Electron Cross-Field Transport in a 100 W Cylindrical Hall Thruster

IEPC-2005-098

Presented at the 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005

Artem Smirnov*, Yevgeny Raitses†, and Nathaniel J. Fisch‡

Princeton University Plasma Physics Laboratory, P. O. Box 451, Princeton, New Jersey 08543

Abstract: Conventional annular Hall thrusters become inefficient when scaled to low power. Cylindrical Hall thrusters, which have lower surface-to-volume ratio, are therefore more promising for scaling down. They presently exhibit performance comparable with conventional annular Hall thrusters. The present paper gives a brief review of the experimental and numerical investigations of electron cross-field transport in the 2.6 cm miniaturized cylindrical Hall thruster (100 W power level). We show that, in order to explain the discharge current observed for the typical operating conditions, the electron anomalous collision frequency ν_B has to be on the order of the Bohm value, $\nu_B \approx \omega_c/16$. The contribution of electron-wall collisions to cross-field transport is found to be insignificant. The optimal regimes of thruster operation at low background pressure (below 10^{-5} Torr) in the vacuum tank appear to be different from those at higher pressure (~10^{-4} Torr).

I. Introduction

The Hall thruster[1] is a well-studied electric propulsion device at intermediate to high power, but it appears to be promising also for relatively low power propulsion on near-Earth missions,[2] such as orbit transfer and repositioning. In a conventional Hall thruster, the plasma discharge is sustained in the axial electric (**E**) and radial magnetic (**B**) fields 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. A large fraction of the discharge electrons is emitted by an external cathode. Electron cross-field diffusion provides the necessary current to sustain the discharge. The thrust is generated in reaction to the axial electrostatic acceleration of ions. Ions are accelerated in a quasineutral plasma, so that no space-charge limitation is imposed on the achievable current and thrust densities. Conventional Hall thrusters designed for operation in 600–1000 W power range have outer channel diameter about 10 cm, maximal value of the magnetic field about 100–200 G, and applied discharge voltage U_d =300V.

The thruster efficiency is defined as $\eta = T^2/2\mu P$, where T is the generated thrust, μ is the supplied propellant flow rate, and P is the applied electric power. The efficiency of the state-of-the-art kilowatt and subkilowatt conventional Hall thrusters is about 50–60%.[1,3] The efficiency can be conveniently factorized as:

$$\eta \approx \frac{I_i M}{e\mu} \times \frac{I_i}{I_i + I_e} \times \alpha \, , \tag{1}$$

* Graduate Student, Program in Plasma Physics, Princeton University, asmirnov@princeton.edu.
† Research Physicist, Princeton Plasma Physics Laboratory, yraitses@pppl.gov.
‡ Professor, Department of Astrophyisical Sciences, Princeton University, fisch@pppl.gov.

where M is a mass of a propellant gas atom, e is the electron charge, I_i and I_e are the electron and ion currents, respectively, and α is the efficiency of ion acceleration. The first fraction in the right hand side of Eq. (1), the so-called propellant utilization, is a measure of how effectively the supplied propellant gas is ionized in the discharge, whereas the second fraction, the so-called current utilization, determines how effectively the electron transport to the anode is suppressed by the applied magnetic field. With all other parameters held constant, the thruster efficiency decreases with increasing electron current. Understanding of the mechanisms of electron transport in the discharge is, therefore, essential for the development of higher efficiency thrusters.

The electrons in Hall thrusters exhibit anomalous cross-field transport: The electron conductivity across the magnetic field is larger than that predicted by the classical electron-atom collision rate.[1,4] It is believed that two collisional processes contribute to the conductivity enhancement in Hall thrusters: i) electron scattering in electric field fluctuations (anomalous or 'Bohm' diffusion[4]), and ii) the electron-wall collisions (the near-wall conductivity[5,6]). The electron-wall interaction plays also a very important role by shaping the electron distribution function (EDF) in the thruster channel. In Hall discharge simulations, in order to account for an enhanced electron cross-field transport, the two non-classical conductivity mechanisms are usually incorporated in models in one or another parametric way. In fluid and hybrid fluid-particle models, some investigators impose the anomalous Bohm conductivity inside the channel,[7-9] while others use only the near-wall conductivity[10] or a combination of both Bohm transport and wall collisions.[11-16] Full particle-in-cell (PIC) simulations[17,18] reveal turbulence increasing the cross-field transport. Some theoretical studies[19,20] suggest that due to the non-Maxwellian shape of the EDF in a Hall thruster, electron-wall collisions do not make a significant contribution to cross-field transport. In a 2-kW Hall thruster operated at low discharge voltage,[21] in the channel region where the magnetic field was the strongest, anomalous fluctuation-enhanced diffusion was identified as the main mechanism of electron cross-field transport. It is important to emphasize here that most of investigations, which addressed the question of the electron conductivity, have been performed for kilowatt and sub-kilowatt thrusters, where the maximal magnetic field strength in the channel is about 100–200 G.

Scaling to low power Hall thrusters requires a thruster channel size to be decreased while the magnetic field must be increased inversely to the scaling factor.[1] Thus, in general, the rate of electron cross-field transport required to sustain the discharge in a low-power thruster may be different from that in kilowatt thrusters. In other types of low-temperature magnetized laboratory plasmas, variation of the electron cross-field diffusion rate with applied magnetic field B occurs indeed: For example, in Ref. 22, cross-field diffusion coefficient $D_\perp$ was observed to approach the Bohm value when B was greater than 2-3 kG, while in B<1 kG case $D_\perp$ was much smaller than the Bohm value.

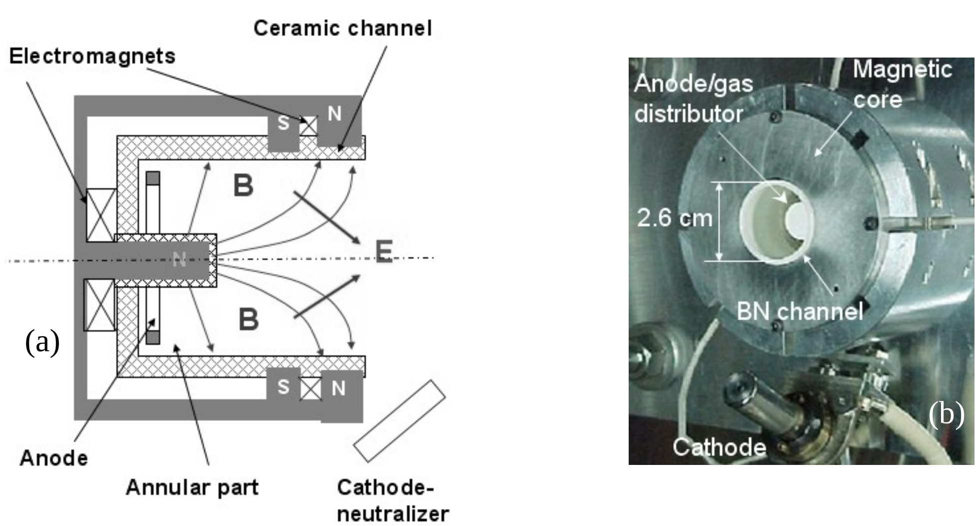

Fig. 1. (a) Schematic of a cylindrical Hall thruster. (b) The 2.6 cm cylindrical Hall thruster.

Increasing the magnetic field while the thruster channel sizes are being reduced is technically challenging because of magnetic saturation in the miniaturized inner parts of the magnetic core. A linear scaling down of the magnetic circuit leaves almost no room for magnetic poles or for heat shields, making difficult the achievement of the optimal magnetic fields. Non-optimal magnetic fields result in enhanced electron transport, power and ion losses, heating and erosion of the thruster parts, particularly the critical inner parts of the coaxial channel and magnetic circuit.

Currently existing low-power Hall thruster laboratory prototypes with channel diameters 2–4 cm operate at 100–300 W power levels with efficiencies in the range of 10%–40%.[2] However, further scaling of the conventional geometry Hall thruster down to sub-centimeter size results in even lower efficiencies, 6% at power level of about 100 W.[23] The low efficiency might arise from a large axial electron current, enhanced by magnetic field degradation due to excessive heating of the thruster magnets, or from a low degree of propellant ionization. Thus, miniaturizing the conventional annular Hall thruster does not appear to be straightforward.

A cylindrical Hall thruster (CHT), illustrated in Fig. 1(a), overcomes these miniaturization problems.[24] It has been studied both experimentally and theoretically.[25-28] The thruster consists of a boron-nitride ceramic channel, an annular anode, which serves also as a gas distributor, two electromagnetic coils, and a magnetic core. The axial electron current in a CHT can be reduced by the magnetic field with an enhanced radial component and/or by the strong magnetic mirror in the cylindrical part of the channel. The magnetic field lines intersect the ceramic channel walls. The electron drifts are closed, with the magnetic field lines forming equipotential surfaces, with $E=-\upsilon_e \times B$. Ion thrust is generated by the axial component of the Lorentz force, proportional to the radial magnetic field and the azimuthal electron current.

The cylindrical channel features a short annular region and a longer cylindrical region. The length of the annular region is selected to be approximately equal to an ionization mean free path of a neutral atom. Compared to a conventional geometry (annular) Hall thruster, the CHT has lower surface-to-volume ratio and, therefore, potentially smaller wall losses in the channel. Having potentially smaller wall losses in the channel, a CHT should suffer lower erosion and heating of the thruster parts, particularly the critical inner parts of the channel and magnetic circuit. This makes the concept of a CHT promising for low-power applications.

In contrast to the conventional annular geometry, in the cylindrical geometry the axial potential distribution is 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 $\mu_e \nabla B$ force, even as they drift azimuthally around the cylinder axis. 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.

A relatively large 9 cm diameter version of the cylindrical thruster, operated in the subkilowatt power range[24], and miniaturized 2.6 cm[25] and 3 cm diameter CHTs,[29,30] operated in the power range 50–300 W, exhibit performance comparable with that of the conventional state-of-the-art annular Hall thrusters of the same size. In Ref. 27 the plasma potential, electron temperature, and plasma density distributions were measured inside the 2.6 cm CHT. It was found that even though the radial component of the magnetic field has a maximum inside the annular part of the CHT, the larger fraction of the applied voltage is localized in the cylindrical region. A significant potential drop was also observed in the plume. Ion acceleration in the CHT is expected to occur predominantly in the longitudinal direction and towards the thruster axis. Therefore, the CHT, having lower surface-to-volume ratio as compared with conventional Hall thrusters, may suffer lower erosion of the channel walls and have a longer lifetime.

In recent work,[28] electron cross-field transport in a 2.6 cm miniaturized cylindrical Hall thruster was studied through the analysis of experimental data and Monte Carlo simulations of electron dynamics in the thruster channel. The numerical model takes into account elastic and inelastic electron collisions with atoms, electron-wall collisions, including secondary electron emission, and Bohm diffusion. It was shown that in the typical operating regime the electron anomalous collision frequency ν_B was of the order of the Bohm value, $\nu_B \approx \omega_c/16$. The contribution of electron-wall collisions to cross-field transport was found to be insignificant.

The present paper gives a brief review of the experimental and numerical investigations of electron cross-field transport in the 2.6 cm CHT and reports a few recent experimental results[31] that suggest directions for further studies.

This article is organized as follows: In Sec. II, the main features of the 2.6 cm CHT are presented and the experimental results, obtained in the vacuum facility with a relatively high background pressure, are reviewed. Section III outlines the key results of the numerical simulations. In Sec. IV, a few recent experimental results, obtained at low background pressure, are presented, and their implications are discussed. In Sec. V, we summarize our main conclusions.

II. Experiments

The results of comprehensive experimental investigations of the 2.6 cm CHT are given in Refs. 25-29.

Experiments described in this section were performed in the Small Hall Thruster facility at Princeton Plasma Physics Laboratory (PPPL).

The 2.6 cm CHT, shown in Fig. 1(b), was scaled down from the 9 cm CHT to operate at about 200 W power level. The total length of the channel is 2.2 cm, the annular region is approximately 0.6 cm long. The outer and the inner diameters of the channel are 2.6 cm and 1.4 cm, respectively. The overall diameter and the thruster length are both 7 cm.

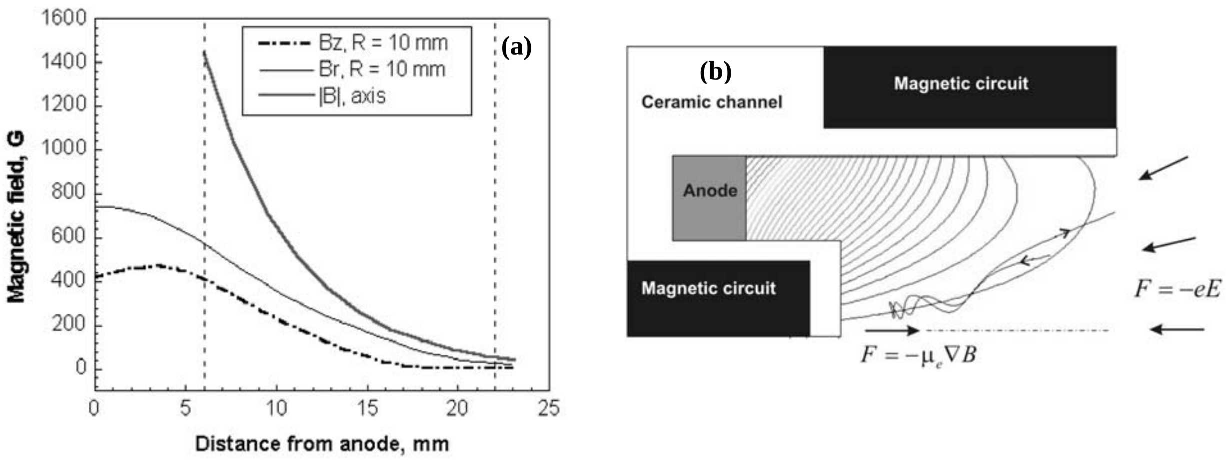

Fig. 2. (a) Magnetic field profiles in the 2.6 cm CHT. I_{back} = 2.5A, I_{front} = -1A. Dashed lines at z=6 mm and z=22 mm show the edge of the annular channel part and the thruster exit, respectively. (b) Probe setup used in the experiments. Magnetic field distribution is given for the same coil currents as in Fig 2(a). Illustrative electron trajectory in the cylindrical part of the channel is indicated, and hybrid mechanism of electron trapping is schematically shown. μ_e is the electron magnetic moment.

The magnetic field profiles in the 2.6 cm CHT are shown in Fig. 2(a). The radial component B_r of the magnetic field reaches its maximum near the anode and then reduces towards the channel exit. Although the axial component B_z is also strong, the magnetic field in the annular part of the channel is predominantly radial, the average angle between the field line and the normal to the walls is about 30° [see Fig. 2(b)]. Magnetic field has a mirror-type structure near the thruster axis, with the maximum B ~ 1400 G at the central ceramic piece wall. Due to the mirroring effect of the magnetic field in the cylindrical part of the channel [see Fig. 2(b)], most of the electrons injected from the cathode are reflected from the region of strong *B* field, and move in the downstream direction. Upon crossing the thruster exit plane and entering the plume plasma, the electrons become unmagnetized and face the potential drop of about 100 V, which reflects them back into the thruster. Thus, most of the electrons injected from the cathode to the CHT appear to be confined in a hybrid trap formed by the magnetic mirror and by the plume potential drop. Diffusion of these electrons across the magnetic field occurs on a time scale much larger than the bounce time in the trap.[28]

The typical discharge parameters for the 2.6 cm CHT are: Xe flow rate μ=0.4 mg/s, discharge voltage U_d=250 V, discharge current $I_d \approx 0.6$ A. Under such conditions, the background gas pressure in the PPPL Small Hall Thruster facility is about 7×10^{-5} Torr, the propellant utilization in the 2.6 cm CHT is about 1, and the current utilization is approximately equal to 0.5.[25] In practice, for the given propellant flow rate, discharge voltage, and background gas pressure, the discharge current is minimized by varying the currents in the magnetic coils. This procedure, which appears to be customary for the annular thrusters, is based on the assumption that, near the discharge current minimum, the variation of the magnetic field affects mainly the electron current to the anode but not the ion current. Thus, the thruster efficiency is maximized by decreasing the discharge current while keeping the generated thrust nearly constant. As shown in Sec. V, this approach is valid for the CHTs operated at a low background gas pressure (in the 10^{-6} Torr range). However, in the relatively high background pressure of the Small Hall Thruster facility (~ 10^{-4} Torr), the reduction of the discharge current in certain magnetic field configurations may be due to the suppression of the background gas ionization. Nonetheless, the operating regime considered in Sec. II-IV is a typical one for the vacuum environment of the Small Hall Thruster facility.

The distribution of plasma potential ϕ, electron temperature T_e, and plasma density N_e inside the 2.6 cm CHT was studied by means of stationary and movable floating emissive and biased Langmuir probes.[28] The probe setup used in the experiments is shown in Fig. 2(b). Measurements were done at the outer channel wall (at four axial locations: z = 5, 10.3, 13.5, and 22 mm), as well as at the thruster axis. The results of the probe measurements are shown in Fig. 3. The potential drop in the 2.6 cm CHT is localized mainly in the cylindrical part of the channel and beyond the thruster exit, in the plume. The potential variation along the thruster axis between the central ceramic piece and the channel exit is insignificant. Its maximum possible value is within the data spread of the measurements, which is about 25 V. Much larger potential drops along the magnetic field lines were observed in the end-Hall ion source,[32] which has a mirror-type magnetic field distribution similar to that in the central part of the CHT.

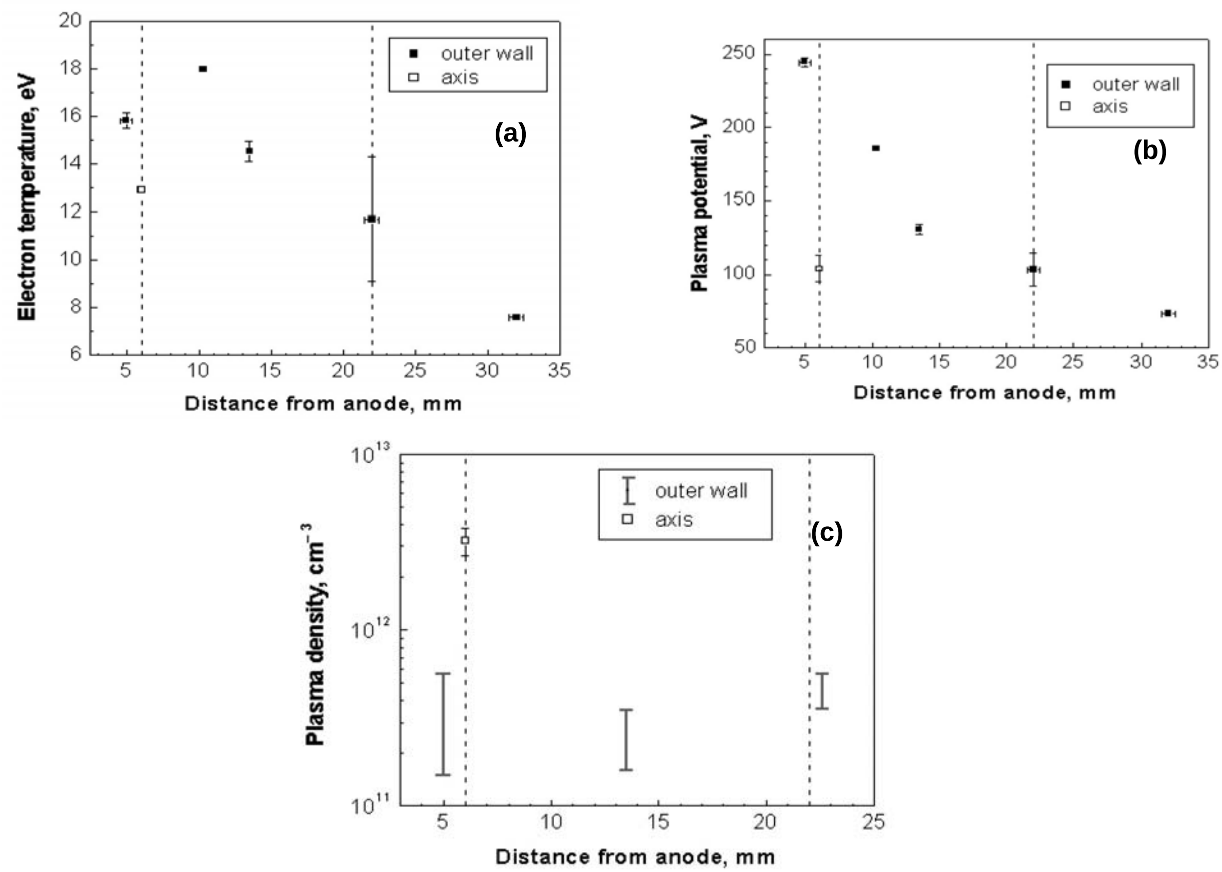

Fig. 3. Electron temperature (a), plasma potential (b), and plasma density (c) profiles in the 2.6 cm CHT.[28] Dashed lines at z=6 mm and z=22 mm show the edge of the annular channel part and the thruster exit, respectively. In (a) and (b), Y-axis error bars represent the entire statistical spread of the measured data. For plasma density measurements near the outer channel wall (c), only the intervals, in which the real values of the plasma density are located, can be given.

Due to a rather large uncertainty of the plasma density measurements, it was possible to determine only the interval, in which the real value of N_e was located. The variation bars in Fig. 3(c) span between the upper and the lower estimates of N_e obtained in the experiments. Due to the reasons discussed in detail in Ref. 27, the real values of the plasma density are believed to be closer to the upper bounds of the corresponding intervals. The plasma density in the 2.6 cm CHT has a prominent peak at the thruster axis: N_e at the axis is 4–8 times larger than in the annular part of the channel. The sharp maximum in N_e might be a manifestation of the convergent ion flux.

III. Summary of numerical results

The comprehensive description of the MC code is given elswhere.[28] We imposed the anomalous Bohm conductivity inside the channel in order to account for fluctuation-enhanced electron transport. It was assumed that electrons scatter primarily in the azimuthal fluctuations of the electric field. When an electron undergoes a collision with the electric field fluctuation, the perpendicular, with respect to B, electron velocity component is assumed to scatter isotropically. The parallel velocity component does not change. Thus, the guiding center of the electron orbit gets a random shift in the plane perpendicular to B on the order of the electron gyroradius. The frequency of Bohm diffusion collisions, $\nu_B=\kappa_B\omega_c/16$, where κ_B is a fitting parameter that does not depend on the electron energy. We performed the parametric study of the dependency of plasma parameters distribution on the electron cross-field conductivity.[25] The main results obtained in the simulations can be summarized as follows:

(i) The maximum electron density is achieved in the annular part of the channel. Although there is a slight elevation of N_e at the thruster axis, its value, as opposed to the results of the experiments, is lower than the density in the annular part of the channel. When κ_B is varied, the distribution of the electron density in the channel does not change qualitatively. The characteristic magnitude of N_e decreases when κ_B is increased.

(ii) In order to explain the observed plasma density, the electron anomalous collision frequency ν_B should be high, on the order of the Bohm value $\nu_B\approx\omega_c/16$. Thus, the value of Bohm parameter κ_B, which, for the low-power CHT, gives the best agreement between the simulations and experiments (κ_B ~ 1), is a few times larger than those obtained typically in the modeling of conventional Hall thrusters (κ_B ~ 0.1 – 0.4).[7-9,11-16] Therefore, the rate of electron fluctuation-enhanced diffusion, which is required to explain the discharge current observed in the CHT, should be higher than that in conventional Hall thrusters. The anomalous electron transport in the CHT is believed to be induced by high-frequency plasma instabilities. Interestingly, in the frequency range below ~100 kHz, the 2.6 cm CHT operates quieter than the annular Hall thruster of the same size.[25]

(iii) Electron-wall collisions deplete the tail of the EDF. The resultant shape of the EDF appears to be bi-Maxwellian. As κ_B (and, consequently, ν_B) decreases, the tail of the distribution function gradually weakens. The general shape of the EDF obtained in simulations appears to be in a good qualitative agreement with the results of work [20], where the EDF in the Hall thruster channel was determined by solving the electron Boltzman equation.

(iv) The electron-wall collisions make an insignificant contribution to the electron current conduction, as compared with the fluctuation-induced electron scattering. The typical average electron-wall collision frequency, ν_{ew}, is on the order of 1×10^7 s^{-1}, while the anomalous collision frequency ν_B, averaged along a magnetic field line, is about 7×10^8 s^{-1}. Inequality $\nu_{ew}<<\nu_B$ is satisfied throughout the thruster channel.

IV. RECENT EXPERIMENTAL RESULTS AND PLANS FOR FUTURE WORK

The effect of the magnetic field on the discharge characteristics and efficiency of the low-power CHTs with channel outer diameters of 2.6 cm and 3 cm was investigated recently.[29,33] In this section, we briefly describe a few interesting results obtained in these experiments. The observed effects (even though the underlying physics remains largely unexplored) have important implications for the problem of electron cross-field transport and suggest the directions for further studies.

The variation of the current in the back magnetic coil of the CHT mainly changes the magnetic field magnitude without altering the shape of magnetic field surfaces. It is generally observed that the increase of the back coil current leads to the monotonic decrease of the discharge current. The variation of the front coil current changes the shape of the magnetic field surfaces, with the most pronounced changes occurring in the cylindrical part of the channel. When the current in the front coil is counter-directed to that in the back coil (I_{front}<0), the "cusp" magnetic field with an enhanced radial component is created (see Fig. 2). Swapping the polarity of the front coil current (I_{front}>0) leads to the enhancement of the axial component of the magnetic field and generation of a stronger magnetic mirror near the thruster axis. The goal of the performed experiments was to investigate the dependence of the discharge current and generated thrust on the current in the front magnetic coil.

The experiments were performed in the Electric Propulsion and Plasma Dynamics Laboratory (EPPDyL) at Princeton University.[34] The operating background pressure of xenon in the EPPDyL vacuum facility was about one order of magnitude smaller than that in the Small Hall Thruster facility at PPPL. Importantly, it was observed that the magnetic field configuration that minimizes the discharge current depends on the background gas pressure in the tank. In Fig. 3, the variation of the discharge current I_d with the current in the front coil I_{front} is shown for the EPPDyL and PPPL facilities. All discharge parameters are the same (anode flow rate μ=0.4 mg/s, U_d=250 V, I_{back}=+3 A), except for the background xenon pressure, which is about 6×10^{-6} Torr for the EPPDyL tank and 7×10^{-5}

Torr for the PPPL tank. In the experiments at EPPDyL, when the background gas pressure in the near-filed thruster plume was raised by increasing xenon flow rate to the cathode, the values $I_d(I_{front})$ were found to shift closer to those corresponding to the PPPL conditions. It is important to emphasize, however, that electrons in the plume plasma are collisionless in both the PPPL and EPPDyL facilities: The electron mean free path is about the size of the tank, which is much larger than the thruster dimensions.

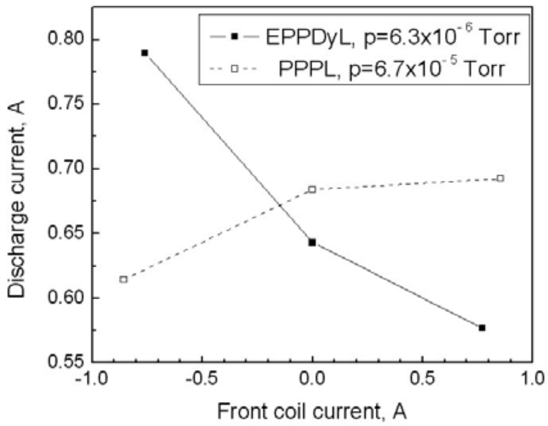

Fig. 3. The dependences of the discharge current on the current in the front magnetic coil in the 2.6 cm CHT for the EPPDyL and PPPL facilities. All discharge parameters are the same (anode flow rate μ=0.4 mg/s, U_d=250 V, I_{back}=+3 A), except for the background gas pressure, which is equal to 6.3×10^{-6} Torr for the EPPDyL tank and 6.7×10^{-5} Torr for the PPPL tank.

It is clear form Fig. 3 that the cusp magnetic field configuration minimizes the discharge current at high background pressure, while the direct configuration does the same at low pressure. Now, at low background pressure, the increase of I_{front} above ~ +1 A leads to the negligible variation of the discharge current. The decrease of I_{front}, on the contrary, brings about a rather sharp increase of I_d. Along with it, as the magnetic field configuration is changed from direct to cusp, the generated thrust slightly decreases (See Fig. 4). Consequently, in the voltage range from 200 to 300 Volts, the anode efficiency in the direct configuration is approximately factor of 1.5-1.7 larger than that in the cusp configuration.

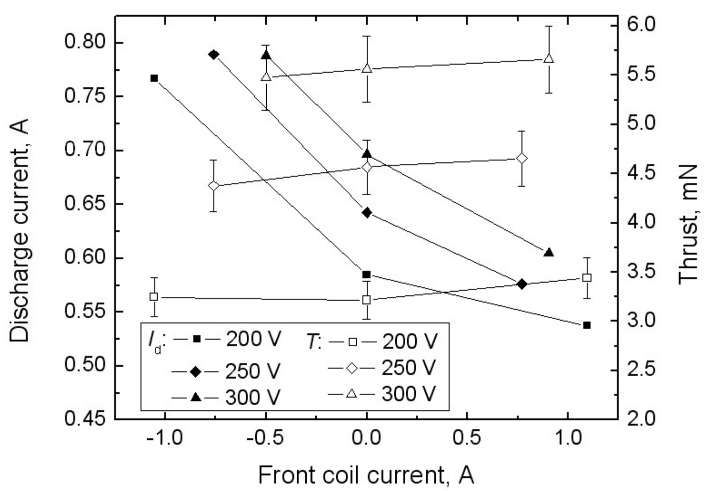

Fig. 4. The dependencies of the discharge current and thrust on the front coil current in the 2.6 cm CHT operated in the EPPDyL facility (background gas pressure ~ 6×10^{-6} Torr). Anode and cathode xenon flow rates are 4 sccm and 2 sccm, respectively; I_{back} = 3A. I_{front}>0 (I_{front}<0) corresponds to the direct (cusp) magnetic field configuration.

The fact that the discharge current decreases with the increase in I_{front} (see Fig. 4) implies that the electron transport to the anode is suppressed more strongly in the direct magnetic field configuration than in the cusp configuration. Indeed, from the data shown in Fig. 4 it follows that

$$I_i^c \sim 0.95 I_i^d \sqrt{\varepsilon^d / \varepsilon^c}\ , \tag{2.a}$$

$$I_d^c \sim 1.37 I_d^d\ . \tag{2.b}$$

Here I_i is the ion current, ε is the mean ion energy, and superscripts "d" and "c" refer to the direct and cusp polarities, respectively. From Eqs. (2) we obtain the ratio of the electron currents in the cusp and direct configurations:

$$\frac{I_e^c}{I_e^d} \approx 1.37 + \frac{I_i^d}{I_e^d}\left(1.37 - 0.95\sqrt{\frac{\varepsilon^d}{\varepsilon^c}}\right). \tag{3}$$

When the thruster magnetic field configuration is changed, it is very unlikely that the average ion energy varies by more than about factor of 2. Thus, the ratio I_e^c / I_e^d is about 1.3 – 1.5.

The fact that the electron current in the direct configuration is smaller does not necessarily imply that the rate of electron cross-field transport is smaller. Plasma measurements, similar to those described in Sec. II, are required to understand how the magnetic field configuration and background gas pressure influence the electron anomalous transport. Studying the dependence of the plasma parameters on the magnetic field and gas pressure is a subject of ongoing research.

V. CONCLUSIONS

Scaling to low-power Hall thrusters requires the magnetic field to be increased inversely with length, as the thruster channel size is decreased. In a strong magnetic field of a low-power Hall thruster, the rate of electron cross-field diffusion, required to sustain the discharge, can differ from that in a Hall thruster operating in the conventional kilowatt or subkilowatt power range. Thus, understanding of the mechanisms of electron transport is essential for the development of higher efficiency low-power thrusters and for scaling to small sizes.

The conventional (annular) Hall thrusters become inefficient when scaled to small sizes because of the large surface-to-volume ratio and the difficulty in miniaturizing the magnetic circuit. Also, the erosion of the walls of a small annular channel can severely limit the thruster lifetime. An alternative approach, which may be more suitable for scaling to low power, is a cylindrical Hall thruster (CHT). The 9 cm CHT, operated in the subkilowatt power range, and the miniature 2.6 cm and 3 cm CHT, operated in the power range 50–300 W, exhibit performance comparable with the conventional state-of-the-art annular Hall thrusters of the same size. Ion acceleration in the CHTs occurs mainly in the cylindrical part of the channel and beyond the thruster exit. Thus, CHTs, having lower surface-to-volume ratio as compared with conventional annular design Hall thrusters, should suffer lower erosion of the channel walls and, therefore, have a longer lifetime.

Plasma potential, ion density, and electron temperature profiles were measured inside the 2.6 cm cylindrical Hall thruster, operated in the vacuum facility with a relatively high background gas pressure (< 10^{-4} Torr). The electron cross-field transport was studied for the typical operating regime. To analyze electron dynamics in the channel region of the 2.6 cm CHT, a Monte Carlo code was developed. The numerical model takes into account elastic and inelastic electron collisions with atoms, electron-wall collisions (backscattering, attachment, and secondary electron emission), and Bohm diffusion. The comparison of numerical and experimental results shows that in order to explain the discharge current, observed in the 2.6 cm CHT, the electron anomalous collision frequency ν_B has to be high. As opposed to most of the conventional Hall thruster models, which predict the ratio ν_B/ω_c to be on the order of 10^{-2}, we find that in the 2.6 cm CHT ν_B has to be on the order of the Bohm value, $\nu_B \sim \omega_c/16$. The anomalous cross-field electron transport in the CHT is believed to be induced by high-frequency plasma instabilities. The EDF in a Hall thruster is depleted at high energy due to electron loss at the walls, thus indicating that the contribution of secondary electrons to cross-field transport is likely insignificant.

The effect of the magnetic field on the discharge current and generated thrust in the 2.6 cm and 3 cm CHTs was studied in the experiments performed at low background gas pressure (< 10^{-5} Torr). These experiments demonstrated that the optimal regimes of thruster operation at low background pressure are, in fact, different from those at higher pressure. For instance, for both the 2.6 cm and 3 cm CHTs the discharge current decreases and the generated thrust slightly increases as the magnetic field configuration is changed from cusp to direct. 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 than in the cusp configuration. The thruster efficiency is accordingly larger in the direct configuration. Future experiments will address the question of how the rate of electron cross-field transport depends on the magnetic field configuration, channel geometric parameters, and the background gas pressure in the tank.

ACKNOWLEDGMENTS

The authors are grateful to Professor Edgar Choueiri for the provided opportunity to work with the EPPDyL thrust stand, and to Mr. Robert Sorenson for his assistance in the thrust measurements. This work was supported by grants from AFOSR, DARPA, and USDOE Contract AC02-76CH0-3073.

REFERENCES

[1]I. Morozov and V. V. Savelyev, in *Review of Plasma Physic*s, vol. 21, p. 203, edited by B. B. Kadomtsev and V. D. Shafranov. Consultants Bureau, New York, 2000.

[2]J. Mueller, in *Micropropulsion for Small Spacecraft, Progress in Astronautics and Aeronautics*, vol. 187, p. 45, edited by M.M. Micci and A.D. Ketsdever. AIAA Progress in Astronautics and Aeronautics, Reston, VA, 2000.

[3]A. Fruchtman, "Limits on the efficiency of several electric thruster configurations", *Phys. Plasmas,* vol. 10, no. 5, pp. 2100-2107, 2003.

[4]G.S. Janes and R.S. Lowder, "Anomalous electron diffusion and ion acceleration in a low-density plasma", *Phys. Fluids*, vol. 9, no. 6, pp. 1115-1123, 1966.

[5]A.I. Morozov and V.V. Savel'ev, "Theory of the near-wall conductivity", *Plasm. Phys. Rep*., vol. 27, no. 7, pp. 570-575, 2001.

[6]A.I. Bugrova, A.I. Morozov, and V.K. Kharchevnikov, "Eexperimental investigation of near wall conductivity", *Sov. J. Plasm. Phys.*, vol. 16, no. 12, pp. 849-856, 1990.

[7]E. Fernandez and M.A. Cappelli, Bull. Am. Phys. Soc., vol. 45, no. 7, p. 166, 2000.

[8]A. Cohen-Zur, A. Fructman, J. Ashkenazy, and A. Gany "Analysis of the steady-state axial flow in the Hall thruster", *Phys. Plasmas*, vol. 9, no. 10, pp. 4363-4374, 2002.

[9]L. Dorf, V. Semenov, Y. Raitses, "Anode sheath in Hall thrusters", *Appl. Phys. Lett.*, vol. 83, no. 13, pp. 2551-2553, 2003.

[10]S. Barral, K. Makowski, Z. Peradzynski, N. Gascon, and M. Dudeck, "Wall material effects in stationary plasma thrusters. II. Near-wall and in-wall conductivity", *Phys. Plasmas*, vol. 10, no. 10, 4137-4152, 2003.

[11]E. Ahedo, J.M. Gallardo, and M. Martinez-Sanchez, "Effects of the radial plasma-wall interaction on the Hall thruster discharge", *Phys. Plasmas***,** vol. 10, no. 8, pp. 3397-3409, 2003.

[12]M. Keidar, I.D. Boyd, and I.I. Beilis, "Plasma flow and plasma–wall transition in Hall thruster channel", *Phys. Plasmas*, vol. 8, no. 12, pp. 5315-5322, 2001.

[13]J. Bareilles, G.J.M. Hagelaar, L. Garrigues, C. Boniface, J.P. Boeuf, and N. Gascon, "Critical assessment of a two-dimensional hybrid Hall thruster model: Comparisons with experiments", *Phys. Plasmas*, vol. 11, no. 6, 3035-3046, 2004.

[14]J.M. Fife, Ph.D. thesis, Massachusetts Institute of Technology, 1998.

[15.]J. Szabo, Ph.D. thesis, Massachusetts Institute of Technology, 2001.

[16]Y. Raitses, D. Staack, M. Keidar, and N.J. Fisch, "Electron-wall interaction in Hall thrusters", *Phys. Plasmas*, vol. 12, 057104, 2005.

[17]O. Batishchev and M. Martinez-Sanchez, "Charged particles transport in the Hall effect thruster", IEPC 03-188, in Proc. 28th International Electric Propulsion Conference, Toulouse, France, 2003.

[18]J.C Adam, A. Heron, G. Laval, "Study of stationary plasma thrusters using two-dimensional fully kinetic simulations", *Phys. Plasmas*, vol. 11, no. 1, pp. 295-305, 2004.

[19]L. Jolivet and J.F. Roussel, "Effects of the secondary electron emission on the sheath phenomenon in a hall thruster", in Proc. 3rd Spacecraft Propulsion Conference, pp. 367–376, Cannes, France, 1999.

[20]N.B. Meezan and M.A. Cappelli, "Kinetic study of wall collisions in a coaxial Hall discharge", *Phys. Rev. E*, vol. 66, 036401, 2002.

[21]N.B. Meezan, W.A. Hargus, and M.A. Cappelli, "Anomalous electron mobility in a coaxial Hall discharge plasma ", *Phys. Rev. E*, vol. 63, 026410, 2001.

[22]M. Stanojevic, M. Cercek, T. Gyergyek, and N. Jelic, "Interpretation of a planar Langmuir probe current-voltage characteristic in a strong magnetic field", *Contrib. Plasma Phys.*, vol. 34, no. 5, pp. 607-633, 1994.

[23]V. Khayms and M. Martinez-Sanches, in *Micropropulsion for Small Spacecraft, Progress in Astronautics and Aeronautics*,

vol. 187, p. 45, edited by M.M. Micci and A.D. Ketsdever. American Institute of Aeronautics and Astronautics, Reston, VA, 2000.

[24]Y. Raitses and N.J. Fisch, "Parametric investigations of a nonconventional Hall thruster", *Phys.Plasmas*, vol. 8, no. 5, pp. 2579-2586, 2001.

[25]A. Smirnov, Y. Raitses, and N.J. Fisch, "Parametric investigation of miniaturized cylindrical and annular Hall thrusters", *J. Appl. Phys.*, vol. 92, no. 10, pp. 5673-5679, 2002.

[26]A. Smirnov, Y. Raitses, and N.J. Fisch, "Enhanced ionization in the cylindrical Hall thruster", *J. Appl. Phys.*, vol. 94, no. 2, pp. 852-857, 2003.

[27]A. Smirnov, Y. Raitses, and N.J. Fisch, "Plasma measurements in a 100 W cylindrical Hall thruster", *J. Appl. Phys.*, vol. 95, no. 5, pp. 2283-2292, 2004.

[28]A. Smirnov, Y. Raitses, and N.J. Fisch, "Electron cross-field transport in a low power cylindrical Hall thruster", *Phys. Plasmas*, vol. 11, no. 11, 4922-4933, 2004.

[29]A. Smirnov, Y. Raitses, and N.J. Fisch, "The effect of magnetic field on the performance of low-power cylindrical Hall thrusters", IEPC paper 2005-099, to be presented at the 28th International Electric Propulsion Conference, Princeton, NJ, October 2005.

[30]K.A. Polzin, T.E. Markusic, B.J. Stanojev, A. Dehoyos, Y. Raitses, A. Smirnov, and N.J. Fisch,"Performance of a low-power cylindrical Hall thruster", IEPC paper 2005-011, to be presented at the 28th International Electric Propulsion Conference, Princeton, NJ, October 2005.

[31]A. Smirnov, Y. Raitses, and N.J. Fisch, "Electron cross-field transport in a miniaturized cylindrical Hall thruster", submitted to *IEEE Transactions on Plasma Science* in Sept. 2005.

[32]H.R. Kaufman, R.S. Robinson, and R.I. Seddon, "End-Hall ion source", *J. Vac. Sci. Technol. A*, vol. 5, no. 4, pp. 2081-2084, 1987.

[33]Y. Raitses, A. Smirnov, and N.J. Fisch, "Cyindrical Hall thrusters", presented at the 15th Annual NASA/JPL/MSFC Advanced Space Propulsion Workshop, Pasadena, CA, 2004.

[34]E. A. Cubbin, J. K. Ziemer, E. Y. Choueiri, and R. G. Jahn, "Pulsed thrust measurements using laser interferometry", *Rev. Sci. Instrum.*, vol. 68, no. 6, pp. 2339-2346, 1997 .