Measurement of Anode Current Density Distribution in a Cusped Field Thruster

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Abstract: The cusped field thruster is a newly emerging electric propulsion device. A radial non-uniformity of current density is supposed at the anode. To further study the anode current density distribution, a multi-annulus anode is designed to directly measure the anode current density for the first time. With the increase of the radial position, the anode current density decreases sharply. The magnitude of the central annulus anode current density is far higher than the other annulus. When increasing the anode voltage, ratio of the current of central annular occupying the total anode current will increase. But the non-uniformity of the anode current density change limitedly by altering anode gas flow rate.

I. Introduction

THE cusped field thruster is a new kind of electric propulsion device developed by THALES Electron Devices GmbH (TEDG), deriving from Hall thrusters and travelling wave tubes[1]. Fig. 1 demonstrates the working principle of a cusped field thruster. By adopting permanent magnets with the same polarity between adjacent magnets, a cusped magnetic field can be generated to confine the electrons and guarantee the ionization rate of the neutral gas. Ions accelerated by the electric field are ejected from the discharge channel at a high speed to produce thrust. The cusped magnetic field topology can shield the high energy ions away from the channel wall, which can prolong the operating life of the thruster[2]. In addition, it has been found during the experiments that the thrust of a cusped field thruster can be adjusted among different orders of magnitudes[1], which is not happened in the Hull Thrusters. It has been planned to be applied into the SmallGEO in the frame of European Space Agency ESA's Artes-11 program[3, 4]. Other institutes, including Massachusetts Institute of Technology (MIT)[5] and Stanford University[6], have also conducted researches on this kind of thruster.

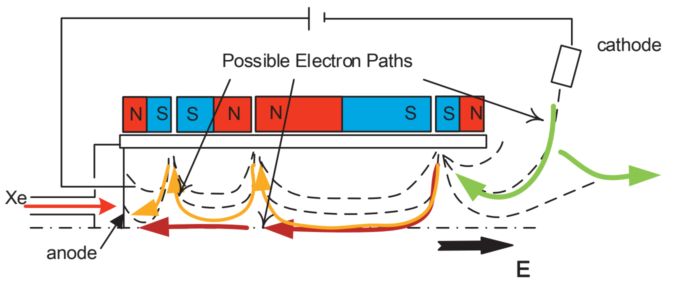

Figure 1. Working principle of a cusped field thruster.

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In the past researches, some characteristics have been discovered in this kind of thruster. Two operating modes were found in experiments, the high current mode and the low current mode[5, 11]. When the anode voltage is low or the anode flow rate is high, the thruster would work in high current mode, which demonstrates high anode current and severe oscillation. Otherwise, the thruster would work in low current mode and demonstrates opposite phenomena.

The thruster has a great radial difference. A 2D Particle-in-Cell (PIC) simulation conducted by HIT Plasma Propulsion Lab (HPPL) has showed that the axial electron current density near the channel axis is much higher than that at other regions[7]. By other PIC simulations, the uneven radial distribution characteristic of the thruster has also been validated[8-10]. As for the experiments, the researchers from MIT took the photos of the discharge channel of the Diverging Cusped Field Thrusters by high speed camera, and it is found that the luminosity near the center of the anode is higher than other regions of the anode[11]. In addition, during the experiments of Cylindrical Cusped Field Thrusters, Louis Boulanger found that the stainless steel parts of anode were melted[12]. It is speculated that the overheating of the anode center is caused by a large number of electron impacts, but the current density on the anode has not been directly measured by experiments yet.

This paper validates the radial non-uniformity of the anode current density by experiments, and discusses the influence of working conditions upon it. A multi-annulus anode is designed to directly measure the uneven radial distribution of anode current density in a cusped field thruster for the first time. Design of the multi-annulus anode and measuring circuit have been described in this paper. The influence of the alternation of the anode flow rate and the anode voltage upon the anode electron density distribution is discussed.

II. Experiment

The 3D engineering section view of the cusped field thruster is presented in Fig. 2. The multi-annulus anode is divided into 4 parts. The black parts are made of graphite and there is 2 mm thickness BN ceramics between each annuluses anode to achieve insulation. The central annulus graphite is at a radius of 3mm. The thickness of other graphite annuluses are 6mm, 6mm and 7mm from inside to outside. Restricted by size, 20 ventholes of 1mm diameter are drilled on the third annulus anode to let the neutral gas enter into the discharge channel. The discharge channel is made of BN ceramics with 2mm wall thickness, surrounded by permanent magnets. The inner diameter of the discharge channel is 56 mm and the outer diameter of the thruster is 104mm. The experiments are conducted in a vacuum tank from HPPL. The tank is 1.2 m in the inner diameter and has a length of 4 m, which is equipped with 2 K-600T oil diffusion pumps with 17000 L/s air exhaust speed. The ultimate pressure can reach at 1.0×10^{-3} Pa.

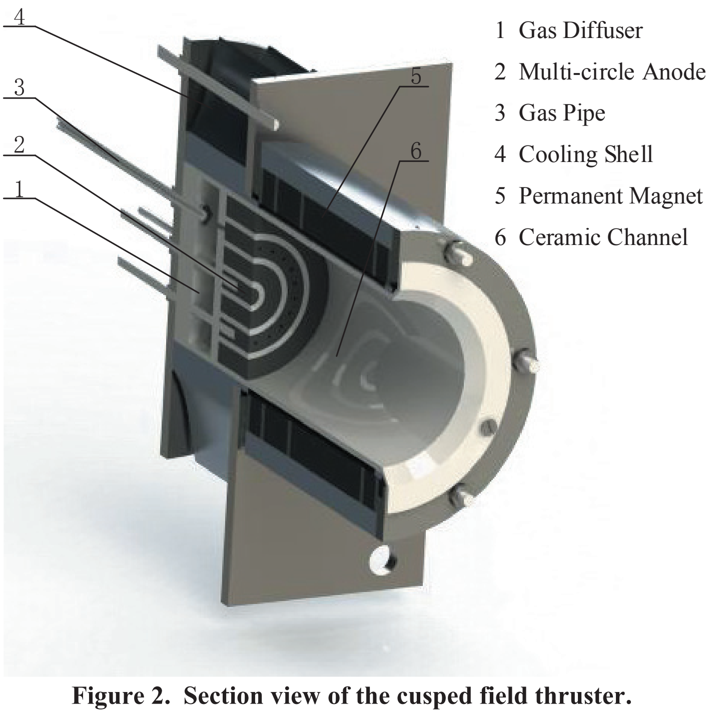


Figure 2. Section view of the cusped field thruster.

The simulated magnetic field and the experimental measuring circuit is shown in Fig. 3. To measure the anode current, 0.1 Ω resistance is in series with each annulus anode to change the current signal into the voltage signal. Then the DL850 recorder collects the voltage signal and transmits the data to the computer. The ratio of the magnet lengths from the left to the right is 1:2:6:1. The magnetic field simulated by FEMM software[16] is presented in Fig. 3. It can be found that along the axis of the channel, the maximum of the magnetic field strength is around 0.08 Tesla, and the magnetic field strength near the separatrix is 0. The magnetic field strength is around 0.18 Tesla near the channel, and the magnetic field strength is closed to 0.02 Tesla near the anode. As for the anode and cathode position, the multi-annulus anode is place at 98 mm away from the channel exit, and the cathode is 60mm away from the channel exit and 50mm away from the channel axis.

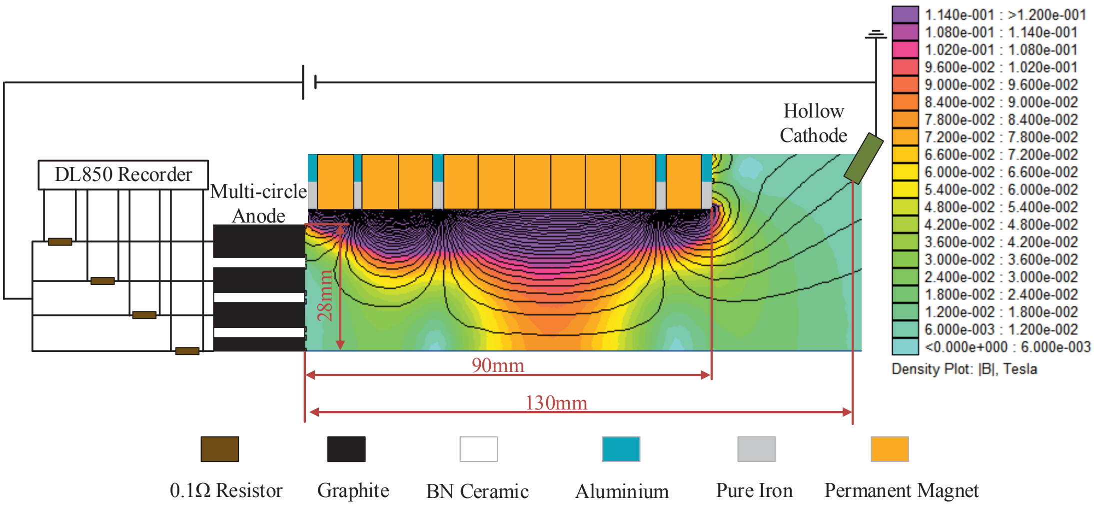
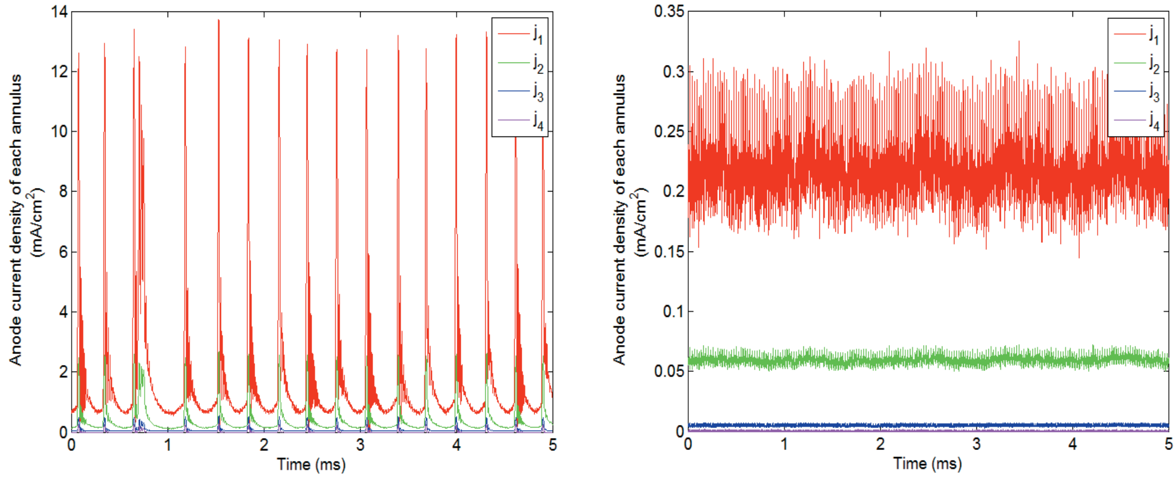


Figure 3. Magnetic field distribution and multi-annulus measuring circuit.

The hollow cathode keeper current is fixed at 1.3 A. The cathode gas flow rate is fixed at 3 sccm. The cathode is placed at 90mm from the exit in horizontal direction and 100 mm from the axis in vertical direction. After the thruster is ignited, the thruster keeps working for 1 hour at 200 V constant anode voltage and 15 sccm constant anode gas flow rate. Then the curves of each annuluses anode current varying with time is collected by the DL850 recorder with anode voltage changing from 100 V to 250 V and the anode gas flow rate changing from 10 sccm to 30 sccm.

III. Result and Discussion

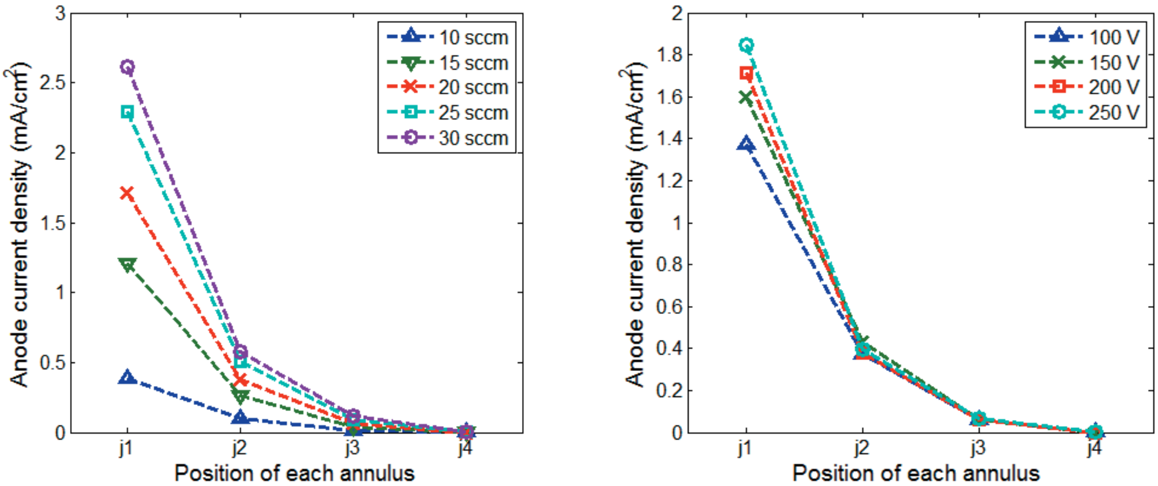
Fig. 4 presents the curves of each annuluses anode current density varying with time both in the high current mode and the low current mode at constant anode voltage of 250V. Parameters, j_1, j_2, j_3 and j_4, represent the anode current density from the inner annulus anode to the outer annulus anode. It can be found from Fig. 4a that in the high current mode, as time goes on, the anode current density increases sharply, and then decreases gradually. The time-averaged anode current in Fig. 4a is 2.14A. In Fig. 4b, the thruster works in low current mode, and no severe oscillations are demonstrated. The time-averaged anode current in Fig. 4b is 0.29A. Similar results can be found in Ref. 11. Compared with every annuluses anode current density in each figure, it can be found the change of each ring's electron current density increases and decreases simultaneously, and the anode current density decreases sharply with the increase of the radial position. The average values of each annuluses anode current density in Fig. 4a are j_1= 1.8468 mA/cm^2, j_2= 0.3985 mA/cm^2, j_3= 0.0680 mA/cm^2 and j_4= 0.0007 mA/cm^2. j_1: j_2: j_3: j_4 equals to 2638: 569: 97: 1. Similarly, in Fig. 4b, the average values of each annuluses anode current density are j_1= 0.2177 mA/cm^2, j_2= 0.0593 mA/cm^2, j_3= 0.0048 mA/cm^2 and j_4= 0.0001 mA/cm^2. j_1: j_2: j_3: j_4 equals to 2177: 593: 48: 1. Therefore, both in high current mode and low current mode, the radial difference of anode current density can be validated. The closer to the channel centerline, the more the current density will be. This result may be reasonable, because there are two main electron paths in the discharge channel, and both of the ends of two electron paths are at the center of the anode[7].



a) b)

Figure 4. Curves of anode current density varying with time in different modes. *a) High current mode. Operating at 250 V constant anode voltage and 20 sccm constant anode gas flow rate. 2.14 A total anode current. b) Low current mode. Operating at 250 V constant anode voltage and 10 sccm constant anode gas flow rate. 0.29 A total anode current.*

Fig. 5 presents the anode current density of each annuluses at varying gas flow rate in high current mode. Fig. 5a operates at 200 V constant anode voltage, and Fig. 5b operates at 20 sccm constant anode gas flow rate. All the data points in Fig. 5 are at the high current mode. It can be found that in every stable operating conditions, with the increase of the radial position, the anode current density decreases and the gradient of the anode current density is much larger near the axis. With the increase of the gas flow rate, the anode current density of each annuluses increase in roughly the same multiples. However, when the anode voltage increases, only the current density of the central annulus demonstrates a significant growth, and there is no obvious increase in other annuluses.



a) b)

Figure 5. Curves of each annulus anode current density varying with the increase of the radius in different gas flow rate and anode voltage. *a) Operating at 200 V constant anode voltage b) Operating at 20 sccm constant anode gas flow rate.*

To imply the extent of the anode current density non-uniformity, a parameter α, which is the ratio of the central annulus current I_1 to the total anode current I, is introduced here.

$$\alpha = \frac{I_1}{I}$$

The α in different operating conditions are shown in Fig. 6. All the data points in Fig. 6 are at the high current mode. As shown, the α changes with the increase of anode voltage but changes negligibly with the alternation of anode gas flow rate. After injected into the channel, the neutral gas diffuse quickly, so the enhancement of the neutral density at different radial position caused by the lifting of the gas flow rate is ever. Therefore, the influence of the anode gas flow rate is limited in terms of the non-uniformity of the anode current density distribution. In addition, it can be found from the Fig. 6 that α rises with the increase of the anode voltage. There are two main electron paths inside the discharge channel. Some electrons are well trapped by the magnetic field. So these electrons would move along the magnetic field lines towards the cusp, cross the separatrix by collision, and arrive at the anode in the end. Other electrons would take the central leak path, which means move along the channel axis and reach the center of the anode directly. When the anode voltage is increased, some of electrons moving to the central area of the channel which might be trapped well by the magnetic field lines at low anode voltage are more likely to be accelerated by stronger electric field, which makes the number of the electrons moving along the central leak path increases. Therefore, α rises when the anode voltage increases.

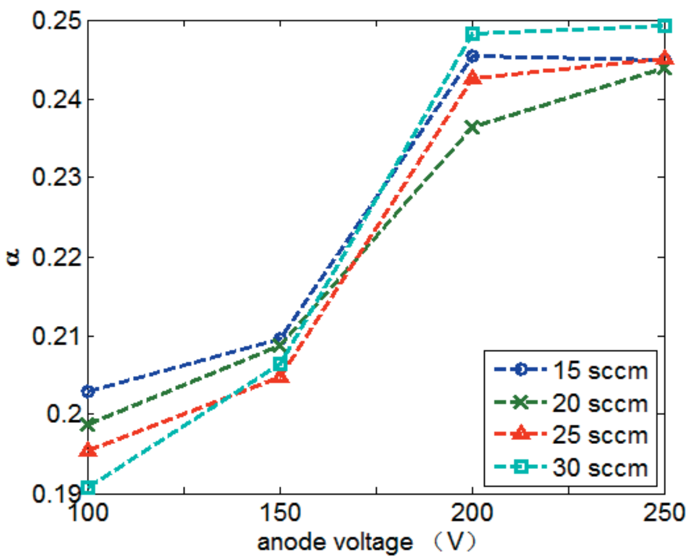


Figure 6. The α in different operating conditions.

IV. Conclusion

In this paper, the anode current density distribution in a cusped field thruster is directly measured for the first time by using a multi-annulus anode. It is found that there is a significant uneven radial distribution of anode current density in the cusped field thruster and the central annulus anode current density's order of magnitude is the highest. The anode current density decreases sharply with the increase of the radius, and the change of each annulus anode current density increases and decreases simultaneously. In terms of the influence of the operating conditions to the uneven anode current density distribution, the alternation of the anode gas flow rate affect limitedly to the current density non-uniformity, but the increase of the anode voltage can lead to the tendency of anode current density concentrating at the center of the anode. The results is instructive to further study the low frequency current oscillations and the electron conduction mechanism.

Acknowledgments

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