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

K. Nagaoka [1,2], R. Nakamoto [1,3], T. Hamajima [2], K. Tsumori [1,4], H. Nakano [1,4], Y. Fujiwara [1,4], K. Ikeda [1], M. Osakabe [1,4], S. Yoshimura [1,2], T. Sasaki [3], NBI group

1) National Institute for Fusion Science, National Institutes of Natural Sciences
2) Nagoya University,
3) Graduate School of Engineering, Nagaoka University of Technology,
4) SOKENDAI (The Graduate University for Advanced Studies)

Introduction and Motivation

The necessity of negative ion beam

Why **negative ion beam**?
⇒ **Charge-exchange properties** *Excellent!*
in particular, in high energy region.

※ When using a gas neutralization cell

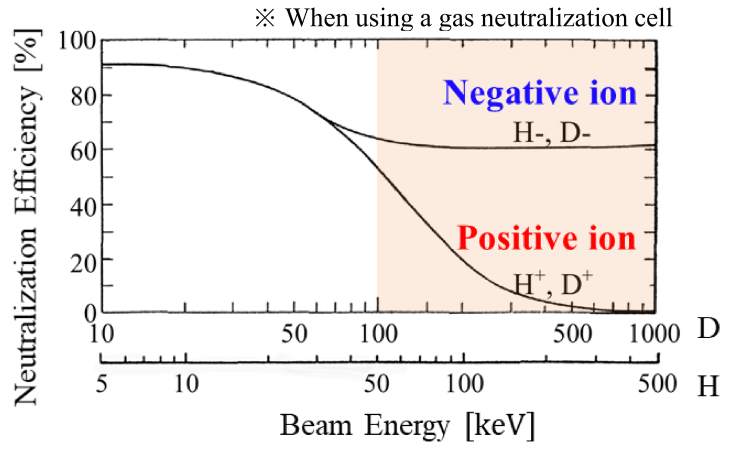
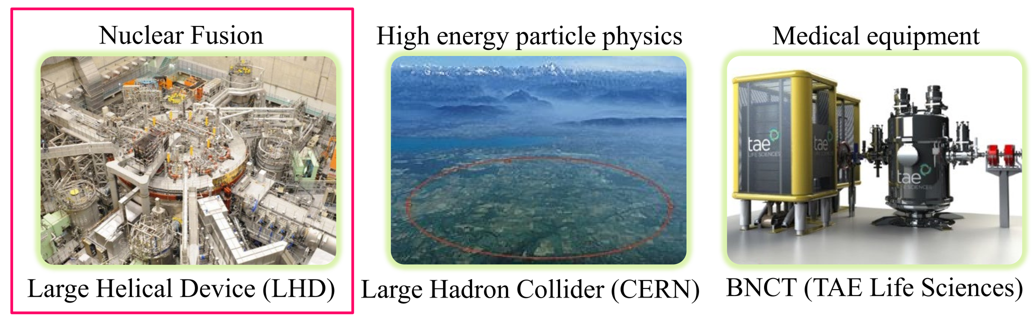


Fig. 1. Energy dependence of neutralization efficiency. [1]
The negative ion beam keeps a high neutralization efficiency of about 60 [%] in the high energy region (≥ 100 [keV]).



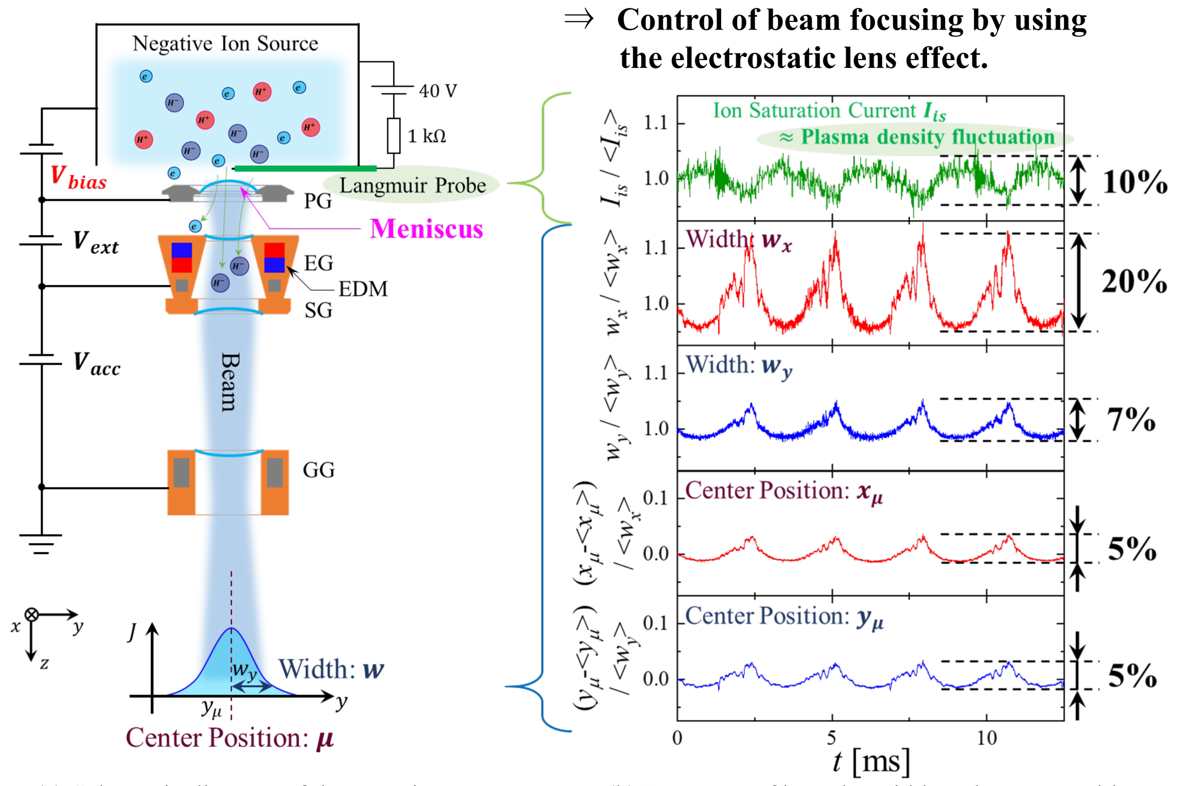
The target of this study

Negative ion beams are widely used in various fields such as academic research and medical fields, etc.

The effect of plasma density fluctuation on beam focusing

The improvement of beam focusing is a common issue in each field.
We focus on the stability of **Plasma Meniscus**.
The boundary between source plasma(quasi-neutral) and beam regions.

⇒ **Control of beam focusing by using the electrostatic lens effect.**



(a) Schematic diagram of the experiment to observe beamlet oscillation
(b) Response of beamlet width and center position to plasma density fluctuation
Fig. 2. Stability evaluation of Negative ion beamlet [2]

Plasma density fluctuation in the ion source → **Meniscus responds** → **Change of beamlet width and center position**

⇒ One of the mechanisms for degradation of beam focusing performance

Stability of the source plasma is also very important for beam focusing

Beam plasma instability in the electron pre-sheath

Ion density fluctuation due to beam plasma instability has been observed in the electron pre-sheath region of plasmas consisting of positive ions and electrons.

- PIC simulations show that the ion density fluctuations due to ion acoustic instability cause sheath edge fluctuations. [3]

⇒ **may degrade beam focusing performance**

- The similar instability has been observed experimentally. [4]

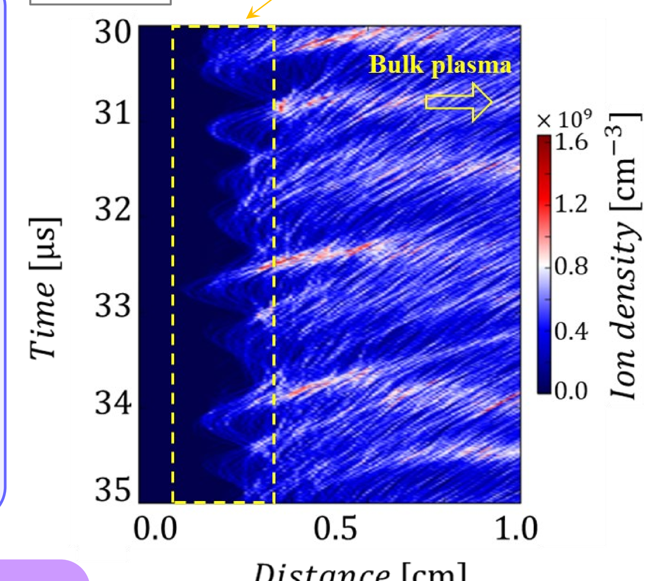


Fig. 3. Time evolution of fluctuations at the sheath [3]

Positive Ions + Electrons
No Negative Ions

Ion density fluctuations induced by instability may have a significant impact on the negative ion beam focusing of NIFS-RNIS.

In this study, in order to investigate the beam instability in the negative ion pre-sheath region, we have performed the following two studies.

1. Linear stability analysis of the beam plasma instability in the negative ion beam extraction pre-sheath region.
2. An experiment at NIFS-RNIS to observe density fluctuation due to the beam instability.

Summary

It was found that the source plasma fluctuation may degrade the negative ion beam focusing.

1. We have performed linear stability analysis of the beam instability in the negative ion beam extraction pre-sheath region.
   - ✓ **The beam plasma instability was found to be unstable due to the positive ion – negative ion coupling.**
   - ✓ The frequency of the unstable mode was estimated to be **several hundred [kHz]**.
2. We have performed an experiment at NIFS-RNIS to observe density fluctuation due to two-stream instability.
   - ✓ Simultaneous measurement of FBM and LP were performed, but the theoretically predicted mode was not observed clearly.

In future,
- ✓ Stability analysis considering a **damping mechanism**. (Landau damping, etc.)
- ✓ Effect of the magnetic field.

References

[1] K. H. Berkner, *et al*.. Intense, mixed-energy hydrogen beams for CTR injection. Nucl. Fusion **15**, 249. (1975)
[2] Y. Haba, *et al*.. Response of beam focusing to plasma fluctuation in a filament-arc-type negative ion source. Jpn. J. Appl. Phys. **59**, SHHA01. (2020)
[3] B. Scheiner, *et al*.. Theory of the electron sheath and presheath. Phys. Plasmas **22**, 123520. (2015)
[4] R. Hood, *et al*.. Laser-induced fluorescence measurements of ion fluctuation in electron and ion presheaths. Phys. Plasmas **27**, 053509. (2020)
[5] Y. Haba. Study on negative ion beam focusing. Nagoya University, 2020, Ph.D. thesis.

Linear Stability Analysis

Modeling of negative ion pre-sheath

We focus on the pre-sheath region near PG in the plasma containing hydrogen negative ions.

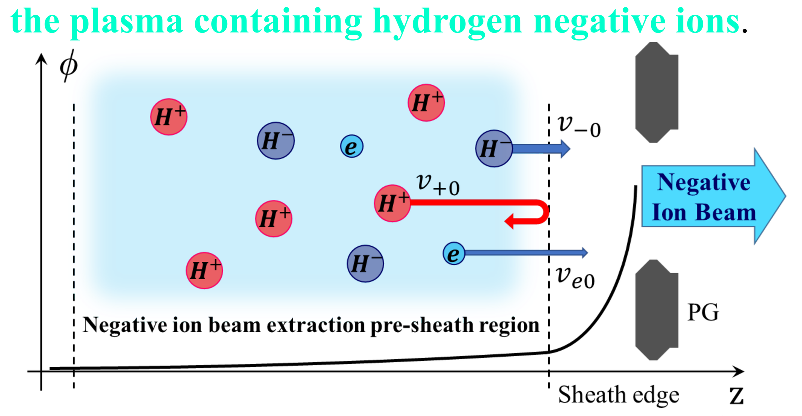


Fig. 4. Schematic of the model of negative ion pre-sheath. $(B = 0)$

Subscript 0: Steady equilibrium component, Subscript 1: Perturbation component

Velocity
$v_+ = v_{+0} + v_{+1}$
$v_- = v_{-0} + v_{-1}$
$v_e = v_{e0} + v_{e1}$

Density
$n_+ = n_{+0} + n_{+1}$
$n_- = n_{-0} + n_{-1}$
$n_e = n_{e0} + n_{e1}$

Electric field
$E = E_0 + E_1$

Quasi-neutrality condition
$n_{+0} = n_{e0} + n_{-0}$

Set of equations

$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial z} = -\frac{e}{m}E$: Equation of motion

$\frac{\partial n}{\partial t} + \frac{\partial}{\partial z}(nv) = 0$: Equation of continuity

$\frac{\partial E_1}{\partial z} = \frac{e}{\varepsilon_0}(n_{+1} - n_{-1} - n_{e1})$: Poisson's equation

Plane wave approximation
$\frac{\partial}{\partial z} \to ik, \quad \frac{\partial}{\partial t} \to -i\omega$

Dispersion relation

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

Bulk ions, Negative ions, Electrons (※)

$\Omega_{pi}^2 = \frac{n_{+0}e^2}{\varepsilon_0 m_+}$: Ion plasma frequency

$\frac{n_{e0}}{n_{+0}} = \alpha$: Density ratio of electrons to positive ions, $n_{-0} = (1-\alpha)n_{+0}$

※Since we focus on low-frequency mode ($\omega \ll \Omega_{pi}$), the third term is neglected.

To investigate the nature of the solution, consider the function $F(\omega)$ defined below.

$$F(\omega) \equiv \Omega_{pi}^2\left\{\frac{1}{\omega^2} + \frac{1-\alpha}{(\omega - kv_{-0})^2}\right\} = 1 \quad \text{(See Fig. 5.)}$$

(The point at which $\frac{dF}{d\omega} = 0$) $\quad \omega_m = \frac{kv_{-0}}{1+\beta}$

The minimum value of the function $F(\omega)$ is as follows.

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

When this condition is satisfied, the plasma is unstable.

Solving for ϕ ⇒

$$0 < \phi < \frac{\Omega_{pi}^2 m_-}{2ek^2}(1+\beta)^3 \quad \text{(See Fig. 6.)} \qquad v_{-0} = \sqrt{\frac{2e\phi}{m_-}}$$

Considering that the hydrogen negative ions is accelerated by the potential ϕ, the frequency of the excited unstable wave can be expressed as follows.

$$\omega_{Re} = \omega_m = \frac{k}{1+\beta}\sqrt{\frac{2e\phi}{m_-}} \quad \text{(See Fig. 7.)}$$

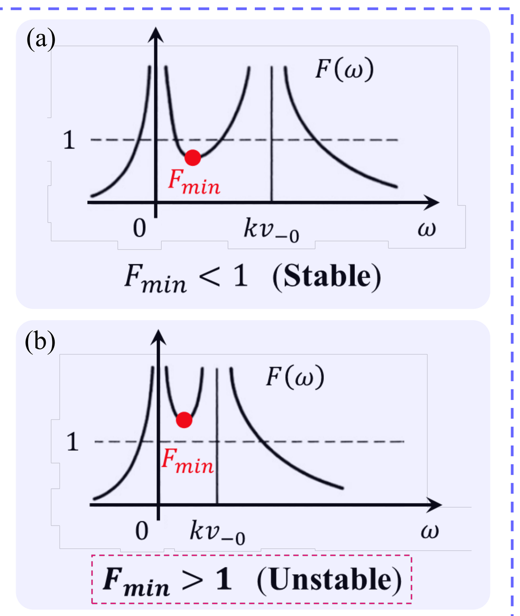


Fig. 5. The function $F(\omega)$ in the two-stream instability. (a)The plasma is stable, (b)The plasma is unstable

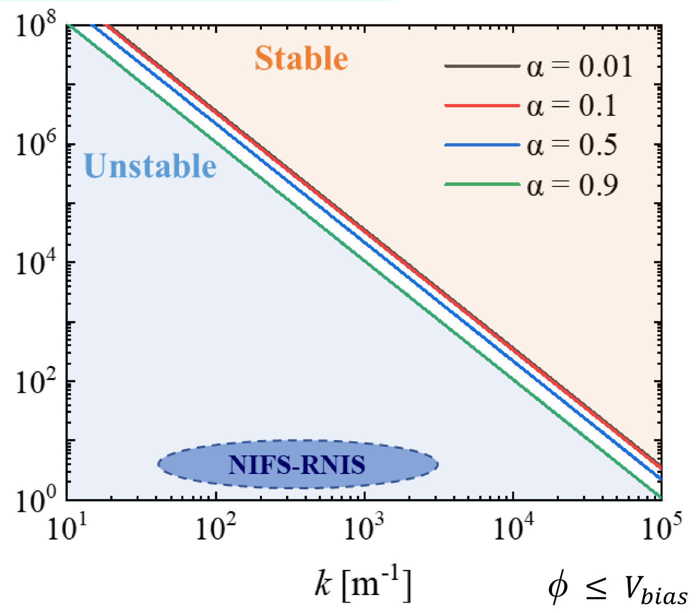


Fig. 6. $\phi - k$ phase diagram of two-stream instability caused by positive ion – negative ion coupling.

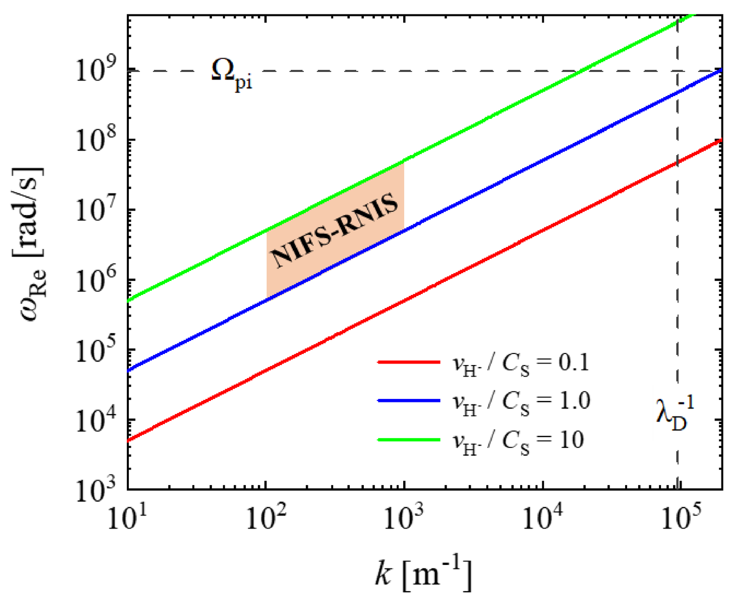


Fig. 7. Differences in dispersion relation with negative ion velocity. (Normalized in the ion-sound speed ($c_s = \sqrt{k_B T_e / m_-}$))

The beam instability was found to be unstable due to the positive ion – negative ion coupling.

⇒ **Negative ion beam focusing may be significantly affected.**

Assuming the wavenumber to be $10^2 < k < 10^3$, the frequency of the unstable mode was estimated to be several hundred [kHz].

Experiments

Setup

- Measurement of density fluctuation using LP.
- Investigation of effects on the beam using FBM.

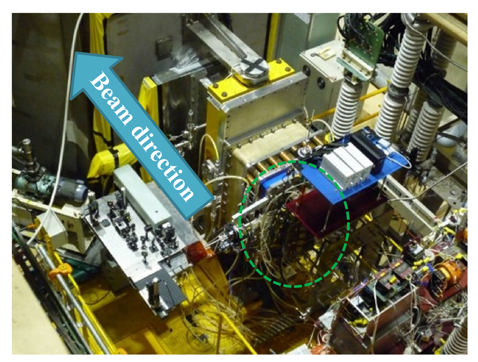


Fig. 8. Research and development Negative Ion Source in the National Institute for Fusion Science (NIFS-RNIS). The green circle indicates the negative ion source.

Typical operating parameters
P_{arc} : 45~75[kW]
V_{ext} : ≈ 3[kV]
V_{acc} : 30~43[kV]

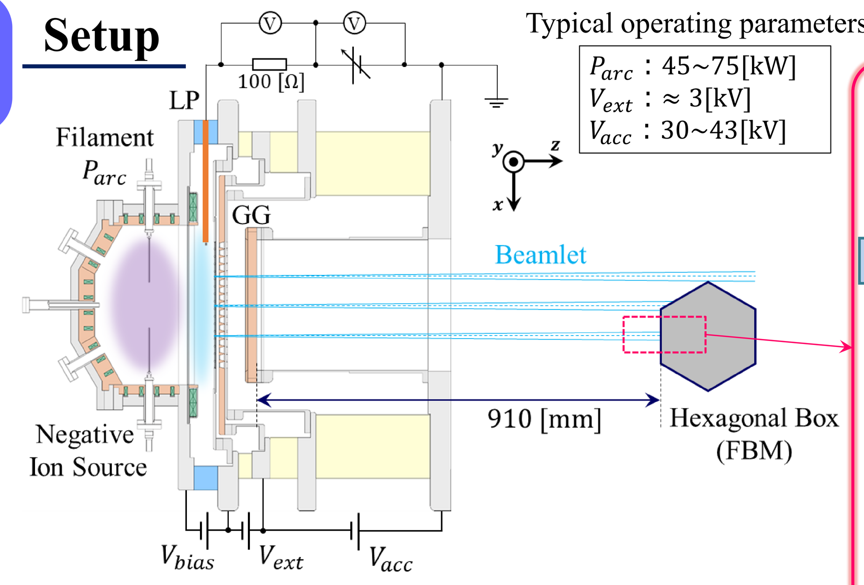
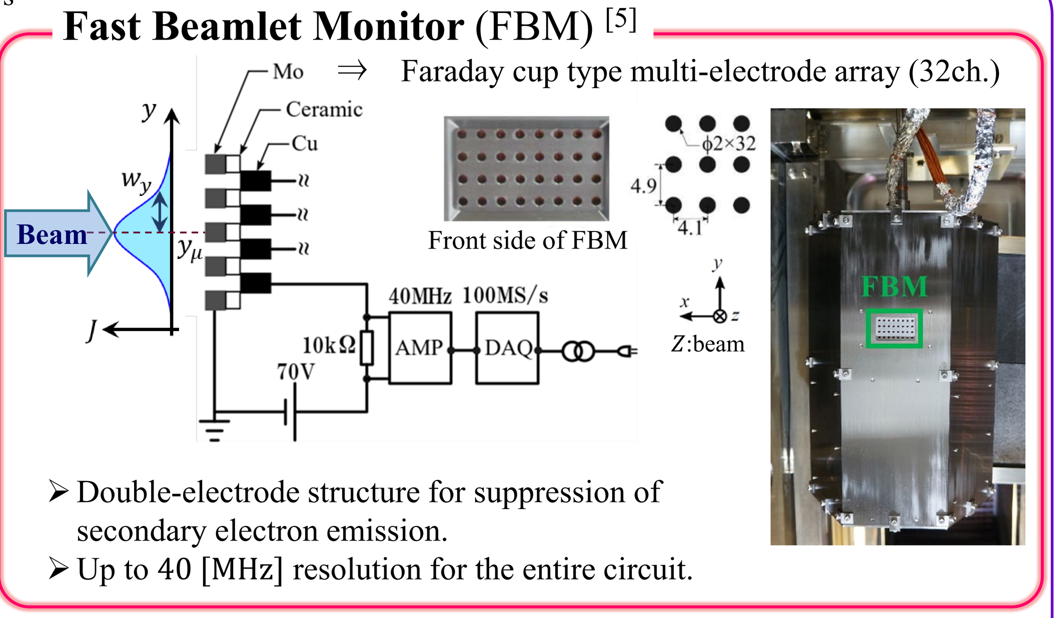


Fig. 9. Schematic diagram of NIFS-RNIS and beamlet measurement system. A plasma is generated in the filament-arc-type negative ion source, and negative ions of hydrogen are accelerated by the accelerator to generate a negative ion beam. Langmuir probe (LP) is also installed for density fluctuation measurement.

Fast Beamlet Monitor (FBM) [5]

Faraday cup type multi-electrode array (32ch.)



- Double-electrode structure for suppression of secondary electron emission.
- Up to 40 [MHz] resolution for the entire circuit.

Fig. 10. Detailed view of the beamlet measurement system. Installation of FBM at 910 [mm] from the Ground Grid.

Results

Shot No. 186666

V_{bias} = 1.0 [V]
V_{ext} = 2.6 [kV]
V_{acc} = 40 [kV]
P_{arc} = 67 [kW]
T_p = 0.1 [s]

T_p : The time of beamlet irradiation.

Source plasma fluctuation

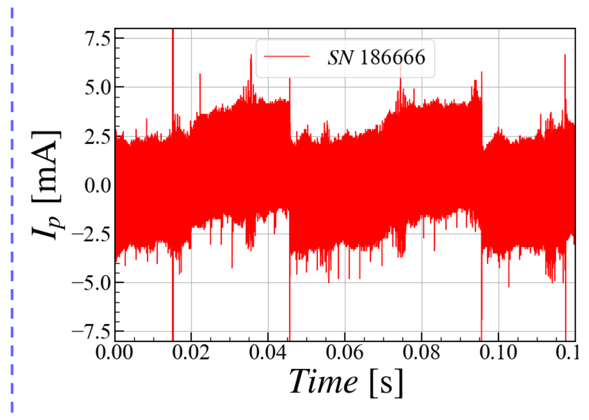
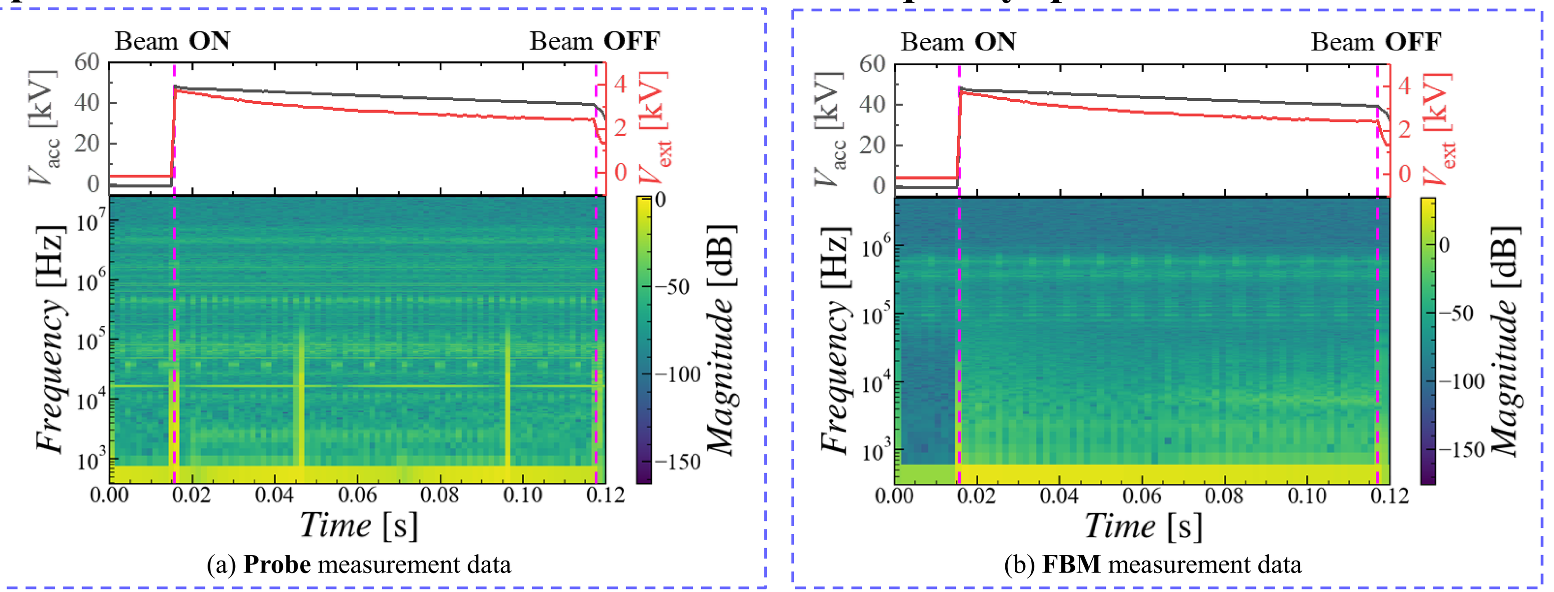


Fig. 11. Probe measurement data (50 [MS/s]) Sweep voltage (−40~40 [V], 20 [Hz])

Frequency spectrum of the beamlet



(a) Probe measurement data
(b) FBM measurement data
Fig. 12. STFT (Short-Time Fourier Transform) results.

In both the Probe and FBM data, fluctuation components of several hundred [kHz] are present **even when the beam is not turned on**.

⇒ It is most likely coming from the power supply system (**not the fluctuation induced by the instability**).

No density fluctuations due to the two-stream instability caused by the positive ion – negative ion coupling were observed.