42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit
9 - 12 July 2006, Sacramento, California

AIAA 2006-4471

Segmented Electrodes in Annual and Cylindrical Hall Thrusters

Y. Raitses,[1] A. Smirnov,[2] D. Staack[3] and N. J. Fisch[4]
Plasma Physics Laboratory, Princeton University, Princeton, NJ, 08543, USA

In recent experiments, a 2 kW Hall thruster with segmented electrodes, which were made of an exceptionally low sputtering and low secondary electron emission carbon fiber velvet material, was operated in the discharge voltage range of 200 - 700 V. The comparison of the voltage-versus–current characteristics and plasma parameters of the Hall thruster with and without segmented electrodes indicates that the magnetic insulation of the segmented thruster improves with the discharge voltage at fixed magnetic field. The observations reported here also extend the regimes wherein the segmented Hall thruster can have a narrower plume than that of the conventional non-segmented thruster. The use of segmented electrodes is also studied for a miniaturized 100 W cylindrical Hall thruster. For an optimized variant of this thruster, we achieved performance improvements, including a 30-40% plume narrowing, reliable discharge initiation, and stable operation in the discharge voltage range of 50 - 600 V.

Nomenclature

V_d	= discharge voltage
L	= length of the acceleration region
E	= electric field
$\mu_\perp$	= electron cross-field mobility
J_i	= ion flux from the thruster
J_e	= electron cross-field current density
I_d	= discharge current
T	= thrust
θ_p	= plasma plume angle

I. Introduction

In conventional Hall thrusters,[1] 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.[2,3] The magnetic field lines curvature and electron pressure are among the factors, which can contribute to the beam divergence in Hall thrusters.[4] 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.[1,2,5] Control of the plasma flow is also possible with emissive and non-emissive segmented electrodes placed at the thruster channel walls.[1,6,7,8] Morozov proposed the use of biased emissive electrodes to control the plasma potential distribution in a Hall thruster. Each emissive electrode is biased to maintain the potential of the magnetic field surfaces intersecting this electrode. The localization of the voltage drop with emissive electrodes can potentially reduce the plume divergence. It was demonstrated experimentally [9,10] that a cathode-biased emissive segmented electrode placed at the channel exit of a 1 kW Hall thruster can substitute a conventional cathode-neutralizer which is normally located outside the thruster. The plasma potential distribution

[1]Research physicist, Princeton Plasma Physics Laboratory, yraitses@pppl.gov, AIAA member.
[2]Graduate student, Princeton Plasma Physics Laboratory, asmirnov@pppl.gov.
[3]Graduate student, Plasma Institute, Drexel University, dstaack@pppl.gov.
[4]Professor, Princeton University and PPPL, nfisch@pppl.gov, AIAA member.

can be also controlled with non-emissive electrodes placed on one of the channel walls or both the inner and outer walls.[11] The effect of a non-emissive electrode is based on the sensitivity of the thruster plasma processes, including plasma-wall interaction and electron cross-field transport, to secondary electron emission (SEE) from the channel walls.[12] In particular, the use of low-SEE electrodes is shown to reduce significantly the electron cross-field conductivity induced by the electron-wall collisions. Since the non-emissive electrodes can alter the axial (and, perhaps, radial) distribution of the electron cross-field current, they can also control the shape of the equipotentials in the thruster,[11,13] and, thereby, can affect the plasma plume. In the experiments, both emissive and non-emissive electrodes were shown to narrow the plasma plume. [7,9,10,14]

The segmented electrode Hall thruster was proposed at the Princeton Plasma Physics Laboratory in 1998.[6,7] Since then, the effects of segmented electrodes on the thruster plasma and performance have been studied both theoretically[8,11,13,15,16] and experimentally[7,9,10,11,12]. Various design and material configurations of the electrodes were developed and tested, including non-emissive[6,7,11,14] and emissive electrodes,[9,10] and different dielectric spacers made of ceramic materials with different SEE properties. The segmented electrodes were shown to improve the thruster performance and to add flexibility to the control of the thruster operation. Moreover, for cylindrical geometry Hall thrusters,[17,18] we also demonstrated several important advantages from using a segmented electrode. Having larger volume to surface area than conventional annular Hall thrusters, the cylindrical Hall thruster is particularly promising for scaling down to low power. With a segmented electrode, we achieved reliable discharge ignition and stable operation of the miniaturized 100 W cylindrical Hall thruster in the discharge voltage range of 50 - 600 V.[19]

One of the critical issues of the segmented electrode operation is that the ion-induced sputtering of the segmented electrodes made from metal[6,7] or carbon materials[10,11] can lead to the deposition of a conductive coating on the ceramic part of the thruster channel. In the case of emissive segmented electrodes, evaporation of the hot electrode material can create a heavy conductive coating on the thruster channel and the anode.[9] For any segmented thruster configuration, the conductive coating of the ceramic channel may significantly alter thruster operation, causing an increase of the discharge current and instability of the discharge, and leading to the degradation of the thruster performance. In recent experiments with a 2 kW Hall thruster, we demonstrated durability of non-emissive segmented electrodes made of low-sputtering carbon fiber velvet material.[12,14] Polycrystalline diamond can be another potential material for the thruster channel walls[20] and segmented electrodes, provided that films of this material can be made thick enough to last sufficiently long.

In this paper, we highlight the key results of recent experiments with non-emissive segmented electrodes. In section II, we describe the results of the plasma and plume measurements for a 2kW annular geometry Hall thruster with low-sputtering carbon velvet electrodes. Section III gives the brief review of recent experimental results for a 100 W cylindrical geometry Hall thruster with and without a segmented electrode.

II. Measurements in a 2kW Annular Hall Thruster with Carbon Velvet Segmented Electrodes

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.[12,14] The thruster channel is made of grade HP boron nitride ceramics. For the segmented thruster configuration, two velvet electrodes with length of 4 mm and 6 mm (Fig. 2) were placed on the inner and outer channel walls, respectively. Carbon fibers have diameter of ~5×10^{-3} mm and length of ~1.5-2 mm. The separation distance between fibers is roughly 0.02 mm. For the non-segmented thruster configuration, the velvet electrodes were substituted with the boron nitride spacers. In each configuration, the thruster was operated at constant xenon mass flow rate of about 2 mg/s. A commercial hollow cathode-neutralizer was operated in the self-heating mode sustained by the main thruster discharge. The magnetic field was held constant.

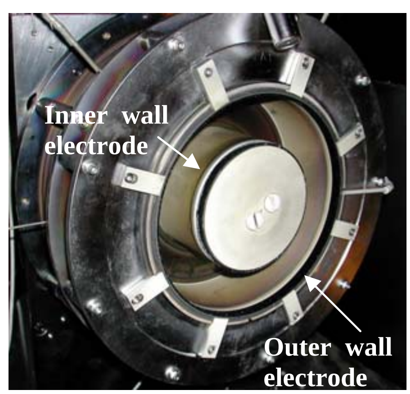


Figure 1. A 2kW Hall thruster with carbon velvet electrodes placed on the inner and outer wall of the ceramic channel (OD= 12.3 cm).

For the segmented thruster, the measurements were carried out with floating electrodes. During the first hour of the segmented thruster operation (total operating time was ~ 50 hours) we encountered arcing between the velvet electrodes and the plasma. A possible mechanism of this arcing is related to field emission from protrusive carbon fibers. A detail analysis of the arcing phenomena in the segmented thruster is given in Ref. 14. We found that a certain conditioning time (~ 1 hour) is required in order to avoid the arcing between the velvet electrodes and the plasma.

The operation of the non-segmented thruster at high discharge voltages exhibits a long (~ one hour) transitional regime, which precedes the steady state operation.[5,12] During the transitional operation, the discharge current is always larger than the steady state value (Fig. 3). It is not clear whether the transitional regime is associated with the thruster reaching a thermal steady state or one of these operating regimes is caused by sputtering effects.

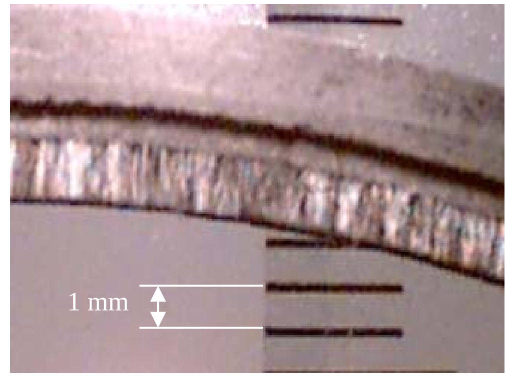


Figure 2. A carbon velvet segmented electrode (outer).

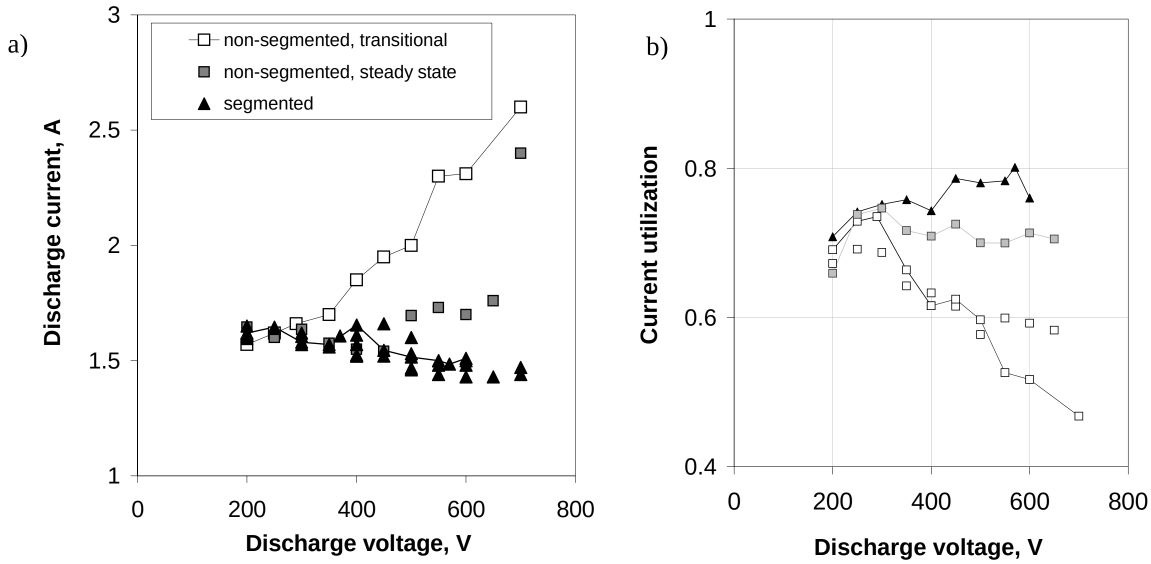


Figure 3. Experimental results for non-segmented and segmented Hall thruster configurations[12,14]: V-I characteristics (a), and the current utilization, I_{ion}/I_d (b). The segmented electrodes are made from a low sputtering and low secondary electron emission carbon velvet material. Xenon flow rate is 2 mg/s. The magnetic field is held constant.

The detail analysis of the thruster V-I, ion flux and plasma plume characteristics is given in Refs. 12 and 14. It was found that the effect of the channel wall material on the discharge current is stronger than on the ion flux from the thruster (Fig. 3). Fig. 4 shows that for the conventional thruster, as opposed to the segmented thruster, the current utilization degrades with the discharge voltage. The shortening of the plasma electric field through the conductive wall is predicted to increase the discharge current in the segmented thruster, as compared with the conventional thruster.[15,16] The fact that this effect is not so evident from our experiments is, probably, due to the relatively small surface area of the segmented electrodes.[15] We observed a certain correlation between the effects of the wall material on the discharge current and on the maximum electron temperature.[12] It was concluded that it is the SEE that is responsible for the temperature saturation and the increased of the electron current observed for the non-segmented thruster. Finally, Fig. 4 demonstrates that the segmented thruster with the carbon velvet electrodes produces a narrower plasma plume than the conventional thruster. This result is qualitatively similar to the previous reported measurements[6,7] for a smaller 1 kW Hall thruster with molybdenum and graphite segmented electrodes.

We now discuss the results of the experiments using the model of the quasineutral plasma flow[21] in the acceleration region and referring to recent measurements of the plasma properties in the non-segmented thruster.[22]

Neglecting the pressure gradient in Ohm's law and assuming that the average electric field is $E = V_d/L$, we obtain the ratio of the electron cross-field current to the ion current:

$$\frac{J_e}{J_i} \sim \langle \mu_\perp \rangle \frac{\sqrt{V_d}}{L} \quad (1)$$

where $\mu_\perp$ is the electron cross-field mobility, V_d is the discharge voltage, L is the length of the acceleration region, and $\langle\rangle$ means averaging along the acceleration region. For the non-segmented thruster operating at high discharge voltages, the average electron cross-field mobility changes insignificantly in the steady state regime, but increases in the transitional regime (Fig. 3a). In the latter case, the length of the acceleration region increases slightly with the discharge voltage. Therefore, for the transitional regime, the overall effect of the discharge voltage is the reduction of the current utilization.

For the segmented thruster, the current utilization increases with the discharge voltage

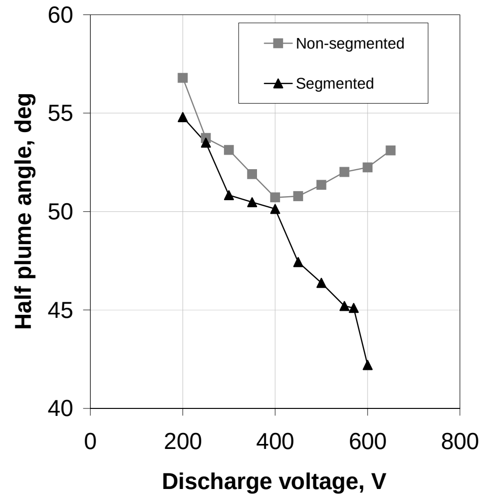


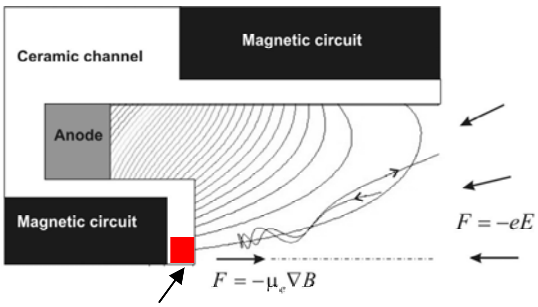
Figure 4. The plume narrowing effect of the segmented electrodes. A comparison of half plume angle estimated for 90% of the total ion flux measured for the non-segmented thruster in a steady state regime and for the segmented thruster with velvet electrodes. The standard deviation of the plume measurements is less than 3%.

Note that in keeping with our previous studies[7,11] the plasma plume narrowing effect of the segmented electrodes is likely associated with an increase of the electric field inside the channel leading to the reduction of the ion residence time in the acceleration region and thereby, to the reduction of the defocusing effect of the radial pressure gradients and magnetic field curvature on ion trajectories. If the electric field increases proportionally to or faster than $\sqrt{V_d}$, then the measured V-I characteristic of this thruster (Fig. 3a) is associated with the reduction of the electron mobility at high discharge voltages. Recent plasma measurements and modeling confirm this prediction. These results will be reported in a separate paper.

III. Experiments with a 100 W Cylindrical Hall Thruster

A. Effects of a segmented electrode on the thruster operation

The operation of the miniaturized cylindrical Hall thrusters at high discharge voltages (> 300 V) is extremely sensitive to the magnetic field, gas flow rate and the cathode conditions. Small changes in any of these parameters may extinguish the discharge. Moreover, in the discharge voltage range of 100-600 V, the miniaturized thruster discharge does not ignite when the strong magnetic field is applied in the channel. It turned out that both of these problems can be solved by placing a segmented electrode on the front wall of the short central ceramic piece of the channel. Fig. 5 shows a graphite segmented electrode installed in the 3 cm CHT thruster. The magnetic field lines near the thruster axis intersect the electrode surface. The electrode is biased positive (50-100 V) with respect to the cathode. A strong magnetic mirror in front of the segmented electrode does not inhibit a discharge (~0.5 A at 4 SCCM of xenon gas flow rate) between this electrode and the cathode. With such a precursor discharge, the main thruster discharge between the thruster anode and the cathode is easily initiated. After the main discharge is initiated, the electrode bias voltage becomes lower than the local plasma potential at the thruster axis near the front wall. If the bias voltage is equal to the floating potential of the segmented electrode, the electrode current becomes zero. When the bias voltage is set below the floating potential, the segmented electrode consumes insignificant power (depending on the bias voltage, from less than 1 W to a few watts) from the power supply during the thruster operation. Note that with the segmented electrode, the thruster operation was feasible and stable up to 600 V (limit of the power supply used in these experiments). It is not clear what mechanisms are responsible for unstable operation of the CHTs at high discharge voltage, uneasy discharge initiation, and the electrode effects. Apparently, the plasma of the precursor discharge between the segmented electrode and the cathode creates conditions for a breakdown in the magnetic configuration of the CHT (Fig. 5). The ability to initiate the CHT discharge in the presence of the strong magnetic field opens the possibility for the use of permanent magnets instead of power consuming electromagnet coils. This is particularly important for miniaturization of the CHT thrusters to micro propulsion regimes.



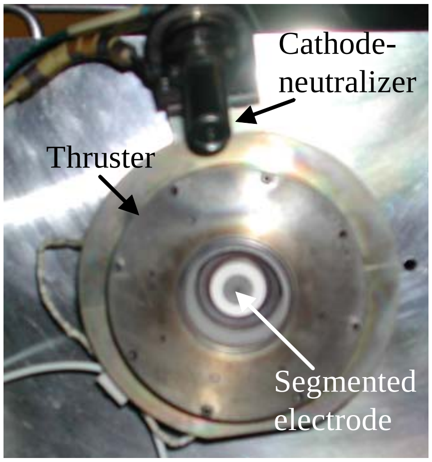


Figure 5. The 3 cm diam 100 W cylindrical Hall thruster (CHT) with a graphite segmented electrode. The electrode is placed on the front wall of the short annular channel on order to provide reliable discharge ignition in the presence of a strong magnetic field (~ 1 kGauss) and stable thruster operation. The electrode bias is 50-100 V with respect to the cathode. During the thruster operation, the electrode potential is negative with respect to the plasma and it drives less than 1 W from a power supply.

Also shown: magnetic field simulations of the 100 W CHT (left figure). The channel diameter is 2.6 cm. Illustrative electron trajectory in the cylindrical part of the channel is indicated, and the hybrid mechanism of electron trapping is schematically shown.

B. Optimization of the cylindrical Hall thruster

The key drawback of existing cylindrical Hall thrusters is the unusually large beam divergence of the plasma plume. The plasma plume angle, θ_p, is customary defined as the angle that contains 90% of the total ion current. For the cylindrical thrusters, the half plume angle can be as large as 70-80° (compared to 45-50° for the state-of-the art annular HTs). Since the CHT has possibly stronger radial electric field than the conventional HTs, more energetic ions may escape at large angles with respect to the thruster axis, which leads to the reduction of the thrust ($T \sim \cos\theta_p$). Very recently, we carried out optimization of the 100 W CHT and achieved a dramatic reduction of the plume angle. Fig. 6 illustrates the drastic decrease of the plume angle for the 2.6 cm CHT thruster at 160 W. Here, the half plume angle was reduced to 55°, which is comparable to the state-of-the-art conventional HTs. If we assume that the ion acceleration is not deteriorated as the plume is narrowed, then the thruster anode efficiency in the direct configuration should be expected to increase to ~ 35%. In fact, the ion energy measurements show that for the optimized thruster the fraction of high energy ions

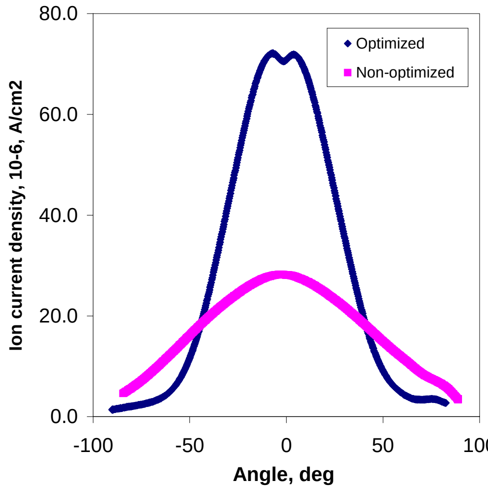
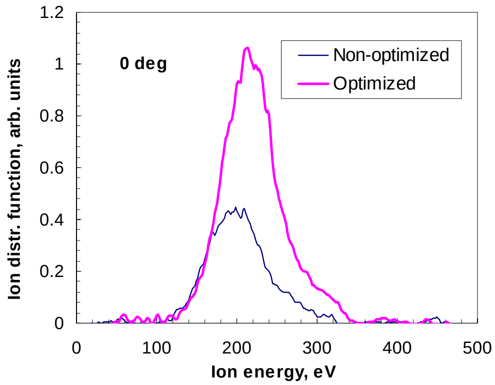


Figure 6. The CHT optimization: 30% plume angle reduction effect. The angular distributions of the ion current density in the far-field plume of the 2.6 cm CHT at 160 W (xenon flow rate 0.4 mg/s). Measurements were conducted in the large vacuum vessel equipped with cryogenic pumps, using a guarding sleeve probe (72 cm from the thruster exit). The background pressure was 3×10^{-6} Torr.

decreases at large angles to the thruster axis (>45°), but increases at small angels to the axis (Fig. 7). Fig. 8 shows the calibration characteristic of a two-grid retarding potential analyzer used in the CHT experiments for measurements of the ion energy distribution function (IEDF). The detailed analysis of these and other measurements related to the optimization of the miniaturized cylindrical Hall thruster will be presented in separate publications.

a)



b)

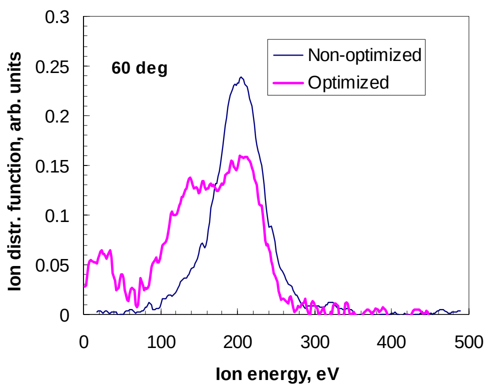


Figure 7. Ion energy measurements for a 100 W CHT at xenon gas flow rate of 0.4 mg/sec and the discharge voltage of 250 V. For an optimized thruster a fraction of high energy ions increases at small angels with respect to the axis (a) and drops at large angles (b).

The ion energy distribution was measured with a 2-grid RPA at the distance of 72 cm from the thruster. The RPA signal is not corrected for the local plasma potential. The background pressure was 3×10^{-6} Torr.

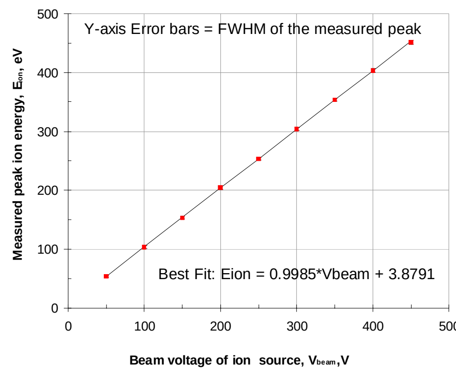


Figure 8. Calibration characteristic of a two-grid retarding potential analyzer (RPA) measured with a commercial neutralized ion beam source.

IV. Conclusions

We demonstrated very effective control of the plasma flow in the annular and cylindrical geometry Hall thrusters. For the conventional annular Hall thruster, the magnetic insulation properties of the thruster discharge with low sputtering carbon velvet electrodes tend to improve with the discharge voltage. Note that for the state-of-the-art Hall thrusters, the typical operating procedure requires the increase of the magnetic field with the discharge voltage in order to suppress the increase of the electron current. Theoretical models predict the need for this procedure in order to maximize the thruster performance. Apparently, for the segmented thruster this is no longer a requirement. The plume narrowing effect of the carbon velvet electrodes is qualitatively consistent with the previously reported results obtained with low-SEE carbon and molybdenum segmented electrodes.

For the cylindrical Hall thruster, performance improvements have been recently demonstrated through the optimization of the magnetic field and discharge parameters and the use of segmented electrodes. Having potentially smaller wall losses in the channel, CHTs should suffer lower erosion and heating of the thruster parts. This makes the CHT concept very promising not only for low-power applications, but also for high power applications.

Acknowledgments

This work was supported by US DOE Contract No. AC02-76CH0-3073 and AFOSR.

V. References

[1] A. I. Morozov and V. V. Savel'ev, in *Reviews of Plasma Physics*, edited by B. B. Kadomtsev and V. D. Shafranov, (Consultants Bureau, New York, 2000), Vol. 21.

[2] L. Garrigues G. J. M. Hagelaar, J. Bereilles, C. Boniface and J.-P. Boeuf, *Physics of Plasmas* **10**, 4886 (2003).

[3] I. Katz, G. Jongeward, V. Davis, M. Mandell, I. Mikeladis, R. Dresseler, I. Boyd, K. Kannenberg, J. Polard and D. Kind, Proceedings of the 37th Joint Propulsion Conference and Exhibit, July, 2001, Salt-Lake City, UT,, AIAA paper No. 2001-3355.

[4] A. Fruchtman and A. Cohen-Zur, Proceedings of the 40th Joint Propulsion Conference and Exhibit, July, 2004, Fort Lauderdale, FL, AIAA paper No. 2004-3957.

[5] R. R. Hofer, Ph. D Thesis, University of Michigan, 2004.

[6] N. J. Fisch, Y. Raitses, L. A. Dorf and A. A. Litvak, Proceedings of the 35th Joint Propulsion Conference and Exhibit, July, 1999, Los Angeles, CA, AIAA paper No. 1999-2572.

[7] Y. Raitses, L. A. Dorf, A. A. Litvak and N. J. Fisch, *Journal Applied Physics*, **88**, 1263 (2000); N. J. Fisch, Y. Raitses, L. A. Dorf and A. A. Litvak, *Journal Applied Physics*, **89**, 2040 (2001).

[8] A. Fruchtman, N. J. Fisch and Y. Raitses, *Phys. Plasmas*, **8**, 1048 (2001);

[9] Y. Raitses, D. Staack and N. Fisch, Proceedings of the 38th Joint Propulsion Conference and Exhibit, July, 2002, Indianapolis, IN, AIAA paper No. 2002-3594.

[10] K. Diamant, J. Pollard, R. Cohen, Y. Raitses and N. J. Fisch, Proceedings of the 40th Joint Propulsion Conference, July 2004, Fort Lauderdale, FL, AIAA paper No. 2004-4098.

[11] Y. Raitses, M. Keidar, D. Staack and N.J. Fisch, *Journal Applied. Physics*, **92** 4906 (2002)

[12] Y. Raitses, D. Staack, A. Smirnov, and N. J. Fisch, "Measurements of secondary electron emission effects in Hall thruster discharge", *Physic*s *of Plasmas*, Vol. **13**, 2006, 014502, 4p.

[13] M. Keidar, A. Gallimore, Y. Raitses and I. D. Boyd, "On potential distribution in Hall thrusters", *Applied Physics Letters* **85**, 2481 (2004).

[14] Y. Raitses, D. Staack, A. Dunaevsky and N. J. Fisch, "Operation of a segmented electrode Hall thruster with low-sputtering carbon-velvet electrodes", *Journal of Applied Physics* **99**, 036103 (2006).

[15] S. Barral, K. Makowski, Z. Peradzy´nski, N. Gaskon, and M. Dudeck, "Wall Material Effects in Stationary Plasma Thrusters. II. Near-Wall and In-Wall Conductivity," *Physic*s *of Plasmas*, Vol. 10, No. 10, 2003, pp. 4137, 4152.

[16] D. Staack, Y. Raitses and N. J. Fisch, Proceedings of the 28th International Electric Propulsion Conference, March 2003, Toulouse, France, IEPC paper 2003-157.

[17] Y. Raitses, N.J. Fisch, "Parametric investigations of a nonconventional Hall thruster", *Phys. Plasmas* 8, 2579, 2001.

[18] A. Smirnov, Y. Raitses, and N.J. Fisch, "Parametric investigation of miniaturized cylindrical and annular Hall thrusters", *J. Appl. Phys.* 92, 5673, 2002.

[19] Y. Raitses, A. Smirnov, and N. Fisch, Proceedings of 37th AIAA Plasmadynamics and Lasers Conference, San Francisco, California, June 5-8, 2006 AIAA-2006-3245.

[20] N. Gascon, M. Cappelli and W. Hargus, Proceedings of the 41th Joint Propulsion Conference and Exhibit, July, 2005, Tucson, AZ , AIAA paper No. 2005-440.

[21] E. Ahedo and D. Escobar, J. Appl. Phys. **96**, 983 (2004).

[22] Y. Raitses, D. Staack, M. Keidar, N. J. Fisch, *Phys. Plasmas* **12,** 057104 (2005);Y. Raitses, D. Staack, A. Smirnov, N. J. Fisch, *Phys. Plasmas* **12**, 073507 (2005).