On the Nonlinear Coupling of the High Wavenumber Fluctuations Exhibiting the Discrete Spectra Observed in PANTA

Yuichi KAWACHI[1)]*, Makoto SASAKI[2,3)], Takashi NISHIZAWA[3,4)], Yusuke KOSUGA[3,4)],
Kenichiro TERASAKA[5)], Shigeru INAGAKI[6)], Takuma YAMADA[7)], Naohiro KASUYA[3,4)],
Chanho MOON[3,4)], Yoshihiko NAGASHIMA[3,4)], Akihide FUJISAWA[3,4)]

[1)] *Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan*
[2)] *College of Industrial Technology, Nihon University, Narashino 275-8575, Japan*
[3)] *Research Center for Plasma Turbulence, Kyushu University, Fukuoka 816-8580, Japan*
[4)] *Research Institute for Applied Mechanics, Kyushu University, Fukuoka 816-8580, Japan*
[5)] *Department of Computer and Information Sciences, Sojo University, Kumamoto 860-0082, Japan*
[6)] *Institute of Advanced Energy, Kyoto University, Uji 611-0011, Japan*
[7)] *Faculty of Arts and Science, Kyushu University, Motooka, Fukuoka 819-0395, Japan*

(Received 23 August 2024 / Accepted 11 September 2024)

We report on the nonlinear coupling properties of high-wavenumber fluctuation, which exhibits discrete frequency spectra with a frequency span comparable to the ion cyclotron frequency observed in PANTA. Bicoherence analysis is used to investigate this nonlinear coupling. The results indicate a finite coupling between individual discrete peaks but no coupling between the ion cyclotron frequency components of these discrete peaks. This suggests that the observed turbulence with a discrete spectrum is destabilized linearly rather than through nonlinear coupling.

Keywords: high wavenumber turbulence, ion cyclotron ranges of frequency fluctuations, nonlinear interaction

DOI: 10.1585/pfr.1201031

Various time- and space-scale fluctuations are excited in magnetized plasmas, affecting confinement performance and heating efficiency. Recently, the importance of studying high-wavenumber and high-frequency turbulence, including electron temperature gradient mode, causing anomalous electron transport [1] and anomalous heating [2] has been emphasized, and experimental studies are required. Ion cyclotron range of frequency fluctuations, which can have high wavenumber, can be excited through wave-particle resonance by fusion-born alpha particles and neutral beam heating or mode conversion by ion cyclotron frequency heating. They have also gained recognition for their importance due to their impact on bulk ion/electron heating efficiency in nuclear fusion reactors [3] and Helicon thrusters [4]. Here, we report nonlinear characteristics of ion cyclotron range of frequency fluctuations with higher wavenumber than ion scale turbulence observed in a linear plasma device PANTA [5–7].

The PANTA is a linear plasma device with a vacuum vessel 450 mm in diameter and 4,050 mm long [8]. High-density Ar plasma with a pressure gradient is produced by 7 MHz, and 3 kW of RF discharge is produced. A steady-state magnetic field in a range of 0.01 T to 0.15 T is generated by 17 pairs of Helmholtz coils. In the high wavenumber turbulence experiment, the magnetic field has been set to 0.0225 T, and the effective ion Larmor radius becomes comparable to the plasma radius. As a result, ion scale turbulence is suppressed. Alternatively, smaller-scale turbulence which has scaled from sub-ion scale to electron scale, is excited [5]. Plasma turbulence is diagnosed by high spatial resolution 64-ch azimuthal probe array [9], which allows us to measure spatiotemporal evolution and the two-dimensional spectrum of the turbulence.

Figure 1(a) shows the typical time evolution of the turbulence observed in the experiments. Repetition of excitation/annihilation of discrete multiple peaks around ion cyclotron range frequency is evident. The discrete peaks have unique characteristics in that the frequency span of each peak is comparable to ion cyclotron frequency (f_{ci}) [7]. The discrete peaks have frequency ranges from fourth to thirteenth harmonics of f_{ci}, as shown in Fig. 1(b). The peak corresponding to the eighth harmonic of f_{ci} has the largest amplitude.

A two-dimensional spectrum is shown in Fig. 1(c). In this figure, the frequency is normalized by the f_{ci} as $f/f_{\mathrm{ci}} = \omega/\Omega_{\mathrm{ci}}$ (Ω_{ci} is angular ion cyclotron frequency), and the azimuthal wavenumber (k_y) is normalized by the ion Larmor radius ρ_i as $k_y\rho_i$. It can be seen that the discrete spectra have comparable spatial scale to ion Larmor radius as around $2 < k_y\rho_i < 8$. The fluctuations of discrete spectral components rotate in an electron diamagnetic direction with phase velocity around ion acoustic velocity and electron

---

*Corresponding author's e-mail: y-kawachi@energy.nagoya-u.ac.jp

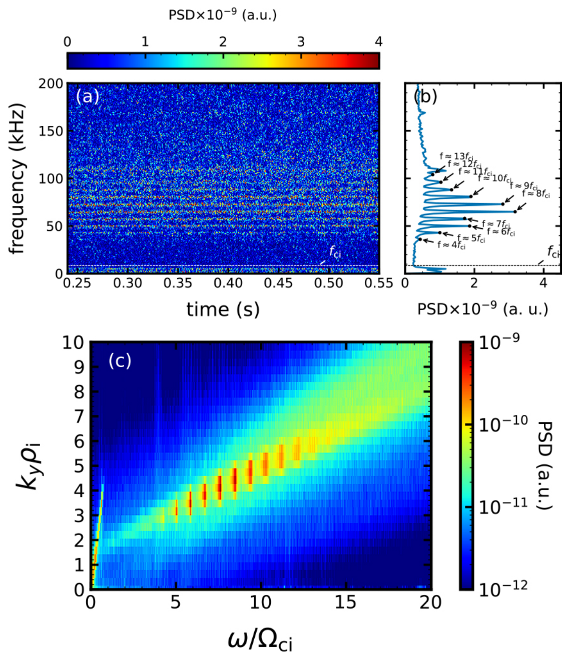

Fig. 1. (a) Typical time evolution of a spectrogram of ion saturation current and (b) time-integrated frequency spectra of the spectrogram. (c) Two dimensional spectrum in normalized frequency ω/Ω_{ci} and normalized wavenumber k_y/ρ_i space.

diamagnetic drift velocity. These characteristics, including discrete frequency spectra with frequency span of f_{ci} and spatial scale comparable to ρ_i, are similar to the ion Bernstein wave characteristics [10].

The discrete spectrum can be formed by nonlinear wave-wave coupling or linear dispersion relation incorporating kinetic effects. To clarify how the discrete spectra form, we evaluate nonlinear coupling strength by bicoherence analysis in frequency domain [11]. Figure 2 shows a contour map of squared bicoherence. Small but finite bicoherence <0.01 can be seen around $f_1 \sim 60$–100 kHz corresponding to couplings between the discrete peaks or self-coupling. For instance, there is coupling between $f_1 = 66$ kHz $\approx 8f_{ci}$ and $f_2 = 51$ kHz $\approx 6f_{ci}$, which leads to the excitation of a fluctuation at the frequency of $f_3 = f_1 + f_2 \approx 14f_{ci}$. We note that only nonlinear couplings producing peaks above $13f_{ci}$ are observed. Indeed, several nonlinear coupling could be important in the system. However, the coupling that can excite the discrete spectra was not observed, which should have a frequency satisfying $f_3 = f_2 + f_1 = nf_{ci}$, where n is an integer in the range $n =$ 413. In particular, if nonlinear coupling were crucial for the excitation of discrete peaks within the f_{ci} interval, it would be expected to observe coupling to fundamental f_{ci} fluctuation. However, no such coupling was observed.

These results suggest the discrete spectra components fluctuate by linear destabilization rather than nonlinear coupling to the fluctuation of fundamental f_{ci}. The observed discrete spectra have characteristics similar to the Bernstein ion wave. Typical free energy sources of the ion Bernstein wave have been considered as gradients in velocity space [10]. However, since only RF heating is used in this experimental setup, it is unlikely that sources of velocity spatial gradients like ion beams will appear. As another candidate, the velocity shear can be considered as discussed in the context of electrostatic ion cyclotron wave [12]. The pressure gradient similarly has a high likelihood of destabilizing ion Bernstein waves. Indeed, in the present experiment, a strong density gradient is formed, and the discrete spectrum exists in regions with large density gradients. In future studies, we will conduct simulations and linear instability analyses incorporating kinetic effects to identify whether the observed fluctuations are Ion Bernstein waves and compare the results with experimental data.

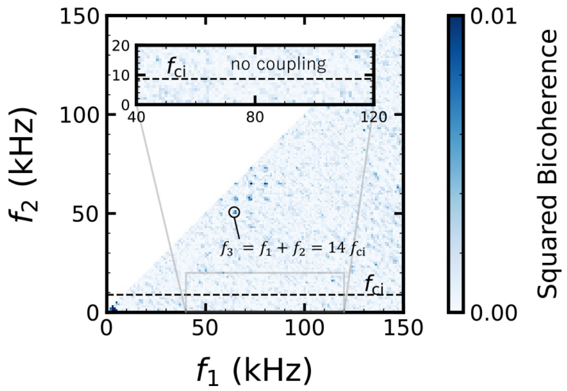

Fig. 2. Squared bicoherence spectrum of ion saturation current measured by one tip of the azimuthal probe array.

In summary, we observed high wavenumber fluctuations with a spatial scale comparable to ion Larmor radius and discrete frequency spectra with frequency spans of ion cyclotron frequency in PANTA. We evaluated the nonlinear coupling of the discrete spectra in the frequency domain. We found the finite nonlinear coupling between each peak and self-coupling, but there is no evidence that the nonlinear coupling destabilizes the discrete spectra. The results suggest the discrete spectra are linearly destabilized, incorporating kinetic effects.

This work was supported in part by JSPS KAKENHI under Grant Nos. JP24K06996, JP23K13082, JP21H01066, 21K03509, JP20J12625, and the Collaborative Research Program of Research Institute for Applied Mechanics Kyushu University.

[1] W. Dorland *et al.*, Phys. Rev. Lett. **85**, 5579 (2000).
[2] V.V. Mikhailenko *et al.*, Phys. Rev. Lett. **31**, 032307 (2024).
[3] R.O. Dendy *et al.*, Phys. Rev. Lett. **130**, 105102 (2023).
[4] D.S. Thompson *et al.*, Phys. Plasmas **24**, 063517 (2017).
[5] Y. Kawachi *et al.*, Sci. Rep. **12**, 19799 (2024).
[6] Y. Kawachi *et al.*, Plasma Phys. Control. Fusion **65**, 115001 (2023).
[7] Y. Kawachi *et al.*, Phys. Plasmas **31**, 044502 (2024).
[8] S. Inagaki *et al.*, Sci. Rep. **6**, 22189 (2016).
[9] T. Yamada *et al.*, Nat. Phys. **4**, 721 (2008).
[10] Ira B. Bernstein, Phys. Rev. **109**, 10 (1958).
[11] Y. Kawachi *et al.*, Phys. Plasmas **28**, 112302 (2021).
[12] W.E. Amatucci *et al.*, Phys. Rev. Lett. **77**, 1978 (1996).