Effects of Hydrogen Partial Pressure within the Vacuum Facility on Plume Focusing of a Hall Thruster

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Abstract: The experimental and numerical methods were introduced to investigate the effects of hydrogen partial pressure, P_H, on plume focusing of a Hall-effect thruster (HET) in Harbin Institute Technology Plasma Propulsion Laboratory (HPPL). Hydrogen always existed in the vacuum chamber of the ground test system, which affected the thruster operation. However, in-depth study on the influence has never been carried out until now. In this paper, P_H was changed by means of directly injecting hydrogen into the chamber using an exterior bypass pipeline. The hydrogen characteristic lines were measured by optical equipments and used to tracking the gas backflow. The jet current was diagnosed by the probe to reflect the degree of beam focusing. The experimental results indicated that the increase of P_H can increase the hydrogen content in the HET discharge cavity. The plume divergence aggravated and discharge current increased when P_H gradually rose. To understand the above phenomenon, a two-dimensional Particle-in-cell (PIC) model of HET discharge channel was developed for the limitation of measuring instruments. The comparison between experimental results and numerical analysis demonstrates: hydrogen backflow changes the status of plasma focusing through affecting electric potential distribution in thruster channel; the electric potential lines become defocusing after hydrogen is injected; with the increase of P_H, the focusing capability of HET declines; the nature of the results attributed to the variation of electron mobility reflected by the increasing of electron current and decreasing of electron temperature.

I. Introduction

Hall-Effect thruster (HET) is a space propulsion device, which uses orthogonal electric and magnetic field to ionizing atoms, accelerating ions, and finally obtaining higher ion exhaust velocity. In recent years, space missions in China, such as station-keeping for high orbit altitude of satellite's platform, deep-space exploration and so on, make intensely application requirements on HET.[1,2] It promotes the investigation on the ground performance experiments of HET.

The ground experiments of HET in the vacuum chamber require low pressure level (10^{-3}Pa) which closes to space environment. So the vacuum chamber must connect with the air exhaust system. However, there is a significant problem for current exhaust system, which has low venting capacity for some substances with low molecular weights, such as hydrogen. In addition, on the condition of the HET operating, the oil and organic macro molecule disintegrated by the high-speed ion flow and generate hydrogen. The above situations cause higher hydrogen component of pressure in the chamber than that in the space. During the experiment, Bugrova A.I observed the different operating characteristic for same HET, but different air exhaust systems (molecular pump or

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diffusion pump, and so on). Especially, the differences of the plasma focus of the HET are very obvious. She attributed this phenomenon to the ratio of hydrogen in background pressure of the vacuum chamber. It is a pity that the verification experiment and intensively investigate have not been found in the publications.[3]

Based on the above mentioned work, exterior hydrogen supply equipment connected directly with the vacuum chamber in the Harbin Institute Technology Plasma Propulsion Laboratory (HPPL). The ratio of hydrogen to background gas in the chamber was changed through controlling hydrogen flow rate. Experimentally study on the hydrogen backflow affect ion focusing and discharge characteristics in the HET. Meanwhile, the Particle-in-Cell simulation technology of HET discharge channel was introduced to investigating the plasma parameters distribution variation which dependent on the magnitude of hydrogen backflow.

This paper is organized as follows. The experimental setup and measurement method are described in Section II. Experimental results and their analysis are presented in section III. Section IV addresses with PIC simulation model. Analysis of plasma parameters variation induced by hydrogen pressure is also described in this section. In Sec.V the important conclusions are given.

II. Experimental setup and measurement method

A. Vacuum system and HET-P70 in HPPL

The vacuum chamber in HPPL was a cylindrical, stainless steel chamber that was 1.2m in diameter and 4m in length. To reach high vacuum, the chamber was equipped with two K-600T oil diffusion pump with pumping speed of 13000L/S. Its preceding stage were one ZJP-600 lobe pump with speed of 600L/S and two 2X-70 rotary vane mechanical pump with speed of 70L/S. In this system, limit pressure of the chamber was 1.0×10-3Pa. When HET-P70 operated with Kr and total mass flow was 3.5mg/s (anode and cathode mass flow were 3mg/s and 0.5mg/s), the base pressure was 2.0×10-2Pa. The pressure measurement used BPG400 composite vacuum gauge. During the experiment, single air bag and bypass pipeline were used to release hydrogen, as shown in Fig. 1. Hydrogen pressure, P_H , was adjusted by flow rate control valve and expressed by

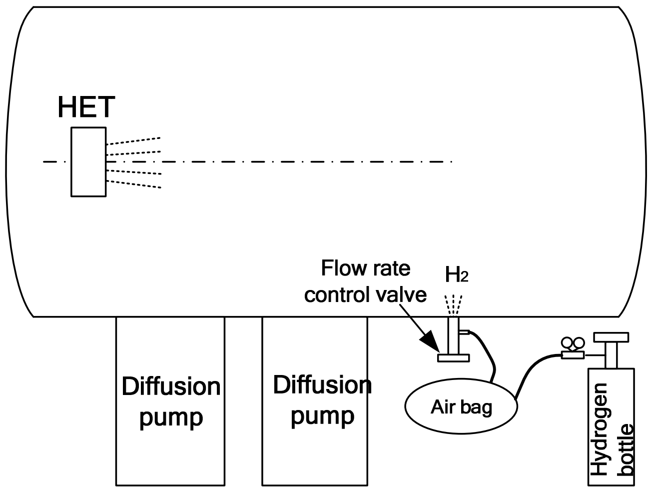

Figure 1. Vacuum system and exterior hydrogen supply equipment.

$$P_H = P - P_0 \tag{1}$$

Where P_0 is vacuum chamber pressure before hydrogen was injected and P is total background pressure.

1 kW annular HET-P70 was used, as shown in Fig.2. It has an outer diameter of 71 mm, a discharge channel width of 14 mm, and a channel depth of 30 mm. Boron nitride ceramic is used to construct the discharge chamber. One outer and two parallel inner magnetic coils are employed to establish various magnetic fields. A hot cathode is located at the 12 o'clock position on the thruster. The cathode orifice is located approximately 40mm downstream from the outer front pole piece. In the following experiments, high purity krypton (99.9996% pure) was supplied through 100sccm and 10sccm CS200 mass flow gauge, control precision 1%, supplied Kr to HET and cathode. In order to obtain spectroscopic data in HET discharge channel for studying axial distribution of plasma parameters, outer ceramic wall and magnetic poles were made to a slot with 1.5mm width along axial direction. During the experimentation, discharge voltage was 450V and anode and cathode mass flow were 3.0mg/s and 0.5mg/s for HET-P70 stable working.

B. Directional probe measurement of ion flow density distribution

Directional probe was used to obtain plasma flow characteristics in the plume of HET-70. The probe consists of a 1.05 mm diameter tungsten filament inside a 1.5 mm diameter Al_2O_3 ceramic insulator tube. The probe respectively parallels and verticals to axial direction of HET for measuring axial z and radial r components of directional ion flow. We fix the probe on a high-speed, reciprocating system. The system is driven by a linear motor, WMU51230-030-D. Its positioning resolution was 5μm. The measurement region was near field of the plume, -180mm< r <180mm， 20mm< z <130mm. When the probe operated, negative bias voltage was loaded to it for collecting ion current and isolated oscillograph, Tektronix TDS2014, completed data acquisition.

The direction and density distribution of ion flux were given through data processing.[4] These results were not only reflecting plasma jet characteristics but also been used to calculate mass utilization factor, χ , and plume divergence half-angle, $\alpha_{0.95}$. This method utilizing near field plasma information reflect jet properties. It reduced effectively the influence of charge exchange collision and ion combination on plume structure.

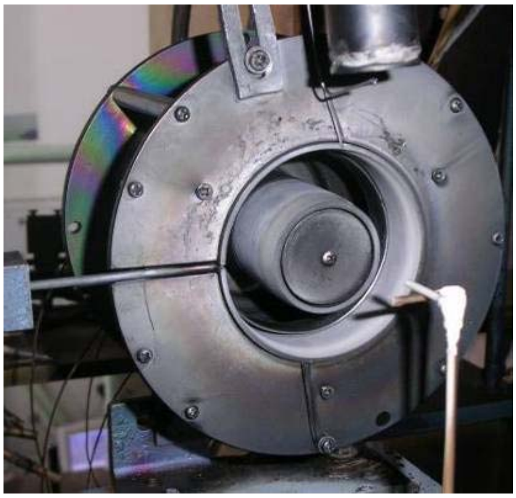

Figure 2. HET-P70 and spectroscopic diagnosis strategy in discharge channel.

C. Spectroscopic diagnosis of atom excitation and ionization in HET-P70 channel

Bugrova A.I. and co-workers had calculated ion number density distribution,[5] also called ionization distribution, in the discharge channel using dual spectrum lines method based on Corona model when thruster was stable operation. This method can calculate the average electron temperature based on the ratio of the intensity of two characteristic spectrum lines for the working gas and corresponding energy level excitation rate. And then, the number density of gas ionization per unit time is obtained by the spectrum line strength. Here, two strong lines for *Kr*, 758.74nm (4s24p5(0P°1/2)5p) and 811.29nm (4s24p5(3P°3/2)5p), were been chosen and paper Ref.6 and Ref.7 given their excitation and ionization cross section. The characteristic wavelength of hydrogen, 656.18nm, was selected to watch the backflow.

All the wavelength data containing *Kr* and *H* were collected by the spectrometer AvaSpecc-2048FT-8-RM. A ceramic tube with 50mm in length, 2mm in inner diameter and 3mm in outer diameter was used to obtain parallel light. The measured deviation was less than 1% through calculating average value of several results.

III. Experimental results and analysis

Before the hydrogen pressure experimentation, the performance of HET-P70 was optimized by adjusting magnetic field and external circuit parameters, and smaller plume divergence angle was hold and measured. The discharge characteristic and all the input parameters were record. Afterwards P_H in the chamber was just altered by control valve in the bypass pipeline. Experimental data were measured accordingly.

Different plasma jet for four P_H in the experiment was shown in Fig.3. It is well known that ion flow should be ejected strictly along axial direction and parallel plume presented under an ideal condition. Thus the plasma density of plume centre was zero since annular discharge channel. However, in real environment parallel jet hardly generated because of ion radial mobility cannot be eliminated. As a result, the ion density in the plume central area was increased and correspondingly the measurement value of ion current density was large, as shown in Fig.3. A comparison of the four pictures in Fig.3 demonstrated that, as the decreased in P_H, ion current density in the plume central region was reduced. It suggested that hydrogen in the chamber affected negatively ion focusing and aggravated ion radial movement which was regarded as one of the energy loss source.

Although we found the plume focusing was related with hydrogen introduced, the main reason of this phenomenon was unclear. Fortunately, other parameters were monitored simultaneously and also varied. As shown in Fig.4, relative intensity of HI 656.2nm was record along axial direction of the thruster and also improved when hydrogen content became large in the chamber. It demonstrated that hydrogen had stronger penetrability. Fig.5 was the distribution of *Kr* ionized number density per unit time, *q*, in different axial position. It can be seen that the density of *Kr* was decreased in -10mm~-4mm upstream of the thruster channel but slightly raised near channel exit, i.e. -4mm~0mm. It suggested that some hydrogen may be excited or ionized by electrons in ionization zone of *Kr*. At the same time, ionization area was enlarged and extended to thruster exit. Azziz mentioned the location of the ionization region as a potential factor affecting plasma focusing in his Doctoral Dissertation.[8] He quoted Raitses' experimental results [9] and illustrated that pushing the ionization region closer to the anode in favor of reducing plume divergence. Azziz's investigations also showed that the ionization region likely occurred closer to the thruster exit in the jet mode, which was relative to collimated mode.[8]

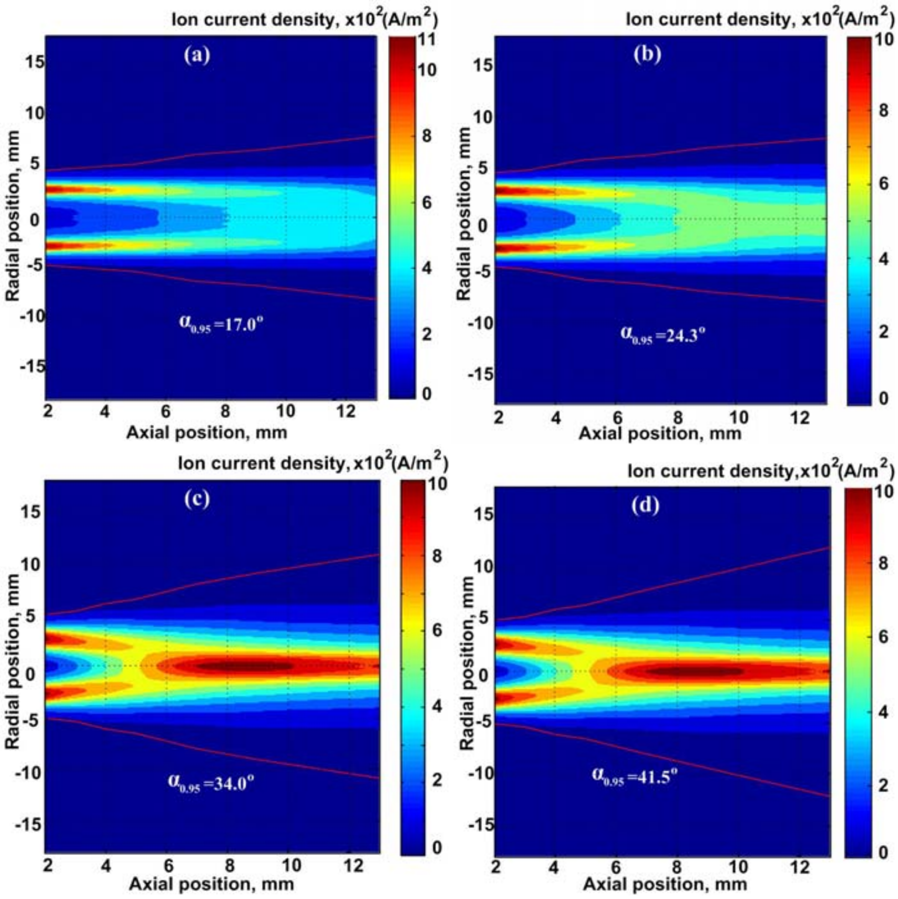

Figure 3. HET plume divergence for different P_H
(a) P_H =0Pa; (b) P_H =0.007Pa; (c) P_H =0.014Pa; (d) P_H =0.04Pa.

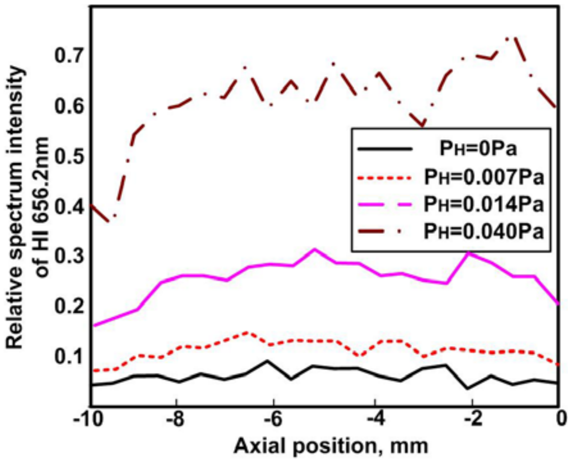

Figure 4. Relative intensity of HI 656.2nm for different P_H in HET channel.

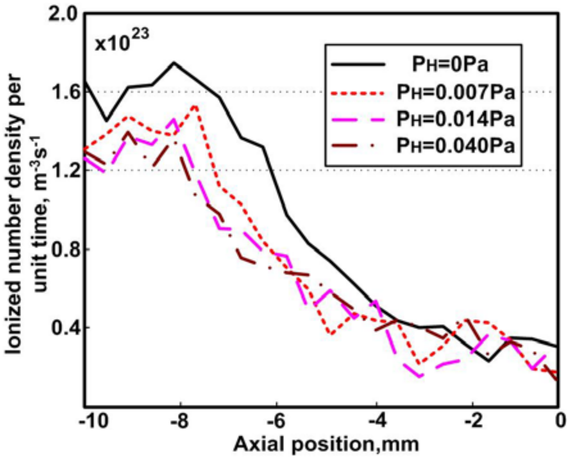

Figure 5. The ionization distribution of Kr for different PH in HET-P70 channel.

IV.Particle-in-cell simulation of plasma parameters on HET-P70 discharge channel existing hydrogen backflow

A. The numerical model

For the limitation of experiment conditions, above results were absence of directly understand the effects of hydrogen pressure on plasma focusing. Therefore, to further clarify the relation between hydrogen backflow and the distribution characteristics of plasma and field in the thruster channel, we developed a complete, self-consistent two-dimensional axial symmetric Particle-in-cell (PIC) model of the HET-P70 discharge channel. Fig.6 showed the calculation area and magnetic field according to the experimental measurement. The primary thought and method of the model had been described in previous working.[10] In this paper, we only gave the modeling differences.

The variation of P_H reflected the change of hydrogen density n_H in the chamber since $P_H = n_H K T_H$, where K is Boltzmann constant and T_H is hydrogen temperature. Considering hydrogen full of all the chamber space, the initial hydrogen density n_{H0} was same in the calculation region. However, for different $P_{H,}$ n_{H0} also was changed. This distribution would be changed at each time step based on the hydrogen self-consistent movement such as colliding with electron or channel wall, excitation or ionization and so on. The data of Kr and hydrogen cross section came from Ref.11 and Ref.12, separately. The key problem of modeling was how to judge an electron collided with *Kr* or hydrogen. Here, we considered comparing their collision frequency $\gamma_e = n_a \sigma v_e$ for a given electron. In fact, electron velocity v_e was same. We only paid attention to the product of neutral density n_a and cross section σ at the electron position. And finally, the electron would collide with the neutral that had larger value of γ_e . All the electrons were handled uniformly whether they interacted with *Kr* or hydrogen.

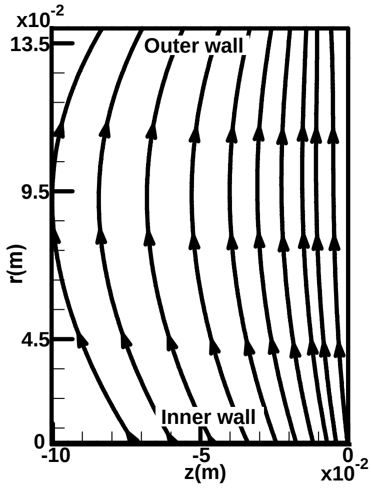

Figure 6. The simulation area and magnetic field lines in the calculation.

B. Simulation results and discussion

The distribution electric potential φ are described with black solid lines in Fig.7 for three cases, (a) n_{H0}=0 and (b) $n_{H0} = 3\times10^{20}\,\mathrm{m}^{-3}$. In Fig.7 (a), hydrogen backflow isn't considered. The electric potential lines convex slightly to the exit and maximum electron temperature focuses on the channel centre area. These distributions are axial symmetric about the channel centerline. It suggests that a majority of ions should be ejected along axial direction. The degree of ion focusing is high. Whereas hydrogen joined will destroy the parameter symmetry, as shown in Fig.7 (b). Near the outer wall, T_e and φ all have slant tendency inward the cavity. And the inclined degree will

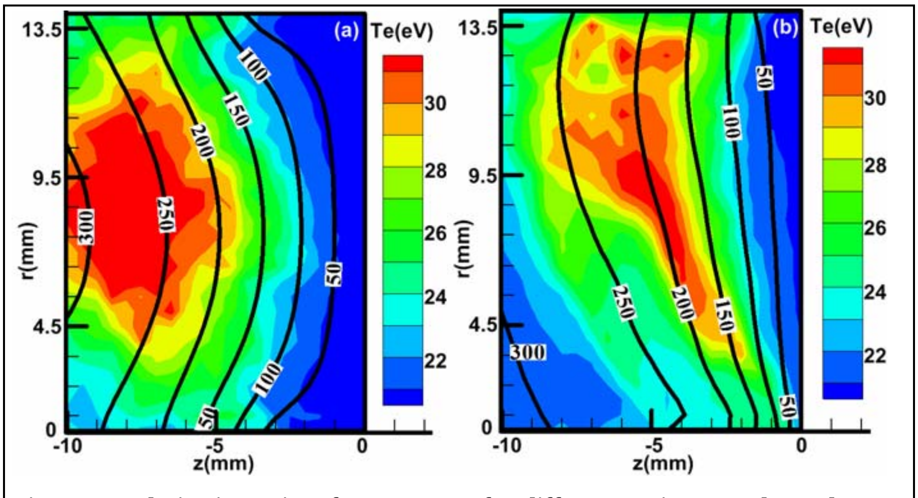

Figure 7. Relative intensity of HI 656.2nm for different P_H in HET channel. (a) P_H =0Pa; (b) P_H =0.014Pa.

aggravate with hydrogen flux increased. Since ions will accelerated by electric field along the vertical direction of φ. This kind of inclined electric potential lines results in the ions moved to the direction of outer wall. When ions enter into near field plume, this state of ion motion will be hold for a while. Consequently, the larger plume divergence angle will be obtained. This result is coincident with the experimental phenomenon.

In HET, the electric potential distribution due to electron conductivity mechanism along the channel decides the ion acceleration effect then decides beam focusing and performance. Generally speaking, the axial electric field and radial magnetic field exist in HET discharge channel. The electrons are constrained by the field in a finite region and form Hall drift in azimuthal direction. Electron movement traversing magnetic field and forming conductivity can not occur until some factors destroy drift movement. At present, three mechanisms that is classical conductivity σ_{ea}, near wall conductivity σ_{ew} and Bohn conductivity σ_B were proposed to affecting Hall drift and changing the conductivity distribution. They can be expressed by Eq.(2), which assumed electron cyclotron frequency ω_{ce} was much larger than the frequency of electron colliding with neutral ν_{ea} and wall ν_{ew} in HET. That is $\omega_{ce} \gg \nu_{ea}$, $\omega_{ce} \gg \nu_{ew}$.

$$\sigma_{ea} = \frac{e^2 n_e \nu_{ea}}{m_e \omega_{ce}^2}$$
$$\sigma_{ew} = \frac{e^2 n_e \nu_{ew}}{m_e \omega_{ce}^2} \tag{2}$$
$$\sigma_B = \frac{e n_e}{(\omega_{ce}\tau) m_e B}$$

where m_e and n_e are electron mass and number density. e is unit charge. B is magnetic field intensity. σ_B always be regarded as a constant in the simulation because its physical mechanism is complex. Both σ_{ea} and σ_{ew} are relate to collision. ν_{ea} and ν_{ew} can be presented by Eqs.(3)-(4)

$$\nu_{ea} = n_a \nu_{eth} Q(T_e) \tag{3}$$

$$\nu_{ew} = \frac{\nu_{eth}}{h_{ch}} \exp\left(-\frac{\Delta\varphi_w}{T_e}\right) \tag{4}$$

In Eq.(3), n_a is neutral number density. ν_{eth} is electron thermal velocity. Q is collision cross section which is the function of T_e. In Eq.(4), h_{ch} is HET channel width. φ_w is the electric potential of insulation wall.[13-15]

When hydrogen exists in the channel, the density of hydrogen goes up according to the experimental results. On this condition, we think that the probability of electrons colliding with neutral (*Kr* or *H*) or wall increases and correspondingly T_e deduces. As a results, ν_{ea} and ν_{ew} should become high on several levels based on Eqs.(3)-(4). Correspondingly, the total conductivity σ_t will improved, as shown in Eq.(2). Because electric field E in the channel can be written by

$$E = J_e / \sigma_t \tag{5}$$

where J_e is electron current density. E can be considered as a constant for the same discharge voltage. Thus, the variation of J_e is directly proportional to σ_t. As P_H increases, J_e increases.

In Table 1, the discharge current and the proportion of electron current are also analyzed corresponding to Fig.7 (a)-(b). Their variation behaviors are same as the experimental results and above analysis. All the results prove that hydrogen participating in the plasma discharge changes electron conductivity and forms diverging distribution of electrical potential and finally results in poor plasma focusing characteristics.

Table 1 Data analysis based on numerical results

	I_d (A)	δ (%)	T_{emax}(eV)
(a)	2.15	41.3	35.82
(b)	2.81	43.9	31.23

In addition, the maximum temperature is decrease with hydrogen pressure, as shown in Table 1 and the area of larger electron temperature T_e have a shrunken tendency in Fig.7(b). It suggests again that electron mobility strengthens since electrons have cooling effect which attribute to losing the energy by collision.

V. Conclusion

The characteristics of beam focusing were studied by experimental and numerical approach. In the experiment, HI 656.2nm was monitored by spectrometer to reflect hydrogen content. We found the spectrum intensity of HI 656.2nm rose when PH was generally improved. Correspondingly the jet became divergence and average discharge current gone up. The PIC numerical results showed that the distribution of electric potential changed from focusing to defocusing before and after considering the hydrogen backflow. And with the increase in PH, the degree of defocusing generally aggravated and the maximum electron temperature decreased obviously. At the same time, both experimental and numerical results all indicated that electron current percent was increase. These consequences suggested that hydrogen movement in the HET channel enhanced the electron mobility that should be attributing to the electrons collision.

Acknowledgments

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