Extraction Probability of Negative Ions from Hydrogen Ion Sources - Effects of Filter Magnetic Field and Gas Pressure -

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Abstract. Trajectories of H^- ions are calculated numerically by solving the 3D motion equation, including effects of collisional destruction, elastic collisions and charge exchange collisions. According to these trajectories, extraction probability of H^- ions produced at any location inside the source and energy of extracted H^- ions are discussed as a function of gas pressure. Effects of production zone and filter magnetic field on extraction probability are also discussed. The probability for surface produced H^- ions keeps nearly the constant value, and that for volume produced H^- ions decreases with gas pressure. The kinetic energy of extracted H^- ions is reduced mainly by charge exchange collision.

INTRODUCTION

Negative ion based neutral beam injection is one of the most promising candidates for heating and current drive of fusion plasma. By seeding a small amount of cesium (Cs) vapor into the volume ion source, H^- production has been increased by a factor of 2-4 and optimum pressure decreases to 0.8-1.0 Pa [1]. Although Cs effects have been observed by many researchers, the mechanism remains to be discussed. We have studied source modeling [2-6] and Cs effects on enhancement of H^- production in a tandem two-chamber system, i.e. the source and the extraction regions. According to our numerical results, it is confirmed that the dominant process for enhancement of H^- production is surface production [5, 6].

For discussing pressure dependence of extracted H^- current, we have also estimated extracted H^- ions, only by taking into account stripping loss in the acceleration grid region [4, 5]. But all of the H^- ions in the source aren't extracted because of collisional destructions. So, it is important to study the behavior of H^- ions in the second chamber, i.e. the extraction region [7]. In addition, it has been reported that the beam divergence of surface produced H^- ions are nearly the same as one of volume produced H^- ions [8]. However, the physical reason has not yet been clarified.

In this article, for discussing pressure dependence of extracted H^- current, we will discuss the extraction probability of H^- ions with using both model calculation [5] and H^- ion transport in the second chamber [7]. Although preliminary results have been presented [9], H^- ion transport is further studied including effects of production zone and filter magnetic field. To clarify good beam optics of surface produced H^- ions, we will also study both mean kinetic energy and the velocity distribution of extracted H^- ions.

SIMULATION MODEL AND PROCEDURE

To study H^- production in a tandem two chamber system, we have used the simulation model (a zero-dimensional code) shown in Fig. 1 [3-5]. In the present study, with using a coordinate system shown in Fig. 2, negative ion trajectory in the second chamber shown in Fig. 1 is calculated numerically, where L = 30 cm. Magnetic filter is set at 2 cm (= L_2) upstream from a plasma grid (PG). The spatial profile of magnetic filter is given by the

Gaussian profile $B_x(y, z) = B_0\exp[-(z-z_0)^2/l_B^2]$, where $z_0 = 2$ cm, $l_B = 1$ cm and $B_0 = 120$ Gauss. Surface confinement magnets field is also present. Sixteen columns of permanent magnets are arranged to construct line cusp field.

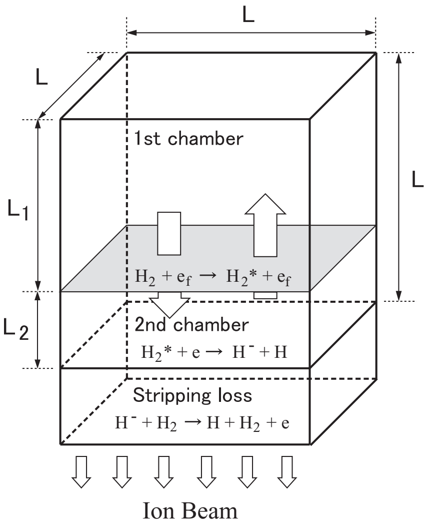


Fig. 1 Simulation model for the tandem two-chamber system.

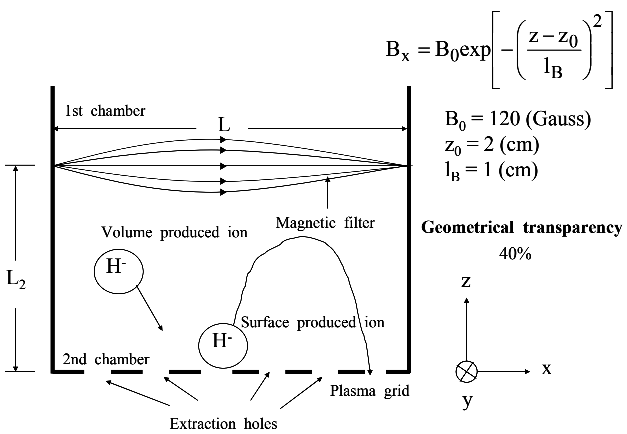


Fig. 2 Cross-sectional view of the model geometry for the second chamber of the tandem system shown in Fig. 1.

When a negative ion is produced, it moves inside the source until destruction or extraction. Trajectories of H^- ions are calculated numerically by solving the 3D motion equation as follows:

$$M d\boldsymbol{v}/dt = q(\boldsymbol{v}\times\boldsymbol{B}) + \boldsymbol{F}_{col}, \quad (A)$$

where M is mass of the H^- ion, q is charge, $\boldsymbol{v}$ is the velocity rector and $\boldsymbol{B}$ is the vector of magnetic flux density. The electric field is neglected in the above equation because it is negligibly small over the entire plasma region to be examined as compared with the electric field in the very narrow region near the plasma grid and chamber walls. The second term on the right-hand side $\boldsymbol{F}_{col}$ is the collision term, which is explained later. When $\boldsymbol{x}$ is the vector of the position, the definition of velocity vector can be described as

$$d\boldsymbol{x}/dt = \boldsymbol{v} \quad (B).$$

We solved these two equations of (A) and (B) in three dimensions using the Runge-Kutta-Gill method as the initial value problem. The collisions between H^- ions and other particles are calculated by the Monte Carlo method [7, 10]. The following destruction, charge exchange and elastic collisions are taken into account: (1) electronic detachment (ED) $H^- + e \rightarrow H + 2e$, (2) mutual neutralization (MN) $H^- + H^+ \rightarrow 2H$, (3) $H^- + H_2^+ \rightarrow H + H_2$, (4) $H^- + H_3^+ \rightarrow 2H + H_2$, (5) associative detachment (AD) $H^- + H \rightarrow H_2 + e$, (6) $H^- + H_2 \rightarrow H + H_2 + e$, (7) $H^- + Cs^+ \rightarrow H + Cs$, (8) $H^- + Cs \rightarrow H + Cs + e$, (9) charge exchange (CX) $H^- + H \rightarrow H + H^-$ [11], and (10) elastic collision (EC) with H^+ ions.

Volume produced H^- ions are launched isotropically in all directions at any location with an initial energy of 0.5 eV except that axial position (z direction) is set at four different points (i.e. z = 0.25, 0.75, 1.25 and 1.75 cm), and surface produced H^- ions are launched from the PG with an initial energy of 0.5, 1 and 2 eV due to potential difference between plasma potential and plasma grid potential. When H^- ions are reached the PG or destroyed by collisional processes, the calculation is finished.

The background plasma profiles are assumed to be uniform, and these values are obtained by the previous model calculation [4, 5] and are used to estimate mean free paths for collisions mentioned above. To determine the electron density dependence of H^- production and particle densities, calculation is performed as a function of electron density $n_e(1)$ in the first chamber on the assumption that other plasma parameters are kept constant [3-5]. A typical numerical result is summarized in Table I. Plasma conditions for model calculation is as follows: the gas pressure p = 5 mTorr, the electron density ratio between two chambers $n_e(2)/n_e(1) = 0.2$, density of e_f in the first chamber $n_{fe}(1)/n_e(1) = 0.05$, electron temperature in the first and second chambers are, respectively, $\kappa T_e(1) = 5$ eV, $\kappa T_e(2) = 1$ eV, and magnetic filter position $L_1 : L_2 = 28 : 2$ cm (i.e. $z_0 = L_2 = 2$ cm).

n_e	Electron density	1.00×10^{12} cm^{-3}
n_H	H atom density	5.22×10^{13} cm^{-3}
n_{H_2}	H_2 atom density	8.31×10^{13} cm^{-3}
n_{H^+}	H^+ ion density	3.73×10^{11} cm^{-3}
$n_{H_2^+}$	H_2^+ ion density	2.71×10^{11} cm^{-3}
$n_{H_3^+}$	H_3^+ ion density	1.52×10^{11} cm^{-3}
n_{Cs^+}	Cs^+ ion density	5.85×10^{11} cm^{-3}
n_{Cs}	Cs atom density	4.41×10^{12} cm^{-3}
T_e	Electron temperature	1.0 eV
T_H	H atom temperature	0.5 eV
T_{H^+}	H^+ ion temperature	0.5 eV

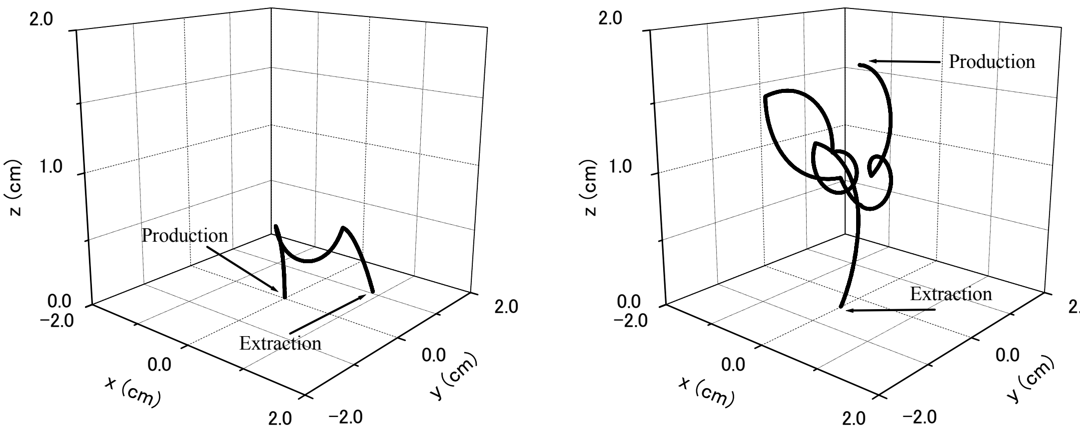
TABLE I Plasma parameters used in this simulation when gas pressure p = 5 mTorr.

NUMERICAL RESULTS AND DISCUSSION

The trajectories of H^- ions are obtained by solving the 3D motion equation until ions are destroyed or extracted (i.e., reached to the PG). Typical orbits of H^- ions in the second chamber of the negative ion source are shown in Fig. 3.

At first, characteristic features of H^- ion trajectories (i.e. properties on H^- ion extraction) are discussed. To this end, for a certain plasma conditions, a set of five calculations (one calculation for surface produced H^- ions and four calculations for volume produced H^- ions with different four z positions) is done. We used 10^3 test H^- ions for one calculation. Table II shows the simulation result, where gas pressure is 5 mTorr. In the present case, 740 surface produced H^- ions reached the PG and extraction probability is about 25.6 % (geometrical transparency of the PG is assumed to be 40 %). For volume produced H^- ions, the probability to reach the PG depends strongly on upstream distance z from the PG. Then, mean value of the extraction probability is 4.2 %.

This probability depends on gas pressure. Extraction probability of volume produced H^- ions decreases with gas pressure. These characteristic features are clearly shown in Fig. 4. Effect of magnetic filter field on H^- trajectories is also discussed. But, there is scarcely difference in extraction probability due to difference of filter field. Numerical result is shown in Fig. 5.



(a) surface produced H^- ions

(b) volume produced H^- ions

Fig. 3 Examples of H^- ion trajectories in the second chamber : (a) a volume produced H^- ion (initial energy : 0.5 eV, birth point (x, y, z) = (0, 0, 1.75 cm)), (b) a surface produced H^- ion (initial energy : 1 eV, birth point (x, y, z) = (0, 0, 0)).

Kinds of H^- ion loss		Surface produced H^- ions	Volume produced H^- ions — Birth point of volume production [cm]			
			0.25	0.75	1.25	1.75
Wall loss		25	38	51	42	50
Collsional destruction	e	11	28	40	73	216
	H^+	46	93	136	123	121
	H_2^+	33	72	92	93	63
	H_3^+	14	30	57	49	42
	H	48	122	158	179	139
	H_2	79	206	260	277	230
	Cs^+	94	69	101	104	100
	Cs	10	31	32	33	28
Total		335	651	876	931	939
Elastic collision	H^+	724	1773	2226	2287	1885
Charge exchange	H	2029	3635	4540	4732	4280
H^- ions reached the PG		640	311	73	27	11
Average energy of H^- ions reached the PG [eV]		0.67	0.46	0.45	0.47	0.40
Extraction probability [%]		25.6	12.4	2.9	1.1	0.4

TABLE II Numerical results of H^- transport when p = 5 mTorr.

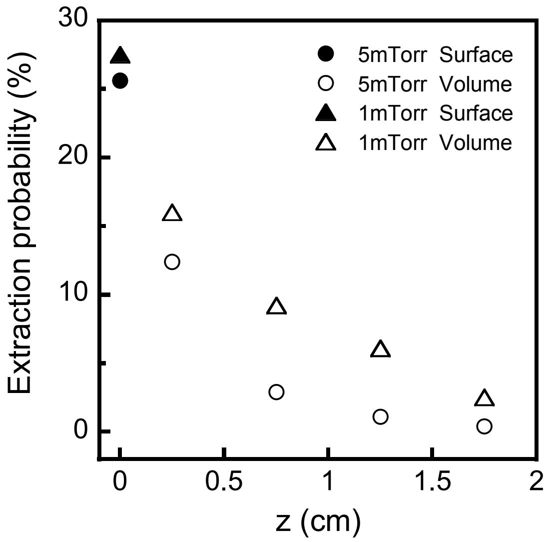


Fig. 4 Extraction probability as a function of z. Parameter is hydrogen gas pressure, where B_0 = 120 G.

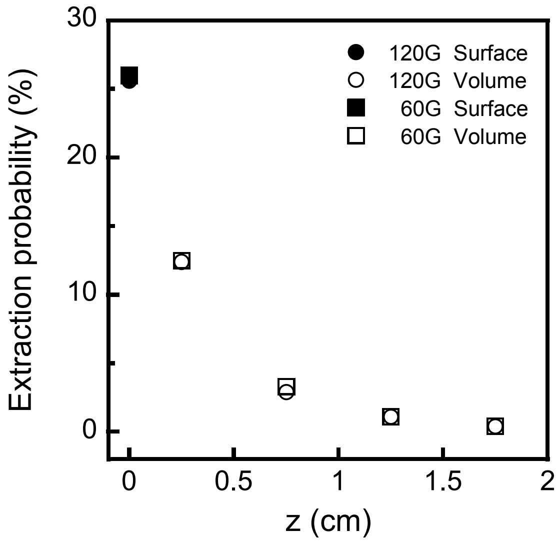


Fig. 5 Extraction probability as a function of z. Parameter is magnetic filter field, where gas pressure p = 5 mTorr.

By the way, for simplicity, the modeling is made for a constant and equal plasma potential in the first and second chambers. With this choice of plasma potential, H^- ions are injected from the first chamber into the second chamber, but this effect is not considered in the present simulation and may modify a little the number of H^- ions reaching the PG. Namely, a little enhancement of extraction probability may be expected.

H^- ion transport (i.e. the extraction probability) depends on gas pressure. Discussing this point, the same calculations described above are done by changing gas pressure. In the present calculation, initial positions (i.e. birth points) of surface produced H^- ions are distributed at any location on the PG and those of volume produced H^- ions are also distributed at any location in the second chamber, i.e. three dimensional. Now, 10^3 test particles for surface produced H^- ions and 2×10^3 test particles for volume produced H^- ions are used, respectively. Numerical results are shown in Fig. 6. It is remarkable that extraction probability of surface produced H^- ions is much higher than that of volume produced H^- ions. Moreover, extraction probability of volume produced H^- ions decrease with gas pressure, but that of surface produced H^- ions keeps a nearly constant value. Physical meaning is as follows: With increasing gas pressure, particle densities increase and mean free path of H^- ions decreases in its value. Therefore, transport of H^- ions in the extraction region decreases due to collisional effects. Namely, surface produced H^- ions injected into plasmas are reflected easily by elastic and charge exchange collisions. On the other hand, volume produced H^- ions are impended to reach the PG by collisional processes.

Kinetic energy (KE) of H^- ions are reduced by elastic [12] and charge exchange [7] collisions. According to the Table II, for surface produced H^- ions with initial energy 1eV, KE of extracted H^- ions is reduced to 0.67 eV. On the other hand, for volume produced H^- ions with 0.5 eV, KE of extracted H^- ions is reduced to 0.445 eV, and lower than that of surface produced H^- ions due to difference in initial energy of H^- ions. Figure 7 shows velocity distribution of extracted H^- ions. Although there is some difference between the velocity distribution of extracted H^- ions for surface produced H^- ions and that for volume produced H^- ions, this energy relaxation and velocity distribution are the cause for good beam optics of negative ion current with Cs seeding [8]. As is shown in Table II, charge exchange collision is the most dominant collision process. Therefore, it plays an important role in energy relaxation of extracted H^- ions.

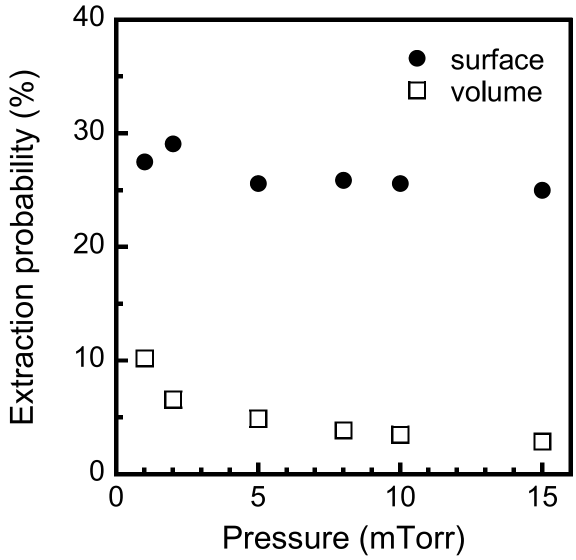
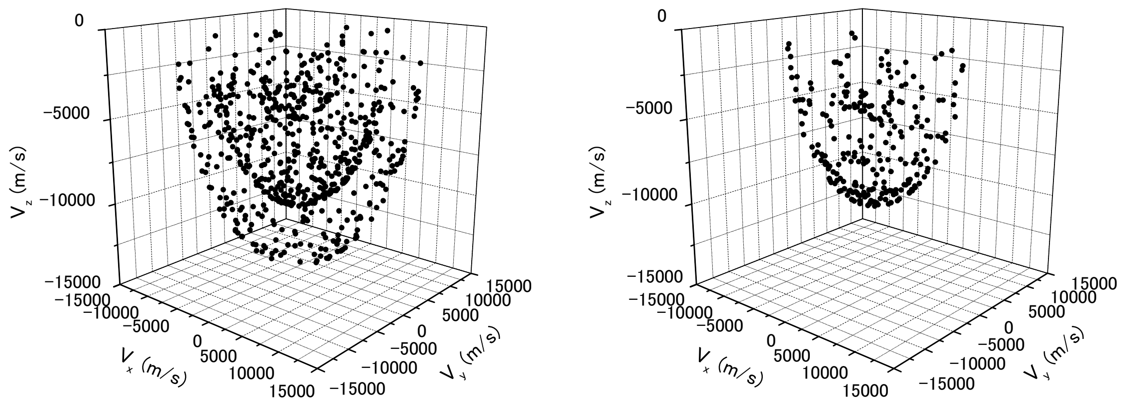


Fig. 6 Pressure dependence of extraction probability for H^- ions : ● for surface produced H^- ions, □ for volume produced H^- ions with Cs.



(a) Surface produced H^- ions

(b) Volume produced H^- ions

Fig. 7 Velocity distribution of extracted H^- ions; (a) surface produced H^- ions, (b) volume produced H^- ions.

CONCLUSIONS

The probability for H^- ions to reach the plasma grid (i.e. extraction probability) is estimated. As a whole, extraction probability is relatively low. It is confirmed that extraction probability for surface produced H^- ions is much higher than that for volume produced H^- ions. Within the present numerical conditions, the extraction probability for surface produced H^- ions keeps nearly the constant value (i.e. 25-28 %), and that for volume produced H^- ions decreases in its value from 10 % to 3 % with increasing gas pressure. The kinetic energy of the extracted H^- ions is reduced mainly by charge exchange collision with H.

There is a certain energy difference in extracted H^- ions between volume produced H^- ions and surface produced H^- ions.

In the future, we will discuss the characteristics of extracted negative ion current with the use of the present numerical results and the results of our previous model calculation.

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