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Phase-space tomography for charge exchange recombination spectroscopy

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It is theoretically predicted that wave-particle nonlinear interaction plays a decisive role for determining plasma heating and transport properties in magnetically confined low collisional plasmas. In particular, particles are trapped in a phase of a wave by which the wave potential nonlinearly evolves and structures form in the phase-space, i.e., the space spanned by real-space and velocity-space coordinates. The phase-space structure can couple with the real space plasma profile, by which a free energy is released and the phase-space structure grows [1,2]. Stochastic overlapping and cascade of the phase-space structures are also possible, resulting in emergence of the so-called phase-space turbulence. Experimental detection of the phase-space structures, i.e., persistent non-Maxwellian velocity-space distribution having a real-space structure, is yet extremely challenging and validation of the theoretical concept has not been comprehensively performed.

One of the issues that makes phase-space structure measurement challenging is the trade-off relationship among time, real-space, and velocity-space resolutions and signal intensity. As the total signal intensity that is determined by the diagnostic system and plasma condition is constant, improving resolution results in a decrease of signal intensity at a single detector pixel [3]. By performing a space-integration (by compromising the spatial resolution), ultrafast measurement of the plasma ion velocity distribution function was successfully performed [4].

Recently, a new signal processing algorithm is proposed to overcome the trade-off relationship among resolutions and signal intensity, that is, the phase-space tomography [5]. In this algorithm, a set of three integrated signals with the same viewing sight is used to recover the three-dimensional resolution in the phase-space. Integrations are performed in each of dimensions, i.e., time, real-space, and velocity-space. As the tomography technique, the maximum likelihood expectation maximization (MLEM) method is used.

This concept is applied to a velocity distribution function measurement by the charge exchange recombination spectroscopy in the Large Helical Device (LHD) observation. The target physics is the energetic-particle driven magnetohydrodynamic (MHD) burst events. After the MHD burst, the Landau damping is observed, which induces the non-Maxwellian distortion of the velocity distribution function. Two different types of the phase-space structures are observed: those with single and dual resonances. The former is characterized by the distribution function tail appearance in a one-side of the toroidal direction, while the latter has positive and negative wave resonances causing tails in both sides. The phase-space tomography is applied for those events, which are shown in Fig. 1. In toroidal magnetic probe array data, waves that are likely causing the observed wave-particle interactions are observed. The appearance of the single and dual resonant events is bifurcative, as shown by the probability density function analysis. Different branches of energetic particle driven instability are predicted potentially to be driven by higher order magnetic configurations in the Heliotron configuration [7]. Three-dimensional magnetic field is suggested as a potential control knob for the wave-particle interaction.

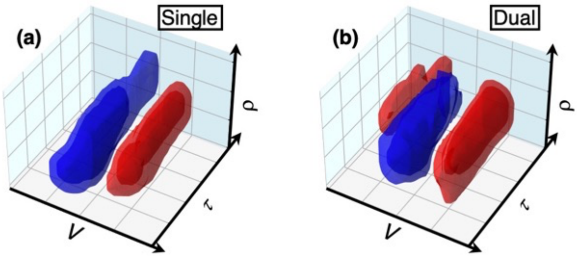

Fig. 1. Results of phase-space tomography. Blue and red colors correspond to $\tilde{f} < 0$ and $\tilde{f} > 0$, respectively. In the single resonance (a), $\tilde{f}$ decreases at V~0 and increases at V>0 region across a resonant velocity. In the dual resonance (b), positive $\tilde{f}$ emerges both in V>0 and V<0 regions, indicating two counter propagating resonant waves.

References

[1] P. W. Terry, P. H. Diamond, and T. S. Hahm, Phys. Fluids B **2**, 2048–2063 (1990)
[2] Y. Kosuga, S.-I. Itoh, P. H. Diamond, K. Itoh, and M. Lesur, Nucl. Fusion **57**, 072006 (2017)
[3] T. Kobayashi, Plasma Fusion Res. **18**, 2402059 (2023)
[4] K. Ida, T. Kobayashi, M. Yoshinuma, et al., Commun. Phys. **5**, 228 (2022)
[5] T. Kobayashi, M. Yoshinuma, W. Hu and K. Ida, Phys. Plasmas **30**, 052303 (2023)
[6] T. Kobayashi, M. Yoshinuma, W. Hu, and K. Ida, submitted (2024)
[7] X. D. Du et al., Phys. Rev. Lett. **114**, 155003 (2015)