Influence of Background Magnetic Field on Hollow Cathode Discharge Characteristics

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Abstract: This article regards magnetic field as a factor involved in Hall thruster-hollow cathode coupling process, and investiged its influence on cathode triode discharge characteristics, as well as plume parameter distribution. Results show that parallel magnetic field is beneficial for cathode discharge, in which both inner region and plume region are affected, and there exists an optimal magnetic field intensity. It is suggested that cathode orients parallel with local magnetic field line, and magnetic field adds into cathode individual test.

Nomenclature

T_e	=	electron temperature
n_0	=	neutral density of atoms
R_L	=	Lamor Radius
λ_{en}	=	mean free path of elastic collisions between electrons and neutral atoms
β	=	ration of Lamor Radius to mean free path of electrons

I. Introduction

STEADY-STATE operation of Hall Effect Thruster (HET) is the result of coupling between cathode plasma source and acceleration channel plasma source. Increasing evidence shows that cathode location and orientation is a degree of freedom for optimizing HET performance.[1,2,3] Past results were acquired by enumeration methods in goal of increasing HET thrust and efficiency, but showed controversial trends on different thrusters.[4,5,6,7] Though confusing, this can be explained from the perspective of electron transport. It can be noted that surrounding factors local to hollow cathode, including magnetic field, neutral density and electric field distribution, have impact on coupling voltage, electron temperature and density distribution in the plasma bridge, hence restraining the boundary conditions for ionization and acceleration process inside HET channel. Therefore, cathode installation is not merely a matter of distance, but rather a problem of matching hollow cathode with field factors that attached to HET.

Among the surrounding factors, HET physics are more sensitive to magnetic field, especially noting that cathode crossing magnetic seperatrix leads to a leap change in HET plume properties.[8] On the other hand, neutral density and electric field are self-cosistent factors. Even though they can be adjusted by changing cathode mass flow rate, the latter is usually limited to save propellent. Thus it is the matching relations between hollow cathode and local magnetic field that dominate the coupling process.

Coupling researches should not be limited exclusively to HET acceleration channel, but provide insights on hollow cathode studies as well. Since magnetic field interferes coupling process, cathode triode discharge configuration should also include magnetic field surrounding. In fact triode discharge configuration is not equivalent to coupling

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discharge,[9,10] under latter circumstances not only discharge current, cathode potential drop are variable because of HET operation conditions, even cathode discharge modes are different.[11,p20] From the perspective of cathode design, it should be studied to validate test design.

Knowledge of HET cathode discharge in magnetic field is limited. Articles related to HET design do not study cathode individually, while articles related to cathode design do not involve magnetic field issues. In the field of HET study, coupling discharge introduces too many variables that the response of cathode is hard to observe. For example two works relate cathode to magnetic field,[12,13] but drew controversial conclusions. In the field of cathode study, published articles of several renowned institutions have not shown specific concern about magnetic field design in cathode test.[14,15,16,17,18,19] The test facility in JPL configures a magnetic coil and a cone anode, but its emphasis seem to be the discharge mode,[20,21,22] not the design of magnetic field. In industry, magnetic field is utilized to control cathode plumein the field of plasma processing,[23,24,25] however it is uncertain whether the results of glow discharge is suitable for arc discharge in electric propulsion.

To match cathode with magnetic field, two effects need to be studied. One is the effect of magnetic field surroundings on hollow cathode plasma source, the other is the effect of local magnetic field configuration on plasma bridge. In the close-loop of electron current in HET system, clarifying the first effect is prerequisite of further understanding plasma bridge behaviors. Therefore, this article studied cathode discharge individually by introducing magnetic field into cathode triode discharge configurations and investigating the influence of magnetic field orientation and intensity on hollow cathode discharge characteristics. We hope relevant results can provide guidance for cathode installation on HET and magnetic field design in cathode test.

II. Experiment Design

The typical magnetic field enclosing HET hollow cathode includes parallel component (magnetic field parallel with cathode axis), perpendicular component (perpendicular to cathode axis), and magnetic separatrix. To simplify problem, this article adopted parallel and perpendicular magnetic field.

The adopted hollow cathode is an orificed LaB6 hollow cathode, enclosed fully by a keeper configuration. Working propellant is 99.9995% Xenon. The tank is vacuumed by an oil diffusive pump providing an ultimate vacuum of 1×10^{-3}Pa and 1×10^{-2}Pa when there is 3sccm of Xenon flow through hollow cathode.

The discharge circuit and magnetic coils are illustrated in Fig. 1. Cathode triode discharge configuration incorporates a keeper power supply and an anode power supply. To initiate cathode discharge, a heater power supply and a high voltage power supply were used. Once ignited, the discharge turns into a self-heated steady-state constant-

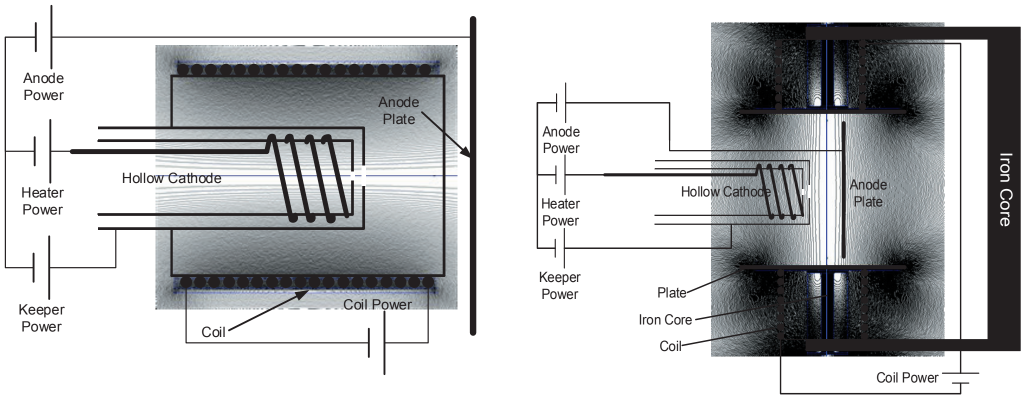


Figure 1. Triode Discharge Circuit and Magntic Coils

current discharge with heater and high voltage power supply turned off. None of the electrodes are grounded.

Parallel magnetic field is formed by the coils in left subfigure. Coil axis is aligned with hollow cathode axis. The coil frame is made by aluminum and is floating. To minimize interactions between coil frame body and cathode plume, the frame diameter was relatively large (Φ100mm) compared to hollow cathode (Φ20mm), and there is a gap of 10mm between coil frame and anode plate. Perpendicular magnetic field is illustrated in subfigure on the right, in which two coils were wound on two coil frames made by invar steel. Each frame has a Φ100mm plate, and the spacing between the two plates is 100mm, in which a uniform magnetic field perpendicular to cathode axis is formed. To minimize the influence of magnetic field asymmetry on cathode plume, the anode plate and cathode are placed just besides magnetic field axis and their spacing is relatively small (25mm). Above all, there exists a 0.4Gauss geomagnetic field, which is omitted comparing to artificial magnetic field on the magnitude of tens of Gauss.

Plume was diagnosed spatially with Langmuir probe scanning along plume axis as illustrated in Fig. 2. The probe tip is Φ0.5mm×0.8mm tantalum wire, supported by a *Φ*1mm alumina ceramic tube. Probe voltage was biased from -10V to +20V compared to cathode negative electrode with a period of 1.3s. The filter module inside the circuit has a 1.5kΩ resistor and a 0.47μF capacitor. Plasma potential was determined from the second derivatives of I-V curve.

The experiments compare discharge characteristics in non-magnetic field, parallel magnetic field and perpendicular magnetic field respectively, by measuring anode voltage, keeper voltage and anode current oscillation amplitude. Because parallel magnetic field seemed to have larger influence, some parameters were recorded including inner pressure, keeper voltage in diode discharge and plume plasma parameters.

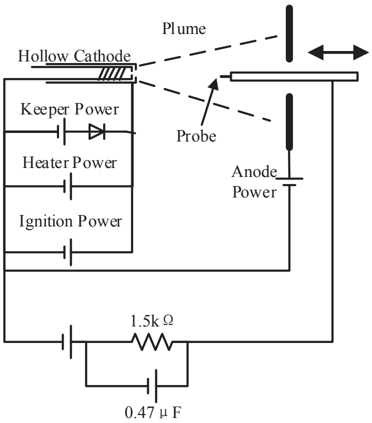


Figure 2. Probe Measurement Scheme in Cathode Plume

III. Experiment Results

Experimental results are presented here in two parts. First part emphasizes on the influence of magnetic field intensity and orientation on discharge characteristics, and the second part is dedicated to locate affected regions of cathode plasma in parallel magnetic field.

A. Influence of Magnetic Field on Discharge Characteristics

Cathode voltage-ampere characteristic curve shows that parallel magnetic field is more beneficial for cathode discharge, and there exists an optimal magnetic intensity.

Influence of parallel magnetic field on cathode discharge under different discharge currents is illustrated in Fig. 3 and Fig 4. As can be seen, anode voltage dropped by 15V and anode current oscillation amplitude decreases by a magnitude. During our experiments cathode plume is observed to concentrate from a ‘trumpet’ shape into a ‘spindle’ shape when increasing magnetic field intensity. As also can be seen, the influence is not monotonic, anode voltage reaches a minimum value when parallel magnetic field reaches 10-20Gauss.

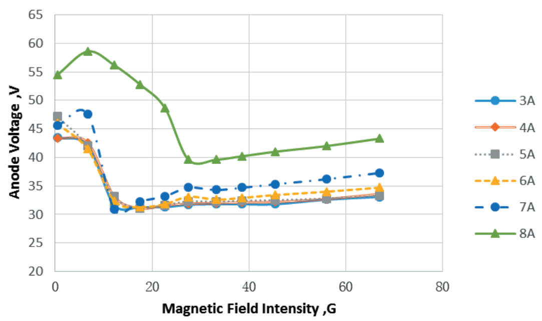


Figure 3. Influence of Parallel Magnetic Field Intensity on Anode Voltage.

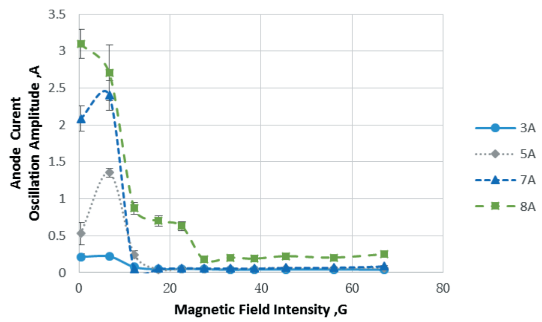
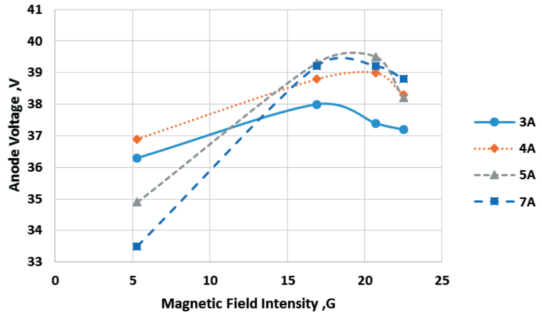


Figure 4. Influence of Parallel Magnetic Field Intensity on Anode Current Oscillation.

Influence of perpendicular magnetic field on cathode discharge under different discharge currents is illustrated in Fig. 5 and Fig. 6. Anode voltage increases by 3-7V with higher perpendicular magnetic field intensity. Similar to parallel magnetic field circumstances, the influence of perpendicular magnetic intensity is not monotonic either. Anode voltage reaches a maximum value when perpendicular magnetic field intensity reaches 15-20 Gauss.

As can be seen from Fig. 4 and Fig. 6, both parallel and perpendicular magnetic field suppress discharge oscillation, but perpendicular magnetic field did not result in the changes of magnitude in amplitude. Besides, when the intensity is strong enough, anode current oscillation increases significantly, meanwhile glittering discharge can be observed visually in cathode plume.



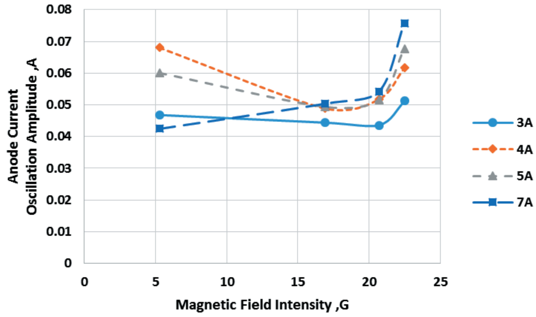


Figure 5. Influence of Perpendicular Magnetic Field Intensity on Anode Voltage.

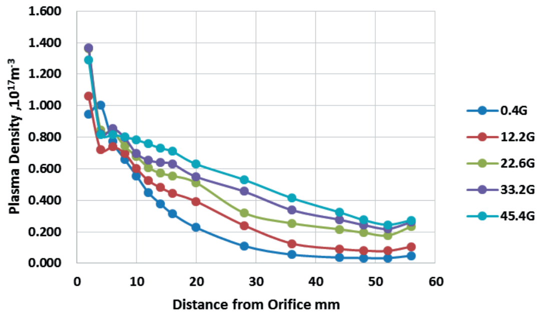
Figure 6. Influence of Perpendicular Magnetic Field Intensity on Anode Current Oscillation.

B. Affected Regions under Parallel Circumstance

Data concerning different regions of cathode plasma shows that magnetic field influences all regions either directly or indirectly. Among them, plume region was most affected. Keeper region plasma follows next and inner region plasma was least affected. Relevant data is presented in this order.

1. Influence of Parallel Magnetic Field on Plume Parameters

Plume parameter distribution indicates that sheath downstream orifice exit was affected and radial diffusion of plume was suppressed. Influence of parallel magnetic field intensity on plume parameters is illustrated in Fig. 7. Plasma density distribution shows three differences compared to pure triode discharge. First, ionization located downstream orifice exit was weaker. In pure triode discharge, there was a plasma density peak downstream orifice exit, indicating occurrence of ionization, while in parallel magnetic field, this peak leveled off and even disappeared. Second, plasma density on orifice exit was higher. Third, density in downstream plume change from exponential attenuation into linear attenuation with respect to z distance, confirming the suppression of radial diffusion of cathode plume.



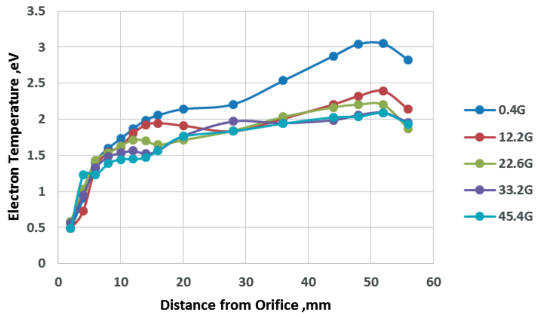


Figure 7. Influence of Perpendicular Magnetic Field Intensity on Anode Voltage.

Figure 8. Influence of Perpendicular Magnetic Field Intensity on Anode Voltage.

Electron temperature distribution is illustrated in Fig. 8. It also showed three differences. First, electron temperature gradient downstream orifice exit was larger. The electron temperature on orifice exit was slightly lower in magnetic field while electron temperature of further downstream was higher, confirming potential drop downstream the orifice was larger. Second, electron temperature in downstream plume was significantly lower, especially in near anode region (from 3eV to 1.5eV). Third, electron cooling zone moved upstream. There exists an area in the plume where electron temperature gradient is relatively small and it appears that electron is cooled therein (or less heated). This area was observed to move towards orifice by 15mm when parallel magnetic field intensity increased from 0.4Gauss to 45.4Gauss.

2. Influence of Parallel Magnetic Field on Keeper Region Plasma

In order to estimate whether high density plasma in keeper region (region between orifice plate and keeper) can be affected by magnetic field, keeper voltage was monitored under both triode discharge and diode discharge (keeper discharge alone), as illustrated in Fig. 9 to Fig. 11. It can be seen that keeper floating potential is sensitive to discharge current under pure triode discharge, in which variation can reach 10V (Fig. 9). However in magnetic field this variation decreases to less than 1V and keeper floating potential remains nearly a constant. Meanwhile, the oscillation amplitude of the floating potential was significantly lowered by a magnitude (Fig. 10). In diode discharge, keeper discharge voltage showed non-monotonic trend with magnetic field intensity, varying between 23-27V (Fig. 11).

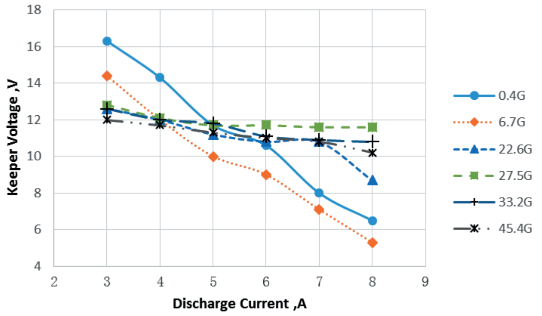


Figure 9. Influence of Parallel Magnetic Field Intensity on Keeper Floating Potential under Triode Discharge.

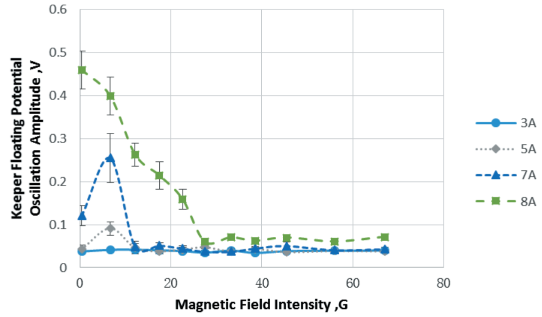


Figure 10. Influence of Parallel Magnetic Field Intensity on Keeper Floating Potential Oscillation under Triode Discharge

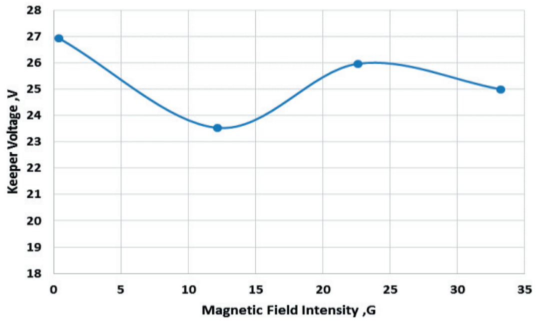


Figure 11. Influence of Parallel Magnetic Field Intensity on Keeper Discharge Voltage under Diode Discharge

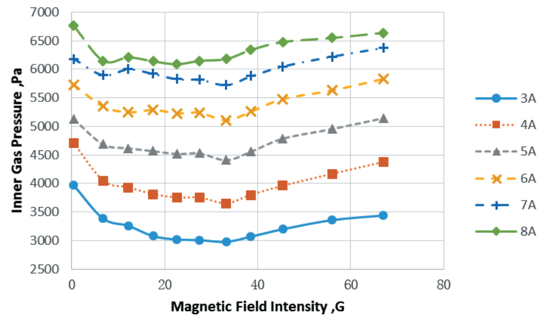


Figure 12. Influence of Parallel Magnetic Field Intensity on Keeper Discharge Voltage under Diode Discharge

Fig. 9 to Fig. 11 reveal that keeper regions plasma can be affected by magnetic field. We guess the magnetized portion should be the sparse plasma far off cathode axis approaching the keeper wall. Weaker interactions between keeper wall and discharge plasma may lead to deviation from keeper erosion in pure triode discharge conditions, and weaker peak-regulation effect of keeper plasma on mainstream discharge plasma. Therefore, there should be an upper limit to keeper orifice diameter of HET hollow cathode.

3. Influence of Parallel Magnetic Field on Inner Region Plasma

Inner pressure was monitored to help estimate whether physics near emitter can be affected. As illustrated in Fig. 12, when increasing parallel magnetic field intensity, inner gas pressure first decreases by 700-1000Pa to a minimum value and increases again. In our experiments, inner pressure was minimum when parallel magnetic field intensity was about 33Gauss.

The surprising variation of inner gas pressure indicates that, physics near emitter is not isolated from cathode plume. Throttling effect is the contribution of plume ion bombarding orifice plate and neutrals in the orifice. Lower anode voltage leads to lower plume average ion energy, and alters the throttling mechanism indirectly. Besides, combined with Fig. 7, it can be seen that ionization zone tends to move inward from the plume, which might change discharge mode.

IV. Discussion

Experiment results show that magnetic field as weak as 10Gauss can lead to a significant change in cathode discharge characteristics. In HET, typical magnetic field intensity local to hollow cathode is above 30Gauss, which is sufficient to affect cathode plasma. Besides, magnetic field orientation does influences in different patterns. So, the magnetic field adopted in this article is in accord with reality.

Inferred from parameters distribution, cathode plume is the region that is directly influenced and other region is influenced indirectly. Here we compare the scale of electron magnetization and electron-atom elastic collision. With plume electron temperature T_e of 2-3eV and neutral density n_0 of $10^{19}m^{-3}$, the Lamor Radius R_L according to induced magnetic field intensity is 2-3mm, while mean free path of elastic collision between electrons and Xenon neutral atoms λ_{en} is 1-10m, then the ratio β of Lamor Radius to mean free path is 10^2-10^4,indicating electron is strongly magnetized. In inner region, assuming electron temperature T_e of 1-2eV, neutral density n_0 of $10^{23}m^{-3}$, corresponding β is on the magnitude of 0.01-0.1, indicating drift and diffusion dominate. In the orifice, electron Lamor Radius might be on the scale of orifice diameter, the effect of magnetic field here is limited.

However, plume magnetization has multiple effects. Soon after magnetic field was introduced, plume electron density was higher because electrons are magnetized and higher conductivity in plume region led to lower potential drop in bulk plume region. However, this led to higher sheath potential drop near anode because effective collecting area was smaller, which is on the contrary of the first effect. The ratio of these two effects influenced throttling effect of hollow cathode, and further might have changed ionization process, because as can be seen from experiment results, inner region gas pressure and plasma density on orifice exit were different. The optimal magnetic field intensity should find a balance between these two effects and create a low voltage and quiet discharge. This is in accord with some works determining cathode locations,[2,5] in which large or small distance between hollow cathode and HET does not necessarily lead to better HET performance, however a medium distance is preferable. The optimal magnetic field intensity might be a reference for cathode location, and therefore a reference for triode discharge to simulate coupling discharge better.

Considering that the cathode erosion is closely related to plume ion energy and plume density, and that orifice and emitter physics is closely related to inner gas pressure, it is suggested to apply real magnetic field surroundings in triode discharge test. On the other hand, since parallel magnetic field leads to lower cathode discharge voltage, which is beneficial for increasing voltage utilization efficiency of HET, it is suggest that cathode be installed parallel with local magnetic field.

V. Conclusion

This article introduced magnetic field into cathode triode discharge configuration and investigated its effect on discharge characteristics. Results show that parallel magnetic field is beneficial for cathode discharge, under which circumstances all regions of cathode plasma were affected. Therefore it is suggested that cathode be installed parallel with local magnetic field, meanwhile considering magnetic field influences discharge mode and erosion conditions, it is also suggested that magnetic field be applied into cathode triode discharge test.

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