Particle-in-cell Simulations for the Effect of Magnetic Shielding and Channel Length on Cylindrical Hall Thruster

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Abstract: The particle-in-cell plus Monte Carlo method is used to simulate a miniaturized Cylindrical Hall Thruster (100W of power level). In PIC-MCC model, the potential distribution, the electron density and the electron temperature in the condition of different magnetic shield place and channel length are achieved, respectively. The results exhibit that the magnetic shield around the central magnetic pole decrease the magnetic field strength near the anode, which lead to the ionization ratio decrease and the electron mobility enhance. On the other hand, with the extension of the channel length (enlarge the front electromagnetic coil region as well), the electrons mobility enhanced through increasing the ion residence time in channel and enhance the ionization. Integrating above factors, it's concluded that the optimization effect on the channel length is better than the magnetic shield.

Nomenclature

CHT	=	Cylindrical Hall Thruster
wpe	=	Plasma Oscillation Frequency
wc	=	Electron Cyclotron Frequency
△t	=	Time Step
Te	=	Simulated Initial Electron Temperature
RPA	=	Retarding Potential Analyzer

I. Introduction

Hall thrusters in large power of high than 300W have been applied maturely. However, scaling down the conventional annular Hall thruster bring the problem of large surface-to-volume , the difficulty of miniaturized magnetic circuit, and the significant erosion of the wall , which effect the performance and lifetime severely. Cylindrical Hall Thruster (CHT) decrease the surface-to-volume compared the annular Hall thruster and solve the problem of inadequate inner pole through shorten the center magnetic pole, which may be the suitable approach of scaling to Hall thruster[1]. Cylindrical Hall thrusters have already been studied experimentally and reach the comparable performance compared the annular Hall thruster[1]. CHT features the high ionization rate, which is validated due to more multi-charged than annular Hall thruster[2].

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Compared with the annular Hall thruster, the magnetic field topology and plasma characteristics in CHT change a lot due to the shorten of inner magnetic pole and manifest the obvious two-dimensional varies[3]. The magnetic field present negative gradient along the axial, and the strongest magnetic field is located near the anode. The magnetic line directions exhibit significant difference along the radial: the magnetic lines located at the channel center are mainly axial, while the radial magnetic field component is increased near the wall. In this magnetic field topology, the strongest confinement to the magnetization electrons occurs near the anode. The main transport path of electrons emitted from the cathode is likely along the channel axis as the contribution of electron-wall collisions to cross-field transport is validated to be insignificant[4]. While the electrons closed to the axis is trapped by the magnetic mirror and bounce over an axial region. The plasma potential drops sharply from the anode toward the downstream region and the radial electric field exists[5, 6]. The slow ions concentrated in downstream of channel center[5].

From the above analysis, the main confined region of the electrons is located in the upstream closed to the axis and the position of main potential drop is also located in upstream due to the magnetic field. But if the main potential drop is close to the anode excessively, it is likely to make the main voltage load to the electrons and prevent the formation of stable ionization and acceleration region. In order to make the main potential drop move towards the exit, it is necessary to increase the electron transport in the vicinity of anode, while electron mobility is mainly associated with the magnetic field strength and the cross section of electrons and heavy particles. In this paper, two ways is proposed to increase the electrons cross-field transit near the anode as following: 1. mounting the magnetic shield around the anode to decrease the magnetic field; 2.extending the channel length to improve the collide frequency.

Jongsub Lee et al. have studied the effect of channel length on thruster by experiment[7] and the results shown that the ion current and the total ion energy were enhanced with the increase of channel length, which was interpreted that the increase of channel length probably increase the ions' residing time and enhance the multi-charged ions, ultimately make the ionization region extend towards the anode so that the ionization region and acceleration region separate clearer. However, their explanation about the link between the increased ions residence time and the extension of the ionization location is undefined, whether the extension of the ionization region towards the anode affect the electric potential distribution is also faint.

This paper emphasizes to research the plasma characteristics and reveal the inner physical mechanism, so we mainly employ the PIC-MCC simulation model [8], which is built by HIT and achieved the application maturely in SPT [9]and HEMPT[10, 11]. While the experiment play the role of validating the model reasonability and was exhibit as supplement.

In this paper, we organize as follow: in section II, the laboratory CHT prototype and their operation condition is exhibit. In section III, the PIC-MCC simulation model of CHT is introduced in detail. In section IV, the simulation result and the related analysis on the effect of changing the magnetic shield length and channel length is achieved, including electron density space distribution, electric potential distribution, electron temperature distribution and so on. In section V, the comparison and analysis of simulation and experiment result. At last, there are several conclusions and prospections.

II. The operation of laboratory CHT prototypes.

The laboratory CHT prototypes applied in PIC model is introduced as following: Three laboratory CHT prototypes are designed as Fig. 1, they are named as C1, C2 and C3, respectively. In C1, the channel length is 15mm and the center magnetic shield wasn't mounted. In C2, the channel length is 15mm and the center magnetic shield was mounted, it was made of pure iron. In C3, the channel length is 25mm and the center magnetic shield wasn't mounted. They all consist of a cylindrical channel, a ring-shaped anode, which also serve a gas distributor, a magnetic core and magnetized sources. The diameter of these thrusters are all 3cm. The current direction in the two coils are in same direction to produce the direct configuration and the front and back coil current are 2A and 5A, respectively.

In our experiment, the cathode was located 4cm radially from thruster centerline, and 2.0cm downstream of the thruster exit plane. The cathode Xe flow rate was 2sccm. The anode voltage and Xe flow rate were fixed at 300V and 4sccm, respectively. The thrusters were placed in a vacuum chamber of 4m long and 1.2m diameter, and the gas pressure kept in 2.4×10^{-3} Pa. The Faraday probe was used for measuring ion current which was mounted on a rotational stage with the distance of 30cm from the pivot at angles of up to 80° from the thruster axis. The ion collecting area of Faraday probe was $0.75 cm^2$, both the probe collector and guard ring were biased to -24V. The RPA was used to measure ion energy distribution and located at 40 cm downstream from the channel exit on the axis. A commercial digital single-lens reflex camera was mounted in a side window of the vacuum chamber to obtain the plume discharge image.

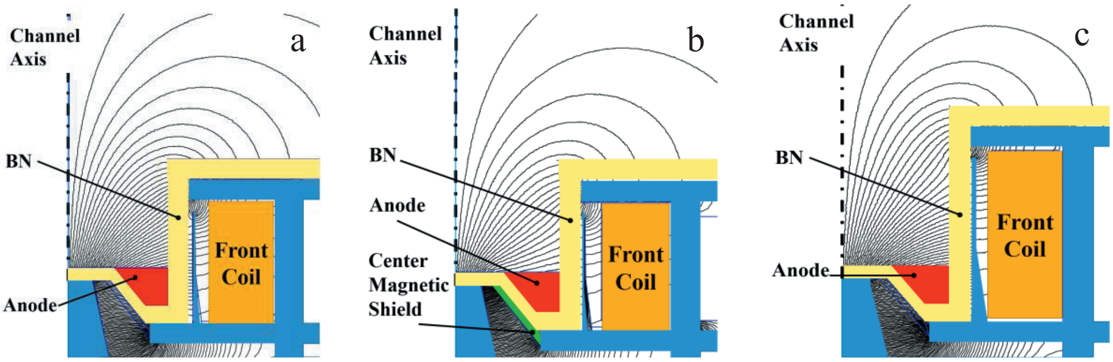

Fig.1 Three configurations of CHT: a. C1: 15mm channel length and without center magnetic shield; b.C2: 15mm channel length and with center magnetic shield; c. C3: 25mm channel length and without center magnetic shield.

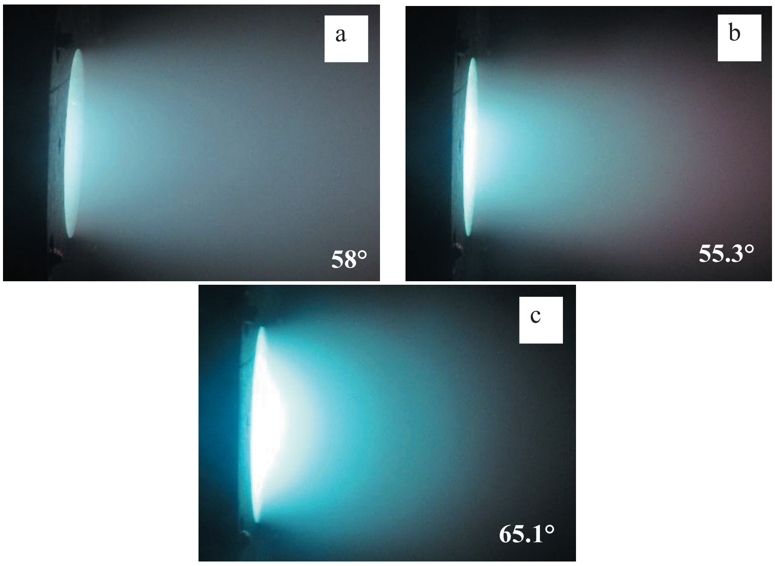

Fig. 2 plume discharge photographs for three configuration CHTs at the anode flow 4sccm and anode voltage 300V, the plume angles (shown in the bottom right corner) contain 90% of total ion current.

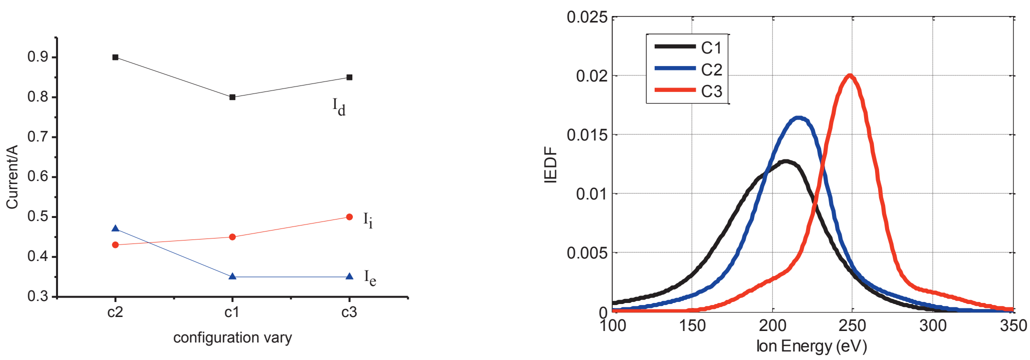

Fig.3 a: component of the discharge current, b: IEDF in z=37cm of axis: C1, C2 and C3.

The plume discharge photographs of different structures are shown in Fig 2, and the plume in C3 emitted the stable blue light and the intensity is obviously stronger than C1 and C2. While the light intensity in C2 is slightly stronger than C1, from which we find that the plume plasma energy in C3 is highest in three thrusters. While the plume angle of C1, C2, C3 are 58°, 55.3°, 65.1°. The ion current, electron current and total discharge current in plume are shown in fig 3a. The electron current and total discharge current in C2 is largest in three structures, while the ion current is smallest. The ion current in C3 is largest in three structures, its total current is larger than C1 and the electron current is almost constant corresponding to C1. The ion energy distribution function in plume are shown in fig 3b. The peak energy in C3 is largest, and its full width at half maximum (FWHM) is narrowest. While the peak energy in C2 is larger than C1 and its FWHM is narrower than C1. As FWHM of ion energy can reflect the relative distance of ionization region and acceleration region. We suggest that the ionization and acceleration region in C3 separate most clearly in three structures and the C2 is inferior.

From the above measurement results, we can conclude as following: with the mounting of center magnetic shield, the increase increment of electron current was much larger than ion current, the plume ion energy enhanced slightly and the ion beam is more convergence. With the extension of channel length, the ion current increased substantially and electron current almost kept constant, the ion energy also enhanced significantly, but the ion beam is more divergence. In order to explain the above phenomenon and reveal the physical mechanism with the mounting of center magnetic shield and the extension of channel length, the PIC-MCC model is built as following:

III. Simulation model

According to the structural features of CHT in different configurations mentioned above, three PIC-MCC models are applied respectively, which axial symmetry is assumed and all azimuthal variations are neglected. In these models, electrons, ions and neutral atoms are solved as Super-Particles (a super simulated particle represent 10^6 real particles) in order to save the computational cost[8, 9]. The initial electron and neutral atom distribution are solved as the half Maxwell distribution. The magnetic field distribution achieved by FEMM software is import into the simulation program and assumed constant (self-induced magnetic field is ignored). The Poisson equation which is solved by Alternating Direction Implicit (DADI) method is applied to achieve the self-induced electric field. The standard leapfrog method is applied to push the particles forward and solve the particle movement. As to the electron cross-field transport, a Monte Carlo model is developed to reveal the mechanism of the electron transport perpendicular to the magnetic field, which accounts for electron-atom collisions, electron-wall collisions and Bohm diffusion. The Bohm coefficient equals 1/64. While the DSMC method is used to solve the collision among the atoms.

With respect to the grid size and time step in the compute region, it's required that the grid size should smaller than the Debye length in order to catch the plasma oscillation and the time step should satisfy that $\omega_c \Delta t \leq 0.3$, $\omega_p \Delta t \leq 0.2$. To accelerate the convergence of the compute region, the vacuum permittivity is increased by 1600 times[9].

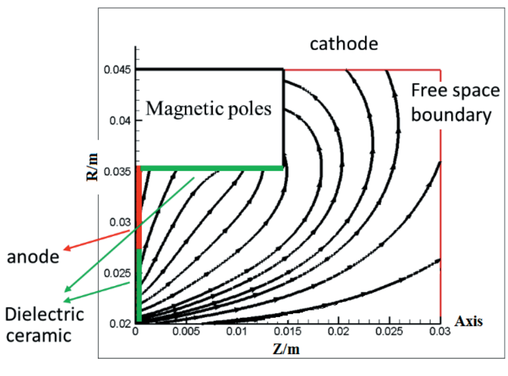

Fig.3 the simulated zone, boundary condition and magnetic field lines in the PIC-MCC model

With respect to the arrangement of boundary condition and simulated regions, as shown in Fig. 3, the axial coordinate of simulated region varies from 0 m to 0.03 m, and the radial coordinate varies from 0.02 m to 0.045 m. The left lateral boundary is the anode (0.0275m＜r＜0.035m) and dielectric ceramic (0.02m＜z＜0.0275m) and the former's length equals the latter, while the lower and upper boundaries are the symmetric axis and dielectric ceramic wall. The plume is also considered in the model, the left boundary of the plume zone is dielectric ceramic and the upper boundary is cathode.

IV. Simulation results and discussion

We performed calculations for a given set of coil currents I_{front}=2A, I_{back}=5A, for anode mass flows of 4sccm, the discharge voltage is 300V, which are consistent with the experiments. The effects of center magnetic shield on the plasma characteristics are shown in section A, which include the electron density distribution, the electric field distribution and the electron temperature. In section B, the effects of the channel length on the plasma behaviors are presented.

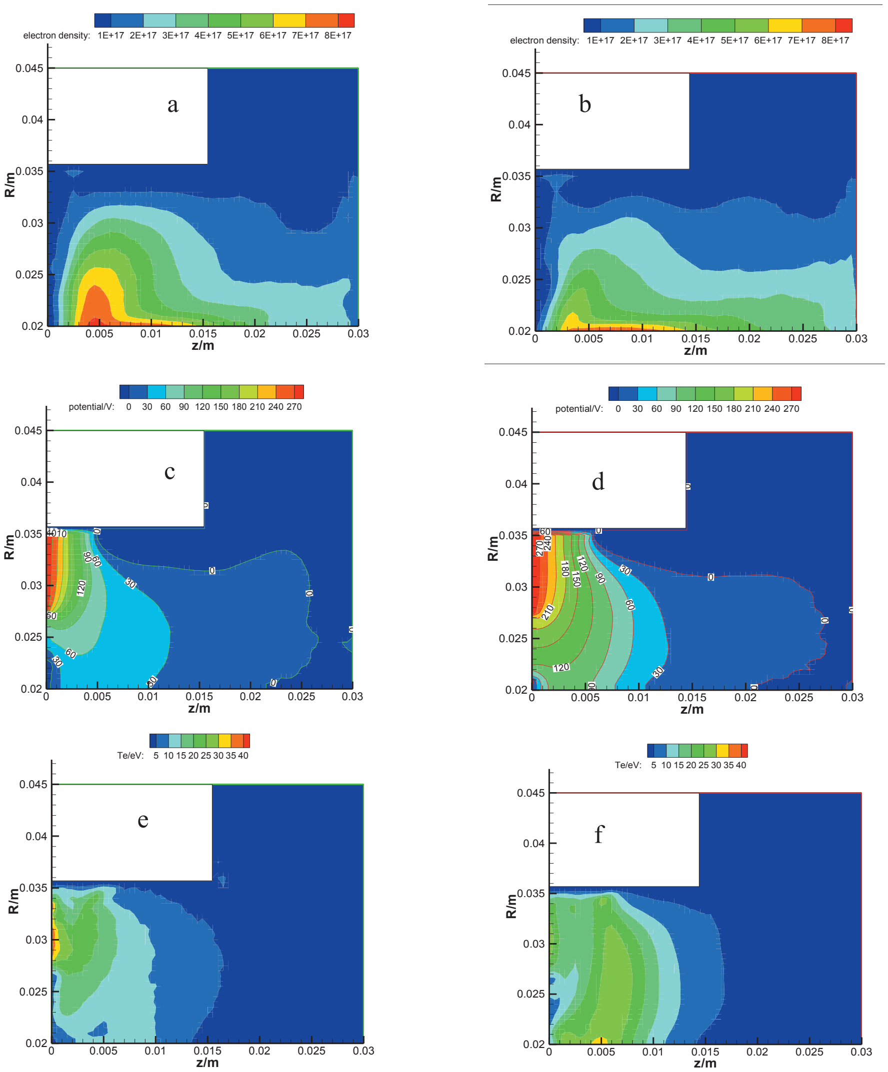

Fig.4 the plasma characteristics distributions: a, c, e indicate the electron density, potential and electron temperature in C1, respectively, the corresponding distributions of C2 are shown in b, d, f.

A .the effect of center magnetic shield on the plasma characteristics

Comparing the magnetic field topology change with the different magnetic shield structure shown in Fig. 1(a)(b), it is clear that the magnetic field strength is decreased generally, the reduction near the anode is most obvious. As shown in Fig. 5, the magnetic field strength in r=0.03m, z=0m (the location of anode) decreases from 500G to 300G, and the anode surrounding area has also obviously reduction, while the magnetic field near the channel axis varied slightly.

Fig. 4(a) and (b) show the simulation results of the electron density distributions for C1 and C2, respectively. It is clear that the electron density near the anode in configuration 2 reduces compared with configuration1, which can be due to the magnetic field change: the magnetic field near the anode is weaken by the magnetic shield ring, and the electron cross-field transport is enhanced, thus the electron density was reduced in the discharge channel.

Fig. 4(c) (d) show the simulation results of potential distribution for C1 and C2, respectively. It is clear that the main potential drop region move towards downstream compared when the magnetic shield ring is mounted in C2, it can be explained that the enhanced electron cross-field transport lead to the decease of potential drop near the anode, as the applied voltage is fixed, the potential drop should move toward downstream along the axis.

As shown in Fig. 4(e) (f), the high electron temperature zone extends to the midstream along the axial direction, which can be due to two factors: the enhanced electron transport lead to the reduction of ionization rate in midstream, at the same time, the electric field strength in this region is increased. Therefore, the electrons can obtain more energy from the electric field with less consume.

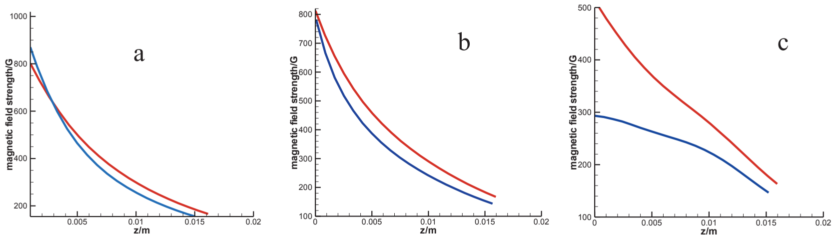

Fig. 5 the magnetic field strength along the axial direction: a. r=0.02m, b. r=0.025m, c. r= 0.03m (red line demonstrates configuration1, blue line demonstrates configuration2)

B. The effect of channel length on plasma characteristic

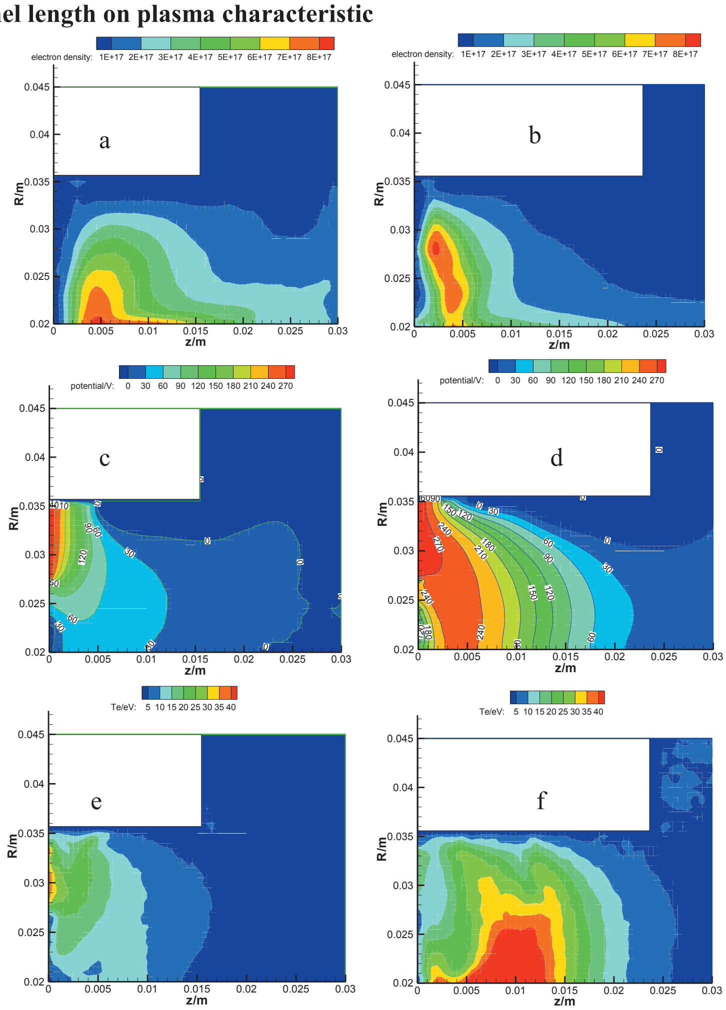

Fig. 6 the plasma characteristics distributions: a, c, e indicate the electron density, potential and electron temperature in C1, respectively, the corresponding distributions of C3 are shown in b, d, f.

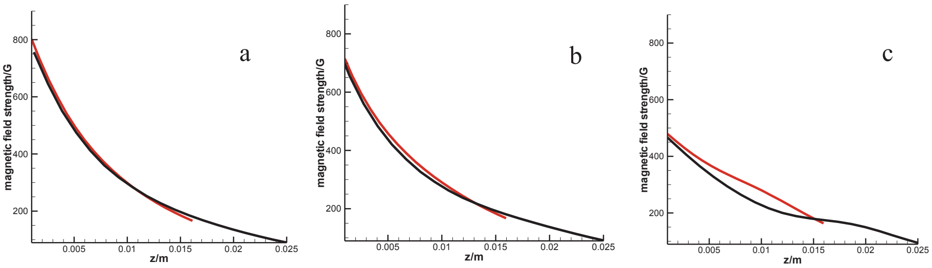

Fig. 7 the magnetic field strength along the axial direction: a r=0.02m; b r=0.025m; c r=0.03m

Fig. 6(a) (c) (e) shown the electron density, potential and electron temperature in C1, respectively: the main potential drop and high electron temperature focus on the vicinity of the anode, while the most crowded electron density is placed on the axis closed to z=0.005m. The largest Ne zone is after the main potential drop zone and this distribution makes the applied voltage mainly load to the electron and may not form the optimized ionization zone and acceleration zone.

While Fig. 6(b) (d) (f) shows the corresponding plasma characteristics in CHT of 25mm channel length, the distribution region of main potential drop and high electron temperature move away the anode compared the former and is placed on the axis closed to z=0.01m, while the electron density Ne is crowded around the anode. The largest Ne zone is closer to the anode compared the main potential drop, which is helpful for the clear separation of ionization zone and acceleration zone.

As to what reduced the significant **c**hange of the plasma behaviors with the extension of channel length, it can be explained as following: With respect to the region z＜0.015m, the change of magnetic field is neglected as fig.7, the magnetization level of electrons is almost constant. With respect to the region 0.015m＜z＜0.025m, the original plume zone become the downstream of channel and the magnetic field intensity in this extend region is also increased, which result in the residence time of slow ions increased and the magnetization level of electrons in this region. So the ionization rate is enhanced and the more second electrons is induced. When the increased second electrons move to upstream, the ionization rate is increased further and the electrons transport is enhanced, so the ionization zone move towards the anode, while the potential fall is decreased near the anode, which results in the main potential drop move towards the exit side and t electron temperature in channel middle enhance, thus the electrons through this path is accelerated further and the ionization rate near the anode is enhanced once again, this positive feedback make the main potential drop move a significant distance towards right side finally.

In addition, we find that the potential drop near the outer wall change slightly with the extend of the channel length from Fig. 6(c) (d), the most possible cause is that the electrons' main transport path is not the outer wall but the channel center, and the contribution of electron-wall interaction to cross-transport transport is insignificant.

V. Analysis the physical mechanism combining the simulation and experimental results

From the simulation result of adding the magnetic shield, we know that firstly reduce the magnetic field near the anode, which make the electrons cross-field transit easier, and the electrons transport current increased; at the same time, the ionization rate reduced, which makes the ion density decrease in plume, while the right movement of the main potential drop enhanced the ion velocity in plume, as the reduction of ionization rate lead to the potential drop distribution change, the decrease increment of ion density is larger than the increase increment of ion velocity, this may be the cause that ion current decreased slightly; With respect to the ion energy at axis, the weight of ion velocity is larger than ion density, it is shown that the total energy enhanced slightly, while the right movement of the main potential drop induce the acceleration zone extend towards downstream, which make the relative distance of ionization zone and acceleration zone separate clearly, so the FWHM of ion energy decreased.

From the simulation results of extending the channel length, we know that firstly increased the residence time of slow ions, which enhanced the ionization rate and the ionization zone extend towards the anode, the main potential drop move towards the exit side, so the ion current and ion energy increased, at the same time, the extension of ionization region towards anode make the ionization region and acceleration region separate more clearly, which may be critical factor for decrease of FWHM; with respect to electron current, although the electron transport enhanced, the increase of ionization rate consume the electron energy at the same time, it may be a significant cause for the hardly constant electron current. While the increase of plume angle may be related with the enhancement of radial component of electric field.

VI. Conclusion

Comparison the results of adding the magnetic shield and extending the channel length, there are some common points: the electron cross-field transport near the anode enhanced and the acceleration zone move towards the exit side, which lead to total discharge current increase and FWHM of ion energy decrease. but they have virtual difference for the cause of electron mobility enhanced: the former improve the electrons mobility through decreasing the magnetic field near the anode, which lead to the ionization ratio decrease, so the increase increment of electron current is much larger than ion current; while the later improve the electrons mobility through increasing the ion residence time in channel and enhance the ionization, which lead to the ionization ratio enhance finally, so the ion current boost significantly but the electron current varied slightly. Integrating above factors, it's concluded that the optimization effect on the channel length is better than the magnetic shield.

Acknowledgments

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