Controlling the Plasma Flow in the Miniaturized Cylindrical Hall Thruster

A. Smirnov, Y. Raitses, and N. J. Fisch

***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 being controlled 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. The observed variation of the plasma potential, electron temperature, and plasma density with the cathode current in the non-self-sustained regime points to the fact that the cathode discharge can affect the electron cross-field transport in the CHT plasma.**

***Index Terms*—Cross-field discharge, Langmuir probe, magnetic mirror, plasma thruster.**

NOMENCLATURE

B	Magnetic field.
e	Electron charge.
E	Electric field.
I_d	Discharge current.
I_{ek}	Current flowing between the cathode's emitter and keeper electrode.
I_{ion}	Total ion current generated by the thruster.
$J_{e\perp}$	Electron cross-field current density.
κ_{B}	Bohm parameter, defined through the equality $\nu_{\mathrm{B}} = \kappa_{\mathrm{B}}\omega_c/16$.
M_{Xe}	Xenon atom mass.
N_e	Plasma density.
P_{c}	Power required to overrun the cathode discharge.
μ	Anode mass flow rate.
ν_B	Anomalous electron collision frequency.
η_C	Current utilization efficiency.
η_P	Propellant utilization efficiency.
ω_c	Electron gyrofrequency.

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 (~100 W and below, as compared with the conventional power range from roughly 0.5 kW to several kilowatts). The efficiency tends to be lower, and the lifetime issues are more aggravated [2]. The cylindrical Hall thruster [3] (CHT) has a lower surface-to-volume ratio than conventional Hall thrusters and thus seems to be more promising for scaling down. The principle of operation of the CHT is shown 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 $E \times B$ electron drift in quasi-neutral plasma. However, it differs fundamentally from a conventional thruster in that magnetized electrons in the cylindrical design provide charge neutralization of nonmagnetized ions not by not moving axially but through being trapped axially in a hybrid magnetoelectrostatic trap [4]. This electron trap is formed by the magnetic mirror on the anode side and by the self-consistent drop of the plasma potential on the cathode side. Accordingly, the underlying physics of this configuration is quite new.

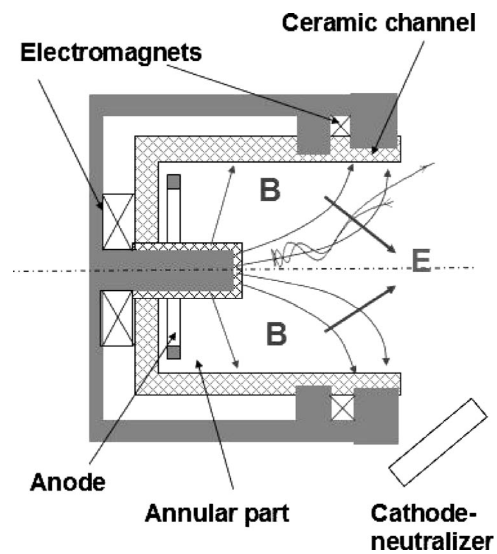

Fig. 1. Schematic of a CHT. Superimposed magnetic-field lines and electron trajectory in magnetoelectrostatic trap are shown for illustrative purposes.

We distinguish between the two configurations of the magnetic field in the CHT. In the cusp configuration, which is produced by counter-directed currents in the thruster electromagnets, the radial component of the magnetic field is enhanced, and there is a null point of the axial component of the magnetic field inside the thruster channel. Alternatively, if the currents in the thruster electromagnets are codirected, the obtained magnetic field is referred to as "direct" (Fig. 1) and is characterized by the enhanced axial magnetic field and a stronger mirror at the thruster axis.

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Various designs of the CHT were developed and tested [3], [5], [6]. Comprehensive experimental and theoretical studies of the physics of the low-pressure $E \times B$ discharge in a miniaturized CHT were conducted and reported elsewhere [4], [7], [8]. The detailed characterization of the plasma discharge in the 2.6-cm cylindrical thruster was carried out, including plasma plume and thrust measurements [5], [10] 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 [8], [10]. The results of the experiments were analyzed with the use of numeric codes (quasi-1-D fluid [9] and 3-D 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 with and, in some cases, larger than that of the state-of-the-art conventional annular low-power Hall thrusters [5], [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 typical 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 a 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. The power required to sustain the auxiliary discharge is somewhat arbitrary and depends primarily on the cathode construction and operating characteristics.

In [12], we reported the results of the detailed measurements of the thrust and the ion-energy distribution function (IEDF) in the non-self-sustained regime. In this paper, we report and compare the results of the probe measurements of plasma parameters in the self-sustained and non-self-sustained regimes of the CHT operation. We also report further details of the dependences of the global discharge parameters, such as discharge current, plume divergence, and propellant and current utilizations, on the cathode current in the non-self-sustained mode.

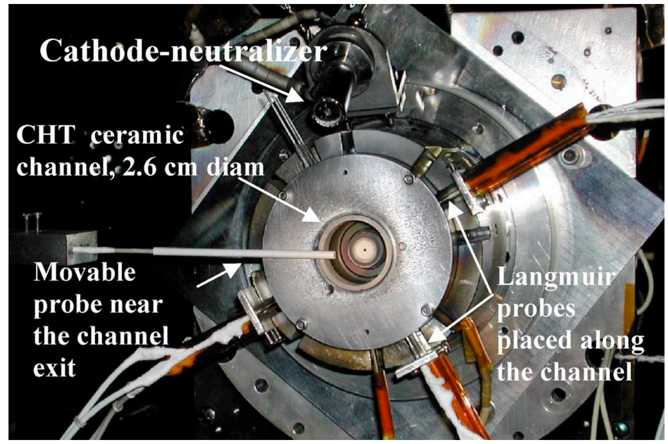

Fig. 2. CHT of 2.6-cm diameter and 100 W with a hollow-cathode neutralizer and planar Langmuir probes. The near-wall probe array inside the thruster channel is stationary. The planar probe outside the thruster channel is mounted on a positioner.

II. Experimental Setup

The thruster, facility, and diagnostics used in these experiments are described elsewhere [4], [5], [7], [12]. The 2.6-cm-diameter 100-W CHT [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 +1 A. The thruster was operated at the discharge voltage of 250 V and 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 [7]). 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, the following two regimes of the cathode operation are distinguished: 1) 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 2) the non-self-sustained mode, in which additional heating is provided to the emitter by an auxiliary discharge between the emitter and 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. The plasma potential, electron temperature, and plasma density were measured with stationary planar biased Langmuir probes placed on the outer wall of the thruster channel (Fig. 2). Similar probes and the probe measurement procedure were used in earlier CHT experiments [7]. The probes were constructed of 0.74-mm-diameter tungsten wire and 1.22-mm-outer-diameter alumina tubing. The collecting surface of the wire was flushed with the edge of the alumina insulator and with the channel wall. The measurements inside the thruster were performed along the outer channel wall at three axial locations, namely, $z = 5, 10.3,$ and 17.5 mm, from the anode. The movable probe in the near-field plume was introduced radially (Fig. 2).

The angular distribution of the ion current in the plasma plume was measured using a planar guard-ring probe (sometimes called as the Faraday probe) placed at the distance of 72 cm from the channel exit and rotated $\pm 90^\circ$ relative to the thruster axis. The probe diameter was 2.54 cm, and the gap between the probe and guard ring was 0.25 mm. In order to determine the total ion current generated by the thruster $(I_{\rm ion})$, 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 [9]. We also calculated the current utilization, $\eta_C \equiv I_{\rm ion}/I_d$, which characterizes how efficiently the magnetic field suppresses the electron cross-field transport, and the propellant utilization, $\eta_P \equiv I_{\rm ion} M_{\rm Xe}/{\rm e}\mu$, 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, $M_{\rm Xe}$ is the mass of xenon atom, and $\rm e$ is the single charge. In addition, in [12], we reported the results of the detailed measurements of the thrust and IEDF 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 increasing 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 magnetic field. Note that the propellant utilization is larger than 100% and increases with the increasing keeper current. Such unusually high ionization efficiency, which points to the presence of multicharge ions, was also obtained in the CHT experiments with a propellantless tungsten filament cathode [17]. Some data from these experiments, 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 [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 shows a few further details of this effect. In particular, it shows the following: 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

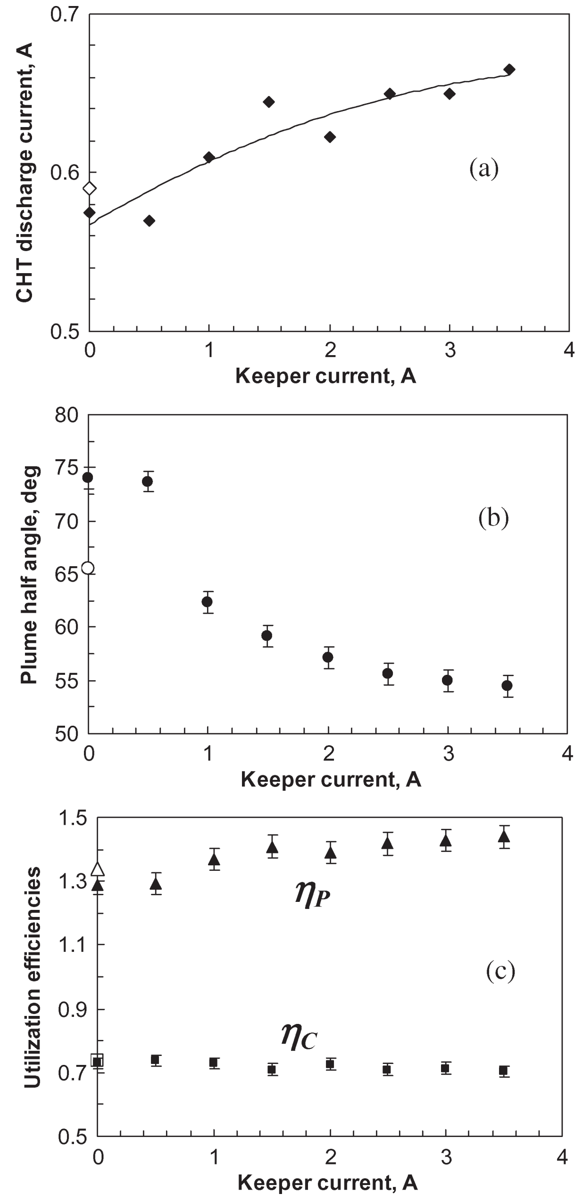

Fig. 3. Effect of the auxiliary discharge between the cathode emitter and the cathode keeper electrode on the (a) discharge current, (b) plasma plume, and (c) propellant (η_P) and current (η_C) utilization efficiencies. The empty symbols at the zero keeper current are data points obtained with a propellantless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

plasma stream decreases abruptly as the keeper current is increased to the threshold value. Above the threshold value, measurements of IEDF 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 [12], [17].

Similar performance enhancements of the overrun current regime can be attained using a hot filament cathode. Fig. 3 shows that a narrower plume angle measured with the filament cathode correlates with the larger discharge current in this configuration, as compared with that 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 are consistent with those in the hollow-cathode configuration with a keeper current of about

1 A. It was also observed that the thruster performance could be enhanced further by optimizing the position of the filament cathode. This effect, which is also observed in conventional annular Hall thrusters [18]–[20], is very different from the performance enhancement due to the overrunning of the cathode current in the CHT. The results of the experiments with the filament cathode [17] will be the subject of a separate paper.

Apparently, the electron emission from the cathode is closely related to and can control the ion-current-density distribution in the plume. The substantially larger plume angles in the self-sustained regime may imply that the cathode self-heating is insufficient for the complete neutralization of the positive space charge of the ion beam. Alternatively, the enhanced electron emission may change the distribution of the plasma potential in the near-field plume and thus improve the conditions for electron injection into the thruster channel.

The improvement of the CHT anode efficiency [12] occurs at the expense of the additional power P_{c} required to overrun the cathode discharge. The observed increase of the thruster anode efficiency by a factor of 1.5–1.6 was accompanied by a much more modest increase of the total efficiency [12]. In the experiments done so far, no special attempt was made to minimize P_{c}. The typical operating values of the additional cathode power were $\sim$10–50 and 50–100 W for the hollow and filament cathodes, respectively. The fact that these values for the two types of cathodes are substantially different, while the observed improvements of the thruster performance are quantitatively similar, suggests that the optimization with respect to the additional power is possible.

The 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 dashed lines at $z = 6$ mm and $z = 22$ mm in Fig. 4 show the edge of the annular part and the channel exit, respectively. The near-anode annular part of the channel corresponds to $0 < z < 6$, and the purely cylindrical part of the channel (no inner pole) corresponds to $6 < z < 22$. 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 self-sustained mode, whereas with the increased keeper current, it is approximately equal to 165 V (100 V in the cylindrical part).

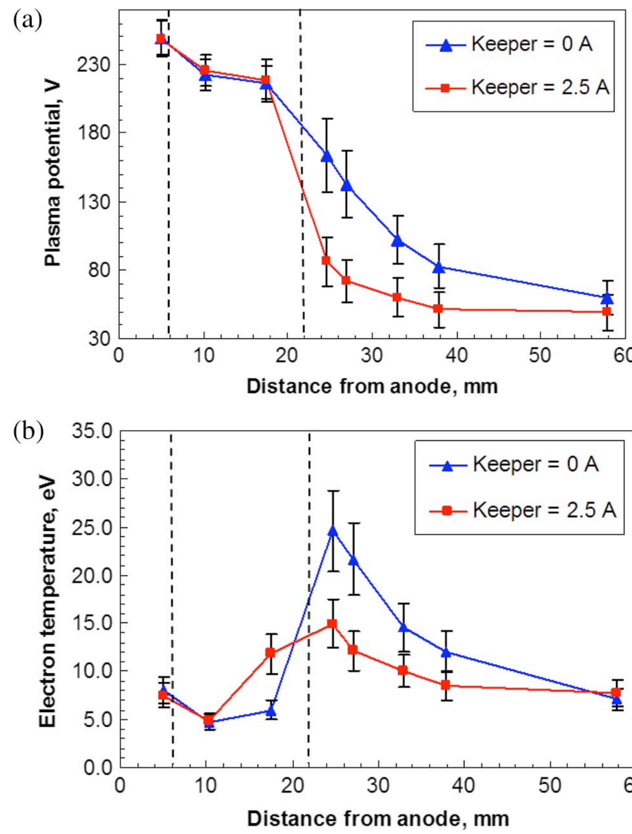

Fig. 4. Results of the plasma probe measurement inside the thruster channel in the self-sustained (keeper current = 0 A) and non-self-sustained (keeper current = 2.5 A) regimes. (a) The plasma potential and (b) the electron temperature were deduced using standard procedures [7] for a biased Langmuir probe. The annular part of the channel is $0 < z\ (\mathrm{mm}) < 6$, and the cylindrical part of the channel is $6 < z\ (\mathrm{mm}) < 22$.

IV. Discussion

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]. Under the assumption of the Bohm-like scaling for the anomalous collision frequency, $\nu_{\mathrm{B}} = \kappa_{\mathrm{B}}\omega_c/16$ [21], with κ_{B} being the dimensionless parameter, it follows from the Ohm's law (neglecting the pressure term, which is smaller than the electric-field term inside the channel) that $\kappa_{\mathrm{B}} \sim J_{e\perp}B/(N_eES)$, where $J_{e\perp} \approx (I_d - I_{\mathrm{ion}})/S$ 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 the self-sustained and non-self-sustained regimes is

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

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 [22], which can propagate to the thruster plasma [23]. In addition, the cathode plasma sets a boundary condition for the thruster discharge and thus can directly affect the global discharge behavior [24].

The mechanism of the improvement of the plume divergence in the CHT is based on controlling the potential profile by means of the injection of (in some sense) "extra" electrons in the thruster channel. This technique holds in common with the plume narrowing in the annular thruster, which was obtained by controlling the electric-field profile through the use of segmented electrodes [25]–[28]. However, in the case of the annular thruster, which already enjoys relatively small plume divergence, the effect of the extra electrode on the plume divergence was much less pronounced. The mechanism of the plume narrowing in the non-self-sustained regime of the CHT will differ substantively, because the electrons are carried by the magnetic field not mainly radially but axially. The narrowing mechanism here will similarly differ from other interesting mechanisms suggested for plume narrowing in the annular thruster, such as might be obtained through a plasma lens effect associated with ionization near a vanishing point for the magnetic field [29].

V. Conclusion

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 over what is normally required for the self-sustained operation, 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. Alternatively, the narrower plume in the non-self-sustained regime might be the result of the increased electric field and the upstream shift of the ion acceleration region measured in this regime. 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.

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