Development of High Power Magnetoplasmadynamic Thrusters in BICE and Beihang University

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Abstract: High power MagnetoPlasmaDynamic Thrusters (MPDTs) are treated as one of the most potential candidates for future high-power space missions, like manned Mars exploration, due to the high specific impulse and high thrust density. Since 2013, a 100kW class applied-field magnetoplasmadynamic thruster (AF-MPDT) has been developed in Beijing Institute of Control Engineering (BICE) and Beihang University. The thruster currently has reached the power of 100kW, the thrust of 3N, the specific impulse of 4300s and the thrust efficiency of 67%. In this paper, configuration of the thruster, some simulation works and the latest ground experiments are introduced.

I.Introduction

High power magnetoplasmadynamic thrusters (MPDTs) are treated as one of the most potential candidates for future high-power space missions[1,2,3], due to the high specific impulse and high thrust density. Taking the manned Mars exploration as an example, assuming the weight of the spacecraft is 100 tons and the total velocity increment is 6.6km/s, 347 tons of fuel are needed for Earth- Mars transfer, if employing conventional chemical propulsion, with specific impulse of 450 s. While, if employing MPDT with specific impulse of 8000s, only 8.78 tons of propellant are needed. Thus, the application of high power MPDT can increase the ratio of payload greatly. Besides the high specific impulse, MPDT can provide relatively large thrust, comparing with Ion thruster and Hall thruster, which can decrease the mission period significantly. In order to obtain high specific impulse and high thrust simultaneity, the power of MPDT need to be raised. Aiming at a MPDT with the potential to be applied in actual space mission, a 100kW class MPDT has been developed under the cooperation of BICE and Beihang University since 2013.

There are several aspects that limit the application of MPDT, such as thrust efficiency, cathode lifetime, heavy magnetic coil. In fact, the thrust efficiency can be promoted significantly by using alkali metal lithium as propellant[4,5,6]. The highest thrust efficiency, with propellant lithium, is 69%, according to reference [1]. However, the high activity of lithium makes it a challenge to apply in the satellite. The latest research from IRS[7] shows that thrust efficiency of MPDT can reach 59% with propellant of Argon, which bring new hope for further promoting of the thrust efficiency of MPDT with regular noble gas propellant. The mass of magnetic coil can be decreased by the application of super-conducting coil or permanent magnet. One of the main causes for the short cathode lifetime is the high current density on the cathode surface. Then, there are two strategies to extand the lifetime of the cathode naturally, i.e. increasing

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the emmision capacity of unit area and increasing the total emission area. The fisrt one is related to cathode meterial and the sencord one is related to cathode structure.

Aiming at the above challenges, we made the following research plans. Firstly, a 100kW class MPDT is designed, with a series of configuration optimization. To extend the cathode lifetime, multi-channels hollow cathodes, made of different meterials. In addition, a super-conducting magnetic coil is under building, will can reduce the total mass of the thruster from 100kg to 35kg.

II.Experiment facility

A. Vacuum chamber

The diameter of vacuum chamber is Φ3 m × 5 m, with a mechanical pump, one molecularity pump, three cryopumps. The total pump speed of the pump group can reach 20000L/s. The ultimate vacuum degree of the vacuum chamber is 1E-4, and the working vacuum degree depends on the actual propellant mass flow rate. For example, when the mass flow rate of propellant is 40 mg/s, the working vacuum degree is 0.01 Pa, and when the mass flow rate of propellant is 80 mg/s, the working vacuum degree is 1 Pa.

Figure 1 The vacuum chamber, employed in the experiment

B. AF-MPD thruster

There are several stages in the development of AF-MPDT in BICE and Beihang University. The initial 20 kW class Radiation-cooling Applied-field Magnetoplasmadynamic thruster(MAT-20), with a single hollow cathode and cylindrical anode, is shown in Figure 2. The highest power of the thruster is 21kW, with thrust of 330mN, specific impulse of 3200s and thrust efficiency of 23%, measured with target thrust stand. There are independent propellant supply channels in the central of hollow cathode and inner face of anode, which can be used to research the influence of propellant supplying strategy on thruster performance. In addition, the outer profile of anode is slim cylindrical, which can provide the convenience to research the influence of axial magnetic field position on the thruster performance.

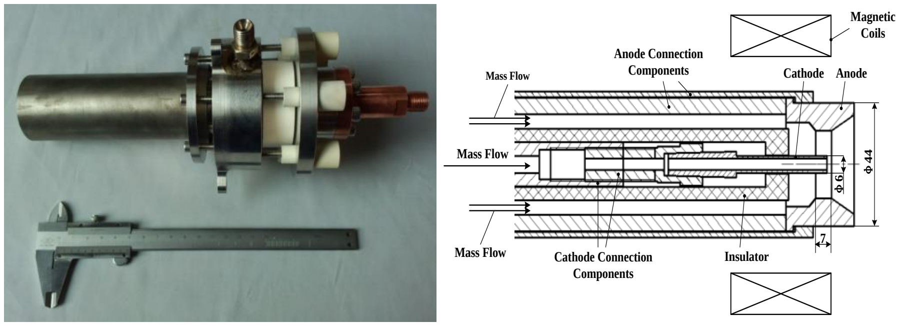

Figure 2 The physical and schematic view of MAT-20

Despite the designing of MAT-20 ensures plenty of adjustable working parameters, it cannot work continually for a long time, due to the limited cooling capacity. To fit the engineering application, a 100kW class Water-cooling Applied-field Magnetoplasmadynamic thruster (MAT-100) was developed under the cooperation of Beijing Institute of Control Engineering and Beihang University. The design targets of the thruster are high performance and capacity of continually working. According to the target, we adapted the following designing:

1) Multi channels hollow cathode. The cathode is made of tantalum tungsten, with nine propellant channels. There is a large cavity inside the cathode base connecting with nine narrow cylindrical channels. The cavity acts as a buffer to increase the uniformity of the propellant distribution in nine channels. The outer diameter of the cathode is 16 mm. There is a water-cooling copper holder around the cathode base, which can take away the heat, deposited in cathode during work.

2) Short divergent anode. According to our previous experiments, divergent anode is more effective for performance improvement, comparing with flat or convergent-divergent anode, despite the stability may be worse. In addition, to decrease the anode power deposition, relative anode length (anode length to anode inner radius) is reduced from 2 to 1, comparing with MAT-20.

3) Cathode-only propellant supplying. We found that increasing the cathode region propellant supplying can improve the thruster performance[8]. In order to obtain better performance and simplify the structure of MPDT, we abandoned traditional anode propellant channel and supply the whole propellant from the nine channels in the hollow cathode.

4) Cathode retraction. Cathode-only propellant supplying strategy may cause anode starving. To improve the stability of the thruster, we retracted the cathode, which can increase the residence time of electrons in the discharge chamber and relieve anode starving further.

5) Water-cooling structure. To ensure the thruster can works continually, effective heat transfer structure is necessary. And considering the design power of the thruster is 100kW, there will be considerable power deposited in anode and cathode[9,10]. Thus, both anode and cathode are equipped with water-cooling structure. To ensure the heat transfer effeciency is high enough to keep the temperature of anode and cathode in acceptable range, we simulated the heat exchange of thruster, the results of which are shown in Figure 4.

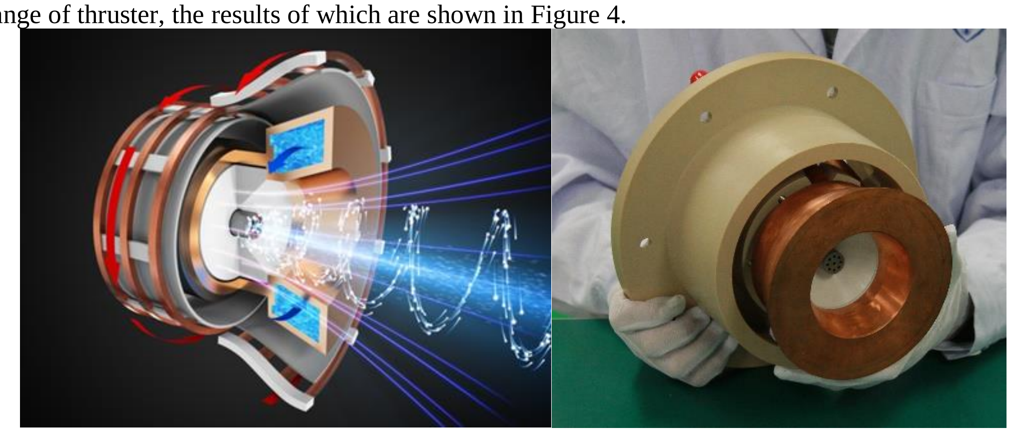
Figure 3 100kW class water-cooling applied-field magnetoplasmadynamic thruster

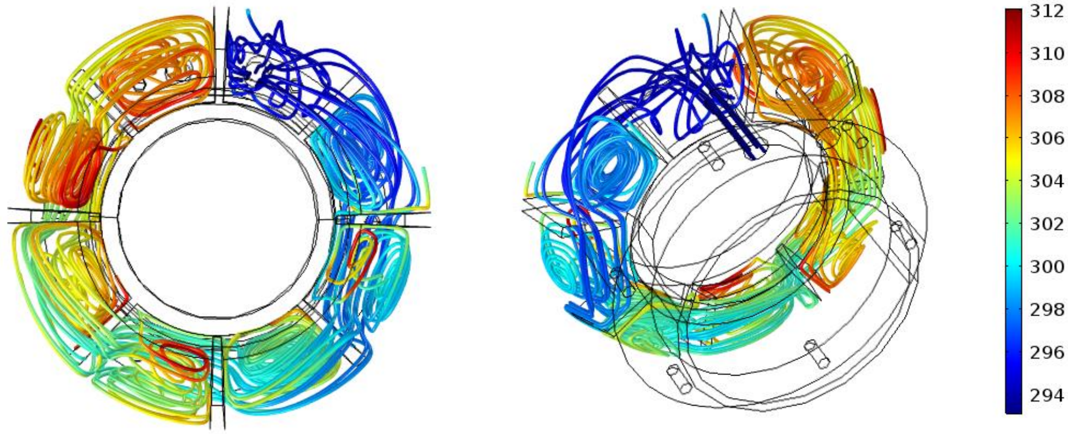

Figure 4 Thermal simulation result of anode

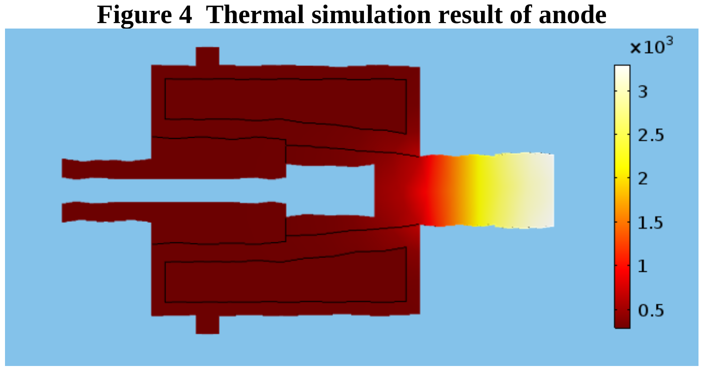

Figure 5 Thermal simulation result of cathode

C. Magnetic coil

The external magnetic field can influent the performance of MPDT significantly, and the shape of the magnetic field is directly determined by the magnetic coil. In order to determine the coil shape suitable for MPD, we simulated the magnetic field of coils with different structures. As shown in Figure 6. Here we define coil parameter $K= (D_O-D_I)/2d$, where D_I is the inner diameter of the coil, D_O is outer diameter, and d is the thickness. The parameter K can be treated as the characterization of coil shape. We simulated the magnetic field of 8 coils, where the value of K is 18,9,6,4,2,1,0.5 and 0.25, respectively. In addition, D_I is set as 200mm according to actual structure of the thruster. And the coil current is set as 100A. Considering that the anode exit face is coincidence with the side face of the coil in actual experiment, we choose the intersection point of coil side face and coil axis as the base point of axil line. Then the axial magnetic field strength of 8 coils can be compared, as shown in Figure 7. It can be found from the figure that, at base point, the strongest magnetic field is reach when K=1.

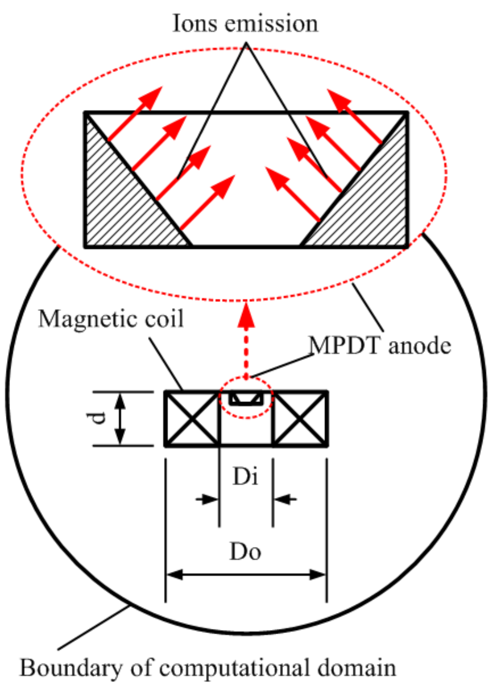

Figure 6 Simulation model of magnetic field and magnetic nozzle

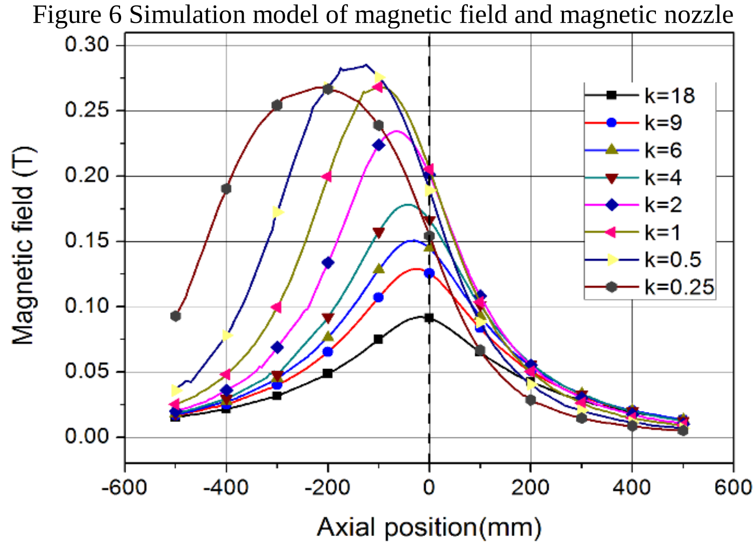

Figure 7 The axial magnetic field strength of the coils based on the exit of the coils

In addition, we simulated the moving of ions in the magnetic field. Assuming that the initial velocity is vertical to anode surface, the initial kinetic is 100eV and the divergence angle of anode is 45°, the changing of axial ions velocities at different axial positions can be drown in Figure 8. It can be found that, with the increasing of axial positions, the axial velocity of ions always decreases first and then increase, which is a part of magnetic nozzle effect[11].

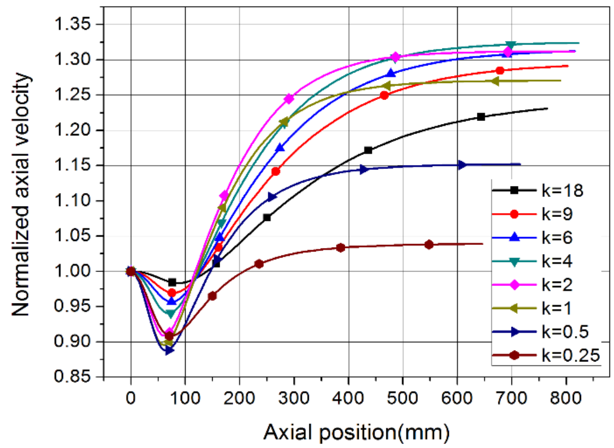

Figure 8 Simulation results for swirl acceleration

We draw the magnetic field intensity and ion kinetic energy conversion rate at the datum point of eight groups of coils in Figure 9, from which, it can be seen intuitively that with the increase of K, the magnetic field intensity and ion energy conversion rate increase first and then decrease. The peak of ion energy conversion rate do not coincide with the peak of magnetic field. The reason is that the concentration degree of magnetic field keep increase with K and an high conversion rate needs both intensity and concentration of the magnetic field.

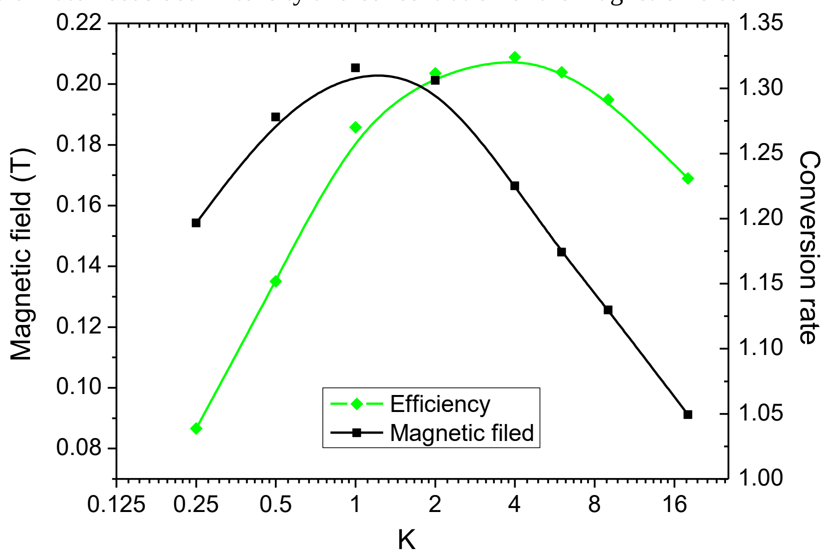

Figure 9 Comparison of magnetic field intensity and thruster energy conversion rate under different magnetic field shapes

D. Thrust stand

Due to the large mass of the magnetic coil and strong oscillation caused by high pressure cooling water, it is a challange for traditional thrust stand to measure the trust of MPDT. Thus, a target thrust stand was designed, as shown in Figure 10. The working mechanism of target thrust stand is shown in Figure 11. the target is made of graphite with diameter of 600mm. the impact force acting on the target bends the elastic beam, the displacement of which will be recored by laser displacement sensor. the relationship between the displacement and the force can be obtained by the callibration of thrust stand, which will be finshed before the thrust measuremnt experiment. the impact force is not exactly equal to the true thrust according to reference [12], the relation between them can be expressed as equation (1), if the plasma beam can be covered totaly by the target.

$$T = F + 3.07\dot{m}\sqrt{T_k/M} \quad (1)$$

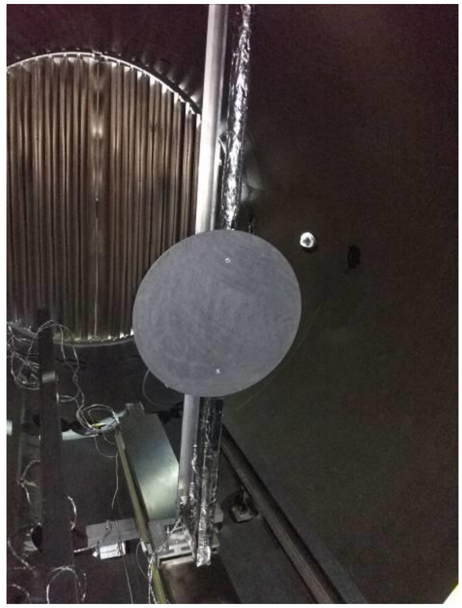

Figure 10 Front view of target thrust stand

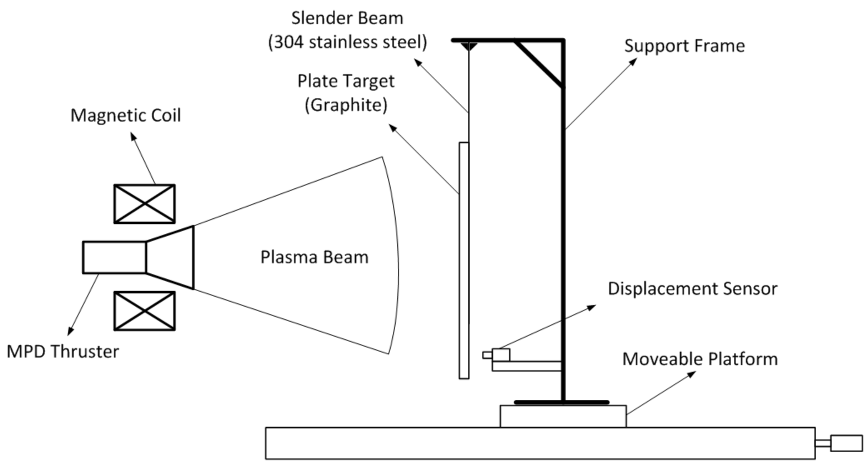

Figure 11 Structure diagram of target thrust stand

To assess the accuracy of target thrust stand, we measured the thrust of a 3kW class Hall thruster, with target thrust stand and traditional thrust stand simultaneously. The measured thrust of target thrust stand is 118mN, while the result of traditional thrust stand is 120mN.

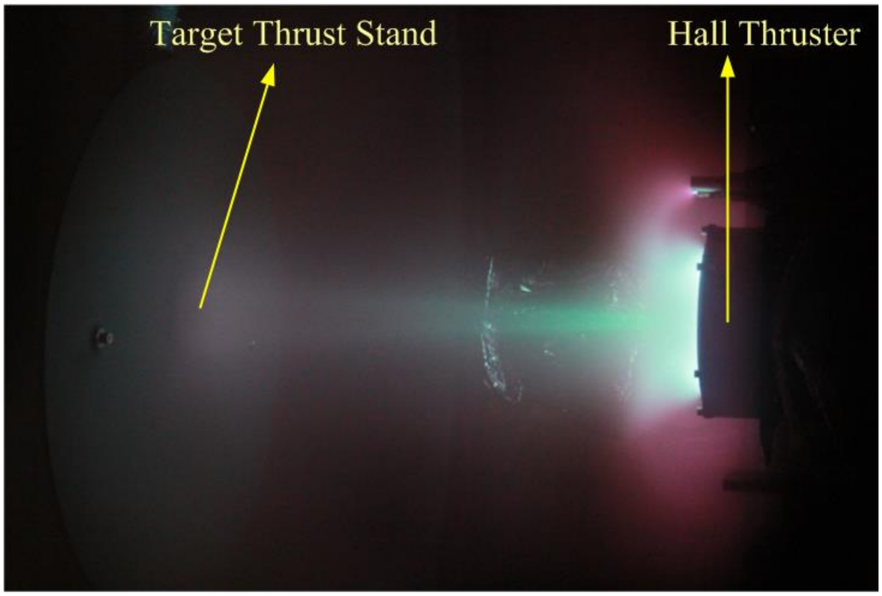

Figure 12 Thrust measuring for 3kW Hall thruster with target thrust stand and traditional thrust stand

III.Experiment works

A. Thruster performance

Series of thrust measurement were held to analysis the thrust characters under the influence of propellant mass flow rates, discharge current and applied magnetic field. the detail operation parameters are listed in Table 1.

Table 1 Trust measurement operations parameters of MAT-100

<table>
<tr><th>Discharge current/A</th><th>Applied magnetic field /mT</th><th>Propellant mass flow rate /mg/s</th></tr>
<tr><td rowspan="8">200</td><td>30</td><td rowspan="8">40</td></tr>
<tr><td>60</td></tr>
<tr><td>90</td></tr>
<tr><td>120</td></tr>
<tr><td>150</td></tr>
<tr><td>180</td></tr>
<tr><td>210</td></tr>
<tr><td>230</td></tr>
<tr><td>140</td><td rowspan="12">90</td><td rowspan="12">40</td></tr>
<tr><td>160</td></tr>
<tr><td>180</td></tr>
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<tr><td>260</td></tr>
<tr><td>280</td></tr>
<tr><td>300</td></tr>
<tr><td>320</td></tr>
<tr><td>340</td></tr>
<tr><td>360</td></tr>
</table>

Figure 13-Figure 15 show how the thrust varies with the applied magnetic field. The vertical coordinate represents the actual measured thrust values. The following conclusion can be obtained from the figures:

(1) Under all working conditions, increasing the applied magnetic field strength can effectively improve the thrust.

(2) In different magnetic field intensity range, the increasing rate of thrust with magnetic field is not uniform. The increasing rate is lower in the range of 20-80mT, and higher in the range of 0-20mT and 80-127mT.

(3) Under the same magnetic field intensity, the thrust can be increased by increasing discharge current and cathode propellant supply ratio (the total propellant supply remains unchanged).

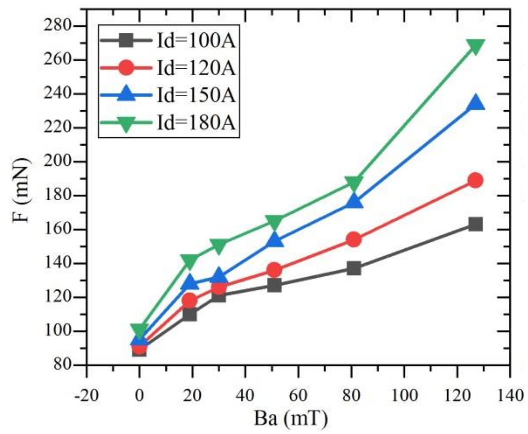

Figure 13 The Variation of Thrust with Applied magnetic field(m_c: m_a =1:4)

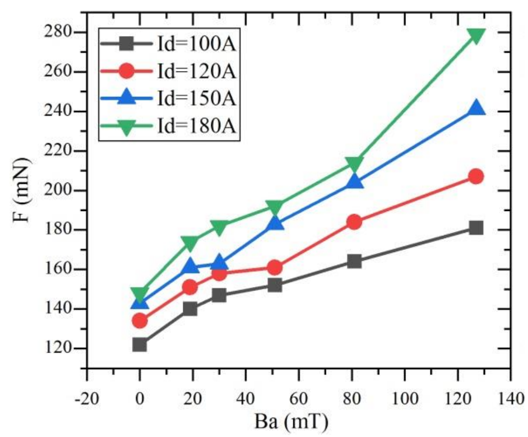

Figure 14 The Variation of thrust with applied magnetic field(m_c:m_a=1:1)

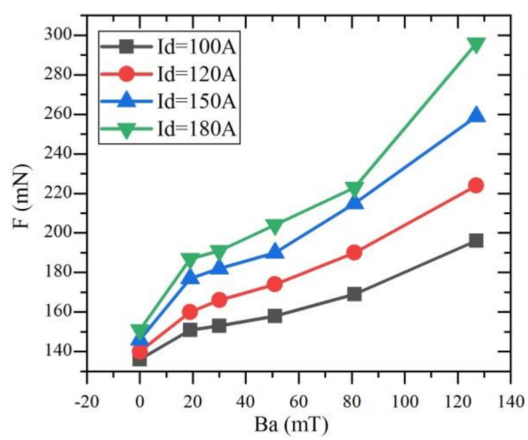

Figure 15 The Variation of thrust with applied magnetic field (m_c:m_a =4:1)

The experimental results of 100 kW MPDT are shown in Figure 17-Figure 24. The thrust, specific impulse, discharge voltage and efficiency of the thruster are used to evaluate the performance of the thruster.

Figure 16 shows the plume of MAT-100 and Figure 17-Figure 20 show the performance changes of the thruster under different applied magnetic field intensities. As can be seen from the figures, with the increasing of the applied magnetic field, the thrust and specific impulse of the thruster increase gradually, and the inflection point appears near 120 mT. The discharge voltage increases linearly with the applied magnetic field. In general, the efficiency increases with the increase of the applied magnetic field, but there is a significant change around 120mT. Before 120 mT, the efficiency increases linearly with the increase of the magnetic field intensity, and after 120 mT, the growth rate decreases rapidly.

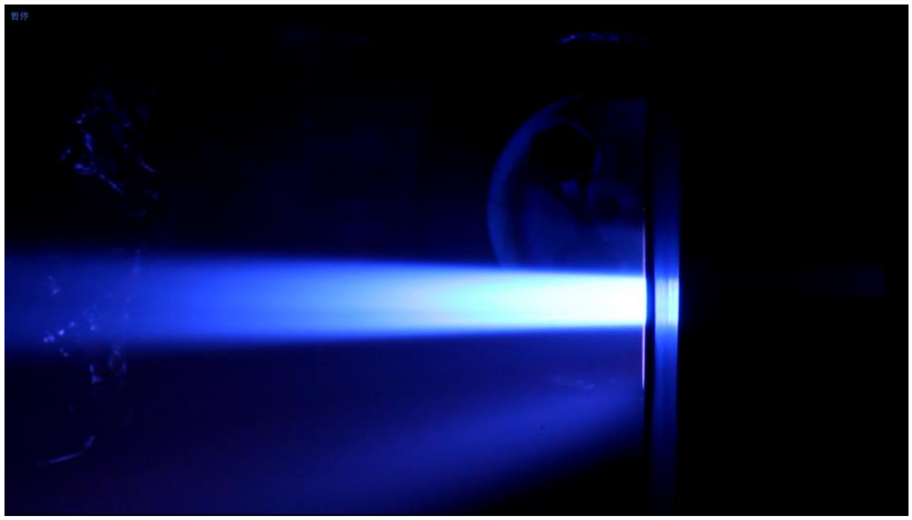

Figure 16 The view of MAT-100 plume

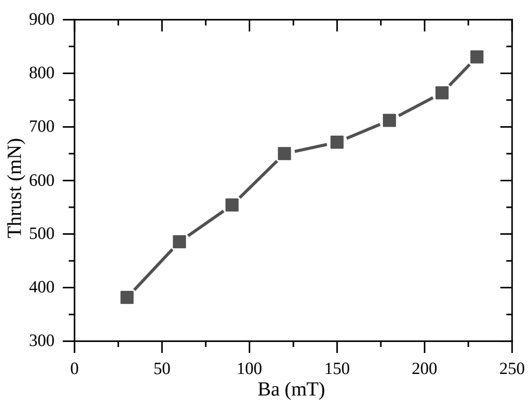

Figure 17 Influence of Ba on thrust

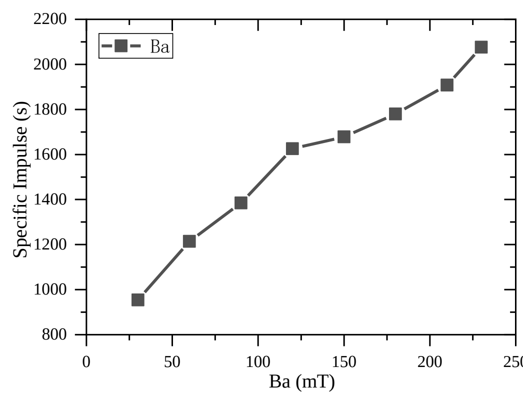

Figure 18 Influence of Ba on specific impulse

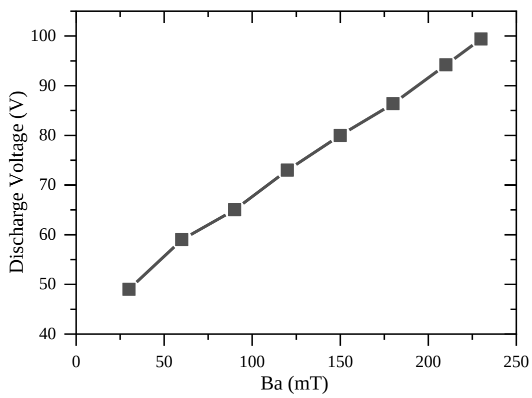

Figure 19 Influence of Ba on discharge voltage

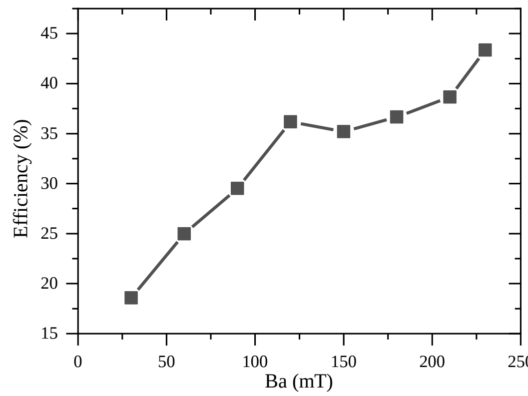

Figure 20 Influence of Ba on thrust efficiency

Figure 21-Figure 24 show the effect of the discharge current thruster on the thruster performance. As shown in the figure, with the increase of discharge current, thrust, specific impulse and efficiency continue to increase. Within the current range of 160-260A, the discharge voltage increases with the increase of current. When the current is below 160A or higher than 260A, the discharge voltage decreases with the increase of discharge current.

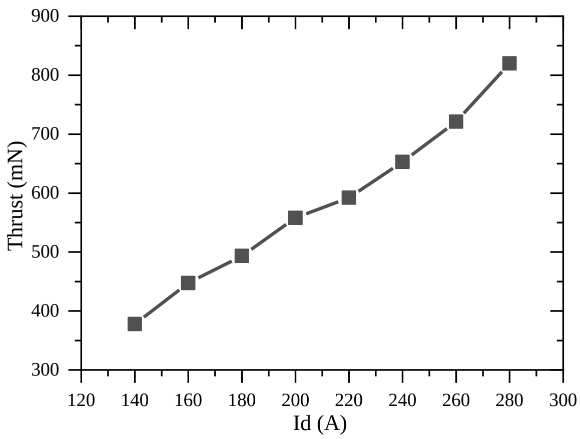

Figure 21 Influence of Id on thrust

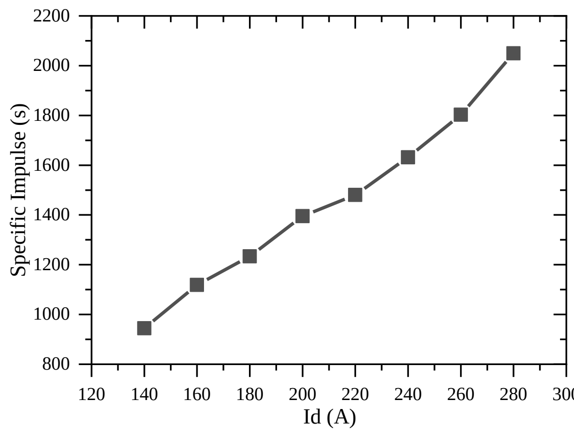

Figure 22 Influence of Id on specific impulse

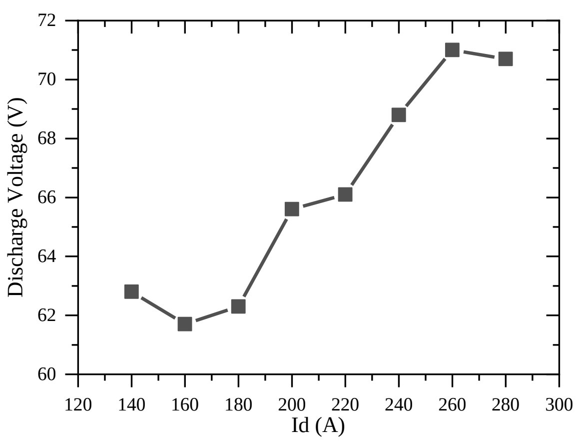

Figure 23 Influence of Id on discharge voltage

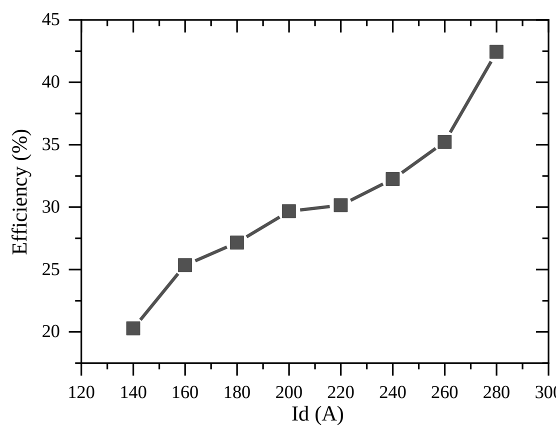

Figure 24 Influence of Id on thrust efficiency

In the thrust measurement for two kinds of thrusters, the influence of applied field strength and discharge current were both researched. According to the experiment results, the sensitivity of thrust to Ba and Id are different for the two thrusters. Figure 25 shows the changing of thrust with different discharge current and applied field magnetic field. And (a)-(c) are the experiment results of MAT-20, with ratio of anode propellant to cathode propellant 1:4, 1:1, 4:1

respectivly. (d) shows the results for MAT-100. It can be found that the thrust of MAT-20 is more sensitive to applied field, comparing with discharge current. And for MAT-100, the influence of Id and Ba are similar.

The origin of the difference may coms from the different thruster structures, where MAT-100 is pure cathode propellant supplying. This structural change will make the heating and ionization of neutral gases easier, caused by the primary electrons emitted from the cathode.

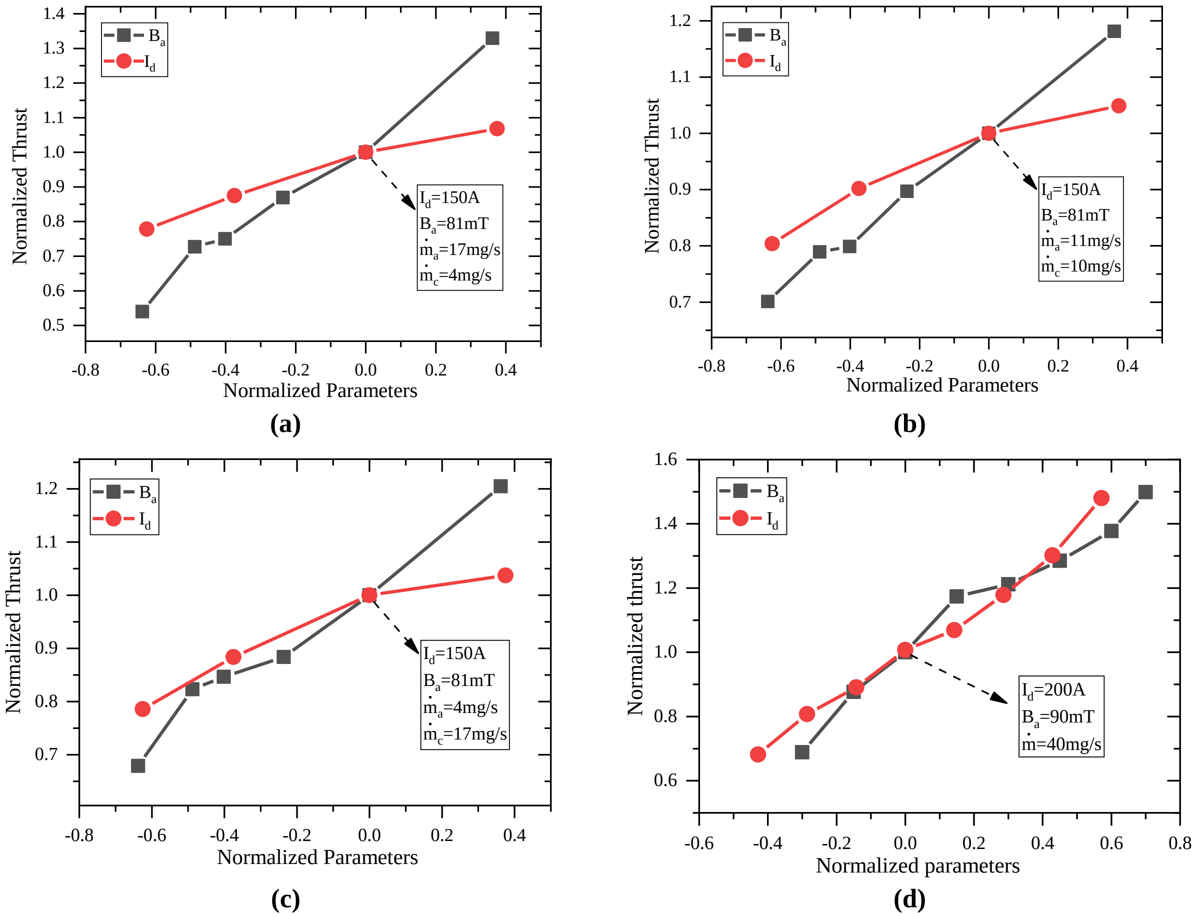

Figure 25 Comparing of thrust measurement results

Table 2 Comparing of the sensitivities of thrust to Id and Ba

	(a)	(b)	(c)	(d)
Cathode propellant to anode propellant	1:4	1:1	4:1	Cathode only
Slope of thrust-magnetic field curve	0.742	0.475	0.485	0.738
Slope of thrust-current curve	0.292	0.243	0.253	0.746
Slope ratio of magnetic field to current curve	2.545	1.958	1.913	0.989

Besides the thrust measurements in low power range, we measured the performance around 100kW, as shown in Figure 26. The largest thrust is obtained at 99.5kW**[13]**, which is 3.2N, with specific impulse of 4359s and thrust efficiency of 67%. The measued thrust is obtained from Eq.1**[13]**, while the theratical thrust is obtained according to Eq.2[14].

$$T_m = \frac{F}{2} \cdot \left(\frac{704}{600}\right)^2 = 0.69F \qquad (1)$$

$$T_t = \frac{25}{A^{0.25}} \sqrt{\frac{a}{\bar{\varphi}} \frac{R(R+1)\sqrt{R-1}}{\sqrt{R^{3.8}}-1}} \sqrt{\dot{m}IB} \qquad (2)$$

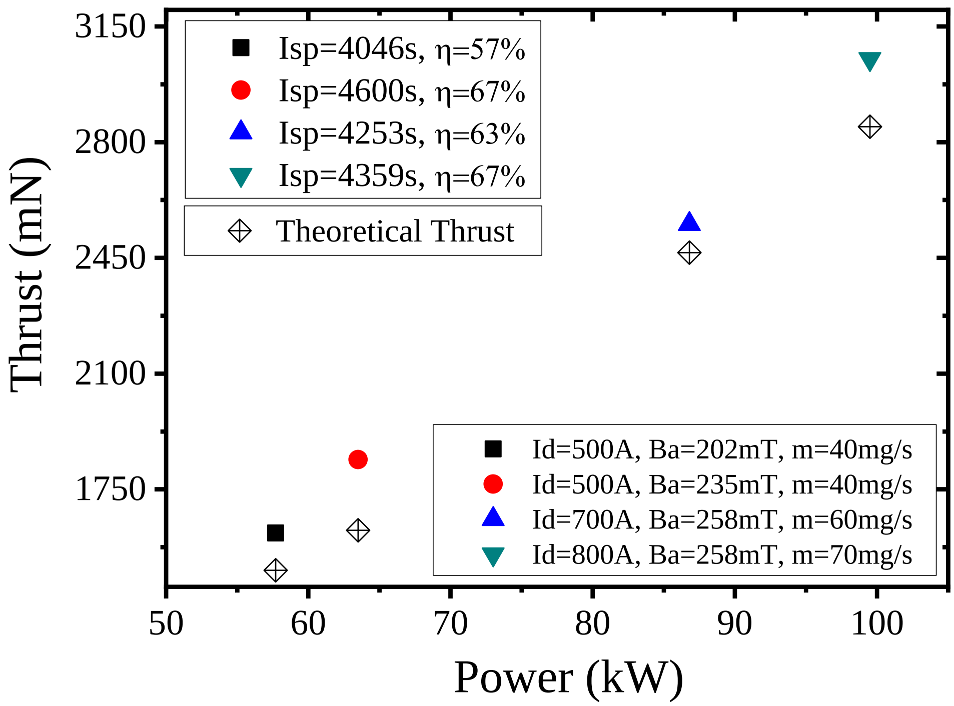

Figure 26 Performance of the thruster in the power range of 50-100kW [13]

In addition, the temperature changes between the inlet and outlet cooling-water of the thruster were measured to evalue the thrust efficiency from the view of energy conversation. Four thermalcouples were adhibitted on the out surface of cooling-water pipes respectively. The mass flow rate of ande cooling-water is 0.59kg/s, with inlet temperature of 11.2℃ and outlet temperature of 15.6℃. And the mass flow rate of cathode cooling-water is 0.54kg/s, with inlet temperature of 10℃ and outlet temperature of 11.5℃. Then the power deposited in the electrodes can be evalued according to Formula (2).

$$P_E = c_w \dot{m}_w \Delta T \tag{3}$$

where P_E is the power deposition in electrodes, c_w is the specific heat capacity of water and ΔT is the termperature changes between inlet cooling-water and outlet cooling-water.

The total electrodes power deposition is 14.4kW, while the total power is 99.5kW. Then the thrust efficiency of should be lower than 85.5%, which is higher than the measued thrust efficiency.

B. Cathode material

Different cathode was employed to analysis the influence of cathode material on cathode erosion characters. As shown in figure 27, the left cathode is made of tungsten, while the right cathode is made of tantalum-tungsten. Due to the improving of cathode material, the erosion rate decreases greatly. And cathodes made of different material show different erosion characters. There are many large melting zones on the surface of pure tungsten cathode. However, the Ta-W cathode is covered with tiny spots, which is the caused by the ions sputtering.


Figure 27 Cathode erosion characters

IV. The latest works

To meet the demand of high-power space mission, a 150kW class AF-MPDT with super-conducting magnetic coil has been buit, which is named as MATS-150. The coil structure is shown in Figure 28 and the largest magnetic field at the center of the coil is 1.2T, which allows further exploration of the thruster performance. And the weight of the coil will be much lower than tradition magnetic coil. The preliminary thrust measurement shows that the performance of the thruster can be improved further. The detail data about MATS-150 will be introduced after the comprehensive test.

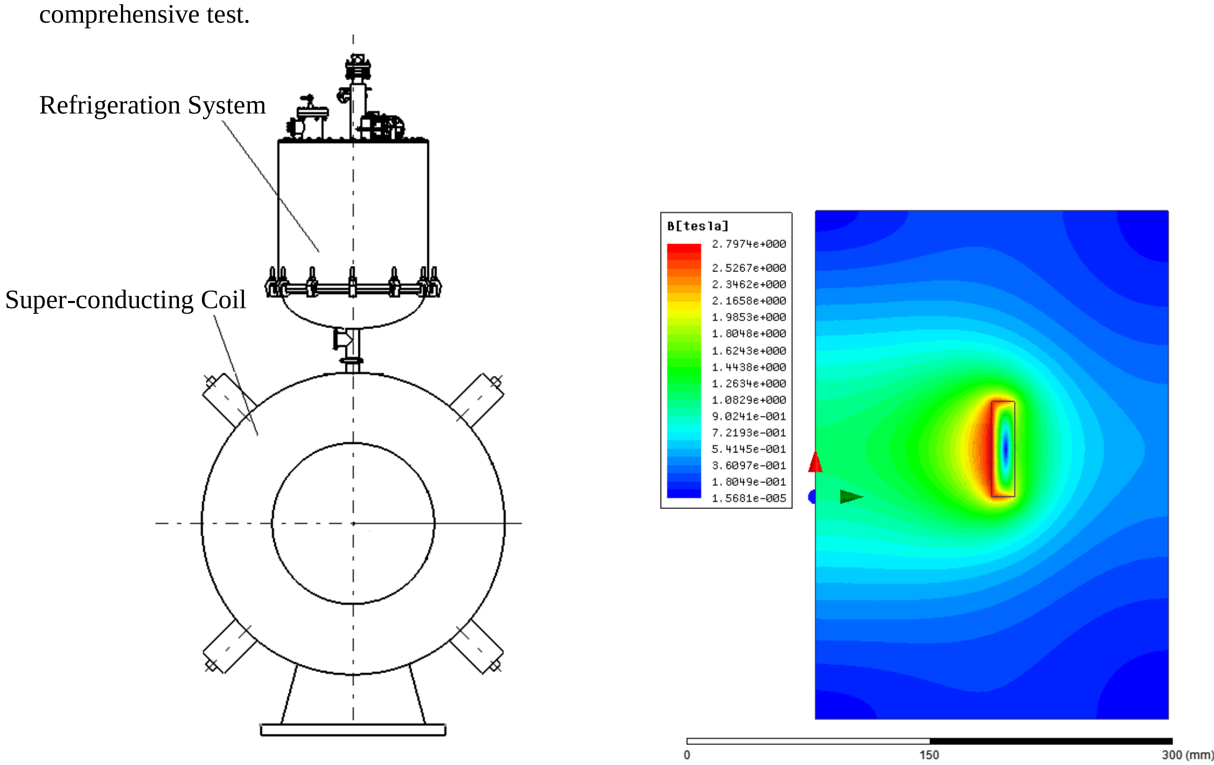

Figure 28 Super-conducting magnetic coil structure and manetic field

V. Conclusion

A new designed 100kW class water-cooling applied-field magnetoplasmadynamic thruster is introduced. A serious of configuration optimizations are applied to the thruster, including multichannels hollow cathode, cathode-only propellant supplying stragedy, shorted flat-devergent anode and cathode retraction layout. The energy translate efficiency of ions under eight groups of magnetic coils with different shapes is simulated and the optimization coil shape is gived. A target thrust stand is designed to measure the thrust. The influence of magnetic coil and discharge current on the thrust is researched at middle power range and the results of which are compared with MAT-20, a 20kW class radiation-cooling AF-MPDT. According to the comparation, the configuration optimizations of MAT-100 can improve the performance effectively. Besides the performance in middle power range, we tested the performance of MAT-100 in high power range. The highest thrust efficiency is 67%, with power of 100kW, thrust of 3N, specific of 4300s. In addition, different materials are employed to bulid the multi-channles hollow cathode.

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