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

The cylindrical Hall thruster features high ionization efficiency, quiet operation, and ion acceleration in a large volume-to-surface ratio channel with performance comparable with the state-of-the-art annular Hall thrusters. These characteristics were demonstrated in low and medium power ranges. Optimization of miniaturized cylindrical thrusters led to performance improvements in the 50-200W input power range, including plume narrowing, increased thruster efficiency, reliable discharge initiation, and stable operation.

Nomenclature

E	=	electric field
B	=	magnetic field
v_e	=	electron velocity
μ	=	electron magnetic moment
Isp	=	specific impulse
V_d	=	discharge voltage
e	=	electron charge
M	=	atom mass
$\dot{m}$	=	propellant mass flow rate
η_i	=	propellant utilization efficiency
η_a	=	anode thruster efficiency
η_i	=	total thruster efficiency
T	=	thrust
θ_p	=	plume angle

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.

Erosion of the ceramic wall materials is also a critical issue for any conventional HT operating at high discharge voltages (> 0.5 kV), including high-power thrusters, despite their relatively high efficiency (>60%). Moreover, the annular geometry Hall thrusters scaled to high power usually feature relatively narrow channels with large central magnetic poles that take up most of the thruster volume.[9]

Alternative approaches to cross-field configurations are implemented in the outside electric field thruster,[10,11] linear,[12] end-[13] and cylindrical[14] Hall thrusters. With the advent of the cylindrical Hall thruster (CHT) concept,[15] several thruster designs with different magnetic field configurations have been developed and studied at the

* Research Physicist, PPPL, MS-17, P.O. Box 451, Princeton NJ 08543, AIAA Member.
** Graduate Student, PPPL, MS-1730, P.O. Box 451, Princeton NJ 08543.
§ Professor, Princeton University and PPPL, MS-1730, P.O. Box 451, Princeton NJ 08543, AIAA Member.

Princeton Plasma Physics Laboratory (PPPL)[5,14,,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]

Like the conventional annular Hall thruster, the cylindrical thruster 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. In this paper, we review plasma and performance studies of CHTs, including some recent results on enhanced performance of the miniaturized cylindrical thrusters.

II. Plasma Flow in CHTs

Fig. 1 illustrates the design of the cylindrical thruster. Fig. 2 shows two laboratory CHTs of different diameters, 9 cm and 2.6 cm, which were designed and built to operate at 1 kW and 100 W power levels, respectively. The 2.6 cm CHT was scaled down linearly from the 9 cm CHT. Details of the 9 cm and 2.6 cm CHTs appear in the literature.[5,14] In addition, a 3 cm diameter CHT was also built for low power operation,[21] and to test operation with segmented electrodes.[23] The thrusters were operated in the PPPL thruster facilities described elsewhere.[5.14,24]

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).[14-16] To maintain ionizing collisions, the anode (gas inlet) is placed in the short annular part of the channel. 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[14,25] for both laboratory cylindrical thrusters (Fig. 3). From numerical simulations,[26] 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. In order to explain the observed discharge current, the electron anomalous collision frequency ν_B has to be on the order of the Bohm value, $\nu_B\approx\omega_c/16$, where ω_c is the electron gyrofrequency.

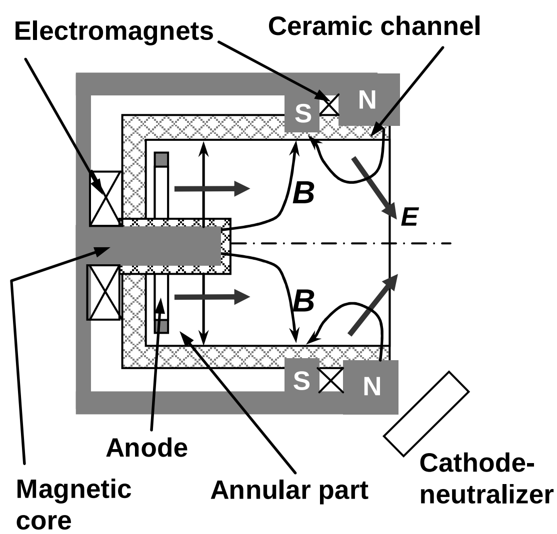


Figure 1. Schematic of a cylindrical Hall thruster

a) b)

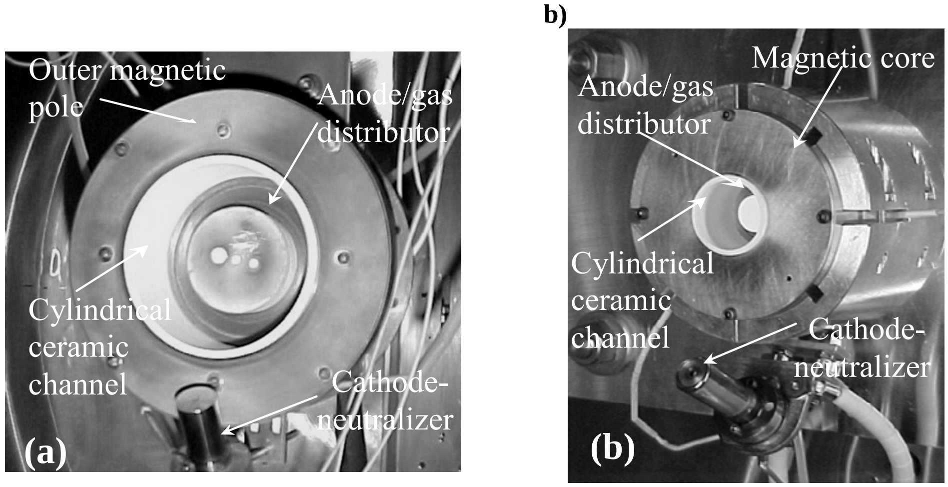


Figure 2. The 9 cm, 1 kW (a) and the 2.6 cm, 100 W (b) cylindrical Hall thrusters.

a) b)

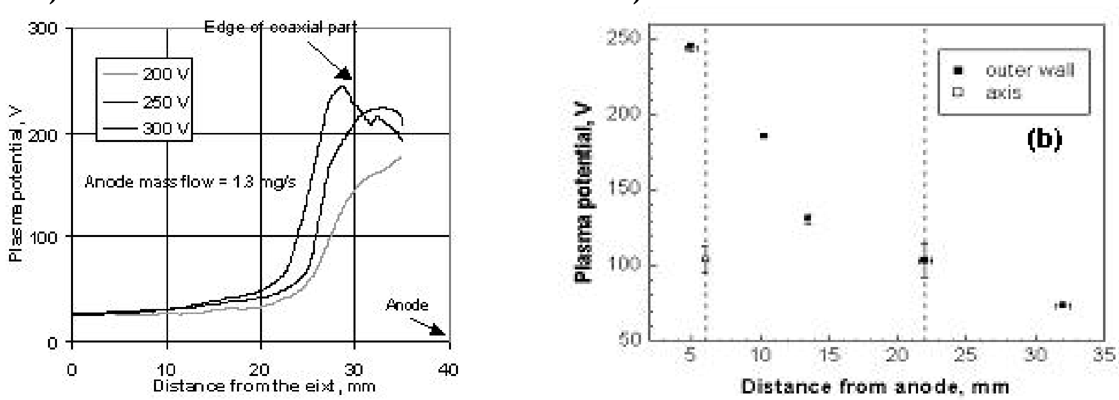


Figure 3. Plasma potential in the cylindrical Hall thrusters: along the channel median of the 9 cm CHT[14] measured with a fast movable emissive probe, at the xenon flow of 13 sccm (a) and in the 2.6 cm CHT[25], measured with stationary biased probes at a xenon flow rate of 4 sccm and the discharge voltage of 250 V.

In recent experiments and simulations of the effect of the channel width for a conventional annular HT, channel narrowing was shown to reduce the electric field inside the annular channel. Therefore, the accelerating electric field is established outside the thruster channel in the fringing magnetic field.[11] This result was explained by the enhancement of the electron cross-field mobility in the annular channel. Physical mechanisms responsible for the enhanced electron cross-field transport in the annular part of the CHT and in the narrowed channel of the annular HT, may be different (e.g. Bohm-type or near-wall conductivity), but in both thruster cases, they lead to a reduction of the plasma-wall interaction. In the HT case, the ion acceleration occurs outside the narrowed thruster channel, i.e. without walls. In the CHT case, the acceleration region is established in the larger volume-to-surface cylindrical channel,[14,25] where the magnetic field distribution can be used to control (e.g. to focus) the plasma flow. This ability to control the plasma flow is an advantage of the CHT compared to outside electric field thrusters.[10,11] Having potentially smaller wall losses in the channel, a CHT should suffer less erosion and heating of the thruster parts than an annular HT, making the CHT concept very promising not only for low-power applications, but also for high-power applications.

In contrast to the conventional annular geometry HTs, the axial potential distribution in the CHT is now critical for electron confinement.[27] This is because the magnetic field now has a large axial gradient over the cylindrical part of the channel (Fig. 4), resulting in outward electron drift through μ grad B forces, even as electrons drift azimuthally around the cylinder axis (Fig. 4a).[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.[13] 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]

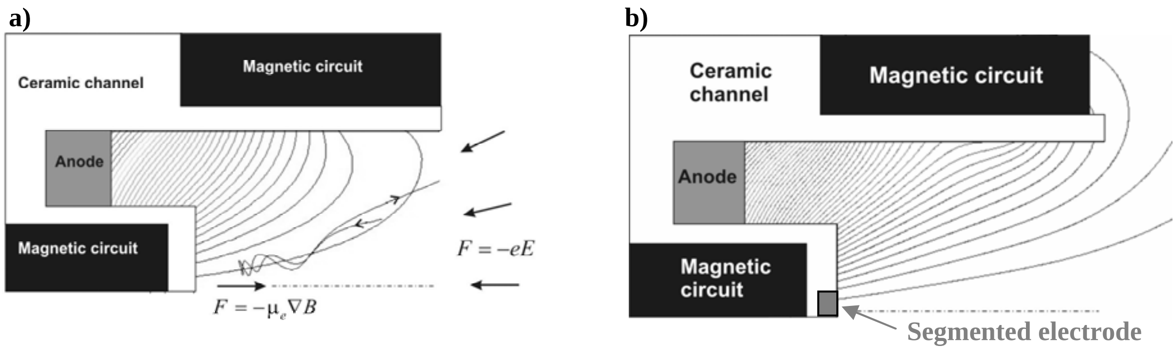


Figure 4. Magnetic field simulations of the 100 W CHT. The channel diameter is 2.6 cm. Illustrative electron trajectory in the cylindrical part of the channel is indicated, and hybrid mechanism of electron trapping is schematically shown.[16,27] The magnetic field distribution is shown for the cusp (a) and direct (b) configurations. A segmented electrode can be used to initiate the thruster 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 electromagnet coil changes the magnetic field distribution, particularly in the cylindrical part of the CHT channel (Fig 4). 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 4a). 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. 4b).[27] This variation of the magnetic field distribution has a stronger effect on the current utilization (the ratio of the ion to discharge currents) than on the ionization efficiency (Fig. 5). The current utilization characterizes how effectively the electron cross field transport is suppressed in the

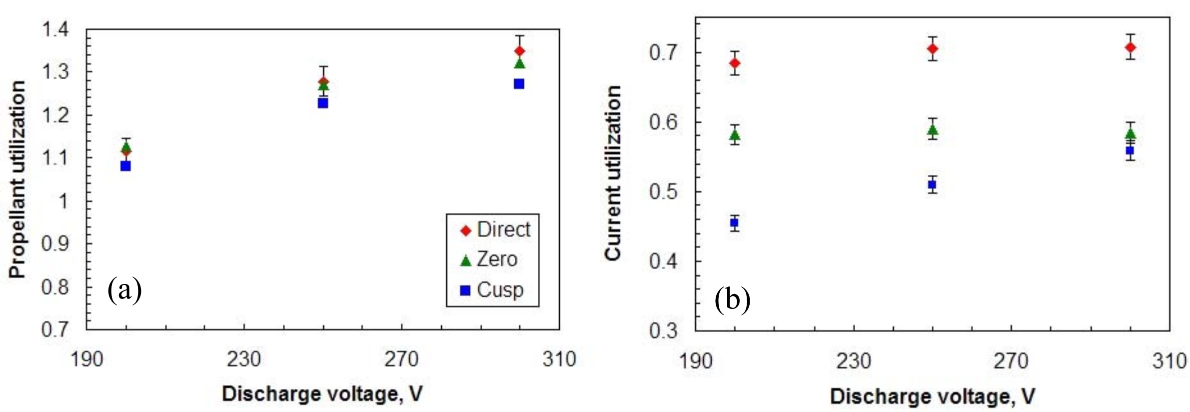


Figure 5. The effect of the magnetic field configuration on the utilization efficiencies,[2] propellant utilization (a) and current utilization (b), for the 2.6 cm CHT thruster. Note that all three configurations use the same current in the back coil (3 A) and 0.95 A, 0, -0.7 A for the front coil current in direct, zero and cusp configurations. Measurements were conducted in the large HTX facility at the background pressure of 3 microtorr. The working gas is xenon.

thruster discharge. In the direct configuration, the electron cross-field current is smaller due to the reduced electron cross-field mobility in the cylindrical part of the channel as compared to that in the cusp configuration.[22,27] Measurement results of the electron transport properties in the CHT will be reported in a separate paper. In addition, the effect of the magnetic field configuration on the operation of the 1 kW and 100 W CHTs is also described and analyzed in greater detail in Refs. 14 and 22, respectively.

The CHTs are surprisingly quiet.[5,14,18] Large amplitude discharge current oscillations seen in Fig 6 are typical for a conventional, annular HT, and are attributed to either ionization waves[29] or a Buneman-type instability.[30] The absence of the large amplitude oscillations is an obviously attractive feature of the CHT. Quiet operation facilitates integration with satellite systems such as power supply and telecommunication electronics. Quiet operation in the low-frequency range is speculated to be a result of enhanced electron transport in the discharge caused by the high-frequency plasma oscillations.[16,27] Although the amplitude of oscillations was relatively lower for the 2.6 cm thruster, the discharge at low propellant flow rates is not as quiet as it was found to be in the large CHT. The characteristic peak of oscillations is at frequencies of about 50 to 60 kHz.[5] Apparently, the typically ~ 20 kHz characteristic frequency for an annular 9 cm HT (Fig. 6), almost triples as thruster dimensions are reduced by about factor of 3.

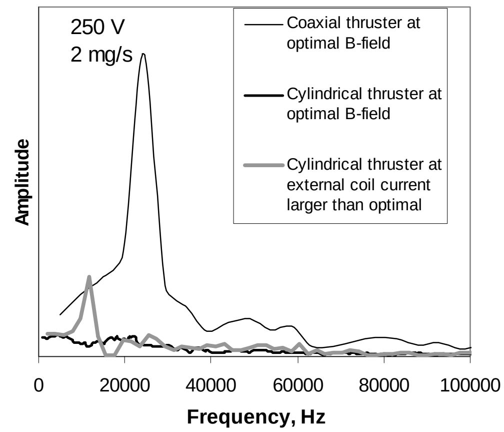


Figure 6. Spectrum of oscillations in the 9 cm cylindrical and annular Hall thrusters.[14]

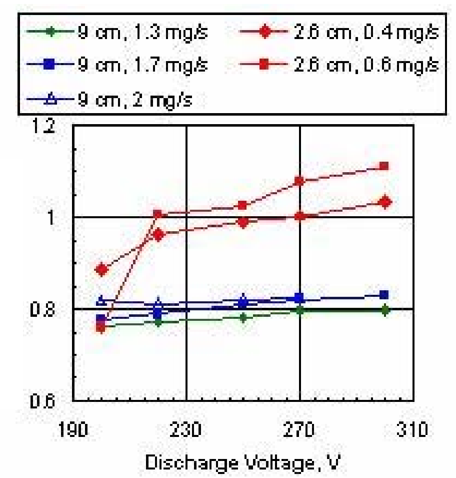
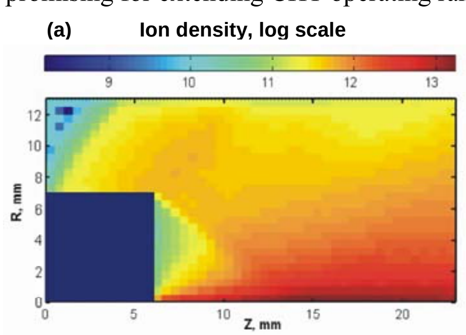


Figure 7. Measured propellant utilization efficiency (Xenon) for the 9 cm and 2.6 cm CHT thrusters.[14,31] The cathode mass flow rate (0.2 mg/s) is not taken into account.

The CHT operation is characterized by unusually high ionization efficiency (Fig. 7). In addition to the reduction of the wall losses predicted by a fluid model,[31] the presence of the hybrid trap for electrons[25] (Fig. 4a) and ambipolar potential for ions[28] (Fig. 8) is believed to explain the very high ionization efficiency typical of the CHTs (Fig. 7).[14,31] 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. As can be seen in Fig. 9, even for the extrapolated "zero cathode flow" and a low background pressure (3 μtorr) during the plume measurements (in the large HTX facility[24]), the propellant utilization of CHTs remains > 100%. Additional supporting evidence for high ionization efficiency of the CHTs was obtained in experiments with a propellantless filament cathode. So unusually high ionization efficiency is promising for extending CHT operating range to low discharge voltages and difficult-to-ionize propellants.



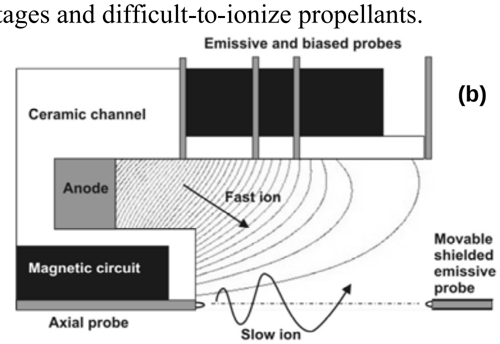


Figure 8. The plasma measurements revealed the plasma density peak at the axis of the cylindrical channel.[25] (a) Monte-Carlo simulations[16,26] suggest that the density peak appears due to ambipolar trapping of slow ions. [28] (b) Probe diagnostic used in plasma measurements in the 2.6 cm CHT.[25]

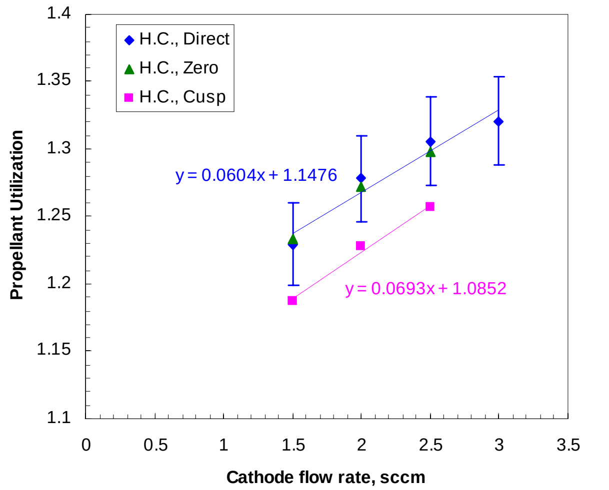


Figure 9. Measured anode propellant utilization (Xenon) for the 2.6 cm CHT thruster operated with three different magnetic field configurations: direct, zero and cusp. A background gas pressure was 3 µtorr.

III. Low Isp Operation

The 9 cm CHT[14] was used to explore the underlying physical concept and to conduct the proof-of-principle experiments. Although this thruster was not optimized, its efficiency is higher than that of end-Hall thrusters,[13] and smaller, but comparable (~40%) to the conventional annular HTs of a similar size (~50%).[14] At low discharge voltages (< 200 V), the performance of typical annular Hall thrusters degrades significantly and the efficiency becomes smaller than that of the CHT. Fig. 10 compares the ratio of the measured Isp for state-of-the art annular HTs[9,32,33,34,35] and the 9 cm CHT to the theoretical maximum, $Isp^{th} \equiv g(2eV_d/M_{ion})^{0.5}$, for a monoenergetic beam of single charged ions accelerated in the voltage potential drop equal to the applied discharge voltage V_d. Since the ionization of propellant atoms and energy utilization tend to be more effective with the increased flow rate and discharge voltage,[2] the distinction between the measured Isp and its theoretical maximum becomes larger at lower discharge voltages (Fig. 10). At $V_d <$ 200 V, the Isp ratio and overall thruster performance drop substantially because of poor ionization. In contrast, the 9 cm diameter CHT exhibits quite opposite behavior at low discharge voltages because it operates with a higher ionization efficiency. The effective electron and ion traps that sustain high ionization in the CHT (Figs. 4a and 8b) are apparently not as sensitive to the discharge voltage. The ability of the CHT to operate efficiently at low discharge voltages may be useful for high-thrust and low-Isp applications of Hall thrusters.

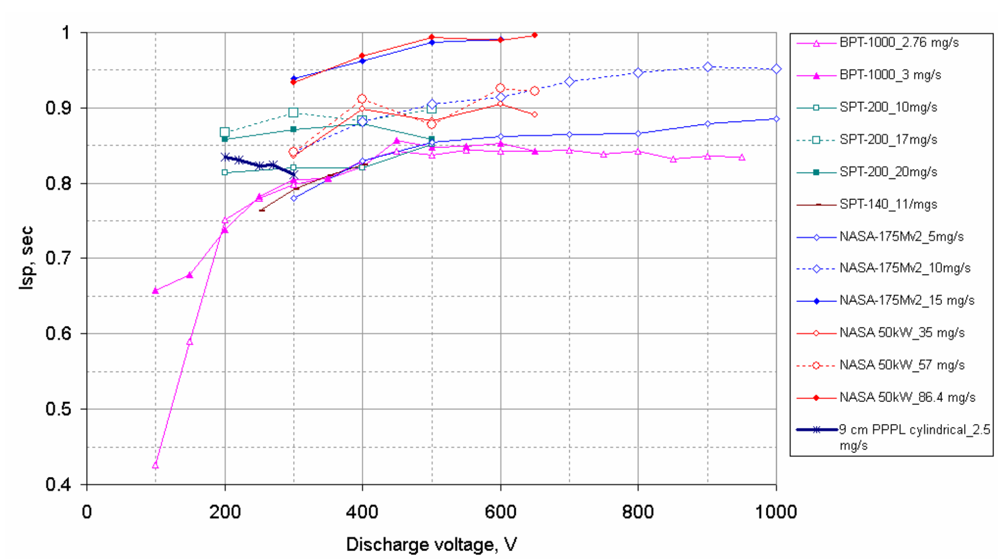


Figure 10. The ratio of Isp/Ispth (b) for the-state-of-the art Hall thrusters and a 9 cm laboratory cylindrical Hall thruster. Ispth $=(2e \cdot V_d/M_{ion})^{0.5} \cdot 1/g$, is for mono energetic beam of single charged ions, where e is electron charge, V_d is the discharge voltage, M_{ion} is the Xenon ion mass, g is the gravity. Thruster references: BPT-1000, [32] SPT-200,[33]; SPT-140,[34] NASA 175Mv2,[35], NASA 50 kW,[9] PPPL 9 cm cylindrical Hall thruster.[14]

IV. Enhanced performance

It follows from Fig. 11 that for a miniaturized 100 W CHT, the thruster efficiency increases when the magnetic field changes from the cusp-type to the direct-type.[16,22] This result is expected because the direct-type magnetic field configuration provides better electron confinement than the cusp and zero types (Fig. 5a), while all three configurations sustain comparable ionization efficiencies (Fig. 5b). Moreover, the increase of the back coil current results in a reduction of the discharge current, leading to an increase in the thruster efficiency.[22] In steady state operation of the CHT, the maximum value of the coil current is restricted by ohmic heating of the coils, particularly, by the maximum operating temperature of the coil wire. This limitation can be overcome with the use of permanent magnets instead of electromagnet coils. Shirasaki and Tahara[18] reported on a miniaturized CHT with permanent magnets, which demonstrated the anode efficiency of 40% at 100-200 W.

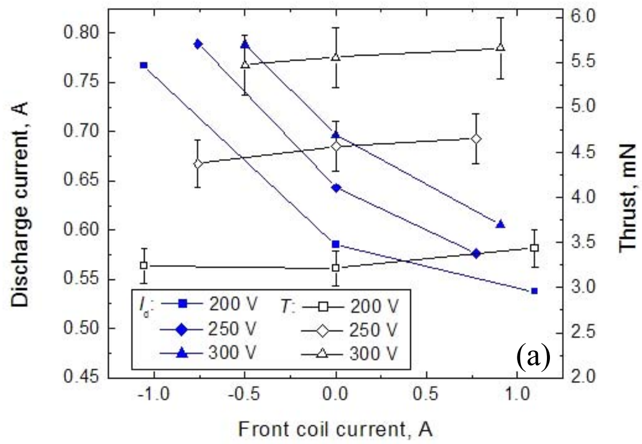


Figure 11. The dependencies of the discharge current and thrust on the front coil current for the 2.6 cm CHT operated in background xenon pressure less than 6 microtorr.[16,22] Anode and cathode xenon flow rates are 0.4 mg/s and 0.2 mg/s, respectively; Iback = +3A. Ifront > 0 (Ifront < 0) corresponds to the direct (cusp) magnetic field configuration.

Fig. 12 shows the anode efficiency obtained for the 2.6 cm and 3 cm cylindrical Hall thrusters. The thrust measurements were conducted at the MAE department[5,16,22] of Princeton University and at the NASA Marshall SFC.[21] The efficiency of non-optimized cylindrical thrusters at the 100 W power level, η_a ~22%, is comparable to, and in some cases larger than, that of the state-of-the-art conventional annular low-power thrusters, such as BHT-200-X2B (η_a ~21%),[7] SPT-30 (η_a ~ 22%),[36] KM-37 (η_{tot} ~ 24%),[37] KM-20M (η_{tot} < 30%),[38,39] and MIT HT (η_{tot} ~ 6%).[3] Furthermore, in the newly discovered current overrun regime, the anode efficiency of the CHT can be much higher than the efficiency of all existing HT designs in the 50-100 W power range (Fig. 12). The thrust and Isp (Fig. 13) are also larger in this regime. These performance improvements are due to the improved production and focusing of energetic ions[40] in the overrun current operation. Note that the current overrun operation is not a self-sustained regime and therefore, requires an additional power. The results shown in Fig. 12 were obtained when this additional power 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. The current overrun operation will be discussed in greater detail in a separate paper.

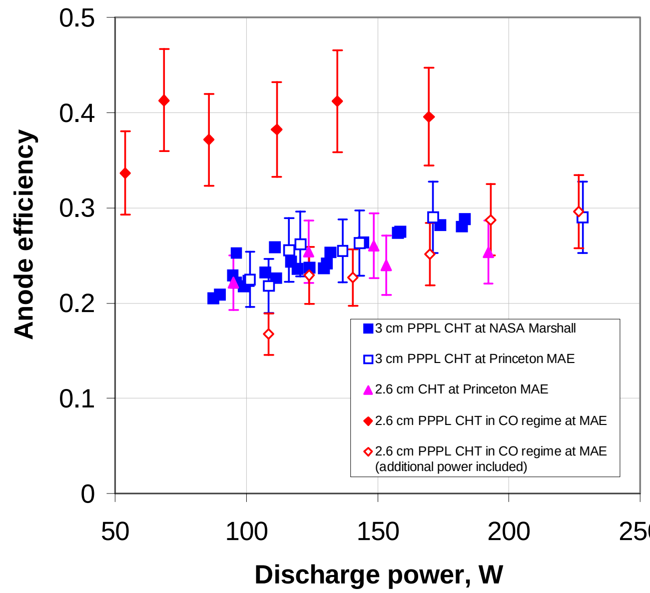


Figure 12. The thruster (anode) efficiency for the 3 cm and 2.6 cm CHTs measured in the direct magnetic field configuration. The thrust measurements were conducted at the MAE department of Princeton University and at the NASA Marshall SFC. Recent results for the current overrun (CO) regime of the CHT are also shown.

The operation of the miniaturized cylindrical Hall thrusters at high discharge voltages (> 300 V) can be extremely sensitive to the magnetic field, gas flow rate and the cathode conditions. Small changes in any of these parameters may cause the discharge to extinguish. Moreover, in the discharge voltage range of 100-600 V, the miniaturized thruster discharge does not ignite when a strong magnetic field is applied in the channel. These problems were solved by placing a biased segmented electrode on the central pole, as is shown in Fig. 4b.[40] The electrode is biased ~50-100 V positive with respect to the cathode. A strong magnetic mirror in front of the segmented electrode (Fig. 4b) does not inhibit a discharge (~0.5 A at 4 SCCM of xenon gas flow rate) between this electrode and the cathode. With such a precursor discharge, the main thruster discharge between the thruster anode and the cathode is easy initiated. After the main discharge is initiated, the electrode bias voltage becomes lower than the local plasma potential at the thruster axis near the front wall. If the bias voltage is equal to the floating potential of the segmented electrode, the electrode current becomes zero. When the bias voltage is varied below the floating potential, the segmented electrode collects ions and consumes very insignificant power (less than 1 W) from the power supply. With the segmented electrode, the thruster operation was feasible and stable at discharge voltages up to 600 V (limit of the power supply used in these experiments).

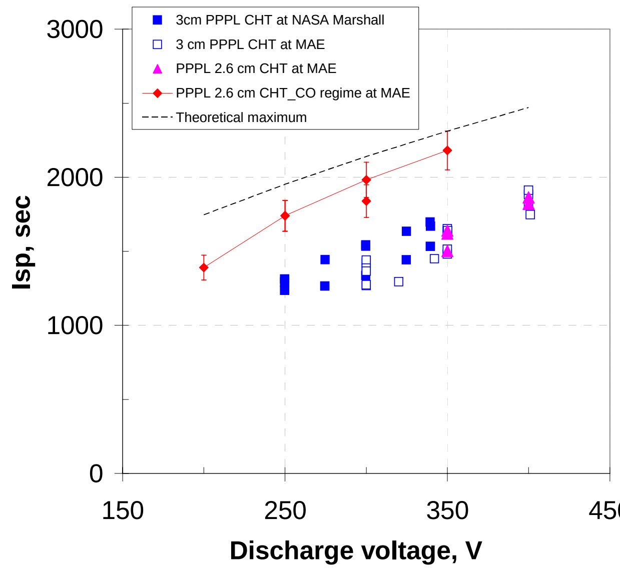


Figure 12. Anode Isp for the 3 cm and 2.6 cm CHTs measured in the direct magnetic field configuration. The thrust measurements were conducted at the MAE department of Princeton University and at the NASA Marshall SFC. Recent results for the current overrun (CO) regime of the CHT are also shown. Theoretical maximum, $Isp^{th} = (2e \cdot V_d / M_{ion})^{0.5} \cdot 1/g$, is for 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.

V. Summary

The cylindrical Hall thruster was shown to exhibit very high ionization efficiency, quiet operation, ion acceleration in the large volume-to-surface ratio channel, and performance comparable with the state-of-the-art Hall thrusters. These characteristics were demonstrated in low-power and medium-power operating regimes. Performance improvements have recently been demonstrated through the optimization of the magnetic field, discharge operation, and the use of segmented electrodes. CHTs should suffer reduced erosion and heating of the thruster parts, due to likely smaller wall losses. This makes the CHT concept very promising not only for low-power applications, but also for high-power applications.

Acknowledgments

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Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov