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Enhancement of pure volume negative ion production using a grid bias method or a magnetic filter method[a)]

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Volume production of hydrogen negative ion H^- is studied in pure hydrogen plasmas using a grid bias method for plasma parameter control. The purposes of the present study are as follows. One is to investigate the possibility of controlling plasma parameters with a grid bias method in dc discharge plasmas; the other is to realize efficient negative ion production in H_2 plasmas and to discuss the difference in plasma parameters control and H^- production between the grid bias method and the usual magnetic filter method. The relationship between plasma parameters and extracted H^- ion currents is discussed. It is confirmed that both high and low electron temperature T_e plasmas are produced in the separated regions when the grid is negatively biased. The negative ion production depends strongly on the grid potential and related plasma conditions. Within certain plasma conditions, H^- production with grid bias method is much higher than one with magnetic filter method. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2805368]

I. INTRODUCTION

In the design of a neutral beam injection (NBI) system for future large fusion devices such as the ITER, sources of H^- or D^- negative ions are required for efficient generation of neutral beams with energies above ≈100 keV / nucleon. In volume H^- source, most of the H^- ions are generated by the dissociative attachment of slow plasma electrons e_s (electron temperature $T_e \sim 1$ eV) to highly vibrationally excited hydrogen molecules $H_2(v'')$ (effective vibrational level $v'' \geqq \geqq 5-6$). These $H_2(v'')$ are mainly produced by collisional excitation of fast electrons with energies in excess of 15–20 eV. Namely, H^- ions produced by the following two-step process:[1]

$$H_2(X\,{}^1\Sigma_g, v''=0) + e_f(E \sim 15-20\ \text{eV}) \rightarrow H_2^*(B\,{}^1\Sigma_u,\ C\,{}^1\Pi_u, v') + e_f', \tag{1}$$

$$H_2^*(v') \rightarrow H_2(X\,{}^1\Sigma_g, v'') + h\nu, \tag{2a}$$

$$H_2(v'' \geqq 5) + e_s(T_e \sim 1\ \text{eV}) \rightarrow H^- + H. \tag{2b}$$

Therefore, spatial control of electron energy distribution (i.e., T_e) is necessary.[2,3] So far, the magnetically filtered multicusp ion source has been shown to be a promising source of high-quality multiampere H^- ions. To enhance H^- ion production and extracted H^- ion currents, a small amount of cesium vapor is usually seeded into the above volume ion source. Therefore, ion source operation is rather complicated—to keep optimum surface condition of the plasma grid for surface production of H^- ions.

Long lifetime ion sources are also required for future NBI systems. Microwave-discharge ion sources[4] and rf-driven ion sources[5,6] are promising as long lifetime ion sources because they have no filaments. Unfortunately, in those high-frequency plasmas, control of plasma parameters using the magnetic filter method is not as effective as in dc plasmas. On negative ion sources, therefore, another important and interesting aspect is to develop the ion sources without filaments, magnetic filter, and cesium injection.

The aims of the present study are as follows. The first is to study the application feasibility of a grid bias method[7,8] for controlling plasma parameters, in particular T_e, in dc discharge H_2 plasmas; the second is to discuss the difference in T_e control and H^- production between the grid bias method and the usual magnetic filter method. At first, using both the mesh grid bias method and the usual magnetic filter method, plasma parameter control in dc discharge plasmas is studied. Preliminary results on the grid bias method are reported here.[9] The relationship between the extracted H^- ion currents and plasma conditions is also briefly discussed.

II. EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows a schematic diagram of the newly designed experimental apparatus for studying the negative ion source with grid bias method.[9] The source chamber (20 cm in diameter) made of stainless steel is divided by a mesh grid (MG) into two parts, i.e., a source region and an extraction region. To produce both high and low electron temperature plasmas separately in the chamber, this MG which is 19 cm in diameter is placed. In the present experiment, three different mesh grids are used, i.e., No. 1 (16 mesh/in.), No. 2 (30 mesh/in.), and No. 3 (50 mesh/in.). Details are shown in Table I. Compared with the usual magnetically filtered multicusp ion source, in Fig. 1, the magnetic filter (MF)

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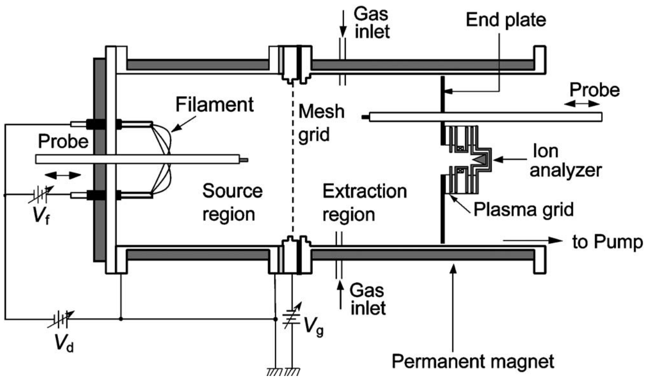

FIG. 1. Schematic diagram of the experimental apparatus.

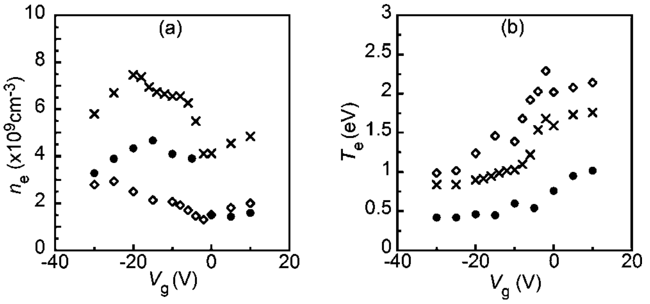

FIG. 2. (a) Electron density n_e and (b) electron temperature T_e for various grid potentials V_g for the different mesh sizes of No. 1 (◇), No. 2 (●), and No. 3 (×) at $z=-3.5$ cm in the extraction region, where the end plate is set at $z_{\text{end}}=-8$ cm. Experimental conditions: discharge voltage $V_d=50$ V, discharge current $I_d=2$ A, and hydrogen gas pressure $p(H_2)=0.4$ Pa.

flange is set instead of the MG flange. The MF consists of four rods. The diameter of each rod is 10 mm and the distance between two rods is 54 mm. In the present experiment, the magnetic field intensity of the MF (B_{MF}) is set at 60 and 100 G. In the source region, steady-state H_2 plasmas are produced by dc arc discharge between the chamber anode and the tungsten filament cathode.

Plasma parameters (electron density n_e, electron temperature T_e, plasma space potential V_s, and floating potential V_f) are measured by two Langmuir probes. They are axially moved from the MG. The negative ion currents (I_{H^-}) are directly detected by a magnetic deflectiontype ion analyzer. The plasma grid has a single hole (10 mm in diameter) through which negative ions were extracted from the ion source.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Plasma production and control

First, we test the grid bias method for H^- production in dc discharge H_2 plasmas.[9,10] Figure 2 shows a typical example of grid bias effect on plasma parameters in the extraction region for three different MGs. For all mesh MGs, there appears a decrease in T_e with a decrease in grid biasing voltage V_g. In the extraction region, generation mechanism of low electron temperature plasma is as follows. In the extraction region, the neutral particles are ionized by higher energy electrons flowing from the source region through the grid.[7,8] The electrons produced in the extraction region cannot be accelerated by the external electric fields because no additional heating power is fed into this region. Therefore, low energy electrons are generated in the extraction region.

The grid bias method is the method to control electrons transported electrostatically and is affected by the mesh size.[7] By using three different MGs, the effect of mesh size is also tested. We estimate the Debye length (λ_D) from the typical plasma parameters (i.e., $n_e \simeq 1 \times 10^{10}$ cm^{-3} and $T_e \simeq 2.0$ eV) at $z=3.0$ cm in the source region and obtain that $\lambda_D \simeq 0.1$ mm. When we suppose that sheath length is about several times the λ_D, distances between two wires of all meshes are within the sheath length. In the extraction region, n_e with No. 3 mesh is higher than other two meshes (i.e., No. 1 and No. 2). This is caused mainly by the difference of transmittance. It is easy for electrons to cross the MG and enter into the extraction region as No. 3 mesh has high transmittance.

TABLE I. Dimensions of the three meshes used in the present experiment.

Mesh	Mesh size (mesh/in.)	Diameter of wire (mm)	Distance between two wires (mm)	Geometric transmittance (%)
No. 1	16	0.6	1	40
No. 2	30	0.25	0.6	50
No. 3	50	0.05	0.46	81

Figure 3 shows axial distributions of plasma parameters (i.e., n_e and T_e) for two different controlling methods. The one is the mesh bias method and the other is the magnetic filter method. High energy electrons pass the MG (set at $z=0$ cm) and enter into the extraction region. As a whole, n_e increases in its value with z and reaches the maximum value and then decreases while T_e decreases in its value. With changing V_g, values of n_e and T_e are varied. Although this feature is not shown clearly in Fig. 3, that characteristic feature is well observed when the end plate is set far from the MG. By changing V_g negatively, values of n_e increase while T_e decreases in its value. At any rate, with varying V_g and the distance between the end plate (i.e., its position z_{end}) and the MG, plasma parameters can be controlled.

We have confirmed numerically that extraction probability of negative ions depends strongly on upstream distance from the extraction grid,[11] i.e., the plasma end plate in the

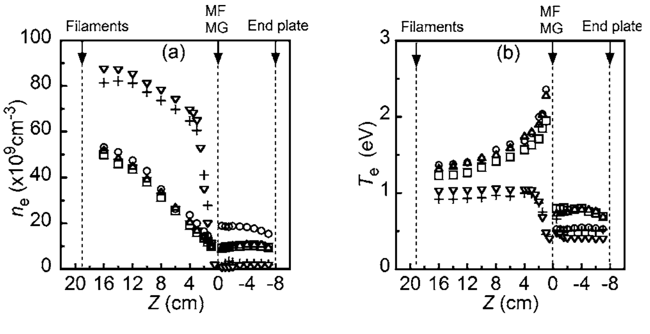

FIG. 3. Axial distributions of plasma parameters: (a) n_e and (b) T_e for the different V_g of −10 (□), −20 (△), and −30 (○) V and for two different MF fields of 60 (+) and 100 (▽) G. Mesh size is 50 mesh/in. The end plate is set at $z_{\text{end}}=-8$ cm. Experimental conditions: $V_d=50$ V, $I_d=2$ A, and $p(H_2)=0.4$ Pa.

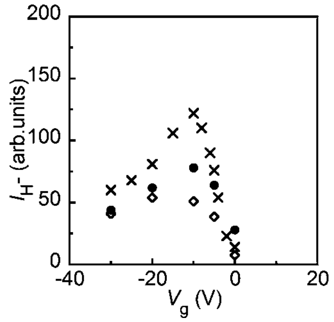

FIG. 4. Extracted negative ion currents as a function of V_g for the different mesh sizes of No. 1 (◇), No. 2 (●), and No. 3 (×). Experimental conditions: V_d=50 V, I_d=2 A, $p(H_2)$=0.4 Pa, z_{end}=−8 cm, and extraction voltage V_{ex}=1 kV.

present case. Therefore, to increase the extracted negative ion currents, production of negative ions near the plasma end plate should be enhanced by optimizing plasma conditions.

According to the results shown in Fig. 3, the grid bias method is more suitable to optimize plasma conditions for negative ion production near the plasma grid, compared with the magnetic filter method.

B. Negative ion production

For negative ion volume production, it is expected that T_e in the extraction region is maintained below 1 eV with n_e kept high.[3] According to the results shown in Figs. 2 and 3, plasma parameters in the extraction region and then production of negative ions strongly depend on both V_g and the position of the end plate (z_{end}). Figure 4 shows the effect of V_g on the I_{H^-} (i.e., H^- negative ion production). There is a certain optimum value of V_g corresponding to the plasma conditions in the extraction region. Values of I_{H^-} are different in mesh size [see Fig. 2(a)].

Figure 5 shows the effect of z_{end} on the I_{H^-}. At first, I_{H^-} increases by decreasing the distance between the MG and the end plate, reaches the maximum at z_{end}=−4–−5 cm, and then decreases gradually. For the mesh bias method, there is a certain optimum position for negative ion extraction. On the other hand, for the magnetic filter method, the extracted negative ion current increases simply by decreasing the distance between the MF and the end plate. This difference is caused by the difference in plasma conditions in the extraction region. These characteristic behaviors are caused by the plasma parameters in the extraction region. Plasma production and then H^- ion production also depend on hydrogen gas pressure $p(H_2)$, although experimental results are not presented here.

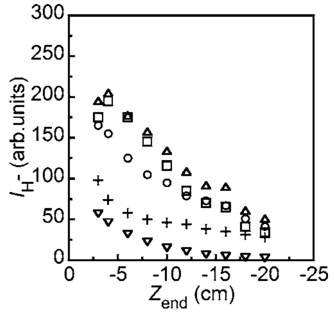

FIG. 5. Extracted negative ion currents as a function of the end plate position for two different cases, i.e., the mesh grid bias method with V_g of −10 (□), −20 (△), and −30 (○) V and the magnetic filter method with the MF fields of 60 (+) and 100 (▽) G. Experimental conditions: V_d=50 V, I_d=2 A, $p(H_2)$=0.4 Pa, and V_{ex}=1 kV.

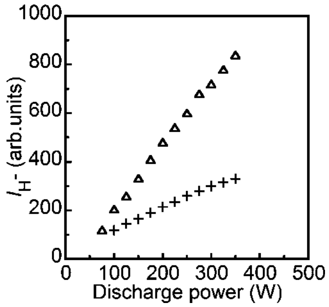

FIG. 6. Extracted negative ion currents as a function of discharge power for two different cases, i.e., the mesh grid bias method with V_g of −20 (△) V, and the magnetic filter method with the MF fields of 60 (+) G. Experimental conditions: V_d=50 V, $p(H_2)$=0.33 Pa, and z_{end}=−4 cm for the grid bias method. V_d=50 V, $p(H_2)$=0.27 Pa, z_{end}=−3 cm for the magnetic filter method, and V_{ex}=1 kV.

Finally, some characteristic features of H^- negative ion production is tested for two different methods of plasma parameter control, i.e., the grid bias method and the magnetic filter method. Figure 6 shows discharge power dependence of I_{H^-}. According to the results shown in Fig. 5 and pressure dependence of the H^- production, pressure and z_{end} are optimized for two cases, respectively. With increasing power, I_{H^-} increases linearly and I_{H^-} in the grid bias method is higher than the magnetic filter method.

The ion analyzer using the experiment consists of a G_1 electrode and a G_C electrode. We observe that the extracted negative currents collected by the G_1 electrode is the extracted electron currents (I_{e^-}) and one collected by the G_C electrode is the extracted negative ion currents (I_{H^-}), respectively. According to the results shown in Figs. 5 and 6, I_{H^-} with the grid bias method is higher than that with magnetic filter method. However, I_{e^-} with the grid bias method is also higher than that with magnetic filter method (not shown here) because n_e with the grid bias method is higher than that with magnetic filter method. In the future, we think that I_{H^-} is more extracted by suppressing the I_{e^-} with a certain transverse magnetic field.

IV. CONCLUSIONS

Using the grid bias method, in dc discharge plasmas, control of plasma parameters and volume production of H^- negative ions are studied experimentally, and preliminary results are presented. We have confirmed that both high and low electron temperature plasmas are produced in the separated regions when the mesh grid is biased negatively. Plasma parameters in the extraction region and H^- negative ion production depend on grid bias voltage. The extracted H^- current is higher than one with the MF method within the present experimental conditions. We hope that further study of controlling plasma parameter with the mesh bias method enhances negative ion production. As, in the future, rf negative ion source is required for the NBI system, the grid bias method is quite useful to control and enhance negative ion volume production in rf plasmas.

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