Overrun Discharge Current Operation of Low Power Cylindrical Hall Thrusters

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Abstract: The discharge current of low power cylindrical Hall thrusters can be increased over and above what is normally required for sustaining the steady state discharge by running an auxiliary discharge between the thruster cathode and an additional electrode. Such a non-self-sustained operation of the thruster is characterized by significantly enhanced performance. This performance enhancement is shown to be extremely sensitive to the background gas pressure in the vacuum chamber.

I. Introduction

The Hall thruster (HT)[1] is an electromagnetic propulsion device that uses a cross-field plasma discharge to accelerate ions. The drawback of the annular-geometry conventional HT is that it has an unfavorable ratio of the channel surface area to the channel volume. The plasma tends to interact with the thruster channel walls, which results in heating and erosion of the thruster parts.[2] This tendency becomes more pronounced when the HT is scaled down to low power.[3,4] The optimization of the magnetic field profile through the use of robust miniaturized magnetic circuits is limited by the properties of the magnetic core materials. Therefore, the efficiency of a low power HT tends to be lower (6-30% at 0.1-0.2 kW),[3-5] plasma divergence larger,[6] and the lifetime issues including heating and erosion of the thruster parts[3,6] become more aggravated. Although highly developed low power HTs, can attain an anode efficiency of 40-50%,[7,8] the lifetime of the miniaturized annular HT with presumably thinner channel walls should be shorter than the lifetime of larger thrusters.

Alternative approaches to cross-field configurations are implemented in the outside electric field thruster,[9,10] linear,[11] end-[12] and cylindrical[13,14] Hall thrusters. Like the conventional annular Hall thruster, the cylindrical Hall thruster (CHT) is based on closed **E**×**B** electron drifts in the quasineutral plasma. However, both the forces on the unmagnetized ions and the means by which the electron drifts close, are quite different, leading to profoundly different operation of the CHT. With the advent of the CHT concept,[15] several thruster designs with different magnetic field configurations and different dimensions have been developed and studied at the Princeton Plasma Physics Laboratory (PPPL)[5,13,16] Osaka University (Osaka, Japan)[17,18] and Korean Advanced Institute of Science and Technology (Daejeon, Korea).[19] One more cylindrical thruster, the high efficiency (at high Isp) multistage plasma thruster (HEMP),[20] was developed at Thales Electron Devices. In terms of electron confinement and ion acceleration, HEMP is essentially a multistage CHT thruster. The CHTs demonstrated performance comparable to the state-of-the-art annular HTs of similar power levels.[5,14,17,18] For a 100 W PPPL CHT, high performance was verified in recent thrust measurements at the AFRL, Edwards, CA, the NASA Marshall SFC,[21] and at the MAE department of Princeton University.[22]

In a recent paper,[23] we reported results for low power CHTs, including very significant plume narrowing, accompanied by the increase of the energetic ion fraction and improvement of ion focusing. These improvements, which were achieved by overrunning the discharge current in the magnetized thruster plasma, led to 50%–60%

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increase of the thruster anode efficiency in the input power range of 50-200 W. From a physical standpoint, the current overrun regime suggests that the electron cross-field current in the low power CHT is limited by the supply of electrons from the cathode. In the present paper, we demonstrate the effect of the background pressure on the plume narrowing in the overrun current operating regime.

II. Review of Self-Sustained CHT Operation

A. Design and Principle of operation

Fig. 1 illustrates the design of the cylindrical thruster. Fig. 2 shows the 2.6 cm laboratory CHT, which was designed and built to operate at 100 W power level by scaling down from a larger 1 kW, 9 cm diam CHT. Details of the 9 cm and 2.6 cm CHTs appear in the literature.[5,13] In addition, a 3 cm diameter CHT was also built for low power operation,[23] and to test operation with segmented electrodes.[24] The thrusters were operated in the PPPL thruster facilities described elsewhere.[5,13,25]

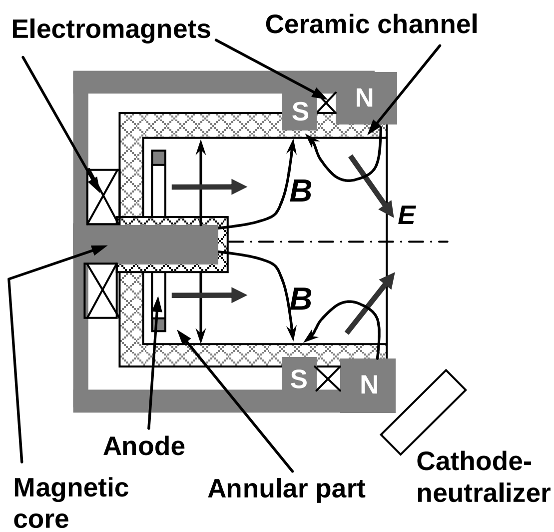


Figure 1. Schematic of a cylindrical Hall thruster

A cylindrical Hall 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) (Fig. 1). The magnetic field lines intersect the ceramic channel walls and form equipotential surfaces. The electron drifts are closed, with $\mathbf{E} = -\mathbf{v_e}\times\mathbf{B}$, where E is the electric field and v_e is the electron drift velocity. The radial component of the magnetic field crossed with the azimuthal electron current produces the axial electric field which accelerates ions, producing thrust. However, the electrons are not confined at a fixed axial position; rather they bounce over an axial region, impeded from entering the annular part of the channel because of magnetic mirroring. The CHT has two electromagnetic coils (back and front coils), which produce a magnetic field with or without a cusp-shape (Fig. 1).[13-16] To maintain ionizing collisions, the anode (gas inlet) is placed in the short annular part of the channel.

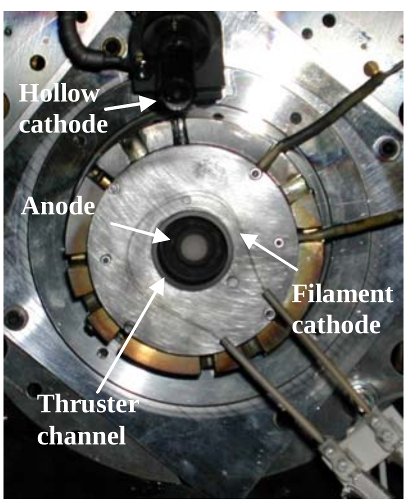


Figure 2. The 2.6 cm, 100 W cylindrical Hall thruster. The thruster can be operated with a commercial hollow cathode or with a propellantless filament cathode. The filament is made from a tungsten wire.

Note that in Ref. 15, we suggested different variations on the theme of the CHT including with and without a short annular channel. The latter configuration was successfully implemented by Shirasaki and Tahara.[17,18] In the former configuration, the length of the annular part of the channel is designed to minimize the ionization mean free path, thus localizing the ionization of the working gas at the boundary of the annular and cylindrical regions. Hence, most of the voltage drop occurs in the cylindrical region that has a large volume-to-surface ratio. This conclusion is supported by the results of plasma measurements.[13,26] From numerical simulations,[27] we found that enhanced electron cross-field mobility in the short annular part of the thruster channel can explain the placement of the acceleration region in the cylindrical channel.

The CHT uses a hollow cathode neutralizer to sustain the thruster discharge and provides charge and current neutralization of the outgoing ion flow. In operation of the low power CHT, the keeper electrode of the cathode 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.

B. Plasma Flow in Different CHT Configurations

In contrast to the conventional annular geometry HTs, the axial potential distribution in the CHT is now critical for electron confinement. This is because the magnetic field now has a large axial gradient over the cylindrical part of the channel (Fig. 3), resulting in outward electron drift through μ grad B forces, even as electrons drift azimuthally around the cylinder axis (Fig. 3a).[16] In the absence of an axial potential, the electrons would simply mirror out of the region of high magnetic field. The axial potential that accelerates ions outwards now also plays an important role in trapping electrons within the thruster.[28] This type of trap, which neutralizes the ion space charge, may lead to a number of curious features related to axial conductivities, sheath physics, or plasma instabilities (spoke oscillations, drift and ionization instabilities). A similar trap may exist in the end-Hall thruster.[12] However, a critical difference between the end-Hall thruster and CHT is apparently stronger magnetic insulation of the plasma in the CHT configuration, since the CHT can operate efficiently at higher discharge voltages than the end-Hall thrusters. The strong radial magnetic field in the short annular channel of the CHT provides the axial confinement of electrons between the anode and the cylindrical part of the channel, and is probably responsible for the improved magnetic insulation as compared to the end-Hall thrusters. In addition, the use of ceramic channel walls may also contribute to more effective electron confinement in the CHT as compared to the end-Hall thruster. In fact, a low-power CHT without annular channel indicated the ability to operate more efficient then the end-Hall thrusters.[17,18]

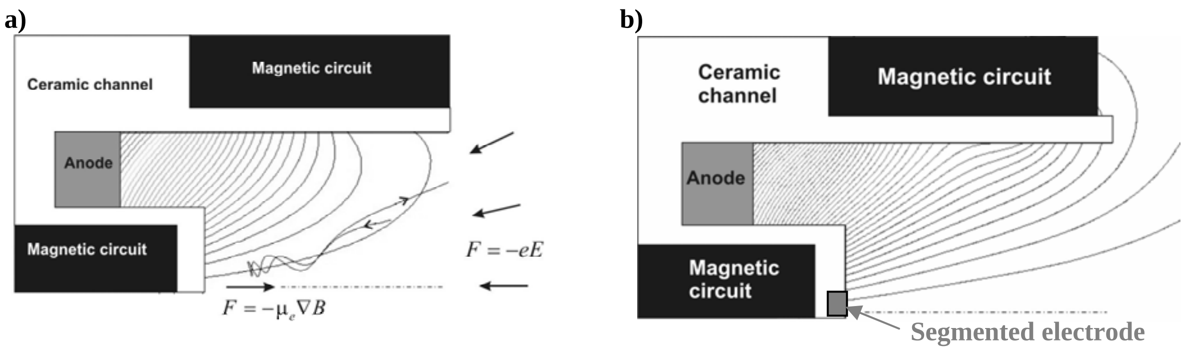


Figure 3. Magnetic field simulations of the 100 W CHT. An illustrative electron trajectory in the cylindrical part of the channel is indicated, and the hybrid mechanism of electron trapping is schematically shown.[16,28] The magnetic field distribution is shown for the cusp (a) and direct (b) configurations. A segmented electrode at the axis can be used to initiate and stabilize the discharge.

The axial electron confinement in the CHT is strongly affected by the magnetic field in the cylindrical channel. The variation of the current in the front electromagnetic coil changes the magnetic field distribution, particularly in the cylindrical part of the CHT channel (Fig 3). When the current in the front coil is counter-directed to that in the back coil, the "cusp" magnetic field with an enhanced radial component is created (Figs. 1 and 3a). Swapping the polarity of the front coil current leads to the enhancement of the axial component of the magnetic field and generation of a stronger magnetic mirror near the thruster axis (Fig. 3b).[14] This variation of the magnetic field distribution has a stronger effect on the discharge current than on the thrust (Fig. 4). This result is expected because the current utilization (the ratio of the ion to discharge currents) increases in the direct

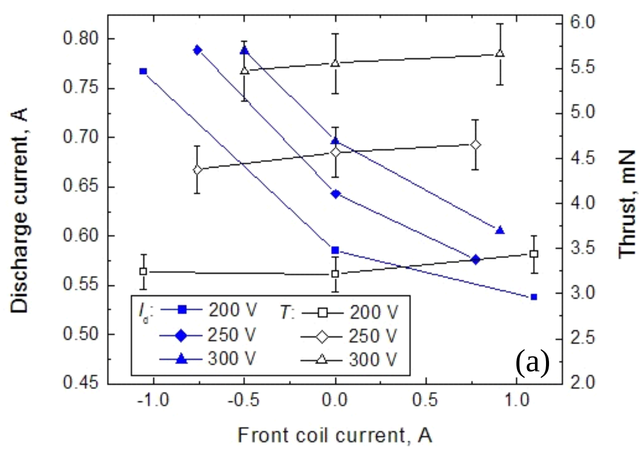


Figure 4. The dependencies of the discharge current and thrust on the front coil current for the 2.6 cm CHT operated in background Xenon pressure less than 6 microtorr.[16,22] Anode and cathode Xenon flow rates are 4 sccm and 2 sccm, respectively; Iback = +3A. Ifront > 0 (Ifront < 0) corresponds to the direct (cusp) magnetic field configuration.

configuration with better electron confinement across the magnetic field, while the ionization efficiency measured in terms of the propellant utilization (the ratio of the total ion current measured in the plasma plume to the input flow of propellant atoms in current units) almost does not change (Fig. 5).[22] It follows from Fig. 4 that the thruster efficiency is larger for the direct configuration.

C. Cathode Effects on Propellant Utilization

The CHT operation is characterized by unusually high propellant utilization efficiency (Fig. 5).[13, 29] In addition to the reduction of the wall losses predicted by a fluid model,[29] the presence of the hybrid trap for electrons[28] and ambipolar potential for ions[28] is believed to explain the very high ionization in the CHTs, including multi-charge ionization.[30]

For the miniaturized CHTs, the gas flow rate through a commercial hollow cathode-neutralizer is typically 1- 2 SCCM, which is 30-100% of the main gas flow rate thought the anode. Under such conditions, it is important to characterize a possible contribution of the cathode flow to the measured propellant utilization. In experiments with the propellantless filament cathode made from a tungsten wire,[31] the propellant utilization of the CHT almost does not change when the additional gas flow is added through non-operational hollow cathode (Fig. 5). In these experiments, the filament cathode was placed near the exit in front of the channel (Fig. 2), while the hollow cathode was at its standard location. The propellant utilization of the CHT with the filament cathode remains > 100%. Fig. 5 shows also results for the conventional CHT operation with the hollow cathode. In contrast to the filament cathode case, there is nearly a linear relationship between the anode propellant utilization (estimated without taking into account the cathode flow rate) with the cathode flow rate. This dependence obtained for the CHT with the hollow cathode is briefly discussed in the following section. A more detailed analysis of this behavior will be presented in a separate paper. Note that the propellant utilization remains > 100% when this dependence is extrapolated to “zero cathode flow”.

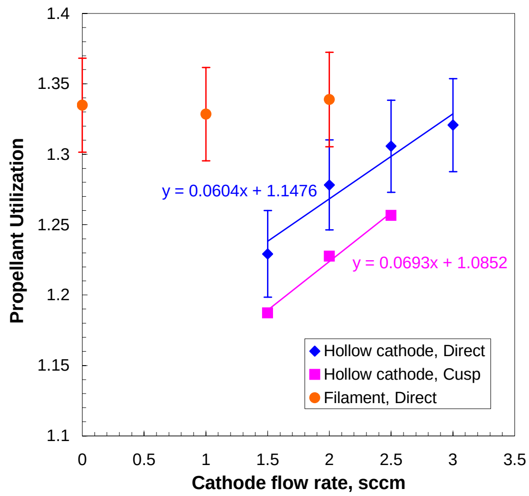


Figure 5. Anode propellant utilization (Xenon) for the 2.6 cm CHT thruster operated with a hollow cathode and propellantless tungsten filament cathode, for direct and cusp magnetic field configurations. A linear fitting is applied to the experimental data. Background pressure did not exceed 3 micro-torr.

III. Non-Self-Sustained CHT Operation

A. Enhanced Performance

In general, two modes of the thruster operation are distinguished: i) the self-sustained mode, in which the discharge current flowing through the cathode provides the necessary conditions to keep the steady-state electron flow from the cathode to the thruster anode and for neutralization of the outgoing ion flow, and ii) the non-self-sustained mode, in which an auxiliary discharge (e.g. between the cathode emitter and the cathode keeper or additional segmented electrode) is provided in order to sustain the steady-state thruster discharge. Note that this non-self-sustained mode is different from a typical two-stage operation of the Hall thruster because the latter usually features an additional discharge between the thruster anode and an additional electrode to maintain ionization and thereby, to separate ionization and acceleration processes in the thruster discharge.

In Ref. 23, we reported that by driving the cathode keeper current, the discharge current of a low power CHT can be increased over and above what is normally required for sustaining the steady-state discharge at given gas flow rate, discharge voltage, and magnetic field. In this overrun current (OC) regime, we achieved a dramatic 20%–30% plume narrowing, substantial increase 50%–60% of the thruster anode efficiency at 100–200 W (Fig. 6), and efficient plasma production and ion acceleration (anode efficiency of 30%–40%) at the lower discharge power. The thrust and Isp (Fig. 7) are also larger in the OC regime.

The OC operation is not a self-sustained regime and therefore, requires an additional power. The results shown in Figs. 6 and 7 were obtained when this additional power (in a keeper discharge) was ~50 W. This was somewhat arbitrary value because it was not minimized. In recent experiments, we showed that this additional power can be reduced to several watts without a degradation of ion production and focusing. A more detailed description and analysis of the OC operation, including ion and thrust measurements for low power CHTs are described in Ref. 23

B. Sensitivity of the overrun current effects

For the CHT operation with the hollow cathode, the increase of the cathode flow rate might have a qualitatively similar effect on the plasma plume as the overrun current. In the OC regime, the discharge current increases with the keeper current. In the self-sustained regime without keeper current, the discharge current increases with the cathode flow rate. This may be related to more efficient self-heating of the cathode emitter leading to enhanced electron emission.[31] Fig. 5 demonstrates that for the self-sustained CHT operation with the hollow cathode, the propellant utilization increases with the cathode flow rate, while the current utilization (not shown here) does not change. Measurements of the plume angle (not shown in this paper, but discussed in detail in Ref. 23) indicated a small plume narrowing (~ 2° for a half plume angle) when the cathode flow rate was increased from 1 to 3 sccm. For different low power CHTs operating in the OC regimes, the half plume angle was reduced by 10° - 20° (Fig. 8 for the 3 cm CHT).[23]

Note that the increase of the discharge current at the fixed voltage, flow rate and magnetic field does not necessarily lead to the performance enhancement. Fig. 8 shows that the increase of the background pressure in the vacuum chamber causes the increase of the discharge current, but also diminishes the advantages of the OC regime as compared to the conventional self-sustained operation. In these experiments with the 3 cm CHT, the additional Xenon flow was introduced through a gas feedthrough on the wall of the vacuum chamber (~ 1 meter upstream of the thruster). The actual background pressure in front of the thruster may be different from that measured by the ion gauges placed on the wall of the vacuum chamber (~ 1.5 meter downstream from the thruster exit).

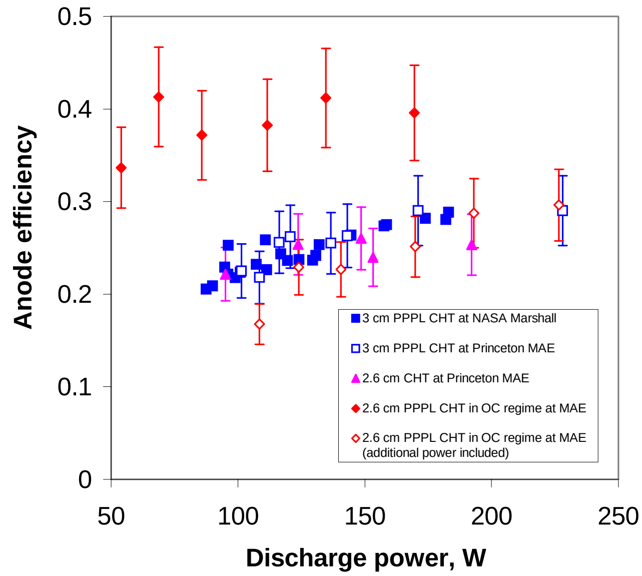


Figure 6. The thruster (anode) efficiency for the 3 cm and 2.6 cm CHTs measured in the direct magnetic field configuration. The thrust measurements were conducted at the MAE of Princeton University[5,22] and at the NASA Marshall SFC.[21] Results for the overrun current (OC) regime[23] of the CHT are also shown.

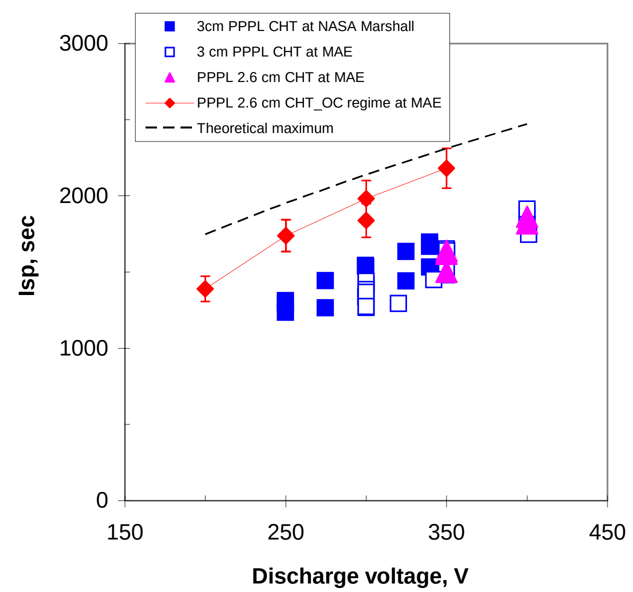
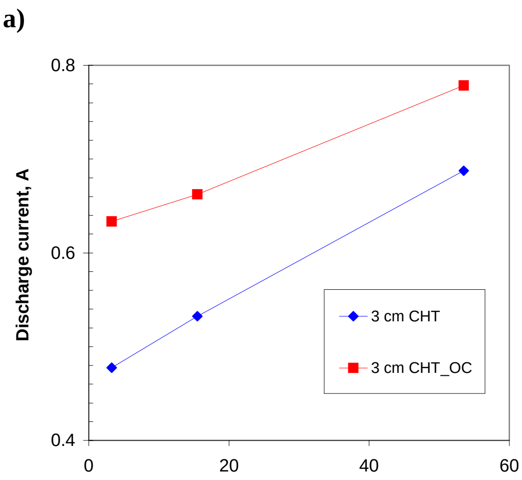
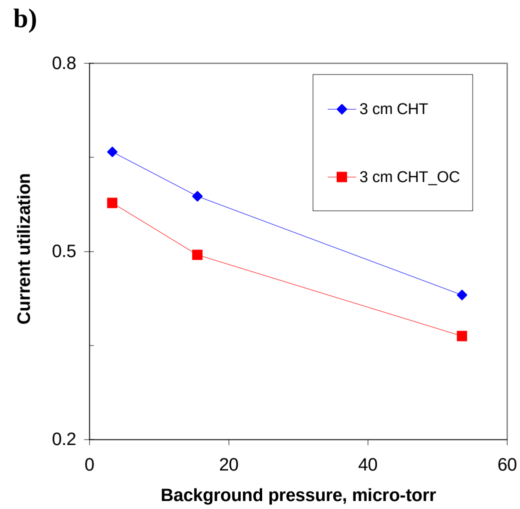


Figure 7. Anode Isp for the 3 cm and 2.6 cm CHTs measured in the direct magnetic field configuration. Theoretical maximum, $Isp^{th} = (2e \cdot V_d/M_{ion})^{0.5} \cdot 1/g$, is for a mono-energetic beam of single-charged ions, where e is electron charge, V_d is the discharge voltage, M_{ion} is the Xenon ion mass, g is the gravity. Results for the overrun current (OC) regime are also shown.





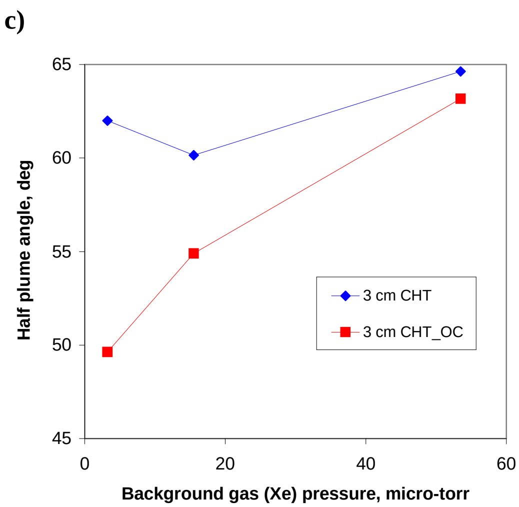


Figure 8. Effect of the background pressure on operation of the 3 cm CHT in the self-sustained and non-self sustained overrun current (OC) regimes: (a) discharge current, (b) current utilization efficiency and (c) half plume angle for 90% of the total ion flux.

The increase of the discharge current is associated with an increase of the electron cross-field current (reduction of the current utilization, Fig. 8b). Plume broadening is observed for both self-sustained and non-self-sustained (OC) operating regimes (Fig. 8 c). Analysis of this interesting behavior, which is likely associated with an increase of electron-atom collisions in the thruster discharge and ion-atom collisions in the discharge and the plasma plume, will be presented in a separate paper.

IV. Summary

In recent paper,[23] we reported that a nearly twofold increase in the fraction of high-energy ions, better focusing of these ions, and a shift of IEDF toward higher energies contributed to the significant increase of the thrust and the thruster anode efficiency in the overrun discharge current regime of the low power cylindrical Hall thrusters. An important observation of the present experiments is that these performance improvements in this non-self-sustained operating regime are highly sensitive to the background gas pressure in the vacuum chamber. Although the overrun current effect on the CHT plasma is dramatic, leading to extraordinary efficiencies in several thruster variations, it remains to understand in detail the physics of this effect and the ways to optimize it.

Acknowledgments

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