

Spatial Distributions of Charged Particles and Plasma Potential before and during Beam Extraction in a Negative Hydrogen Ion Source for NBI^{*)}

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In order to understand the physics of the production and extraction mechanism of negative ions, experiments with a single Langmuir probe are carried out to investigate the local spatial distribution of the plasma in the vicinity of the plasma grid in a negative hydrogen ion source. The results show that the electron density is lower in the aperture region than that in its peripheral region. It is attributed to the cusp magnetic field introduced with the electron deflection magnets near the plasma grid. In addition, the linkage of the filter field with the electron deflection magnetic field contributes to the increment of electron density. The profile of plasma potential indicates that an electric field exists between the aperture and its peripheral region, and then a local negative ion flow can be introduced near the plasma grid.

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1. Introduction

The neutral beam injection with high beam energy (NBI) and high power is necessary to heat the plasma in a magnetic confinement fusion reactor [1]. NBI system based on positive ions is insufficient for this requirement for the large-scale fusion reactor due to its low neutralization efficiency at high beam energy. As an example, the neutralization efficiency of D^+ beam is only about 20% at energy of 200 eV. On the other hand, the D^- beam keeps neutralization efficiency higher than 60% even at energy of 1 MeV [2]. Therefore, negative ion based NBI (N-NBI) system becomes an indispensable device.

Since the first negative-ion-based beam line starts to work on JT-60U in 1996 [3], N-NBI system has reached its practical application. After a long term, non-stop research on the negative ion source, ion-ion plasma [4–7], in which the charge neutrality is conserved by positive and negative ions mainly, has been produced in the test stand-negative hydrogen ion source at NIFS [8]. In the operation of a negative ion source, electrons are extracted together with negative ions. The co-extracted electrons have to be deflected by a magnetic field and absorbed by the extraction grid (EG) and cause an additional heat load to the EG. Technically, NBI system benefits from ion-ion plasma because of the reduction of heat load on the EG, and then long pulse

extraction is supported, as well as the increment in the beam current of the negative ions. However, during beam extraction the ion-ion plasma is contaminated by electrons from so-called driver region and converted to electronegative plasma in the vicinity of the plasma grid (PG). Understanding of the physics of this phenomenon requires the knowledge of the production and extraction mechanisms of negative ions near the PG. The spatial distribution of plasma parameters is necessary for this purpose. Therefore, experiments using a single Langmuir probe are carried out to investigate the local plasma distribution near an aperture of the PG.

2. Experimental Setup

The experiments are performed in the negative hydrogen ion source on test stand at NIFS. The ion source schematically illustrated in Fig. 1 is divided into a driver region and an extraction region by a filter magnetic field. Source plasma is produced in the driver region by filament-arc discharge in multi cusp magnetic field. The magnetic filter field plays an important role to reduce the electron temperature in order to minimize the loss of negative ions due to collisions with energetic electrons. The negative ions are produced in the extraction region and its yield is enhanced by seeding Cs into the ion source. The plasma chamber and the plasma grid (PG) are electrically isolated with a flange called bias insulator. A bias voltage is ap-

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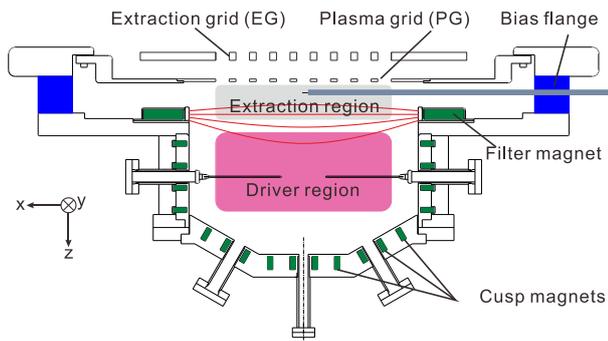


Fig. 1 Cross sectional view of the plasma chamber with a Langmuir probe installed on the bias flange.

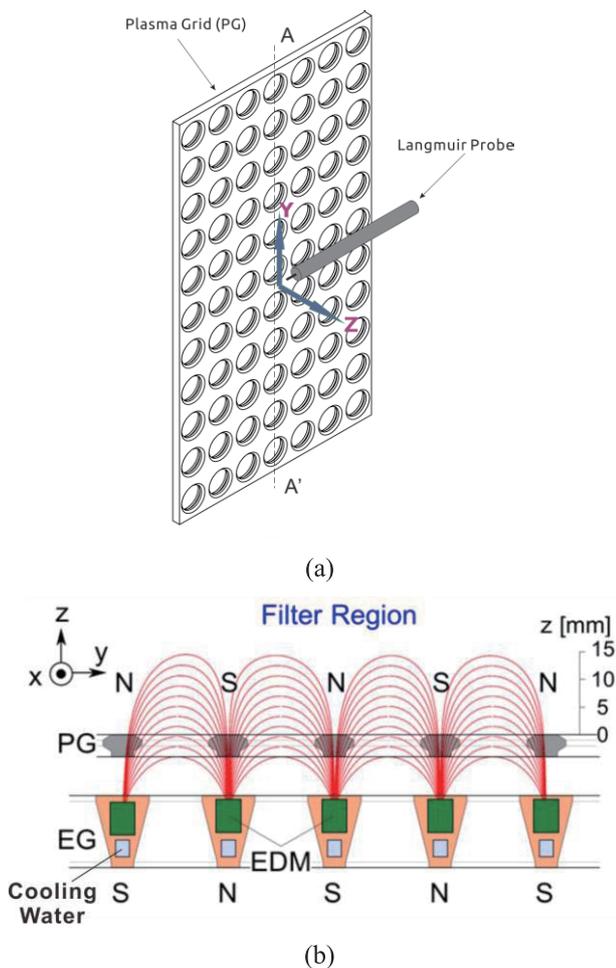


Fig. 2 (a): the plasma grid and the location of the single Langmuir probe; (b): cross sectional view of A-A' and the magnetic field produced by electron deflection magnets (EDM). The probe moves in Y and Z directions.

plied to the PG with respect to the plasma chamber. In this experiment the bias voltage is set to -4 V and 2.4 V . The single Langmuir probe is installed through the bias insulator.

The plasma grid, movable directions of the Langmuir probe and the electron deflection magnetic field are shown

in Fig. 2. The Langmuir probe moves in Y and Z directions shown in Fig. 2, because the electron deflection magnetic field varies in these two directions. As indicated in a smaller figure, X and Y are parallel to the PG surface and Z is normal direction to the grid. The position of the probe is controlled with a manipulator. Sweeping probe voltage with a frequency of 20 Hz is applied to the probe tip made of tungsten to acquire the time evolution of the plasma parameters. The probe controlling system including a sweeping power supply, an ADC and a PC is installed on the high voltage stage with the same potential as the plasma chamber. Controlling instructions and acquired data are transmitted via Ethernet isolated with an optical fiber. Using this system, it is available to measure the data obtained with Langmuir probe with and without beam extraction. The ion source is operated at low bias voltage thus the plasma is electronegative plasma, and not ion-ion plasma in order to investigate the behavior of electrons.

3. Results and Discussion

The absolute electron and ion densities are difficult to be obtained from the single Langmuir probe due to the relatively strong and complex magnetic field. In addition, the negative hydrogen ion (H^-) and electron have same charge. It is also difficult to separate electron and negative ion components from the probe current. The probe is more sensitive to the electrons than that to the ions. Therefore, in this experiment the negative and positive saturation currents are considered as the alternatives of electron and positive ion densities. The negative saturation current contains electrons and H^- ions, and the positive saturation current is the traditional positive ion saturation current. In this experiment the extraction voltage (V_{ex}) is set to 8.0 kV and the acceleration voltage (V_{ac}) is turned off.

The distributions of negative and positive saturation currents in Y direction before and during beam extraction are shown in Fig. 3. Cross sectional view of PG aperture is also illustrated below the figure to indicate the relation of the distributions and aperture position of PG. Distance of the probe tip is 4 mm apart from the upper PG surface. Beam is extracted in lower direction in this figure.

The positive saturation current is almost uniform in Y direction and increases slightly during beam extraction. This result is consistent with the ballistic ion movement estimation. In the vicinity of the PG, the magnetic field is 50 to 100 Gauss, which is high enough to magnetize the electrons ($T_e \sim 0.5\text{ eV}$), while insufficient to bind the ions to the magnetic lines since the gyro radius of an ion is comparable to the dimension of the plasma chamber. Ions move ballistic and a uniform local distribution in a short distance is observed.

The local electron distribution is influenced by the magnetic field significantly. The negative saturation current is lower on the aperture than that on the peripheral region and the current has an increment during beam ex-

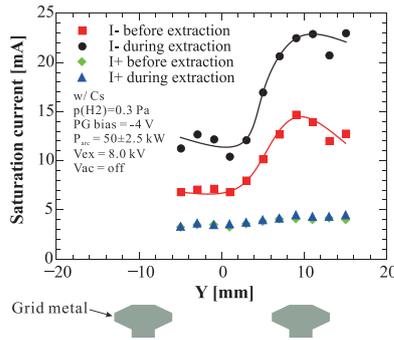


Fig. 3 Negative and positive saturation currents before and during beam extraction together with the cross sectional view of the plasma grid.

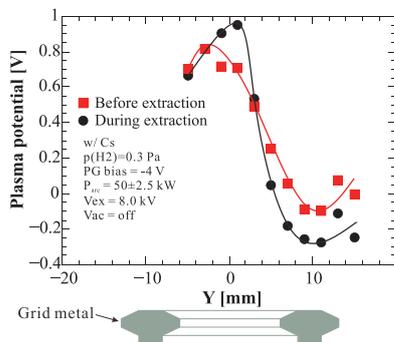


Fig. 4 Plasma potential before and during beam extraction.

traction. Since the result using cavity ring-down measurement has shown that the negative ion density is uniform in Y direction [9], and the probe are sensitive to the electrons, the variation in the distribution of negative saturation current is caused by electrons. Magnetic cusps due to electron deflection magnet exist between two apertures as shown in Fig. 2. Higher negative saturation current suggests that electrons are trapped in the cusp field between two apertures. In addition, a part the filter magnetic field is connected with the cusp field. Electrons in the driver region are possible to flow along an inter-linkage magnetic field induced with the filter and electron deflection fields. During beam extraction, H^- ions are extracted and electrons are considered to preserve the charge neutrality by diffusing from the driver region to the extraction region. Thus the negative saturation current has an overall increment. The probe saturation current is not symmetric about $Y = 0$. A possibility is the $B \times Grad B$ drift in the filter magnetic field.

The profile of plasma potential in Y direction is shown in Fig. 4. The plasma potential is higher in aperture region than that in the peripheral region before and during beam extraction. Assuming the potential of the plasma grid as the boundary condition, the plasma potential can be expressed as

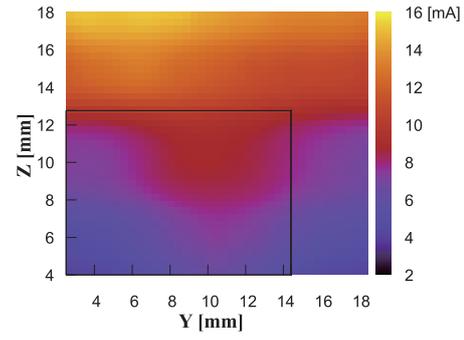


Fig. 5 Two-dimensional distribution of negative saturation current (PG bias = 2.4 V, $P(H_2) = 0.3$ Pa and $P_{arc} = 50 \pm 2.5$ kW).

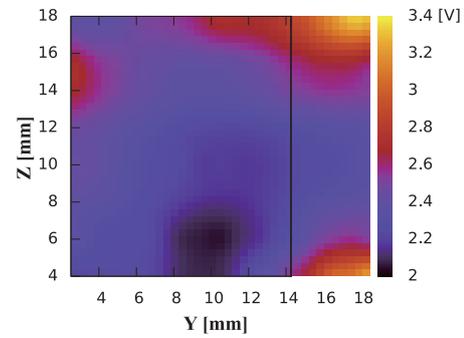


Fig. 6 Two-dimensional distribution of negative saturation current (PG bias = 2.4 V, $P(H_2) = 0.3$ Pa and $P_{arc} = 50 \pm 2.5$ kW).

$$V_{pl} = \int_0^z E(l) \cdot dl + V_{PG}. \quad (1)$$

Where V_{pl} is the plasma potential, $E(l)$ is the electric field as a function of distance to the plasma grid plane and V_{PG} is the plasma grid potential which is treated as the boundary potential. Since the plasma potential is higher in the aperture region, the electric field is stronger. The electric field difference between aperture and its peripheral region is attributed to the different ratio of H^- ion density to electron density. In addition, it can be found that an electric field in Y direction exists between the aperture region and its peripheral region. Because of the magnetic field indicated in Fig. 2, a cross field drift of electrons may be introduced.

The two-dimensional distributions of the plasma parameters are obtained by scanning the probe tip in both Y and Z directions. Figure 5 shows the two dimensional distribution of negative saturation current before beam extraction, which is consistent with the profile of the electron

deflection magnetic field, since electrons are magnetized and move along the magnetic field. The effect of the cusp field to the electrons can be observed in Fig. 5. In the region far from the plasma grid surface, the profile of the negative saturation current becomes flat.

The two dimensional distribution of plasma potential before beam extraction is shown in Fig. 6. In the peripheral region of the aperture, where the electrons are trapped in the cusp field and negative saturation current is higher, the plasma potential is lower. It indicates that in the vicinity of the plasma grid, the shielding of the electric field is enhanced in the case of higher electron density.

4. Summary

The spatial distribution of the plasma is obtained by scanning a single Langmuir probe in the vicinity of the plasma grid. Negative and positive saturation currents are characterized as electron and positive ion densities respectively. The positive saturation current is almost uniform due to the ballistic movements of positive ions. The negative saturation current is lower in the aperture region than that in its periphery, because electrons are trapped into the cusp field on the plasma grid. Another possibility is the linkage of filter field and the cusp field brings electrons from the driver region. In addition, the plasma potential is

lower in the cusp field where electron density is high. It suggests that shielding of the electric field in the vicinity of plasma grid is enhanced with higher electron density. The plasma potential difference between the aperture region and its periphery can introduce a local flow of negative ions.

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