Observation of Quasi-Periodic Two-Dimensional Velocity Fields in Plasma Using Tomographic Laser-Induced Fluorescence Spectroscopy

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Recently, a new method that applies vector tomography to laser-induced fluorescence has been introduced, enabling the measurement of quasi-periodic two-dimensional velocity field in plasma [H. Arakawa *et al.*, Plasma Fusion Res. **18**, 1401032 (2023)]. In this study, we experimentally demonstrated this method in a linear magnetized plasma and presented the initial measurement results. The observed two-dimensional velocity field allowed the evaluation of Reynolds force and its energy transfer.

Keywords: magnetized plasma, laser-induced fluorescence, vector tomography, velocity field, Reynolds force

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In the field of plasma turbulence, the observation of plasma fluctuations and flow structure is crucial for understanding plasma transport [1]. Laser-induced fluorescence (LIF) spectroscopy provides a means to observe absolute ion velocity [2, 3]. However, measuring two-dimensional (2D) ion velocity field in low-density plasm is challenging owing to the poor signal-to-noise ratio (S/N). Therefore, a velocity field measurement method using vector tomography based on line-integrated data with better S/N has been proposed and evaluated using simulation [4, 5]. Despite these efforts, 2D velocity field observation has not been realized because flow field reconstructions require a large number of measurement points. Recently, a method was proposed for observing the 2D velocity field in coherent plasmas that exhibit a quasi-periodic behavior, where the flow propagates azimuthally while maintaining its structure [6]. This method combines LIF, vector tomography, and Langmuir probe measurements. In this study, we experimentally demonstrated for the first time the reconstruction of a two-dimensional velocity field using this method, and evaluated the fluctuation-induced Reynolds force and its energy transfer.

Plasma excitation experiments were performed in the linearly magnetized plasma PANTA at Kyushu University [7]. Cylindrical argon plasma, with a diameter of ∼ 10 cm and a length of 4.05 m, was excited under 0.1 Pa argon gas pressure, 0.09 T axial magnetic field strength, and 3 kW radio frequency power. Quasi-periodic density fluctuations were observed at 2.5 kHz, with typical plasma parameters of 1×10^{18} m^{-3} central plasma density and 3 eV central electron temperature [8]. The azimuthal mode number of the density fluctuations at $r = 4$ cm was $m = 2\pi r k_\theta = 1$, where k_θ denotes the wave number.

The measurement system and analytical method involved the following steps [6]. (i) The ion saturation current was observed using a Langmuir probe placed at $r = 4$ cm. The rotational phase of the fluctuations in the azimuthal direction, θ, was determined using the Hilbert transform. (ii) The LIF excitation system has a laser oscillator and intensity modulator (see [9] for details). The laser frequency ν was varied at 0.5 GHz intervals in the range of 448.379 GHz ± 5 GHz to excite the Ar II levels. The laser was injected from a direction perpendicular to the magnetic field [6]. The injection positions were spaced at 1 cm intervals from the plasma radius r ranging from 1 to 5 cm. (iii) At each injection radius position r and laser frequency shift ν', the fluorescence intensity along the path of the

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laser injection on the plasma, $L(r, \theta)$, was measured using a photo-multiplier tube. (iv) The fluorescence intensities, $I(v'; r, \theta)$, were obtained by conditional averaging of each variable measured simultaneously. From the fluorescence intensities, the zero- and first-order spectral moments, $\mu^{(0)}$ and $\mu^{(1)}$, were calculated using the following equation [4].

$$\mu^{(0)}(r,\theta) = \int_{-\infty}^{\infty} I(v'; r,\theta) dv' = \int_{L(r,\theta)} \epsilon_0(\boldsymbol{x}') dl,$$

$$\mu^{(1)}(r,\theta) = \int_{-\infty}^{\infty} I(v'; r,\theta) v' dv' = \int_{L(r,\theta)} \epsilon_0(\boldsymbol{x}') \boldsymbol{v}(\boldsymbol{x}') \cdot d\hat{l},$$

where $\epsilon_0(\boldsymbol{x}')$ is the spectral integration of local fluorescence intensity at $\boldsymbol{x}'$ on the plasma frame, $\boldsymbol{v}(\boldsymbol{x}')$ is the velocity field, and $\hat{l}$ is the unit vector of L. Here, the plasma density distribution was assumed to be proportional to ϵ_0. The reconstruction was based on the principles of the filtered back projection method [6, 10]. During the reconstruction, $\mu^{(0)}$ and $\mu^{(1)}$ were set to zero at $r = 6$ cm as the boundary condition.

Figures 1 (a) and (b) show the evaluated $\mu^{(0)}$ and $\mu^{(1)}$, respectively. For velocity field reconstruction, the 2D structure of the density was first reconstructed from the zero-order spectral moments. Figure 1 (c) shows the reconstructed image of the density structure, and Fig. 1 (e) shows the azimuthal average. The 2D flow vector was reconstructed from the first-order spectral moments, as shown in Fig. 1 (d). The direction of the flow is indicated by arrow. Figure 1 (f) shows the azimuthal average of v_θ and v_r, where the ion-diamagnetic direction is positive. The local v_θ distribution (for $r < 3$ cm) was also separately measured by local LIF, and the results agree with those reconstructed within the measured region.

The Reynolds force and energy transfer from the fluctuations to the azimuthal flow were evaluated. Figure 2 (a) presents the fluctuation components of velocity (arrows) and density (filled contour). It is evident that the velocity fluctuations rotate in opposition to each other in response to the density fluctuations. Figures 2 (b) and 2 (c) demonstrate the Reynolds stress, denoted by $\langle \pi_{r\theta} \rangle = \langle \tilde{v}_r \tilde{v}_\theta \rangle$, and Reynolds force, defined as $-\partial_r \langle r\pi_{r\theta} \rangle / r \equiv F_{\mathrm{R}}$, at each radial position, respectively. Here, $\langle \rangle$ represents the azimuthal average. The Reynolds stress attained its maximum in regions with high flow shear around $r = 4$ cm, as shown in Figs. 1 (d) and (f). The Reynolds force also aligns with the flow structure for $r > 3$ cm (Fig. 1 (f)), implying that these fluctuations primarily drive the flow. Figure 2 (d) depicts the energy transfer (normalized by mass) to the azimuthal flow, $\partial_t E_n = F_{\mathrm{R}} \langle v_\theta \rangle$. The energy transfer is positive around $r = 3.5$ and 4.5 cm, indicating a dynamic transfer of fluctuation energy to the azimuthal flow. However, the energy transfer is minimal where $r < 3$ cm, suggesting that the origin of the flow pattern may be distinct from these fluctuations. Assessing the error of the flow vectors generated by this method will be addressed in future studies.

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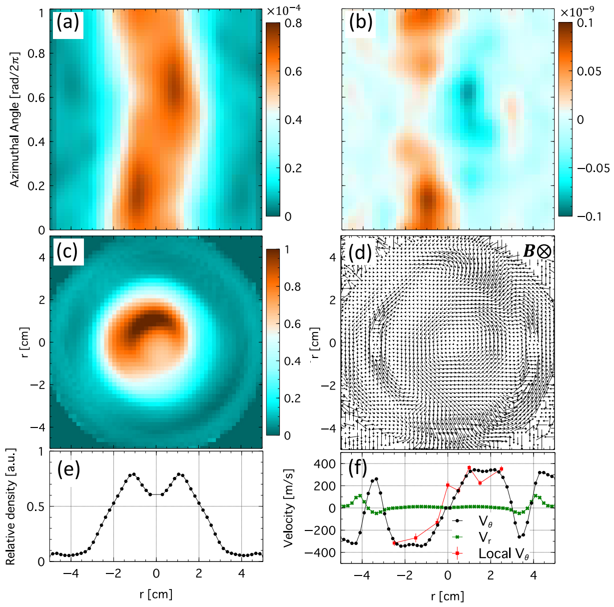

Fig. 1 Sinogram of (a) the 0^{th} spectral moment ($\mu^{(0)}$) and (b) the 1^{st} order moment ($\mu^{(1)}$). (c) Reconstructed relative density. (d) Reconstructed velocity field. (e) Azimuthal average of the density. (f) Azimuthal average of the velocity (v_θ and v_r) and local azimuthal velocity (Local v_θ).

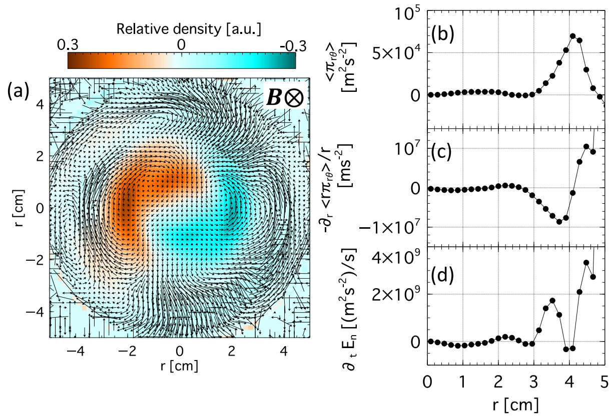

Fig. 2 (a) Reconstructed velocity field fluctuation (arrows) and density fluctuation (filled contour), (b) Reynolds stress, (c) Reynolds force, and (d) energy transfer.

[1] A. Fujisawa, A review of zonal flow experiments, Nucl. Fusion **49**, 013001 (2009).

[2] R.A. Stern and J.A. Johnson, Plasma ion diagnostics using resonant fluorescence, Phys. Rev. Lett. **34**(25), 1548 (1975).

[3] F. Anderegg, R.A. Stern, F. Skiff, B.A. Hammel, M.Q. Tran, P.J. Paris and P. Kohler, Ion heating due to rotation and collision in magnetized plasma, Phys. Rev. Lett. **57**(3),

329 (1986).

[4] J. Howard, Vector tomography applications in plasma diagnostics, Plasma Phys. Control. Fusion **38**(4), 489 (1996).

[5] A.L. Balandin, Y. Murata and Y. Ono, Radial velocity profile reconstruction by doppler spectroscopy measurements, Eur. Phys. J. D: Atomic, Molecular, Optical Plasma Phys. **27**(2), 125 (2003).

[6] H. Arakawa, M. Sasaki, S. Inagaki and A. Fujisawa, Reynolds force evaluation of quasi-coherent structure by tomographic laser-induced fluorescence spectroscopy, Plasma Fusion Res. **18**, 1401032 (2023).

[7] S. Inagaki, T. Kobayashi, Y. Kosuga, S.-I. Itoh, T. Mitsuzono, Y. Nagashima, H. Arakawa, T. Yamada, Y. Miwa, N. Kasuya *et al*., A concept of cross-ferroic plasma turbulence, Sci. Rep. **6**, 22189 (2016).

[8] Y. Nagashima, A. Fujisawa, K. Yamasaki, S. Inagaki, C. Moon, F. Kin, Y. Kawachi, H. Arakawa, T. Yamada, T. Kobayashi *et al*., A proposal to evaluate electron temperature and electron density fluctuations using dual wavelength emission intensity tomography in a linear plasma, J. Phys. Soc. Jpn. **92**(3), 033501 (2023).

[9] H. Arakawa, S. Inagaki, Y. Kosuga, M. Sasaki, F. Kin, K. Hasamada, K. Yamasaki, T. Kobayashi, T. Yamada, Y. Nagashima *et al*., Ion temperature measurement by laserinduced fluorescence spectroscopy in panta, IEEJ Trans. Electr. Electron. Eng. **14**(10), 1450 (2019).

[10] J. Hseih, *Computed Tomography - Principles, Design, Artifacts and Recent Advances*, 01 2009.