Modeling and Measurement of Hydrogen Ion Species Fractions in a Penning Plasma Discharge

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1. Introduction

Proton ion sources are useful in various fields. Traditionally, the main field of use is accelerator. Today's accelerators require increasingly higher beam power [1]. Another area where proton ion sources are used is nuclear fusion. A neutral beam injector is used for plasma heating or diagnostics in the fusion field. It requires a high current beam of high energy too [2,3]. Neutron generators are also an important application area of proton ion sources [4,5]. Deuteron-triton or deuteron-deuteron collisions are often used for neutron generation, so a high-performance deuteron (proton) beam ion source is essential. Thus, the critical performance required of the proton ion source is high beam power or current. On the other hand, it is also important to make more efficient beams. A high monoatomic fraction beam is the case. If molecular ion beam such as H_2^+, H_3^+ are incident on the facilities, this will result in beam loss or reduce the reaction within the facilities.

In this work, a model to calculate the ion species fraction of hydrogen plasma is established. Using this model, the tendency of the change of the ion species fraction according to the plasma parameters is grasped, and the direction to increase the monoatomic fraction is set up. To obtain the experimental results, a PIG (*P*enning or *P*hilips *I*onization *G*auge) ion source is used. To measure the ion species fraction, a dipole mass analyzing magnet is used. Finally, the improvement direction of the ion source is set by comparing the experimental results with the tendency indicated by the model.

2. Numerical Model of Hydrogen Ion Species

The ratios of the ion species can be calculated from the equations of particle balance in production and destruction for each species of neutral particles and ions in the source plasma. The most general form of the particle balance equation for the steady state of the discharge is thus

$$\frac{dn_i}{dt} = \sum_{j=1}^{N_p} a_j^p k_j^p \prod_{l=1}^{N_j^p} n_{jl}^p - \sum_{j=1}^{N_d} a_j^d k_j^d \prod_{l=1}^{N_j^{pd}} n_{jl}^d - k_r n_i = 0 \quad (1)$$

where p and d indicate production and destruction processes for the ith species, n_i is the species density, a_j is the number of particles of the species, k_j is the rate constant of the process, N_j is the number of the reactants involved, n_{jl} is the density of the lth reaction partner and k_r is rate constant for surface process reactions [6]. In addition to Eq. (1), the conservation of total hydrogen atoms and the charge neutrality is used together to solve the problems.

$$n_{H_2} + \frac{1}{2}n_H + \frac{1}{2}n_{H^+} + n_{H_2^+} + \frac{3}{2}n_{H_3^+} = \frac{p}{k_B T_g} \quad (2)$$

$$n_{H^+} + n_{H_2^+} + n_{H_3^+} = n_e \quad (3)$$

The volume reaction processes considered in the model and its notation for the corresponding rate coefficients are as Table I [7,8].

Table I: List of Volume Process Reactions

Reactions	Rate coefficients $<\sigma v>$
$H + e \rightarrow H^+ + 2e$	a_1
$H^+ + e \rightarrow H + h\nu$	a_2
$H_2 + e \rightarrow 2H + e$	a_3
$H_2 + e \rightarrow H_2^+ + 2e$	a_4
$H_2 + e \rightarrow H^+ + H + 2e$	a_5
$H_2^+ + e \rightarrow 2H^+ + 2e$	a_6
$H_2^+ + e \rightarrow H^+ + H + e$	a_7
$H_2^+ + e \rightarrow 2H$	a_8
$H_3^+ + e \rightarrow H_2 + H$	a_9
$H_3^+ + e \rightarrow H^+ + 2H + e$	a_{10}
$H_2^+ + H_2 \rightarrow H_3^+ + H$	a_{11}

Table II: List of Surface Process Reactions

Reactions	Rate constants
$H \xrightarrow{\text{(wall)}} \frac{1}{2}H_2$	$\gamma D_{eff}^H / \Lambda_{eff}^2$
$H^+ \xrightarrow{\text{(wall)}} H$	$1/\tau_{H^+} = u_{B,H^+} A_{eff}/V$
$H_2^+ \xrightarrow{\text{(wall)}} H_2$	$1/\sqrt{2}\tau_{H^+} = u_{B,H_2^+} A_{eff}/V$
$H_3^+ \xrightarrow{\text{(wall)}} H_2 + H$	$1/\sqrt{3}\tau_{H^+} = u_{B,H_3^+} A_{eff}/V$

Table II is the list of surface process reactions [6,9]. τ_{H^+} is the characteristic for ion wall loss, u_{B,H_x^+} is the Bohm velocity of the relevant positive ion, A_{eff} is an effective area. D_{eff}^H is the effective diffusion coefficient describing the superposition of free Knudsen diffusion and collisional diffusion processes, Λ_{eff}^2 is the effective diffusion length and γ is the wall recombination factor.

Fig. 1 represents the change of reaction rate coefficients according to the electron temperature [10].

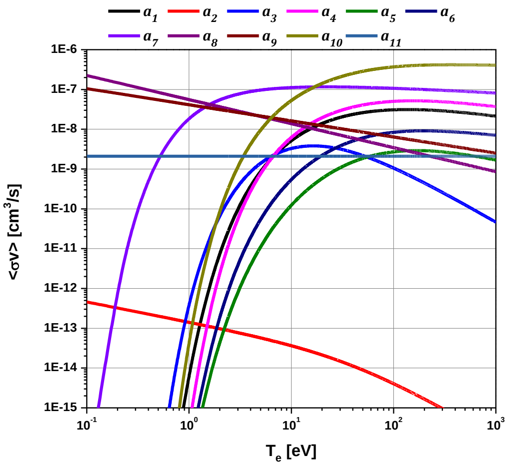


Fig. 1. Reaction rate coefficients of 11 reactions listed in Table I.

If this established model is calculated according to the change of the plasma parameters, the ion species fraction of the hydrogen plasma can be obtained. Among the plasma parameters, the operating pressure and the electron temperature have the following relationship [11,12].

$$\frac{K_{iz}(T_e)}{u_B(T_e)} = \frac{1}{n_g d_{eff}} \tag{4}$$

Where K_{iz} is the rate constant for electron impact ionization, n_g is the neutral density and d_{eff} is the effective plasma size which is defined as the ratio of plasma volume V to effective area A_{eff}.

Considering Eq. (4), we can obtain the result as shown in Fig. 2 by calculating the given model. Fig. 2(a) is plasma density dependence of ion species fraction. The operating pressure is fixed at 10 mTorr. It shows that as the plasma density increases, the monoatomic fraction of the hydrogen plasma increases. In order to obtain a ratio close to 90%, the plasma density should be increased around to 1×10^{13} cm^{-3}. Fig. 2(b) is operating pressure dependence of ion species fraction. The plasma density is fixed at 1×10^{12} cm^{-3}. In this case, as the operating pressure decreases, the monoatomic fraction increases. The dotted line in Fig. 2(b) is the change of electron temperature by operating pressure. From this relation, the monoatomic fraction increases as the electron temperature increases.

In summary, to increase the monoatomic fraction, the plasma density should be increased and the pressure should be lowered.

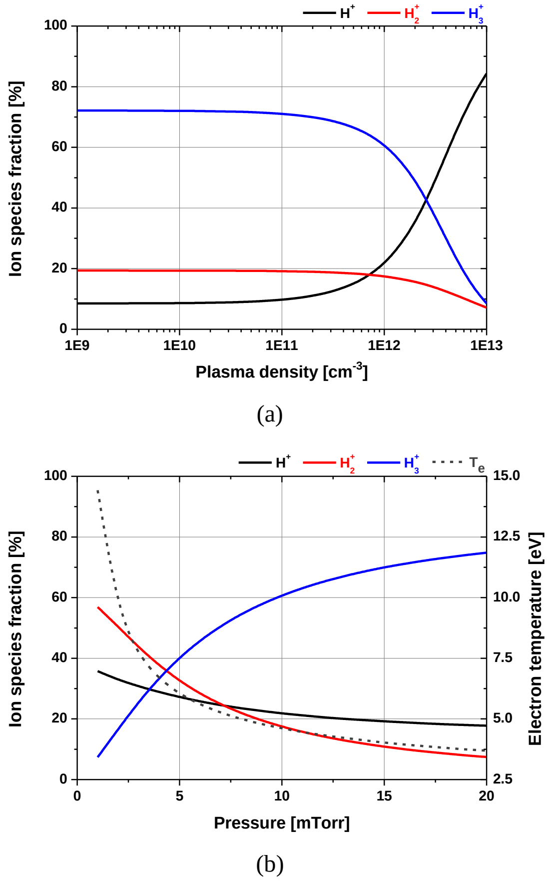


Fig. 2. Changes of hydrogen ion species fractions (a) by plasma density (pressure = 10 mTorr), (b) by operating pressure ($n_e = 1\times10^{12}$ cm^{-3}).

3. Experiments and Results

The Penning plasma ion source is constructed as shown in Fig. 3. It consists of a tubular anode and 2 cathodes at each side. The inner diameter of anode is 25 mm, and its length is 40 mm, 25 mm diameter cathodes are set away from anode by 5 mm. So the discharge volume is 25 mm (D) × 50 mm (L).

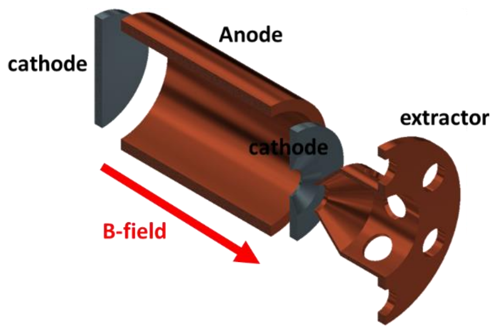


Fig. 3. Basic structure of Penning discharge plasma ion source.

At one of the cathodes, an aperture is placed to extract ion beam. An extractor is set by the extraction hole. To make Penning discharge, magnetic field is set along the axis of anode. Magnetic field is generated by a solenoid coil and can be changed by adjusting coil current.

The discharge is performed by changing conditions as the magnetic field, 400 – 1000 G, the operating pressure, 2 – 20 mTorr and the discharge current, 10 – 400 mA. The ions in the discharged Penning plasma is extracted by 5 kV potential and ion mass is analyzed by dipole magnet. Fig. 4 is an example of analyzed ion mass and the fraction of its species.

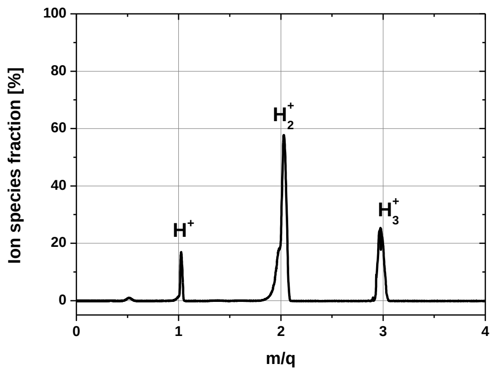
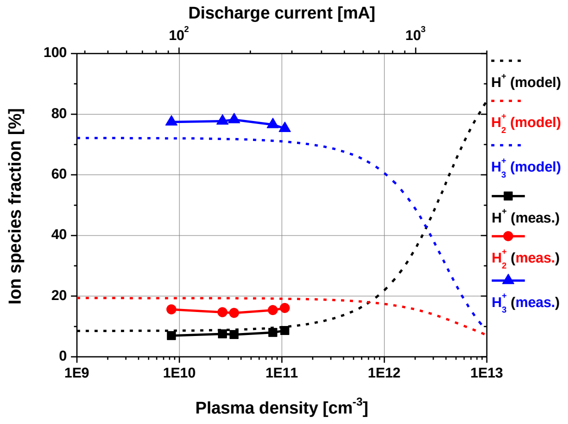


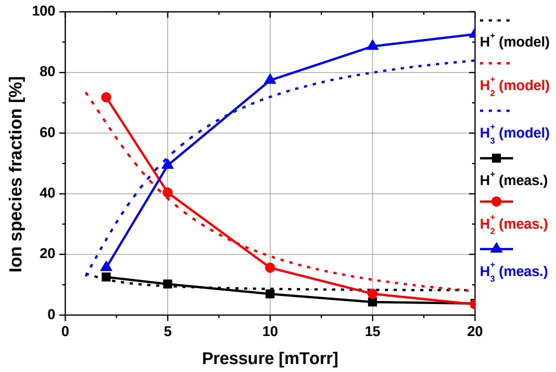
Fig. 4. An example of hydrogen ion species fraction measurement.

Fig. 5 is the changes of ion species fraction by discharge conditions and the comparison with the results of modeling. The variables of this discharge are magnetic field, discharge current and operating pressure. In this case the magnetic field is fixed at 800 G. Fig. 5(a) shows the discharge current about 100 – 300 mA corresponds to the plasma density around 1×10^{10} – 1×10^{11} cm^{-3}. The measured monoatomic fraction is below 10%. In Fig. 5(b) the discharge current of experiment is approximately 100 mA and the plasma density of the modeling is 1×10^{10} cm^{-3}. In these condition, the behavior of ion species fraction by pressure is similar between the experiment and the modeling. It also shows the monoatomic fraction is very low and the discharge current is insufficient to make high density plasma.

In this experiment, the power supply which applies the discharge current to the plasma source do not have enough power to draw several amperes of current, so that just a maximum of a few hundred milli-amperes of current can be applied. It is a glow discharge regime and plasma density is not so high. To get high monoatomic fraction, the plasma density has to be raised drastically. So new power system which can apply several amperes to the discharge should be set up.



(a)



(b)

Fig. 5. Measurement of hydrogen ion species fractions and comparison with the model results (a) by discharge current (B = 800 G, pressure = 10 mTorr), (b) by operating pressure (B = 800 G, discharge current = 100 ± 10 mA / $n_e = 1\times10^{10}$ cm^{-3}).

4. Conclusions

A model for the hydrogen ion species fraction was developed and performed. It is demonstrated that high plasma density and low operating pressure are likely to increase the monoatomic fraction. The hydrogen ion species fraction is actually measured at a Penning plasma discharge source and compared with the model. The measured monoatomic fraction is about 10% or below. This is because the discharge current is low and so the density of the generated plasma is low too.

In order to obtain a monoatomic fraction close to 90%, the plasma density should be increased around to 1×10^{13} cm^{-3}. To obtain that plasma density, the discharge regime has to transit glow to arc. For that, several amperes of the discharge current are needed. To accomplish this performance, new power systems have to be set up.

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