The Effects of Magnetic Field in Plume Region on the Performance of Multi-cusped Field Thruster

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Abstract: The performance characteristics of a multi-cusped field thruster depending on the magnetic field in the plume region were investigated. Five magnetic field shielding rings mounted near the exit of discharge channel are designed to decrease the strength of magnetic field in the plume region. The results show that magnetic field strength in the plume region plays a critical role to the performance of the multi-cusped field thruster. Weaker confinement of electrons in the plume region can increase the electron current, which can both lead to a higher propellant utilization and lower current utilization. Besides, the results also indicate that there are similar effects between the magnetic field strength in the plume region and discharge voltage on the mode transitions, and it seems to be a reasonable explanation for the totally opposite trends of anode efficiency with magnetic field strength in the plume region in different anode voltage conditions.

Nomenclature

HEMP	=	High Efficiency Multistage Plasma Thruster
DCFT	=	Diverging Cusped Field Thruster
e	=	fundamental charge
I_d	=	discharge current
I_i	=	Ion current
I_e	=	electron current
M	=	the atom mass of Xe
η_p	=	propellant utilization
η_c	=	current utilization
η_a	=	anode efficiency

I. Introduction

The multi-cusped field thruster is a novel concept in electric propulsion[1-3], which employs alternating polarity permanent magnets to create periodic magnetic field with a set of axial and para-radial cusps which serve as the dominant electron confinement to enhance the propellant ionization and to protect the electrically insulating walls of the discharge chamber. Therefore, the lifetime of the thruster is prolonged obviously compared with other types of electric thrusters, and this magnetic field configuration is commonly occurred in different type of thrusters, such as the Thales's HEMPT[4], MIT's DCFT[5] and Stanford's DCF[6]. There is an unusual halo shape plume with a majority of

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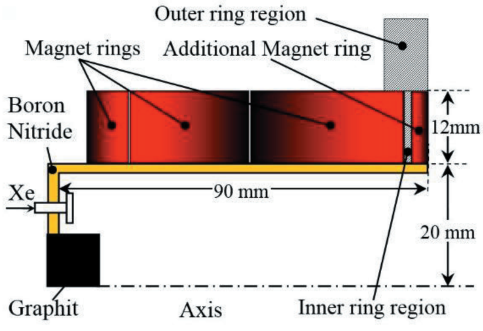
high energy ions flowing at large angles with respect to the thruster centerline, and the unique beam profile reflects the inner fundamental physics from an aspect, for there is a considerable potential drop and a noticeable separation between the ionization and acceleration region is formed spatially. Researchers in various agencies have been committed to the theoretical and experimental research on the relationship between the magnetic field and diverging plume. The Thales reduced the divergence angle of HEMPT effectively through optimizations of various specifications, but the method for the change was not discussed explicitly in their literature[7]. From 2010 to 2011, Taylor Scott Matlock *et al*. tried to change the conical plume shape of DCFT through the addition of magnetic shield and positing electromagnet[8]. Besides, the experiment results suggested that the highly divergent ion current profile was also exhibited in the Princeton's CHTpm, and the plume shape can be optimized by the magnetic shielding rings[9]. At the same time, the study on the discharge characteristics also become a hotspot. Daniel G. Courtney et al. found two modes of operation with a clear transition manifested by a sharp drop of anode current and the hollow plume with distinct edges occurred as the anode potential was increased[5]. Further studies have found that the HC mode exhibited higher utilization efficiency but the beam efficiency was well maintained[10]. Besides, the laser-induced fluorescence velocity measurements were introduced to compare the structure of the acceleration region in these two operation modes[11,12].

The present research status have shown that the magnetic field in the plume region plays a key role in the performance of multi-cusped field thrusters and the characteristics of operation. Besides, its significant effects on the mode transitions are clearly reflected in the differences of plume geometries. On those aspects, no systematic research has been conducted so far. In this paper, the relationship between magnetic field in the plume region and the characteristics of multi-cusped field thruster are studied. Five unique magnetic field shielding rings are designed to decrease the magnetic field in the plume region while the magnetic field in the discharge channel are well maintained. The paper is organized as follows. In the second part, the relevant design aspects of the thruster and magnetic field shielding rings are induced along with the experimental conditions and diagnostic devices. And the experimental results are presented and discussed in the third part, and this part contains three contents: the change trends of discharge characteristics with the magnetic field strength in the plume region, the effects of magnetic field strength in the plume region on the mode transitions and the changes of anode efficiency with magnetic field strength in the plume region in different anode voltage conditions. Finally, the conclusions are made in the last part.

II. Experimental setup

The thruster used in our experiment is shown in Figure 1(a), the length and diameter of boron nitride channel are 90 and 35mm respectively. The thickness of each permanent magnet rings are 10, 30 and 38mm. The regions with black slant lines were designed to mount the magnetic shielding rings, as shown in in Figure 1(b), the were designed to weaken the magnetic field in the plume region on different levels, and the magnetic field strength decreases in order from A to E. The outer pure iron ring was used to greatly increase the magnetic conductance and the local magnetic saturation was formed in the inner ring position. The inner rings were used to adjust the magnetic flux in this region, and the magnetic field in the plume region changed accordingly. Besides, in Figure 1(a), an additional permanent magnetic ring (4mm thick) was mounted near the exit to fix the position of last cusp with different shielding rings.



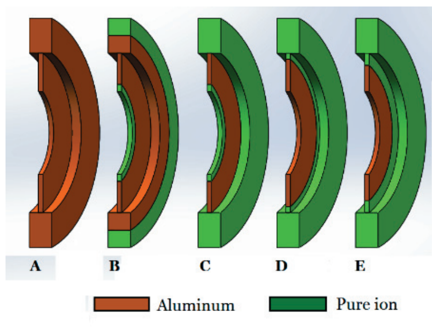
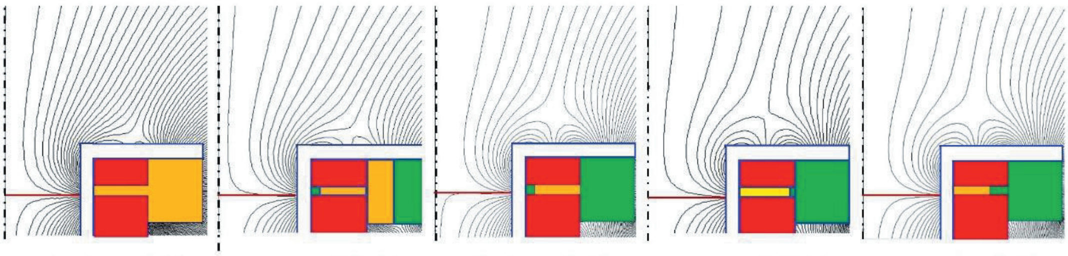


Figure1: (a) the schematic of the multi-cusped field thruster under experiments and (b) the profiles of different magnetic field shielding rings.

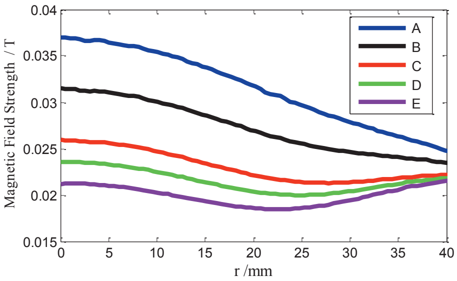
Figure 2(a) shows the magnetic distributions of multi-cusped field thrusters with different magnetic shield rings (simulated by the FEMM software as the former work[13,14]). As shown in Figure 2(b) and Figure 2(c), the shielding rings are capable to weaken the magnetic field in the plume region effectively. Besides, in the region of discharge channel, the magnetic field remained nearly unchanged and the separatrix (The null magnetic potential line with zero magnetic flux[15]) was well kept in the same position which were marked by the red lines in Figure2(a). To be convenient for explanation, the parameter β, which is defined as the maximum magnetic field strength along the axis in the plume region, was used to name these magnetic fields, namely 0.09T-field, 0.08T-field, 0.07T-field, 0.06T-field and 0.05T-field.

All of the experiments were carried out in the Plasma Propulsion Laboratory of Harbin Institute of Technology (HPPL). The stainless-steel vacuum chamber has a length of 4 m and an inner diameter of 1.2 m. The ultimate pressure in the tank can reach 1.0×10^{3}Pa. The flow rate of the hollow cathode was 3sccm, and the cathode position was found to have significant impact on the stability of multi-cusped field thrusters[5,6,16], an axial distance of 10cm from the exit plane and a radial distance of 12cm were chosen to reduce the current oscillation.

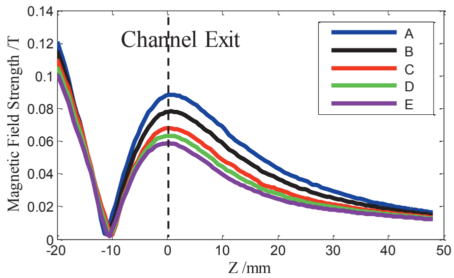
The plasma plume diagnostics used in our experiments include a Faraday probe and a Retarding Potential Analyzer (RPA). The Faraday probe was used for the measurement of ion current density distribution which was mounted on a rotational stage with the distance of 30cm from the pivot at angles of up to 80° from the thruster axis. The ion collecting area of Faraday probe was $0.75cm^2$, both the probe collector and guard ring were biased to -24V. The Collected current was recorded by measuring the voltage across a 200.3Ω shunt resistor. In our experiments, the RPA was located 40 cm downstream from the channel with a fixed angle of 39° from the axis, which was therefore close to the current density peak of the plume. The RPA used four grids, the first grid was floating, the second biased to -24 V with respect to ground to repel plasma electrons, the third biased with an 0-600 V positive voltage to filter ions, and the fourth grid was biased to -24 V to block secondary electrons generated by ion impact with the first two grids.



(a)



(b)



(c)

Figure 2: (a) Magnetic field of multi-cusped field thrusters with different shielding rings and the black dashed lines represent the axis of thruster. (b) Radial magnetic field distribution in the plan with a distance of 24 mm from the thruster exit. (c) Magnetic field distribution along the central axis.

III. Experimental results and discussion

Figure 3 shows test results of the thruster in different magnetic fields, and the anode flow rate were 10 sccm with the applied voltage of 350V. When the magnetic field strength was weakened from 0.09T-Field to 0.05T-Field, the electron current met an obvious increase, from 0.09A to 0.29A, as shown in Figure 3(a). According to former researches on the cusped field thrusters, the electron confinement of magnetic field is expected to be significant in the plume region, and the electrons are strongly confined and a sharp potential drop is formed near the exit [14, 16]. Therefore, it can be speculated that the electron confinement ability of last cusp is decreased in weaker magnetic field, more electrons can go across the magnetic field in the plume region and reach the discharge channel, thus the electron current increase obviously. In addition, the results of faraday probe have shown that the weaker magnetic field in the plume region can give rise to an obvious rise in the ion current near the axis and the hollow plume is 'filled in' [Figure 3 (b)]. This suggest that the radial profile of electric field is also weakened relative to the axial direction. Despite lack of sufficient evidence, the variation of electric field appears to be attributed to the enhancement of cross field radial conduction process of electrons for the weaker magnetic field in the plume region.

It should be noted that the propellant utilization η_p ($=I_i M/e\dot{m}$, where M, e, $\dot{m}$ are the mass of a Xe atom, electron charge, and Xe mass flow rate, respectively) exhibit sharp increase from 0.68 to 0.90 as the magnetic field decreased from the 0.09T-field to the 0.07-Tfield, which is shown in Figure 3 (c). The increase of η_p, stems from the increase of I_i, from 0.49A to 0.65A (by 0.16A), which is smaller than the increase of I_e from 0.09A to 0.15A (by 0.06A), as shown in Figure 3(a), and the current utilization η_c [$=I_i/(I_i+I_e)$] decreased slightly from 0.84 to 0.81[Figure 3(c)]. This can be explained that when the magnetic field is weakened, the ionization process is enhanced in the discharge channel for the increase of I_e, especially near the upstream of last stage, which is the main ionization region as has been validated by former simulated and experimental results[2,11]. And as a result, the increase of ion current is much higher than electron current when the magnetic field decrease from 0.09T-field to 0.07-Tfield.

However, when the magnetic field is further weakened from 0.07T-field to 0.05-Tfield, the η_c significantly decreases to 0.69 while η_p remained nearly unchanged. During this process, the discharge current I_d increases with the enhancement of oscillation amplitude and the electron current increment (about 0.135A) was much larger than the ion current, as shown in figure 3(b). The reverse trend of η_c and η_p with the decrease of magnetic field in the plume region may be explained that, in the 0.07-Tfield case, the η_p have reached 0.90, for the anode voltage and anode flow rate is remained unchanged, the ionization rate is likely close to the point of saturation. Therefore, when the magnetic field in the plume region is further weakened, the additional electron current could not promote ionization process effectively, but on the other hand, the weaker electrons confinement of magnetic field could lead to the decrease of η_c, and the sharp potential drop near the ultimate separatrix cannot be well formed near the exit for the increase of electron mobility, and the acceleration region extends to extend upstream, which can be validated in the normalized IEDF that there is a remarkable increase of FWHM (full width at half maximum) from 41 eV to 67 eV and the peak energy decreases from 342 eV to 324 eV as shown in figure 3(d).

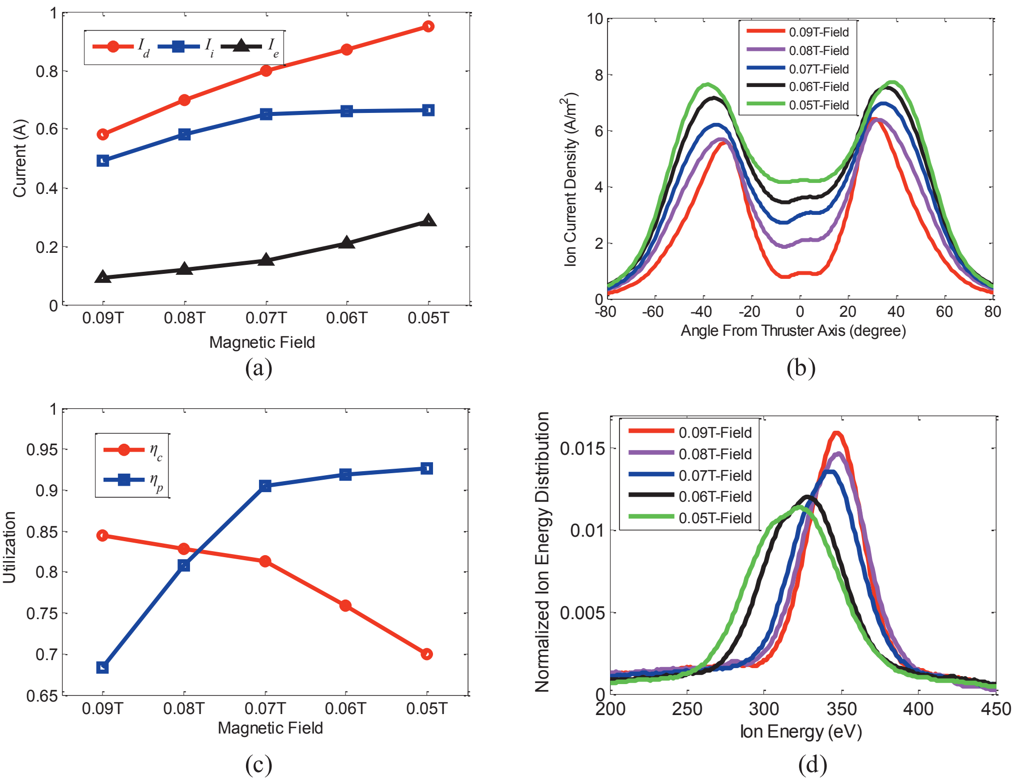
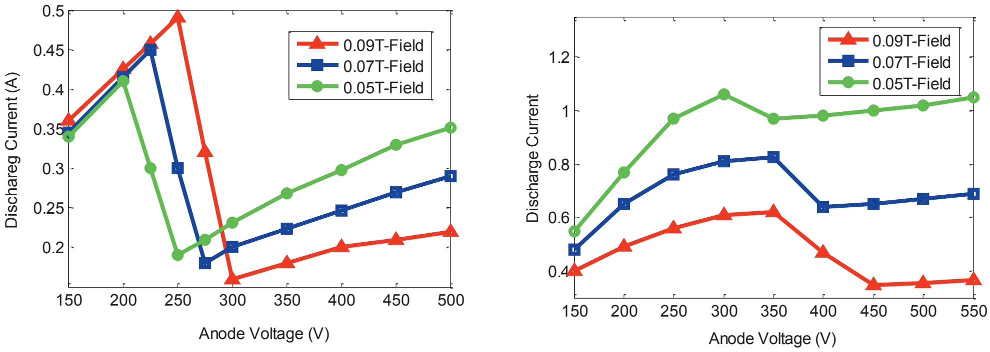


Figure 3: (a) Components of the discharge current. (b) The ion current density distribution. (c) Current utilization and propellant utilization. (d) The normalized IEDF.

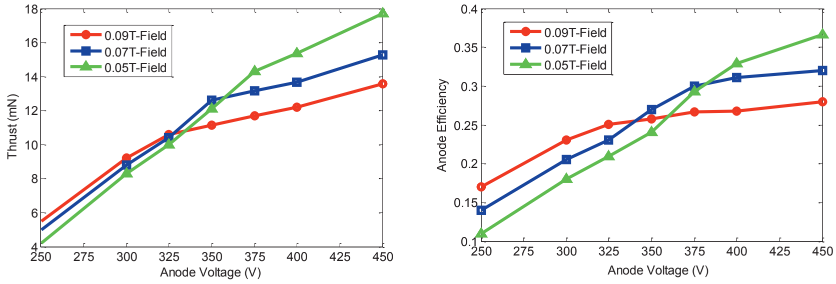
It has been validated that the Multi-cusped Field Thruster exhibits two modes of operation, it would change from the LC mode to HC mode when the anode potential was increased[5, 10, 16]. In our experiment, additional tests on the different operating conditions (varying the anode voltage and anode flow rate) are conducted in different magnetic fields, as shown in figure 4(a) and figure 4(b), the mode transition is more significant in the lower flow rate conditions, manifested by its steeper drop of discharge current ΔI, which is defined as the peak-valley value of discharge current between the mode transitions. The common characteristic of these two flow rate condition is that the ΔI is smaller in the weaker magnetic field with significant increase of discharge current in the higher voltage conditions. This means that lower magnetic field in the plume region can make the mode transition less obvious, or in other words, the difference of plasma characteristics between these two modes are diminished. Besides, the mode transition voltage U_m (means the anode voltage correspond to the start point of mode transition) also meet an obvious decreases from 300V to 250V in 5sccm condition and 350V to 400V in 10sccm condition, this implies that the effect of decreasing the magnetic field strength in the plume region and lowering the anode voltage may have similar effects on the promoting of the mode transitions. In addition, many characteristics of thruster operations in stronger magnetic field in the plume region conditions are similar with the higher discharge voltage conditions, they both have lower discharge current with higher η_c and clear hollow plume with bright plasma edges, on the contrary, both the weaker magnetic field and lower discharge voltage conditions may lead to higher discharge current, higher η_p and diffuse plume without bright plasma edges. Despite we are lack of sufficient evidence to prove the internal relations, but for the change of magnetic field is mainly set in the plume region, we can speculate that the similarities are induced by the electron conduction process in the plume region.



(a) (b)

Figure 4: The discharge current with anode voltage in 5sccm flow rate condition (a) and in 10sccm flow rate condition (b).

By setting the constant flow rate of 10sccm, the curves of thruster performance in different magnetic fields are shown in figure 5. It can be found that in all these magnetic fields, both the thrust and anode efficiency can be increased in higher discharge voltage conditions. Besides, in the lower voltage conditions (such as 250-300V), the thrust changes little but the anode efficiency is higher in the stronger magnetic field. But on the contrary, both the thrust and anode efficiency is higher in the weaker magnetic field in the higher voltage conditions (such as 400-450V). This can be account for the similar effects between discharge voltage and magnetic field strength in the plume region. In the lower voltage condition, the thruster is operating in the HC mode, and the low η_c become the main limiting factor for the increase of anode efficiency. In such a situation, higher magnetic field strength in the plume region is helpful to restrain the electron current and improve η_c, and in the end increase the anode efficiency, meanwhile it could also lead to a tiny decrease of η_p and give rise to the diminishment of thrust slightly. On the other hand, when the thruster is operating in the LC mode with higher anode voltage, the low η_p become the determinant factor for the anode efficiency and in this condition, lower magnetic field strength in the plume region is helpful to increase the number of energetic electrons reaching the discharge channel and improve the ionization and give rise to the increase of thrust. Besides, the 350V discharge voltage condition, which is intermediate condition between these two modes that both η_c, and η_p play the important role in the thruster performance, and the middle ranked 0.07-T field exhibited the highest anode efficiency, as shown in figure 5(b).



(a) (b)

Figure 5. Performance curves in different anode voltage conditions. (a) Thrust. (b)Anode efficiency.

IV. Conclusion

In summary, the magnetic field in the plume region plays a critical role in the performance of the multi-cusped field thruster. Weaker confinement of electrons in the plume region can lead to an increase of electron current, and the additional electron current inputted in the discharge channel can both lead to a higher η_p and lower η_c. We have found that there are similar effects between discharge voltage and magnetic field strength on the plasma characteristics during the mode transitions. And it can also explain the performance change character that the anode efficiency is higher in stronger magnetic field with lower anode voltage or in weaker magnetic field with higher anode voltage condition. Therefore, by adjusting the magnetic field strength in the plume region, it is instructive for the design optimization to achieve higher performance with different operation voltages that weaker magnetic field in the plume region is helpful to improve the anode efficiency in the higher operation voltage conditions. Furthermore, the relationship between the magnetic field strength in plume region and the mode transitions should be studied in the further research. At the same time, the similarities between the magnetic field strength in the plume region and discharge voltage should be analyzed in more detail to reveal the formation of inner physical mechanism.

Acknowledgments

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