Efficient negative ion production in rf plasmas using a mesh grid bias method

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Using a grid bias method for plasma parameter control, volume production of hydrogen negative ions H− is studied in pure hydrogen rf plasmas. Relationship between the extracted H− ion currents and plasma parameters is discussed. It is confirmed that both high and low electron temperature Te plasmas are produced in the separated regions when the grid is negatively biased. In addition, with changing grid potential Vg, values of ne increase while Te decrease in their values. The negative ion production depends strongly on the grid potential and related plasma conditions. © 2008 American Institute of Physics. [DOI: 10.1063/1.2805372]

I. INTRODUCTION

Development of negative ion sources for neutral beam injection (NBI) system is required for large experimental fusion devices such as the ITER. In the present negative ion sources, source plasma is generated by dc arc discharge, so the lifetime of the ion source is limited to several hundred hours due to erosion and fatigue of the cathode filament. Thus a long-lifetime ion source is required for future NBI systems. Microwave-discharge ion sources1 and rf-driven ion sources2,3 are promising as long-lifetime ion sources because they have no filaments.

In pure hydrogen (H2) plasmas, most of the H− ions are generated by the dissociative attachment of slow plasma electrons (electron temperature Te~1 eV) to highly vibrationally excited hydrogen molecules H2(ν).4 These molecules are mainly produced by collisional excitation of fast electrons with energies of 15–20 eV. Therefore, spatial control of electron energy distribution (i.e., Te) is necessary.5,6 With the use of a magnetic filter, the electron energy distribution function in dc plasmas is well controlled for H− formation. Unfortunately, in rf discharge plasmas, plasma parameter control with magnetic filter is not so effective as one in dc plasmas.1,2 Therefore, using a grid bias method3,8 for plasma parameter control, volume production of hydrogen negative ions H− is studied in pure hydrogen rf plasmas.

The purpose of the present study are as follows: one is to investigate the possibility of controlling plasma parameters, in particular Te, with grid bias method in rf-driven plasmas; and the other is to realize negative ion production in rf plasmas and to discuss the difference in Te control and H− production between the mesh grid bias method and the magnetic filter method.

II. EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows a schematic diagram of rf negative ion source. The source chamber (21 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. The rf power (13.56 MHz) is supplied to a stainless circular disk antenna with 12 cm diameter. In the experiment, we use hydrogen (H2) gases under a pressure of 3 mTorr. rf power is varied from 100 to 300 W. To produce both high and low electron temperature plasmas separately in the chamber, a grid 20 cm in diameter is placed 18.5 cm away from the rf antenna. In the experiment, three different meshes are used, i.e., No. 1 (7 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) flange (i.e., the rod-type filter) is set instead of the MG flange. The present MF is composed of four rods where diameter of the rod is 10 mm and the distance between two rods is 54 mm. In the present experiment, magnetic field intensities of the MF are 60 and 100 G. The negative ion currents are directly detected by a magnetic deflection-type ion analyzer. The plasma grid has a single hole (10 mm in diameter) through which negative ions were extracted from the ion source. Plasma parameters (electron density ne, electron temperature Te, plasma space potential Vp, and floating potential Vf) are measured by three Lang-
muir probes. The one is movable along the axial direction from the mesh grid in the extraction region. The others are set at \( z = 3.7 \) cm and \( z = 11 \) cm in the source region.

### III. EXPERIMENTAL RESULTS AND DISCUSSION

#### A. Plasma production and control

The aim of the present work is production and control of rf plasmas to enhance and to optimize \( \text{H}^- \) volume production in rf plasmas.

Figure 2 shows axial distributions of plasma parameters (i.e., \( n_e \) and \( T_e \)) controlled by the MF. In the extraction region, \( T_e = 4 \) eV. The value of \( T_e \) is high for negative ion production. In addition, \( n_e \) decreases drastically in the extraction region. Although \( T_e \) is decreased by increasing the field intensity of the MF, at the same time, \( n_e \) also decreases more drastically. On negative ion volume production, a desired condition for plasma parameters is as follows: \( T_e \) in the extraction region should be reduced below 1 eV with \( n_e \) keeping higher. Therefore, in rf plasmas, plasma parameter control with using the MF is not so effective.

Similar measurements have been made with using a mesh grid bias method. Figure 3 shows axial distributions of plasma parameters for three different MGs. High energy electrons pass the mesh (set at \( z = 0 \) cm) and enter into the extraction region. As is shown clearly, \( n_e \) increases in its value with \( z \) and reaches the maximum value and then decreases while \( T_e \) decreases in its value and keeps nearly equal to or lower than 1 eV. This is suitable condition for negative ion volume production. The mechanism is explained as follows: In the extraction region, the neutral particles are ionized by higher energy electrons flowing from the source region through the grid. 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. According to the results shown in Figs. 2 and 3, the grid bias method is more suitable to optimize plasma conditions for negative ion, compared with the magnetic filter method.

Figure 4 shows the dependence of plasma parameters on grid bias voltage for three different MGs in the extraction region. With changing \( V_g \), values of \( n_e \) increase while \( T_e \) decrease in their value. There appears a decrease in \( T_e \) with a decrease in grid biasing voltage \( V_g \). We also measure the \( T_e \) at \( z = 3.7 \) cm in the source region and obtain \( T_e = 3 \) eV, which is almost independent of \( V_g \). Therefore, \( T_e \) in the extraction region has a lower value than that in the source region. Behaviors of plasma parameters are nearly the same as the ones in dc plasmas.10,11

Grid bias method is the method to control electron transport electrostatically and is affected by the mesh size.7 Then, with using three different MGs, the effect of mesh size is also tested. We estimate the Debye length (\( \lambda_D \)) from the typical plasma parameters (i.e., \( n_e = 1 \times 10^{19} \text{ cm}^{-3} \) and \( T_e = 3.0 \) eV) at \( z = 3.7 \) cm in the source region and obtain that \( \lambda_D = 0.41 \) mm. When we suppose that the sheath length is about several times of \( \lambda_D \), 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 cross the MG and enter into the extraction region as No. 3 mesh has high transmittance.

We have confirmed numerically that extraction probab-

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<table>
<thead>
<tr>
<th>Mesh</th>
<th>Diameter of wire (mm)</th>
<th>Distance between two wires (mm)</th>
<th>Geometric transmittance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>7</td>
<td>1.03</td>
<td>48.5</td>
</tr>
<tr>
<td>No. 2</td>
<td>30</td>
<td>0.25</td>
<td>49.7</td>
</tr>
<tr>
<td>No. 3</td>
<td>50</td>
<td>0.05</td>
<td>81.3</td>
</tr>
</tbody>
</table>

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The production of negative ions depends strongly on upstream distance from the extraction grid, i.e., the plasma end plate in the present case. At any rate, to increase the extraction of negative ions, production of negative ions near the plasma end plate should be enhanced by optimizing plasma conditions.

**B. Negative ion production**

We discuss H⁻ ion production in the present rf plasmas. According to the results shown in Fig. 3, plasma parameters in the extraction region depend on the position of the end plate, and then production of negative ions. Figure 5 shows the effect of end plate position z_end on extracted negative ion currents I_{H⁻} (i.e., H⁻ ion production). At first, I_{H⁻} increases with z_end, reaches maximum at z_end = −5 to −7 cm, and then decreases. The changes in I_{H⁻} are caused by the plasma parameters in the extraction region. Plasma production and then H⁻ ion production also depended on hydrogen gas pressure p(H₂).

Figure 6 shows the rf 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. In addition, rf power dependence of I_{H⁻} with magnetic filter method is shown in Fig. 6 for comparison. With increasing power, I_{H⁻} increases linearly. I_{H⁻} in the grid bias method is much higher than that in the magnetic filter method. It is clear from plasma parameter. Within the present experimental conditions, plasma production and control in the extraction region well done for negative ion production when No. 3 mesh is set due to high transmittance.

**IV. SUMMARY**

Control of plasma parameters and enhancement of extracted H⁻ ion currents in rf plasmas are studied by using the magnetic filter method and the mesh grid bias method. With using the magnetic filter method, electron temperature in the extraction region is not well controlled for H⁻ ion formation. However using the mesh grid bias method, we have confirmed that both high and low electron temperature plasmas are produced in the separated regions in the chamber, respectively, when grid potential V_g is negative. Extracted negative ion currents I_{H⁻} depend on some experimental conditions and I_{H⁻} in the grid bias method is much higher than that in the magnetic filter method. As, in the future, rf negative ion source is required for the NBI systems; the mesh grid bias method is quite useful to control and enhance negative ion volume production in rf plasmas.

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