Development of a 14 GHz Microwave H^- Source[*)]

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Microwave power at 14 GHz has excited a H_2 plasma in a 2 cm inner diameter 9 cm long alumina tube to generate negative hydrogen ion (H^-) beam. A pair of permanent magnets created a magnetic field with the intensity corresponding to an electron cyclotron resonance condition for the input microwave. The ion source produced stable plasmas with the H_2 pressure more than 0.5 Pa, while the amount of H^- current decreased exponentially against increasing ion source pressure above 0.6 Pa. When the source produced H^- beam with constant H_2 pressure at 0.6 Pa, the H^- beam current saturated against the increase of microwave power above 200 W. These characteristics of the H^- beam current indicate poor transport of vibrationally excited hydrogen molecules and that of H^- to the ion extraction electrode.

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

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1. Introduction

Radio frequency (RF) electrical power will excite plasmas of a negative hydrogen ion (H^-) sources for neutral beam injection system in the current ITER planning [1]. Test ion sources utilize RF power at MHz range to produce high current density H^- beams [2]. A higher frequency electromagnetic wave makes an alternative approach to produce a H^- source plasma with larger efficiency, as a lot of knowledge obtained from Electron Cyclotron Resonance (ECR) ion sources for producing multiply charged ions [3] applies to design the H^- source structure. The source operation with higher frequency electrical power also presents other advantages like reduction in size of the power transmission waveguides, and removal of massive isolation transformers.

Ion sources operated with microwaves with the frequency higher than 10 GHz employ a sophisticated magnetic field structure to realize ECR conditions. One example is the minimum-B configuration composed of mirror magnetic field and sextupole magnetic field. This field arrangement enables the source to produce multiply charged ions because microwave power accelerates electrons to higher kinetic energy in an enhanced electron confinement field [4]. These high energy electrons in a H_2 plasma efficiently produce vibrationally excited molecules (H^*_{2v}), which are the parent molecules for H^- in electron volume process [5]. In this process, formed H^*_{2v} dissociate to pairs of an atomic hydrogen and a H^- by capturing low energy electrons. However, the produced H^- do not survive in a plasma with high energy electrons, as they lose electrons in their affinity level by electron detachment collisions. A modification of the negative ion source structure can resolve this problem by separating the source into two regions [6]; driver region of high electron temperature where high energy electrons produce H^*_{2v}, and the extraction region near the ion extraction holes where electrons in low temperature plasma dissociate H^*_{2v} to H^-.

The so-called "magnetic filter" field [7] divides ion source into two regions. Magnetic field lines of force in the direction perpendicular to the H^- beam extraction suppress the penetration of high energy electrons into the extraction region. Optimization of the magnetic filter field geometry is indispensable for increasing H^- current from the ion source. This paper reports the current status of research started to investigate if a magnetic field structure for 14 GHz ECR can make an effective coupling to a magnetic filter field for a H^- source.

2. Experimental Apparatus

Figure 1 shows a schematic diagram of the compact ion source driven by 14 GHz microwave. A pair of permanent magnets creates a magnetic field of the intensity greater than 5 kG corresponding to the ECR condition at

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14 GHz. A 20 mm inside diameter 91 mm long alumina ceramic tube perpendicularly intersects the magnetic field lines of force with the center coincides with the center of the ECR field. The tube serves as the vacuum sealing wall of the ECR discharge region. A slow leak valve feeds hydrogen gas from one end of the alumina tube, while a multi-hole metallic plate attached at the other end of the tube shields microwave leakage.

Microwave power from an amplifier attached to a rectangular waveguide traverses the alumina tube at a right angle. The wave propagates with the E-plane of the wave guide aligned parallel to the ECR magnetic field, so that the fundamental TE_{10} mode realizes induction of AC electric field in the direction perpendicular to the static magnetic field. The produced plasma diffuses toward the microwave shield, and further expands its volume into the area between the alumina tube and the extraction electrode.

A single aperture three electrode extraction system forms the H^- beam. The diameter of apertures opened on 1 mm thick electrodes is 5 mm, and each spacing between the two adjacent electrodes is 3 mm. A movable beam diagnostic probe that can travel in the direction perpendicular to the beam is located 125 mm downstream of the extractor. Figure 2 shows the structure of the probe. It consists of a front Faraday cup having a 16 mm entrance aperture to measure the total ion beam current, and an $E \times B$ Wien filter to analyze the species composition of the ion beam. A 0.6 mm diameter hole opened at the bottom of the front Faraday cup serves as the beam defining aperture of the $E \times B$ filter. A 30 channel Faraday cup array located at 665 mm downstream of the extractor measures the spatial profile of the extracted beam.

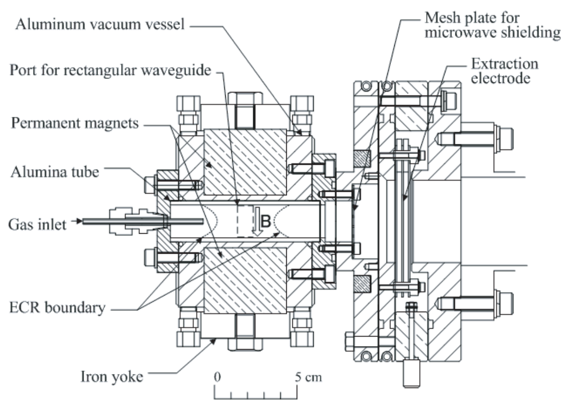

Fig. 1 Schematic illustration of a 14 GHz ECR H^- source.

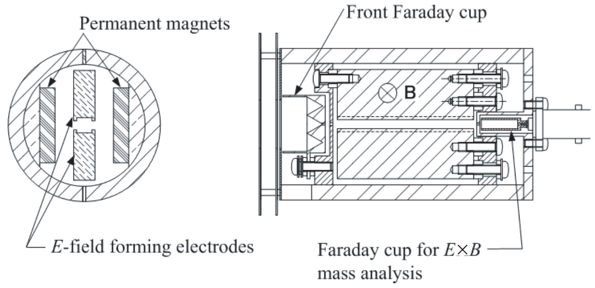

Fig. 2 An $E \times B$ velocity filter to monitor ion beam composition.

3. Experimental Results

3.1 Shape of plasma column

A digital camera has recorded the image of plasma light emission by observing the ECR region by removing the extractor electrodes. Microwave with the power more than 10 W maintained a steady state discharge by filling the source with Ar at a pressure more than 0.1 Pa measured downstream of the microwave shield. There were observed two different modes of plasma excitation. When the pressure was about 0.1 Pa, a thin plasma column aligned itself to the magnetic field lines of force as shown in Fig. 3 (a). The plasma filled the entire region inside the alumina tube for Ar pressure higher than 0.1 Pa as shown in Fig. 3 (b).

The position at which the magnetic field intensity equalizes to the value of ECR for 14 GHz is 17 mm from the center of the magnetic field. Meanwhile, the observed diameter or the thickness of the discharge column was about 3 to 4 mm as shown in Fig. 3 (a). In this region, the magnetic field intensity is as large as 6 kG and 20% larger than the intensity corresponding to the ECR at 14 GHz. This deviation from the ECR condition indicates the mechanism causing the plasma excitation of the constricted mode is different from ECR. The constricted mode discharge required Ar pressure to be less than about 0.1 Pa, below which the present microwave power supply could not ignite a plasma due to large microwave reflection.

3.2 Effect of microwave power

The present microwave amplifier can generate microwave power up to 500 W. If we assume the region inside of the alumina tube absorbs this microwave power, the dissipation power density is as large as 17 W/cm^3. This value is comparable to the discharge power density of ion sources

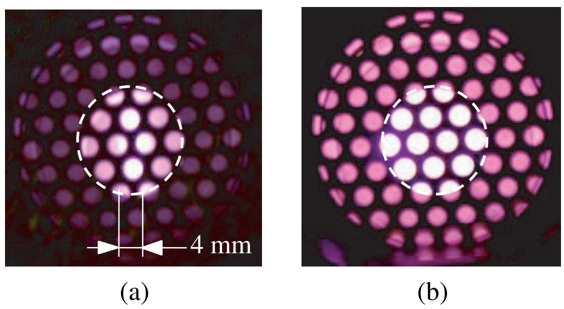

Fig. 3 Pictures showing two different modes of microwave plasma excitation. (a) constricted mode observed at lower pressure operation and, (b) homogeneous excitation mode at higher pressure. Dashed lines in pictures indicate the inside wall of the alumina discharge tube.

used for neutral beam heating systems. Power density of the ion source should affect the production rate of vibrationally excited hydrogen molecules. If the power density is low, the production rate of H^*_{2v} increases in accordance with the increase of discharge power. Above some limit, the rate saturates or even decreases against input power as H_2 density decreases due to dissociation into atoms. The H^- signal was measured to see the dependence upon discharge power by applying 1.5 kV to the plasma electrode while biasing the lens electrode to the ground potential. Figure 4 shows the dependence of the H^- current detected by the $E \times B$ filter. As shown in the figure, the extracted H^- current tended to saturate at a higher microwave power.

3.3 Effect of pressure

Figure 4 shows the H^- current increased from 0.5 Pa to 0.6 Pa, but it rapidly decreased with the increasing source pressure. The dependence of H^- current upon pressure was measured by keeping the input power to the ion source constant. As Fig. 5 shows, the dependence of H^- current upon pressure is almost linear in a semi-logarithmic plot. Curves in Fig. 5 indicate that the magnitude of H^- current is determined from a loss process related to some neutral collision with a constant loss cross section.

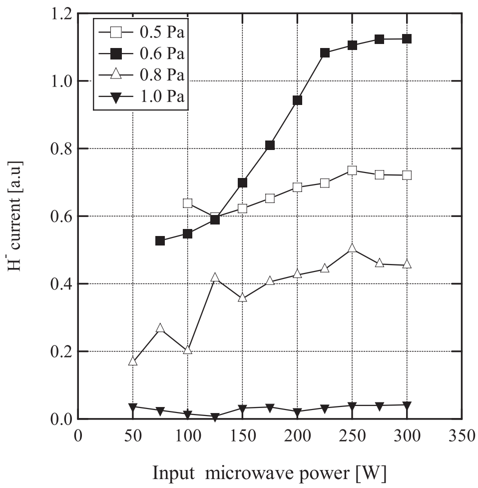

Fig. 4 Intensities of H^- current detected by an $E \times B$ filter plotted as functions of microwave power for different source operating pressures.

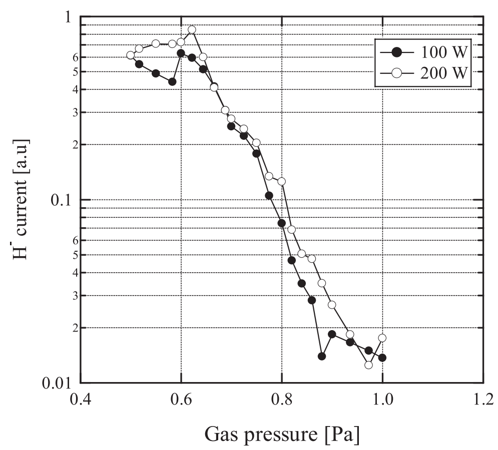

Fig. 5 H^- current detected by an $E \times B$ filter plotted as functions of microwave power for different source operating pressure.

4. Discussion

The two step H^- volume production model predicts that there exists an optimum pressure for H^- beam extraction dependent upon the discharge power for any configuration of volume H^- ion source. The production rate of H^*_{2v} is nearly proportional to the neutral pressure, and the reaction rate of dissociative electron attachment to H^*_{2v} is proportional to the electron density in the extraction region. These reaction rates change sensitively to electron energy distribution functions, and increase in pressure reduces density of high energy electrons by neutral collisions. At H_2 pressure smaller than the optimum condition, H^- current increases with pressure as high energy electrons produce more H^*_{2v} with larger H_2 density. When electron temperatures of both driver and extraction regions become too small, H^- current decreases with increasing pressure above the optimum. The optimum pressure for H^- current becomes higher with increasing discharge power [8], as larger discharge power compensates electron cooling due to neutral collisions at higher pressure.

The pressure dependence of H^- current in the present ion source agrees with the above mentioned model, provided one takes into account of the H^*_{2v} loss due to collision with neutrals. Around the optimum pressure the increase in production rate of H^*_{2v} and the decrease in dissociative electron attachment rate balance, and the transport of H^*_{2v} from the driver region to extraction region determines the magnitude of the H^- extraction current. When the reduction in electron temperature due to pressure increase neither changes H^*_{2v} formation nor electron attachment rates, loss of H^*_{2v} due to collisions during the transport from the high electron energy plasma region to extraction region should cause logarithmic decrease of H^- current against pressure.

The magnetic filter geometry largely affects H^- current in the present ion source design. Depending upon the filter field strength and the distance of the region separating extraction region from driver region, amount of the maximum extractable H^- current should change [9]. The "line-integrated filter strength" is used as the parameter to characterize magnetic filter field, and the reported value is about 850 G-cm for an actual negative ion source of a neutral beam heating system [10]. In case of the present ion source, the integrated strength is more than 9,000 G-cm if one calculates the line-integrated strength by setting the starting point to the edge of the ECR zone. When the filter strength is too large, electrons destroy H^*_{2v} before they

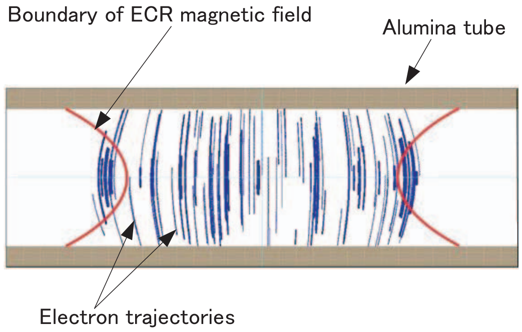

Fig. 6 Electron trajectories inside the ECR region.

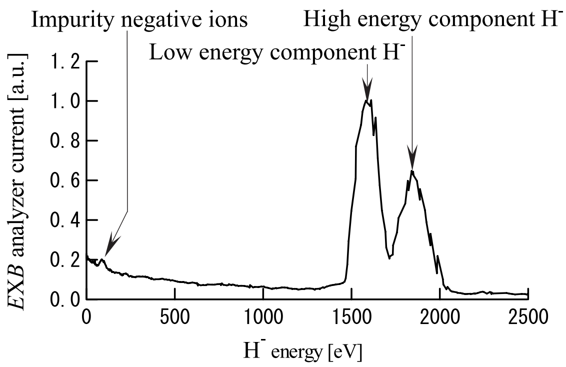

Fig. 7 Energy spectrum of negative ion beam obtained by the $E \times B$ filter.

reach the extraction region. Also, the electron temperature near the extractor can become too low for efficient electron attachment to H^*_{2v}. Both processes reduce H^- current by increase in pressure.

The present structure of the ECR zone affects plasma transport to the extractor hole by another mechanism. Figure 6 shows the electron trajectories in the ECR magnetic field. The mirror ratio of the magnetic field at the center is about 1.14, and the field efficiently confines electrons of larger pitch angles in the central region. The insulating alumina wall does not absorb excess electrons confined in the region, but it makes local plasma potential negative due to electron space charge. Negative plasma potential inside of the alumina tube accelerates H^- toward the extraction region. The $E \times B$ analyzer clearly indicates this high energy component of H^- in the measured energy spectrum as shown in Fig. 7. The plasma potential corresponding to the peak of high energy component of H^- is 200 eV more negative than the peak of lower energy H^-.

5. Summary

A compact negative ion source equipped with a 14 GHz ECR structure has produced sizable amount of H^- current, but reduction in operation pressure is necessary to enlarge the extractable H^- current. The geometrical size and the magnetic field strength of the present ECR zone are too large to efficiently transport H^*_{2v} to the extractor hole, and to attach electrons to H^*_{2v} for producing H^-. Design modification of ECR zone structure is being made to realize highly efficient ion source operation at reduced pressure.

Acknowledgements

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