Princeton Plasma Physics Laboratory

PPPL- 4303

PPPL- 4303

Controlling the Plasma Flow in the Miniaturized Cylindrical Hall Thruster

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March 2008

Prepared for the U.S. Department of Energy under Contract DE-AC02-76CH03073.

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Abstract

A substantial narrowing of the plume of the cylindrical Hall thruster (CHT) was observed upon the enhancement of the electron emission from the hollow cathode discharge, which implies the possibility for the thruster efficiency increase due to the ion beam focusing. It is demonstrated that the miniaturized CHT can be operated in the non-self-sustained regime, with the discharge current limited by the cathode electron emission. The thruster operation in this mode greatly expands the range of the plasma and discharge parameters normally accessible for the CHT.

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I. Introduction

The Hall thruster [1] is a mature electric propulsion device that holds considerable promise in terms of the propellant saving potential. The annular design of the conventional Hall thruster, however, does not naturally scale to low power. The efficiency tends to be lower, and the lifetime issues are more aggravated [2]. The cylindrical geometry Hall thruster (CHT) [3] has a lower surface-to-volume ratio than conventional thrusters and, thus, seems to be more promising for scaling down. The principle of operation of the CHT is illustrated in Fig. 1. It is in some ways similar to that of a typical annular Hall thruster, i.e., it is based on a closed E×B electron drift in quasineutral plasma. However, it differs fundamentally from a conventional 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 [4]. Accordingly, the underlying physics of this configuration is quite new.

Different designs of the CHT were developed and tested [3]-[6]. Comprehensive experimental and theoretical studies of the physics of the low pressure E×B discharge in a miniaturized CHT were conducted and reported elsewhere [7]-[10] The detailed characterization of the plasma discharge in the 2.6 cm cylindrical thruster was carried out, including plasma plume [9] and thrust measurements [5], [11] and probe measurements [4], [7], [10] of the plasma parameters inside the thruster. Several interesting phenomena were observed, such as, for example, the unusually high ionization efficiency [9] and the enhanced electron transport across the magnetic field [4], [8], [10]. The results of the experiments were analyzed with the use of numeric codes (quasi-1D fluid [9] and 3D kinetic Monte Carlo [8]). The numeric simulations 1) suggest the existence of strong fluctuation-enhanced electron diffusion 2) predict the non-Maxwellian shape of the electron distribution function with depleted high energy tail due to wall collisions, and 3) show that the contribution of electron-wall interaction to the cross-field transport is likely insignificant. Through the acquired understanding of the new physics, ways for further optimization of the CHT, including improvements of the magnetic configuration and the use of segmented electrodes were suggested and implemented. In particular, we showed that the anode efficiency of the miniaturized CHTs at 100 W increases to 22% as the magnetic field topology is changed from a cusp-shape to a magnetic nozzle type [4], [10]. This efficiency is comparable to and in some cases larger than that of the state-of-the-art conventional annular low-power thrusters [3], [5], [6], [11]. Although the CHTs are likely to have a very important advantage over the annular design thrusters, namely, a longer lifetime, their key drawback is a large plasma plume divergence (almost twice larger than typically values for high performance medium and high power annular Hall thrusters) leading to the thrust reduction and, potentially, to satellite integration issues.

In a recent paper [12], it was shown experimentally that for miniaturized CHTs, the plasma plume can be significantly narrowed (from a half plume angle of 70-80° to 50-55°) leading to the increase of the thruster anode efficiency by factor of 1.5 - 1.6 in the input power range of 50-200 W. These performance improvements were achieved by running an auxiliary discharge between the thruster cathode and an additional electrode. In such a non-self-sustained operating regime of the CHT, the main discharge current (between the thruster cathode and the thruster anode) can increase over and above what is normally required for sustaining the steady state discharge. In the present paper, we report and compare the results of plasma measurements for the self-sustained and non-self-sustained regimes of the CHT.

II. Experimental setup

The thruster, facility, and diagnostics used in these experiments are described elsewhere [3]-[5], [7] [12]. The 2.6 cm diameter 100 W cylindrical Hall thruster [5] (Fig. 2) has two electromagnet coils. In this paper, we describe the results of thruster experiments for the direct magnetic configuration [10] with the back coil current of + 2.5 A, and the front coil current of + 1A. The thruster was operated at the discharge voltage of 250 V, Xenon mass flow rates of 4 sccm through the anode and 2 sccm through the cathode. During these experiments, the background pressure in a 28 m^3 vacuum vessel equipped with cryopumps did not exceed 3 μtorr.

A commercial hollow cathode was used as a cathode-neutralizer. Its position with respect to the thruster is similar to that used in the previously reported experiments (See for example in Refs. [4] and [11]). The cathode has a keeper electrode, which is used to initiate the main discharge between the cathode and the thruster anode, and to maintain it when the current emitted by the cathode to the outside plasma is insufficient to provide the self-heating for stable operation. In general, two regimes of the cathode operation are distinguished: i) the self-sustained mode, in which the main discharge current flowing through the cathode provides enough heating to keep the emitter at the emission temperature, and ii) the non-self-sustained mode, in which additional heating is provided to the emitter by an auxiliary discharge between this cathode and the keeper. The keeper power supply was operated in the current-regulated regime.

Various models of the hollow cathode operation predict that the increase of the keeper current I_{ek} intensifies the heating of the cathode emitter and, thereby, makes the plasma density inside the cathode chamber grow proportionally to I_{ek} [13], [14]. Thus, the density of the plasma ejected from the cathode grows with I_{ek} as well [15]. The value of the electron current drawn from the cathode by the main discharge depends on the details of the interaction between the expanding cathode plasma and the ambient plasma with an accelerated ion beam [16].

In the described experiments, we conducted plasma measurements inside the thruster and in the plasma plume. Plasma potential, electron temperature and plasma density were measured with biased planar Langmuir probes placed stationary on the outer wall of the thruster channel (Fig. 2). Similar probes and the probe measurement procedure were used in previous CHT experiments [7]. The angular distribution of the ion current in the plasma plume was measured using a guard ring probe (sometimes called as the Faraday probe) placed at the distance of 72 cm from the channel exit and rotated ±90° relative to the thruster axis. In order to determine the total ion current generated by the thruster, I_{ion}, the measured angular distribution of the ion current was integrated assuming the axial symmetry of the plasma flux. The plasma plume angle was defined as the angle that contains 90% of the total ion flux [17]. We also calculated the current utilization, $\eta_C \equiv I_{ion}/I_d$, which characterizes how efficiently the magnetic field suppress the electron cross field transport, and the propellant utilization, $\eta_P \equiv I_{ion}M_{Xe}/e\mu$, which determines the ionized fraction of the propellant mass flow rate, μ, under the assumption of single ionization. Here, I_d is the discharge current, M_{Xe} is the mass of Xenon atom and e is the single charge. In addition, in Ref. 12, we reported the results of the detailed measurements of the thrust and the ion energy distribution function for the same thruster and the same operating conditions.

III. Experimental results

The effects of the auxiliary keeper discharge on the discharge current, plume divergence, and utilization coefficients are shown in Fig. 3. The increase in both ion and electron currents with the keeper current facilitates the overrun of the discharge current above what is normally required for self-sustained steady state discharge at the constant discharge voltage, mass flow rate and the magnetic field. Note that the propellant utilization increases above 100% with the keeper current. Such unusually high ionization efficiency, which points to the presence of multi-charge ions, was also obtained in the CHT experiments with a propellantless tungsten filament cathode [18]. Some data from experiments with a filament cathode, which are not described in this paper, are shown in Fig. 3.

The dramatic plume narrowing (20-30%) at large values of the keeper current (2.5 -3 A) was already reported in Ref.12. The plume narrowing was evident not only from the probe measurements, but also from the observation of the plasma glow distribution with the naked eye. Fig. 3 demonstrates this effect in some new details. In particular, it shows 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. The beam divergence of the generated

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Nomenclature

E = electric field

B = magnetic field

I_d = discharge current

I_{ion} = the total ion current generated by the thruster

μ = anode mass flow rate

e = electron charge

M_{Xe} = Xenon atom mass

η_C = current utilization efficiency

η_P = propellant utilization efficiency

$J_{e\perp}$ = electron cross-field current density

v_B = anomalous electron collision velocity

ω_c = electron gyro frequency

N_e = plasma density

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Note that this role of the electron emission from the cathode is supported by the experiments with the filament cathode [18]. Fig. 3 shows that a narrower plume angle measured with the filament cathode correlates with the larger discharge current in this configuration as compared to that obtained in the self-sustained regime of the CHT with the hollow cathode. It appears that the values of the discharge current and plume divergence angle in the filament cathode configuration correspond to those in the hollow cathode configuration with a keeper current of about 1A.

Probe measurements of the plasma parameters inside the 2.6 cm CHT and in the near-field plume also demonstrate that the thruster discharge with the increased keeper current differs in several respects from the self-sustained mode. In Fig. 4, we show the results of the probe measurements attained in the non-self-sustained mode of operation with the 2.5 A keeper current. The increase of the keeper current leads to the upstream shift and narrowing of the acceleration region. As seen in Fig. 4, the voltage drop between z = 18 mm and z = 24 mm is about 86 V (60 V in the cylindrical part) in the non-self-sustained mode, while with the increased keeper current, it is approximately equal to 165 V (100 V in the cylindrical part).

IV. Discussions

The difference in the plasma potential distribution inside the cylindrical part of the channel for the self-sustained and non self-sustained regimes can be analyzed using the generalized Ohm's law in the direction across the magnetic field. The electron cross-field transport in the miniaturized CHT is anomalous [4], [8], [10]. Under the assumption of the Bohm-like scaling for the anomalous collision frequency, $\nu_B = \kappa_B \omega_c/16$ [19], it follows from the Ohm's law (neglecting pressure term, which is smaller than the electric field inside the channel) that $\kappa_B \sim J_{e\perp}B/(N_e E S)$, where $J_{e\perp} \approx (I_d - I_{ion})/S$ is the electron cross-field current, B is the magnetic field, N_e is the plasma density, E is the electric field and S is the cross-sectional area. Due to a quite large measurement uncertainty [7], it is hard to make any quantitative conclusions regarding the plasma density inside the thruster channel. On the other hand, changes of the average plasma density in the thruster channel are likely reflected in changes of the propellant utilization. Then, for the constant magnetic field and cross sectional area, the ratio of the anomalous collision frequency parameter κ_B for self-sustained and non-self sustained regimes is

$$\frac{\kappa_{B\_self}}{\kappa_{B\_non-self}} \propto \frac{J_{e\perp\_s}}{J_{e\perp\_ns}} \times \frac{N_{e\_ns}}{N_{e\_s}} \times \frac{E_{ns}}{E_s} \approx 1.5 \div 2 .$$

Thus, the rate of the electron cross field transport is likely smaller in the operating regime with the keeper-maintained cathode. In general, the anomalous transport occurs as the result of electron interaction with the field fluctuations of the unstable plasma waves. It seems quite plausible that the coupling between the cathode plasma and the main CHT discharge plasma could affect the stability of some plasma modes. The cathode discharge is known to be the source of noise [20], which can propagate to the thruster plasma [21]. Besides, the cathode plasma sets a boundary condition for the thruster discharge, and, thus, can directly affect the global discharge behavior [22].

It should be noted that the mechanisms for the improvement of the plume divergence, and in general for controlling the potential profile, in the non-self sustained regime of the cylindrical Hall thruster will differ substantively from the narrowing obtained in the annular thruster. In the case of the annular thruster, the narrowing of the plume was obtained by controlling the electric field profile through the use of low secondary electron emission (SEE) segmented electrodes, which modify the axial and radial distributions of the electron-cross field transport [17]. This technique holds in common with the plume narrowing in the cylindrical thruster that in some sense "extra" electrons are injected into the discharge. However, in the case of the annular thruster, which already enjoys relatively narrow plume divergence, the effect of the extra electrode on the plume narrowing was much less pronounced. In addition, the electrons are carried by the magnetic field not mainly axially but radially. Besides low SEE segmented electrodes, the narrowing mechanism here will similarly differ from other interesting mechanisms suggested for plume narrowing in the annular thruster such as absorbing [23] and emissive [1] segmented electrodes, which directly control the plasma potential distribution in the thruster channel, such as might be obtained through a plasma lens effect [1], [24]-[26] associated with either reduced radial plasma flow to the walls [24] or with ionization near a vanishing point for the magnetic field [1], [26].

V. Conclusions

The low-current, self-sustained regime of the CHT operation is normally limited by the cathode electron emission. The observed plume narrowing, caused by the enhancement of the hollow cathode discharge, suggests that the thruster efficiency increases due to the ion beam focusing. The substantially larger plume angles in the self-sustained mode suggest that the cathode self-heating might be insufficient for the complete neutralization of the positive space charge of the ion beam. The difference in the plasma potential distributions, observed with and without the keeper current, points to the fact that the cathode discharge might influence the electron cross-field transport in the CHT plasma.

References

[1] Morozov, A. I., and Savel'ev, V. V., in *Reviews of Plasma Physics*, edited by Kadomtsev, B. B., and Shafranov, V. D., (Consultants Bureau, New York, 2000), Vol. 21, p. 206.

[2] Khayms, V., and Martinez-Sanchez, M., "Fifty-Watt Hall Thruster for Microsatellites", *Micropropulsion for Small Spacecraft*, edited by M. M. Micci and A. D. Ketsdever, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 2000, Vol. 187, Chap. 9, pp. 233-254.

[3] Raitses, Y., and Fisch, N. J., "Parametric Investigation of a Nonconventional Hall Thruster", *Phys. Plasmas*, Vol. 8, No. 5, 2001, pp. 2579-2586.

[4] Smirnov, A., Raitses, Y., and Fisch, N. J., "Experimental and theoretical studies of cylindrical Hall thrusters", *Phys. Plasmas*, Vol. 14, 2007, 057106.

[5] Smirnov, A., Raitses, Y., and Fisch, N. J., "Parametric Investigation of Miniaturized Cylindrical and Annular Hall Thrusters", *J. Appl. Phys.*, Vol. 92, No. 6, 2002, pp. 5673-5679.

[6] Shirasaki, A., and Tahara, H., "Operational Characteristics and Plasma Measurements in Cylindrical Hall Thrusters", *J. Appl. Phys.*, Vol. 101, 2007, 073307.

[7]Smirnov, A., Raitses, Y., and Fisch, N. J., "Plasma Measurements in a 100 W Cylindrical Hall Thruster", *J. Appl. Phys.*, Vol. 95, No. 5, 2004, pp. 2283-2292.

[8] 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, 2004, pp. 4922-4933.

[9] Smirnov, A., Raitses, Y., and Fisch N. J., "Enhanced Ionization in the Cylindrical Hall Thruster", *J. Appl. Phys.*, Vol. 94, No 2, 2003, pp. 852-857.

[10] Smirnov, A., Raitses, Y., and Fisch N. J., "Electron cross-field transport in a miniaturized cylindrical Hall thruster" , *IEEE Trans. Plasma Sci.*, Vol., 34, No 2, 2006, pp. 132-141

[11] 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", J. *Propulsion Power*, Vol.23, No 4, 2007, pp. 886-888.

[12] Raitses, Y., Smirnov, A., and Fisch, N. J., "Enhanced Performance of Cylindrical Hall Thrusters", *Appl. Phys. Lett.* , Vol. 90, 2007, 221502.

[13] Siegfried, D., and Wilbur, P. J., "A model for mercury orificed hollow cathodes: Theory and Experiment", *16th International Electric Propulsion Conference*, New Orleans, LA, November 1982, AIAA paper 1982-1889.

[14] Salhi, S., and Turchi, P. J., "A first-principles model for orificed hollow cathode operation" *28th Joint Propulsion Conference*, July 1992, Nashville, TN. AIAA paper 1992-3742.

[15] Mikellides, I. G., Katz, I., Goebel, D. M., and Polk, J. E. (2005). "Hollow cathode theory and experiment. II. A two-dimensional theoretical model of the emitter region", *J. Appl. Phys.* 98, 2005, 113303.

[16] Williams, J. D., and Wilbur, P. J. "Electron emission from a hollow cathode-based plasma contactor", *Spacecraft and Rockets* 29, 1992, 820.

[17] Raitses, Y., Dorf, L. A., Litvak, A. A., and Fisch, N. J., "Plume reduction in segmented electrode Hall thruster", J. Appl. Phys., Vol. 88, pp. 1263-1270, 2000;

Raitses, Y., Smirnov, A., Staack, D., and Fisch, N. J., "Measurements of secondary electron emission effects in Hall thrusters," Phys. Plasmas, Vol. 13, 014502, 2006.

[18] 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.

[19] Boeuf, J. P., and Garrigues, L., "Low Frequency Oscillations in a Stationary Plasma Thruster", *J. Appl. Phys.* 84, 1998, 3541.

[20] Goebel, D. M., Jameson, K. K., Katz, I, and Mikellides I. G., "Potential fluctuations and energetic ion production in hollow cathode discharges", *Phys. Plasmas*, Vol.14, 2007, 103508.

[21] Beiting, E. J., and Garrett, M. L., "Spectral Characteristics of Radiated Emission from SPT-100 Hall Thrusters," *29th International Electric Propulsion Conference*, Princeton, NJ, Oct. 31, 2005, IEPC paper 2005-221.

[22] Barral, S., Makowski, K., Peradzyski, Z., and Dudeck M., "Transit-time instability in Hall thrusters", *Phys. Plasmas*, Vol. 12, 2005, 073504.

[23] Fruchtman, A., and Fisch, N. J., "Variational Principle for Optimal Accelerated Neutralized Flow," Physics of Plasma 8, 56-58 (2001).

[24] Hofer, R. R, Jankovsky, R. S., Gallimore, A. D., "High-Specific Impulse Hall Thrusters, Part 1: Influence of Current Density and Magnetic Field" Propul. Power, Vol. 22, pp. 721-731, 2006.

[25] Garrigues, L., Hagelaar, G. J. M., Bareilles, J., Boniface, C., and Boeuf J. P., "Model study of the influence of the magnetic field configuration on the performance and lifetime of a Hall thruster Phys. Plasmas, Vol. 10, pp. 4886-4892, 2003.

[26] Fruchtman, A. and Cohen-Zur, A.,"Plasma Lens and Plume Divergence in the Hall Thruster," Appl. Phys. Lett. , Vol. 89, 111501, 2006.

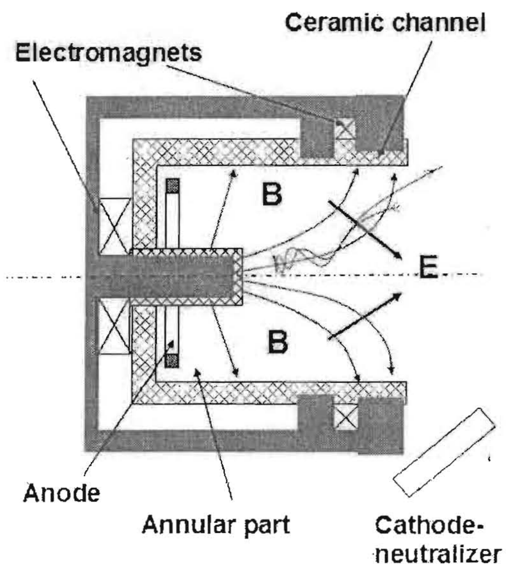


Fig. 1. Schematic of a cylindrical Hall thruster. Superimposed magnetic field lines and electron trajectory in magneto-electrostatic trap are shown for illustrative purposes.

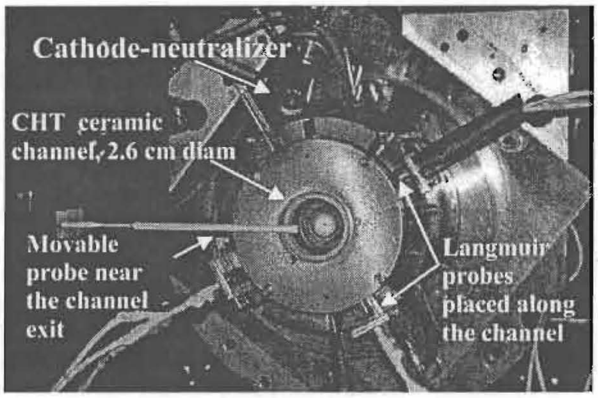


Fig. 2. The 2.6 cm diameter 100 W cylindrical Hall thruster with a hollow cathode-neutralizer and planar Langmuir probes. The near-wall probe array inside the thruster channel is stationary. The planar probe outside the thruster channel is mounted on a positioner.

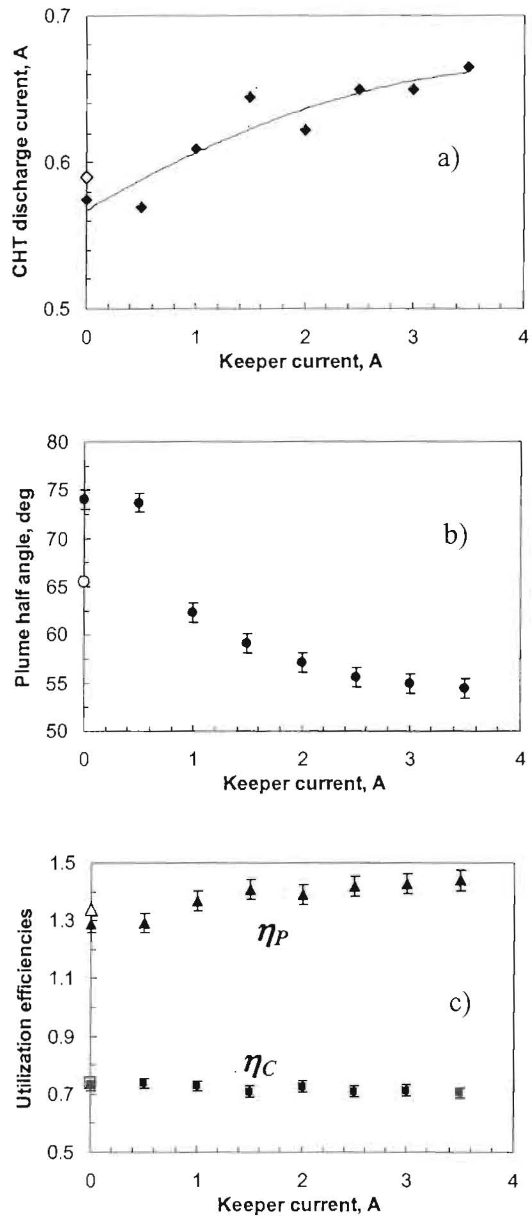
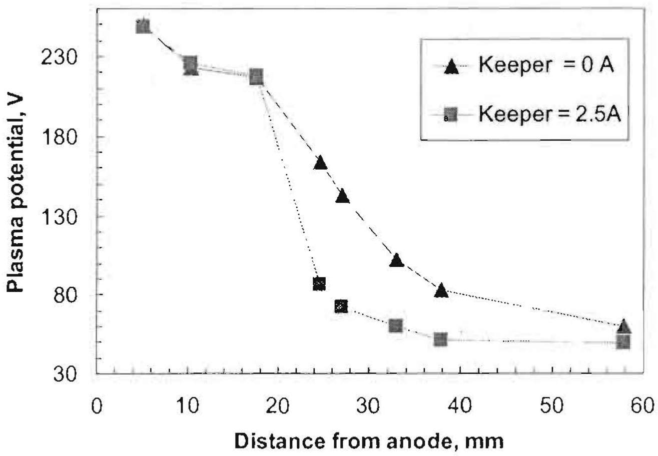


Fig. 3 The effect of the auxiliary discharge between the cathode emitter and the cathode keeper electrode on the discharge current (a), plasma plume (b) and propellant (η_P) and current (η_C) utilization efficiencies (c). The empty symbols at the zero-keeper current are data points obtained with a propellantless tungsten filament cathode.

a)



b)

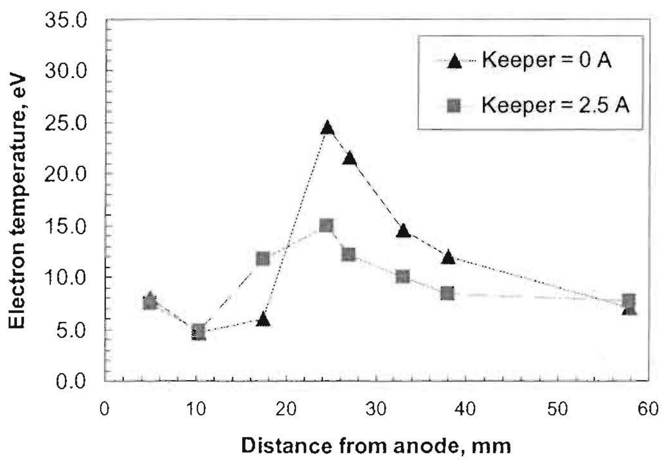


Fig. 4 Results of the plasma probe measurement inside the thruster channel in the self-sustained (keeper current = 0 A) and non-self-sustained (keeper current = 2.5 A) regimes. The plasma potential (a) and the electron temperature (b) were deduced using standard procedures[7] for a biased Langmuir probe.

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