

Experiment Research on a Variable Magnet Length Cusped Field Thruster

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Abstract: The concept of multistage cusped field thruster came from German¹. Due to its advantages, the multistage cusped field thruster (CFT) has been developed by MIT², Stanford University and many other research groups around the world. Since the optimum magnetic field configuration is still uncertain, a Variable Magnet Length Cusped Field Thruster (VML-CFT) is designed by HIT Plasma Propulsion Lab, taking the adjustment of magnetic field configuration into consideration. This paper introduces the effect of different magnet length on the performance of VML-CFT. The optimum combination of the magnetic field cusps can be found by analyzing experimental data and results.

I. Introduction

MULTI stage cusped field thruster is an emerging type of electric propulsion concept currently. It has advantages of high specific impulse, long life, compact structure, small volume, which gradually catch the attention and favor of aerospace industry. Error! Reference source not found. is a brief view of a cusped magnetic field thruster concept with its magnetic field topology.

Generally, the discharge channel wall of the thruster is made of ceramic. The channel wall is surrounded by multistage permanent magnets, and two adjacent ones have opposite polarity. The anode is in the upstream of the

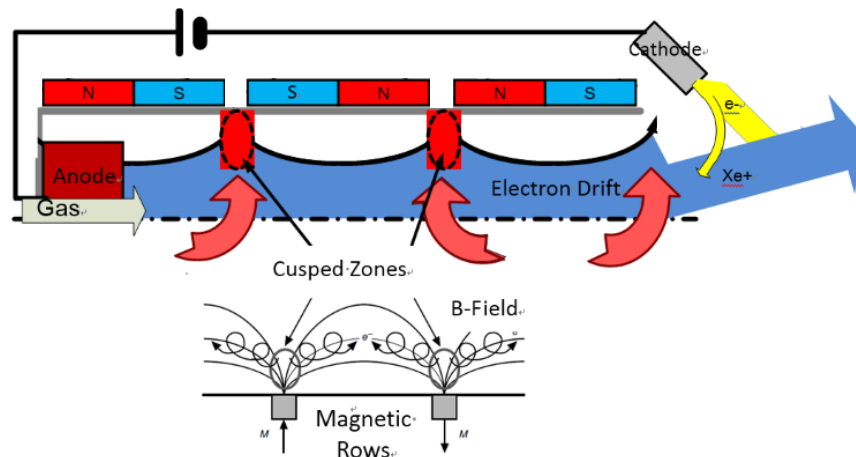


Fig.1 A view of multistage cusped magnetic field plasma thruster concept

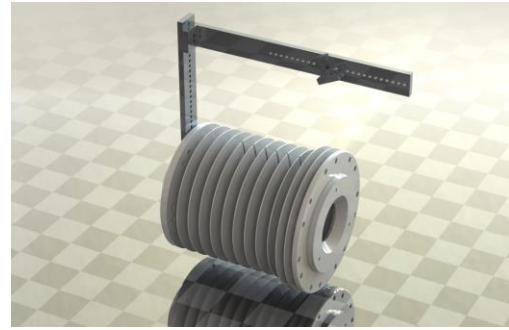
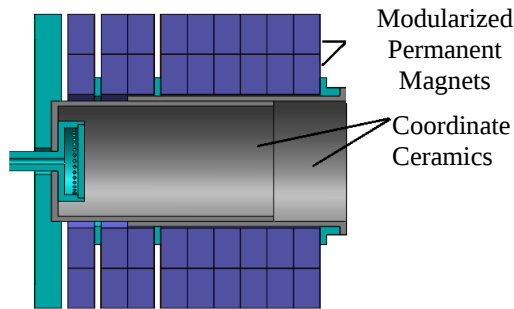
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channel. Working gas (typically Xenon) is injected into the discharge channel through the gas supply pipeline. The magnetic field of most zones is mainly parallel with the channel wall except the magnetic field cusp regions. The magnetic mirror effect generated by the radial magnetic field at the magnetic cusp blocks electrons and limits the interaction between ions and the wall effectively. Therefore the electrons are bounded to do spiral movement along the magnetic field lines, which enhance the ionization of Xenon atoms. Electrons will move towards anode through the collision with neutral atoms in the process and collide with the anode to form a discharge circuit eventually. Ions produced by electron ionization of Xenon atoms are accelerated and ejected by electric field to produce thrust. This multistage design improves ionization rate and separates the acceleration zone and the ionization zone, so as to improve performance correspondingly.

II. Design of the Thruster

A Variable Magnet Length Cusped Field Thruster (VML-CFT) is designed by HIT Plasma Propulsion Lab. The configuration of the magnetic field is the most significant factor to be considered in the design progress. The variable magnet length cusped field thruster utilizes the design of modularized permanent magnets. The picture of the prototype of the designed VML-CFT is shown in **Figure 2**.



Error! Reference source not found.2 **A view of a Variable Magnet Length Cusped Field Thruster Prototype**

VML-CFT designed by HIT Plasma Propulsion Lab is 250mm long, 200mm in outer diameter, with the weight of 4.5kg. The different configuration of magnetic field can be achieved by adjusting the length of modularized permanent magnets in each stage. The anode and gas distributor are designed as one object made of stainless steel. 36 holes with diameter of 1mm are drilled uniformly in azimuthal direction to eject the working gas into the discharge channel. The position of cathode has great influence on the performance and oscillating characteristic of the thruster, therefore, an adjustable cathode stand is designed and it can be used to find the optimal position of cathode. The main shell of the thruster is made of Aluminum with multistage radiation cooling rings outside the main shell.

The experiment facility is a vacuum Chamber, as shown in **Figure 3**. The pumping rate is 17000 liters per second. The minimal pressure in the vacuum system can reach 2.0×10^{-3} Pa.



Fig.3 Vacuum system

III. Experimental Study

Three kinds of magnetic field configurations with different length in each stage are assembled during the experiments. The configuration 1 has three magnetic stages with the ratio of 2:6:1, the cusp field intensity is strong in the exit. The ratio of magnetic stages in configuration 2 is 2:7:0.5. The ratio is 2:8:0.5 in configuration 3 with the longest stage of magnet in the middle stage and weak cusp field intensity in the exit. All these three configurations have the same width of discharge channel. The power supply which offers anode voltage ranges from 0 to 531V. The working gas is Xenon. The Xenon flow rate in the cathode maintains 3sccm, while the Xenon flow rate in anode varies from 0 to 50sccm.

Figure 4 shows different plume of VML-CFT in magnetic field configurations 1, 2 and 3, respectively. The least magnetic field interface lies in the configuration 3. The magnetic field interface results to the smallest plume divergence angle in the magnetic field configuration 3. The reduced plume divergence angle contributes to a higher thrust and efficiency of the thruster.



Configuration 1

Configuration 2

Configuration 3

Fig.4 Plume of magnetic field configuration 1, 2 and 3

The thrust and efficiency variations with different Xenon flow rate are shown in **Figure 5** and **Figure 6** respectively, with a constant discharge voltage of 500V. It can be found that by varying the anode Xenon flow rate from 0 to 50sccm, the performance is different in three different magnetic field configurations.

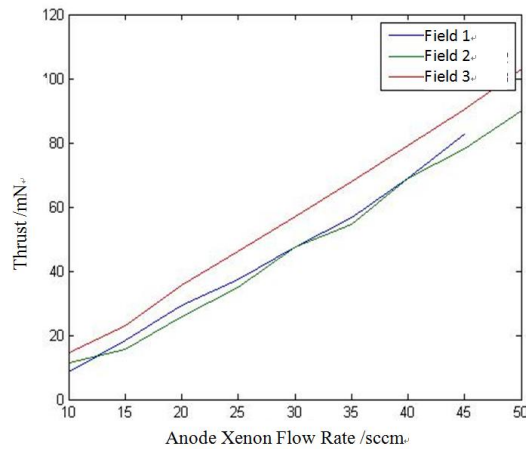


Fig.5 Curve of thrust change with Xenon flow rate in 3 different configurations at 500V discharge

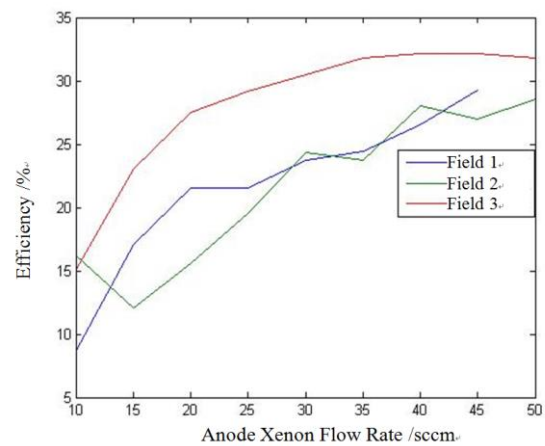


Fig.6 Curve of efficiency change with Xenon flow rate in 3 different configurations at 500V discharge voltage

The maximum thrust is 102mN in magnetic field configuration 3 when the Xenon flow is 50sccm in anode. The thrust and efficiency increase with the increase of Xenon flow in anode at the same discharge voltage. With the increase of anode discharge voltage at the same Xenon flow rate in each configuration, the thrust and efficiency increase while the efficiency increasing rate decreases gradually. The figures show that thruster obtains the largest thrust and efficiency in magnetic field configuration 3.

The variation of thrust and efficiency with discharge voltage in three magnetic field configurations is shown in **Figure 7** and **Figure 8** respectively at anode Xenon flow rate of 30sccm. Thrust increasing rate decreases with the increase of anode discharge voltage at the voltage lower than 300 V. But the curve is almost linear at voltage higher than 350V, which is similar to the results of HEMPT-3050⁴ in Germany. The results show that the thruster can produce more thrust in higher voltage. At magnetic field configuration 3, the efficiency reaches 36.06% at 500V and 38.02% at 531V, which is higher than the efficiency in other two configurations. Due to power supply limitations, higher discharge voltage than 531V cannot be offered. Results show that the efficiency increases with the increase of anode voltage at each magnetic field configuration. A higher efficiency of thruster can be expected at higher anode discharge voltage.

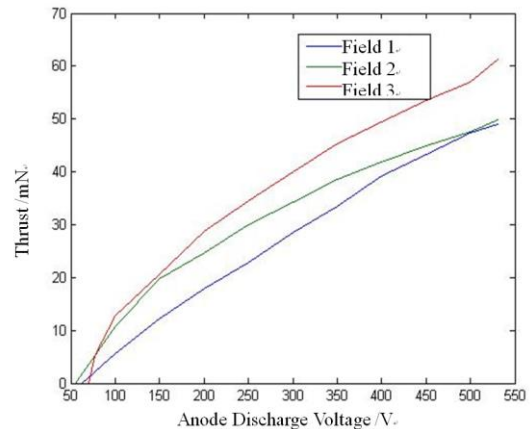


Fig.7 Curve of thrust change with discharge voltage in 3 different configurations

The change trends of discharge current varying by adjusting anode discharge voltage of three different kinds of magnetic field configuration at the anode Xenon flow rate of 30sccm are shown in **Figure 9**. The trends are roughly the same among different magnetic field configurations. The current in magnetic field configuration 3 is larger than that in the other two configurations at the same discharge voltage. The current tends to be stable when the discharge voltage is over 200V in all these three magnetic field configurations. The volt-ampere characteristics of discharge current in magnetic field configuration 3 at different anode Xenon flow rate as shown in **Figure 10**, which is similar to the other two kinds of magnetic field configurations. With the increase of anode Xenon flow rate, the discharge current also increases gradually. The increasing trends of volt-ampere characteristics of discharge current are roughly the same at different anode flow rates from 10 to 50sccm.

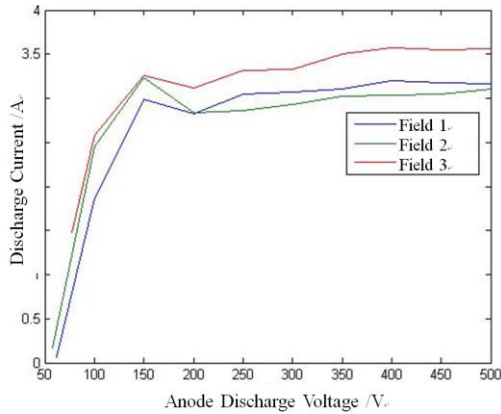


Fig.9 Volt-ampere characteristics in 3 different configurations at constant flow rate

The thrust and the efficiency of the thruster increases with the increase of anode Xenon flow rate at a constant voltage, magnetic field configuration and Xenon flow rate. The functional relation between thrust and the anode gas flow rate is linear, but the functional relation between efficiency and anode gas flow rate is approximate parabola shape. The increasing rate of efficiency decreases with the increase of anode flow rate.

The experimental results of German Thales Electron Devices GmbH showed that the trends of volt-ampere characteristics of discharge current maintain stable when the discharge voltage is over 300V at different anode flow rates from 10 to 46.5sccm⁵. The results are roughly coinciding with the results in this paper. The comparison with German HEMP-T 3050 and 30250⁶ shows that the thrust and plume divergence have achieved good results in these experiments. The thruster can achieve higher thrust and higher efficiency with higher power supply. The efficiency still needs to be improved by optimizing magnetic field configuration to increase ionization rate.

At the same time, the filtering oscilloscope, which monitors the low frequency oscillation of anode current, shows that the anode current oscillation characteristic of magnetic field. According to oscillation situation of discharge current, the performance can be divided into 3 different working modes: Low Oscillation mode (LO mode), High Oscillation mode (HO mode) and Cyclical Damped Oscillation mode (CDO mode). LO mode is a relatively stable mode that the thruster can work in a sustainable stable situation. HO mode is an unstable mode with high amplitude of oscillation in discharge current. CDO mode is a coincidence mode mixed with low oscillation parts and damped oscillation parts cyclically. It is found that in these 3 magnetic field configurations, the oscillation situation undergoes these 3 modes with the increase of anode discharge voltage. Take magnetic field configuration 3 as an example. When the discharge voltage is lower than 150V, the thruster is in LO mode. The oscillation of discharge current gets more severe with the increase of anode discharge voltage. When the anode discharge voltage is 250V, the amplitude of oscillation reaches peak, the thruster gets into HO mode. The HO mode turns into CDO mode with the increase of anode discharge voltage gradually. When the anode discharge voltage is larger than 300V, the oscillation of discharge current maintains LO mode. In these 4 steps of oscillation variation, the amplitude is lowest configuration design 3.

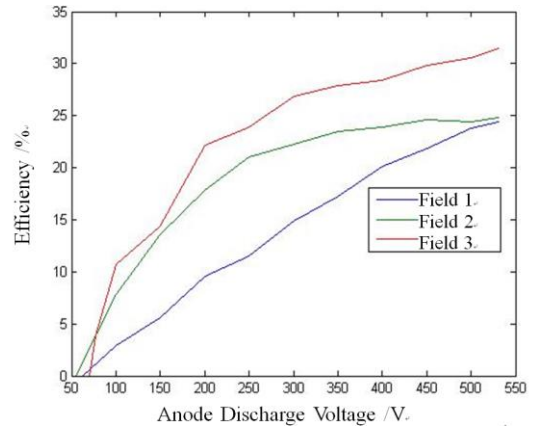


Fig.8 Curve of efficiency change with discharge voltage in 3 different configurations

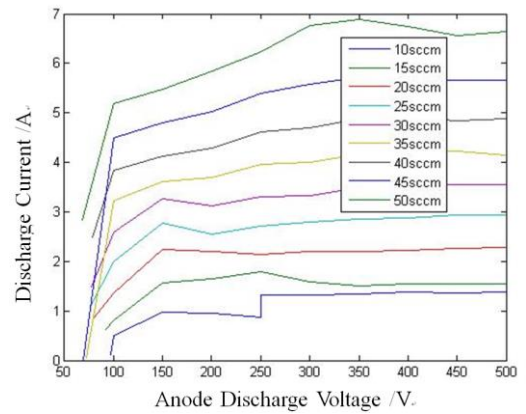


Fig.10 Volt-ampere characteristics at configuration 3 in different flow rate

IV. Conclusions

Through principle research, numerical simulation, prototype design and experimental study of VML-CFT Mk2, it is proved that the performance of thruster varies in different magnetic field configurations. The results show that the VML-CFT designed by Harbin Institute of technology has achieved the performance of 107.45mN in thrust, 38.02% in efficiency, 2232s in specific impulse and effectively controlled plume divergence less than 20 degree at the conditions of 3037W in power, 3sccm in cathode Xenon flow and 50sccm in anode Xenon flow. The best magnetic field configuration is 3 of these three kinds. The thruster with a longer middle stage, less magnetic interface angle and weak cusp field intensity in the exit has a greater thrust and efficiency.

Some problems still need to be solved in the following designs and experiments. The magnetic field configuration needs further research to optimize. It would be effective to realize the real-time adjustment of the cathode position in the experiment to study the impact that cathode position has on the discharge current oscillation. The anode discharge power supply voltage variation range need to be increased.

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