44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit
21 - 23 July 2008, Hartford, CT

AIAA 2008-5188

Effects of Cathode Electron Emission on Hall Thruster Discharge

Yevgeny Raitses,* Erik Granstedt, **Artem Smirnov,†† Enrique Merino‡‡ and Nathaniel J. Fisch§
Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, 08543

Low power cylindrical and annular geometry Hall thrusters are operated in a non-self-sustained regime with different thermionic cathode-neutralizers. The enhancement of the electron emission with a keeper current for the hollow cathode and with a wire heating for the filament cathode leads to a significant (up to 30%) narrowing of the plasma plume and increase of the energetic ion fraction. For the cylindrical Hall thruster, the observed variations of the plasma potential, electron temperature, and plasma density with the keeper current suggest that the electron emission from the cathode can affect the electron cross-field transport and the ionization in the thruster channel.

I. Introduction

In a typical Hall thruster (HT),[1] a steady-state cross-field discharge is self-sustained between the anode and a hollow cathode-neutralizer. The cathode is placed outside the annular ceramic channel in the fringing magnetic field. Several experimental studies[2-5] reported that the cathode placement can affect the thruster-cathode coupling, which involves the injection of the emitted electrons in the fringing magnetic field and their conduction across the magnetic field towards the anode.[3,4] A better coupling should imply smaller power losses in the thruster discharge. For high performance medium power (1-8 kW) HTs, the optimization of the cathode placement was shown to improve the thruster performance (5% increases of the anode efficiency[4]) and narrow the plasma plume (typically 2-5% plume narrowing but in some regimes up to 20%[5]).

In addition to the cathode placement, the cathode operating parameters, including the mass flow rate, cathode heater and keeper currents can also affect the thruster discharge.[2,4,6] In general, two regimes of the hollow cathode operation are distinguished: i) the self-heating or self-sustained mode, in which the main thruster discharge current flowing through the cathode emitter provides enough heating to keep the insert at the emission temperature, and ii) the non-self-sustained mode, in which additional heating is provided to the emitter either by auxiliary discharge between the cathode keeper electrode and the cathode emitter or by supplying additional current from the heater. State-of-the-art HTs operate usually in the self-sustained regime. It is commonly accepted that the thruster discharge current is limited by ionization of the working gas, wall losses and electron transport across the magnetic field, and not by the supply of electrons from the cathode. Nevertheless, even for high performance HTs, the additional heating of the cathode may affect the thruster parameters (for SPT-100 thruster a 5% increase of the thrust with the heater current[6]).

Among different Hall thrusters of various configurations and different power levels, the strongest cathode effect was observed in low power cylindrical geometry Hall thrusters with mirror and cusp-types magnetic field distributions.[7-11] A 20-30% plume narrowing, accompanied with improvement of ion focusing, led to a substantial increase of the thruster anode efficiency (30-40%) in the input (anode) power range of 50-200 W.[7,8] These improvements were achieved by driving a current of 2-3 A between the keeper and the emitter of the hollow cathode neutralizer. The keeper current was 3-5 times larger than the thruster discharge current.[7-9,] Because the discharge current increased with the keeper current, over and above what is normally required for sustaining the steady state discharge (at given gas flow rate, discharge voltage, and magnetic field), this non-self-sustained regime was referred to as the overrun discharge current regime.[7] Moreover, the cathode placement was shown also to affect the thruster

---

* Research Physicist, PPPL, MS-17, P.O. Box 451, Princeton NJ 08543, AIAA Member.
** Graduate Student, PPPL, MS-1730, P.O. Box 451, Princeton NJ 08543.
†† Current position: Research scientist, Tri Alpha Energy, Foothill Ranch, CA.
‡‡ Research Assistant, MS-16, P.O. Box 451, Princeton NJ 08543.
§ Professor, Princeton University and PPPL, MS-1730, P.O. Box 451, Princeton NJ 08543, AIAA Member.

operation in different configurations of non-conventional Hall thrusters, including CHT[10] and so-called diverging-cusped field Hall thruster.[11]

In order to clarify physical mechanisms responsible for the overrun current regime, a set of recent experiments was conducted in which the CHT was operated with the filament cathode instead of a hollow cathode.[10] As the heating of the filament wire was increased, the discharge current increased, while the plasma plume became narrower. This behavior is similar to the keeper current effect in the CHT with a hollow cathode.[7] It was concluded then that the enhancement of the electron emission from the thruster cathode leads to the overrun current regime.[10] Plasma measurements in the miniaturized CHTs with the hollow cathode and the filament cathode revealed that the performance improvements in this non-self-sustained regime might be associated with the increased axial electric field inside the thruster channel and the upstream shift of the ion acceleration region.[9,10]

In this paper, we highlight recent results of plasma measurements for low power CHTs with the filament and hollow cathodes. These results are described in greater detail in Refs. 9 and 10. In addition, we demonstrate that a strong effect of the electron emission on the plasma plume can be also attained for the low power Hall thruster of conventional annular geometry. These results imply that for low power Hall thrusters, the cathode self-heating of the hollow cathodes may not provide sufficient and effective supply of electrons into the thruster discharge and plasma plume. Preliminary results for a permanent magnet version of the miniaturized CHT are also reported.

II. Miniaturized cylindrical and annular Hall thrusters

The CHT[12] (Fig. 1) features a combination of both end-Hall thruster[13] (EHT) and conventional annular Hall thrusters of stationary plasma thruster[1] (SPT) type. A detail comparison between the CHT and EHT is presented in Ref.14. Like the EHT, the CHT has a lower surface-to-volume ratio than do SPT and, thus, seems to be more promising for scaling down to low power space applications. The principle of operation of the CHT is in many ways similar to that of a typical annular Hall thruster, i.e., it is based on a closed E×B electron drift in a quasineutral plasma. However, the CHT differs fundamentally from a conventional annular thruster in that magnetized electrons in the cylindrical design provide charge neutralization of non-magnetized ions not by not moving axially, but through being trapped axially in a hybrid magneto-electrostatic trap.[15] Comprehensive studies of the CHT with cusp-type and mirror-type magnetic field configurations are reported elsewhere.[12,15,16] For the miniaturized low power CHT, the optimal magnetic field configuration was shown to be an enhanced mirror-type.[17]

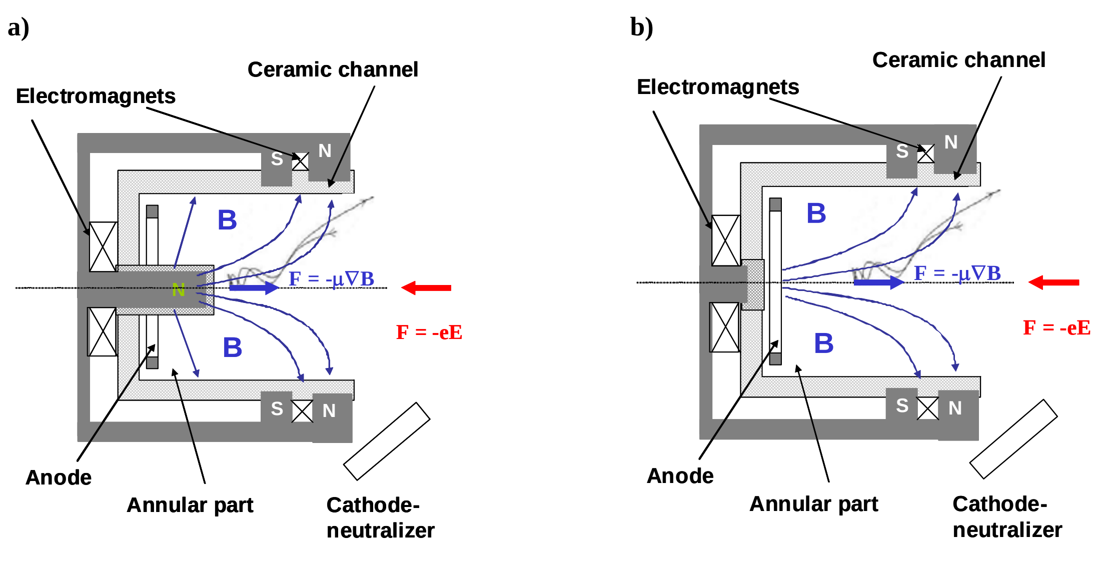


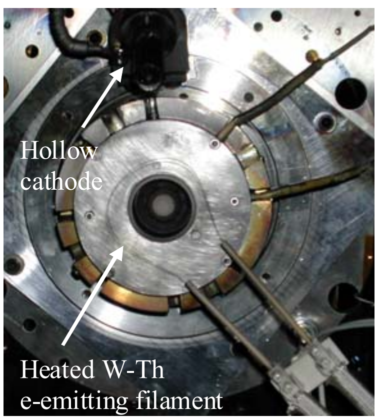
Figure 1. Schematic of a cylindrical Hall thruster (CHT) with (a) and without (b) a short annular part.[7,8,15] The thruster can use electromagnet coils or permanent magnets to form direct (enhanced mirror) or cusp magnetic field configurations.

A similar axial trap for electrons should exist in the mirror-type magnetic configuration of the EHT. However, the electron cross-field transport in the CHT is suppressed much better than in the EHT.[15,18] In addition, the CHT can operate more efficient and at higher discharge voltages (larger Isp).[19,20] Plasma measurements in the EHT suggest that the ions are electrostatically accelerated along the mirror with non-equipotential magnetic field surfaces towards the source exit where the magnetic field is weaker.[13] This is in contrast to the CHT, where the magnetic field lines form nearly equipotential surfaces.[21] Even so, assuming that the ways in which the electric field is produced in both these thruster types are similar, the observed differences in discharge characteristic and performance must be attributed to the differences in the channel geometry and material, configuration and location of the anode and gas injection.[14]

Fig. 1 illustrates typical designs of the CHT. The thruster consists of a cylindrical ceramic channel, a ring-shaped anode, which serves also as a gas distributor, a magnetic core, and electromagnet coils (or permanent magnets). The channel can be with or without a short annular part (Fig. 1a and b, respectively), which serves to maintain a high ionization of the propellant gas and a strong magnetic insulation of the anode.[22,23] Although performances of the CHTs with and without annular part were shown to be comparable,[8] the absence of the annular channel part adds more simplicity to the CHT design.

Fig. 2 shows two laboratory CHTs with electromagnet coils (left) and permanent magnets (right), respectively. These thrusters are designed to operate in the input power range of 100-200 W. Each CHT has the channel with outer diameter of 2.6 cm. Both thrusters have similar magnetic field distributions inside the channel. For the enhanced magnetic mirror (direct) configuration, two cobalt-samarium magnets of the same polarity are included in the magnetic circuit of the CHT with permanent magnets (CHTpm). Compared to the CHT with electromagnet coils, the key advantages of this CHT are i) much smaller total power consumption (power to electromagnet coils~ 50-100 W) and ii) twice lighter (350 g). In addition, the CHTpm is more compact (overall dimensions: 5.5 cm D × 3.5 cm L) than its counterpart with the electromagnet coils (7.8 cm D × 7 cm L).

a)



b)

Figure 2. The laboratory 100-200 W CHT thrusters with electromagnet coils (a) and Co-Sm permanent magnets (b). The channel diameter of these thrusters is 2.6 cm. The overall dimensions of the CHT with permanent magnets are 5.5 cm Diam ×3.5 cm Length. The thruster mass is 350 g.

The design of the 2.6 cm CHT with electromagnet coils has a flexible and modular design.[19] By extending the central pole of the magnetic core and the central ceramic piece up to the exit plane of the channel, the cylindrical thruster can be converted to the conventional annular thruster. The outer and the inner diameters of the annular channel are 2.6 cm and 1.4 cm, respectively. In our previous studies, [19] both annular and cylindrical configurations of the 2.6 cm thruster demonstrated comparable performance. In the present study, we compare the effect of the thermionic hollow cathode in these thrusters. Moreover, a slightly larger version of the CHT[7,8,20] (3 cm channel diameter) with similar magnetic field distribution as the 2.6 cm CHT was used in experiments with the filament cathode.[10]

III. Experimental setup

The thruster, facility, and diagnostics used in these experiments are described elsewhere.[7,19,21,24] In experiments with the hollow cathode, the thrusters were operated in the large PPPL Hall Thruster facility.[7,24] The background pressure in a 28 m^3 vacuum vessel equipped with cryopumps did not exceed 3 μtorr. In experiments with the filament cathode, the 3 cm CHT was operated in a 0.4 m^3 vacuum chamber of the small Hall Thruster facility.[19,21] This facility is equipped with a turbomolecular pump. The use of the gate valve between the chamber and the pump allows a convenient access to the thruster in order to change filament wires, when they burned. The 3 cm thruster was operated at 2 sccm Xe, a reduced flow rate compared with previous experiments in the large vacuum chamber, in order to maintain the background pressure below 20 μTorr.[10]

A commercial Heatwave 250 model hollow cathode electron source is used as the cathode-neutralizer. For both annular and cylindrical thruster configurations the cathode position with respect to the thruster was similar to that used in the previously reported experiments (See for example in Ref. 21). The cathode has a keeper electrode, which is used to initiate the main discharge between the cathode and the thruster anode, and to maintain the overrun current regime. In the described experiments, the cathode gas (Xenon) flow rate was maintained constant, 2 sccm. Previous studies reported that variations of the cathode flow rate from 1.5 to 3.5 sccm (Xenon) had a small effect affect on the CHT performance (less than a 10% increase in the propellant utilization[25]).

In experiments with a filament cathode, the cathode was constructed from a 0.25 mm diameter thoriated Tungsten wire. To enable extended thruster operation without opening the vacuum vessel, a filament holder assembly was constructed which held four filaments and allowed a new one to be rotated into place after a failure. In practice, filament lifetime ranged from 15 minutes to several hours. A detail description of the filament cathode setup is given in Ref. 10

The plasma diagnostics used in these experiments included planar plume probes with guarding rings,[24,,26] retarding potential analyzers for measurements of ion energy distribution function[7,10] and set of miniaturized Langmuir probes[21] for measurements inside the thruster channel. The plume angle was estimated from the measured angular ion flux distribution for 90% of the total ion current.

IV. Experimental results on cathode effects

A. Hollow cathode

The dramatic plume narrowing (20-30%) in the 2.6 cm and 3cm CHTs at large values of the keeper current (2.5 - 3 A) was already reported in Refs. 7 and 8. Fig. 3 demonstrates further details of this effect, including 1) monotonic changes of the discharge and plume parameters as the keeper current increases and 2) the presence of a keeper current threshold (~ 2 A) above which this keeper current effect saturates.[9] Above this threshold value, measurements of the ion energy distribution function in the far plume demonstrated that the plume narrowing is associated with a nearly twofold increase in the fraction of high-energy ions, better focusing of these ions and a shift of IEDF toward higher energies. The improvements in the ion production and focusing lead to the 20-30% increase of Isp in the input power (anode) range of 50-200 W.[7]

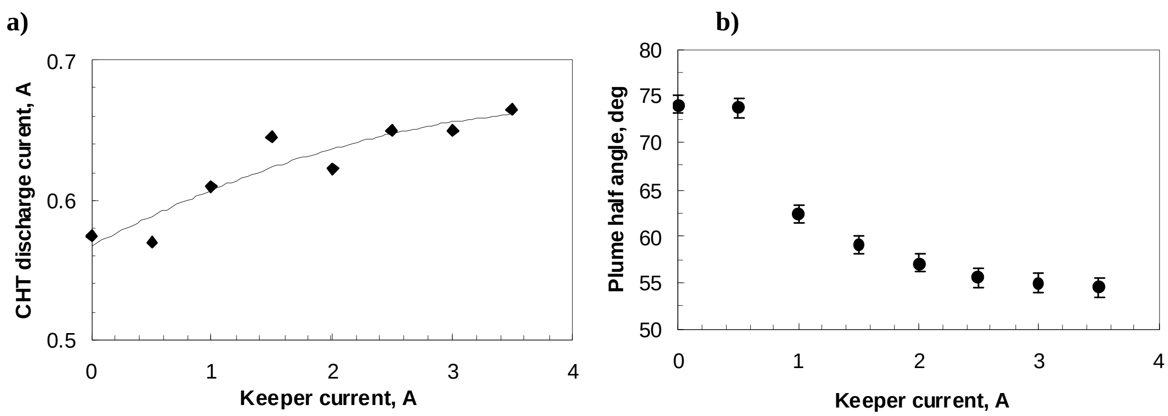


Figure 3. The effect of the keeper current on the discharge current and the plasma plume angle in the 2.6 cm CHT with electromagnet coils (thruster configuration is shown on Fig. 1a and Fig. 2a).[7,9] Thruster parameters: discharge voltage is 250 V; anode Xenon flow rate is 4 sccm; cathode Xenon flow rate is 2 sccm.

Plasma measurements inside the 2.6 cm CHT revealed that the plume narrowing with the keeper current correlates with the increase of the accelerating voltage potential drop inside the thruster channel.[9] Above the keeper current threshold, the voltage drop inside the CHT channel is twice larger than that in the self-sustained regime of the CHT discharge (Fig. 4). The analysis of these results in Ref. 9 suggested that the rate of the electron cross field transport is likely smaller in the non-self-sustained operating regime with the keeper-maintained cathode. Thus, the mechanism of the improvement of the plume divergence in the non-self-sustained CHT discharge could be based on controlling the potential profile by means of suppressing the electron cross-field transport in the CHT discharge.

This technique holds in common with the plume narrowing in the annular thruster, which was obtained through the use of segmented electrodes. [27]

An interesting observation from the plasma measurements is also that the electron temperature tends to be smaller in the non-self-sustained regime of the discharge.[9] This result may be a signature of the electron kinetic effects, which occur in the magnetic mirror and are associated with the cooling of E×B rotating particles moving along equipotential magnetic field surface. [28]

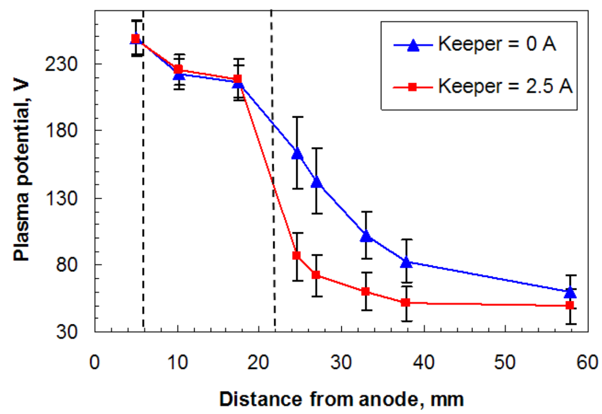


Figure 4. Measurements of the plasma potential inside the 2.6 cm CHT in the self-sustained (keeper current = 0 A) and non-self-sustained (keeper current = 2.5 A) regimes.[9] Thruster parameters: discharge voltage is 250 V; anode Xe flow rate is 4 sccm; cathode Xe flow rate is 2 sccm.

B. Filament cathode

A qualitatively similar plume narrowing of the overrun current regime can be also achieved using a hot filament cathode.[9,10] The discharge current also increases with the filament heating.[10] This particular result of the filament heating on the discharge current was also measured in a miniature annular Hall thruster[29] and for the plasma source of the EHT-type at low discharge voltages.[30] However, these studies did not address the effect of the wire heating of the filament cathode on plasma plume, ion energy distribution or performance of these devices. Fig. 5 shows the plume narrowing with increased discharge current from higher filament heater current for the 3 cm CHT.[10] These results demonstrate that thruster operation and performance can be varied by adjusting the electron emission from a thermionic cathode. The observed effect of electron emission on thruster parameters extends and clarifies performance improvements obtained for the overrun discharge current regime of the same type of thruster, but using a hollow cathode-neutralizer.[7-9] A detail analysis of the CHT operation with the filament cathode, including the effect of the electron emission on ion focusing and ion energy distribution function in the plasma plume is described in Ref. 10 It is also shown that the saturated values of thruster discharge parameters and performance can be additionally enhanced by optimal placement of the cathode wire with respect to the magnetic field.

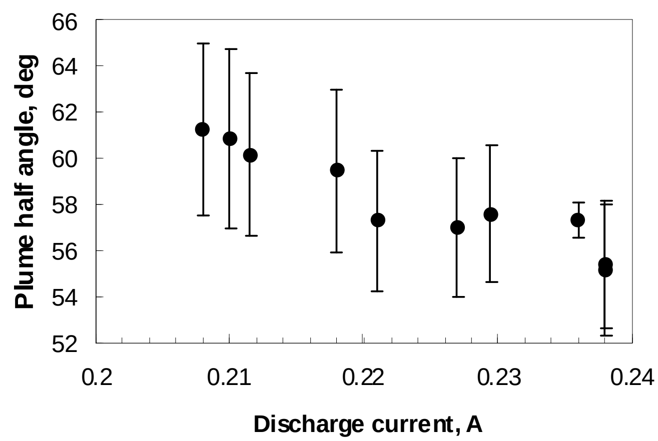


Figure 5. The effect of the filament cathode heating on the plasma plume in the 3 cm CHT with electromagnet coils (250 V, anode xenon flow rate of 2 sccm).[10] The discharge current increases with the filament heating.

C. Cathode effects in different Hall thruster configurations

Performance improvements (20-30% plume narrowing and 20% increase of the Isp) induced by the keeper current of 2 A were measured for the CHT with both direct and cusp-types of the magnetic field, and, most recently, for the 3 cm CHT without a short annular part (so-called full CHT (FCHT).[8] Moreover, Fig. 6 demonstrates that an appreciable reduction of the plasma plume angle with the keeper current of 2 A can also be attained for the annular Hall thruster. Similar to the CHT, the plume narrowing effect in this thruster is accompanied with an improved focusing of energetic ions.[7] The results of these experiments with the annular thruster will be the subject of a separate paper.

Finally, our further studies will be also focused on characterization of the cathode effect in the permanent magnet version of the CHT. Preliminary results of discharge and plume measurements in the 2.6 cm FCHT with permanent magnets indicated that a stronger magnetic field in this thruster allows this thruster to operate at larger flow rates (up to 8 sccm) and with a better suppression of the electron-cross field transport than its counterpart with the electromagnets.

V. Conclusions

It is shown that the electron emission from the cathode can control the plasma flow in the Hall thruster discharge of cylindrical and annular geometry with different magnetic field topologies. The substantially larger plume angles in the normal self-sustained regime of these low power thrusters may imply that the cathode self-heating does not provide sufficient and effective supply of electrons into the thruster discharge and plasma plume. Although the cathode effect on the Hall thruster plasma is dramatic, leading to extraordinary plume narrowing performance improvements in several conventional and non conventional thruster variations, it remains to understand in detail the physics of this effect and the ways to optimize it.

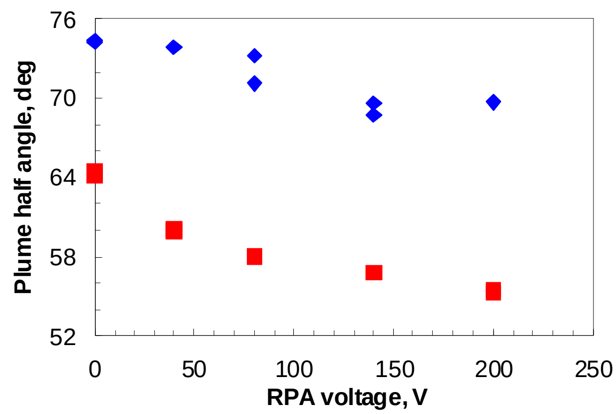


Figure 6. Results of ion energy measurements with a retarding potential analyzer (RPA) for the 2.6 cm annular Hall thruster (250 V, 4 SCCM, xenon) in the self-sustained (blue diamond markers) and non-self-sustained (red square markers) regimes. The keeper current in the non-self-sustained regime is 2.5 A. The half-plume angle estimated for 90% of the total ion current. The RPA voltage is given with respect to ground. Note that only ions with energies higher than eV_{RPA} can reach the RPA collector.

Acknowledgments

The authors wish to thank Dr. Kevin Diamant, Dr. Leonid Dorf and Mr. Martin Griswold for fruitful discussions. This work was supported by grants from AFOSR and US DOE.

References

[1] Morozov, A. I., and Savel'ev, V. V., in *Reviews of Plasma Physics*, edited by B. B. Kadomtsev and V. D. Shafranov, (Consultants Bureau, New York, 2000), Vol. 21, p. 206.
[2] Tilley, D. L., de Grys, K. H., and Myers, R. M., "Hall Thruster-Cathode Coupling", in the 35th AIAA Joint Propulsion Conference and Exhibit (Los Angeles, CA, 1999), AIAA paper 99-2865.
[3] Walker, M. L. R., and Gallimore, A. D., "Hall Thruster Cluster Operation with a Shared Cathode", Prop. Power 2007 0748-4658 vol.23 no.3 (528-536).
[4] Sommerville, J. D., and King, L. B., "Effect of Cathode Position on Hall-Effect Thruster Performance and Cathode Coupling Voltage" in the 30th International Electric Propulsion Conference (Florence, Italy, 2007), IEPC paper 2007-78.
[5] Hofer, R., Johnson, L., Goebel, D., and Fitzgerald, D., "Effects of an Internally-Mounted Cathode on Hall Thruster Plume Properties" in the 42nd Joint Propulsion Conference (Sacramento, CA, 2006) AIAA paper 2006-4482.
[6] Albarede, L., et al., "Correlation between Hollow Cathode operating conditions and Hall Thruster (SPT100-ML) performances", in the 38th Joint Propulsion Conference & Exhibit (Indianapolis, IN, 2002), AIAA paper 2002-4101.
[7] Raitses, Y., Smirnov, A., and Fisch, N. J., "Enhanced Performance of Cylindrical Hall Thrusters", Appl. Phys. Lett. , Vol. 90, 2007, 221502.
[8] Diamant, K. D., Pollard, J. E., Raitses Y., and Fisch N. J., "Low Power Cylindrical Hall Thruster Performance and Plume Properties", in the 44th Joint Propulsion Conference (Hartford, CT, 2008), AIAA paper 2008-4998
[9] A. Smirnov, Y. Raitses and N. J. Fisch, "Controlling the plasma flow in the miniaturized cylindrical Hall thruster", to appear in IEEE Trans. Plasma Sci. (Special Issue on Plasma Propulsion), 2008.
[10] Granstedt, E. M., Raitses, Y., and Fisch, N. J., "Characterization of the plasma plume in the current overrun regime of cylindrical Hall thrusters", presented at 49th Annual Meeting of the American Physical Society Division on Plasma Physics, Orlando, FL, Nov. 12–16, 2007 (Also submitted to J. Appl. Phys. (2008)).
[11] Courtney, D, and Martinez-Sanchez, M., "Diverging cusped-field Hall thruster", in Proc. 30th International Electric Propulsion Conference, Florence, Italy, 2007, IEPC paper 2007-39.

[12] Raitses, Y., and Fisch, N.J., "Parametric Investigations of a Nonconventional Hall Thruster," Physics of Plasmas, Vol. 8, No. 5, May 2001, pp. 2579-2586.
[13] Kaufman, H. R., Robinson, R. S., and Seddon, R. I., "End-Hall ion source", J. Vac. Sci. Technol. A 5, 2081 (1987).
[14] Raitses, Y., Smirnov, A., and Fisch, N. J., "Comment on "Effects of magnetic field gradient on ion beam current in cylindrical Hall ion source", submitted to J. Appl. Phys., 2008.
[15]Smirnov, A., Raitses, Y., and Fisch, N. J., "Experimental and theoretical studies of cylindrical Hall thrusters", Phys. Plasmas 14, 057106 (2007).
[16] A. Smirnov, Y. Raitses and N. J. Fisch, "Electron cross-field transport in a miniaturized cylindrical Hall thruster", *IEEE Trans. on Plasma Science*, 34, Issue 2, Part 1, pp. 132 – 141, 2006.
[17] Smirnov, A., Raitses, Y., and Fisch, N.J., "The Effect of Magnetic Field on the Performance of Low-Power Cylindrical Hall Thrusters," in the 29th International Electric Propulsion Conference (Princeton, NJ, 2005), IEPC paper 2005-099.
[18] Smirnov, A., Raitses, Y., and Fisch, N. J., "Electron Cross-Field Transport in a Low Power Cylindrical Hall Thruster", Phys. Plasmas, Vol. 11, No. 11, pp. 4922-4933, 2004.
[19] Smirnov, A., Raitses, Y., and Fisch, N. J., "Parametric Investigation of Miniaturized Cylindrical and Annular Hall Thrusters", J. Appl. Phys., Vol. 92, No. 6, pp. 5673-5679, 2002.
[20] Polzin, K.A., Markusic, T.E., Stanojev, B.J., Dehoyos, A., Raitses, Y., Smirnov, A., and Fisch, N.J., "Performance of a Low-Power Cylindrical Hall Thruster," Journal of Propulsion and Power, Vol. 23, No. 4, July-August 2007, pp. 886-888.
[21] Smirnov, A., Raitses, Y., and Fisch, N. J., "Plasma Measurements in a 100 W Cylindrical Hall Thruster", J. Appl. Phys., Vol. 95, No. 5, pp. 2283-2292, 2004.
[22] Raitses, Y. and Fisch, N.J., "Cylindrical Geometry Hall Thruster," US Patent No.: 6,448,721 B2, September 2002; Raitses, Y., Fisch, N.J., Ertmer, K.M., and Burlingame, C.A., "A Study of Cylindrical Hall Thruster for Low Power Space Applications," AIAA 2000-3421, 36th Joint Propulsion Conference, Huntsville, AL, July 2000.
[23] Shirasaki, A. and Tahara, H., "Operational Characteristics and Plasma Measurements in Cylindrical Hall Thrusters," Journal of Applied Physics 101, 073307 (2007).
[24] Raitses, Y., Staack, D., Dunaevsky, A., Dorf, L., and Fisch, N. J., "Measurements of Plasma Flow in a 2 kW Segmented Electrode Hall Thruster", in the the 28th International Electric Propulsion Conference, (Toulouse, France, 2003), IEPC paper 03-0139.
[25] Raitses, Y., Smirnov, A., and Fisch, N. J., "Optimization of Cylindrical Hall thrusters", in the 43rd AIAA Joint Propulsion Conference and Exhibit (Cincinnati, OH, 2007), AIAA paper 2007-5204.
[26] Smirnov, A., Raitses, Y., and Fisch, N., "Enhanced Ionization in the Cylindrical Hall Thruster," J. Appl. Physics, Vol. 94, No. 2, July 2003, pp. 852-857.
[27] Raitses, Y., Keidar, M., Staack D., and Fisch, N. J., "Effects of Segmented Electrodes in Hall Current Plasma Thrusters", J. Appl. Physics, 92, 4906 (2002).
[28] Fisch, N. J., Fetterman, A., Raitses, Y., Fruchtman, A., Rax, J. M., "Kinetic Mechanisms of Plume Narrowing in a Cylindrical Hall Thruster" presented at the 44th Joint Propulsion Conference (Hartford, CT, 2008).
[29] Ito, T., Gascon, N., Crawford, W. S., and Cappelli, M. A., "Ultra-Low Power Stationary Plasma Thruster", in the 29th International Electric Propulsion Conference (Princeton, NJ 2005), IEPC paper 2005-198,
[30] Zhurin, V. V., Kaufman, H. R., Kahn, J. R., and Hylton, T. L., "Biased target deposition ", J. Vac. Sci. Technol. A 18, 37 (2000).