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To cite this article: K. Nagaoka *et al* 2022 *J. Phys.: Conf. Ser.* **2244** 012043

Beam instability in the vicinity of beam extraction region of negative ion source

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Abstract. Beam instability in the presheath region of negative ion beam extraction is investigated in theoretically and experimentally. The linear stability analysis shows that the beam instability is unstable due to coupling between positive ion flow and negative ion flow. On the other hand, no clear activity can be seen in the experiment in the frequency range predicted by the theory. The beam instability in the presheath region of negative ion beam extraction may not cause the degradation of the beam focusing because of collisional damping and/or Landau damping.

1. Introduction

Negative ion beam technique is applied to plasma experiment for fusion research, particle physics experiment using huge accelerators, Boron neutron capture therapy etc. The negative ion beam focusing is a common issue for all applications. For example, the negative ion beam focusing is one of the most important issues for development of RF negative ion source for ITER [1-2]. Recently, an oscillation of negative ion beamlet with the same frequency as the RF frequency was observed by the emittance measurement with high-time resolution in the RF negative ion source for J-PARC [3]. In the filament-arc type negative ion source, the beamlet was also observed to responses to the plasma density oscillation in the vicinity of the plasma grid [4]. These experimental observations suggest the importance of the meniscus stability for the negative ion beam focusing. Moreover, it was found that the beam instability (two-stream instability) may cause density fluctuation in the presheath region [5-6].

Therefore, the beam instability was investigated theoretically and experimentally in this study. The linear stability analysis is discussed with the parameter regime of negative ion source plasma in section 2. The experimental observation of the fluctuation of the negative ion beamlet is presented in section 3, and summary is given in section 4.

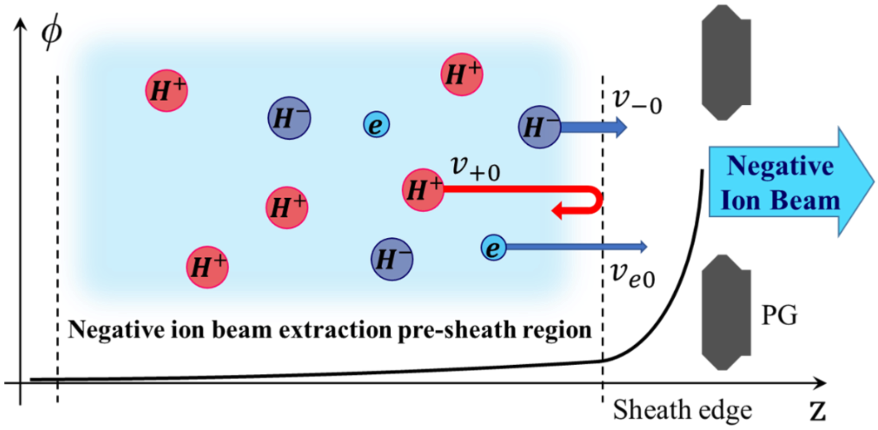

Fig. 1 Schematic of the pre-sheath region of negative ion extraction boundary.

2. Linear stability analysis of beam instability

The negative ion source plasma composed with positive ions, negative ions and electrons is considered here. When negative ion beam is extracted from the source plasma, the pre-sheath (finite electric field region) penetrates deeply from the plasma grid (PG) aperture toward the plasma (see Fig. 1). The linear stability analysis for the negative ion source plasma is described here. The set of equations are equation of motion and equation of continuity given by

$$\frac{\partial v_j}{\partial t} + v_j \frac{\partial v_j}{\partial z} = -\frac{e_j}{m_j} E, \tag{1-1}$$

$$\frac{\partial n_j}{\partial t} + \frac{\partial}{\partial z}\left(n_j v_j\right) = 0, \tag{1-2}$$

where v_j, e_j, m_j, n_j and E are velocity, charge, mass, density of the j particle species and electric field, respectively. The subscript $j = +$ for positive ion, $-$ for negative ion and e for electron. We consider streaming negative ions, streaming electrons and fixed positive ions, then linearization is given by

$$v_+ = v_{+1} \quad (2\text{-}1) \qquad n_+ = n_{+0} + n_{+1} \quad (3\text{-}1)$$

$$v_- = v_{-0} + v_{-1} \quad (2\text{-}2) \qquad n_- = n_{-0} + n_{-1} \quad (3\text{-}2)$$

$$v_e = v_{e0} + v_{e1} \quad (2\text{-}3) \qquad n_e = n_{e0} + n_{e1} \quad (3\text{-}3)$$

where the equilibrium components are indicated by a subscript “0” and the perturbation components are indicated by a subscript “1”. The charge neutrality is kept for the equilibrium density component ($n_{+0} = n_{-0} + n_{e0}$). The Poisson’s equation is given by

$$\frac{\partial E_1}{\partial z} = \frac{e}{\varepsilon_0}\left(n_{+1} - n_{-1} - n_{e1}\right). \tag{4}$$

Using Fourier transformation and plane wave approximation, the dispersion relation is given by

$$\Omega_{pi}{}^2 \left\{ \frac{1}{\omega^2} + \frac{1-\alpha}{(\omega - k v_{-0})^2} + \frac{m_+}{m_e}\frac{\alpha}{(\omega - k v_{e0})^2} \right\} = 1 \tag{5}$$

where $\Omega_{\mathrm{pi}} = \sqrt{n_{+0} e^2/\varepsilon_0 m_+ \mathrm{e}}$ is ion plasma frequency, and $\alpha = n_{e0}/n_{+0}$ is the electron density normalized by positive ion density. Three terms in the left-hand side of the eq. (5) represent positive ion contribution, negative ion contribution, and electron contribution, respectively. Low frequency mode is our interest, thus, the third term is neglected. In order to investigate the properties of the solution of the dispersion relation, we define a function as

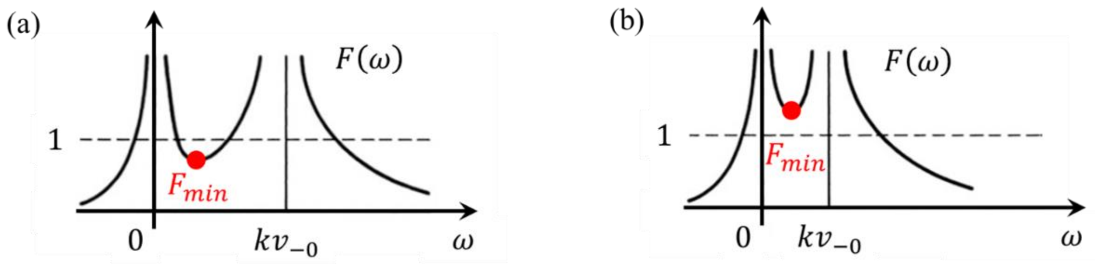

Fig. 2 The function $F(\omega)$ has four real roots is shown in (a) and two real roots and two imaginary roots is show in (b).

$$F(\omega) \equiv {\Omega_{pi}}^2 \left\{ \frac{1}{\omega^2} + \frac{1-\alpha}{(\omega - kv_{-0})^2} \right\} = 1 \tag{6}$$

When eq. (6) has complex solutions, the mode become unstable. It can be evaluated by whether extremity value is larger than unity or not, which is shown in Fig. 2. The condition that the mode is unstable is given by

$$F_{min} = F(\omega_m) = \frac{{\Omega_{pi}}^2}{(kv_{-0})^2}(1+\beta)^3 > 1 \tag{7}$$

where $\omega_m$is the root of $\partial F/\partial\omega = 0$ and $\beta = \sqrt[3]{1-\alpha}$. The negative ion velocity is written by mean of the electric potential ϕ; ($v_{-0} = \sqrt{2e\phi/m}$), then this inequality can be solved for the electrical potential as

$$0 < \phi < \frac{{\Omega_{pi}}^2 m_-}{2ek^2}(1+\beta)^3 \tag{8}$$

The stability boundary in the ϕ and k space is shown in Fig. 3 (a). The parameter regime of the negative ion source plasmas (NIFS-RNIS : National Institute for Fusion Science - Research and development Negative Ion Source) is in the unstable region. The frequency of the beam instability is given by

$$\omega_{Re} = \omega_m = \frac{k}{1+\beta}\sqrt{\frac{2e\,\phi}{m_-}} \tag{9}$$

The predicted frequency range is the order of 10^5-10^6 Hz, which is shown in Fig. 3 (b). The linear stability analysis of the beam instability shows that the mode is unstable in the presheath region of negative ion beam extraction in negative ion source (NIFS-RNIS).

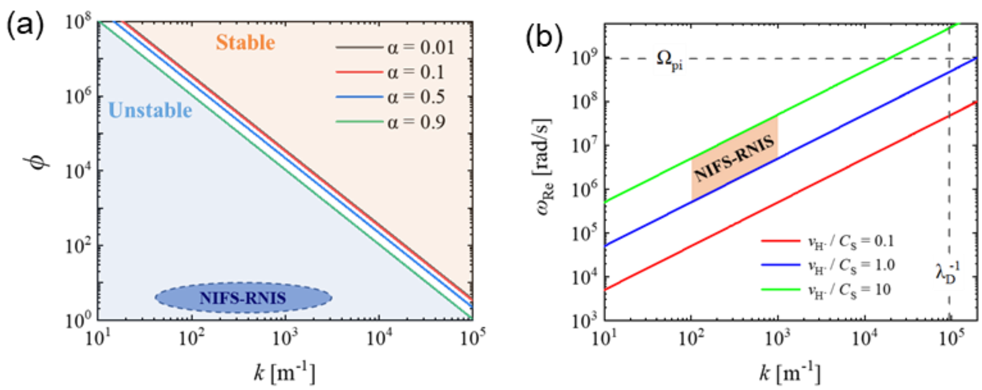

Fig. 3 (a) The stability boundary in p and k space. (b) The frequency of the beam instability. The parameter regime of NIFS-RNIS is also shown.

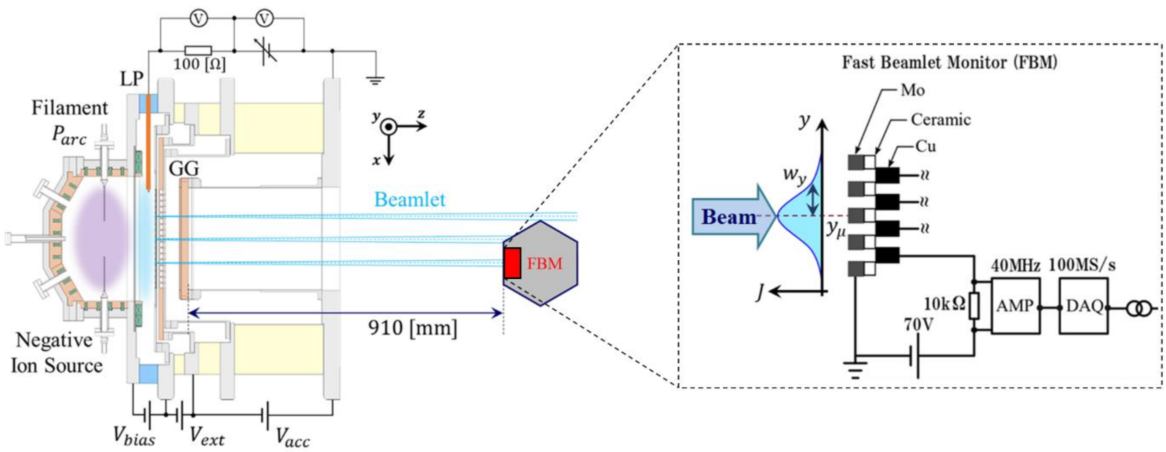

Fig. 4 Schematic of the experimental setup. Langmuir probe (LP) and fast beamlet monitor are used for fluctuation measurements in negative ion source plasma and the beamlet.

3. Experiment

The experiment to confirm the linear stability analysis for the beam instability in the presheath of negative ion beam extraction was conducted at NIFS-NBTS (Negative ion Beam Test Stand at National Institute for Fusion Science). The NIFS-RNIS, which is a filament-arc type negative ion source with one third scaled the negative ion source for the LHD (Large Helical Device), was used. The schematic of this experiment is shown in Fig. 4. The density fluctuation in the vicinity of the PG is measured by a Langmuir probe (LP) [7]. The location of the probe measurement is 12 mm from the PG, and at the almost center of the aperture, where the presheath is formed when the extraction voltage is applied to the second grid (extraction grid). The voltage applied to the LP is swept from -40 V to +40 V with repetition frequency of 20 Hz. The probe signal is digitized with 50 MS/s. The beamlet profile was measured by fast beamlet monitor (FBM), which is a 32ch Faraday cup array with the time resolution of 40 MHz [8]. The secondary electron emission current is reflected with the bias voltage to the collectors. The FBM is inserted at the 910 mm downstream from the NIFS-RNIS. The beamlet to which LP is applied is different from that where FBM measurement is carried out to avoid the disturbance to beamlet formation / beam focusing.

The parameters of this experiment are 45 – 75 kW of arc power, beam extraction voltage of 3 kV and acceleration voltage of 30 - 43 kV. The typical example of this experiment is shown in Fig. 5. The probe voltage is swept up in time and the jump down at $t = 0.045$ s and $t = 0.095$ s. The frequency

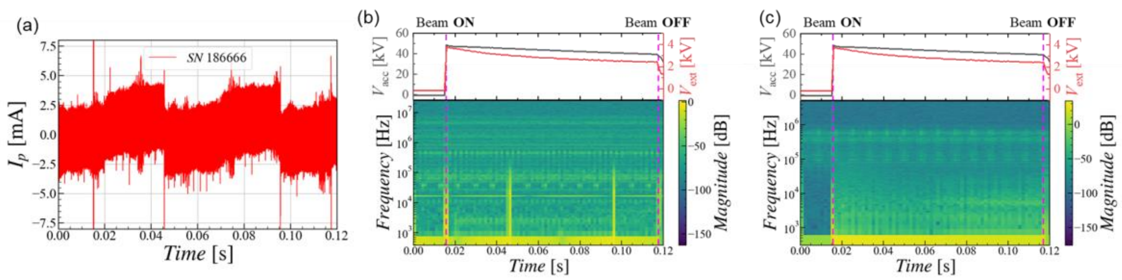

Fig. 5 (a) Time evolution of probe current. The probe voltage is swept in time and jumps at $t = 0.045$ s and $t = 0.095$ s. (b) The time evolutions of beam extraction and acceleration voltage and the frequency spectra for the probe current in the source plasma. (c) The time evolutions of beam extraction and acceleration voltage and the frequency spectra for beamlet current density measured by FBM.

spectra of probe current and negative ion beam current measured by the FBM are shown in Fig. 5 (b) and (c), respectively. One can see no clear activities, which is excited only when beam extraction turns on, in the frequency range predicted by the linear stability analysis. Therefore, it is found that the beam instability in the presheath region of negative ion beam extraction does not drive density fluctuation and does not cause the degradation of the negative ion beam focusing.

4. Concluding remarks

The negative ion beam focusing is a common issue in the development of negative ion source for a variety of application. The beam instability in the presheath of negative ion beam extraction was investigated in this study for negative ion source for fusion research. The linear stability analysis shows the beam instability become unstable due to the positive ion – negative ion coupling. The frequency of the unstable mode is 10^5-10^6 Hz. However, the activity was not observed in the experiment carried out at NIFS-NBTS. The collisional damping is a candidate to explain the experimental observation because the ion-ion collision frequency is close to the growth rate of the beam instability. Landau damping is also considered, but the precise ion velocity distribution function measurement is necessary to evaluation of the damping rate. It should be noted that the beam instability does not degrade the beam focusing of the negative ion source for LHD, and the situation could be the same for ITER because the parameter regime in the vicinity of the plasma grid of RF type negative ion source for ITER is almost identical to that for LHD.

Acknowledgments

The authors would like to thank the technical staffs of the LHD-NBI group for supporting the experiment. This research is supported by the NIFS (NIFS20KLER103) and JSPS KAKENHI (17H03002 and 18KK0080).

References

[1] B Heinemann, Ursel Fantz, W Kraus, L Schiesko, Christian Wimmer, Dirk Wünderlich, F Bonomo, et al., New Journal of Physics 2017, **19**, 015001.
[2] M Barbisan, F Bonomo, Ursel Fantz, and Dirk Wünderlich, Plasma Physics and Controlled Fusion 2017, **59**, 055017.
[3] T. Shibata, K. Shinto, M. Wada, H. Oguri, K. Ikegami, K. Ohkoshi, and K. Nanmo, AIP Conference Proceedings 2021 **2373**, 050002.
[4] Y. Haba, K. Nagaoka, K. Tsumori, M. Kisaki, K. Takahashi, H. Nakano, K. Ikeda, S. Yoshimura, and M. Osakab, Japanese Journal of Applied Physics 2020, **59**, SHHA01.
[5] B. Scheiner, S.D. Baalrud, B.T. Yee, M.M. Hopkins, and E.V. Barnat, Physics of Plasmas 2015, **22**, 123520.
[6] R. Hood, S.D. Baalrud, R.L. Merlino, and F. Skiff, Physics of Plasmas 2020, **27**, 053509.
[7] K. Tsumori and M. Wada 2021 Appl. Phys. Rev. **8**, 021314
[8] Y. Haba, K. Nagaoka, K. Tsumori, M. Kisaki, H. Nakano, K. Ikeda, Y. Fujiwara,S. Kamio, S. Yoshimura, and M. Osakab, Review of Scientific Instruments 2018, **89**, 123303.