Cathode Effects on Operation and Plasma Plume of the Permanent Magnet Cylindrical Hall Thruster

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The use of permanent magnets instead of electromagnet coils can be advantageous for low power Hall thrusters. Previous measurements revealed that the miniaturized cylindrical Hall thruster (CHT) with permanent magnets and electromagnet coils operate rather differently.[1] In particular, the plasma flow from the permanent magnet CHT (CHTpm) has a halo shape with a majority of high energy ions flowing at large angles with respect to the thruster centerline. It was suggested that a strong axial magnetic field outside the permanent magnet CHT causes this unusual shape of the plasma plume. The use of a magnetic shield was shown to restore a conic shape of the plasma flow and to significantly narrow the plume.[2] New result reported in this paper is that when the magnetic field magnitude outside the permanent magnet thruster is sufficiently reduced by the magnetic shield, 1) the cathode placement with respect to the magnetic separatrix and 2) the auxiliary cathode-keeper discharge can affect to some degree the plasma plume of the CHTpm. With the cathode placement at the magnetic separatrix, an additional plume narrowing can be achieved by running the cathode keeper discharge without a significant degradation of the current utilization efficiency. This cathode effect on the plume angle is however not as strong as the effect of the magnetic shield.

I. Introduction

FOR Hall thrusters, the use of permanent magnets instead of electromagnet coils can offer a significant reduction of both the total electric power consumption and the thruster mass. These advantageous are particularly important for miniaturized low power Hall thrusters. Cylindrical geometry Hall thrusters[3,4] have lower surface-to-volume ratio than conventional annular Hall thrusters and, thus, seem to be more promising for scaling down to operate at low power levels. Two permanent magnet versions of the miniaturized cylindrical Hall thruster (CHT) of different overall dimensions were operated in the power range of 50W-300 W.[1,2,5,6] The discharge and plasma plume measurements revealed that the CHT with permanent magnets (CHTpm) and electromagnet coils (CHTem) operate rather differently. In particular, the angular ion current density distribution from the permanent magnet thrusters has an unusual halo shape, with a majority of high energy ions flowing at large angles with respect to the thruster centerline. The defocusing of energetic ions could explain lower efficiencies measured for the CHT with permanent magnets as compared to the electromagnet CHT.[1,6]

In recent studies,[2] we demonstrated that the differences in the plume and performance characteristics between the cylindrical thrusters with electromagnet coils and permanent magnets are associated mainly with a stronger axial magnetic field outside the channel of the thruster with permanent magnets. For the permanent magnet thrusters, this outside magnetic field connects naturally to the location of the magnetic separatrix with respect to the thruster channel exit. By adding the magnetic shield to the magnetic circuit of the CHTpm, the magnitude of the outside magnetic field reduces significantly, while the magnetic separatrix moves outside the thruster channel.[2] It was shown that the CHTpm with the magnetic shield produces the plasma plume of a conic shape and can operate with significantly narrower plasma plume than the CHTpm without the magnetic shield and even more traditional CHTs with electromagnet coils.

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In this paper, we describe the effect of the cathode placement and cathode keeper discharge on the discharge and plume characteristics of the CHTpm thrusters with and without magnetic shield. These results point to the existence of an optimal cathode placement with respect to the thruster with the magnetic shield. In particular, when the cathode is placed closer to the magnetic separatrix, the thruster operation is overall more efficient in terms of the ion performance and plasma plume than the thruster configurations with the cathode placement further away from the separatrix. This effect of the cathode placement may be also relevant to other types of Hall thrusters with magnetic separatrix outside the thruster channel, including cylindrical geometry thrusters with permanent magnets such as HEMP[7] and DCF[8]. In fact, the critical role of the magnetic separatrix for these non-conventional Hall thrusters was suggested in Refs. 9 and 10. These works predicted the link between the last magnetic separatrix (the closest to the thruster exit) and the formation of the ionization and acceleration region in the DSF and HEMP thrusters. The present work suggests that only when the magnetic field outside the permanent magnet thruster is reduced by the magnetic shield, the cathode placement with respect to the magnetic separatrix can affect the thruster operation and the plasma plume. Although these cathode effects are not as strong as the effect of the magnetic shield, they can be useful for a fine tuning of the thruster operation.

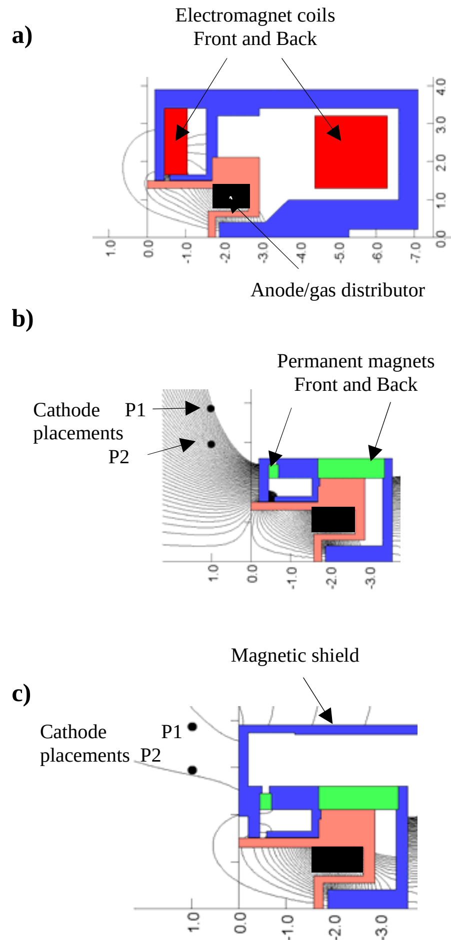


Figure 1. Magnetic field (simulations) for the direct configurations of the 2.6 cm diameter CHT with electromagnets, B_{zmax} = 1.86 kGauss at the axis on the back wall (a), and with permanent magnets without the magnetic shield, B_{zmax} = 2.5 kGauss, (b) and with the magnetic shield, B_{zmax} = 1.76 kGauss. All dimensions are in cm. Magnetic iron parts are marked in blue. Two cathode placements, P1 and P2 used in CHTpm experiments are also shown.

II. Thruster design and experimental setup

A typical CHT (Fig. 1) consists of a cylindrical ceramic channel, a ring-shaped anode, which serves also as a gas-distributor, a magnetic core made from a low carbon steel, and electromagnet coils (Fig. 1a) or permanent magnets (Figs. 1b and 1c). In the present experiments, we use the 2.6 cm diameter CHT with permanent magnets. The main design considerations of this thruster were described in detail in Refs. 1, 2 and 5. The CHTpm has two axially magnetized permanent magnet rings made from a cobalt-samarium alloy (Figs. 1b and 1c). In order to implement the direct (enhanced mirror) configuration of the CHTpm both permanent magnet rings were placed with the same polarity. The magnetic field generated by a the ring shaped magnet being different than the one of a coil, the similarities between the magnetic field distributions produced with permanent magnets and electromagnets can only be reproduced inside the thruster channel. Outside the thruster channel, the magnetic circuit with the permanent magnets produces a different magnetic field topology. In particular, even in the direct configuration, the CHTpm has a cusped magnetic field near the channel exit (Fig. 1b). Moreover, the magnetic field outside the permanent magnet CHT thruster is much stronger than the magnetic field outside the CHT with the electromagnet coils (Fig. 2).

The above differences between the CHTem and CHTpm are due to the differences in the magnetic field produced by a current-carrying coil and an axially magnetized permanent magnet ring.[2] The use of magnetic shield can alter the magnetic field outside the magnetic circuit (Fig. 1c). In fact, for the CHTpm, it allows to significantly reduce the magnetic field outside the magnetic circuit (Fig. 2).

The 2.6 cm diam. CHTpm was operated with and without magnetic screen in the large PPPL Hall Thruster facility.[11] Xenon gas was used in all experiments. The background pressure in a 28 m^3 vacuum vessel equipped with cryopumps did not exceed 3 μtorr. A commercial Heatwave 250 model hollow cathode electron source was used as the cathode-neutralizer. The cathode was placed on a motorized X-Y table in order to change its placement with respect to the thruster axis. The cathode gas flow rate was held constant, 2 sccm. The cathode keeper electrode was used to initiate and maintain the auxiliary cathode-keeper discharge, and to supply electrons for the initiation of the main discharge between the cathode and the thruster anode. In addition, the auxiliary cathode discharge (keeper current of 0.5 A) was also used to maintain the low current operation (less than 1 A) of the 50-200 W CHTem and CHTpm thrusters. In previous experiments with electromagnet CHTs, this keeper current was enough to maintain a stable cathode operation, but not to achieve the current-overrun regime. The latter is characterized by a strong cathode effect on the plasma plume. This regime was usually achieved at the keeper current of larger than 1 A.[2,4,12,13,14]

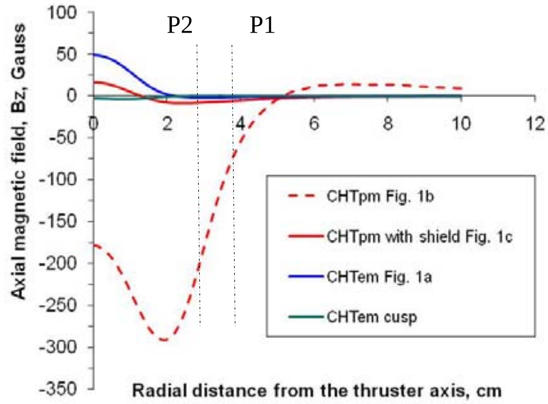
In the experiments with electromagnet CHT, the cathode placement with the respect to the thruster was fixed. The cathode outlet orifice was located approximately 5.4 cm away radially and 2.0 cm downstream from the center of the channel exit. For the CHTpm thrusters, we measured the thruster and plume characteristics for various cathode placements. In this work, we compare results obtained for two cathode placements, P1 and P2 (Figs. 1 and 2) and CHTpm operation with the keeper current of 0.5 A and 2.5 A.

The plasma plume diagnostics used in these experiments included a 2.54 cm diam. planar plume probe with guarding ring for measurements of the angular ion flux distribution in the plume.[9] The plume probe is suspended on the rotating platform. The distance between the thruster and the planar plume probe was 73 cm.

III. Experimental results and discussions

Table 1 summurizes the discharge and plume parameters measured for the 2.6 cm CHTem and CHTpm thrusters. These thrusters were operated at the discharge voltage of 250 V and xenon anode gas flow rate of 3.5 sccm. For the CHTpm thrusters, the results are shown for two cathode placements with respect to the channel axis in the radial direction, P1 and P2 (Fig. 1 and 2). We selected these radial placements for two partiuclar reasons: 1) P1 was used to start up the CHTpm without the shield. For farther radial placements, the CHTpm discharge was not easy to ignite. 2) For the CHTpm with the magnetic shield, the discharge current changes with the cathode radial placment. It reaches the minimum value at the P2 placement.

a)



b)

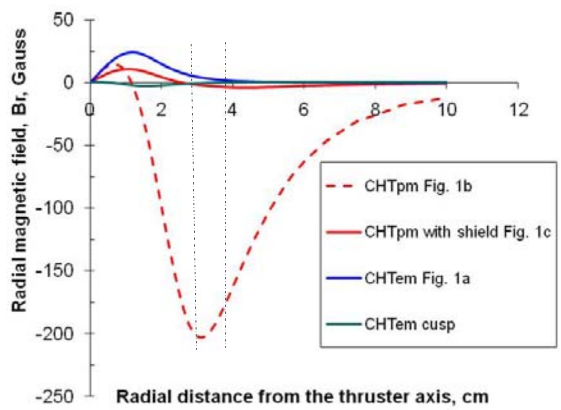


Figure 2. Simulation results of the magnetic field distribution (axial and radial components) in the radial direction at about 1.0 cm from the exit of the 2.6 cm diameter channel of the cylindrical thruster configurations (corresponding to the distance between the cathode orifice and the channel exit in the axial direction) shown in Fig. 1: CHTem and CHTpm with and without magnetic shield. Two cathode placements, P1 and P2 are shown with vertical dashed-dot lines. The channel outer wall is at R ≈ 1. 5 cm.

Fig. 3 compares the angluar ion current density distribution measured for the CHTpm with and without the magnetic shield at two different cathode placements, P1 and P2. It was already reported in our previous works[2] that one of the most striking effects of the magnetic shield is on the shape of the plume (Fig. 3a). For both cathode placements, P1 and P2, the use of the magnetic shield leads to a dramatic change of the plume shape: from a halo-type – typical shape for the CHTpm without the shield – to a conic shape. The plume of the magnetically shielded CHT is always narrower than the plume of the CHTpm without the shield. For both cathode placements of the shielded thruster, the cathode keeper discharge affects an additional plume narrowing. Furthermore, with the keeper current of 2A and higher, the plume of the CHTpm with the shield can be even narrower than the plume of the CHTem in the current overrun regime (CO) (Fig. 3b). Without the magnetic shield, the variation of the cathode placement has insignificant effect on the CHTpm operation (Table 1) and the plume from this thruster (Fig. 3a).

We shall now focus on the effect of the cathode placement on the discharge current for the CHTpm with the magnetic shield. When the cathode is placed further away from the channel (e. g. at the P1 placement), the increase of the cathode keeper current affects the reduction of the discharge current (Table 1). This is different from the thruster configuration with the cathode at the P2 placement. At this cathode placement, the keeper discharge causes an insignificant increase of the discharge current. When the cathode was moved closer to the thruster axis than the P2 placement, the increase of the discharge current with the keeper current was even stronger. For example, at the cathode placement about 1 cm below the P2 placement, the discharge current increased from 0.71 A to about 0.77 A as the keeper current was varied from 0.5 A to 2.5 A. Because the propellant utilization was almost unaffected by changes of the cathode placement, the increase of the discharge current led to the degradation of the current utilization efficiency at this cathode placement.

Although for the cathode placement P2, the cathode keeper discharge affects the reduction of the plume angle, the increase of the discharge current with the keeper current causes the reduction of the current utilization efficiency (Table 1). This is not the case for the cathode at the P1 placement. Here, the current utilization increases with the keeper discharge to the same level as for the cathode at the P2 placement without the keeper discharge. Thus, the current utilization efficiency can be affected by the cathode placement and the cathode operating mode. The latter likely determines properties of the electron flow supplied from the cathode (e.g. energy distribution function of the cathode electrons).

Note that for the P1 placement, the cathode effect on the magnetically shielded CHTpm is similar to the cathode effect on the CHTem with the cusp magnetic configuration.[10] In contrast, for the cathode placements at the P2 and below, the cathode effect of the magnetically shielded CHTpm is similar to the current overrun regime of the CHT with the direct configuration of the electromagnet coils (mirror-type magnetic field configuration).[4,10] This interesting dependence on the cathode placement may be attributed to the magnetic field topology outside the CHTpm with the magnetic shield (Fig. 1). With the cathode at the P1 placement, the electrons from the cathode are injected into the magnetic field configuration of the CHTpm, which replicates the cusp configuration of the CHT with electromagnet coils.[10] When the cathode is placed closer to the thruster axis than the P2 placement, the cathode electrons are injected into the magnetic field configuration (Fig. 1c), which is similar to the direct configuration of the CHTem (Fig. 1a). For the P2 placement, the electron injection is near the magnetic separatrix (Fig. 1c). This seems to be an optimal cathode placement because for current-overrun operation, the degradation of the current utilization efficiency is insignificant, while the plume angle is the smallest (Table 1).

Table 1: A comparison of the discharge and plume characteristics of the 2.6 cm diam. cylindrical Hall thrusters with electromagnet coils and permanent magnets at the discharge voltage of 250 V, anode (Xe) gas glow rate of 3.4 sccm and cathode gas flow rate of 2 sccm. The cathode position was different for different thrusters (See explanation in Fig. 5).

Thruster	Discharge current, A	Keeper current A	Current ratio, Ii/Id	Propellant utilization	Half plume angle, deg
CHT elmg. coil	0.57	0	0.73	1.3	74
CHT elmg. Coil CO	0.65	3	0.71	1.43	55
CHTpm P1	0.44	0.5	0.72	1.27	76
CHTpm P1 CO	0.44	2.0	0.71	1.25	77
CHTpm P2	0.47	0.5	0.7	1.3	75.5
CHTpm P2 CO	0.46	2.0	0.7	1.3	75.5
CHTpm shield P1	0.7	0.5	0.57	1.6	62.17
CHTpm shield P1 CO	0.61	2.5	0.65	1.6	57
CHTpm shield P2	**0.62**	**0.5**	**0.65**	**1.60**	**58.5**
CHTpm shield P2 CO	**0.64**	**2.5**	**0.63**	**1.60**	**54**

a) b)

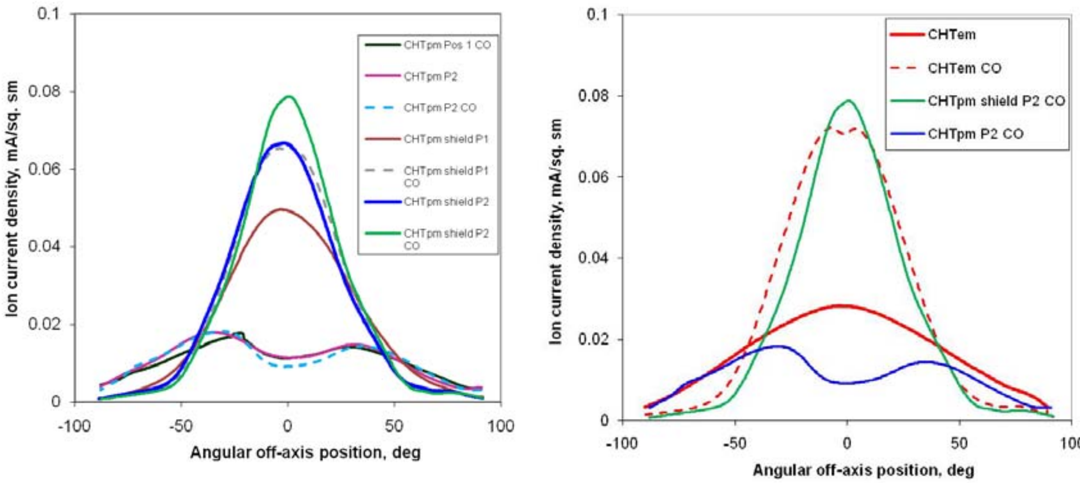


Figure 3. Angular ion current density distribution measured for different CHT thrusters: a) the effect of the magnetic shield, cathode placement (P1 and P2 positions) and the cathode-keeper discharge (current overrun, (CO)) for the permanent magnet CHT thrusters; b) a comparison of the plume for CHTpm and CHT with electromagnet coils (CHTem) of the magnetic mirror-type (direct) configuration. All thrusters were operated at the discharge voltage of 250 V and Xenon gas flow rate of 3.5 sccm. The cathode placements P1 and P2 are shown in Figs. 1 and 2. For the CHTem thrusters, the cathode placement was different: the cathode outlet orifice was located approximately 5.4 cm away radially and 2 cm downstream from the center of the channel exit.[14]

III. Concluding remarks

For permanent magnet CHT thrusters, a strong axial magnetic field outside the thruster connects naturally to the location of the magnetic separatrix with respect to the channel exit. It is additionally confirmed in this work that the strength of the outside magnetic field is a key factor responsible for the halo shape of the plasma plume observed for the permanent magnet CHT. The use of a magnetic shield, which drastically reduces the outside magnetic field, allows 1) to restore a conic shape of the plasma flow and 2) to substantially narrow the plasma plume. When the outside magnetic field is sufficiently reduced, the cathode placement and the auxiliary cathode- keeper discharge can also affect to some degree the plasma plume narrowing. In particular, it is shown that for the magnetically shielded CHTpm, the cathode effects on the current of the main thruster discharge and the current utilization efficiency depend on the cathode placement with respect to the magnetic separatrix. The thruster operates more efficient when the cathode is placed near the magnetic separatrix. Its ion performance parameters and plume are comparable with the CHTem operating in the current-overrun regime. Without the magnetic shield, the magnetic separatrix is located deeper inside the thruster channel. A strong magnetic field outside the CHTpm significantly reduces the dependence of the thruster operation on the cathode auxiliary discharge and the cathode placement with respect to the thruster axis in the radial direction. This is because a strong axial magnetic field outside the CHTpm impedes the electron flow from the cathode to the thruster.

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