 mm and the width of 25 mm. We refer to this thruster configuration as to "wide". In the second thruster configuration, referred to here as "narrow", two boron nitride spacers are added to the inner and outer channel walls of the wide channel (Fig. 1). With each spacer being 5 mm thick, the width of this channel becomes 15 mm. Because the magnetic field was kept constant, the insertion of these ceramic spacers reduced the magnetic mirror ratio near the inner wall from 2.1 to 1.5.[8] For plasma measurements inside the thruster channel and in the near field plasma plume, we employed a fast movable setup with low disturbing shielded probes.[16] The plasma potential and electron temperature were deduced from the floating emissive and cold probe measurements along the channel median. The measurement procedure and analysis of physical uncertainties of the probe measurements are described in detail in Refs. 9 and 17. In addition, the angular distribution of the ion flux from the thruster was measured with a planar guarding sleeve probe.[18]

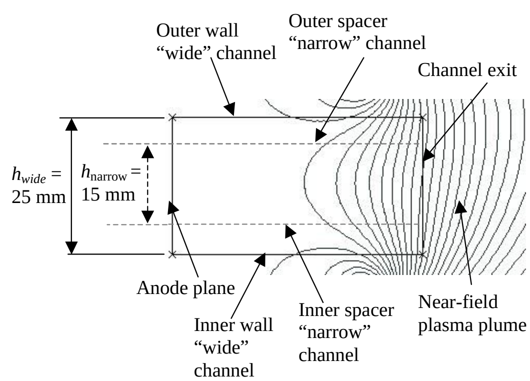

Figure 1. Schematic of the thruster channel for two different channel widths (15 mm and 25 mm) with superimposed magnetic field lines.[8]

III. Experimental Results

A detail analysis of the discharge and ion plume characteristics and plasma parameters measured for the wide and narrow thruster configuration is given in Refs. 8. The channel narrowing, which should enhance electron-wall collisions, causes large changes of the plasma potential distribution. For the narrow channel configuration, the acceleration region is located almost completely in the near field plasma plume (Fig. 2). We found that this result holds for all discharge voltages used in these experiments (Fig. 2b), i.e., below and above the voltage threshold for the electron temperature saturation. The enhanced anomalous cross-field mobility (near-wall or Bohm-type) was suggested by a hydrodynamic model[8] as an explanation to the reduced electric field measured inside the narrow channel. From our simulations described in Ref. 8, it appears that the variation of the channel width only is insufficient to reproduce the experimental result. This reflects the fact that near-wall conductivity depends on the electron EDF.[19] In addition, the reduced magnetic mirror near the inner wall (Fig. 1) of the narrow channel might also affect the plasma potential distribution.[10,20]

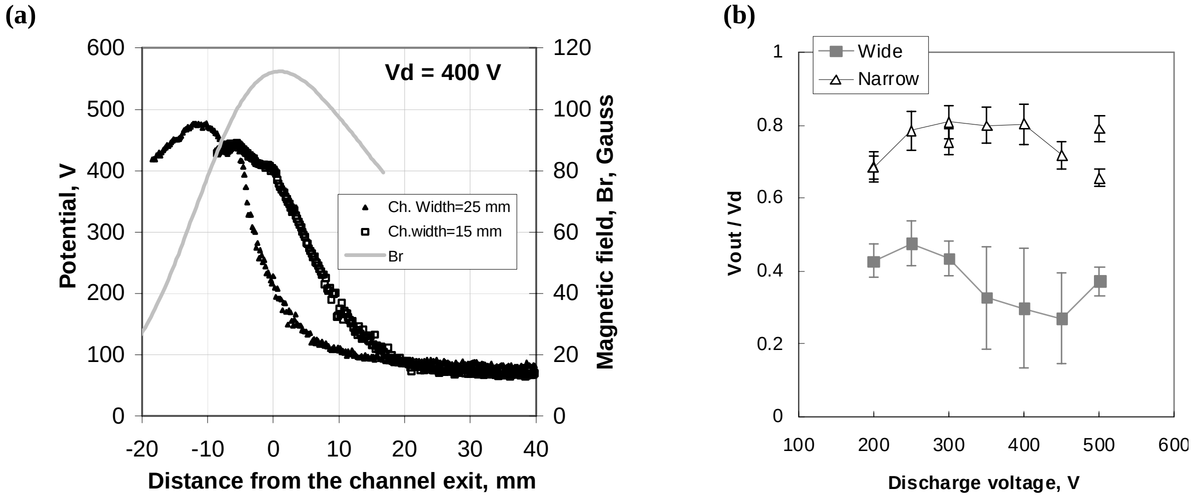

Figure 2. Plasma measurements for two thruster configurations with different boron nitride channels of 25 mm width and 15 mm width: the plasma potential distributions for the discharge voltage of 400 V (a); the outside voltage drop in the near-field plasma plume, V_{out}, as a function of the discharge voltage, V_d (b).[8] Magnetic field is not changed with the discharge voltage.

Having a larger potential drop in the near field plasma plume can have some advantages and disadvantages for thruster applications. A possible advantage is that fewer energetic ions can strike the walls and cause the channel erosion.[3] However, the ion acceleration occurs in the fringing magnetic field, where the plasma flow is divergent due to the defocusing equipotential surfaces.[3,5] Within the accuracy of plume measurements, we obtained a less than 10% larger plume angle for the narrow channel, as compared with the wide channel (Fig. 3). Interestingly, as the discharge voltage increases above 600 V, the difference in the plume angle diminishes, but the thruster with the narrow channel operates more efficiently in terms of the product of the current and propellant utilization efficiencies.

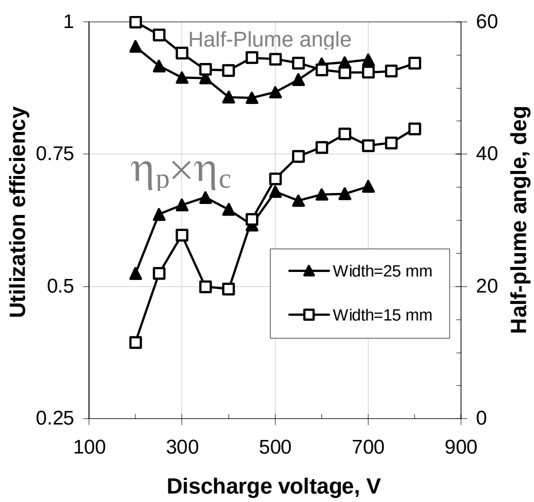

Figure 3. Results of plume measurements for two thruster configurations with two different channel widths: 25 mm and 15 mm. Propellant utilization times current utilization[8] and half-plume angle obtained for 90% of the total ion flux. Magnetic field is not changed.

IV. Conclusions

We showed that the channel narrowing significantly reduces the electric field inside the channel and causes the accelerating voltage drop to be established mainly in the near-field plasma plume. Enhanced anomalous cross-field mobility was suggested by a hydrodynamic model[8] as an explanation to the reduced electric field measured inside the narrow channel. A practical implication of the channel narrowing effect is that it may be used to reduce the channel erosion, which is more critical for high discharge voltage operation because of a larger energy of ions impinging the channel walls.

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