Depth of Influence on the Plasma by Beam Extraction in a Negative Hydrogen Ion Source for NBI[*]

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Experimental measurements with Langmuir probe and laser photodetachment in beam extraction region of a cesium-seeded negative ion source for NBI has been conducted in order to investigate the response of charged particles to applied external field. The profiles of probe saturation current and H^- ion density in the direction normal to the plasma grid (PG) surface were measured by scanning the tip position. By comparing the results before and during beam extraction, the charged particle responses due to the beam extraction have been analyzed. During beam extraction, probe saturation current increases since H^- ions are extracted and electrons flow into the extracting region for charge neutrality. The maximum increment of the probe saturation current due to electron flow appears in the range of 15 - 25 mm apart from the PG surface. Meanwhile, the maximum decrement of the H^- ion density is at around 18 mm from the PG. In the region far from the PG, probe saturation current increment is low as well as the decrement of the H^- ion density. The extrapolations of the profiles suggest that the depth of the influence on the plasma by beam extraction is 42 mm from the plasma grid surface.

Keywords: negative hydrogen ion source, beam extraction, plasma response, Langmuir probe, photodetachment

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1. Introduction

Neutral beam injection (NBI) is one of the most desirable methods for plasma heating and current drive for a fusion reactor since the heating mechanism of NBI has been well understood and NBI is essentially not affected by the edge plasma condition [1]. In order to realize a high penetration depth of a neutral beam to the plasma and heat the core of the plasma in a fusion reactor, high energy neutral beam is required [2]. However, the neutralization efficiency of a positive hydrogen ion beam decreases as the beam energy increases. On the other hand, the neutralization efficiency of a negative hydrogen ion beam can keep as high as 60% even the beam energy reaches 1 MeV [3]. Therefore, a negative ion based neutral beam injector plays essential roles in a magnetically confinement fusion device.

In a negative ion based neutral beam injector, the beam quality, power and stability are determined by the negative ion source. Research oriented to improvements of the negative ion source is necessary. A lot of efforts have been contributed to the improvements of negative hydrogen ion (H^-) sources, in order to increase the performance of negative ion based NBI systems [4–13]. It has been observed that the H^- ion rich plasma in which the H^- ion density is much higher than the electron density, is generated in the beam extraction region [9]. However, the H^- ion rich plasma is affected by the extraction field. During beam extraction, the ratio of the H^- ion density to the electron density decreases. In order to investigate the distribution of the plasma response to the extraction field and understand the process of the response, the local plasma information before and during beam extraction is necessary. Experiments to measure the local plasma response have been carried out in the beam extraction region of a negative ion source.

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2. Experimental Setup

The experiments were conducted on the Research & Development Negative Ion Source at the National Institute for Fusion Science (NIFS-RNIS) which is schematically illustrated in Fig. 1. The ion source is divided into a driver region and an extraction region by a filter field. Plasma is generated in the driver region by filament-arc discharge and diffuses to the extraction region. A bias voltage is applied between the plasma grid (PG) and the plasma chamber to suppress electrons [14]. Having the advantages of simplicity and measuring local plasma parameters, a Langmuir probe was applied in the experiments. As illustrated in Fig. 1, a four-pin probe was installed in the beam extraction region through the bias insulator. The arrangement of each tip of the probe is shown in Fig. 2. The probe was ro-

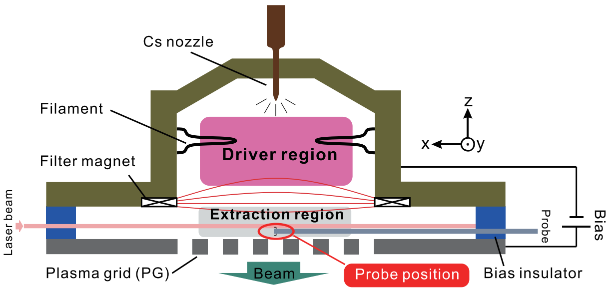

Fig. 1 Schematic illustration of the negative ion source and probe position.

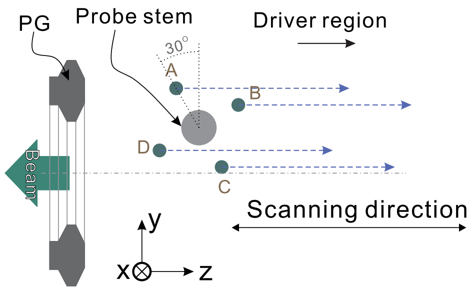

Fig. 2 Location and scanning direction of each probe tip. The probe is rotated by 30°.

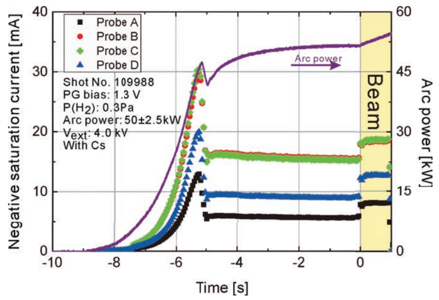

Fig. 3 Time evolution of probe negative saturation current.

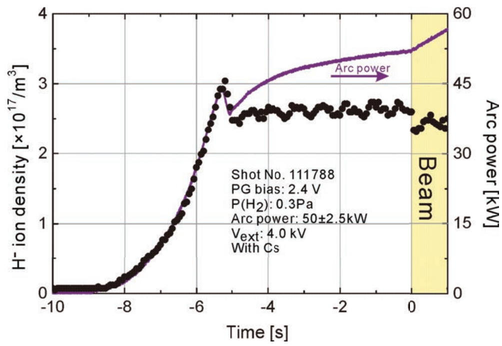

Fig. 4 Time evolution of H^- ion density.

tated by 30° so that the probe tips had different positions in y direction and four profiles can be obtained from one scan. The probe can work in electrostatic and photodetachment modes. In electrostatic mode the probe worked as a regular Langmuir probe. In the photodetachment mode, a laser beam was irradiated into the plasma and H^- ions in the laser column were detached by photons. In this process, the excess electron detached from an H^- ion by a photon conserved the charge neutrality. A probe tip was located in the laser beam co-axially and biased at 40 V. The detached electrons were collected by the DC biased probe tip. Then a current increase named photodetachment current was observed from the probe and it was proportional to the local H^- density. Then the local H^- ion density can be measured by the photodetachment current. The detail calibration method and photodetachment experimental configuration can be found in Ref. 13.

3. Plasma Response to Extraction Field

The negative ion source is a pulsed ion source. In a duty period, the filaments are warmed up for 6.9 s at first, and then the arc discharge starts and sustains for 9.9 s. At the final stage of the arc discharge, extraction voltage is applied and sustains for 1 s. Figure 3 shows the time evolution of negative saturation current measured by each probe tip and Fig. 4 shows the time evolution of H^- ion density. The term "negative saturation current" refers to the probe current which contains electrons and H^- ions. In Figs. 3 and 4, time 0 indicates the moment when the extraction voltage is applied. It can be observed that during beam extraction, the negative saturation current has an increment and meanwhile, H^- ion density decreases. The increase of negative saturation current is attributed to the electron density increase since H^- ion density shows a decrement.

During beam extraction, a part of H^- ions are extracted. As a consequence, the H^- ion density decreases. Meanwhile, electrons flow from the driver region to the extraction region for charge neutrality. An increase of electron density can be observed. By scanning the probe position in z direction normal to the PG, profiles of electron density increase and H^- ion density increase can be investigated.

4. Profile of Negative Saturation Current Increase

Figure 5 shows the profile of negative saturation current increase ΔI_{neg} which represents the electron density increase during beam extraction. The origin of the horizontal axis indicates the position of PG. Near the plasma grid, ΔI_{neg} is lower and has a peak as the increasing distance from the PG. The peak ΔI_{neg} appears in the range of 15 - 20 mm from the PG at 1.3 V bias voltage of the PG. The peak moves to the range of 20 - 25 mm by increasing the PG bias voltage to 5.7 V as shown in Fig. 6. The linear extrapolations of the profiles show the influence of the extraction field on the negative saturation current reaches 42 mm from the plasma grid.

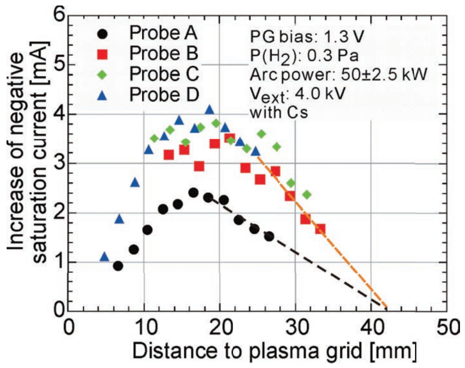

Fig. 5 Profile of increase of negative saturation current measured by each probe tip at PG bias voltage of 1.3 V.

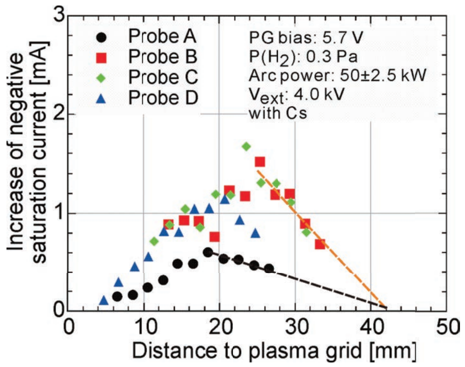

Fig. 6 Profile of increase of negative saturation current measured by each probe tip at PG bias voltage of 5.7 V.

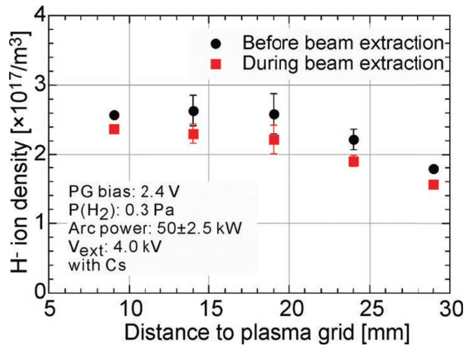

Fig. 7 Profile of H^- ion density before and during beam extraction.

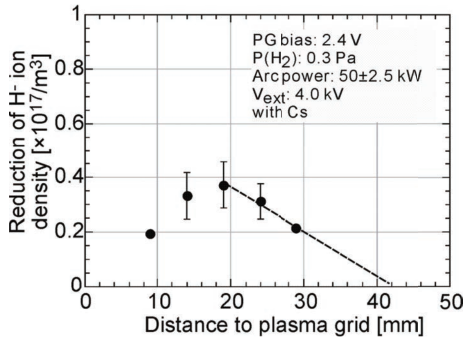

Fig. 8 Profile of reduction of H^- ion density.

5. Profile of H^- Ion Density Reduction

The profile of H^- ion density before and during beam extraction is shown in Fig. 7. In the whole measurement region, H^- ion density decreases during beam extraction. The density reduction of H^- ions Δn_{H^-} shown in Fig. 8 indicates a peak exists and appears at ~ 18 mm from the PG at PG bias voltage of 2.4 V. The linear extrapolation of the profile indicates the reduction of H^- ion density diminishes to zero at 42 mm from the PG. This characteristic is similar as the one of the profile of the negative saturation current increment.

6. Discussion

In the Cs-seeded negative hydrogen ion source, the H^- ions are mainly produced on the PG surface. One can expect the maximum response of plasma appears near the PG during beam extraction. However, the measurement results indicate that the maximum response of the plasma is far away from the PG. During beam extraction, the stable state of the plasma is changed since the extraction voltage is applied and a part of the H^- ions is extracted. If we compare the difference of the plasma stable state before and during beam extraction, a change is the supply of H^- ions to the extraction region is reduced. The reduction exhibits its effect far from the PG. A possibility is that the transport of H^- ions from the PG surface to the extraction region is not simple because of the magnetic field near the PG. If we consider the movement of a H^- ion in only y-z plane shown in Fig. 2, a H^- ion experiences gyration in filter magnetic field, since the filter magnetic field exists in large area in x direction with a strength of around 0.006 T. The H^- ion temperature was measured to be around 0.1 eV [15, 16]. The gyroradius is calculated to be around 9 mm or the diameter of the gyration is around 18 mm. One of the possibilities is the H^- ions experience long distance travel to reach the extraction region. During beam extraction, the travel of H^- ions may be disturbed by the extraction field and some H^- ions cannot finish a full gyration and reach the extraction region. As a consequence the maximum reduction of H^- ion density appears at around 18 mm from the PG. Further investigations on H^- ion dynamics are required to understand this phenomenon.

In the negative hydrogen ion source, plasma is produced in the driver region and diffuses to the extraction region across the filter field. Therefore, low density and low temperature plasma can be found in the extraction region. During beam extraction the plasma in the extraction region is indirectly influenced by the extraction field. On the other hand, the plasma in the driver region has high density and high temperature. This plasma is not influenced by the beam extraction field. In the experiments, it has been found that the depth of influence of the beam extraction field on the plasma can reach 42 mm apart from plasma grid surface. We may regard the position which is 42 mm apart from plasma grid surface, as the connection point of driver region and extraction region.

7. Summary

A four-pin Langmuir probe and photodetachment technique have been applied to the extraction region of the NIFS-RNIS to investigate the influence of the extraction field on the plasma. The maximum response of the plasma to the extraction region appears in the range of 15 - 20 mm from the PG at 1.3 V bias voltage of the PG and moves to the range of 20 - 25 mm at 5.7 V bias voltage of the PG. The profile of H^- ion density reduction has a peak at around 18 mm from PG at PG bias voltage of 2.4 V. Both of the Langmuir probe and photodetachment measurements suggest the depth of the influence of the extraction field on the plasma reaches 42 mm from the PG.

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