Plume Narrowing and Suppression of Low Frequency Oscillations in Cylindrical Hall Thrusters

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Abstract: A significant plume narrowing and a complete suppression of low frequency current oscillations can be achieved for the low power annular and cylindrical Hall thrusters [Y. Raitses et al., Phys. Plasmas 16, 057106 (2009)], by running an auxiliary discharge between the cathode emitter and an intermediate cathode-keeper electrode. Modifications of the plasma plume and discharge properties with the keeper current can be monotonic and non-monotonic. The external heating of the cathode emitter, which is usually used to initiate the cathode and thruster discharges, changes the V-I characteristic of the cathode discharge, but does not produce similar effects to the keeper current. The plume narrowing and suppression of discharge oscillations are not sensitive to changes of the cathode V-I characteristics including with and without negative differential resistance. These results may support the suggestion of previous studies that the measured changes of the plasma potential distribution in the thruster discharge play a major role in the plume narrowing and the suppression of low frequency current oscillations.

I. Introduction

IN a typical Hall thruster (HT),[1] a steady-state cross-field discharge is sustained between the anode and a hollow cathode-neutralizer. In the normal self-sustained regime of the thruster operation, the supply of electrons from the cathode, the ionization of the working gas, and the ion acceleration can be strongly coupled and, therefore, are not easy to control and optimize. Three major issues, which are difficult to treat because of such a coupling, are large plasma plume divergence, enhanced electron cross-field transport, and large amplitude discharge current oscillations[1] usually related to an ionization instability.[2,3,4] It was recently shown that in the non-self-sustained mode of the thruster discharge, decoupling of the cathode electron supply from the main plasma processes leads to a better focusing of the plasma flow, enhances the insulating properties of the magnetized plasma, and suppresses the ubiquitous discharge oscillations.[5,6] The maximum improvements were achieved for low power Hall thrusters in the limit of a strong electron emission from the cathode.[5,7] Under such conditions, the thruster discharge current at a given gas flow rate becomes limited just magnetically as opposed to the normal self-sustained mode, limited also by the electron source (cathode).[6]

The performance improvements with the enhanced electron supply from the thermionic hollow cathode were demonstrated for conventional annular geometry Hall thruster[6] and for cylindrical Hall thrusters of two different magnetic field topologies, including mirror- and cusp-types.[5,7,8] The cathode electron supply was increased by running an auxiliary discharge, powered from a separate power supply, between the cathode emitter and the cathode keeper. The obtained results implied that with all thruster parameters the same, there can be more than one thruster steady-state, which for a given cathode placement with the respect to the magnetic field, depends on the electron supply from the cathode or, more generally, on the boundary conditions imposed by the cathode.

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Several experimental studies[9,10] reported that the cathode placement can affect the thruster-cathode coupling,[11,12] which involves the injection of the emitted electrons in the fringing magnetic field and their conduction across the magnetic field towards the anode. 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[9]) and narrow the plasma plume (typically 2-5% plume narrowing but in some regimes up to 20%[10]). However, the non-self-sustained operation of smaller, low power Hall thrusters with the enhanced electron supply from the cathode makes a more dramatic impact on the thruster performance. For example, for the cylindrical Hall thruster (CHT),[13,14] a 30% plume narrowing, accompanied by the increase of the energetic ion fraction led to up 20% increase of the thrust and 50%–60% increase of the thruster anode efficiency.[5,7]

Based on the results of plasma measurements inside the thrusters and in the plasma plume, it was suggested that the enhancement of the electron supply from the cathode leads to the reduction of the electron cross-field transport inside the thruster channel.[6,8] The resulted changes of the electron transport properties cause the voltage potential drop to increase inside the thruster channel on the expense of the outside voltage drop. Apparently, the measured plume narrowing is due to a smaller electric field in the outside region of the defocusing magnetic field. A better focusing of the ion flow is the primary contributing factor to the increase of the thrust and thruster performance with the enhanced electron supply from the cathode.[6,7]

Another remarkable feature of the non-self sustained thruster discharge is that in the magnetically-limited mode, it is free of two principle modes of low frequency discharge current oscillations, including longitudinal breathing mode[2-4] and E×B rotational mode (the so-called rotating spoke).[6] In recent experiments,[15,16] high speed imaging measurements revealed the existence of the roational mode in the self-sustained discharge of the CHT. Moreover, rotational oscillations were previously detected and well characterized for the annular Hall thrusters,[17] including low frequency spoke, which usually occurs at the non-saturated part of the thruster V-I characteristic (e.g. at low discharge voltages <200 V).[18,19] It is believed that the spoke is responsible for the anomalously large electron conductivity across the magnetic field measured in these regimes.[17-19] If this was the case for the CHT thruster, it could explain the obtained reduction of the electron transport with the enhanced electron supply from the cathode, when the spoke disappears.[6] More work has to be done to understand the mechanisms of both rotational and breathing modes of the discharge oscillations and their influence on the main processes in the Hall thruster discharge.

Importantly, the suppression of low frequency oscillations at a constant discharge voltage correlates with change of the local V-I characteristics of the plasma discharge inside and outside of the thruster channel, including the region between the cathode emitter and the cathode keeper electrode. In particular, at the limit of the strong cathode electron emission, there are no potentially unstable plasma regions with the negative differential conductivity, which are normally observed for the self-sustained regime.[6]

In this paper, we continue studies of the transition between self-sustained and non-self-sustained discharges of the CHT thruster with a thermionic hollow cathode. It is known that such a cathode can generate low and high frequency oscillations, which may couple with the plasma processes in the main thruster discharge.[20,21] Some of these transient-time phenomena in the cathode plasma are directly associated with the negative differential conductivity of the cathode-keeper discharge and the cathode sheath.[20] Here, we present preliminary results on the dependence of the transition between the thruster discharge modes on steady-state and transient characteristics of the hollow cathode-neutralizer.

II. Experimental Setup

A. CHT Thrusters

The CHT[5-8] (Fig. 1) features a combination of the gridless Kaufman ion source (end-Hall thruster)[22] and the conventional annular HT with ceramic channel walls (SPT-type).[1] The detailed comparison of these thrusters is presented in Ref. [23]. The CHT has a lower surface-to-volume ratio than the SPT and, thus, seems to be more suitable for miniaturization, which is required for low power space applications. The principle of operation of the CHT is in many ways similar to that of the SPT, i.e., it is based on a closed E×B electron drift in a quasineutral plasma. However, the CHT differs fundamentally from the SPT in that electrons in the cylindrical design provide charge neutralization of ions not by not moving axially, but being trapped axially in a hybrid magneto-electrostatic trap.[24] A similar axial trap for electrons should exist in the mirror-type magnetic configuration of the end-Hall thruster with conductive channel walls. However, the weaker insulating properties of the magnetized plasma in this thruster limit operation to relatively lower discharge voltages (~ 100 V) than in the CHT and SPT.

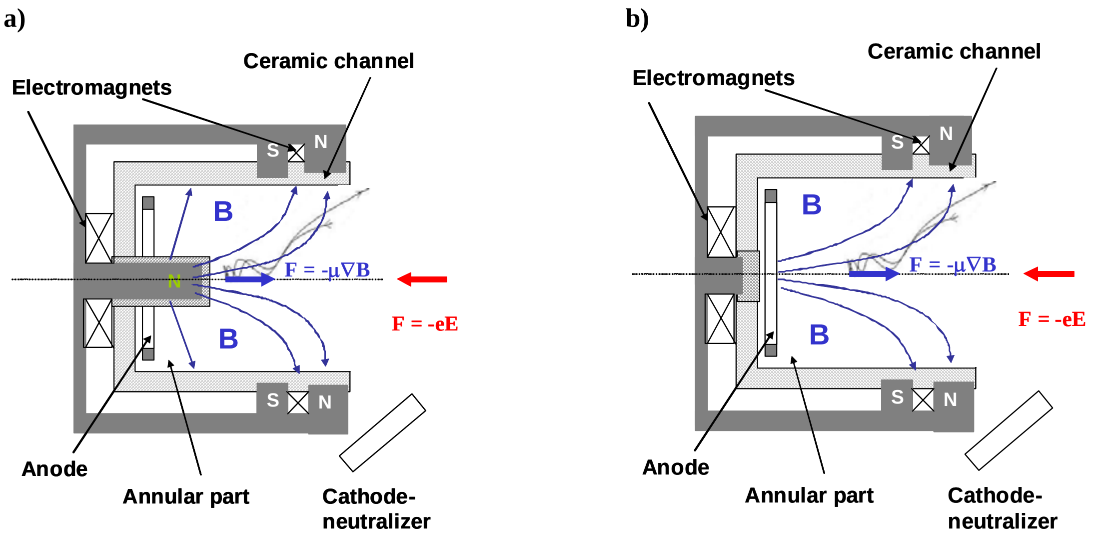

Figure 1. Schematic of a cylindrical Hall thruster (CHT) with (a) and without (b) a short annular part. The thruster can use electromagnet coils or permanent magnets to form direct (enhanced mirror) or cusp magnetic field configurations.

A typical CHT (Fig. 1) 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. Although performances of the CHTs with and without annular part are comparable,[7,25] the absence of the annular channel part adds more simplicity to the CHT design.[7,26]

In the described experiments, the 2.6 cm CHT with the short annular part was used.[14] By varying the relative polarity of the currents in the thruster electromagnets, two magnetic field configurations can be generated: "direct" (or enhanced mirror) with an enhanced axial component of the magnetic field (Fig. 2a) and "cusp" with an enhanced radial component (Figs. 2b) in the cylindrical part of the channel. The results of the comprehensive studies of the CHT with cusp-type and mirror-type magnetic field configurations were reported elsewhere. The thruster was operated in the large PPPL Hall Thruster facility. The xenon gas was used in all experiments. The background pressure in a 28 m^3 vacuum vessel equipped with cryopumps did not exceed 3 μtorr.

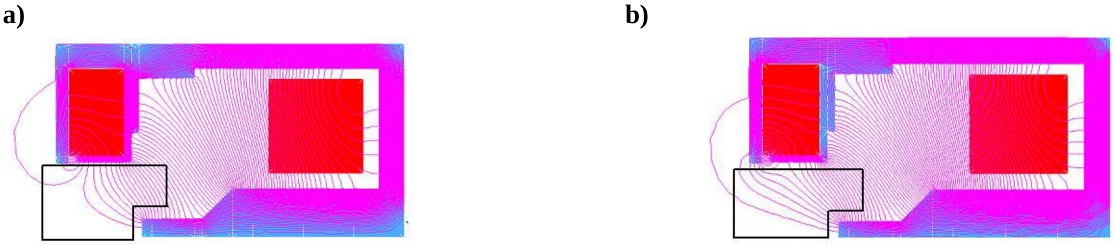

Figure 2. The 2.6 cm thruster in two configurations used in the experiments, and superimposed magnetic field lines: a) CHT with a cusp magnetic field, b) CHT with the direct (mirror-type) magnetic field.

B. Hollow Cathode-Neutralizer

A commercial Heatwave 250 model hollow cathode electron source[27] is used as the cathode-neutralizer. This cathode appears to have design similarities with other thermionic hollow cathodes developed for space applications (in particular, to the 250 model hollow cathode by Electric Propulsion Laboratory Inc.[28]). The cathode emitter is made of porous tungsten impregnated with the low-work-function composite material (usually, barium oxide, calcium oxide, and aluminum oxide). For the initiation of the thermionic emission, the cathode emitter is heated

Ohmically. The choked orifice design of the cathode facilitates the ionization by increasing the gas pressure in the cavity of the hollow emitter. The intermediate cathode keeper electrode is used to initiate the discharge and 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 discharge current flowing through the cathode 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 intensifying the discharge with the keeper current or by supplying additional current from the heater.

In previous experiments,[5-8] the cathode keeper electrode was used to enhance the electron supply from the cathode and thereby, to maintain the non-self-sustained discharge current. In the present experiments, for some operating regimes with and without the thruster discharge, the heater is also turned on. The keeper discharge is powered from two different commercial dc power supplies, namely, a switching Power Ten power supply and a Kepco linear stabilizer power supply with a higher internal resistance. The latter can potentially provide a more stable operation with a load which has a negative differential resistance (when R_{in} > -dV/dI). The cathode gas (Xenon) flow rate was maintained constant, 2 sccm.

C. Diagnostics

The diagnostics used in these experiments are described elsewhere.[5,6,8] A planar plume probe with guarding ring is used for measurements of the angular ion flux distribution in the plume. The probe is suspended on titanium arms of the rotating platform. The distance between the thruster and rotating plume diagnostics is 73 cm. In other experiments, the RPA, two-plate analyzers and bi-directional guarding ring probes were also used to characterize the plasma plume from the thrusters. These diagnostics tools and the results of measurements are described elsewhere. Moreover, in experiments at the Aerospace Corporation, the cathode effect on the plume characteristics of CHT thrusters, including using time-of-flight spectrometer[4] and LIF diagnostics.[29]

In these experiments, the measured ion current to the plume probe was corrected to account for background plasma effects. The total ion current was then estimated by integrating over measured angular ion flux distribution. The propellant and current utilization efficiencies were estimated as the ratios of the corrected ion flux to the mass flow (in unit of current) and the discharge current, respectively. The plume angle was estimated from the measured angular ion flux distribution for 90% of the total ion current.

Discharge current oscillations were measured in the main anode and the cathode keeper electric circuits. In each circuit, a 15 MHz differential probe (LeCroy AP031) was placed across a 1 Ω series resistor and recorded by digital storage oscilloscope (LeCroy LT-264M) with high-enough sampling rate. Finally, for high speed imaging of the thruster plasma, the Phantom V7.3 High Speed Camera (192,000 frame-per-sec in non turbo mode) was used, and placed about 7 meters from the thruster, looking straight at the thruster channel. Unfiltered emissions in the visible spectrum were recorded.

III. Experimental Results

D. Cathode Operation

Fig. 3 shows illustrative curves of the V-I characteristic and the frequency spectrum of the cathode discharge between the cathode emitter and the keeper electrode. The V-I characteristics are compared for two Heatwave 250 model cathodes (referred to as Cathode 1 and Cathode 2) with and without the thruster discharge. The cathode discharge was powered from two linear and switching dc power supplies in the current-regulated mode. The V-I characteristic of Cathode 2, which was used in our previous experiments with a switching keeper power supply, is briefly analyzed in Ref. 6. In addition, the V-I characteristic of the cathode discharge with external heating (without the thruster) is also shown. The obtained shape of the V-I characteristics without the external heating and the thruster discharge is typical for hollow cathodes used for ion and Hall thrusters (Fig. 3a).[20,30] With the same power supply, the Cathode 1 requires larger discharge voltages to maintain the same keeper current than the Cathode 2. This is the only reliably detected difference between these two cathodes. When the thruster discharge on, the difference between the V-I of the cathode-keeper discharges becomes insignificant (within the reproducibility of these measurements).

For small keeper currents, each cathode V-I has a potentially unstable region with a negative slope (with the thruster discharge, - dV/dI ~ 13-20 Ohm) (Fig. 3a). In these regimes, the linear power supply provides generally a more stable operation of the cathode discharge especially at the keeper current of less than 1 A. At larger keeper currents, both keeper power supplies sustain a similarly stable cathode discharge. Adding the external heating to the cathode discharge improves the discharge stability at low currents. The V-I characteristic of this augmented cathode discharge is nearly horizontal. Without the external heating, a similar voltage-saturated mode of the cathode discharge is achieved at large keeper currents (> 1.5 A). In addition to the horizontal V-I, this mode is characterized by the appearance of high frequency (~ 5 MHz) oscillations (Fig. 3b). These cathode discharge oscillations are observed with both keeper power supplies with and without the external heating. Although these oscillations are not a subject of the present study, we note that their characteristic frequency is not so typical for thermionic hollow cathodes used in plasma propulsion. This frequency is an order of magnitude smaller than the ion cyclotron frequency (estimated for typical plasma densities, 10^{12}-10^{14} cm^{-3}, inside the hollow cathode) and an order of magnitude higher than the frequency of oscillations recently associated with two-stream instability.

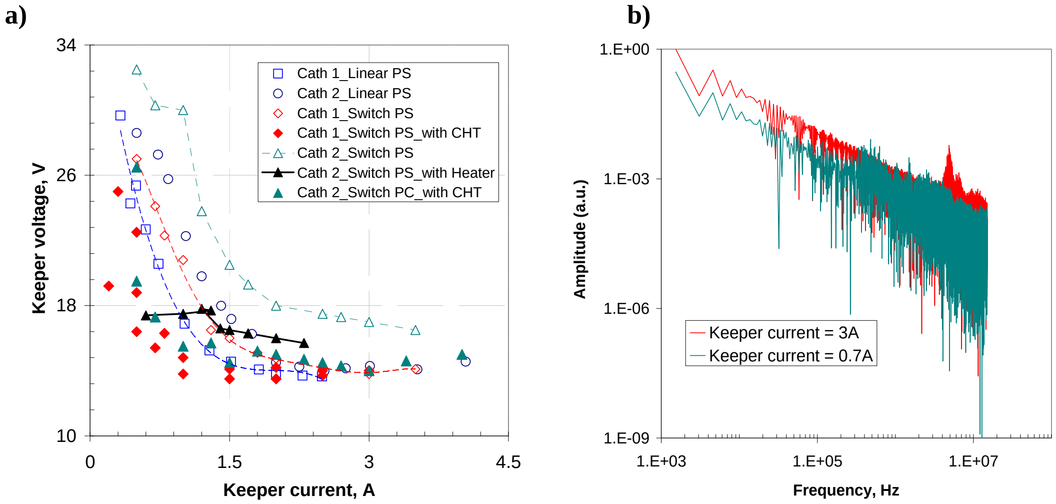

Figure 3. Characteristics of Heatwave 250 model thermionic hollow cathode neutralizers used in Ref. 1 (Cathode 1) and in the described experiments (Cathode 2) : (a) V-I characteristics of the cathode keeper-emitter discharge powered with two different power supplies (linear and switching) with and without the CHT thruster discharge. The cathode discharge with the external heating (~250 W) is also shown. (b) Frequency spectrum of the cathode discharge (Cathode 2) powered from the switching power supply without the thruster on. Similar spectrum was measured for the cathode discharge with a linear power supply.

E. Cathode Effects on the Plasma Plume and Discharge Current Oscillations

A strong plume narrowing effect of the enhanced cathode operation is shown in Fig. 4. In our previous studies, this effect was already demonstrated and analyzed for annular and cylindrical Hall thrusters of different magnetic field configurations. The main conclusion was that that the changes of the thruster configuration from the CHT to the conventional annular HT, or the magnetic field topology and thruster operating parameters, including the gas flow rate, the discharge voltage, and the magnitude of the magnetic field do not change the general trends of the cathode effect on the plume angle (Figs. 4 and 5). However, with different cathodes, the behavior of the plume angle and the discharge current with the keeper current are different (Fig. 5). For example, in the present experiments with Cathode 2, the changes of these parameters are non-monotonic, while in the previous experiments of Refs. 2, 3 and 5 with Cathode 1, they were monotonic (Fig. 5). Similar to Cathode 1 monotonic behavior was also reported in Ref. 7 for a different 3 cm CHT operated with another Heatwave 250 model cathode. Nevertheless, when the keeper current is large enough (≥ 2A), both cathode 1 and cathode 2 discharges affect similar maximum changes of the thruster discharge parameters and the plume. For the direct CHT, the maximum plume narrowing is achieved when the discharge current is overrun above its normal steady-state self-sustained value. For the cusp CHT, the maximum plume narrowing is achieved when the discharge current is underrun below its steady state self-sustained value. This result is similar for both cathodes. Then, following the results of plasma measurements described in Refs. 6 and 8, it is reasonable to expect that for both magnetic field configurations of the CHT with Cathode 2, the electron cross-field transport inside the thruster channel reduces when the cathode keeper current is above 2 A.

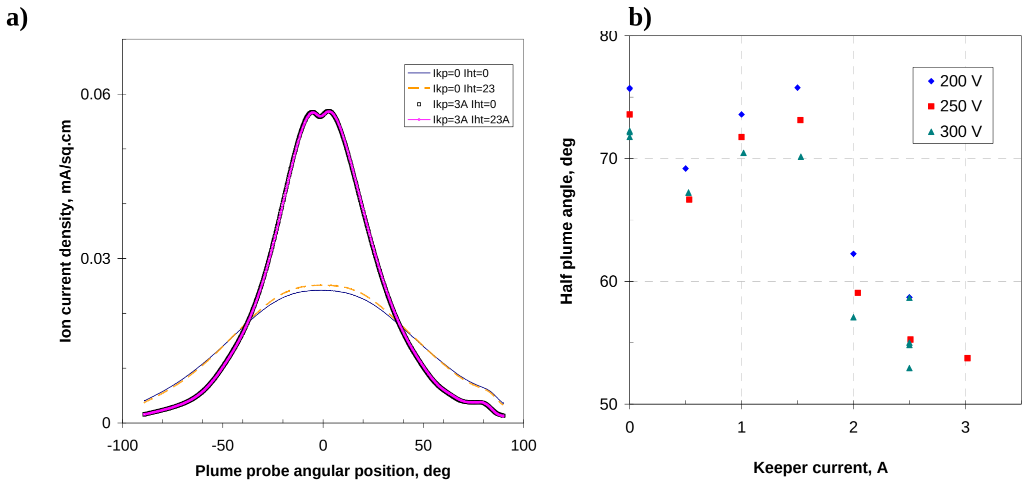

Figure 4. Plume narrowing effect of the auxiliary cathode (Cathode 2) discharge (Ikp is the keeper current) measured for (a) the cusp CHT at the discharge voltage of 250 V and (b) direct CHT . The xenon gas flow rate is 3.4 sccm. The external heating of the cathode emitter (~ 250 W, Iht = 23 A) is shown to have no effect on the plume (left figure). The plume narrowing is shown for different discharge voltages (right figure).

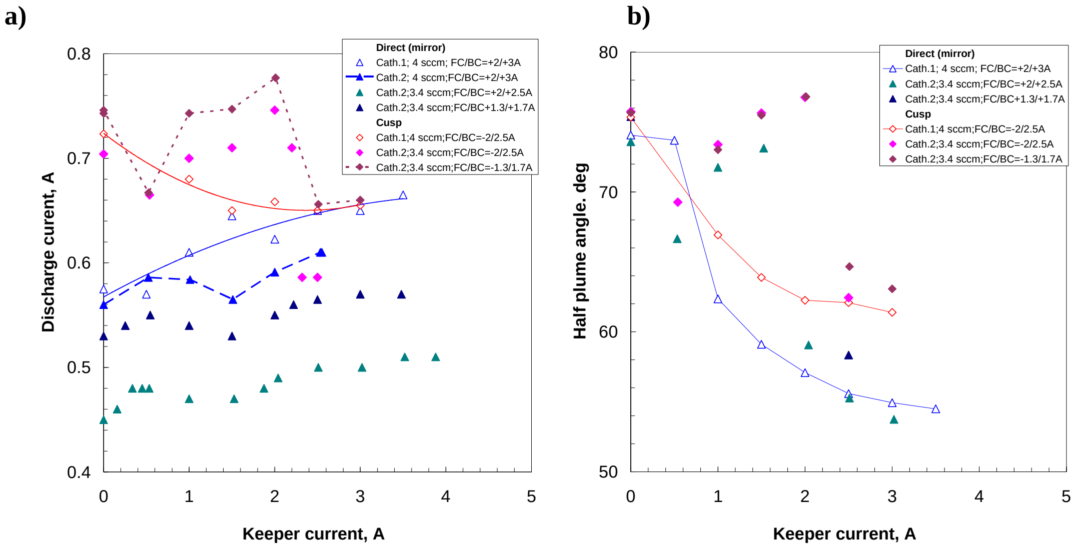

Figure 5. Monotonic and non-monotonic changes of the discharge current (a) and plasma plume (b) affected by the auxiliary cathode-keeper discharge with Cathode 1 and Cathode 2. The CHT was operated with two different Heatwave 250 model cathodes. The thruster operating conditions: the discharge voltage of 250 V and the xenon flow rate of 4 sccm. The magnetic field is controlled by the front and back coils currents (FC and BC, respectively), Fig. 2.

Interesting, that in contrast to the auxiliary cathode discharge, the external heating of the cathode emitter (~250 W), which is used to initiate the cathode and thruster discharges, induces almost no changes in the plasma plume (Fig. 4a) and only slightly attenuate low frequency (~ 10 kHz) discharge current oscillations (Fig. 6). According to high speed imaging of the thruster plasma,[15] these are breathing oscillations. They are almost completely suppressed with and without heating when the cathode keeper current is above 1.5 A. A similar cathode effect was observed for the rotational oscillations (~ 20 kHz), which are not detected in the traces of the discharge current waveform. The results of spoke studies will be presented in a separate paper.[15]

Fig. 7 shows changes of the coefficient of variation (COV) of the discharge current (the ratio of the standard deviation to the mean value) with the keeper current. The variations of the COV do not follow the behavior of the plume angle or the discharge current with the keeper current. For the cusp configuration of the CHT, the COV grows

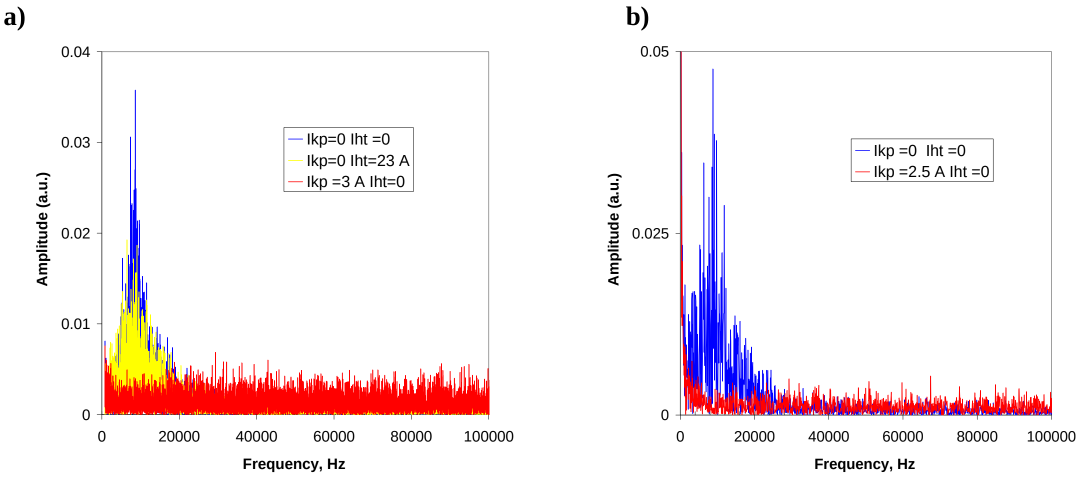

Figure 6. Frequency spectrum of the discharge current oscillations measured for the self-sustained and non-self-sustained regimes (with the keeper current) of the 2.6 cm CHT operated in the cusp magnetic field configurations. The auxiliary cathode-keeper discharge (Ikp is the keeper current) was powered from two different power supplies: switching (a) and linear (b). The external heating (~250 W, heating current, Iht =23 A) was applied during the CHT operation in self-sustained mode. The thruster operating parameters: discharge voltage of 250 V, the xenon gas flow rate of 3.4 sccm.

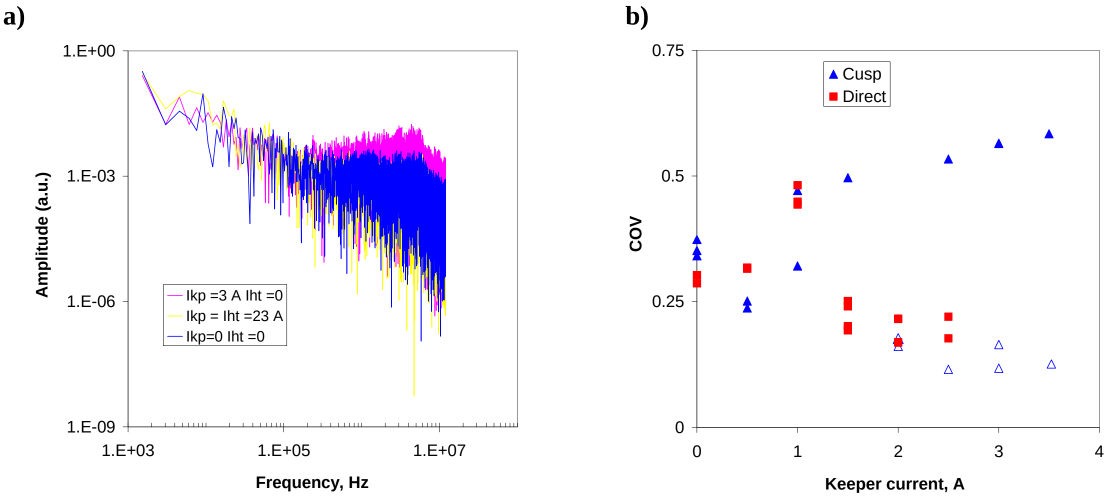

Figure 7. Characterization of discharge current oscillations in the cusp 2.6 cm CHT thruster for the self-sustained and non-self-sustained regimes (with the auxiliary cathode keeper discharge) The cathode discharge (Ikp is the keeper current) was powered from a switching power supply. a) A comparison of high frequency spectrum of the discharge current oscillations measured with and without the cathode keeper current. The thruster operation with the external heating of the cathode (~ 250 W, heater current, Iht =23 A) is also shown. b) Coefficient-of-variation (COV) of the discharge current as a function of the keeper current. The empty triangles are for the filtered waveform of the discharge current oscillations (low pass filter with cut-off frequency of 100 KHz). The thruster operating parameters: discharge voltage of 250 V, the xenon gas flow rate of 3.4 sccm.

with the keeper current due to the appearance of high frequency oscillations with a peak frequency at around 5 MHz. It is not clear if these oscillations are originated from a coupling of the thruster discharge with the cathode oscillations measured at high keeper currents (Fig. 3b). Apparently, their appearance in the thruster discharge depends on the magnetic field configuration of the thruster. For the direct CHT, these oscillations were not as strong as for the cusp CHT. The COV of the direct CHT reduces with the keeper current. The COV of filtered (low-pass filter with cut-off frequency at 100 kHz) waveform obtained for the cusp CHT also reduces with the keeper current. Thus, independent on the discharge characteristics of the thermionic hollow cathode used in these experiments, the enhancement of the electron supply from the cathode stabilizes the thruster discharge in the low frequency range.

IV. Conclusion

In recent studies of the annular and cylindrical Hall thrusters with thermionic hollow cathode-neutrlaizers,[5-8] we showed that a significant plume narrowing and a complete suppression of low frequency discharge current oscillations can be achieved by running an auxiliary discharge (~20-50 W) between the cathode emitter and an intermediate cathode-keeper electrode. Moreover, when the thrusters operate with the hot filament cathode, the plume narrowing can also be achieved when the heating of the filament wire increases.[31] In this case, the plume narrowing is directly associated with the increase of thermionic emission from the hot filament cathode.

In this paper, it is shown that for the cylindrical Hall thruster with a hollow cathode, modifications of the plasma plume and discharge properties with the keeper current can be monotonic and non-monotonic. When the hollow cathode operates in self-heated mode, adding the external heating of ~ 250 W to its thermionic emitter almost does not change to the plume angle or low frequency current oscillations. These results suggest that the effects of the cathode discharge on the plume and the discharge oscillations are not necessarily due to the direct enhancement of the thermionic electron emission from the hollow cathode emitter. The exact mechanism by which the auxiliary discharge of the hollow cathode affects the thruster operation is not understood. It could be that this discharge causes changes in the internal physics of the hollow cathode leading to a more efficient supply of electrons from to the thruster plasma.

Because the cathode-keeper V-I characteristics with and without the external heating are very different (Fig. 3a), it appears that plume and low frequency current oscillations, which are almost unaffected by this heating, are not so sensitive to the shape of the cathode characteristic. These results support the suggestion of our recent study[6] that the changes of the plasma potential distribution in the thruster discharge, including outside and inside the thruster channel, play a major role in both plume narrowing and the suppression of the low frequency discharge current oscillations.

Acknowledgments

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