Performance characteristics according to the channel length and magnetic fields of cylindrical Hall thrusters

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(Received 31 May 2011; accepted 6 September 2011; published online 28 September 2011)

Performance characteristics of low power cylindrical Hall thrusters are investigated in terms of the length of the discharge channel. Thrust, efficiency, discharge current, and propellant utilization are evaluated for different channel lengths of 19, 22, and 25 mm. It is found that the propellant utilization and ion energy distribution function are strongly associated with the channel length. Increase of thrust and efficiency are also found with increasing channel lengths. These characteristics of the thruster are interpreted with possible generation of multi-charged ions due to increased residing time within the extended space inside the channel. © *2011 American Institute of Physics*. [doi:10.1063/1.3643435]

Small size satellites have recently garnered much attention due to their short development time, low cost, and comparable performance compared to large satellites. Interest in small satellites can be further grown if several small satellites can achieve a mission of a large satellite through constellation or formation flying.[1,2] Consequently, the demand for low power electric thrusters, especially Hall thrusters, as essential components of such small satellites will also be expanding.[3,4] Low power Hall thrusters generally have reduced mass and size, consume less electric power, and have lower mass flow rates. However, scaling down of conventional Hall thrusters increases the difficulty in designing the magnetic circuits because the magnetic field must be enhanced in order to maintain electrons magnetized.[5] In addition, the problems, such as large surface-to-volume ratio, center pole heating, etc., lead to lower efficiency compared to conventional kW-class Hall thrusters. Cylindrical Hall thrusters (CHTs) offer smaller surface-to-volume ratio by reducing the inner sections, and recent research has demonstrated comparable performance compared to the annular type Hall thrusters.[6–8]

The channel structure for CHTs is defined by the anode position and the inner section including the dielectric channel and inner core. In CHTs, electrons are confined not only by the $E \times B$ drift but also by the magnetic mirror effect which results from the strong magnetic field in the center of the upstream region.[2] Due to the inner core position, the magnetic field changes with the channel length in a similar fashion as the different magnetic coil current is supplied. This can affect the electron confinement and performance of the thruster. In this paper, the performance of the CHT depending on the channel length and magnetic fields are investigated. The effect of magnetic fields is separately investigated by changing the magnitude of coil currents.

Figure 1 illustrates the structure of the CHT under experiments. The inner and outer diameters of boron nitride channel are 27 and 40 mm, respectively. The experiments were performed for three different channel lengths: 19, 22, and 25 mm, which were allowed by a movable anode. The magnetic field shapes dependent on the channel length simulated by finite element method magnetics are depicted in Fig. 2(a). The inner and outer coil currents were 1.5 A and −1.0 A per turn, respectively, as a reference case, which make the cusp magnetic field configuration. As the channel length L increases, the magnetic field shape becomes different, and the field strength decreases due to the increase of the distance between the iron disk and the inner core. The maximum strength of the radial magnetic field B_r is 420 G for $L = 19$ mm. As shown in Fig. 2, the magnetic fields with different L tend to have similar configurations with different inner coil currents.

A Heatwave HWPES-250 electron source was used as an external cathode/neutralizer. Throughout the experiments, the

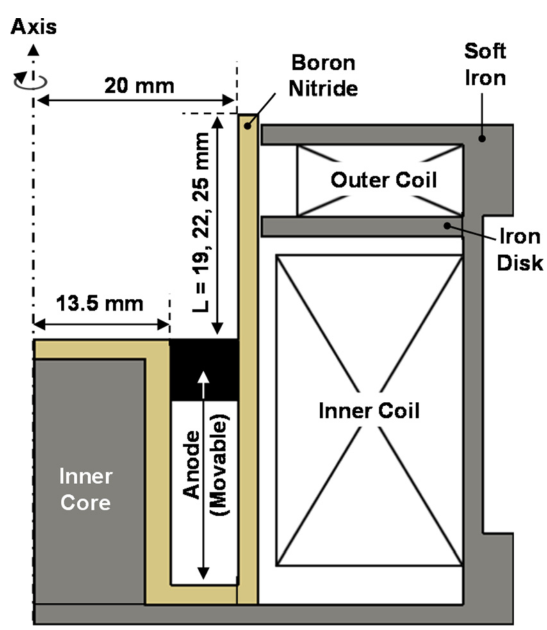

FIG. 1. (Color online) Schematic of the CHT under experiments.

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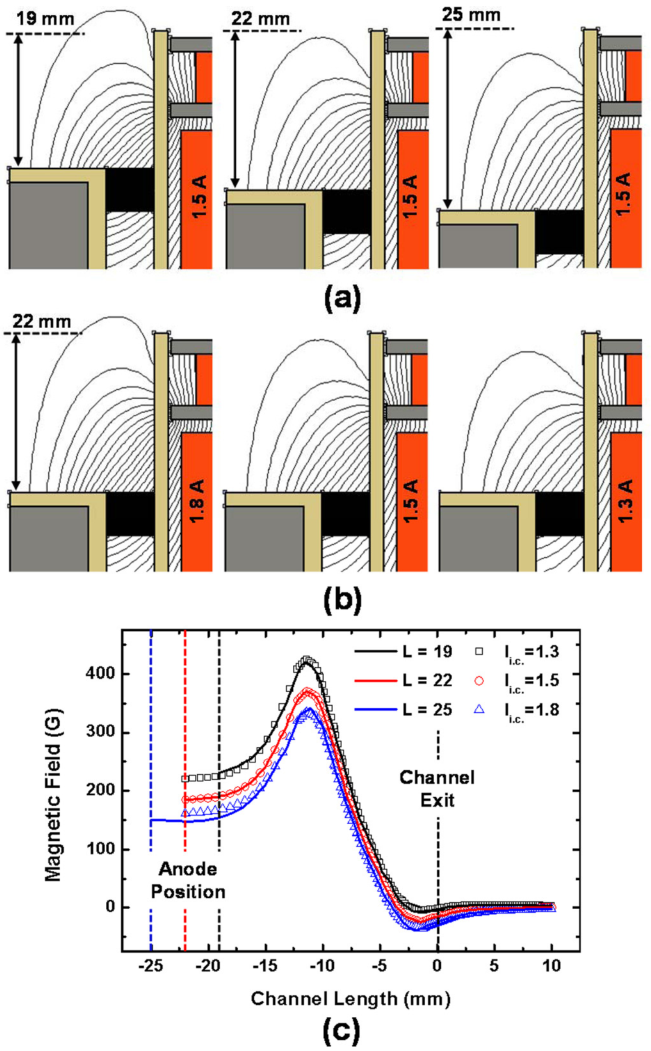

FIG. 2. (Color online) (a) Magnetic field lines of $L = 19$, 22, 25 mm at fixed coil currents (1.5 A inner and 1.0 A outer coils, respectively). (b) Field configurations similar to (a) are produced by having different inner coil currents (1.3, 1.5, 1.8 A, respectively) with a fixed L ($L = 22$ mm). (c) Similarity in the field configurations is seen in the plot of B_r at the outer channel wall surface.

cathode keeper current and Xe flow rate were 1.5 A and 1 sccm, respectively. The anode voltage and Xe flow rate were fixed at 212 V and 4 sccm, respectively. The operating pressure inside the vacuum chamber of 1.9 m long and 1 m in diameter was lower than 5×10^{-5} Torr at a total flow rate of 5 sccm Xe. The thruster was mounted on a pendulum type thrust stand which was placed on two-point knife edge pivots for frictionless swing. The small displacement of the stand induced by the thruster operation was measured by using a laser and a position sensitive detector combination. The calibration was undertaken using the weight and pulley method with several 0.33 g masses as illustrated in Fig. 3. The measurement accuracy was about $\pm$ 0.08 mN.[9] A retarding potential analyzer for measuring ion energy distribution and a Faraday probe for measuring ion current were mounted on the rotary stage which was placed 38 cm from the thruster exit. The total ion current was obtained by integrating the ion current density swept at $\pm 90°$ with respect to the thruster axis. The electron current was determined by subtracting the total ion current from the discharge current.

Figure 4 shows the experimental results obtained for different channel length L. As L was increased from 19 mm to

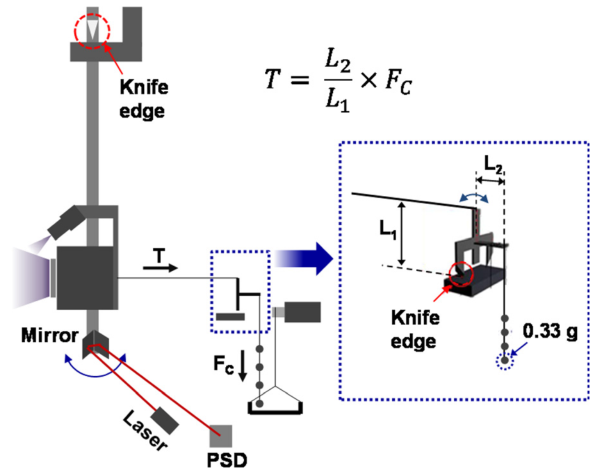

FIG. 3. (Color online) Schematic of the thrust stand.

25 mm, the discharge current I_d increased from 0.529 A to 0.608 A. Among the increment of I_d, the ion current increment was much larger (68%) than the electron current increment [Fig. 4(a)]. As a result, the current utilization U_c ($= I_i/(I_i + I_e)$ where I_i and I_e are the ion and the electron currents, respectively) was maintained as shown in Fig. 4(b). On the other hand, the propellant utilization U_p ($= I_i M/e\mu$ where M, e, μ are the mass of a Xe atom, electron charge, and Xe mass flow rate, respectively) significantly increased from 1.32 to 1.50. Previous works have experimentally[4,7] and numerically[4,10] reported that CHTs show high U_p (>1) due to the multi-charged ions, but not due to the background neutral pressure.[4] The increase of U_P (i.e., increase of I_i) with the larger L may be attributed to the two reasons: longer residing time of slow ions in the extended upstream region and/or enhancement of ionization. First, longer residing time means more generation of multi-charged ions and thus, an increase of I_i. Second, more ionization can also bring about an increase of I_i. If this is the case, I_e should be increased. Figure 4(a), however, shows only the small I_e increment compared to the I_i increment despite the enhanced electron cross field transport as a result of the reduced magnetic field strength. Therefore,

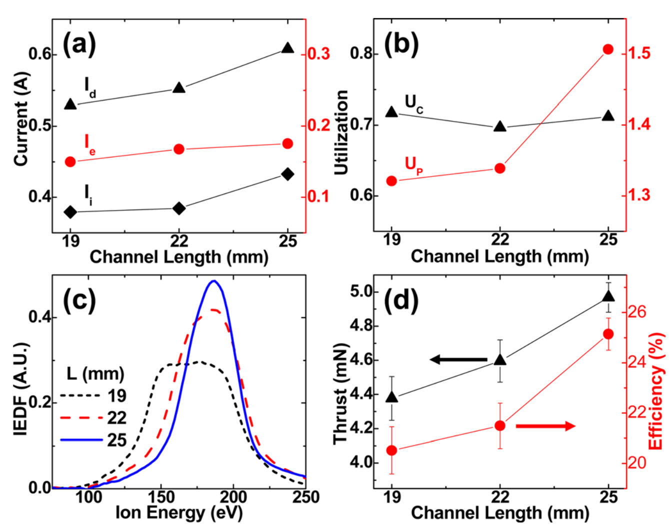

FIG. 4. (Color online) (a) Components of the discharge current, (b) current and propellant utilizations, (c) IEDF, and (d) thrust and efficiency, depending on L.

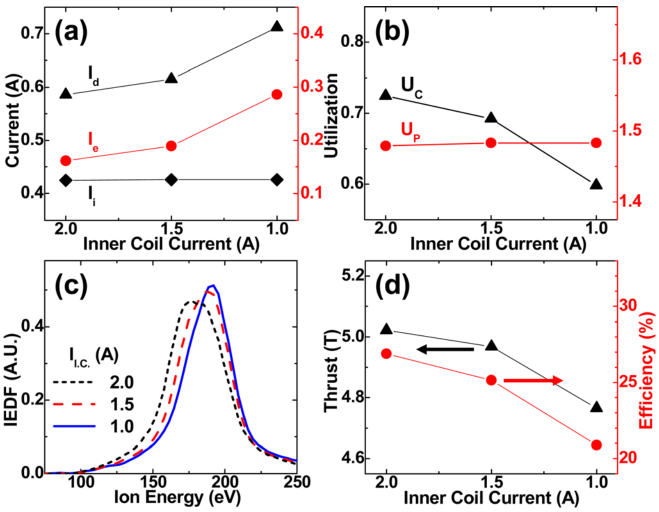

FIG. 5. (Color online) (a) Components of the discharge current, (b) current and propellant utilizations, (c) IEDF, and (d) thrust and efficiency, depending on the inner coil current.

we suggest that the increase of U_P is due to the multi-charged ions from the extended space inside the discharge channel.

Figure 4(c) shows the ion energy distribution function (IEDF) with $L = 19$, 22, 25 mm. The peak and full width at half maximum (FWHM) of the ion energy at the 212 V anode voltage were 176, 185, and 187 eV, and 68, 52, and 39 eV, respectively. The observed decrease of the FWHM and increase of the peak energy, together with an increase in I_i, for larger L could be explained as follow. It is expected that as L is increased in this experiment, a more extended ionization region is formed due to the more space in front of the anode. In this extended ionization region, electrons collide with slow Xe neutrals and ions for higher degree of ionization. Smirnov *et al.*[4] previously suggested the formation of the region where slow ions must move back and forth along the axial direction leading to a longer residing time for multi-charge ionization. Along with the extension of the ionization region, we further suggest that clearer separation of the acceleration region from the ionization region is achieved with a longer channel length. As they move along the axial direction, ions gain most of their energy in the acceleration region where a large electric field occurs, so that the distribution of the ion energy gained in the acceleration region will be narrower as the ionization and acceleration regions are more separated. Therefore, less broadening and higher peak of ion energy in the measured IEDF for the longer channel suggests that such separation indeed takes place within the channel.

In Fig. 4(d), the thrust and efficiency are presented. The efficiency η is defined as $\eta = T^2/2\mu I_d V_a$ where T is the thrust and V_a is the anode voltage. As a result of the increased propellant utilization U_p and ion energy, both T and η increased with an increase in L.

The above experiments demonstrate the effects of channel length combined with those of the magnetic field because field configuration changes with respect to the channel length L. As depicted in Figs. 2(a) and 2(b), similar magnetic field configurations can be reproduced by only changing the inner coil current for a fixed L. An additional experiment was performed to demonstrate the effect of magnetic fields while keeping L the same. The experiments were performed with inner coil currents of 1.0, 1.5, and 2.0 A with $L = 25$ mm. Figure 5 shows the experimental results plotted as the coil current decreases, i.e., B-field decreases. As the magnetic field decreased (similar to the case with increased L), the discharge current increased [Fig. 5(a)]. The increment is mainly due to I_e increase and not by I_i, which is very different from the dependence on L presented in Fig. 4. Therefore, it seems obvious that the effect of magnetic fields only increased I_e, and thus, the discharge current. As a result, U_c decreased and U_p was maintained almost constant [Fig. 5(b)].

Figure 5(c) depicts the measured IEDF. As the coil current was decreased, the ion energy peak shifted to the higher energy and the FWHM decreased slightly. Although this tendency is similar to the dependence of the increment of the channel length, the FWHM difference was about 9 eV, which is much smaller than the results from the channel length dependence (29 eV). This indicates that the magnetic field in the range was not effective in changing the ionization and acceleration regions but rather the channel length strongly affected the IEDF.

The thrust and efficiency are shown in Fig. 5(d). As the coil current was decreased, both T and η decreased. The enhancement of electron cross field transport may be responsible for the decrement of the current utilization and the power to thrust ratio. This result is opposite to the dependence of the channel length, shown in Fig. 4(d). Therefore, these results clearly support our suggestion that the extended ionization region, well separated from the acceleration region, enhances the propellant utilization.

In summary, it was found that longer channels improved the thrust and efficiency, in particular, the propellant utilization. Also, the peak of the ion energy increased and the FWHM of the ion energy distribution became reduced with increasing the channel length. On the other hand, both thrust and efficiency were reduced at the field configuration similar to that with the larger channel length obtained by lowering the coil current, which suggests the limited role of the magnetic field. Our tentative interpretation of these findings is that extension of ionization region has been made where electrons collide with slow Xe neutrals and ions for higher degree of ionization. Clearer separation of the ionization region from the acceleration is also expected from the measurements of ion energy distribution functions.

This work was supported partly by the STSAT-3 Program (Grant No. 2010K000664) and also partly by National Space Laboratory (NSL) (Grant No. 2009-0091569) through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology.

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