Characterisation of negative ion beam focusing based on phase space structure

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Abstract

Negative ion beam focusing is a key element for advanced applications of negative ion beams such as accelerators for particle physics, compact accelerators for medical fields, and plasma experiments for nuclear fusion because complicated magnetic fields exist both inside of the source plasma and the grid system. In order to understand the beam focusing, phase space structure measurements for a single beamlet have been performed with a research-and-development negative ion source at the National Institute for Fusion Science. A complicated phase space structure is observed in the direction parallel to the filter magnetic field in the vicinity of the plasma grid, while a single-Gaussian beamlet structure is observed in the direction perpendicular to the filter field. Detailed analyses for the phase space structure of the single beamlet reveal that the complicated structure can be identified as a combination of three beam components with different beam axes. The shifts of each axis are also observed to depend on the ratio of the acceleration voltage for the extraction voltage, which may significantly degrade the beamlet focusing.

1. Introduction

Negative ion beams have been applied for variety of applications such as accelerators for particle physics, compact accelerators for medical fields, and plasma experiments for nuclear fusion [1]. Neutral beam injection (NBI) is one of the most important plasma heating methods in nuclear fusion experiments [2–4]. Negative-ion-based NBI has the particular advantage of neutralisation efficiency. The neutralisation efficiency of positive ions drops sharply as the ion kinetic energy exceeds 60 keV, whereas that of negative ions is maintained around 60% and is independent of the beam energy in high energy region, for example, $E \geq 100$ keV for D$^{-}$ beams [5, 6]. As the plasma confinement devices increase in size, the higher beam energy is required to penetrate the beam particles deep inside of the plasmas. Therefore, negative-ion-based NBI is inevitable for large plasma confinement devices such as the ITER.

So far, negative ion sources with filament-arc discharge systems have been developed and applied for plasma heating and current drive for the JT-60U tokamak and the large helical device (LHD) [7, 8]. LHD-NBI has achieved negative ion beam energy of 190 keV and beam current of 37 A (beam current density of 340 A m$^{-2}$), which are higher than the designed values of 180 keV-30 A [9]. The beam divergences of 4.1 mrad and 6.1 mrad in the horizontal and vertical directions have been obtained, respectively [10]. At present, the development of negative ion sources for the ITER project is one of the most important subjects for nuclear fusion research. The design of the ion sources for the ITER project is the radio frequency (RF) driven negative ion sources developed by the Max-Planck-Institut für Plasmaphysik, Garching [11]. The requirements due to the design of ITER-NBI are beam duration of up to 1000 s for H$^{-}$ beams or 3600 s for D$^{-}$ beams, accelerated current densities of 230 A m$^{-2}$ for 0.87 MeV H$^{-}$ beams and 200 A m$^{-2}$ for 1 MeV D$^{-}$ beams, and beam divergence of 3–7 mrad [12, 13]. The accelerated current density of 237 A m$^{-2}$ for H$^{-}$ beams over 1000 s has been fulfilled at the test facility ELISE.
The relatively large beam divergence of 17–35 mrad with perveance matched condition has been reported [16, 17], and experimental studies of the beam focusing are being carried out at the ELISE and BATMAN. Therefore, further understanding of the negative ion beam focusing is required and the demonstration of the beam divergence control is necessary for the development of negative ion sources for the ITER project, which is performed with the Source for Production of Ion of Deuterium Extracted from RF plasma (SPIDER) [18] and the Megavolt ITER Injector Concept Advancement (MITICA) at the Consorzio RFX, Padova [19, 20].

One of the most important factors that determines the beam focusing is the formation of a plasma meniscus, which is the boundary between the source plasma and the beam [21, 22]. The meniscus is physically defined as the equipotential surface, where the quasi-neutrality is broken [23, 24]. The meniscus plays a role of an electrostatic lens for the first stage of the beam acceleration. Although the meniscus formation is a key to the beam focusing, it is extremely difficult to observe the meniscus experimentally. In numerical simulations, it is pointed out that the meniscus shape is important for the beam halo generation and the beam divergence [25–27]. A similar result was also reported by the inverse beam calculation to evaluate the meniscus shape [28]. However, a physics model to determine the meniscus formation has not been developed yet.

In the experimental studies to characterise the beam focusing, the beam emittance and/or the beam divergence are utilised. The emittance is defined by the total area of a phase space structure and is an invariant for beam transport [29, 30]. The emittance is a useful parameter to govern the beam brightness, hence it becomes important especially in the development of the particle accelerator for high energy physics [31–33]. The beam divergence is widely used for applications in nuclear fusion, because the port-through beam power, which is important for designing beam injectors, can be evaluated with the beam divergence [10, 34]

In this study, the phase space structures of the negative ion beam have been experimentally measured. It is demonstrated that the obtained phase space structures can be characterised by some parameters, which are considered to be related to the meniscus formation. In section 2, the experimental setup is described. In section 3, the phase space structures of the negative ion beam are characterised. In section 4, the behaviour of the phase space structures is presented. The discussions and the conclusion are presented in sections 5 and 6, respectively.

2. Experimental setup

All the experiments in this study have been carried out in a neutral beam test stand at the National Institute for Fusion Science (NIFS-NBTS). The NIFS-NBTS is a test facility of NBI including a research-and-development negative ion source in the NIFS (NIFS-RNIS) and a beamline. The NIFS-RNIS is constructed with a filament-arc discharge chamber and a beam accelerator system, whose beam extraction area is approximately one-third of that in LHD-NBI [35]. The beam accelerator system in the NIFS-RNIS is almost identical to that in LHD-NBI, consisting of four electrode grids, as shown in figure 1. In this experiment, x and y refer to the horizontal axis and the vertical axis, respectively, whose directions are perpendicular to the beam axis represented by z. The first grid is a plasma grid (PG) with thickness of 3.5 mm. The aperture of the PG is designed to have a diameter of φ11 mm with 45° chamfer on the plasma side. The external magnetic filter of 52 G is created along the x-direction in front of the PG [36, 37]. The second grid is an extraction grid (EG) containing permanent magnets, which are called electron deflection magnets (EDM), for removal of the co-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 aperture diameters of upstream surface and downstream surface of the EG are φ9.5 mm and φ15 mm, respectively. The third grid is a steering grid (SG) for correction of the beam axis bent by the EDM field. The SG is attached to the EG, hence both grids share the same electrical potential. The aperture diameters of upstream surface and downstream surface of the SG are φ10 mm and φ12 mm, respectively. The fourth grid is a slot-type grounded grid (GG) [10]. The longer side of the slot is arranged parallel to the x-direction, and the shorter side is along the y-direction with a length of 13 mm. The gap sizes of PG-EG, EG-SG, and SG-GG are 5.5 mm, 3.0 mm, and 41 mm, respectively. Typical parameters of the NIFS-RNIS operation in this experiment are arc discharge power ($P_{arc}$) of 30–70 kW, H₂ gas pressure of 0.3 Pa, H⁻ ion density ($n_{H^-}$) of $3 \times 10^{17}$ m⁻³, H⁻ ion current density ($j_{H^-}$) of 100 A m⁻² at the exit of the GG, electron current ratio for H⁻ ion current ($I_e / I_{H^-}$) of 0.35, beam extraction voltage ($V_{exc}$) of 3.1 kV, and beam acceleration voltage ($V_{acc}$) of 43–53 kV.

2.1. Pepper-pot-type phase space analyser (PPSA)

The pepper-pot method was originally proposed as a method to measure the beam emittance and is constructed with a pepper-pot plate and a position-sensitive detector [38, 39]. Although many methods have been developed including the quadrupole scan and the optical diffraction/transition radiation interference contrast, the pepper-pot method remains a powerful technique applied for phase space structure measurements [40–44].
A pepper-pot-type phase space analyser (PPSA) has been developed and applied for the phase space structure measurements of a negative ion beam produced by the NIFS-RNIS. Figure 1 shows the principle of the phase space structure measurement using the PPSA. The PPSA consists of a pinhole array and a position-sensitive detector. We consider the single beamlet, which is defined in this paper as the beamlet extracted from the isolated aperture. The beamlet is irradiated to the pinhole array and subdivided into many narrow beams. Those narrow beams passing through each pinhole reach the position-sensitive detector after travelling a fixed distance, L. The displacement of the beamlet detection position from the pinhole centre position denoted as Δy corresponds to the velocity in the y-direction denoted as vy with the relation

\[ \frac{v_y}{v_z} = \frac{\Delta y}{L}, \]

where \( v_z \) is the beam velocity in the z-direction. In this experiment, two-dimensional footprints of the beamlet are obtained, hence a four-dimensional distribution function \( f(x, y, v_x, v_y) \) can be described, where \( v_x \) is the velocity in the x-direction.

The thickness of the pinhole plate made of copper is 1.5 mm. Each pinhole is designed to have a diameter of \( \phi 0.4 \) mm with a taper structure of 1 mm in depth. The total number of pinholes is 630 (18 in the x-direction \( \times \) 35 in the y-direction). The pinholes are arranged in a square grid with the interval (or spatial resolution) of 3 mm. A Kapton foil with thickness of 50 \( \mu \)m is utilised as a position-sensitive detector, which is located at \( L = 166 \) mm downstream from the pinhole array, and covers the beamlet survey area (62 mm in the x-direction \( \times \) 110 mm in the y-direction). The normalised velocity resolution \( (\Delta v_y/v_z) \) can be evaluated by equation (1) with \( \Delta y \sim 0.4 \) mm, and is 2.4 mrad.

2.2. Fast beamlet monitor (FBM)

The FBM, which has a Faraday-cup-type 32-channel electrode array (8 channels in the x-direction \( \times \) 4 channels in the y-direction), is applied to evaluate the beamlet width. In this study, the FBM has been utilised to investigate the basic beam focusing properties: the voltage ratio \( (V_{\text{acc}}/V_{\text{ext}}) \) dependence of the beamlet width and the negative ion density \( n_{\text{H}}^- \) dependence of the beamlet width. The spatial resolutions of the FBM are 4.1 mm and 4.9 mm in the x and y directions, respectively. Each electrode made of copper has the effective cross section of \( \pi \) mm². The negative ion current injected into each electrode is converted to the voltage with a resistive of 10 kΩ. Details on the FBM are shown in [45]. The beamlet width is simply evaluated by fitting a Gaussian distribution to the beamlet current profile observed by the FBM

\[ J_{\text{fit}}(x, y) = I_p \exp \left\{ -\frac{(x-x_\mu)^2}{w_x^2} - \frac{(y-y_\mu)^2}{w_y^2} \right\}, \]

where \( I_p \) is the amplitude of the beamlet current density obtained at the beamlet centre positions \( (x_\mu, y_\mu) \), \( w_x \) and \( w_y \) are the e-folding half-widths in the x and y directions, respectively.
2.3. Hexagonal box

Figure 2(a) shows the experimental configuration to measure the beamlet produced by the NIFS-RNIS. By masking the surrounding apertures, as shown in figure 2(b), the beamlet measurements can be performed without any overlap of neighbouring beamlets. The FBM and three sets of PPSAs are mounted on one hexagonal box, which is installed at 910 mm downstream from the GG. The hexagonal box containing three sets of PPSAs can be rotated in the vacuum chamber, so that the phase space structure measurements can be carried out with scanning a particular parameter of the beamlet acceleration without opening the vacuum chamber. In addition, by using the linear drive system, the vertical position can be scanned remotely within the 410 mm stroke.

3. Phase space structure of negative ion beamlet

The phase space structure measurements of the negative ion beamlet, which is accelerated through the isolated aperture shown in figure 2(b), have been carried out with the PPSAs. Figure 3 shows a two-dimensional distribution of footprints on the Kapton foil. A vertical elongated distribution of the beamlet can be seen, which is commonly observed when the beamlet is accelerated with the slot-type GG [10].

Footprint data on the Kapton foil can be digitised by a scanner with a resolution of 9600 dpi, which allows us to know the information of 2.6 μm/pixel in position and of 18 μm/pixel in normalised velocity. After subtracting the background level of the Kapton foil, the increase of the blackness degree on the Kapton foil, denoted as $\Delta \eta$, is obtained. It has been confirmed that the $\Delta \eta$ is proportional to the time integral of the negative ion current density ($J_{\text{fi}}$) at a fixed beam energy [45]:

$$\Delta \eta \propto \int J_{\text{fi}} \, dt. \quad (3)$$

A one-dimensional footprint profile (indicated by the dashed rectangle in figure 3) was used to create a one-dimensional $\Delta \eta$-profile in the $y$-direction, which allowed us to construct the two-dimensional phase space structure, as shown in figure 4(a). One can see the linearly elongated elliptic-structure in the phase space of $y$ and $v_y$. The longer axis of the elliptic-structure has a positive slope, $\partial v_y/\partial y > 0$, indicating that the beamlet is a diverging beam [46, 39]. In order to characterise the observed phase space structure, the width of individual peaks and the intervals between neighbouring peaks were evaluated. The e-folding half-width is 0.583 ± 0.004 mm and the interval is 3.502 ± 0.037 mm, both of which have standard deviations of ≤1%.

Hence, the one-dimensional $\Delta \eta$-profile in the $y$-direction is modelled by a multi-Gaussian distribution:

$$\Delta \eta_y \approx \sum_{n=-11}^{11} a_n \exp \left[ -\frac{(y - y_0 - n\lambda)^2}{\sigma_{vy/vz}^2} \right]. \quad (4)$$

where $n$ is the numbering of the peaks, $a_n$ is the $n$th peak amplitude, $a_0$ is the highest peak amplitude, $y_0$ is the position of the highest peak, $\sigma_{vy/vz}$ is the e-folding half-width, and $\lambda$ is the interval between neighbouring peaks. Both $\sigma_{vy/vz}$ and $\lambda$ are regarded as constant values. The constant $\sigma_{vy/vz}$ means the uniform perpendicular temperature. The constant $\lambda$ indicates diverging beam with single focal point. Figure 4(b) shows the one-dimensional $\Delta \eta$-profile in the $y$-direction and the fitting results based on equation (4). One can see that this model can reproduce the experimental observation, indicating the two assumptions are validated. Figure 4(c)
shows the amplitude profile, $a_d(y)$, which roughly agrees with a Gaussian distribution

$$J(y) = J_c \exp \left[ -\frac{(y - y_c)^2}{\sigma_y^2} \right],$$

where $J_c$ is the amplitude, $y_c$ is the beamlet centre position, and $\sigma_y$ is the e-folding half-width of the beamlet in the $y$-direction. A diverging phase space structure aligned a long line is eventually concentrated in single point when the phase space structure is moved inversely in time while the spreading in space remains. In this study, the definition of a Gaussian beam with single focal point is the Gaussian distribution in real space with single line-alignment in the phase space. Therefore, the optical property of the beamlet in the $y$-direction is a diverging Gaussian beam with single focal point.

On the other hand, a different phase space structure of the beamlet is observed in the $x$-direction, which is shown in figure 5(a). At least two linearly elongated elliptic-structures in the phase space of $x$ and $v_x$ can be observed. The same procedure of the analysis for the one-dimensional $\Delta \eta$-profile has been applied to characterise the observed phase space structure in the $x$-direction. The model for one-dimensional $\Delta \eta$-profile is a combination of three components given by

$$\Delta \eta_x = G_u + G_l + G_c,$$

The subscripts of $G_u$, $G_l$, and $G_c$ correspond to ‘upper’, ‘lower’, and ‘centre’ elliptic-structures in the phase space of $x$ and $v_x$. The three sets of multi-Gaussian components are modelled by the formula identical with equation (5), that is

$$G_u = \sum_{n=--5}^5 u_n \exp \left[ -\frac{(x - x_{0u} - n\lambda_u)^2}{\sigma_{\lambda x/u}^2} \right].$$

Figure 3. Two-dimensional distribution of footprints on the Kapton foil. The total duration of the beamlet irradiation is 20 s (=1 s/shot $\times$ 20 shots with the shot interval of 180 s). The NIFS-RNIS operation parameters are arc discharge power of $P_{arc} = 53 \pm 7$ kW, beam extraction voltage of $V_{ext} = 3.1$ kV, and beam acceleration voltage of $V_{acc} = 48$ kV. The negative ion density in the vicinity of the PG is $n_{it} = 3.3 \times 10^{17}$ m$^{-3}$, and the current density of the negative ion beamlet is $j_{it} = 97 \pm 3$ A m$^{-2}$. The dashed rectangle (- - -) and the dotted rectangle (......) denote the one-dimensional footprint distributions analysed to construct the phase space structures in the $y$-direction and in the $x$-direction, respectively.
where $n$ is the numbering of the peaks with $n = 0$ corresponding to the highest peak, $u_n$, $l_n$, and $c_n$ are the $n$th peak amplitudes, $x_{0\theta}, x_{0\lambda}, x_{0c}$ are the positions of the highest peak, and $\lambda_u, \lambda_l, \lambda_c$ are the intervals between neighbouring peaks for the upper, lower, and centre components, respectively. In this model, the e-folding half-width represented as $\sigma_{x_0/v_z}$ is assumed to be common in all components. Figure 5(b) shows the one-dimensional $\Delta \eta$-profile observed on the Kapton foil ($z = 1076$ mm). The fitting profile given by equation (4) is shown in blue. (c) Distribution of the individual peak amplitudes ($a_n$). The fitting profile given by equation (5) is shown with the solid line.

Figure 4. (a) Phase space structure of the negative ion beamlet in the $y$-direction at pinhole position ($z = 910$ mm). Each discrete structure corresponds to each peak of the one-dimensional $\Delta \eta$-profile shown in (b). The contour is the increase of blackness degree on the Kapton foil ($\Delta \eta$) normalised by the maximum value ($\Delta \eta_{\text{max}}$). The dashed ellipse (- - -) in blue shows the envelope of the beamlet in the phase space. (b) One-dimensional $\Delta \eta$-profile observed on the Kapton foil ($z = 1076$ mm). The fitting profile given by equation (4) is shown in blue. (c) Distribution of the individual peak amplitudes ($a_n$). The fitting profile given by equation (5) is shown with the solid line.

\[ G_l = \sum_{n=-5}^{5} l_n \exp \left[ -\frac{(x - x_{0\lambda} - n\lambda_l)^2}{\sigma_{x_0/v_z}} \right] \]  

\[ G_c = \sum_{n=-5}^{5} c_n \exp \left[ -\frac{(x - x_{0c} - n\lambda_c)^2}{\sigma_{x_0/v_z}} \right] \]
$s = J_x J_{xx} \exp \left( \frac{1 - \frac{x}{x_0}}{2} \right)$

where $J_{u0}, J_{l0},$ and $J_{c0}$ are the amplitudes, $\sigma_{u0}, \sigma_{l0},$ and $\sigma_{c0}$ are the e-folding half-widths, and $x_{u0}, x_{l0},$ and $x_{c0}$ are the centre positions for each component, respectively. It can be concluded that the phase space structure in the $x$-direction is decomposed by the three-Gaussian components with the different axes.

4. Impacts of behaviour of phase space structure on beam focusing

The single beamlet focusing with LHD-NBI type accelerators is mainly affected by two lens effects. The first lens is the meniscus formed between the source plasma region and the beam region. The second lens is the electrostatic lens at the extraction and SGs, which can be controlled by the voltage ratio, $V_{\text{acc}}/V_{\text{ext}}$. In order to obtain the optimum condition for the beamlet focusing, the negative ion density scan with a fixed voltage ratio of $V_{\text{acc}}/V_{\text{ext}} = 15.3$ and the voltage ratio scan with a fixed negative ion density of $n_{\text{H1}} = 3.3 \times 10^{17} \text{ m}^{-3}$ have been...
carried out, which are shown in figure 6. The beamlet width is evaluated with the FBM and the negative ion density in the source plasma is measured with a cavity ring down (CRD) method [47, 48]. The negative ion density dependence can be considered as a perveance dependence, where the perveance is defined as \( P = I_{\text{H}^-}/V_{\text{ext}}^{1.5} \), because the negative ion density is proportional to the negative ion beam current \( (I_{\text{H}^-}) \).

Figure 6(a) shows the optimum condition for the beamlet focusing is slightly different between \( x \) and \( y \) directions; \( V_{\text{acc}}/V_{\text{ext}} \sim 15.5 \) in the \( x \)-direction and \( V_{\text{acc}}/V_{\text{ext}} \sim 14.5 \) in the \( y \)-direction. It is apparent from figure 6(b) that the beamlet is well focused in the high negative ion density region, \( n_{\text{H}^-} > 3.2 \times 10^{17} \text{m}^{-3} \).

Here, we focus on the behaviour of the phase space structure and its impacts on the beamlet focusing. In order to investigate the behaviour of the phase space structure, the voltage ratio scan of \( V_{\text{acc}}/V_{\text{ext}} = 13.6, 15.3, \) and 17.1 has been carried out with fixed extraction voltage of 3.1 kV and a fixed negative ion density of \( n_{\text{H}^-} = 3.3 - 3.5 \times 10^{17} \text{m}^{-3} \), which indicate that the perveance is kept at the optimum condition. The voltage ratio of \( V_{\text{acc}}/V_{\text{ext}} = 15.3 \) corresponds to the optimum condition for the beamlet focusing, and \( V_{\text{acc}}/V_{\text{ext}} = 13.6 \) and 17.1 are defocusing conditions. Figures 7(a)–(c) show the phase space structures in the \( x \)-direction for \( V_{\text{acc}}/V_{\text{ext}} = 13.6, 15.3, \) and 17.1, respectively. Figures 7(d)–(f) show one-dimensional \( \Delta \eta \)-profiles with \( V_{\text{acc}}/V_{\text{ext}} = 13.6, 15.3, \) and 17.1, respectively. The same analyses based on equations (6)–(12) show that the three components are identified for all cases, and the peak amplitude profiles of individual components agree with Gaussian profiles, which are shown with the solid lines in blue for the upper component, in green for the lower component, and in red for the centre component. The beamlet current density profiles calculated by

\[
J(x) = J_u(x) + J_l(x) + J_c(x)
\]

are also shown with solid lines in orange. One can see that the widths of the three-Gaussian components become the minimum with \( V_{\text{acc}}/V_{\text{ext}} = 15.3 \). It should be noted that the upper and lower components move along their axes of elongated elliptic-structures in the phase space, depending on the voltage ratio, and their directions are opposite to each other. These phenomena affect the beamlet focusing.

In order to discuss the effect of the change of each component width on the beamlet focusing, the beamlet width \( (\sigma_y) \), which is the e-folding half-width of \( J(x) \), is compared with the individual component widths \( (\sigma_u, \sigma_l, \) and \( \sigma_c \)). As shown in figure 8(a), a sharp drop of \( \sigma_y \) can be observed at \( V_{\text{acc}}/V_{\text{ext}} = 15.3 \). However, the increase of each component width in the large \( V_{\text{acc}}/V_{\text{ext}} \) region is significantly smaller than that of \( \sigma_y \). Therefore, the drop of \( \sigma_y \) cannot solely be explained by the drop of each component width.

In order to characterise the impact of the spatial shifts of the three components, we introduce a parameter corresponding to the standard deviation of the three axis positions and is defined by
The beamlet width, in other words, the degradation of the beamlet focusing. The large relative distance as having core and tail structures with the larger dependence indicates that the focal condition for the axis positions of the upper and lower components are.

The shifts of the upper and lower components seem to dominate the dependence of $\delta$ on the voltage ratio as shown in figures 7(a)–(c). We introduce another parameter, $\delta_{lu}$ which is the relative displacement normalised by the beamlet width,

$$\delta_{lu} = \frac{x_l - x_u}{\sigma_x},$$  \hspace{1cm} (15)$$

Figure 8(c) shows that $\delta_{lu}$ decreases with the voltage ratio and changes the sign around $V_{acc}/V_{ext} = 15.3$. This dependence indicates that the focal condition for the axis positions of the upper and lower components are under-focusing for $V_{acc}/V_{ext} < 15.3$, well-focused at $V_{acc}/V_{ext} = 15.3$, and over-focusing for $V_{acc}/V_{ext} > 15.3$. The large relative distance $|\delta_{lu}| \sim 1$ at $V_{acc}/V_{ext} = 17.1$ indicates significant impact on the beamlet focusing, which can be seen in figure 7(f). One can also see the larger asymmetry in total beamlet profile in figures 7(d)–(f) with the larger $\delta$. The similar asymmetry in the beamlet profile has been observed with the FBM, and recognised as having core and tail structures [49]. It should be noted that the tail structure observed with the FBM in the $x$-direction can be explained by the shifts of the three axis positions observed in this experiment.

The three-Gaussian model successfully characterise the behaviour of the phase space structure with scanning of the beamlet focal condition. All the parameters obtained in this study are summarised in table 1. Based on this
analysis, it is claimed that the control of the positions of the three-Gaussian components, minimising $\delta$, plays a crucial role for the focusing of the negative ion beamlet.

5. Discussions

The negative ion beamlet accelerated with the LHD-NBI type accelerator is identified as the combination of the three-Gaussian components in the $x$-direction. Similar structures, which are called ‘$S$-shaped’ distribution in the phase space, were reported by simulation studies [1, 50]. In the simulations, the strong edge effect at the grids, so-called ‘aberration’, generates S-shaped phase-space distribution in both $x$ and $y$ directions. In the present analysis, it was also tried to decompose the phase space structure observed in the $y$-direction (figure 4) to two components, however, two components model did not reproduce the $\Delta \eta$-profile. Therefore, it is concluded that different phase space structure is observed in the $x$ and $y$ directions, that is, the three-Gaussian components in the $x$-direction and the single-Gaussian component in the $y$-direction. In order to explain the origin of the three-Gaussian components, other effects should be taken into account. One candidate is a three-dimensional meniscus shape. Recently, a three-dimensional meniscus shape is reported with particle-in-cell simulations [21, 22]. Three-dimensional magnetic fields and the inhomogeneity of the negative ion flux may cause the three-dimensionality of the meniscus. Another possibility, which may also play a role to create the three components, is the EDM field near the EG. However, further investigation is necessary to be certain about the origin of the three-Gaussian components.

The observed three-Gaussian components ($\sim 30\%$ each) are not related to other species such as stripping neutrals and positive ions, because the total stripping loss of negative ions in our accelerator is typically 12% [51], and the positive ion rate is much smaller than that. It is also noted that the three-Gaussian components differ from the beam halo, which has a divergence more than three times as large as the e-folding half-width around the beamlet axis [26].
6. Conclusion

The phase space structure of the negative ion beamlet accelerated by the NIFS-RNIS has been measured to discuss the single beamlet optical properties. The three-Gaussian components in the $x$-direction and the single-Gaussian component in the $y$-direction are identified with the characterisation of the phase space structure. A significant impact of the three-axis dispersion parameterised by $\delta_{\text{xy}}$ on the beamlet focusing is pointed out, which gives a new aspect for designs of beam accelerators. At least the different beamlet focusing properties in the parallel and perpendicular directions to the EDM field should be taken into account, while further experimental and numerical studies to investigate the origin of the three-Gaussian components are required. It is also noted that the characterisation of the phase space structure demonstrated in this study is a powerful technique for validation of numerical and physics models of negative ion beam focusing.

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Table 1. Summary of the parameters obtained in this study. The subscripts $u$, $l$, and $c$ correspond to the upper, lower, and centre elliptic-structures in the phase space of $x$ and $v_x$. The normalised 95%-emittances $(\varepsilon_x, \varepsilon_y)$ are also included [29, 30]. The $\varepsilon_y$ is estimated to be the summed area of the three ellipses.

| Parameter | Unit | Description |
|-----------|------|-------------|
| $V_{\text{acc}}/V_{\text{ext}}$ | | Voltage ratio |
| $\sigma_y$ | [mm] | e-folding half-width of the beamlet |
| $\sigma_x$ | [mm] | e-folding half-width of each component |
| $\sigma_u$ | [mm] | |
| $\sigma_l$ | [mm] | |
| $\sigma_c$ | [mm] | |
| $\theta_y$ | [mrad] | Beamlet divergence |
| $\theta_x$ | [mrad] | |
| $\lambda_y$ | [mm] | Peak interval of $\Delta \eta_y$-profile |
| $\lambda_u$ | [mm] | Peak interval of $\Delta \eta_y$-profile |
| $\lambda_l$ | [mm] | (slope of the elongated elliptic axis) |
| $\lambda_c$ | [mm] | |
| $x$ | [mm] | Position of the beamlet axis |
| $x_u$ | [mm] | |
| $x_l$ | [mm] | |
| $x_c$ | [mm] | |
| $\alpha_u$ | | Normalised current of each component |
| $\alpha_l$ | | |
| $\alpha_c$ | | |
| $\sigma_{v_x/v_z}$ | [mrad] | Velocity dispersion |
| $\sigma_{v_y/v_z}$ | [mrad] | |
| $\varepsilon_y$ | [$\pi$ mm mrad] | Normalised 95%-emittance |
| $\varepsilon_x$ | [$\pi$ mm mrad] | |
| $\delta$ | | |
| $\delta_{xy}$ | | |

Table 2. Parameters obtained in this study. The subscripts $u$, $l$, and $c$ correspond to the upper, lower, and centre elliptic-structures in the phase space of $x$ and $v_x$. The normalised 95%-emittances $(\varepsilon_x, \varepsilon_y)$ are also included [29, 30]. The $\varepsilon_y$ is estimated to be the summed area of the three ellipses.

| Parameter | Unit | Description |
|-----------|------|-------------|
| $V_{\text{acc}}/V_{\text{ext}}$ | | Voltage ratio |
| $\sigma_y$ | [mm] | e-folding half-width of the beamlet |
| $\sigma_x$ | [mm] | e-folding half-width of each component |
| $\sigma_u$ | [mm] | |
| $\sigma_l$ | [mm] | |
| $\sigma_c$ | [mm] | |
| $\theta_y$ | [mrad] | Beamlet divergence |
| $\theta_x$ | [mrad] | |
| $\lambda_y$ | [mm] | Peak interval of $\Delta \eta_y$-profile |
| $\lambda_u$ | [mm] | Peak interval of $\Delta \eta_y$-profile |
| $\lambda_l$ | [mm] | (slope of the elongated elliptic axis) |
| $\lambda_c$ | [mm] | |
| $x$ | [mm] | Position of the beamlet axis |
| $x_u$ | [mm] | |
| $x_l$ | [mm] | |
| $x_c$ | [mm] | |
| $\alpha_u$ | | Normalised current of each component |
| $\alpha_l$ | | |
| $\alpha_c$ | | |
| $\sigma_{v_x/v_z}$ | [mrad] | Velocity dispersion |
| $\sigma_{v_y/v_z}$ | [mrad] | |
| $\varepsilon_y$ | [$\pi$ mm mrad] | Normalised 95%-emittance |
| $\varepsilon_x$ | [$\pi$ mm mrad] | |
| $\delta$ | | |
| $\delta_{xy}$ | | |

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