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Cylindrical Hall Thrusters

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The cylindrical Hall thruster concept, proposed and studied at the PPPL features high ionization efficiency, quiet operation, ion acceleration in a large volume-to-surface ratio channel, and performance comparable with the state-of-the-art Hall thrusters. These characteristics were demonstrated in low and medium power ranges. For a miniaturized 100 W cylindrical thruster, we achieved performance improvements, including a 30-40% plume narrowing, reliable discharge initiation, and stable operation in the discharge voltage range of 50-600 V.

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 thrust is a reaction force to this acceleration, exerted upon the thruster magnetic circuit. In a conventional HT, axial electric and radial magnetic fields are applied in an annular channel. The magnetic field is large enough to lock the electrons in the azimuthal **E**×**B** drift, but small enough to leave the ion trajectories almost unaffected. Because of the reduced electron mobility across the magnetic field, a substantial axial electric field can be maintained in the quasineutral plasma and electrons can effectively ionize neutral atoms of the propellant gas. Under such conditions, the electric field supplies energy mainly to accelerate the unmagnetized ions. Unlike the space-charge limited gridded ion engine, the HT accelerates the ions in the quasineutral plasma. Thus, larger ion current and thrust densities can be achieved.

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 therefore 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] The optimization of the magnetic field profile through the use of robust magnetic circuits is limited by

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the properties of the magnetic core materials. Thus, it should not be surprising that the existing low power HTs are inefficient (6-30% at 0.1-0.2 kW),[4,5] as compared to their larger counterparts (>50% at 1 kW). Apparently, erosion of the ceramic wall materials becomes a critical issue for any conventional HT operating at high discharge voltages (> 0.5 kV), including very high power HTs, even though their efficiency seems to be relatively high in such regimes (>60%). Moreover, the annular geometry Hall thrusters scaled to high power usually feature relatively narrow channels with large central magnetic poles that take up (in the radial direction) most of the thruster volume.[6]

Consider instead a cylindrical geometry Hall thruster (CHT),[7] which was proposed and developed at the PPPL. The ratio of the channel surface area to volume is reduced, limiting electron transport and ion losses.[8,9] Initially developed for a kilowatt power level, this non-conventional HT concept was extensively studied and developed for micro propulsion applications.[8-10] The CHTs demonstrated performance comparable to the state-of-the art annular HTs of similar power levels.[7,11] For a 100 W CHT, high performance were verified in recent thrust measurements at the AFRL, Edwards, CA, the NASA Marshall SFC, and at the MAE department of Princeton University. [12,13] Various CHT-type thrusters are now studied and developed in Japan,[14] Germany,[15] and Korea. Also, they have recently been recognized as an attractive option for high power applications.

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, which leads to profoundly different operation of the CHT as compared to the conventional annular HT. In this paper we reviews the present status of the PPPL cylindrical thrusters and highlight the most recent results on a miniaturized low power CHT, including a 30-40% plume narrowing and stable operation in the discharge voltage range of 50-600 V.

II. Characteristics of Plasma Discharge

Fig. 1 illustrates the principle of operation of the cylindrical thruster. Two laboratory CHTs of different diameters, 9 cm and 2.6 cm, were designed and built (Fig. 2) 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.[7,11,13] The thrusters were operated in the PPPL Thruster Facilities described elsewhere.[7,11,16]

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 magnetized sources (Fig. 1). The magnetic field lines intersect the ceramic channel walls. The electron drifts are closed, with the magnetic field lines forming equipotential surfaces, 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 thrust. However, the electrons are not confined to an axial position; rather they bounce over an axial region, impeded from entering the annular part of the channel because of magnetic mirroring. Two magnetized sources, electromagnetic coils with opposite currents, can produce a cusp-like magnetic field in the channel, with a strong radial component. To maintain ionizing collisions, the anode (gas inlet) is placed in the short annular part of the channel. 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 large volume-to-surface ratio. This conclusion is supported by the results of plasma measurements[7,10] for both laboratory cylindrical thrusters (Fig. 3) and by Monte-Carlo simulations[9,17] for the 100 W thruster. We found that 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.

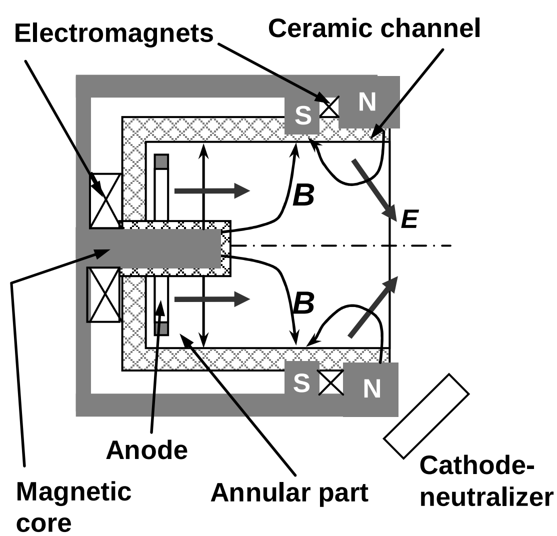

Figure 1. Schematic of a cylindrical Hall thruster

In addition, recent experiments and simulations of the effect of the channel width for a conventional annular HT demonstrated that the channel narrowing reduces the electric field inside the annular channel and causes the accelerating voltage drop to be established mainly in the fringing magnetic field in the near-field plasma plume.[18] In the CHT case, the acceleration region is established in the larger volume to surface cylindrical channel, where the magnetic field distribution can be used to control the plasma flow. Having potentially smaller wall losses in the

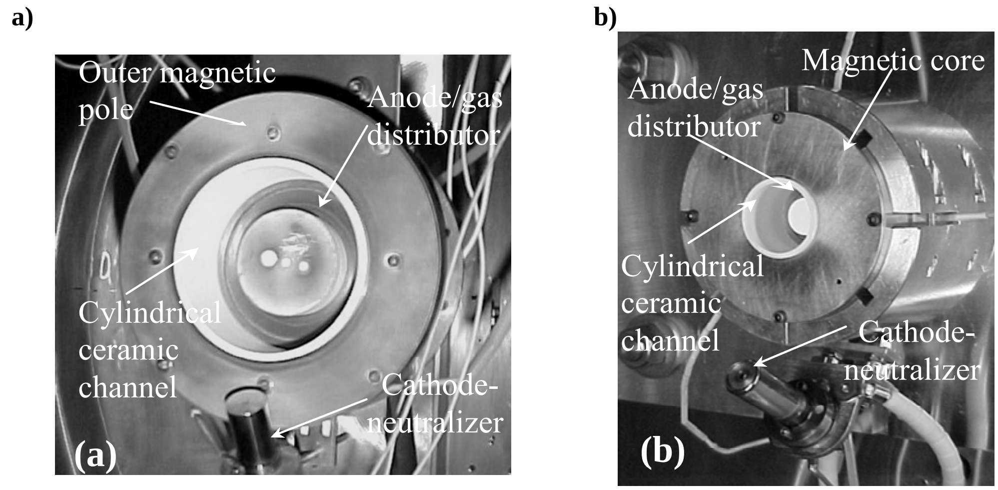

Figure 2. The 9 cm, 1 kW (a) and the 2.6 cm, 100 W (b) cylindrical Hall thrusters.

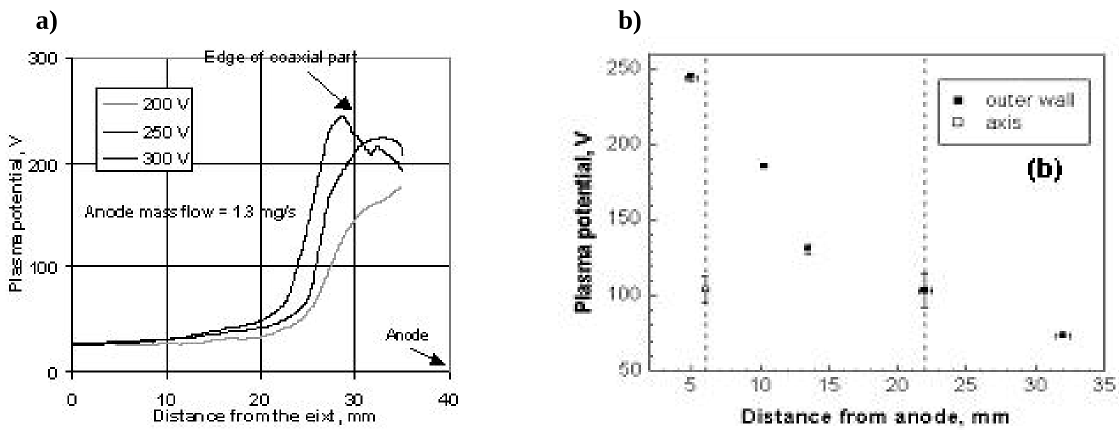

Figure 3. Plasma potential measurements in the cylindrical Hall thrusters: in the 9 cm CHT using a fast movable emissive probe along the channel median at the xenon flow of 13 sccm (a) and in the 2.6 cm CHT with stationary biased probes at a xenon flow rate of 4 sccm and the discharge voltage of 250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

channel, a CHT should suffer lower erosion and heating of the thruster parts. This makes the concept of a CHT very promising not only for low-power applications, but also for high power applications.

In contrast to the conventional annular geometry, in the cylindrical geometry the axial potential distribution is now critical for electron confinement. This is because there is now a large axial gradient to the magnetic field over the cylindrical part of the channel, which means that electrons drift outwards through the μ grad B forces, even as they drift azimuthally around the cylinder axis (Fig. 4). 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 confining electrons within the thruster. However, the most critical differences between the cylindrical and the annular thruster configurations relate to the fact that in the cylindrical thruster electrons are no longer confined to axial positions; rather they are trapped between magnetic mirrors on the anode side and by the voltage potential in the plasma plume on the cathode side. 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).

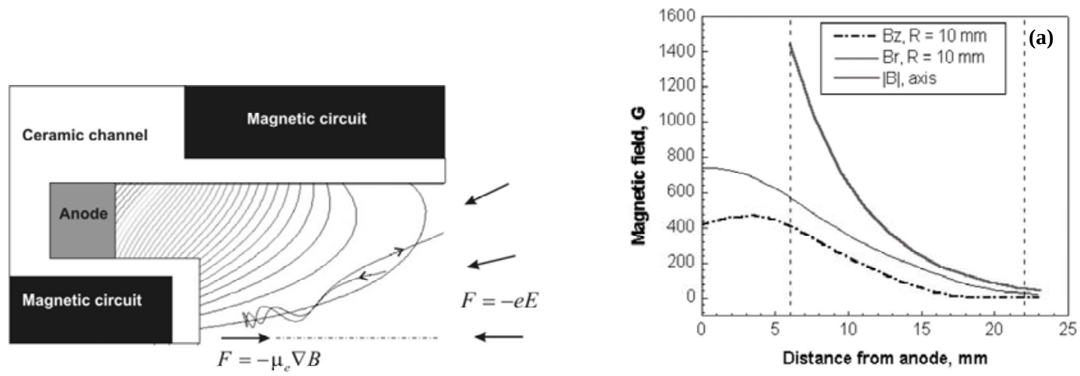

Figure 4. Magnetic field simulations of the 100 W CHT. The channel diameter is 2.6 cm. Illustrative electron trajectory in the cylindrical part of the channel is indicated, and hybrid mechanism of electron trapping is schematically shown.[9,17]

The CHT thruster is surprisingly quiet. Large amplitude discharge current oscillations seen in Fig 5 are typical for conventional annular HT and attributed to either ionization waves[19] or Buneman-type instability.[20] The absence of the large amplitude oscillations is an obviously attractive feature of the cylindrical thruster. Quiet operation facilitates integration with satellite systems such as power supply and telecommunication electronics. One speculation is that the quiet operation in the low frequency range results from enhanced electron transport in the discharge caused by the high-frequency plasma oscillations.[9,17] 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 thruster. The characteristic peak of oscillations is at frequencies of about 50 to 60 kHz. Apparently, the characteristic frequency, which is typically ~ 20 kHz for annular 9 cm HT (Fig. 5), almost triples as thruster dimensions are reduced by about factor of 3.

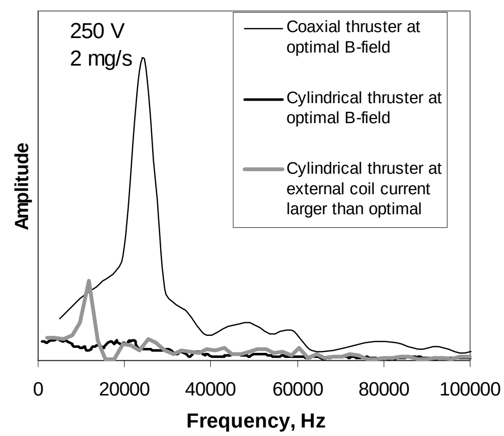

Figure 5. Spectrum of oscillations in the 9 cm cylindrical and annular Hall thrusters.[7]

In addition to the reduction of the wall losses predicted by a fluid model, the presence of the hybrid trap for electrons (Fig. 4) and ambipolar potential for ions (Fig. 6), which is supported by the plasma measurements and Monte-Carlo simulations,[9,13,17] is believed to explain very high ionization efficiency typical of the CHTs. The

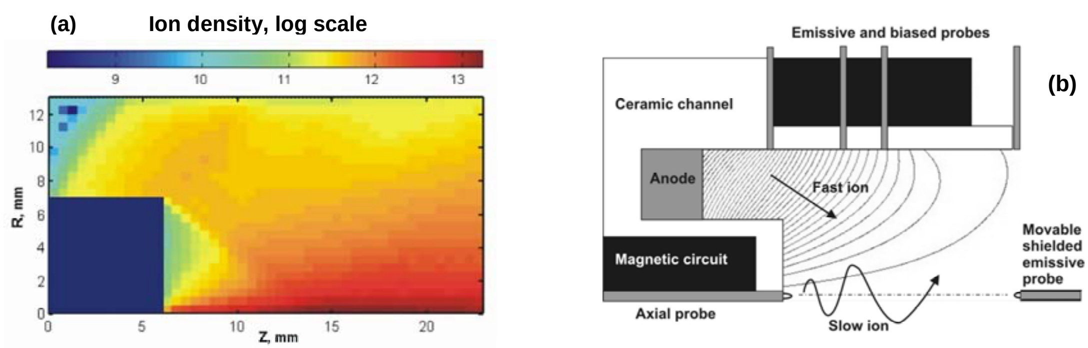

Figure 6. The plasma measurements revealed the plasma density peak at the axis of the cylindrical channel. (a) Monte-Carlo simulations[9,17] suggest that the density peak appears due to ambipolar trapping of slow ions. [9] (b) Probe diagnostic used in plasma measurements in the 2.6 cm CHT.

thruster ionization efficiency is characterized by a so-called propellant utilization coefficient η_I – a ratio of the total ion current I_i at the thruster exit plane to the propellant flow rate measured in units of electric current. Namely, $\eta_I = I_i M / e\dot{m}$, where M is a mass of a propellant gas atom, e is the electron charge and $\dot{m}$ is the mass flow rate. The total ion current is estimated by integrating the angular ion flux distribution, which is measured with a guarding sleeve rotational probe placed in the plasma plume.[7,8] Fig. 7 shows that the CHTs have unusually high propellant utilization. It is higher than that in the conventional annular thrusters at the same flow rates.[7,8] This anomalously high ionization efficiency, characteristic of the cylindrical configuration, is promising for the extension of the thruster operating range to low discharge voltages and difficult-to-ionize propellants.

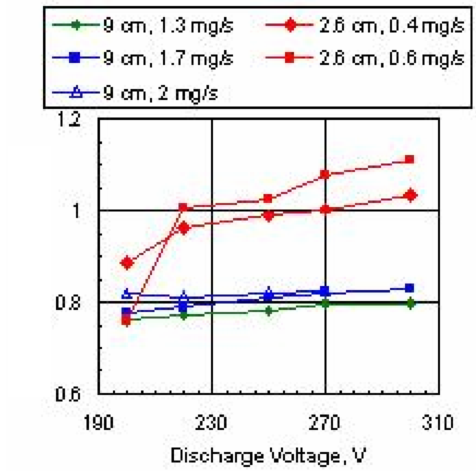

Figure 5. Measured propellant utilization efficiency for the 9 cm and 2.6 cm CHT thrusters.[7,8] The cathode mass flow rate (0.2 mg/s) is not taken into account.

Note that, for the miniaturized thruster, the same values of the propellant utilization were measured when a propellantless tungsten filament cathode was used instead of the hollow cathode-neutralizer.

III. Thruster Performance

The 9 cm CHT 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,[21] and smaller, but comparable (~40%) to the conventional annular HTs of a similar size (~50%). 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. 6 compares the ratio of the measured Isp for state-of-the art annular HTs[6,22,23,24,25] 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. 6). At $V_d < 200$ V, the Isp ratio and overall thruster performance drop substantially because of poor ionization. In contrast, the 9 cm diameter cylindrical Hall thruster 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 are apparently not so sensitive to the discharge voltage (Fig. 5).

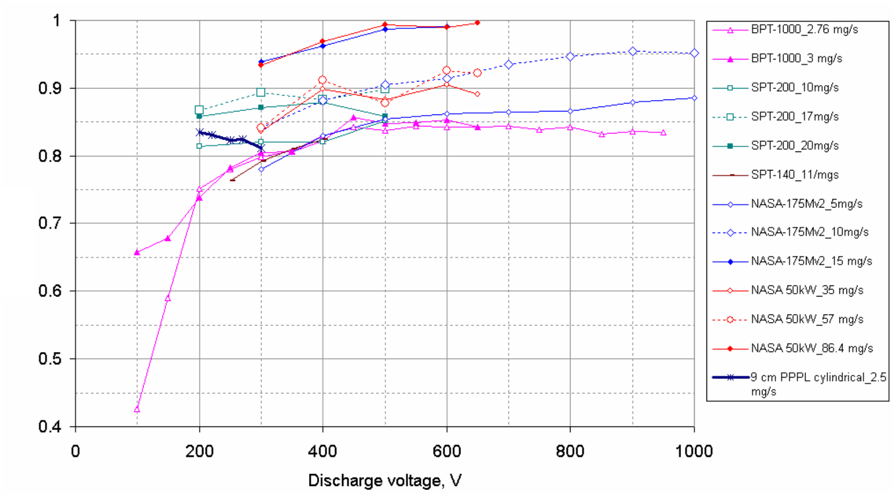

Figure 6. The ratio of Isp/Isp^{th} (b) for the-state-of-the art Hall thrusters and a 9 cm laboratory cylindrical Hall thruster. $Isp^{th} = (2e \cdot V_d/M_{ion})^{0.5} \cdot 1/g$, is for mono energetic beam of single charged ions, where e is electron charge, V_d is the discharge voltage, M_{ion} is the Xenon ion mass, g is the gravity. Thruster references: BPT-1000, SPT-200,; SPT-140,[24] NASA 175Mv2,, NASA 50 kW,[6] PPPL 9 cm cylindrical Hall thruster.

The ability of the CHT thruster to operate efficiently at low discharge voltages may be useful for high thrust and low Isp applications of Hall thrusters.

Fig. 7 shows the performance for the 2.6 cm and 3 cm cylindrical Hall thrusters in the input power range of 90-230 W. The thrust measurements were conducted at the MAE department of Princeton University and at the NASA Marshall SFC.[12] For the smaller 2.6 cm thruster, the performance of the cylindrical and annular geometry configurations were nearly identical. Also, we have recently demonstrated that the cross-field electron transport in the miniaturized thrusters is very sensitive to the shape of the magnetic field lines in the hybrid trap, the background pressure,[17] and other discharge and thruster parameters.[26] For instance, when the 2.6 cm and 3 cm CHTs operate at low background pressure (< 10^{-5} torr), the discharge current decreases and the generated thrust slightly increases as the magnetic field configuration is changed from cusp (coils currents are counter-direct) to direct (coils currents co-direct).[13,17,26] This, most likely, implies that the electron transport to the anode is suppressed more strongly and the directionality of ion acceleration is better in the direct magnetic field configuration (Fig. 7) than in the cusp configuration. The thruster efficiency is accordingly larger in the direct configuration.[13] On the other hand, the 9 cm CHT thruster demonstrated higher efficiency in the cusp configuration. The effect of the magnetic field on the thruster operation and its dependence on discharge parameters and conditions is analyzed in detail in Ref. 26.

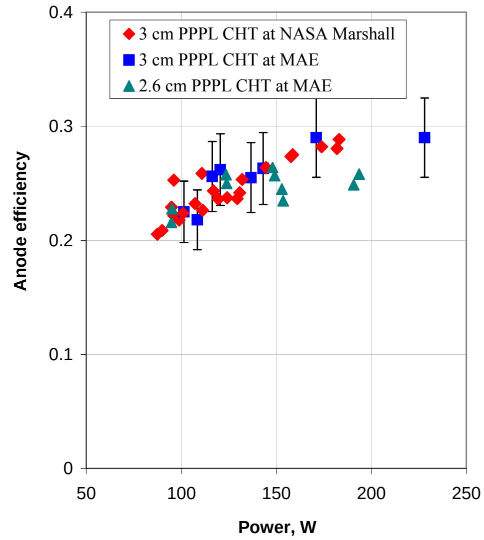

Figure 7. The thruster (anode) efficiency of the 3 cm CHT measured in the direct magnetic field configuration. The thrust measurements were conducted at the MAE department of Princeton University and at the NASA Marshall SFC.

The efficiency of the cylindrical thrusters at 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%), SPT-30 (η_a ~ 22%),[27] KM-37 (η_{tot} ~ 24%),[28] KM-20M (η_{tot} < 30%),[29,30] and MIT HT (η_{tot} ~ 6%). However, the cylindrical thrusters are likely to have a very important advantage over the annular design thrusters, namely, a longer lifetime. Yet another thruster that may improve on certain design issues associated the channel erosion and magnetic circuit miniaturization, is a linear Hall thruster of Ref. 20[31]. However, the electron drift in linear thrusters terminates on the channel walls, the Hall electric field is no longer zero. The advantage of a large Hall parameter, which leads to a smaller electron current, is lost and the thruster efficiency tends to be relatively low, η_a ~ 9% at P = 100 W.

IV. Further Miniaturization and Optimization

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 the strong magnetic field is applied in the channel. It turned out that both of these problems can be solved by placing a segmented electrode on the front wall of the short central ceramic piece of the channel. Fig. 8 shows a graphite segmented electrode installed in the 3 cm CHT thruster. The magnetic field lines near the thruster axis intersect the electrode surface (Fig. 4). The electrode is biased positive (50-100 V) with respect to the cathode. A strong magnetic mirror in front of the segmented electrode 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

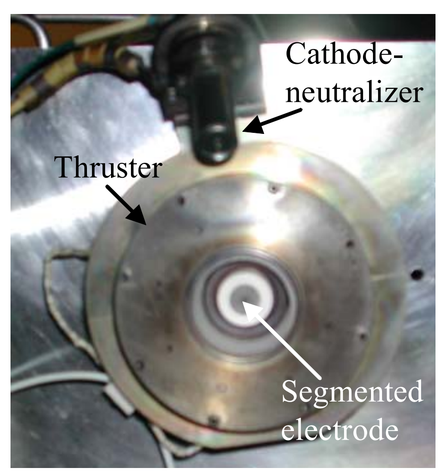

Figure 8. The 3 cm diam CHT with a graphite segmented electrode.

the local plasma potential at the thruster axis near the front wall (Fig. 5b). 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 can still consume very insignificant power (depending on the bias voltage, from less than 1 W to a few watts) from the power supply during the thruster operation. Note that with the segmented electrode, the thruster operation was feasible and stable up to 600 V (limit of the power supply used in these experiments). It is not clear what mechanisms are responsible for unstable operation of the CHTs at high discharge voltage, uneasy discharge initiation, and the electrode effects. Apparently, the plasma of the precursor discharge between the segmented electrode and the cathode creates conditions for a breakdown in the magnetic configuration of the CHT (Fig. 4). The ability to initiate the CHT discharge in the presence of the strong magnetic field opens the possibility for the use of permanent magnets instead of power consuming electromagnet coils. This is particularly important for miniaturization of the CHT thrusters to micro propulsion regimes.

The key drawback of existing cylindrical Hall thrusters is an unusual large beam divergence of the plasma plume.[7,11,15] The plasma plume angle, θ_p, is usually defined as the angle that contains 90% of the total ion current. For the cylindrical thrusters, the half plume angle can be as large as 70-80° (compared to 45-50° for the state-of-the art annular HTs). Because the CHT has possibly stronger radial electric field than the conventional HT, more energetic ions may escape at large angles with respect to the thruster axis causing the thrust reduction (because $T \sim \cos\theta_p$). Very recently, we conducted optimization of the 100 W CHT thruster and obtained a dramatic effect on the plume angle. Fig. 9 illustrates the drastic reduction of the plume angle for the 2.6 cm CHT thruster at 160 W. Here, the half plume angle was reduced to 55°, which is comparable to the state-of-the-art conventional HTs. If we assume that the ion acceleration is not deteriorated as the plume is narrowed, then the thruster anode efficiency in the direct configuration should be expected to increase to ~ 35%.

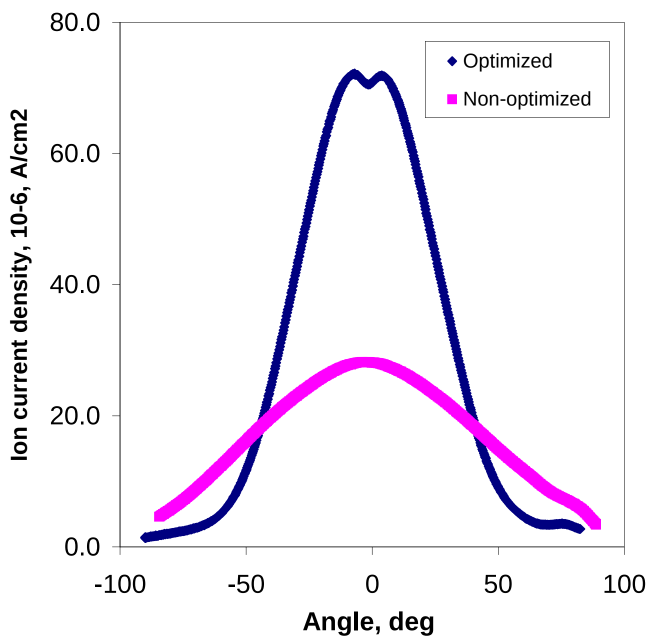

Figure 9. The CHT thruster optimization: 30% plume angle reduction effect. The angular distributions of the ion current density in the far-field plume of the 2.6 cm CHT at 150 W (xenon flow rate 0.4 mg/s). Measurements were conducted in the large vacuum vessel equipped with cryogenic pumps, using a guarding sleeve probe (72 cm from the thruster exit). The background pressure was 3×10^{-6} Torr.

V. Conclusions

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 been recently demonstrated through the optimization of the magnetic field and discharge parameters and the use of segmented electrodes. Having potentially smaller wall losses in the channel, CHTs should suffer lower erosion and heating of the thruster parts. This makes the CHT concept very promising not only for low-power applications, but also for high power applications.

Acknowledgments

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