Progress of experimental study on negative ion production and extraction

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Abstract. Negative ion sources for plasma heating are required to form the high energy and high current negative ion beam with small co-extracted electron current. For deuterium operation, the negative ion current decreases according to the Child-Langmuir law, and the co-extracted electron current increases. In order to overcome these issues, dedicated experiments were conducted in NIFS-NBI systems. In series of experiments, it was found that the electron transport to the plasma grid aperture is restricted by cusp field formed by electron deflection magnets, and that a ratio of electron density to negative ion density becomes small in the vicinity of the plasma grid aperture due to the cusp field. The negative ion flow was measured in the extraction region. It was observed that the negative ion produced on a metal surface flows into the plasma and turn to the plasma grid aperture during the beam extraction. The stagnation point of negative ion flow was observed in the region of 20 mm from the plasma grid. The negative ion density drastically decreased with beam extraction in the same region. These observations imply that the negative ion is extracted mainly from the plasma volume rather than metal surface. In the beam acceleration experiments, unexpected enhancement of the negative ion production efficiency was observed. The arc efficiency was improved with a factor of two by changing a shape of grounded grid holes without any modification on the plasma source chamber.

1. Introduction

Development of the high performance negative hydrogen ion source is a fundamental demand in realizing fusion reactor. Especially for ITER, many laboratories are pursuing R&D activities for the negative ion source [1-3]. In the Large Helical Device (LHD), three negative-ion-based NBIs (N-NBI) have been installed and the total neutral beam power of 16 MW with the energy of 180-190 keV has been successfully injected [4]. In addition, the negative hydrogen ion current density has reached 340 A/m^2, and this is comparable with the target current density of ITER NBI for hydrogen (H) operation [5]. However, the deuterium plasma operation is planned in the LHD and for deuterium (D) operation the high power neutral beam formation is expected to be more difficult because the negative ion current decreases according to the Child-Langmuir law and the co-extracted electron current increases [6], which results in rise of the grid heat load and degradation of the voltage holding capability.

In negative hydrogen ion sources, the H^-/D^- production is enhanced by introduction of Cs because the Cs lowers the work function of the metal surface facing to the plasma and the incident hydrogen atom and/or positive ion on the surface are converted into the H^-/D^-. In series of our experiments, it was found that the negative ion rich plasma, which mainly consists of the positive ion and negative ion with small fraction of the electron, is formed in the negative hydrogen ion source with proper amount of Cs [7]. This indicates that high negative ion current with small co-extracted electron current is achieved because of formation of the negative ion rich plasma. Moreover, it is important to efficiently extract the negative ion produced on the metal surface and accelerate it to high energy.

From this point of view, we have surveyed temporal and spatial variations of the negative ions and electrons in order to clarify characteristics of negative-ion rich plasmas and the extraction mechanism of H^-. In parallel to this work, the beam acceleration experiments have been performed by changing the accelerator configuration in order to study the negative ion beam optics.

In this paper, we discuss a role of the magnetic field in the formation of the negative ion rich plasma and response of the charged particles to the extraction electric field. In addition, unexpected result obtained in beam acceleration experiments is reported.

2. Experimental setup

Characteristics of the negative ion source plasma have been investigated in NIFS R&D negative ion source (NIFS-RNIS) [8]. Figure 1(a) shows a cross-sectional view of NIFS-RNIS. The source chamber volume is the half of that of LHD N-NBI. The hydrogen plasma is generated by the filament-arc discharge. The discharge chamber is divided into two regions, driver region and extraction region, by the transverse magnetic field formed with a pair of permanent magnets. The Cs is fed into the plasma discharge chamber from the back plate to enhance the H^- production. The accelerator of NIFS-RNIS consists of 4 grids, which are the plasma grid (PG), extraction grid (EG), steering grid (SG), and grounded grid (GG). The strong local magnetic field is formed with the electron deflection magnets (EDM) embedded in the EG in order to suppress the co-extracted electrons. The magnetized direction of the EDM changes alternately from row to row, and the EDM creates the cusp field in the extraction region. The discharge chamber is electrically insulated from the PG with an insulation flange, on which diagnostic tools are installed to monitor the plasma in the vicinity of the PG.

Figure 1(b) shows arrangement of diagnostics. The negative hydrogen ion density (n_{H-}) is obtained by means of the Cavity-Ring-Down method (CRD) [9] and the Langmuir probe assisted laser photo-detachment technique (LPD) [10]. Both of them can measure the 2D distribution of n_{H-} with a sophisticated remote drive mechanism. The Langmuir probe has four probe tips, and the charged particle flow is measured by rotating it. The detail procedure for particle flow measurement is written in Ref. 11. The negative ion flow can be obtained in the same manner with a combination of the LPD [12]. The spatial distribution of extracted negative ions is observed by means of the Hα-imaging CCD technique, which takes difference between the Hα images of extraction region obtained before and during beam extraction [13]. The processed image shows the distribution of the extracted negative ions in the form of reduction of the Hα intensity. These diagnostic tools operate with applying high voltage over several tens kV on the ion source, and response of the plasma to beam extraction can be examined.

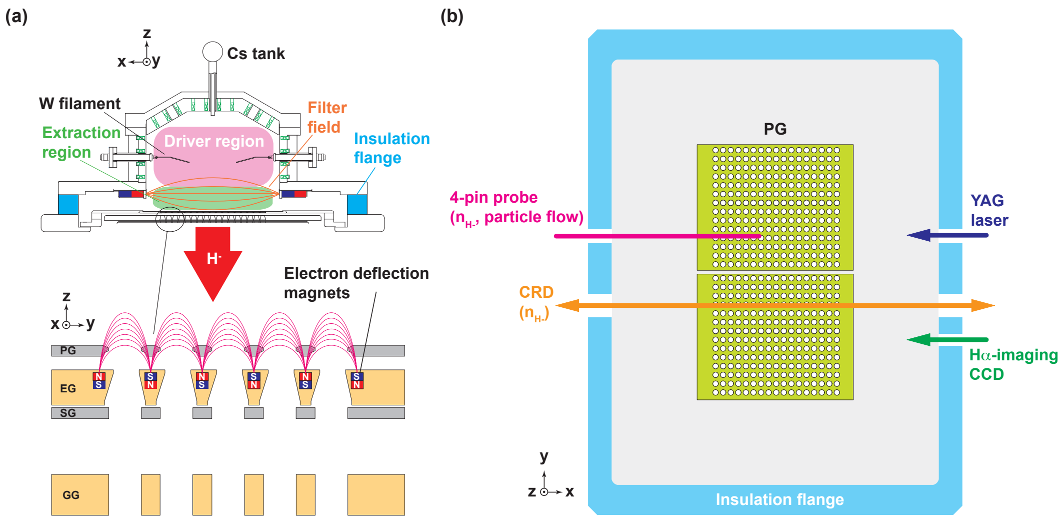

Fig. 1. (a) schematic illustration of NIFS-RNIS and (b) arrangement of diagnostics.

3. Experimental results

3.1. Characteristics of negative-ion rich plasma

The magnetic field structure in the extraction region becomes complicated due to superposition of EDM and filter fields, where the magnetic field strength is several mT. This is expected to affect the plasma profile near the PG. The Langmuir probe measurement was performed in various positions in order to investigate influence of the magnetic field on the plasma profile. Figure 2 shows 2D map of the probe negative saturation current (I_{neg}). The 2D distribution of I_{neg} has a distinguishing structure in which I_{neg} is high above the metal part of PG and increases with distance from the PG. This structure depends on the cusp field formed by the EDM, and this indicates that the electron transport toward the PG aperture is restricted by the EDM field, and that the electron is absorbed by the PG metal. Effect of the EDM field on the electron transport extends to 10 mm from the PG surface. Accordingly, the negative ion rich plasma is formed locally in the vicinity of the PG. This indicates that the EDM field plays an important role in formation of the negative-ion rich plasma as well as suppression of the co-extracted electron, and implies that the negative-ion rich plasma appears more widely in the extraction region with stronger EDM field.

As for response of the charged particles to the beam extraction, it has been found that the n_{H-} decreases simultaneously with the beam extraction, and the electron flows into the extraction region from the driver region together with the positive ion in order to maintain the charge neutrality [14]. The n_{H-} was measured in different positions to clarify how far the influence of the extraction field reaches inside the plasma. Figure 3 shows 2D distributions of the n_{H-} before and after the beam turn-on, and the decrement of the n_{H-} (Δn_{H-}), where the n_{H-} was evaluated by the photodetachment technique. The 2D distribution of n_{H-} also has a distinguishing structure. The n_{H-} becomes high in the region apart from the PG, where the same tendency was observed with the CRD [15]. This indicated that the H^- produced on the surface is transported to the plasma along the EDM field. During the beam extraction, the n_{H-} decreases widely in the extraction region except for near the PG metal, and maximum response of the n_{H-} appears in the region of 20 mm from the PG aperture. These observations indicate that the extraction field affects the particle dynamics in a wide region extending over 30 mm from the PG. This feature is completely different from that of positive hydrogen ion sources. It should be noted that these results also imply that the meniscus formation based on

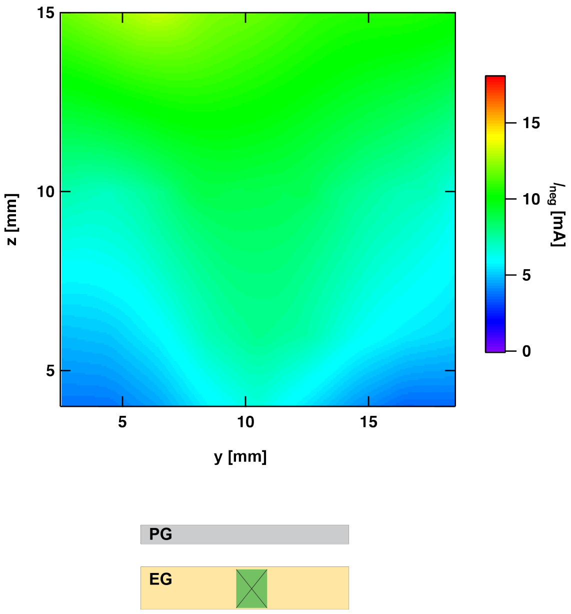

Fig. 2. 2D map of negative saturation current.

Bohm's theory, which is implemented in the conventional particle trajectory codes, is not applicable for negative hydrogen ion sources.

To investigate the particle dynamics, the charged particle flow measurements were carried out by means of the Langmuir probe with a combination of the LPD. A streamline plot of the H^- flow at beam-on phase is shown in Fig. 4. The H^- flows into the plasma in the extraction region, and it turns to the PG aperture during the beam extraction. The stagnation point of H^- flow is observed in the region of 20 mm from the PG surface, where maximum response of the n_{H-} is observed in the same region as shown in Fig. 3(c). This implies that the extraction process occurs in a region near the aperture with boundary of about 20 mm from the PG. From the above results, the H^- seems to be extracted mainly from the plasma volume rather than the metal surface. This is supported by the particle simulation and the experimental observation. The extraction process of H^- is intensively studied with a particle-in-cell (PIC) method, and some authors reported that the H^- extracted directly from the metal surface turns to a beam halo, which has high divergence angle, in extraction process [17, 18]. On the other hand, it was found experimentally that the extracted H^- beam has small divergence angle of 5 mrad [19], and that the H^- temperature is about 0.12 eV in NIFS-RNIS [12, 15]. These results imply that the extracted H^- originates mainly from the plasma volume.

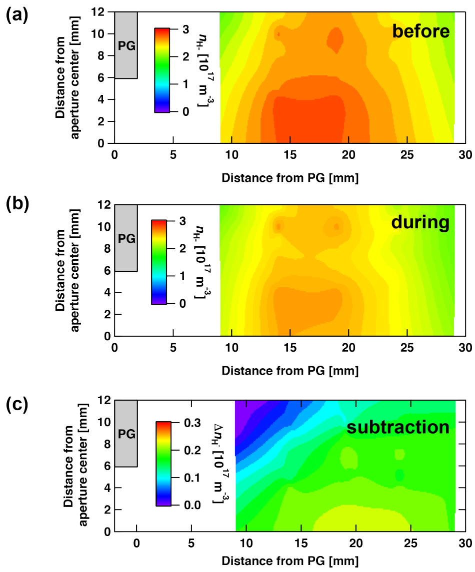

Fig. 3. Distributions of n_{H-} (a) before and (b) during beam extraction, and of (c) Δn_{H-}.

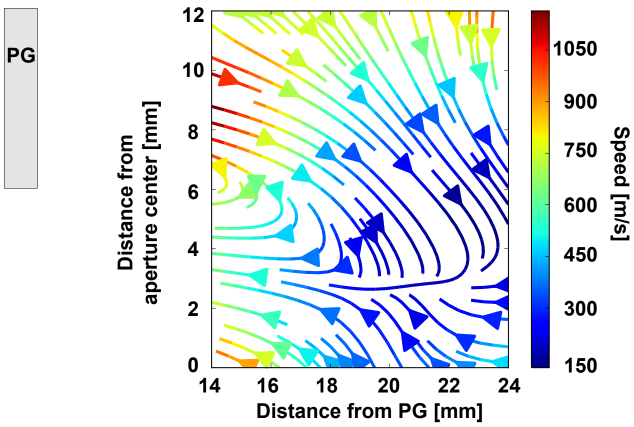

Fig. 4. Negative hydrogen ion flow during beam extraction [16].

3.2. Enhancement of H⁻ production efficiency by modification on accelerator

In the previous section, the characteristics of negative-ion rich plasmas were discussed. Here, effect of the Cs recycling stimulated by the back-streaming ion on the H^- production is introduced. The beam acceleration experiments have been carried out in LHD NBIs to study beam optics with multi-slot grounded grid (slot GG) instead of a multi-aperture grounded grid (aperture GG). In these experiments, we found unexpected increase of the H^- production efficiency. Figure 5 shows an H^- beam current as a function of the input arc power, where the beam current was estimated from the heat load on the residual ion dumps and calorimeter. For the first time, we found that the arc efficiency becomes twice higher by using the slot GG without any modification on the plasma chamber. (We had enhanced the injected beam power to the LHD with modification of the ion source chamber together with the accelerator previously.) We assumed that the behavior of the back-streaming ion was affected by changing the GG, and the back-streaming ion trajectory was analyzed with the beam trajectory simulation [21, 22]. Figure 6(a) and (b) shows the heat loads dissipated by the back-streaming ion with the aperture GG and slot GG, respectively, where the outlines of the heat load maps are added to compare the area. The heat load map with the slot GG is enlarged in vertical direction due to the lens effect on the GG. The maximum heat load with the aperture GG is higher than that with the slot GG, and the back-streaming ion distributes in the larger area on the back plate with the slot GG. In another series of experiments, it was observed that the Cs^0 emission obtained by the optical emission spectroscopy was rapidly increased with beam extraction [23]. This implies that some part of condensed Cs on the back plate was evaporated from larger area by the back-streaming ion with the slot GG and that Cs flux onto the PG surface increased, which resulted in the enhancement of the negative ion production. In fact, in this experiment the temperature on the Cs reservoir was lower than that in previous experiments using the circular GG by 2 ℃, and further investigations are necessary to optimize the reservoir temperature with consideration of Cs recycling by the back-streaming ion. This result suggests that the accelerator configuration is one of the key factors to determine the negative ion production efficiency and that the Cs consumption can be reduced by the Cs recycling from the wall of the ion source chamber.

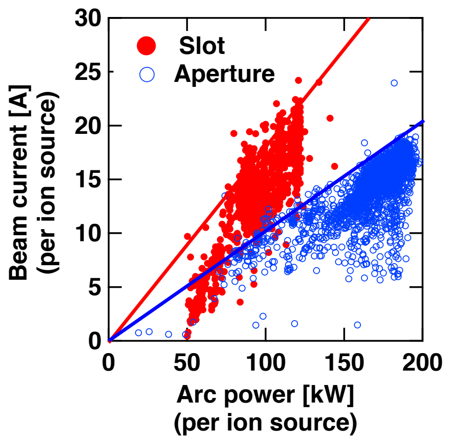

Fig. 5. Arc efficiency between accelerators with aperture GG and slot GG (reproduced from Fig. 6(b) in Ref. 20).

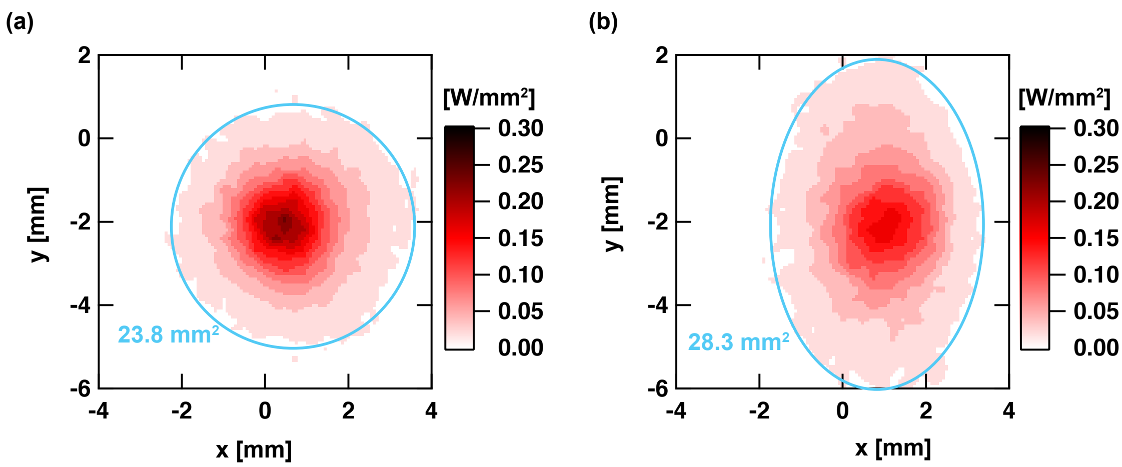

Fig. 6. Heat loads dissipated by back-streaming ion on back plate with (a) aperture GG and (b) slot GG.

4. Summary

Toward high power neutral beam injection in deuterium operation, dedicated experiments were conducted in NIFS-NBI systems. In series of experiments, it was found that the electron transport to the PG aperture is restricted by cusp field formed by the EDM, and that a ratio of electron density to negative ion density becomes small in the vicinity of the PG aperture due to the cusp field. This suggests that increase in the co-extracted electron current expected in D operation is mitigated with stronger EDM field. As for the particle dynamics, the H^- flow in the extraction region was successfully measured with newly developed method, and it was confirmed experimentally that the H^- flow changes its direction toward the PG aperture with beam extraction. Further investigations are necessary in order to clarify the origin of the extracted H^-. The flow measurement is useful for this purpose and will be performed in a region closer to the PG surface. In the beam acceleration experiments, we discovered that the negative ion production efficiency is improved by changing an accelerator configuration. This finding relates with optimization of the Cs recycling, and leads to decrease in the Cs consumption. The findings described above will expand the general physical understanding of the H^- extraction mechanism and provide insight for designing negative ion sources with enhanced performance in the H^- production efficiency.

Acknowledgements

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