

Effect of magnetic field on anode temperature distribution in a Hall thruster

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Abstract: The power dissipation caused by the absorption of electron energy from the anode is a prominent power loss in the Hall thruster, and the resulting anode heat will have an effect on the performance and reliability of the thruster. In this paper, we focus on a Hall thruster with a structure of anode loop, and study the variation rule and mechanism that a change of magnetic field intensity and gradient affects the axial power distribution of the anode loop power, with both the experimental measurement and Particle-in-Cell simulation. It is proposed to establish an understanding of the electronic regulation by magnetic field in the near-anode region by this study, and to guide the matching design of the magnetic field and the anode in the near-anode region. It is found that the axial temperature distribution on the anode ring does not change along with the magnetic field intensity. In order to understand more deeply the interaction between discharge plasma and channel wall and provide references for the design of modern Hall thrusters, the rule and mechanism that a divergent channel affects the performance of a Hall thruster are investigated in this paper. With both the experimental measurement and Particle-in-Cell simulation, it is found that there is a moderate divergence angle that can further improve the optimal performance

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obtained with a straight channel. The reason is that the divergence of channel near the channel exit can enhance ion acceleration and reduce ion recombination on the wall effectively, which is favorable for the promotion of thrust and efficiency. However, the divergence angle should not be too large; otherwise, both the density of propellant gas and the two dimensional distribution of plasma potential in the channel would be influenced, which is harmful for the propellant utilization and beam concentration. Therefore, the design of the magnetic field near the anode is very important.

I. Introduction

Hall thrusters are ion thrusters with wide applications in aerospace and broad prospects for future development¹. Compared with chemical propulsion, the electric propulsion has the advantage of high specific impulse, which can increase either the payload ratio of satellites or the total impulse of propulsion system greatly. Therefore, the electric propulsion is replacing the chemical propulsion to be the main power engine on satellites at present². In principle, a Hall thruster is a kind of plasma discharge device, in which an orthogonal electric and magnetic field is utilized to ionize and accelerate the propellant gas³.

Anode is an important part of Hall thruster. The high potential of the anode is the energy source of the charged particles, on the one hand, give the electrons sufficient energy to ionize neutral gas, on the other hand, make the ionized gas get enough electric field energy to accelerate, thus ensuring the efficient output of the Hall thruster. When the thruster is working, the anode will continue to absorb various electrons which conduct from somewhere else, including the cathode emission, ionization and wall secondary emission, etc. to ensure the continued discharge. When the electrons are absorbed by the anode to form a loop current, the energy in electron is converted into heat by the anode, putting the anode in a high temperature state.

A number of specialized studies on theoretical and technical issues related to the anode have been carried out. L. Dorf et al. by theoretical analysis found that the state of the anode sheath is related to the operating conditions of the thruster (discharge voltage, mass flow, etc.). They found with the experimental diagnosis that the anode sheath state change with the impact of the anode surface state (clean or coated)⁴. Finally, the formation mechanism of the anode sheath is obtained by analyzing the path of electron current in the anode closed loop⁵. L. Dorf argues that since the coating greatly reduces the effective area of the anode, the power density deposited on the anode is significantly increased and easily lead to overheating. In addition, C. F. Book and M. L. R. Walker exerted active cooling on the anode. They found with experimental measurements that the anode temperature can significantly improve the performance of the Hall thruster for certain conditions by influencing the flow rate of the neutral gas. It is advisable to take thermal management measures on the anode⁶.

The studies above have taken note of the close relationship between the anode temperature and the performance and reliability of the Hall thruster, which is an important factor that must be considered in the anode design. Based on this, the temperature distribution characteristics and formation mechanism of the anode of the Hall thruster are studied in this paper.

With the continuous development of technology, the structure of Hall thruster has become diversified (various), so it is with the structure of anode. On a classic configuration thruster, represented by SPT-100, the gas distributor is powered and acts as an anode⁷. And on this basis, many Hall thrusters have been designed to extend the structure of anode. The SPT-ATON turns the anode into a separate component, which is designed in a circular shape to fit the outer wall of the discharge channel⁸. The BPT-4000 replaced the inner and outer walls, which was originally insulating ceramic material inside the discharge channel, with a ring-shaped metal conductive material, as part of the anode⁹. In the bipolar Hall thruster, such as SPT-MAG, DS-HET, an annular metal part was arranged, which was close to the inner wall or the outer wall, as the anode.

The Hall thruster studied in this paper has an separate anode structure, which is similar to that of the bipolar Hall thruster as in Ref.[8], as shown in Figure 1. In addition to the gas distributor, there is a separate metal loop near the outer wall as the anode. When the gas distributor and the metal ring are loaded voltage, the discharge mode turns into the bipolar mode of operation. However, in the study of this paper, the gas distributor was placed in a suspended state, and only the metal anode loop was applied discharge voltage, and all the electrons were absorbed by the anode loop. On the premise of this, the characteristics of the axial distribution of the annular anodes at different magnetic field intensities and gradients are studied in this paper. The mechanism of the temperature distribution on the anode loop in the near-anode region is clarified, which guides the matching design between the anode loop and magnetic field.

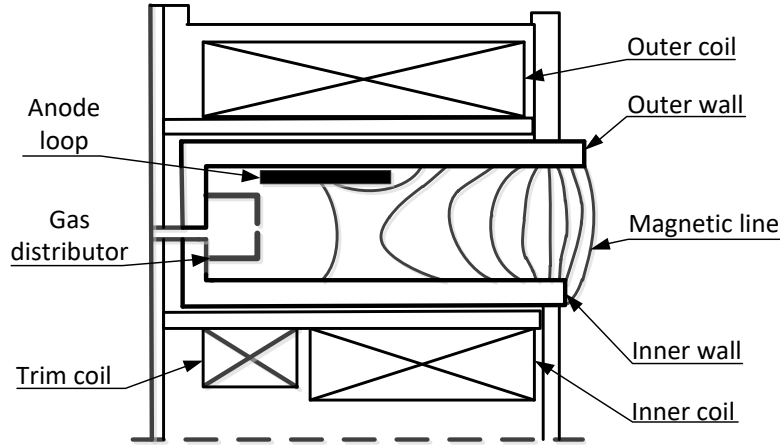


Figure 1. P100 Hall Thruster

The following structural arrangements are as follows: the second part introduces the method and scheme of studying the temperature distribution of the anode loop. The third part expatiates and discusses the research results. The fourth part summarizes the research work and gives the conclusion.

II. Research program

A. Experimental design and apparatus

In this experiment, the temperature of the anode loop was measured by K-type thermocouple. The K-type thermocouple has a high sensitivity and a good linearity, and basically covers the temperature range of thruster anode. The thermocouple is evenly fixed in the axial direction on the anode ring by means of spot welding. The anode ring is in a high potential state of several hundred volts when the thruster is working. Therefore, we directly measured the potential difference of the thermocouple at both ends, with the Model 34401A Agilent Precision Digital Multimeter. And then we interpolated to get the specific temperature value with thermocouple indexing table.



Figure 2. P100 Hall thruster

The thruster used in the experiment is the prototype of the model P100, the schematic structure has been given in Figure 2. Its inner and outer diameters of the channel are 70mm and 100mm, respectively; its nominal power is 1.5kW, which is the same with the SPT-100. The axial length of the P100 anode loop is 10mm, and 5 thermocouples are arranged in a straight line along the axial direction. The interval is 1.8mm, as shown in Figure 3. The thermocouple closest to the outlet of the channel is 1mm away from the outer end of the anode loop.

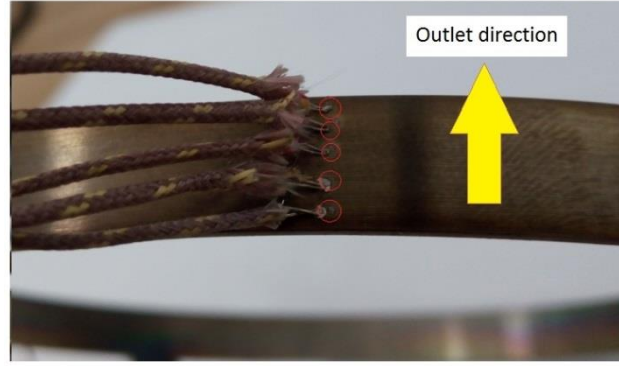


Figure 3. The 5 thermocouples on the anode loop

P100's magnetic circuit contains inner and outer and trim coils. Unlike the SPT-100, which has several outer coils that wound around several magnetic posts, only one outer coil of the P100 is wound around the circumference of the thruster and surrounds the entire discharge path. So the structure of P100 is completely axisymmetric. The number of inner and outer coil turns is more, generating magnetic field with the same direction. The coils were energized in series to form the main magnetic field in the discharge channel. The number of trim coil is small and the direction of the magnetic field, generated by it, is opposite to that of the inner and outer coils. It is mainly used to adjust the magnetic field distribution in the near anode region. In general, the trim coil can make the zero magnetic point in the near anode region. In the P100 magnetic circuit design, it is intended that the axial adjustable range of the zero magnetic point is placed in the axial area occupied by the anode loop, so that the magnetic field shape of the near anode region can be changed to a large extent, and convenient for feature diagnosis. With the excitation characteristics of the coils mentioned above, it is easy to obtain a magnetic field distribution of different magnetic field intensity and gradient. In this experiment, in order to keep the magnetic field configuration unchanged and make the magnetic field intensity overall change in the channel, we kept the trim coil is not energized and changed the inner and outer coil current at the same proportion, as shown in Figure 4. In order to obtain different magnetic field gradients, we adjusted the current of the trim coil to change the axial position of the zero-magnetic point, as shown in Figure 5. However, the larger the trim coil current, the lower the overall magnetic field intensity in the channel, so that in order to ensure the size and position of the maximum magnetic field intensity on the center line of the channel are constant when the magnetic field gradient change, we need appropriately compensate the current of the inner and outer coils. By measuring the static magnetic field of P100, we determined the compensation relationship between the current of inner and outer coils with the trim coil current variation.

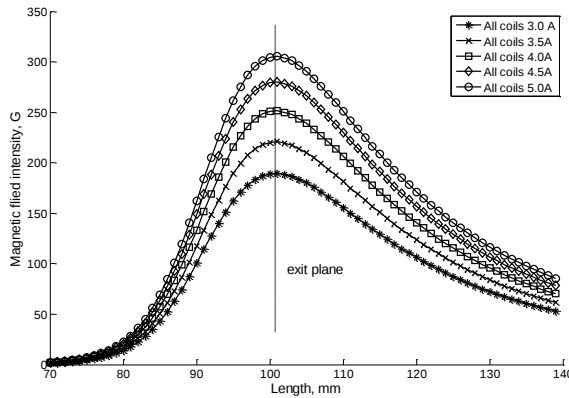


Figure 4. The distribution of different magnetic field intensity in the channel center

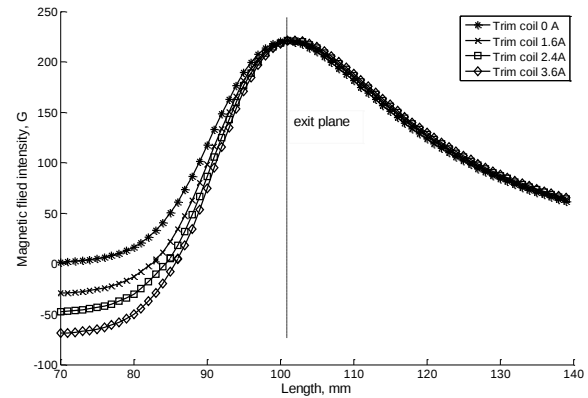


Figure 5. The distribution of different magnetic field gradient in the channel center

On the basis of above preparation, we conducted the experiments in a vacuum tank of Harbin Institute of Technology. The tank has a length of 5m and an inner diameter of 2m. The ultimate pressure in the tank can reach $1.0\text{e-}4\text{Pa}$. With the discharge of P100 at a Xenon flow rate of 5mg/s , the working pressure is about $1.0\text{e-}2\text{Pa}$.

B. Numerical model and method

In order to understand the results of the anode loop temperature measurement reasonably, we applied numerical simulation as an auxiliary means. Since the structure of the thruster is axisymmetric, and the focus of this paper is on the axial distribution of the temperature on the anode loop, therefore, assuming that the discharge is uniform along the azimuthal direction, the simulation model is built in the axial (z) and radial (r) plane, as shown in Figure 6. In general, atom, ion and electron are regarded as discrete individual particles, and then solve the discharge process of the thruster with Particle-in-Cell (PIC) numerical method.

The specific model area contains a part of the discharge channel near the exit and a part of the plume area. The position of $r = 0$ is the axis of the thruster, the diameter of the channel is 45mm, and the channel length is 33mm. The length of the plume is 30mm and the width is 70mm. Our group has established earlier a PIC program, which is capable of simulating the Hall thruster discharge.

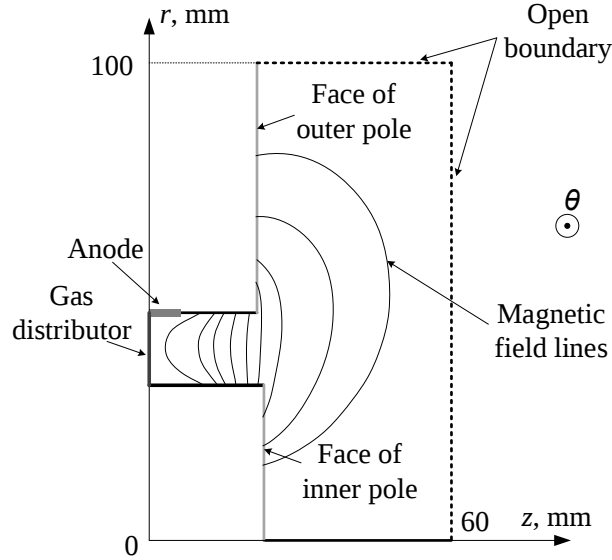


Figure 6. Simulation domain for P100 discharge

The simulation domain inside the channel includes three solid boundaries. The left boundary represents the gas distributor. The propellant neutrals enter into the channel through this boundary with a half-Maxwellian distribution. The anode of P100, which is different from that of SPT100, is a metal ring independent of the gas distributor and attached on the outer wall near the channel bottom; therefore, the inside part of upper boundary is the anode. By reaching on both the gas distributor and the anode, electrons are absorbed; ions are neutralized and reenter into the channel. The potential on the anode is set as the discharge voltage exactly. The metallic gas distributor is floating; it is deemed as a capacitance of $1.0\text{E-}8\text{F}$ and the potential is calculated as $\phi = Q/C$, where Q is the net charge accumulated by the distributor surface. Besides, the outside part of the upper boundary, as well as the whole lower boundary, is the insulator wall, where secondary electron emission (SEE) due to incident electrons from the plasma bulk is considered¹⁰. Ions are also neutralized and scattered on those boundaries. The wall potential is floating and the normal electric field is calculated as $E_n = -\sigma/2\epsilon_0$, where σ is the net surface density that charged particles deposit and ϵ_0 is the vacuum permittivity. The divergence angle of the inner and outer walls are labeled as θ_i and θ_o , respectively. Further treatment on the particle-boundary interaction, such as the energy accommodation, follows Ref. [11].

The simulation domain outside the channel is semi-open. The left boundary, except the channel exit, is the faces of inner and outer magnetic poles. As those faces are metallically floating, they are dealt with the same method as that to the gas distributor. The lower boundary is the symmetry axis of P100 and so is a mirror-reflecting boundary; the electric field is set zero here. The upper and right boundaries are open; all species of particles are deleted from the program when they pass through. By integrating the flux and momentum of those disappeared particles, the performance, such as thrust, propellant utilization, et al., is obtained. The open boundaries are also quasi-neutral, which is guaranteed by supplying extra electrons in those boundary cells that are positive charged; besides, the boundary potential is set zero.

In the simulation domain, charged particles are driven to move under the joint function of electric and magnetic fields, obeying Newton's law. The magnetic field is static and comes from the magnetic circuit model of P100,

which is prior established and solved with a freeware package — Finite Element Method Magnetics (FEMM)¹². The electric field, rising from the non-neutrality of local charge, is obtained by solving the Poisson equation. As to the collision between particles, only single ionization, excitation and elastic collision between electron and neutral are considered. Besides, a Bohm-type collision is taken into account to compensate the insufficient electron cross-field mobility. When the collision occurs, the electron is elastically scattered in the axial and azimuthal plane and participates in the cross-field transport in an anomalous way¹³. The collision frequency is described as $\nu_B = C_B eB/m_e$, where C_B is an empirical coefficient. It is well-known that with the current level of awareness on Hall thruster physics, no model exists to describe the electron migration in a transverse magnetic field exactly¹⁴. It was suggested that C_B outside the channel is greater than that inside the channel¹⁵. In this study, C_B is adjusted in each simulation case to match the measured discharge current.

The numerical algorithms adopted to simulate the particle movement; potential formation and particle collision have been well-documented in Refs. [16, 17, 18] respectively and so are not repeated here. The oblique boundary lines due to channel divergence are approximated as polylines and the simulation domain is discretized with a rectangle mesh.

III. Results and Discussion

A. Experimental results of the anode loop temperature changing with Magnetic field intensity and gradient

First of all, we need to determine the magnetic field intensity in the experiment, that is, the range of the inner and outer coil current. As we all know, with the magnetic field intensity changing, Hall thruster discharge mode will change. There is always a moderate range of magnetic field intensity, which makes the Hall thruster in a more efficient state, where the discharge current and discharge oscillation are small, here we called the range stability interval; once beyond the range, the discharge current and discharge oscillation will increase dramatically, and performance drop, here we called it as unstable interval. On one hand, the large discharge oscillations in the unstable interval interfere with the temperature signal measured by the thermocouple. On the other hand, the rated operating point of the Hall thruster will avoid the unstable interval. Therefore, in this paper, we only choose to work point in the stability interval of the P100 thruster to carry out temperature experiments. The discharge condition for temperature measure experiment is discharge voltage 300V and gas mass flow 3.0mg/s. In this case, the magnetic field-current properties of the test results show that when the inner and outer coil current changes in the range of 3A to 5A (the trim coil current is 0), P100 work in a stable interval.

The experimental result of the axial temperature distribution of anode loop changing with different magnetic field intensity is given in Figure 7. The axial position coordinates indicated by the horizontal axis in the figure are relative to the front face of the anode loop near the exit plane of the channel. In order to rule out the effect of the non-thermal steady state of the anode, where the temperature of anode rose slowly when acquired temperature signal, we increased the excitation current of the inner and outer coils from 3A to 5A and then decreased to 3A, to determine the temperature variation of each measuring point is consistent in the process of excitation current changing. It can be seen from the figure that, on the one hand, the position of the peak of the anode loop temperature does not change with the magnetic field intensity, which indicates that the power density distribution of the anode surface deposition does not change; in addition, taking the peak as the dividing line, the temperature near the outlet of the channel is substantially higher than the temperature near the bottom of the channel, indicating that the power density of the anode front portion is larger. On the other hand, with the increase of the magnetic field intensity, the overall temperature of the anode loop decreased firstly and then increased slightly. At the same time, the average discharge current also had a process of decreasing first and then increasing, both changes just as shown in Figure 9. Although the relative change in the discharge current is less than the relative change in temperature, it is also possible to show that the overall change in temperature is strongly related to the overall flux deposition change of the electrons on the anode loop.

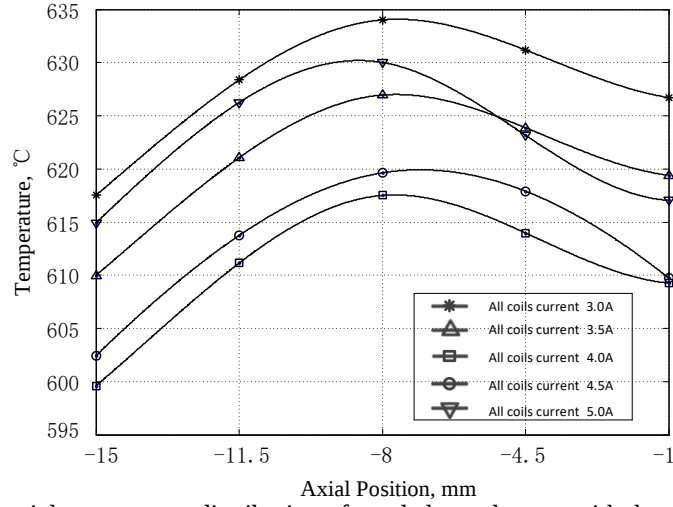


Figure 7. The axial temperature distribution of anode loop changes with the all coils current

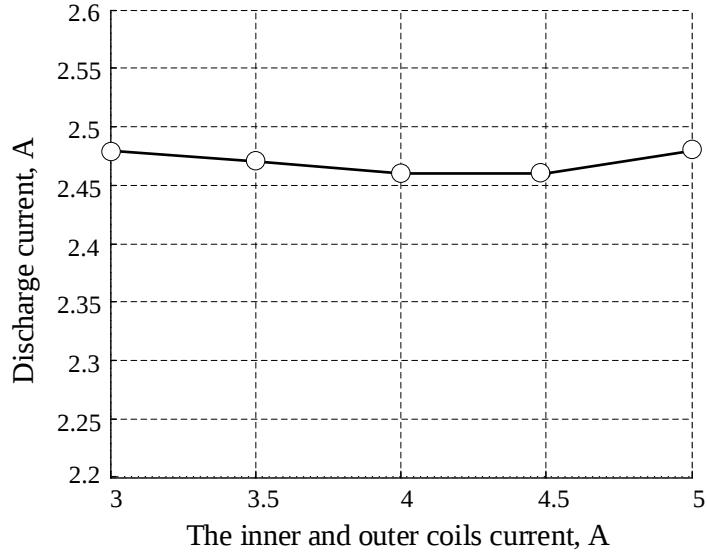


Figure 8. The discharge current changes with the all coils current

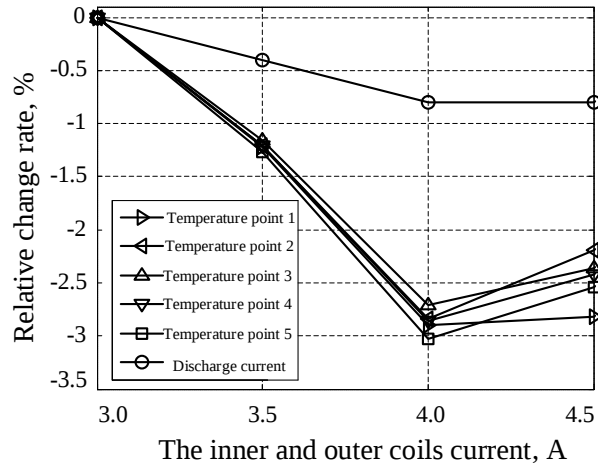


Figure 9. The relative change rate of the temperature and discharge current

Next, the effect of the magnetic field intensity on the whole temperature of the anode loop will be analyzed. In the first three magnetic field intensity of the coil currents range, the whole temperature of the anode loop decreases with the magnetic field intensity increasing. In the latter two magnetic field intensity, the whole temperature of the anode loop slightly increases with the magnetic field intensity increasing. Intuitively, with the magnetic field strength increasing, the constraint capacity of the curved magnetic field to the electrons increases and the deposited power on the anode loop decreases. However, for the general Hall thruster, the magnetic characteristic shows that the discharge current decreases first and then increases with the all coil currents. The curve is like the type of "U", which may explain the anomalous performance of the later stage in Figure 10. The following will be combined with the simulation of the content to do more specific mechanism analysis.

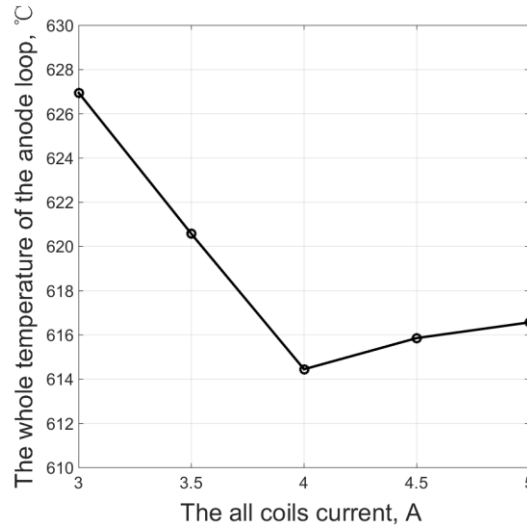


Figure 10. The whole temperature of the anode loop changes with the all coils current

The variable magnetic field intensity and gradient experiments are used the same discharge condition. In the corresponding stable discharge interval, we select the magnetic field formed by the inner and outer coil current 3.4A (trim coil current 0) as a reference, and use the method described in Part 2 of this paper to achieve different magnetic field gradient acquisition. In the experiment, the trim coil current is changed from 0 to 3.6 A; By static magnetic field measurement, it is found that this will cause the axial position of the zero-magnetic point move about 6.8mm towards to the discharge channel exit. Also, to exclude the effect of the non-thermal steady state of the anode on the temperature measurement, we make the magnetic field gradient change back and forth.

Figure 11 shows the experiment results of the axial distribution of the anode loop temperature change with different magnetic field gradients. It can be seen that, on one hand, the peak point of the anode ring temperature gradually moves toward the channel exit as the increase of the trim coil current (ie, the increase of the magnetic field gradient). This is synchronized with the axial movement of the zero magnetic point. In addition, it can be roughly estimated from the figure that the axial distance of the temperature peak is about 7 mm, which is also close to the axial distance of the zero magnetic point. Thus, it is closely related to the matching between the magnetic field and the anode loop that the effects of the magnetic field gradient on the surface temperature distribution of the anode loop and the deposition of the power density. On the other hand, as the magnetic field gradient increases, the temperature of the whole anode loop drops significantly, particularly the part near the bottom of the discharge channel. However, the discharge current is almost unchanged, as shown in Figure 12. This means that the main energy reaching the anode surface is reduced. Besides, this result suggests that the increase in the magnetic field gradient has a positive effect on reducing the heat load of the anode loop.

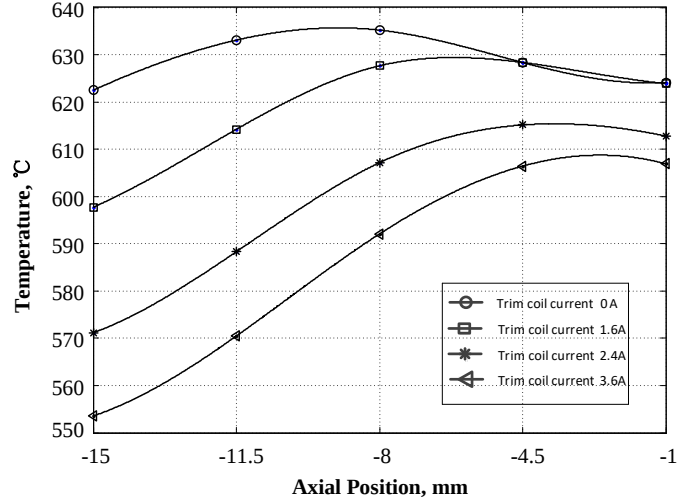


Figure 11. The axial temperature distribution of anode loop changes with the trim coil current

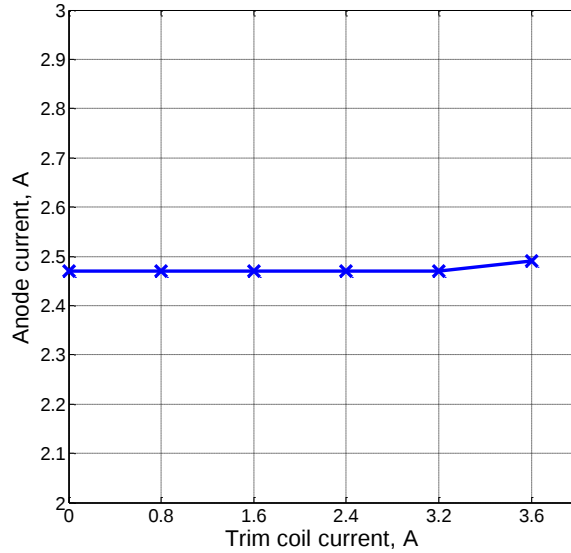


Figure 12. The discharge current changes with the trim coil current

B. Theory Analysis and Discussion

a. The simulation results and analysis about the magnetic field intensity

The different simulation cases have the same discharge condition, the discharge voltage is 300V and the flow mass rate is 4.6mg/s, and the other boundary conditions are consistent. The unique variable among the simulation cases is the different magnetic field topology.

Figure 13 shows that the different magnetic field intensity has a great effect on the axial power distribution of the anode loop. In the following, we will analyze the internal mechanism that how the magnetic field intensity effects the power distribution of anode loop.

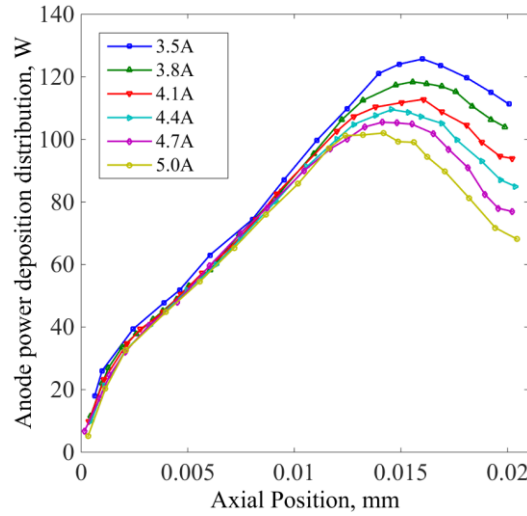


Figure 13. The axial power distribution of the anode loop with different magnetic field intensity

Under the constraint of the orthogonal electromagnetic field, the electrons in the discharge channel will act as a Hall drift in a limited area and no axial displacement. However, because of the influence of electron and heavy particle collision, the stable Hall drift is destroyed and the electrons move to the anode. That's the reason for the macroscopic conduction current occurs.

By analyzing of the magnetic field topology in the discharge channel, as shown in Figure 14, it can be seen that the magnetic field in the axial direction of the anode can be divided into two parts, one part is the front curving magnetic field produced by the outer magnetic screen and the outer magnetic pole, and the other part is the back vertical magnetic field caused by the inter magnetic screen and the magnetic pole. For the electrons toward the anode, it must be affected by these two parts of the magnetic field. In addition, the intensity of the front magnetic field is about 80~90 Gauss, while the intensity of the back magnetic field is 10~20 Gauss. According to the formula we can know, for the same state of the electrons, the roundabout radius in the front magnetic field is only 1/4 of the back magnetic field. Therefore, due to the conduction mechanism, when the electrons leave the ionization zone toward the anode, the front of the anode is significantly larger than the bottom of the anode for the electron capture and constraint capacity. When the electrons are captured by the front curved magnetic field, the electrons tend to travel along the magnetic field lines to the anode (even if there exist collisions), so that they will deposit more to the intersection of the curving magnetic field and the anode loop, that is, the axial position of the anode loop.

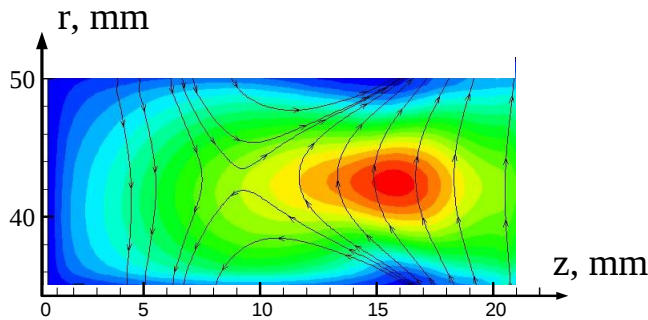


Figure 14. The distribution of the magnetic field in the discharge channel

Therefore, the difference in the axial direction of the anode loop caused by the presence of the zero magnetic point in the near anode region leads to a significant "segmentation" phenomenon of the electrons deposited on the anode loop.

Combining with the temperature distribution from Figure 7, in term of the different axial position on the anode loop, with different intensity magnetic field, the temperature at the front of the anode loop is significantly higher than that of the back. That's means in the experiment the many more electrons are deposited at the front of the anode loop, which is in line with the above-mentioned anodic segment analysis.

Besides the above-mentioned the axial position temperature law of the anode loop, the anode loop overall power deposition changes with the magnetic field intensity also have obvious laws. As the limit of the experiment, in the experiment we only can measure the anode loop temperature distribution, the lack of access to diagnosis the plasma parameter in the discharge channel, so in this part we will mainly analysis the internal laws and mechanisms by the simulation.

As shown in the Figure 13, with the increase of the coils current, that's means, the magnetic field intensity increases, the anode loop deposition power gradually reduced. The reason of the power deposition on the anode loop is the bombardment of the electrons, so in order to explain the above-mentioned law of the anode loop deposition power, it is possible to analyze the flux and energy of the electrons, since these two factors determine the deposition power on the anode loop, the detail distribution curve is shown in Figure 15.

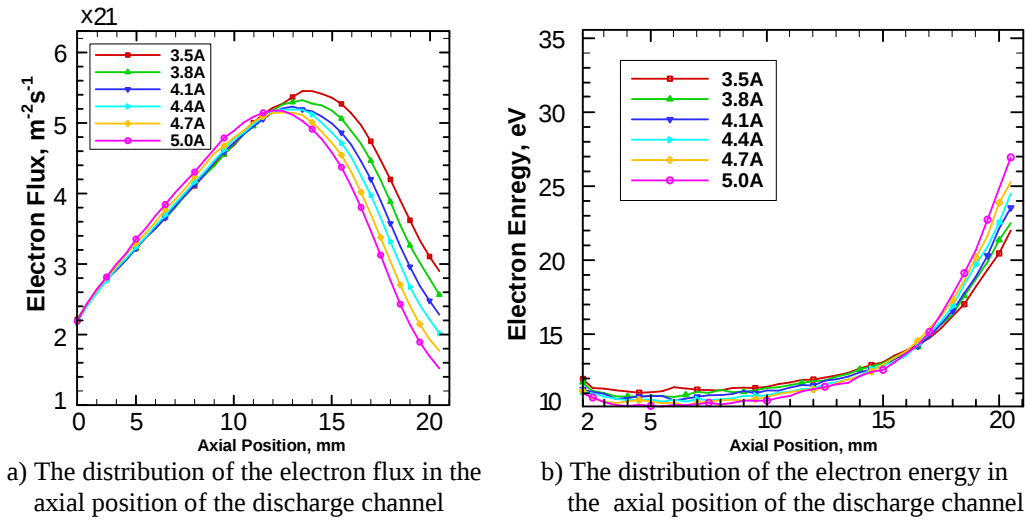
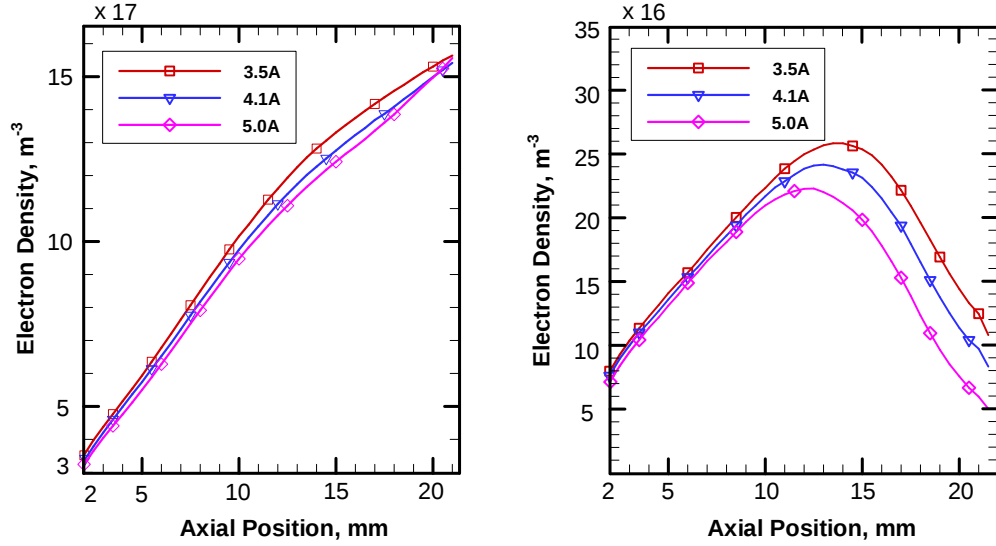


Figure 15. The distribution of the electron flux and energy on the anode loop

As shown in Figure 15, the reason of deposition power reduced is the decline in the reduction of electron flux, that is, the change of the electron density in the discharge channel produces the above law. Figure 16 shows the electron density distribution in the axial position of the discharge channel. During the stable operation of the Hall thruster, the electrons are continuously generated by the cathode, and the electrons are moved to the anode by conduction. In this process, after the electrons near the center of the channel across the ionization region, the moving electron density in the channel rapidly reduced. On one hand, after the ionization region, the neutral gas is sufficient and the elastic impact of electrons in the region is strong, so it is easy to be caught by other magnetic field lines. And it is affected by the magnetic field at the front of the anode, the electrons tend to move along the curved magnetic field lines, so that they are more deposited to the front of the anode loop, which is consistent with the above-mentioned anode loop electron deposition section analysis. On the other hand, when the electrons reach the discharge wall, because a negative potential is accumulated, so a sheath will be formed and it hinders the diffusion of electrons move into the anode. The sheath includes pre-sheath and sheath, for the sheath, the thickness of the sheath is about several Larmor radius, which have a strong effect on hinder the electrons movement, and for the pre-sheath, the thickness of the pre-sheath is substantially the same order of magnitude as the channel size, and the characteristic is effected region large but less resistance. So the more internal movement to the discharge channel, the strongly resistance from sheath for the electrons, resulting in reduced electronic density.



a) The distribution of the electron density on the axial line of the discharge channel

b) The distribution of the electron density near the anode loop region

Figure 16. The distribution of the electron density in the discharge channel

In addition, for the electron density distribution at the center of the channel, there is a turning point between the ionization region and the anode position where the electron density is high. The main reason for this change is also related to the sheath. In the ionization and acceleration region, when the magnetic field intensity decreases, the resistance to the electrons from the magnetic field will decrease, which causes more electrons move to the anode, and it must be improve the barrier of the discharge wall and anode sheath. In the Hall thruster, the movement of electrons in the discharge channel determines the distribution of the potential. When the magnetic field intensity decreases, the potential between the center of the discharge channel and the anode will increase. It's indicating that the resistance of the sheath to electrons is increased, which in turn acts on the electrons moving toward the anode, so that the electron flux through the sheath decreases and the electrons "accumulates" in the center of the channel. That can explain the transition of the electron density distribution at the center of the discharge channel.

b. The simulation results and analysis about the magnetic field gradient

For the axial temperature distribution of the anode loop, the simulation results show a certain consistency with the experiment. Figure 17 shows the distribution of the axial power deposition on the anode loop by the simulation. With the magnetic field gradient increasing, the deposition power of the front anode loop is rapidly increasing and the deposition power at the bottom of the distributor is reduced. This change in the axial power deposition is manifested in the temperature, as the gradient increases, the maximum temperature of the anode ring moves forward.

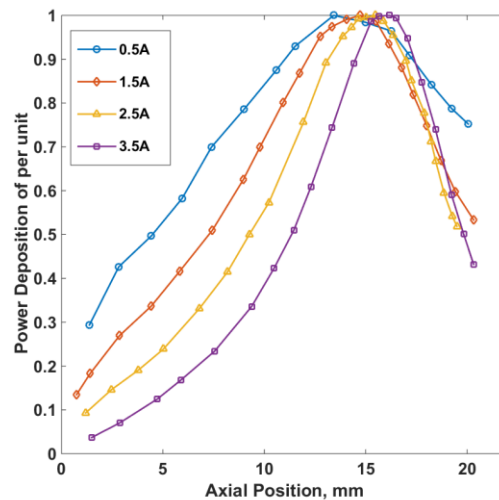


Figure 17. The per-unit distribution of the deposited power on the anode loop

This is consistent with the results obtained by the temperature test. The mechanism is as follows:

1. With the magnetic field gradient increasing, the zero-magnetic point in the center of the discharge channel is regularly moved, as shown in Figure 18. As previously discussed the "segmentation" theory of the anode loop axial heat deposition, the zero magnetic field point also divide the magnetic field near the anode into two parts. With the magnetic field gradient increasing, the whole curved magnetic field in front of the anode is moved forward and the central region is closer to the ionization region. Therefore, the curved magnetic field can capture more electrons and finally deposit them on the front of the anode loop, so leading to the front of the anode loop becoming the highest temperature point. Because the intensity of the vertical magnetic field at the rear of the anode loop is low, the capability to restrain the electrons is weak. In addition, the existence of the sheath near to the discharge channel inner wall, gas distribution surface and other walls, it is greatly hindered the electrons transit into the discharge channel. In summary, when the magnetic field gradient changes, the control conditions for the electrons near the anode region in the discharge channel have changed significantly, and leading to the electrons be captured by the magnetic field at the front of the anode, and deposited to the anode front.

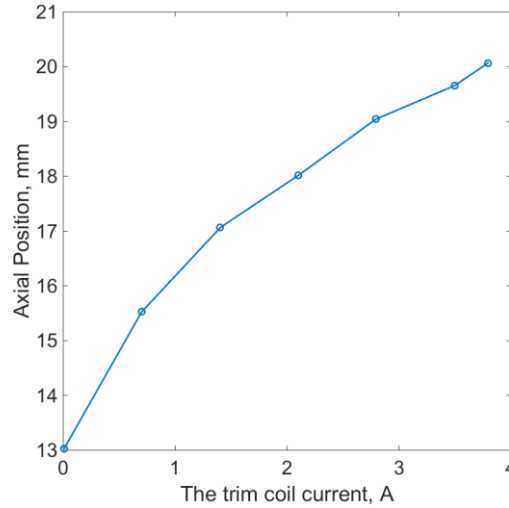


Figure 18. The position of the zero magnetic field changes with the trim coil current

2. The location of the ionization region changed significantly.

Figure 20 shows the ionization rate distribution in the channel center. With the magnetic field gradient increasing, the maximum point of ionization rate in the channel center move forward to the channel exit, which indicates that the axial position of the ionization region transits to the channel exit. Because the characteristics of plasma in the discharge channel aren't diagnosed in the temperature measurement experiment, it's not estimate the place of the ionization region. However, according to the other experiments results in the past by our laboratory, we found that the ionization region move to the channel exit with the trim coil current increasing, and this is consistent with the simulation performance. The outward movement of the ionization region causes the electron source to be further away from the anode loop, so that the electrons transition to the bottom of the anode loop requires more collisions, which increases the difficulty of electron deposition to the bottom of the anode loop. Therefore, the same probability of collision, the electrons tend to be deposited to the anode loop front. That is, with the magnetic field gradient increasing, the highest temperature point of the anode loop moves forward.

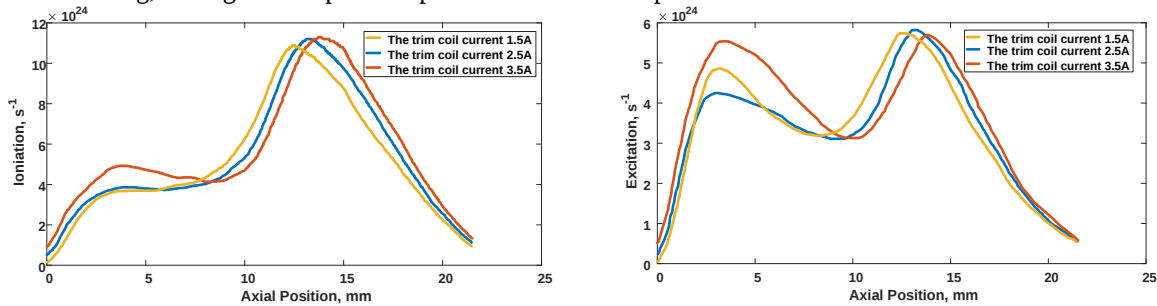


Figure 19. The frequency of ionization and excitation in near anode region

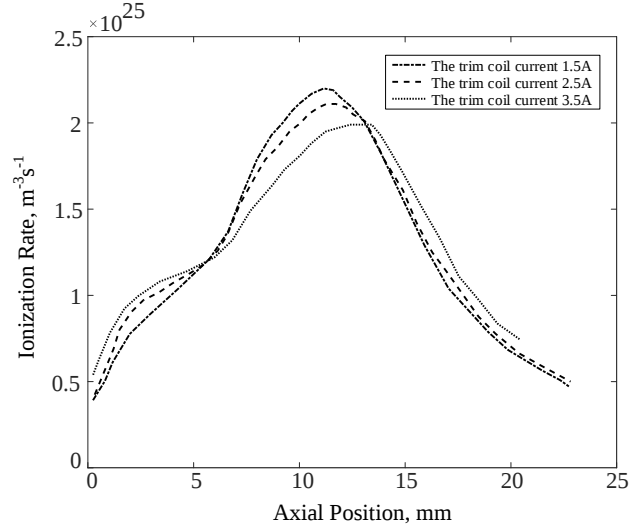


Figure 20. The distribution of the ionization rate

Finally, we analyze the temperature distribution of the whole anode loop. In the experiment we find that the temperature of the whole anode loop decreased with the increasing of the magnetic field gradient, which is mainly related to the change of the electron energy in the near anode region. At first, as shown in the Figure 20, the distribution of electron density moves inward towards to discharge channel, that is, after the zero point of magnetic field intensity, the electron density trend to increase. However, it is mentioned that as the gradient increases, the ionization region moves towards outside of the discharge channel. So we can determine that the electrons are secondary ionized with the neutral atom between the zero magnetic field point and the gas distributor.

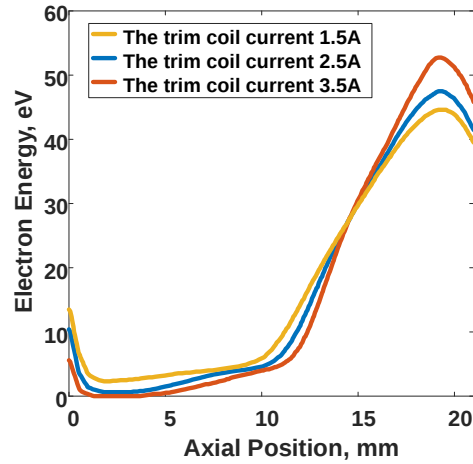


Figure 21. The distribution of electron energy in near anode region

On basis of the description of the electrons behavior, we can divide the path of the electrons transit to the anode into two parts. For the Path 1, due to the effect of the magnetic field between the zero point of the magnetic field and the gas distribution, the electrons pass through the ionization region and the zero point of the magnetic field, and finally the electrons deposit to the back of the anode loop; For the path 2, the electrons passing through the ionization region are captured by the curved magnetic field at the front of the anode loop and are finally deposited to the front of the anode loop. For the electrons passing the path 1, when the magnetic field gradient increases to a certain extent (the increasing of the gradient in this paper is achieved by increasing the trim coil current), the magnetic field intensity between the zero point and the gas distributor can reach 80 gauss, the ability of the magnetic field bounding electron is enhanced. Coupled with this region near to the gas distribution, neutral atomic density is high, so the non-elastic collision must be taken place in this area between the electrons and the neutral atoms. Figure 19 is just to verify that conclusion. The presence of the non-elastic collision reduces the energy of the electrons passing through this region, so that the energy of the electrons deposited on the anode through the path 2 decreases as the magnetic field gradient increases, as shown in Figure 21. This explains why the whole temperature of the anode loop decreases with the magnetic field gradient increasing, and the overall analysis is shown in Figure 22.

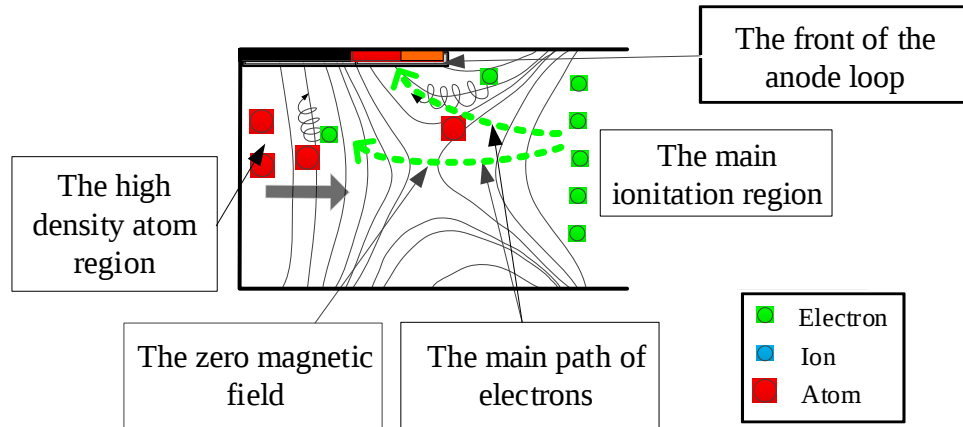


Figure 22. The diagram of the whole discharge channel

IV. Conclusion

In this paper, by measuring the temperature distribution of the anode loop at different magnetic field, we explore the influence of the magnetic field on the temperature distribution of the anode loop. The whole conclusion can be summarized into two parts.

First, the characteristic of the anode loop axial temperature distribution is not affected by the change of the magnetic field, and the axial center point of the anode loop is the highest point of temperature. With the magnetic field intensity increasing, the whole temperature of the anode loop showing decreases and then a slightly increases.

The electrons are more deposited on the front of the anode loop. On the other hand, the more internal movement to the discharge channel, the strongly resistance from sheath for the electrons, resulting in reduced electronic density.

Second, the magnetic field gradient has a great influence on the axial temperature distribution of the anode loop. It shows that when the magnetic field gradient increases, the highest point of the axial temperature of the anode loop moves towards outside the discharge channel, and the temperature of the anode loop near the distributor is obviously decreased. In terms of the temperature of the whole anode loop, with the magnetic field gradient increasing (the increasing of the magnetic field gradient in this paper is realized by increasing the trim coil current), the temperature of the whole anode loop decreases.

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