46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit
25 - 28 July 2010, Nashville, TN

AIAA 2010-6621

Effect of the Magnetic Field on the Plasma Plume of the Cylindrical Hall Thruster with Permanent Magnets

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A low power miniaturized cylindrical Hall thruster with permanent magnets (CHTpm) was operated with and without the magnetic shield. The magnetic field outside the thruster channel is shown to play a critical role in the formation of an unusual halo shape of the plasma flow from CHTpm without the magnetic shield. It is suggested that this result is applicable for other types of permanent magnet cylindrical thrusters, including diverge-cusp field (DCF) and HEMP thrusters. For the CHTpm, the use of a magnetic shield allows to restore a conic shape of the plasma plume, which is typical for conventional annular Hall thrusters and cylindrical Hall thrusters with electromagnets, and to reduce the plasma plume divergence.

I. Introduction

The principle of operation of the cylindrical Hall thruster (CHT)[1] is based on a closed E×B electron drift and electrostatic acceleration of non-magnetized ions in quasineutral plasma in a hybrid magneto-electrostatic trap. The magnetic field configuration of the CHT can be cusp-type and magnetic mirror-type. Comprehensive studies of the CHT with electromagnet coils are reported elsewhere.[2] It was found that for the miniaturized 100-200 W-class CHTs (Fig. 1), the optimal magnetic field configuration is an enhanced mirror-type (the so-called direct configuration with the co-direct currents in both electromagnet coils). The highest performance parameters of this thruster were achieved when the maximum magnetic field at the mirror was ~ 1.5-2 kGauss. In these regimes, the electromagnet coils consumed 50-100 W. For the low power thruster, this additional power consumption reduces drastically the overall thruster efficiency. 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.

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.[3,4] The discharge and plasma plume measurements revealed that the CHT with permanent magnets and electromagnet coils 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.[5] In this paper, it is shown that these differences in the plume and performance characteristics between the cylindrical thrusters with electromagnet coils and permanent magnets are associated with a stronger axial magnetic field outside the channel of the thruster with permanent magnets. .

II. Design considerations

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 or permanent magnets.[6,7] Fig. 2 compares results of simulations of the magnetic field for the 2.6 cm outer channel diameter CHT thrusters with electromagnets and permanent magnets.[4] The CHT with permanent magnets (CHTpm) uses two axially magnetized permanent magnet rings made from a cobalt-samarium alloy. These magnet rings are incorporated into the thruster magnetic circuit as shown in Fig. 2b. In order to implement the direct (enhanced mirror) configuration of the CHT both permanent magnet rings are placed with the same polarity. According to magnetic field simulations and measurements, a similarity between the magnetic field distributions produced with permanent magnets and electromagnets exists only inside the thruster channel. However, in the vicinity of the channel exit and outside the

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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. 2b). Moreover, the magnetic field outside the permanent magnet thruster is much stronger magnetic field than outside the CHT with the electromagnet coils (Figs. 2, 3).

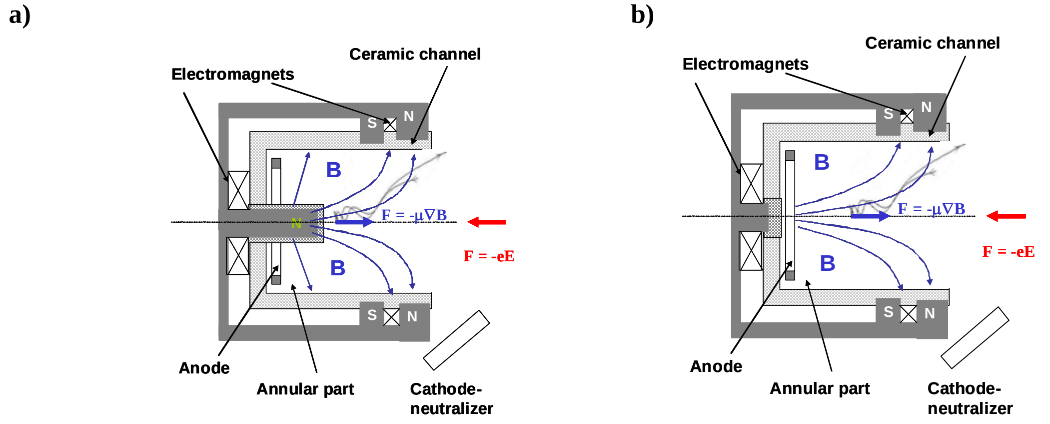

Figure 1. Schematic of a cylindrical Hall thruster (CHT) with (a) and without (b) a short annular part. The thruster can use electromagnet coils or permanent magnets to form direct (enhanced mirror) or cusp magnetic field configurations.

The above differences between the CHT and CHTpm are due to the differences in the magnetic field produced by a current-carrying coil and an axially magnetized permanent magnet ring (Fig. 4). With a uniform magnetization, the magnetic field produced by a magnetized object is equal to the field produced by the bound surface currents.[8] Therefore, the magnetic field produced by a ring-shaped permanent magnet (Fig. 4b) can be approximated by two concentric current-carrying coils of an opposite polarity (Fig. 4c). When the axially magnetized permanent magnet ring is placed in the magnetic circuit, it produces a very different path of the magnetic flux than the electromagnet coil (Figs. 2a and 2b). The use of magnetic shield can significantly alter the magnetic field outside the magnetic circuit (Fig. 2c). In fact, for the CHTpm, it allows to significantly reduce the magnetic field outside the magnetic circuit (Fig. 3). The optimization of the magnetic shield for the CHTpm will be described in a separate paper.

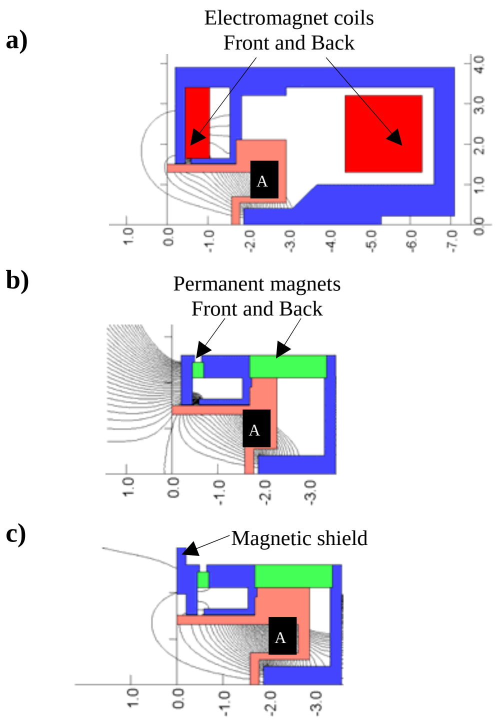

Figure 2. Magnetic field (simulations) for the direct configurations of the 2.6 cm diameter CHT with electromagnet coils, B_{zmax} = 1.86 kGauss at the axis on the back wall (a), and with permanent magnets without the magnetic shield (and without a short annular part) B_{zmax} = 2.55 kGauss (b) and with the magnetic shield (only a part of the shield is shown) B_{zmax} = 1.76 kGauss. The shield design will be discussed in a separate paper. All dimensions are in cm. Magnetic iron parts are marked in blue.

III. Experimental setup

The 2.6 cm diam. CHTpm was operated with and without magnetic screen in the large PPPL Hall Thruster facility.[9] 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.

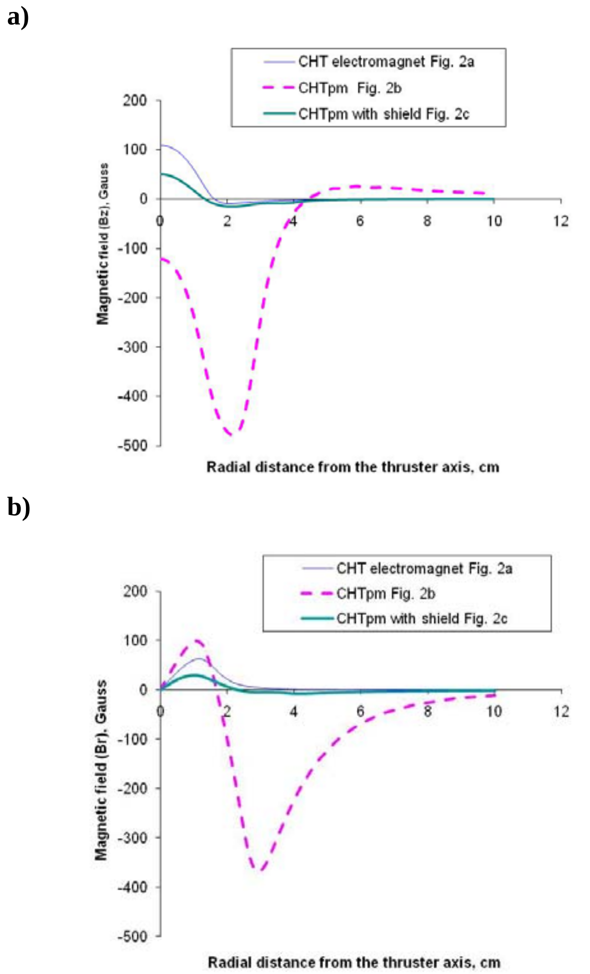

Figure 3. Simulation results of the magnetic field distribution (axial and radial components) in the radial direction at 0.4 cm from the exit of the 2.6 cm diameter channel of the cylindrical thruster configurations shown in Fig. 2: CHT with electromagnet coils, and CHTpm with and without magnetic shield.

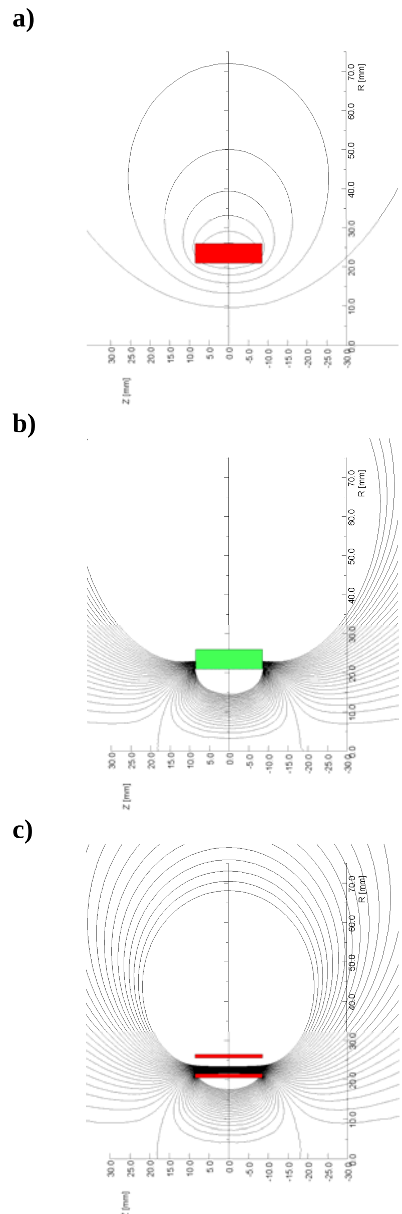

Figure 4. Magnetic field for an electromagnet coil (a), axially magnetized permanent magnet ring (b) and a set of two concentric current-carrying coils of an opposite polarity (c), which emulates roughly the magnetic field produced by the permanent magnet ring.

The cathode keeper electrode was used to initiate the main discharge between the cathode and the thruster anode, and to maintain the discharge current. The keeper current was 0.5 A during the thruster operation.

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] and a 5 cm diam. bi-directional probe for measurements of the direct ion flux from the thruster and the back ion flux from the background plasma.[10] Both probes are suspended on the rotating platform. The distance between the thruster and the planar plume probe was 73 cm.

IV. Experimental results

A detailed comparison between the discharge and plume characteristics of the CHTpm and CHT with electromagnets is described in Refs. 3 and 4. The most curious difference between the CHTpm and the CHT thrusters with electromagnet coils is in the shape of their plumes (Fig. 5). In particular, for the direct configurations, the CHTpm thrusters produce a halo plume with larger ion flux at larger angles with respect to the axis than at the centerline: ~ 30-40°. This shape can change, but still exists at different cathode placements. However, with the addition of the magnetic shield, the plume acquires a conical shape, which is typical for Hall thrusters.

Table 1 compares discharge and plume parameters of the 2.6 cm cylindrical thrusters with electromagnets and permanent magnets, including with without magnetic shield for the same operating conditions, namely, discharge voltage of 250 V and anode gas flow rate of 4 sccm. Apparently, the CHTpm with the magnet shield is capable to produce a significantly narrower plasma plume than the CHTpm without the magnetic shield. Furthermore, the utilization efficiencies and the plume angle measured for the CHTpm with the magnetic shield are comparable to those obtained for high performance current overrun regime of the CHT with electromagnets.[11] In Ref. 11, this regime was achieved by running a relatively high current (~2-3 A) 50 W auxiliary cathode-keeper discharge. For the CHTpm, the cathode-keeper discharge helped to sustain a stable operation of an aged cathode used in the present experiments. However, for that purpose the keeper current of 0.5 A was sufficient and therefore, the additional power consumed by this auxiliary cathode-keeper discharge was less than 10 W.

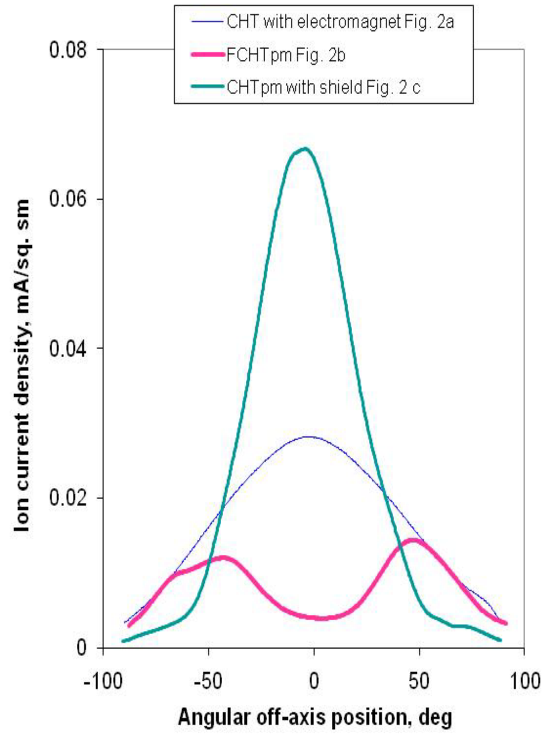

Figure 5. Ion current density distribution for the CHTs with electromagnet coils and permanent magnets with and without magnetic shield. The cathode position was different for different thrusters, but always within the same region: about 1 cm, radially from the channel exit and 3-4 cm from the thruster axis. The effect of the cathode position in the CHTpm will be discussed in a separate paper.

IV. Concluding remarks

The presented results support our previous suggestion that for the CHTpm without magnetic shield, the outside electric and magnetic fields play a critical role in the formation of the plasma flow and, thereby, the thrust generation. Furthermore, similarities between the magnetic field outside the channel and the plume shape measured in the CHTpm without magnetic shield, DCF[12] and HEMP[13,14] suggest that all these three thruster types operate in a similar way. However, even with the magnetic shield, the electron confinement appears to be more effective in the CHT with electromagnets and multi-cusp configurations than in the CHTpm (Table 1). This may explain generally lower anode efficiency measured for this permanent magnet thruster as compared to the CHT with electromagnets.[15] Finally, in view of the above results for the CHTpm, a key fundamental question is to what extent the magnetic field lines are equipotential in the thrusters with permanent magnets. For CHT with electromagnets, results of Ref. 16 provide an initial insight to this problem. In particular, it shows that equipotential lines significantly deviate from the magnetic field lines in the very near field plasma plume region between the thruster exit and the cathode.

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	0.65	3	0.71	1.43	55
CHTpm	0.39	0.5	0.56	0.77	82
CHTpm shield	0.62	0.5	0.65	1.63	58
CHTpm shield	0.64	2.5	0.63	1.63	54

Acknowledgments

The authors wish to thank Prof. Michael Keidar of the George Washington University, Dr. Kurt Polzin of NASA Marshall SFC, Drs. Slava Spektor and Kevin Diamant of the Aerospace Corporation, Drs. Konstantin Matyash and Ralf Schneider of Max Plank Institute of Plasma Physics, Germany, and Prof. Amnon Fruchtman, of Holon Institute of Technology, Israel, for fruitful discussions. This work was supported by the AFOSR.

References

[1] Y. Raitses, Y., and N. J. Fisch, "Parametric Investigations of a Nonconventional Hall Thruster," Phys. Plasmas, Vol. 8, No. 5, May 2001, pp. 2579-2586.

[2] A. Smirnov, Y. Raitses, and N. J. Fisch, "Experimental and theoretical studies of cylindrical Hall thrusters", Phys. Plasmas 14, 057106 (2007).

[3] Y. Raitses, E. Merino, J. B. Parker and N. J. Fisch, "Operation and Plume Measurements of Miniaturized Cylindrical Hall Thrusters with Permanent Magnets", in the proceedings of the 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, August 2008, Denver, CO, AIAA paper 2009-4810.

[4] Y. Raitses, E. Merino, J. B. Parker and N. J. Fisch, " Cylindrical Hall thrusters with permanent magnets" submitted to Journal of Applied Physics (2010).

[5] K. A. Polzin, E. S. Sooby, A. C. Kimberlin, Y. Raitses, E. Merino, and N. J. Fisch "Performance of a Permanent-Magnet Cylindrical Hall-Effect Thruster" 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Denver, CO, Aug. 3–5, 2009, AIAA-2009-4812.

[6] A. Smirnov, Y. Raitses, and N. J. Fisch, J. Appl. Phys. **92**, 5673 (2002).

[7] Y. Raitses and N. J. Fisch, "Cylindrical Geometry Hall Thruster," US Patent No.: 6,448,721 B2, September 2002; Raitses, Y., Fisch, N.J., Ertmer, K.M., and Burlingame, C.A., "A Study of Cylindrical Hall Thruster for Low Power Space Applications,", 36th Joint Propulsion Conference, Huntsville, AL, July 2000, AIAA paper 2000-3421.

[8] D. J. Griffiths, Introduction to Electrodynamics, 3rd ed. Englewood Cliffs, NJ: Prentice-Hall, 1998.

[9] Y. Raitses, D. Staack, A. Dunaevsky, L. Dorf and N. J. Fisch, "Measurements of Plasma Flow in a 2 kW Segmented Electrode Hall Thruster", in the proceedings of the 28th International Electric Propulsion Conference, Toulouse, France, March 2003, IEPC paper 03-0139.

[10] Y. Raitses, T. Moeller, J. Szabo, "AEDC plume measurements using bi-directional ion flux probes", in the proceedings of the 30th International Electric Propulsion Conference , Florence, Italy, September 2007, IEPC paper 2007-334.

[11] Y. Raitses, A. Smirnov, and N. J. Fisch, "Effects of enhanced cathode electron emission on Hall thruster operation", Phys. Plasmas 16 057106 (2009).

[12] D. G. Courtney, P. Lozanoy, and M. Martinez-Sanchez., "Continued Investigation of Diverging Cusped Field Thruster", 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, July 2008, Hartford, CT, AIAA paper 2008-4631.

[13] N. Koch, H. –P. Harmann, G. Kornfeld " Development and test status of the THALES high efficiency multistage plasma (HEMP) thruster family" Proceedings of the 29th International Electric Propulsion Conference, Princeton, NJ, October 2005, IEPC paper 2005-297.

[14] K. Matyash, R. Schneider, A. Mutzke, O. Kalentev, F. Taccogna, N. Koch, and M. Schirra, "Self consistent kinetic simulations of SPT and HEMP thrusters including the near-field plume region", to be published in IEEE Trans. Plasma Sci. (2010).

[15] K. A. Polzin, Y. Raitses, J-C Gayoso and N. J. Fisch, "Comparisons in Performance of Electromagnet and Permanent-Magnet Cylindrical Hall-Effect Thrusters" in the proceedings of the 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, July 2010, Nashville, TN, AIAA paper-2010-6695.

[16] R. Spektor, K. D. Diamant, E. J. Beiting, Y. Raitses and N. J. Fisch, "LIF Measurements of the Cylindrical Hall Thruster Plume", in the proceedings of the 31st International Electric Propulsion Conference, September 2009, Ann Arbor, MI, IEPC paper 2009-137.