Response of beam focusing to plasma fluctuation in a filament-arc-type negative ion source

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Beam focusing is one of the most important elements for the stable and safe operation of high power negative ion beams, such as neutral beam injection into magnetically confined fusion plasmas. In order to investigate impacts of the source plasma fluctuation on beam focusing, a simultaneous measurement of the source plasma fluctuation and the beam current profile has been carried out in the research-and-development negative ion source at the National Institute for Fusion Science. The responses of beam width and of the beam centre deviation are observed for the first time, indicating the importance of the source plasma stability for the negative ion beam focusing.

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1. Introduction

Negative ion sources with filament-arc discharge chambers have been developed for the JT-60U tokamak,1,2 the JT-60SA,3,4 and the large Helical device (LHD).5,6

Negative ions with high energy (>100 keV) have higher neutralisation efficiency in comparison with positive ions,7,8 so that a negative ion-based neutral beam injector (NBI) has been intensively developed to penetrate the beam particles deep inside of the magnetically confined plasmas. To date, negative ion-based NBIs with filament-arc discharge systems have achieved sufficiently well-focused beams with beam divergences of 5 mrad on the JT-60U,9 and 4.1 mrad and 6.1 mrad in the horizontal and the vertical directions, respectively, on the LHD.10

On the other hand, the negative ion sources for the ITER project are the RF driven sources developed by the Max-Planck-Institut für Plasmaphysik, Garching.11,12 The ITER project requires negative ion beams with beam divergence of 3–7 mrad.13 A relatively large beam divergence of 17–35 mrad with a perveance matched condition has been reported,14,15 and experimental studies of beam focusing are being performed at the ELISE and BATMAN Upgrade.16,17

A key element to determine the beam focusing is the shape of a plasma meniscus, which is the boundary between the source plasma and the beam.18,19 Because the shape of the plasma meniscus plays the role of an electrostatic lens for the first stage of the beam acceleration,20,21 the time dependent change of the plasma meniscus shape may degrade the beam focusing. Recently, a beam current fluctuation and a plasma density oscillation responding to the RF frequency of a negative ion source have been observed at the Japan Proton Accelerator Research Complex.22,23 In a positive ion source, it is observed that the oscillation of a beam halo is induced by the potential oscillation of the source plasma.24

In the present study, we focus on the evaluation of the stability of the beam focusing. For this purpose, the external perturbation is applied to a filament-arc-type negative ion source and the time dependent change of the negative ion beam width has been experimentally measured and compared with the source plasma oscillation. This perturbation method is suitable to study the plasma meniscus response to the source plasma oscillation. In Sect. 2, the experimental methods are described. In Sect. 3, the results and discussions are presented. The conclusion is presented in Sect. 4.

2. Experimental methods

All the experiments in this study have been carried out with a research-and-development negative ion source in the National Institute for Fusion Science (NIFS-RNIS).25 The NIFS-RNIS is constructed with a filament-arc discharge chamber and a beam accelerator system, which is almost identical to that of a NBI in the LHD.

Figure 1(a) shows a conceptual view of the simultaneous measurements of the source plasma fluctuation and the width of a single “beamlet” produced by the NIFS-RNIS. Here, we define the beamlet as the isolated beam extracted from the single aperture. x and y refer to the horizontal axis and the vertical axis, respectively, whose directions are perpendicular to the beam axis denoted by z. The beam accelerator in the NIFS-RNIS consists of four electrode grids. The first grid is a plasma grid with aperture of φ11 mm in diameter. The second grid is an extraction grid containing electron deflection magnets (EDM) for removal of the extracted electrons. Then, negative ions are also deflected in the x-direction by the EDM field, whose maximum strength along the y-direction is 470 G. The third grid is a steering grid for correction of the beam axis bent by the EDM field. The steering grid is attached to the extraction grid, hence both grids share the same electrical potential. The fourth grid is a slot-type grounded grid. The detailed structure of the four
The fast beamlet monitor (FBM) consisting of a Faraday-cup-type 32-channel electrode array [8 × 4 channels, see Fig. 1(b)] has been applied to measure the beamlet width. The intervals of nearest electrodes are 4.1 mm and 4.9 mm in the x and y directions, respectively. A grounded plate of the FBM made of molybdenum is installed at the upstream of the copper electrodes. Each electrode is positively biased (+70 V) with respect to the grounded plate to suppress an effect of the secondary electrons emitted from the electrode surface, whose circuit is also shown in Fig. 1(a). The detailed description of the FBM can be seen in Ref. 29. The FBM is installed at 910 mm downstream from the grounded grid. A linear drive system with stroke of 410 mm is provided to remotely control the vertical position of the FBM.

The beamlet widths in the x and y directions are simply evaluated by Gaussian fitting

\[
J(x, y) = J_e \exp \left[-\frac{(x-x_0)^2}{w_x^2} - \frac{(y-y_0)^2}{w_y^2}\right],
\]

where \(J_e\) is the amplitude of the beamlet current density at the beamlet centre positions (\(x = x_0, y = y_0\)). The \(w_x\) and \(w_y\) are the e-holding half-widths in the x and y directions, respectively.

A Langmuir probe has been installed exactly the same vertical position of the isolated aperture on the plasma grid in Fig. 1(a), and the distance from the plasma grid to the probe tip is 12 mm.25,30) where the point is as close as possible to the plasma grid. The probe is negatively biased (−40 V) with respect to the discharge chamber in order to measure the ion saturation current (\(I_{s}\)). It should be noted that the \(I_{s}\) measurement is more appropriate for investigation of the source plasma oscillation than the measurement of the negative ion current because of the contamination of the electron current in the present experiment.

3. Results and discussions

Two-dimensional distribution of the beamlet current density has been measured by the FBM, which is shown in Fig. 2(a). The FBM position is scanned in the y-direction on a shot by shot basis. All the operational parameters are fixed during this experiment, such as arc discharge power of 64–67 kW, hydrogen gas pressure of 0.3 Pa, negative ion density of \(2.6 \times 10^{17} \text{ m}^{-3}\), electron current ratio for negative ion current of \(I_e/I_{s} = 0.1\), bias voltage of \(V_{bias} = 3.0 \text{ V}\), beam extraction voltage of \(V_{ext} = 3.1 \text{ kV}\), and beam acceleration voltage of \(V_{acc} = 48 \text{ kV}\). One can see the vertical elongated distribution of the beamlet, which is commonly observed when using the slot-type grounded grid for beam acceleration.10,28) Figure 2(b) shows the one-dimensional distribution of the beamlet current density in the x-direction. A tail component can be seen. However, our interest is a core component near the beamlet centre. The width of the beamlet core (\(w_i\)) is evaluated by Eq. (1) without the tail component. The core and tail components are shown with closed and open circles in Fig. 2(b), respectively. Figure 2(c) shows the one-dimensional distribution of the beamlet current density in the y-direction near the beamlet centre. The closed circles show the observed data by scanning every 2.5 mm in the y-direction, and the dotted line shows a result of the Gaussian fitting to all the open circles. The closed circles show the observed data measured simultaneously with the fixed FBM, and the solid line shows a result of the Gaussian fitting to the four closed circles. The agreement of the beamlet width with \(w_{i, scan} = \text{0.96 ± 0.04}\) is obtained.

In order to investigate the response of the beamlet focusing to the source plasma fluctuation, the simultaneous measurements of the source plasma fluctuation and the beamlet width have been carried out. Figure 3 shows the time dependent change of the ion saturation current (\(I_{s}\)), the beamlet widths
In this experiment, the fluctuation of the source plasma density occurs in the thyristor switching cycle of the bias power supply, whose frequency is 360 Hz. The source plasma fluctuation of 10%, the beamlet width fluctuation of 20% in the x-direction, and the beamlet width fluctuation of 7% in the y-direction at maximum can be seen in Fig. 4(a). The response of deviations of the beamlet centre positions are also clearly observed in Fig. 4(b). The dashed lines in Figs. 4(a) and 4(b) show the results of the static experiments, in which the arc discharge power was scanned on the shot by shot basis and the time-averaged values of \( I_n^s, w_x, w_y, x_c, y_c \) were evaluated. One can see the consistency between the transient experiment and the static experiments.

Furthermore, strong correlations between \( w_x/\langle w_x \rangle \) and \( x_c - \langle x_c \rangle \), and \( I_n^s/\langle I_n^s \rangle \) are found, which are shown in Figs. 5(a) and 5(b), respectively. This indicates that \( w_x \) may not be changed with the fixed \( w_y \), and \( x_c - \langle x_c \rangle \) cannot be changed with the fixed \( y_c - \langle y_c \rangle \). These characteristics can be reasonably explained by the response of the plasma meniscus to the source plasma fluctuations. From the viewpoint of the physical aspect, the plasma meniscus is formed with a competition between the penetration of the extraction field and the Debye shielding effect. When the source plasma density is increased, the Debye shield becomes strong. Hence, the source plasma pushes the plasma meniscus, and the curvatures of the plasma meniscus change in both x and y directions. This would be a
possible explanation of the correlation between \( w_x \) and \( w_y \).

Regarding the change of the beamlet axis position, the deflection angle caused by the steering grid is another possibility. However, the deflection via steering is only in the \( x \)-direction in the present accelerator. Therefore, the strong correlation between \( (x_c - \langle x_c \rangle) / \langle w_x \rangle \) and \( (y_c - \langle y_c \rangle) / \langle w_y \rangle \) is considered as an evidence that the origin of the beamlet axis shift is the plasma meniscus shape, of which axis is deviated from the central axis of the plasma grid aperture. The dashed lines show the results of the static experiments, and the horizontal and the vertical parameters are shown in the top and the right hand side axes, respectively.

In this experiment, the source plasma fluctuation was induced by switching cycle of the bias power supply, of which frequency is 360 Hz. This frequency is lower than the typical RF frequency (~1 MHz) of negative ion sources based on RF discharge. However, the ion plasma frequency (~100 MHz) is much higher than the RF frequency. From the viewpoint of the ion responsibility, the beamlet oscillation observed in the present experiment indicates the possibility of the degradation of the beam focusing caused by the RF field oscillation in negative ion sources based on RF discharge.

4. Conclusion

The simultaneous measurement of the source plasma fluctuation and the beamlet current profile is performed and the responses of the beamlet width and the beamlet centre deviation are observed. The significant correlation between the beamlet widths in the \( x \) and \( y \) directions is also identified. These observations indicate the response of the plasma meniscus to the source plasma fluctuation. In addition, it should be noted that the beamlet core is affected by the source plasma fluctuation, which differs from the experimental observation with the positive ion source. Therefore, the source plasma stability is also of crucial importance for the negative ion beamlet focusing.

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