Spatiotemporal oscillation of an ion beam extracted from a potential-oscillating plasma source

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Keywords: ion beam, rf plasma, potential oscillation

Abstract
A radiofrequency oscillation is successfully superimposed on a plasma potential of a filamented source plasma in an ion beam source while maintaining a constant plasma density, in order to investigate the effects of oscillating source plasma potential on an extracted ion beam. The experiment is preliminarily performed with a positive argon ion beam source. A class-D amplifier operational over a wide range of a frequency from a few tens of kHz to several MHz is installed; leading the oscillation of the plasma potential in the plasma source for the frequency range being tested. The beam current profile downstream of the extraction grids shows an oscillation of the beam current at the peripheral region of the ion beam; implying that the oscillation of a beam halo is induced by the potential oscillation of the source plasma.

1. Introduction

A neutral beam injection (NBI) heating is one of the powerful and promising techniques for plasma heating in nuclear fusion researches [1–3]. In typical hydrogen/deuterium negative ion beam sources, the negative ions produced in a plasma source (called extraction region) are electrostatically extracted and accelerated by a grid system. The negative ion beam is neutralized via a gas neutralizer system, where the energetic ion beam is converted into the neutral beam via a charge exchange process and reaches the fusion plasma core surrounded by a strong magnetic field [4]. The extraction energy and current density of the negative ion beam required in International Thermonuclear Experimental Reactor (ITER) are about 1 MeV and 280 A m⁻² for deuterium [2, 5]; the conversion efficiency from the positive ion beam to the neutral beam via a charge exchange process is significantly lowered for such a high energy range due to the decrease in the reaction cross section, while the higher conversion efficiency close to 60% is still maintained for the negative ion beam case [4]. Therefore development of a hydrogen/deuterium negative ion beam source is crucial to establish the fusion reactor, where the ITER-NBI requires the divergence angle in the range of ~0.17°–0.4° (3–7 mrad) [5].

The negative ion sources are typically divided into two types of a filamented-arc source and a radiofrequency (rf) source. In the former, the plasma is produced by the filamented arc discharge; the high energy electrons destroying the negative ions are filtered by a magnetic filter located in the vicinity of the first grid (called a plasma grid) and cooled down to the temperature less than 1 eV [6–8]. The negative ions are mainly produced via a surface reaction process at the plasma grid and extracted electrostatically, where the grid system has to be designed to minimize the ion loss to the grids and the beam divergence, e.g. a beam divergence of about 4 mrad has been obtained in [9]. The plasma source is replaced by an rf plasma source operated at several hundreds of kHz to a MHz typically for the latter case for extending the lifetime of the plasma source [10, 11]. Although the plasma is mainly sustained by an inductively coupled discharge, a part of the rf power is coupled via a capacitive mode, which often enhances the rf oscillation of the plasma sheath or the plasma potential [12]. A Faraday shield...
has been installed inside the plasma source of the rf negative ion source to minimize the thermal load to the insulator source tube [2]; simultaneously it can suppress the capacitive coupling between the rf antenna and the plasma as demonstrated in the studies on the inductively coupled plasma [13]. The driving frequency is known to affect many aspect of the plasma device performance, e.g. the electron energy distribution function, the rf potential oscillation, the power coupling between the antenna and the plasma, and the plasma production, as investigated in the field of the plasma processing, e.g. in [14]. A recent experiment on the rf helicon hydrogen negative ion source has also shown the standing helicon wave characteristics in the bent magnetic field structure and the resultant electron heating process [15]. The well-collimated negative ion beams have been obtained in the negative ion source using the filamented-arc source as described above, while the collimation of negative ion beam in the rf ion source is still a challenging issue toward the ITER-NBI development since a great effort has been devoted to the investigation of the attainable current density rather than the beam optics; the divergence of the negative ion beam extracted from the rf negative ion source is recently reduced to about 1.5° [16]. For the case of the rf hydrogen negative ion beam source, the rf effect on the potential structure and particle dynamics near the beam extraction grid might be one of the additional key issues to improve the performance, since both the static and dynamic potential structures will affect the transport of the negative ions and the extracted beam optics. Furthermore, the modulation of the ion density by the rf power [17] might cause the fluctuated ion beam current. A previous study on the beam characteristics in a focused ion beam for industrial applications has implied that the energy of the focused ion beam spreads due to the potential oscillation of the plasma source attached to the acceleration grids [18]. More recently, a fluctuation of the negative ion beam current has been detected in the rf ion beam source [19].

One of the possible approaches to investigate the above-mentioned effects of the temporally varying potential is detailed diagnoses of a plasma source, a potential structure near the grids, and a beam extracted by the grids in a fundamental laboratory experiment. However, it would be difficult to control only the potential oscillation in the rf negative ion source in the laboratory, since some types of the rf coupling processes (capacitive, inductive, and wave couplings) are actually superimposed in the device and simultaneously affect both the plasma-density and plasma-potential oscillations. Hence superimposition of a controlled rf voltage to the plasma potential of the filamented ion source will be one of options to understand the physics underlying the plasma dynamics near the extraction grids and the rf effect on the beam performance, e.g. such an experiment might give optimization of the driving frequency from the view point of the beam extraction.

Here a plasma device yielding the superimposition of the rf potential oscillation on filamented plasma source is developed, where the rf voltage source utilizing a class-D switching circuit operational over a wide range of the frequency up to a few MHz is installed. Only the potential oscillation can be superimposed on the plasma source while having no density modulation. The preliminary experiment is performed with the positive argon ion beam and the spatial profile of the beam current downstream of the grids is investigated by using a retarding field energy analyzer. The results implies the current oscillation at the peripheral region of the ion beam, i.e. the oscillation of the beam halo.

2. Experimental setup

Figure 1 shows the schematic diagram of the experimental setup. The beam extraction and acceleration grids consisting of a plasma grid (PG), an extraction grid (EG), and a grounded grid (GG) are attached to a 280 mm diameter and 600 mm long diffusion chamber, which is evacuated by a turbomolecular pumping system to a base pressure less than $10^{-3}$ Pa. The grids have 9 mm diameter single center holes for the beam extraction and electrically isolated by insulator vacuum flanges. A plasma source consisting of a spiral tungsten filament and a 158 mm diameter and 145 mm long discharge chamber is further attached to the upstream side (left side of figure 1) of the grids via an insulator structure, where $z = 0$ is defined as the axial location of the upstream flange of the discharge chamber and then the axial location of the PG is $z = 150$ mm. To inhibit the plasma loss to the discharge chamber, permanent magnets forming cusp magnetic fields are set around the chamber wall. Argon gas is introduced into the discharge chamber via a mass flow controller; the pressure measured in the diffusion chamber is maintained at 0.5 Pa. A dc current of about $I_{\text{heater}} \sim 40$ A is supplied to the tungsten filament located at $z = 15$ mm to emit thermionic electrons, which are accelerated by applying a discharge voltage $V_{\text{dis}}$ between the filament and the discharge chamber via a resistor of 10 Ω limiting the discharge current and ionize the argon neutrals via an electron impact ionization process. After turning on the dc power supply for the heater current, the discharge voltage can be pulsed by using an insulated gate bipolar transistor (IGBT) inserted between the dc power supply and the resistor to minimize thermal load. The plasma density measured by a Langmuir probe located at $z = 70$ mm (not shown in figure 1) is about $10^{17}$ m$^{-3}$ in the present experiment. The whole structure of the plasma source can be biased by inserting the bipolar power supply ($V_{\text{bias}}$) between the discharge chamber and the plasma grid for the control of the plasma potential with respect to the PG, being similar to [20, 21]. The
positive ion beam can be extracted and accelerated from the plasma source by applying extraction and acceleration voltages $V_{ext}$ and $V_{acc}$ between the EG and PG and between the GG and EG, respectively, where $V_{ext} = 1.5$ kV and $V_{acc} = 8$ kV are chosen in the present experiment. It should be mentioned that the fast ions in the diffusion chamber may cause the ion-neutral ionization process there; providing the electrons and slow ions, i.e. a beam-oriented plasmas.

To superimpose an rf voltage between the PG and the plasma source, a class-D switching amplifier shown in figure 2(a) is connected to the circuit as shown in figure 1 via an inductance of about 400 $\mu$H. The amplifier includes two field-effect transistors switched alternately. The output voltage from the amplifier is transferred to the load via a transformer and a LC resonance circuit. Since the impedance of the inductance inserted into the discharge circuit in figure 1 is large, the resonance conditions is mainly determined by the values of $(L, C_1, C_2)$ in figure 2(a); the frequency giving the LC resonance can be adjusted by changing the two capacitors of $C_1$ and $C_2$. The amplifier is confirmed to be operational from a few tens of kHz to 2 MHz by changing the frequency of the gate signals, where the amplitude of the output voltage $V_{rf}$ is changed by both the frequency and the dc voltage in figure 2(a).

A cylindrical Langmuir probe (LP) is inserted at $z = 125$ mm from the sideport of the discharge chamber. The first derivative of the current–voltage characteristic of the LP give a steady-state local plasma potential $V_p$, where the probe voltage is swept for about 50 ms during the discharge pulse and the first derivative can be obtained by an analogue differentiation technique [22, 23]. The LP is also used to identify the oscillation of the plasma potential in the plasma source by measuring the floating potential via a high-impedance voltage probe. A retarding field energy analyzer (RFEA) is located at $z = 275$ mm to measure a spatial profile of the ion beam extracted by the grids, where a detailed structure of the RFEA is shown in figure 2(b) and consisting of a 6 mm diameter entrance ceramic orifice, three grids ($G_1, G_2, G_3$), and a collector electrode. By supplying a negative voltage to the second grid ($G_2$), the electrons are reflected there and only the positive charge can reach to the third grid ($G_3$) and the collector, where $G_2$ and the collector are electrically connected to minimize the effect of the secondary electron emission from the collector surface. Since the secondary electrons emitted from $G_3$ and the collector would be reflected by the negatively biased $G_2$, the effect of the secondary electrons would be small in the present configuration. Furthermore, only the high energy positive beam ions can reach the collector and $G_3$ by biasing those at the positive potential higher than the plasma potential $V_p$ as sketched in figure 2(b). The collector current signal $I_c$ is converted into a voltage signal via a resistor inserted between the collector and the dc power supply, where the voltage of the resistor is measured by a digital oscilloscope via a precise isolation amplifier operational up to 1 MHz. The signal of the applied rf voltage can be taken by connecting a high voltage ceramic capacitor ($V_{rf} \sim V_{rf}$ in figure 1), which can remove the dc high voltage. The rf amplitude $|I_c|$ of the collector current and its phase difference $\Delta \phi$ with respect to $V_{rf}$ can be obtained from the amplitude spectrum and cross spectrum analyses. The RFEA is mounted on a L-shaped shaft passing through a vacuum port at the downstream flange; approximately radial measurement can be performed with rotating the shaft by using a stepping motor.

![Figure 1. Schematic diagram of the experimental setup.](image-url)
3. Results

Figure 3 shows the steady-state local plasma potential $V_p$ measured at $z = 125$ mm as a function of the bias voltage $V_{bias}$ between the PG and the plasma source, where the extraction and acceleration voltages ($V_{ext}$ and $V_{acc}$) and the rf voltage $V_{rf}$ are set to zero. It is clearly observed that the plasma potential in the upstream plasma source is proportional to the bias voltage $V_{bias}$ for $V_{bias} > 0$, while no clear change can be observed for $V_{bias} < 0$. To force to oscillate the upstream plasma potential by the rf voltage $V_{rf}(t)$, the source should be operated with $V_{bias} + V_{rf}(t) > 0$.

Figure 2. (a) Circuit diagram of the class-D amplifier. (b) Schematic diagram of the retarding field energy analyzer together with a potential model used for the positive ion beam measurement.

Figure 3. Plasma potential measured $z = 125$ mm as a function of the dc bias voltage $V_{bias}$, where the extraction and acceleration voltage are set to $V_{ext} = V_{acc} = 0$ V.
Typical temporal evolutions of the ion saturation current \( I_s \) and the floating potential \( V_f \) of the LP measured in the upstream plasma are shown by red lines in figure 4, where the extraction and acceleration voltages are set to \( V_{\text{ext}} = V_{\text{acc}} = 0 \) V and the frequency and amplitude of the rf voltage are chosen as 30 kHz and \( \sim 12 \) V, respectively. It should be mentioned that both the rf voltage \( V_{\text{rf}} \) and the heater current \( I_{\text{heater}} \) are continuously turned on as shown by the arrow in figure 4. For comparison, the ion saturation current \( I_s \) with no rf voltage is plotted by the black line in figure 4(a). No noticeable change by applying the rf voltage is observed in \( I_s \), while the oscillation of the floating potential is observed during the discharge pulse between \( t = 0 \) and \( t \sim 105 \) ms as in figure 4(b). Since the ion saturation current is proportional to the plasma density and the square root of the electron temperature, the stable signal of \( I_s \) implies that both of them are not oscillated by the rf voltage. Hence only the plasma potential is forced to be oscillated while maintaining the constant plasma density and electron temperature.

By taking the amplitude spectrum of \( V_f \) from the data for \( t = 50–100 \) ms via a Fast Fourier Transform, the amplitude at the frequency corresponding to the applied rf voltage can be obtained. Figure 5 shows the amplitude of \( V_f \) normalized by the applied rf voltage as a function of the frequency, which are taken at \( z = 125 \) mm for \( V_{\text{ext}} = V_{\text{acc}} = 0 \). It is found that the potential oscillation induced by applying the rf voltage reduces with an increase in the frequency. However the present setup will be able to provide the investigation for the wide range of the frequency close to a few MHz with a single rf power supply.

The amplitude reduction of the potential oscillation for the high frequency range has been observed in the previous study [24] and has been briefly understood by resistive and capacitive rf sheath models for the low and high frequencies, respectively. Very briefly, the amplitude ratio of the rf sheath voltages \( |V_{\text{p}}|/|V_{\text{g}}| \) at the powered and grounded electrodes in a capacitive discharge configuration can be given as

\[
\frac{|V_{\text{p}}|}{|V_{\text{g}}|} = \left( \frac{n_{\text{p}}A_{\text{g}}}{n_{\text{p}}A_{\text{p}}} \right)^q,
\]

where the powered and grounded electrodes correspond to the discharge chamber and the PG, respectively, in the present experiment, and the numerator and denominator of the left-hand side in equation (1) correspond to the effective contact area of the plasma with the grounded and powered electrodes, respectively; being given by the sheath edge densities \( (n_{\text{p}} \text{ and } n_{\text{p}}) \) and the surface areas \( (A_{\text{g}} \text{ and } A_{\text{p}}) \). The factor \( q \) is known to increase with an increase in the rf frequency, i.e. variation from the low-frequency resistive model to the high-frequency
capacitive model \cite{12, 24}. The amplitude $|V_f|$ of the potential oscillation measured by the LP would be close to $|V_{gs}|$ in the present configuration if assuming a negligible voltage drop within the plasma. If the cusp magnetic field set around the plasma source reduces the effective area $n_{ps}A_{ps}$ and provide the numerator larger than the denominator in the LHS of equation (1), the value of $|V_{ps}|/|V_{gs}|$ increases with the increase in the factor $q$, i.e. the increase in the frequency. This is equivalent to the decrease in $V_{ps}$, i.e. the reduction of the rf amplitude of the floating potential $V_f$ in figure 5 can be qualitatively understood. The detailed calculation of the potential oscillation is out of scope of the present paper.

To investigate the ion beam extracted from the source by applying the two high voltages $V_{ext}$ and $V_{acc}$, the basic I–V characteristic of the RFEA is firstly investigated with the positive-beam extraction. It is once again mentioned that the extracted ion beam might cause the ion-atom ionization collision since the mean free path for this collisional process is about 150 mm being shorter than the diffusion chamber, where the previously measured cross section of $5 \times 10^{-20}$ m$^2$ \cite{25, 26} and the argon pressure of 0.5 Pa are used for the calculation. Since the beam-oriented slow ions will appear around the plasma potential in the diffusion chamber, it is

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{Amplitude of the potential oscillation in the plasma source as a function of the rf frequency, where the measured amplitude $|V_f|$ of the floating potential of the LP is normalized by the amplitude $|V_{rf}|$ of the applied rf voltage.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{(a) Current ($I_p + I_b$)–voltage ($V_{g1}$) characteristic of the first grid $G_1$ of the RFEA, which is used as a Langmuir probe in the diffusion chamber to identify the downstream plasma potential. (b) Current ($I_p + I_b$)–voltage ($V_{c}$) characteristic of the collector electrode of the RFEA, which is operated in the electron repelling mode. The dashed line is a linear line fitted to the measurement for $V_c \geq 40$ V.}
\end{figure}
important to know the plasma potential. The first grid $G_1$ exposed to the beam and beam-oriented plasma is used as a Langmuir probe and the current $I_{g1} – \text{voltage } V_{g1}$ characteristic of the $G_1$ grid is shown in figure 6(a). The change of the current is observed at around $V_{g1} \sim 30 – 40$ V corresponding to the downstream plasma potential. It should be mentioned that the current $I_{g1}$ is positive over the whole range of $V_{g1}$, which originates from the presence of the high energy positive ion beam, i.e. the current for $V_{g1} < 20$ V is the sum of the ion beam current $I_{ib}$ and the saturation current $I_{ip}$ of the slow ions in the beam-oriented plasma, while that for $V_{g1} > 50$ V corresponds to the sum of $I_{ib}$ and the electron saturation current $I_{ep}$ of the beam-oriented plasma.

Then the electrical circuit of the RFEA is set as that in figure 2(b) and the collector current $I_c$ — the collector voltage $V_c$ characteristic is taken as plotted by open circles in figure 6(b) where the electrons are reflected by the negative bias voltage of the repeller. The dashed line shows the linear line fitted to the data for $V_c \leq 40$ V, implying the deviation of the measured current from the linear line for $V_c \geq 40$ V. This deviation seems to be due to the presence of the slow ions around the plasma potential close to $\sim 40$ V, i.e. the net current corresponds to the ion beam current $I_{ib}$ for $V_c > 40$ V and to the sum of $I_{ib}$ and the saturation current of the slow ions for $V_c < 40$ V. Therefore, only the beam ions is detectable by biasing the collector above the plasma potential. Based on the above-described characteristic of the RFEA, the collector voltage for the beam measurement described hereafter is chosen as 100 V.

Radial measurement of the ion beam current is performed with the rf voltage for $V_{bias} = 50$ V, $V_{ext} = 1.5$ kV, $V_{acc} = 8$ kV, where the amplitude and frequency of the rf voltage are chosen as $\sim 7.5 \pm 2 V_0$ and 550 kHz, respectively. The dc and rf components of the collector current $I_c$ are obtained by taking the amplitude spectrum via a Fast Fourier Transform. Figure 7(a) shows the radial profiles of the dc ($I_{dc}$, open squares) and rf ($|I_{rf}|$, open circles) components in the units of $\mu A$ and $\mu A_{\mu0}$, together with the dc component.
for zero rf voltage (crosses). Since the amplitude of the potential oscillation in the upstream plasma source is reduced to be factor of 0.2 of the applied voltage at 550 kHz based on the result in figure 5, the expected amplitude of the potential oscillation at \( z = 125 \) mm is about \( 1.5 V_{0-\rho} \), which is smaller than the measured electron temperature (about 3–4 eV) and implies the experiment being in a small amplitude linear regime. Actually, the dc component of the beam current is unchanged as compared with the open squares and the crosses in figure 7(a). Figure 7(b) shows the radial profile of the rf component amplitude \( |I_{\text{rf}}| \) normalized by the dc component \( I_{\text{dc}} \) in the collector current \( I_c \). The results in figures 7(a) and (b) show that the dc component has a maximum at the radial center, while the amplitude of the rf component increases at the peripheral region (often called a ‘beam halo’) of the beam core, e.g. at around \( r \sim 8 \) mm. Surprisingly, the maximum amplitude ratio approaching to several tens of percent of the dc component even for the small amplitude of the potential oscillation. The phase difference \( \Delta \phi \) of the rf component with respect to the reference signal \( V_{\text{ref}} \) is obtained from the cross spectrum of \( I_c \) and \( V_{\text{ref}} \) as in figure 7(c); fairly symmetric profile can be obtained.

To imagine clearly the spatiotemporal beam current including the dc and rf components, the total collector current \( I_{\text{total}} \) is re-constructed from the amplitude and phase data in figures 7(a) and (c) as

\[
I_{\text{total}}(r) = I_{\text{dc}}(r) + |I_{\text{rf}}(r)| \sin(\omega t - \Delta \phi(r)).
\]

Assuming the axisymmetric profile, the two-dimensional images of the total current for various phases \( \omega t \) are artificially made as shown in figure 8, being corresponding to the spatiotemporal profile of the beam current during an rf cycle, where the vertical axis and contour color is in logarithm of the current. The data for \( r \geq 0 \) in figure 7 are used here. As clearly seen, the beam current oscillates at the peripheral region of the beam core, rather than at the beam core. This is probably due to the oscillating meniscus of the equipotential structure between the upstream plasma and the PG, where the curvature of the equipotential lines near the edge of the extraction grid hole is significantly affected by the potential oscillation. This temporal change of the meniscus seems to cause the oscillation of the beam halo around the beam core.

It is still unknown if the oscillation of the beam profile occurs in the rf hydrogen negative ion source, as the Faraday shield inhibiting the capacitive coupling has been installed. However, the previous experiment on the inductively coupled plasma device operated at 200 W has shown that the amplitude of the potential oscillation is still \( \sim 2 V_{\rho-p} \) even if the Faraday shield is employed [13]. It should be noted that the electron temperature near the plasma grid is lower than 1 eV. Hence the potential oscillation of only a few of V might affect the dynamic meniscus behavior; further investigation with the negative ion beam configuration is required.
4. Conclusion

The effect of the rf potential oscillation in the upstream plasma source on the extracted ion beam is investigated. The switching amplifier is used to superimpose the rf voltage; only the plasma potential in the plasma source is successfully forced to be oscillated with maintaining the constant plasma density. The beam characteristic is preliminarily investigated with the positive ion beam extraction by using the RFEA, where the presences of both the extracted ion beam and the beam-oriented plasma are confirmed. The radial measurement shows that only the beam halo component at the peripheral of the beam core is spatiotemporally oscillated by the rf potential oscillation in the upstream plasma. The similar experiment with the hydrogen negative ion beam is still an undergoing issue, which can be done with the wide range of the frequency by using the present rf amplifier in near future.

Acknowledgments

This work is partially supported by JSPS KAKENHI (Grants No. 17H03002, 18KK0080, 18K18746, 19H00663) and NIFS Collaboration Research Program (NIFS18KLER079).

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