Extraction of Negative Hydrogen Ions from Radio Frequency Driven Plasma Sources for Fusion Plasma Heating*)

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Microwave power at 14 GHz frequency coupled to a magnetic field aligned parallel to the beam extraction axis successfully excited a plasma in a compact negative hydrogen (H^-) ion source. A volume of low electron temperature plasma was formed based on the idea of "tent filter" magnetic field geometry by placing the extraction aperture at a recess made inside of a magnetic material. The amount of H^- current increased by enlarging a volume of low electron temperature plasma, which seemed consistent with the two step model of H^- production via vibrational excitation of hydrogen molecules. The depth of the recess was made shallower expecting the H^- current with the magnitude halfway between the one without the volume of low electron temperature plasma and the one with the volume. The result has indicated the expected correlation between the size of the volume and the H^- current at low H_2 pressure. Meanwhile, the beam current density has abruptly increased as the microwave discharge power was raised above 60 W, indicating a change of discharge mode around that input power.

Keywords: ion source, negative ion, electron cyclotron resonance, vibrationally excited molecule

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1. Introduction

Negative hydrogen ion (H^-) current with the density exceeding 28 mA/cm^2 is required to heat plasma up to a nuclear fusion condition in ITER [1]. Small ion sources deliver H^- into proton accelerators with the similar current density [2]. Injection of Cs into the ion source are routinely done, as the proper coverage of Cs on the plasma grid enhances the extractable amount of H^- current and reduces electron current co-extracted with H^- current [3]. These observations indicate that Cs injection into the ion source results in not only H^- production due to H^- emission from low work function plasma grid, but also electron density reduction in the region near the extractor electrode. It has been recently verified by Tsumori *et al.* that the charge neutrality in the region near the surface of plasma grid is mainly determined by negative and positive hydrogen ion densities, and the electron density in the region is substantially smaller than the ion densities [4].

The amount of Cs injection into the ion source should be minimized, even though Cs injection improves ion source performance. Leakage of Cs from the ion source to the extractor causes break-down of acceleration system. Frequent voltage break-down damages accelerator electrodes and power supplies, which shortens the life-time and decreases reliability of a nuclear fusion reactor. Only a milligram order Cs introduction was reported sufficient to operate a small ion source for a proton accelerator [5], while gram order Cs is charged to an ion source used for fusion experiments [6]. The reason for this huge difference in Cs consumption is attributable to the extraction area of the ion source; namely, the Cs evaporation has to cover wide area of the entire plasma grid for a fusion experiment ion source, while it can be concentrated to only a small area of extraction collar in case of an ion source for a proton accelerator.

There are two major processes leading to H^- production in an H^- source. One is the surface production from low work function surface, and the other is volume production in which the following two steps with plasma electrons are involved.

$$H_2 + e_f \rightarrow H_{2v*} + e_f', \quad (1)$$

$$H_{2v*} + e_s \rightarrow H^- + H. \quad (2)$$

The symbol H_{2v*} signifies a hydrogen molecule in the state of vibrational excitation level. The vibrational excitation reaction of eq. (1) requires electrons with the energy of more than 11 eV. These electrons called "fast" electrons denoted by the symbol e_f, exist in the ion source plasma as ionizing electrons. The cross sections for electron attachment to vibrationally excited hydrogen molecules, or the reaction indicated by eq. (2), have the maxima from

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0.4 (v = 8) to 1.8 (v = 4) eV, and rapidly decrease with the increasing electron energy. The region confining these "slow" electrons, e_s, has to be separated from the region for exciting hydrogen molecules to higher vibrational levels, because high energy electrons detach electrons from produced H^-. Thus, by separating region of fast electrons from that of slow electrons by so-called "magnetic filter field", or the magnetic field geometry that inhibits direct penetration of ionizing electrons into extraction region, H^- can be efficiently produced and extracted from an H^- source. Increase in H^- current of volume production component may result in reduced amount of Cs introduction for the ion source operation, and the optimization of volume production has been started utilizing high frequency plasma excitation.

2. Experimental Apparatus

Shown in Fig. 1 are the structure of the ion source and the magnetic field intensity distribution along the axis of the ion source. Contrary to the previous design which had the axis of the magnetic field for the electron cyclotron resonance (ECR) intersecting perpendicularly to the axis of the H^- extraction [7], the magnetic field direction of the dipole permanent magnet has been aligned parallel to the beam extraction axis. The field intensity rapidly decreases toward the plasma electrode (or single aperture plasma grid that forms the beam extractor) and the magnetic field forms a structure close to a "tent filter field" employed in a large scale H^- source [8]. Microwave power at 14 GHz excites a plasma in a 50 mm diameter 40 mm deep alumina ceramic discharge chamber. A plunger determines the end of the waveguide located at the confronting position of the input waveguide across the discharge chamber to form a resonant cavity structure. The direction of the microwave electric field has been set parallel to the ECR magnetic field.

The magnetic field intensity of 5 kG corresponding to the ECR condition at 14 GHz is realized at a location about 7 mm from the inside wall of the back end of the alumina discharge chamber. The magnetic field lines of force leaving the surface of the dipole magnet radially expand toward the plasma grid to penetrate into the hollow cylinder made of magnetic material (mild steel). The surface of the magnetic material cylinder having 26 mm inside diameter is covered by 50 µm thick Cu plating in order to avoid microwave absorption. With this structure, the magnetic field intensity reduces down to 2 kG with only 24 mm distance from the surface of the dipole magnet to the plasma electrode. The magnetic circuit forms two field concentrated regions; near the surface of the magnetic material cylinder, and near the surface of dipole magnet. This field geometry guides the high energy electrons produced at the ECR region to strike the periphery of the plasma electrode, creating a low electron temperature plasma region near the beam extraction hole. This shielding effect against high energy electron to penetrate into the region near the extraction hole is schematically illustrated in Fig. 2.

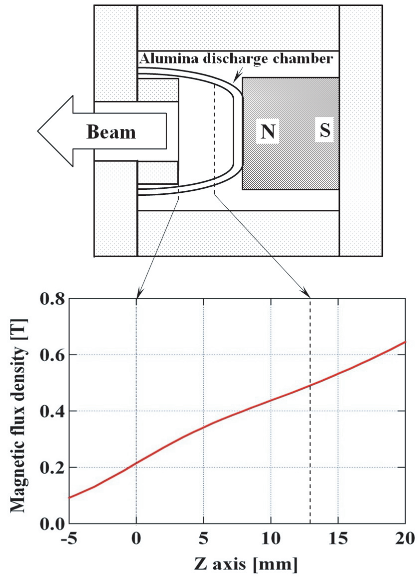

Fig. 1 Magnetic field intensity along the center axis of the ion source.

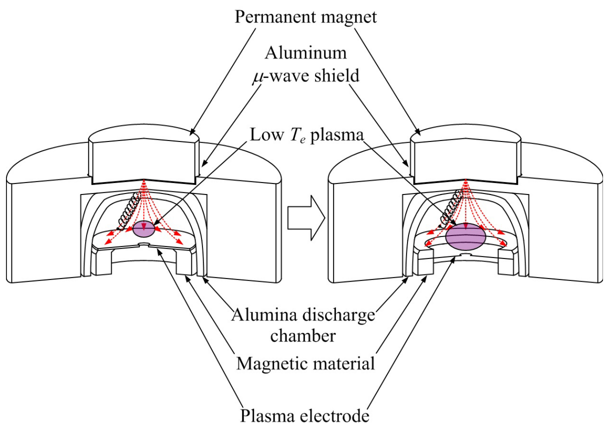

Fig. 2 Modification of plasma electrode structure to enlarge volume of low electron temperature plasma.

The ion source has been modified to investigate the validity of two step reaction model described by equations (1) and (2). First the thickness of the plasma electrode has been changed from 1.5 mm to 50 µm, so that the insertion of the non-magnetic (Mo) plasma electrode does not largely increase the magnetic resistance of the cylinder. Secondary, the thin plasma electrode was placed at the position of 3 mm and 7 mm from the top of the magnetic material cylinder. By increasing the space between the plasma electrode surface and the top end of the magnetic material cylinder, the volume of the low electron temperature plasma can be enlarged.

The H^- beam has been extracted by a simple three electrode extraction system of an accel-decel potential configuration. The positive and negative beam currents were measured by a Faraday cup located 30 cm downstream of the extraction electrodes. In the following experiments, the beam extraction potential was fixed at 2 kV.

3. Experimental Results

Figure 3 shows the amount of H^- current extracted from the ion source with 1.5 μm thick, and 50 μm thick plasma electrodes placed at the top end of the magnetic cylinder. The H^- current was always larger when it was extracted with 50 μm thick plasma electrode for 3.0, 5.0 and 7.0×10^{-3} Pa pressure downstream of the extractor. The pressure inside of the ion source cannot be directly measured in the present configuration, but the pressure inside of the ion source has been estimated to be about 200 times the pressure downstream of the extractor from the result of the setup to observe the pressure difference between the upstream and downstream of the extractor.

In all conditions, H^- current showed saturation for more than 50 to 60 W microwave power. The common saturation characteristics shown in both electrode thicknesses may be interpreted as the saturation of H^- production due to production/transport loss of H_{2v*} compensated by enhanced electron attachment in the low electron temperature region. Namely, the increase of production rate by low energy electrons is counteracted by the reduced production and/or enhanced destruction rate of H_{2v*}. The pressure dependence of the H^- saturation values also seems to indicate that some loss process of H^- due to neutral collision takes place in the ion source.

Figure 4 shows the dependence of H^- current extracted from the ion source when the discharge power was kept constant at 60 W. This corresponds to the power at which the saturation characteristic against pressure in the region downstream of the extraction electrode was observed in Fig. 3. The amount of H^- current increased with increasing volume of low electron temperature region at low pressure ($P_{\text{downstream}} < 3 \times 10^{-3}$ Pa). However, at higher pressure, the H^- current was smaller for the ion source geometry with the 3 mm distance from the top of the magnetic material cylinder to the plasma electrode than that with the plasma electrode located at the top of the magnetic cylinder. The sudden increase in H^- current at $P_{\text{downstream}} < 3 \times 10^{-3}$ Pa can be due to change in ECR discharge condition that appears as a "mode jump". This kind of jump from a low efficiency mode to a high efficiency mode for plasma excitation is commonly observed in the course of increasing the microwave power for a fixed discharge condition [9]. The jump can be also seen in Fig. 3. The threshold power for the sudden increase in H^- current seems to become larger with pressure, as observed in the 1.5 mm electrode thickness case in Fig. 3. Namely, the threshold for the jump appears to increase with the increasing ion source pressure.

The positive ion beam should give more direct information on the local plasma density near the plasma electrode, and the positive ion current was extracted with the experimental conditions identical to the ones employed to take data shown in Fig. 4. The positive ion current increased rapidly from 2×10^{-3} Pa downstream pressure as

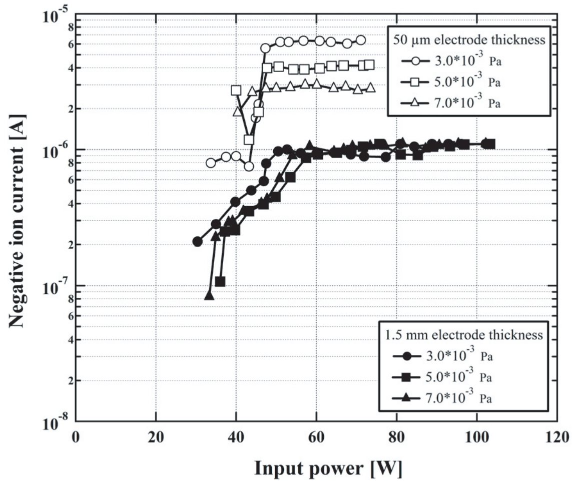

Fig. 3 Effect of plasma electrode thickness on negative ion beam current.

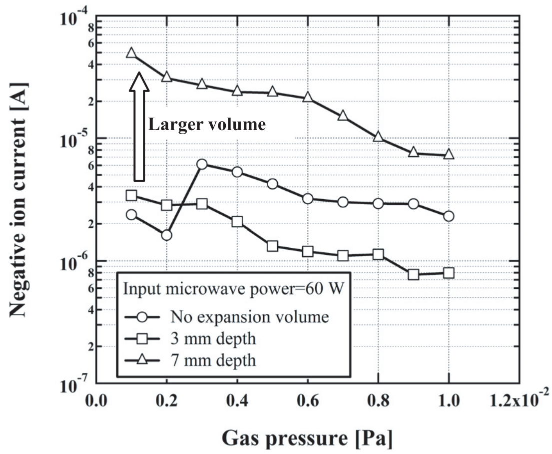

Fig. 4 Negative ion current plotted as functions of gas pressure for different values of depth of plasma expansion volume.

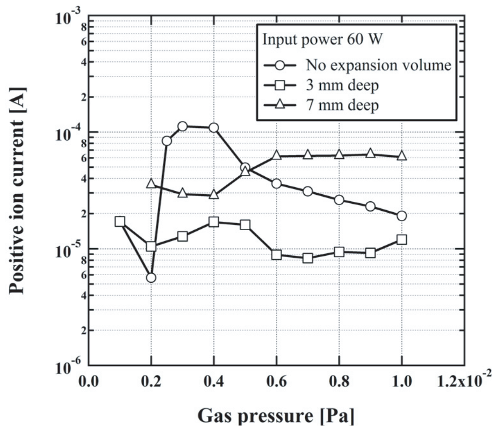

Fig. 5 Positive ion current plotted as functions of gas pressure for different values of depth of plasma expansion volume.

shown in Fig. 5, when the extractor was positioned at the top end of the magnetic cylinder. In the meantime, the positive ion current had kept a constant value for cases that the plasma electrodes were located 3 mm and 7 mm away from the top end of the magnetic material cylinder. The observed sudden increase of H^- current at 2.5×10^{-3} Pa downstream pressure for the plasma electrode placed at the top end of the magnetic material cylinder seems to coincide with the increase in local plasma density near the extraction hole.

4. Discussion

The decreasing trend of H^- current against increasing pressure for a fixed discharge power, as observed in Fig. 4, has been recognized from the previous design of this type of ion source [7]. Based on models to predict H^- density at the extraction aperture of tandem H^- sources [10, 11], the observed reduction of H^- current at higher pressure has been attributed to loss of produced H^- and/or H_{2v*} to the extractor region. The dependence upon the distance from the ECR region to the extraction hole indicates that some H^- formation mechanism in the low electron temperature region of the source has overcome the loss of H_{2v*} during the transport from the high temperature region to the extraction region. Two reasons are possible to explain the observed enhancement in H^- current by the increased volume, or the spacing between the ECR zone and the extraction aperture. One is the enhanced associative detachment by the reduction in electron temperature due to increased separation distance from the high temperature region. The other is the increased confinement of high energy electrons due to enlarged volume of the ion source leading to more production of H_{2v*}.

The observed result for positive ion current in Fig. 5 means the local positive ion flux is higher for larger spacing between the plasma electrode and the top end of the cylinder, at least in the lower pressure range. This corresponds to the higher ionization efficiency of the ion source with the enlarged volume. The increase of positive ion current with the increasing pressure does not explain decrease in H^- current at higher pressure, were it not for some mechanism to reduce H^- production including smaller transport of H_{2v*} to the extraction region, or that to enhance H^- destruction at higher pressure due to larger density of high energy electrons. The latter seems unlikely, because the current jump either due to pressure increase or power increase was observed for both positive and negative ions. If the pressure range of the ion source is higher than the one giving maximum production and successive transport of H_{2v*} from the high electron temperature region to the H^- extraction region, the H^- current can be enhanced by enlarging the source size from the present design, and operating the source at a reduced pressure. To further clarify these points, measurements of local plasma parameters will be made to compare the results with two-step model predictions.

5. Conclusion

Efficient transport of vibrationally excited molecules to the extraction region requires a short distance of magnetic filter field region. However, to warrant enough production of vibrationally excited hydrogen molecules, the size of the plasma for confining high energy electrons has to be adequately large. The situation of a large ion source for fusion plasma heating seems identical to the one studied here with a small ion source. The size of the ion source, however, should influence the optimization of the source structure due to different surface to volume ratio of the confined plasma. More precise model that takes the effect of wall collisions into account should predict the final H^- output from a source accurately, and the corresponding laboratory experiments with enough plasma and surface diagnostic tools are being prepared.

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