Demonstration of Beam Optics Optimization Using Plasma Grid Bias in a Negative Ion Source

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Plasma grid bias has been utilized for reducing an electron density in the vicinity of a plasma grid in negative ion sources for fusion, resulting in achievement of low co-extracted electron current. In this study, the effectiveness and feasibility of the plasma grid bias on beam optics optimization are demonstrated. It is shown that the beam optics strongly depends on the bias voltage and is successfully optimized at different bias voltages depending on the discharge power. Responses of the beam properties such as the perveance and the current ratio to the plasma grid bias are also shown for both hydrogen and deuterium beams.

Keywords: hydrogen negative ion source, beam optics, meniscus, perveance, plasma grid bias

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Physical model of meniscus formation in hydrogen negative ion sources, in which negative ions are produced on the metal surface with low work function and electrons coexist, has not been established yet. In practical operations of ion sources, a meniscus shape is modified by adjusting the plasma density in the vicinity of a plasma grid (PG), where the gas pressure and/or the discharge power are control parameters. In negative ion sources for fusion, the PG is positively biased with respect to a discharge chamber in order to suppress electrons extracted with negative ions [1]. In recent studies, reduction of negative ion and electron densities in the vicinity of the PG was observed as the bias voltage was increased [2, 3]. In addition, the numerical simulation pointed out that the curvature of the meniscus depends on the H^+ or H^- profile near the PG [4]. These results suggest that the plasma grid bias affects the meniscus formation and acts as a control knob for optimizing the negative ion beam optics.

In order to investigate effects of the plasma grid bias on the negative ion beam optics, we conducted experiments with the negative-ion-based neutral beam injector (N-NBI) in the Large Helical Device (LHD). In the LHD, three N-NBIs are routinely operated as the main plasma heating devices, where two ion sources are installed in each beamline. The nominal values of beam energy and beam current are 180 keV and 40 A/source, respectively. The plasma is generated by the filament-arc discharge, and the beam is accelerated with an electrostatic accelerator consisting of four grids, PG, the extraction grid (EG), the steering grid (SG), and the grounded grid (GG), where a detailed description of LHD N-NBI can be found elsewhere [5]. The negative ion current ($I_{\rm ion}$) is estimated from total heat loading on the beamline components and from the acceleration power-supply drain current. The co-extracted electron current ($I_{\rm e}$) is defined as the difference between the drain currents of extraction and acceleration power-supplies. The spatial distributions of the beam in horizontal and vertical directions are monitored by thermocouple arrays embedded in the calorimeter.

Figure 1 (a) shows the full-width at half-maximum (FWHM) beam width in the horizontal direction as a function of the bias voltage ($V_{\rm bias}$) at various discharge powers ($P_{\rm arc}$) for deuterium operations, where the extraction voltage ($V_{\rm ext}$) and acceleration voltage ($V_{\rm acc}$) were maintained at 6.98 kV and 127 kV, respectively. It is clearly shown that the beam width changes with the $V_{\rm bias}$ and reaches a minimum at higher $V_{\rm bias}$ for higher $P_{\rm arc}$. The mechanism

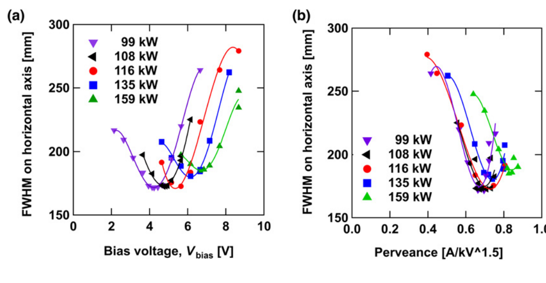

Fig. 1 Beam width as a function of (a) bias voltage and (b) perveance for various discharge powers.

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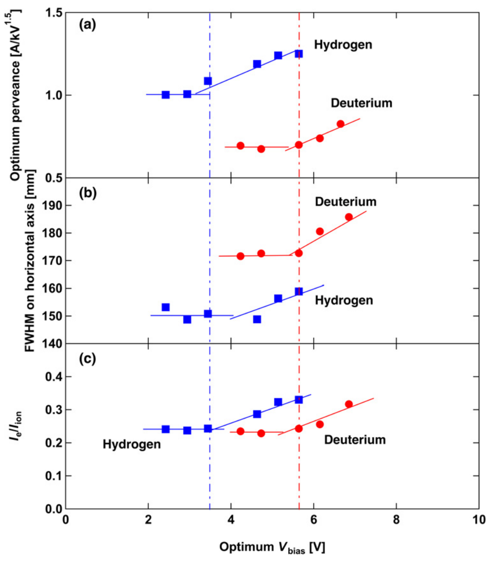

Fig. 2 (a) Optimum perveance, (b) beam width, and (c) current ratio at each optimum bias voltage.

of this property can be qualitatively explained as the perveance matching, which is normally achieved by adjusting the discharge power and/or the gas pressure. Thus, the plasma density near the PG increases with the P_{arc}, and it is necessary to apply higher V_{bias} in order to suppress the plasma density to the optimum. However, in this V_{bias} scan it was found that the beam optics was optimized at different perveance as the P_{arc} was high, as shown in Fig. 1 (b), where the perveance is defined as $I_{\mathrm{ion}}/V_{\mathrm{ext}}{}^{1.5}$. This is not observed in the positive ion sources, in which the beam optics changes along the identical perveance curve regardless of operational conditions on the plasma production and beam extraction.

Beam properties such as perveance, beam width, and current ratio ($I_{\mathrm{e}}/I_{\mathrm{ion}}$) at each optimum bias voltage for both hydrogen and deuterium operations were plotted in Fig. 2. The data was obtained in the same series of experiments for Fig. 1. According to the Child-Langmuir law, the optimum perveance of D^- beam is lower than that of H^- beam by a factor of $1/\sqrt{2}$. The optimum perveance increases with the optimum V_{bias} above certain threshold, as mentioned above. This result suggests that production of the high perveance beam with small divergence can be potentially achieved, and this is favorable for enhancement of the injection power. However, as shown in Fig. 2 (b), the beam width broadens for both hydrogen and deuterium operations. Note that the beam width is wider in deuterium operations than that in hydrogen operations because negative ion beamlets are steered by the aperture displacement technique applied on the SG in order to compensate the beam deflection due to the magnetic field generated by electron deflection magnets in the EG and the steering angle is optimized for the H^- beam [6]. From an engineering point of view, the current ratio is another important parameter to be considered, which is shown in Fig. 2 (c). An electron contamination in the extracted beam also increases above the same threshold of the V_{bias}, and this implies that the ratio of the electron density to the negative ion density plays an important role for the meniscus formation. At hydrogen operations, the threshold of the optimum V_{bias}, above which the beam properties changes, is lower than that at deuterium operations by 2 V. The plasma potential in deuterium plasmas may be 2 V higher than that in hydrogen plasmas because the ion loss rate to the chamber wall is expected to be smaller in deuterium plasmas due to its heavier mass [7]. Then, the threshold could be shifted by 2 V in order to achieve the same potential difference between the PG and the plasma.

We demonstrated that the plasma grid bias effectively acts as a control knob for optimizing the negative ion beam optics and found that the pearvence is enhanced with the optimum V_{bias} while the beam broadening and the increase of the I_{e} coincide. Further experimental and theoretical analyses of beamlets and source plasmas are necessary to clarify a relation between the meniscus formation and the plasma grid bias. These studies will contribute to the design of an accelerator that produces the high current beam with low divergence and small electron contamination.

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