Variable operation of Hall thruster with multiple segmented electrodes

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Variable plasma jet velocity with low beam divergence over a range of mass flow rates can be achieved through segmented electrode operation of the Hall plasma accelerator. With the use of just a cathode side electrode at the cathode potential, the beam divergence can be decreased substantially, at some cost in efficiency. However, the additional use of an anode side electrode retains the same reduced plume divergence, but at efficiencies comparable to the nonsegmented operation. The high efficiency persists also when the anode side electrode is biased at an intermediate potential, thus producing two-stage Hall accelerator operation. [DOI: 10.1063/1.1337919]

I. INTRODUCTION

The Hall plasma accelerator is an electrical discharge device in which a plasma jet is accelerated by a combined operation of axial electric and magnetic fields applied in a coaxial channel. Since both the ionization of the working gas atoms and the acceleration of the resulting ions takes place in the same quasineutral electric discharge, neither process is subject to space charge limitations. Hence, Hall accelerators can provide high jet velocities (10–20 km/s) with larger current densities ($\sim$0.1 A/cm^2) than can conventional ion sources.[1]

The design of existing Hall accelerators, including the channel geometry, the material, and the magnetic field distribution, depends strongly on the input parameters of the accelerator, such as, the working gas, the gas flow rate, and the discharge voltage.[2] Hall plasma thrusters for satellite station keeping were developed, studied and evaluated extensively for xenon gas propellant and jet velocities of about 15 km/s, which is at a discharge voltage of 300 V.[3,4] Hall thrusters of different geometry optimized for different input power levels (0.5–10 kW) were developed. Furthermore, 0.6 kW and 1.4 kW thrusters have been successfully flown on communication satellites.[4]

What remains a challenge is to develop a Hall thruster capable of efficient operation under variable conditions, such as at different input powers or at varying output thrusts.[5] A number of issues arise with variable operation of Hall current accelerators.[6–8] These issues include decreased thruster efficiency, $\eta=T^2/2mP_e$, where T, m, and P_e are the thrust, mass flow rate, and the input power, respectively, for low mass flow rate and for low discharge voltages.[6,7] At lower mass flow rates, the lower atomic density in the channel increases the ionization mean free path of propellant atoms, reducing the ionization efficiency and leading to increased ion losses in the channel.[6] Moreover, an extended ionization region produces a spread of ion energies, including slow ions, which contribute particularly to enlarge the plumedivergence. This is a crucial issue even for nonvariable operation. A similar effect would be incurred through the use of not easily ionized gases.[8]

II. SEGMENTED ELECTRODE HALL THRUSTER

In conventional Hall accelerators, the key element controlling ionization and acceleration processes in the channel is the magnetic field distribution.[1,2] A different control approach, which involves segmented electrodes along a dielectric channel, was suggested in Ref. 9. Figure 1 shows a schematic view for the case of two segmented electrodes. Electrodes are placed along the channel axis on the low potential side (negative side or NS electrode), as well as on the positive side (PS). If these electrodes are emissive and biased with cathode (NS) and anode (PS) potentials, the magnetic field lines, which intersect the emitting surfaces of these electrodes, should be at the corresponding potentials due to the emitted electrons moving along these lines. As a result, the accelerating electric field should be established across the dielectric gap between these electrodes.[9] This electric field and, as a result, the beam divergence in the channel and the plume should then be sensitive to the details not only of the magnetic field distribution, but also to the gap extent. Moreover, it is possible to bias these electrodes by different potentials from separate power supplies, for example, in order to separate ionization and acceleration processes in the channel.

In Refs. 9 and 10 we reported that, even if the NS segmented electrode is not emissive and floating, it can still strongly affect operation of the accelerator. The difference between the segmented and nonsegmented acceleration cases was attributed to a difference in secondary emission coefficients of channel and electrode materials.[10,11] Decreased plume divergence was reported in parametric studies of a Hall accelerator employing a single segmented electrode placed at the cathode side of the channel.[10] Although the plume divergence could be substantially improved over conventional operation, particularly at low mass flow rates, the single electrode configuration entails some decrease in propellant and current utilization efficiencies.

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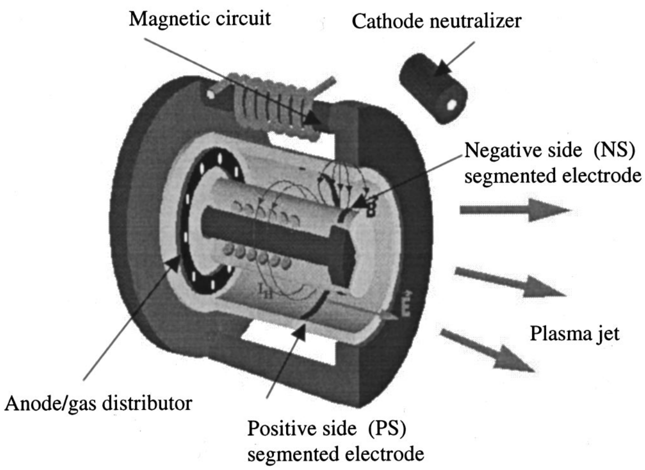

FIG. 1. A schematic drawing of Hall current accelerator with two segmented electrodes. E is the accelerating electric field, B is the applied magnetic field, and I_H is the electron Hall current.

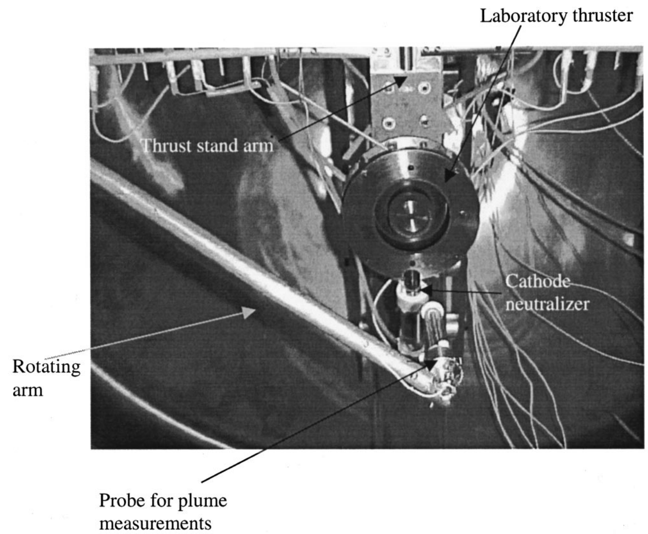

FIG. 2. PPPL segmented electrode Hall thruster.

In order to overcome the observed reduction of the propellant utilization, a certain channel profile is apparently useful. Reference 6 reported that a reduction of the channel cross section in the ionization region can increase the ionization. The increase might be due either to the increased atomic density at small mass flow rate[6] resulting in more frequent ionization collisions, or to a more uniform and focused neutral flux.[7] The present study shows that the low plume divergence operation is possible without the loss in efficiency if a second anode-side segmented electrode with a certain profile is employed in addition to the cathode-side electrode. That anode-side segment tends to increase the efficiency if it is biased at the anode potential, or sometimes even if it is not biased. If the anode-side segment is biased at an intermediate potential, then two-stage operation, similarly at high efficiency and low plume divergence, can be achieved.

Thus, the use of these electrodes extends considerably the parameter regimes for favorable operating characteristics of Hall plasma accelerators. Through simple switching of electrode energizing, one may achieve such a variable mode operation. Consistent with the principle of operation of segmented electrodes, and in view of the results reported in Refs. 6, 9, and 10, the precise placement of these electrodes along the channel, as well as their precise shape and emissivity, are likely to be significant.

III. EXPERIMENTAL SETUP

The experiments took place in a 28 m^3 stainless steel vacuum vessel. Figure 2 shows an experimental Hall current accelerator with two segmented electrodes. The accelerator is suspended on a 0.5 mN resolution pendulum-type thrust stand, which measures the thrust. The thrust resolution was taken equal to the smallest directly measured calibrated weight. On the other hand, the smallest difference between the calibrating weights, which was reliable detected, was equivalent to the thrust of 0.2 mN. Although thrust stand calibration measurements, which were performed with and without thruster operation, exhibited deviation between different sets of calibrating measurements less than 0.5 mN, the thrust stand absolute error was equated to the directly measured thrust resolution.[10,12] The jet velocity and the efficiency were derived from thrust mass flow and power measurements without taking into account the gas flow rate through the cathode, but correcting for the background gas pressure effect.[6] Following Ref. 12, the relative errors in determining the thruster performance were estimated as the rms total static error. For the results of thruster efficiency described later, the relative error was no more than ±5% of the measured value.

An electrostatic probe, mounted on a rotating arm, measures the angular ion flux distribution from the accelerator. In the present set of experiments, the distance between the probe and the accelerator was 33 cm. Since the diameter of

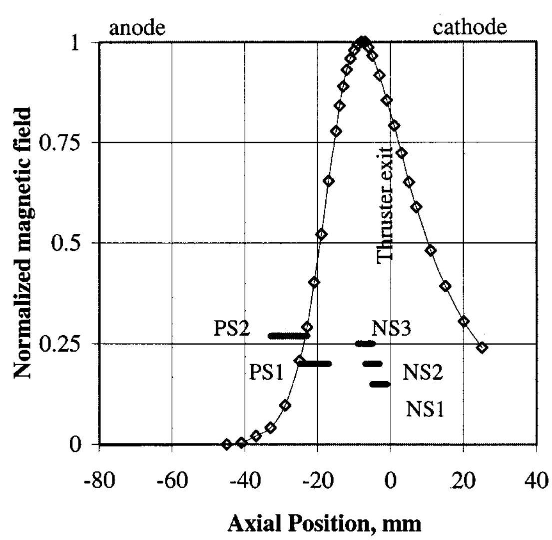

FIG. 3. Measured profile of the radial component of the magnetic field along the thruster axis near the channel median. Magnetic field is produced by a 2.1 A electromagnet current. NS1, NS2, NS3, PS1, and PS2 are locations of inner (negative side) and outer (positive side) segmented electrodes along thruster axis.

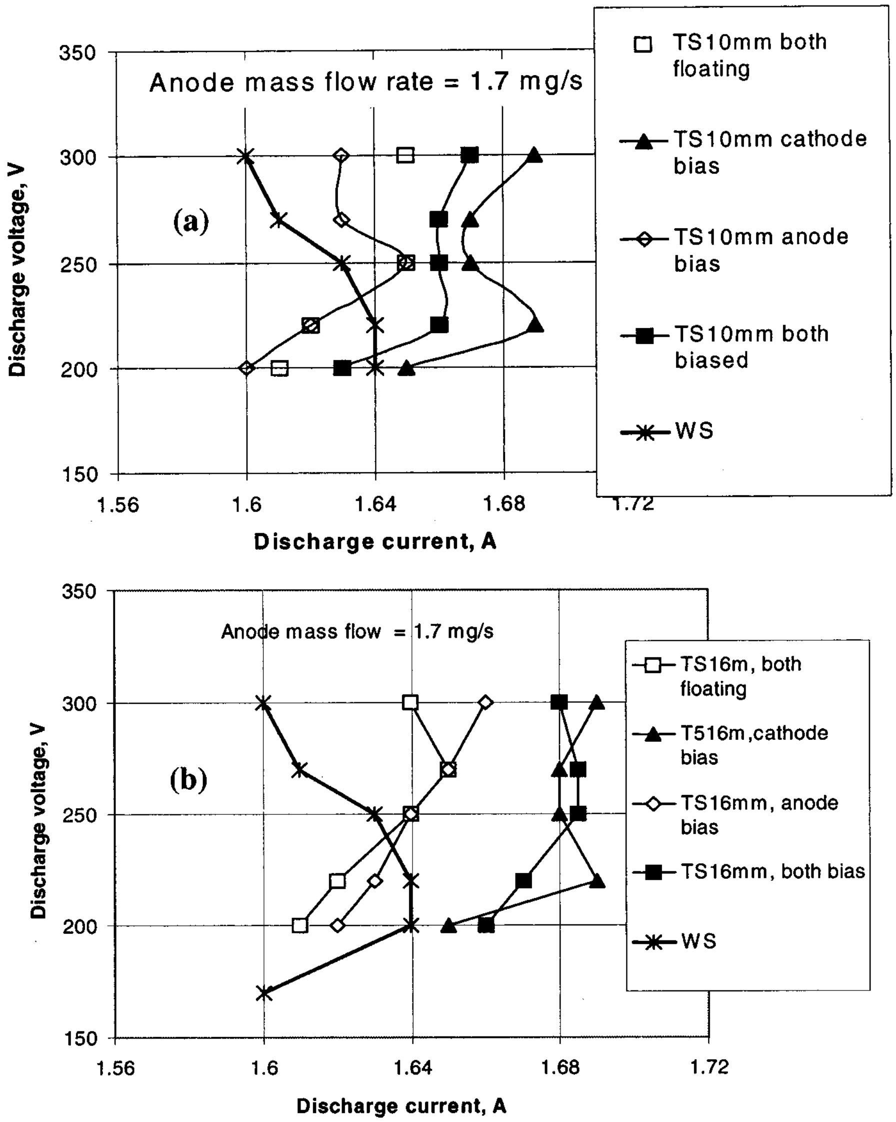

FIG. 4. Discharge voltage vs discharge current at 1.7 mg/s for 10 (a) and 16 mm (b) spacing between the segmented electrodes. TS is ''two-segment'' case, WS is ''without segment'' or conventional Hall thruster case.

vacuum vessel is about 2.3 m, the probe was far enough from the walls of the vacuum vessel to minimize the influence of backflows on the probe measurements. By integrating over the angular distribution, the total ion flux and plume angle for 90% of the flux are estimated. Based on the results of Refs. 3, 6, 7, 9, and 10, this specific fraction of the total ion flux for plume angle estimations should be within the total plume angle of roughly 80°–110°. Within such a plume angle, different ion species including energetic and slow ions, contribute to the total ion flux. Even at the limiting angles, the ratio between the back ion flux to the direct measured flux is still small (less than 10%).[3] At larger angles, due to an increased facility effect (which was indicated in Ref. 3 as an increase in back ion fluxes to the Faraday cap), this ratio tends to increase, producing large uncertainties in estimates of the plume. In any case, all estimated ion fluxes of the present work are also corrected for a background plasma effect due to back ion fluxes.[3] The measured reproducibility of plume measurements is ±4° of the full angle. The propellant utilization, which is the ratio of the total ion flux to the total input flow of neutral atoms, is derived from the probe and mass flow measurements. The test facility, thruster, diagnostic setup, and experimental procedure are described in greater detail in Ref. 10.

To produce high emissive current, both the anode-side and cathode-side segmented electrodes have about 1 mm thickness of LaB_6, plated in a rhenium mesh to allow a strong structure of the emissive layer. This mesh was mounted on a molybdenum substrate ring of 3 mm thickness for each electrode. The length of the NS and PS electrodes was 4 and 10 mm, respectively. The same sizes were used in Ref. 9 for tantalum segmented electrodes. In addition to heating by plasma, external heaters of a filament type can be incorporated with each segmented electrode in order to maintain surface temperature of LaB_6 (~1400 °C) enough to implement high emissive regimes. However, the results of the present article were obtained with no additional heaters, i.e., in low emissive regimes.[10]

The various locations where the electrodes might be placed can be seen from Fig. 3. In the present work, the NS segmented electrode was attached to the inner wall, while PS electrode was inserted into the channel on its outer wall. This placement of the segmented electrodes made for easier

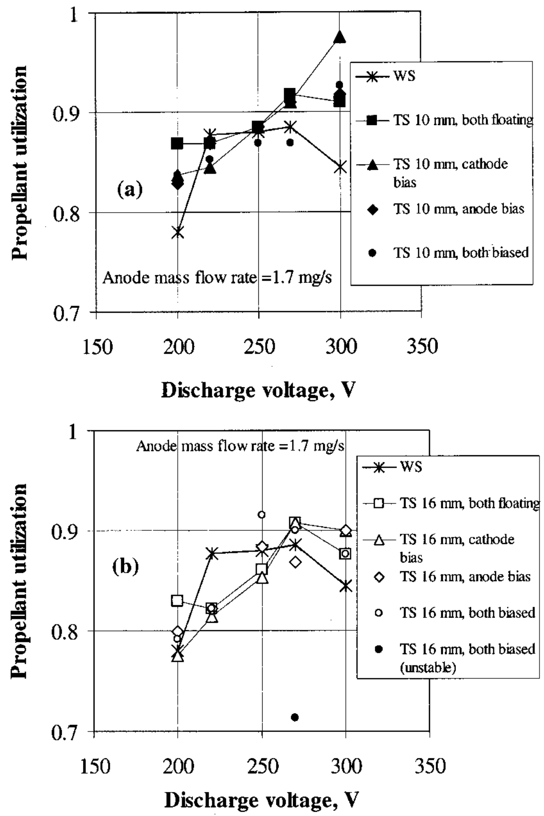

FIG. 5. Propellant utilization, which is the ratio of the ion current to equivalent mass flow current, vs discharge voltage at 1.7 mg/s for 10 mm spacing (a) and 16 mm spacing (b) between the segmented electrodes. Reproducibility of probe measurements at 30 cm from the thruster exit is less than ±4% of the total ion flux.

implementation of operation with two segmented electrodes and prevented electrical breakdown along the channel wall. Note that the positive side segmented electrode has a triangular cross section of a 5 mm height pointed towards the accelerator axis. The two electrode sides, which are not attached to the wall, have a LaB_6 layer. Thus, this electrode reduces the channel cross section area by 33% at the peak of the triangle.

The earlier locations of the segmented electrodes correspond to those in the previously reported investigation of the one segmented case, where electrodes are placed at either the cathode side or the anode side.[9,10] In the two segmented electrode cases described later, the cathode-side electrode is always at position NS2. When the anode-side electrode is in position PS2, exactly 16 mm separates the two electrodes. When the anode-side electrode is in position PS1, exactly 10 mm separates the two electrodes. Accordingly, those two cases are sometimes referred to respectively as the 16 and 10 mm cases. Accelerator operation with segmented electrodes are compared to those measured with nonsegmented configuration of the accelerator referred later to WS.

IV. RESULTS AND DISCUSSION

One of the features of segmented electrode operation is an increase in the discharge current when a cathode-side electrode is biased at the cathode potential.[10] It is of interest that the propellant utilization is significantly increased over the conventional nonsegmented case at some operating regimes such as at discharge voltages of larger than 250 V. In the case of a single segmented electrode configuration, we attributed this increase to a reduced magnetic insulation. This insulation decreases as the length of the acceleration and ionization region decreases, due to the low secondary emission from the metal wall of the NS electrode. Figure 4 shows that this increase in the discharge current at gas flow rate of 1.7 mg/s persists when an anode-side electrode is inserted, whether that anode-side electrode is at floating potential or biased to the anode potential. Note that the mere presence of the segmented electrodes when the cathode-side electrode is not biased does not particularly produce an increase in the discharge current.

Figure 5 shows the propellant utilization. It is of interest that the propellant utilization is significantly increased over the conventional nonsegmented case. An interesting comparison can be made also to the previously reported results for one segment only, at NS2, where no anode side segmented electrode was present.[10] In the case of cathode side bias, the propellant utilization is increased by as much as 10% by the mere presence of the anode-side electrode,

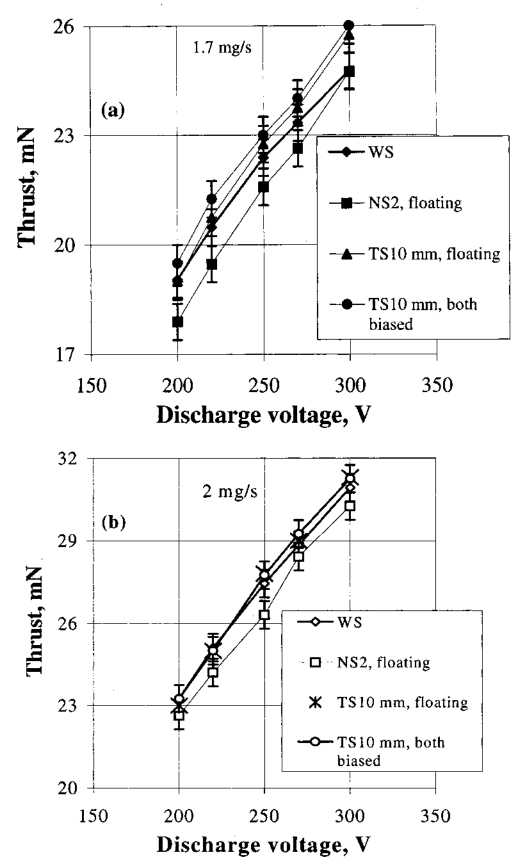

FIG. 6. Thrust vs discharge voltage at the anode mass flow rates of 1.7 (a) and 2 mg/s (b) measured for accelerator configurations with two segmented electrodes, one segmented electrode (NS) and without segmented electrodes. The thruster efficiency was estimated with taking into account the mass flow rate through the cathode.

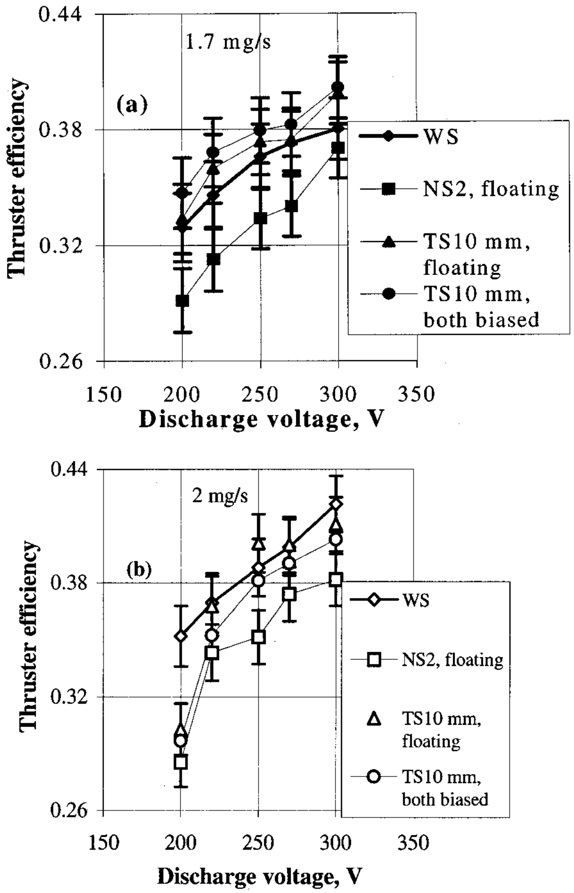

FIG. 7. Thruster efficiency vs discharge voltage at the anode mass flow rates of 1.7 (a) and 2 mg/s (b) measured for accelerator configurations with two segmented electrodes, one segmented electrode (NS) and without segmented electrodes. The thruster efficiency was estimated taking into account the mass flow rate through the cathode.

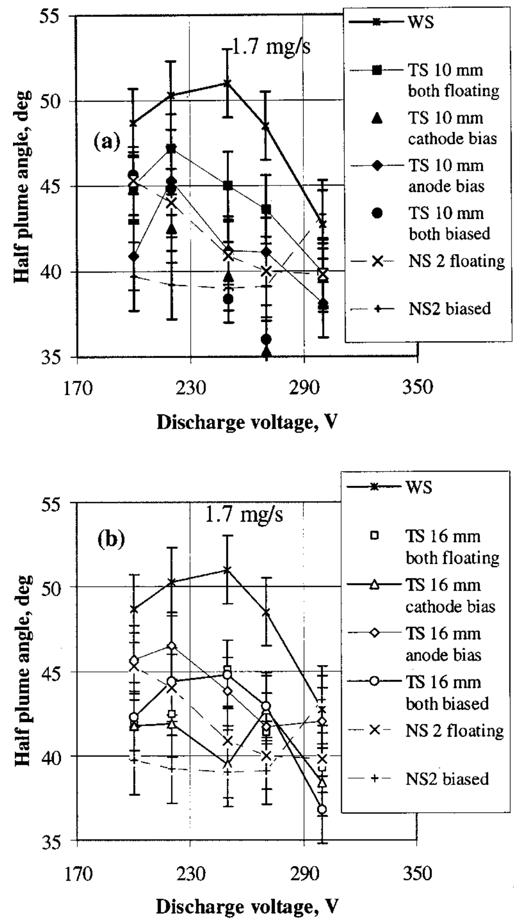

FIG. 8. Half plume angle vs discharge voltage at a mass flow rate of 1.7 mg/s for two spacing between the electrodes 10 (a) and 16 mm (b), and for one segmented electrode configuration (NS2 floating and cathode biased), and without segmented electrodes (WS). Reproducibility of the full plume angle results is ±4°.

whether the anode-side electrode is biased or floating. The reason for this might be that the triangle-shaped anode-side electrode increases the density or possibly increases the uniformity of the density.[6] For whatever reason, the increased propellant utilization can lead to increased performance.

The increase in discharge current accompanied by increased propellant utilization, compared to conventional operation, leads to an overall performance for two-segmented operation not worse than conventional operation. Figures 6 and 7 give the thrust and the thruster efficiency, respectively, as a function of the discharge voltage. Note that the one-segmented electrode case gives less thrust and poorer efficiency than both the conventional operation and the two-segment operation.

In general, the thruster performance reported here is lower than that previously measured with the same thruster, but with a conventional configuration and at mass flow rates of 2.5 and 3 mg/s.[9] For example, for the different thruster configurations studied in the present work, the maximum efficiency measured for the operating regime of 2 mg/s and 300 V was in the range of 37%–42% [see Fig. 7(b)]. In experiments with the same thruster at the designed mass flow rate, 3 mg/s, it had been about 57%.[9] Such a degradation of the thruster efficiency is typical for conventional Hall thrusters. It can be attributed to a reduction of the propellant utilization at lower mass flow rates.[6]

Note that a relatively sharp drop of the efficiency at low discharge voltages was observed for the TS10 cases and NS2 at 2 mg/s. The reason for this phenomenon is unclear. Typically, however, such a drop is observed together with an increase of the discharge current and an increase in the amplitude of low frequency discharge current oscillations as the discharge voltage is reduced from 220 to 170 V. In addition to the data obtained at 2 mg/s, we observed similar behavior with the NS2 configurations at mass flow rate of 2.5 mg/s. The increase in the discharge current at low discharge voltages and at large mass flow rates may be associated with the behavior of the minimum discharge current versus the coils current (magnetic field). This behavior deviated from $B^2/V_d \sim$ constant, which is what would be typical for conventional Hall thrusters.[13] For example, at discharge voltages larger than 200 V, as the coil current was varied, at least two minimums to the discharge current were observed instead of one minimum. One minimum occurs for the same configurations at lower discharge voltages as is indeed typical for Hall thrusters. This interesting behavior of the discharge current and efficiency is not easily understood and needs further investigation.

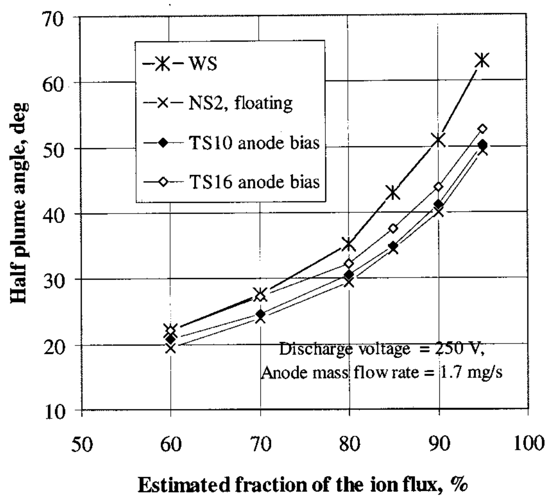

FIG. 9. Half plume angle obtained from probe measurements for different fraction of the ion flux from a distance of 30 cm from the thruster exit with four thruster configurations: without segmented electrodes, one segmented electrode (NS2 floating), and with two segmented electrodes (anode biased PS and floating NS electrodes) with 10 and 16 mm spacing.

With the efficiency and thrust comparable to conventional operation, the two-segment approach is superior to the one-segment approach, so long as the favorable plume characteristics of the one-segment operation are retained. Figure 8 shows that the favorable plume characteristics are in fact largely unaffected by the presence of the second, anode-side electrode. Figures 8(a) and 8(b) shows the persistence of the reduction in half angle plume divergence by 10° at low mass flow rates. This low mass flow rate regime is where the plume reduction tends to be greatest. In Ref. 10, the narrower plume in segmented electrode cases at low mass flow rates was explained as due to the lower fraction of secondary electrons that occurs with metal electrodes than that occurs with just ceramic walls. As a result, the electron temperature should be larger in the presence of the metal, segmented electrodes, reducing the length of the ionization and acceleration region. Because of the shorter ionization region, both the spread of ion energies should be smaller and the output sector of ions not hitting the channel walls should be narrower. Both Figs. 8 and 9 support this interpretation. In Fig. 9, the plume angle was estimated for different fractions of the total ion flux from the thruster (from 60% to 95%). As can be seen from Fig. 9, the plume reduction for the two-segmented and for the one-segmented configurations with a floating NS2 electrode is more significant for ions leaving the channel at large angles. According to Ref. 3, the flux of slow ions should become more appreciable at large angles. On the other hand, at smaller angles, although we observe a smaller advantage in the segmented electrode configurations, the narrowing of the plume still persists. These smaller angle measurements, however, are near the accuracy limit of the plume measurements ($\pm 2°$ for half angle). Note that this behavior was measured both with floating and biased segmented electrode configurations. Thus, the effect cannot be due merely to the collection of the slow ions from the plasma through the negatively biased, segmented electrodes. The plume angle reduction obtained in the floating cases indicates that a more significant role might be played by the

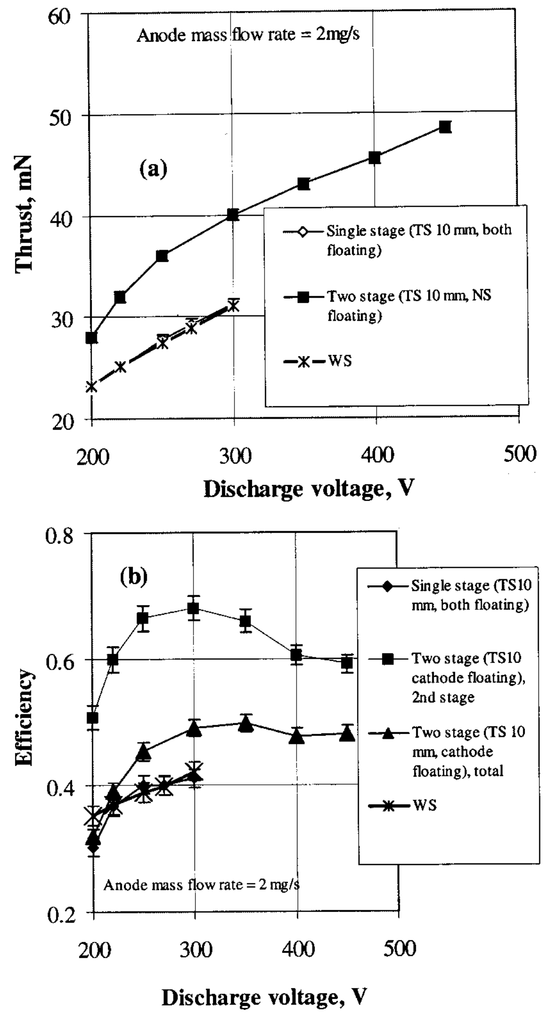

FIG. 10. Thrust (a) and the efficiency (b) vs discharge voltage measured for a two stage accelerator configuration at a mass flow rate of 2 mg/s and their comparison with conventional thruster configuration without segmented electrodes and with two segmented thruster configuration for 10 mm spacing between electrodes.

differences in the extent of the ionization and acceleration regions, which in turn occurs because of differences in the electron temperature between the segmented and WS cases.

Interestingly, the plume divergence is largely dictated by the location of the cathode-side electrode, with the anode-side electrode playing a very minor role. Yet, the anode-side electrode plays a very telling role in increased propellant utilization. The combined effect thus creates the opportunity for variable thrust at no cost in efficiency but with favorable plume divergence.

The opportunity for variable operation in much enhanced because the anode-side electrode can also be biased not necessarily at the anode potential, but at a potential intermediate between the anode and the cathode. Figure 10 shows this so-called ''two-stage'' operation, with the anode-side electrode biased 100 V negative with respect to the anode and 200 V positive with respect to the cathode. Of course, this requires a separate power supply. Note that the efficiencies are similar to conventional operation, whereas the cathode-side electrode segment can be used to control the plume divergence.

V. SUMMARY

The use of a second segmented electrode on the anode-side of the Hall thruster combines the favorable plume divergence characteristic of single-segmented operation with the high efficiency of conventional operation. The increase of the ionization efficiency at low mass flow rates might be attributed to the smaller effective channel cross sectional area in the localization region in which the PS electrode is placed. The decrease in plume divergence is particularly significant at low mass flow rates. There are a number of studies, which already reported the possibility of improved performance in variable thrust Hall thrusters by means of the channel profile and/or channel length. Perhaps, the use of multisegmented electrode configurations with a certain profile will also enable improvements in the ionization efficiency and, as a result, in thruster performance, in addition to the narrower plume. Therefore, it appears that the added flexibility through the use of these electrodes can extend the parameter regimes for favorable operating characteristics of Hall thrusters. Through simple switching of electrode energizing, one may achieve such a variable mode operation.

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