Exploiting laser-induced fluorescence method with a single optical path to multidimensional flow-velocity measurements

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The laser-induced fluorescence (LIF) method is widely used as a versatile technique to measure the velocity distribution functions of ions and neutrals from low-temperature plasmas to magnetic-field confinement plasmas. The LIF spectrum obtained by scanning the laser wavelength (frequency) can be interpreted as a visualization of the density of the particles that satisfy the resonant absorption condition. When the particles are moving relative to the propagation direction of the laser beam, the Doppler shift must be considered. For example, when the wavenumber vector of the plane-wave laser propagating in the z direction is $\boldsymbol{k}$, and the velocity vector of the particle is $\boldsymbol{v}$, the Doppler shift of the absorption frequency is given by $\delta = -\boldsymbol{k} \cdot \boldsymbol{v} = -k_z v_z$. Only the velocity component parallel to the wavenumber vector modifies the absorption condition, indicating that this measurement is essentially one-dimensional.

Recently, it has been reported that the use of Laguerre-Gaussian (LG) modes known as optical vortex beams instead of plane-wave lasers may overcome this one-dimensionality and extend the LIF method to multidimensional measurements [1, 2]. The LG modes are cylindrically symmetric solutions of the Helmholtz equation in the paraxial approximation and have a spatial phase factor $e^{il\varphi}$, where l and φ denote the topological charge and the azimuthal angle, respectively; the beam center is a phase singularity, resulting in a doughnut-shaped intensity distribution, as shown in Fig. 1(a). In 1994, Allen *et al.* derived the expression of the Doppler shift for an atom moving in an optical vortex beam [3]. The Doppler shift of the absorption frequency has two primary terms as follows: $\delta_{\mathrm{LG}} = -k_z v_z - \frac{l}{r} v_\varphi$. The first term is the translational Doppler shift used in the conventional LIF method, while the second term is the azimuthal one, i.e., perpendicular to the beam's propagation direction. Therefore, the LIF spectrum obtained using the optical vortex beam contains information on the velocity in the φ direction. When a uniform flow traversing the LG beam exists, the magnitude of the second term varies with position in the beam cross-section. If any arbitrary portion of the beam could be used to obtain the LIF spectrum, the interpretation of the center frequency shift of the spectrum would be straightforward; however, in the experiment, the LIF photons from the entire beam would be received. Consequently, the integrated LIF spectrum will show an increase in width rather than a frequency shift, and information on flow direction will be lost [1].

A beam with partially localized intensity while maintaining the azimuthal phase gradient would allow LIF measurements with sensitivity to the direction of transverse flow across the beam. An asymmetric optical vortex beam [4, 5] is a promising alternative with such characteristics. Figure 1(b) shows an example of the intensity distribution of an asymmetric optical vortex beam. In this case, the intensity is localized at the top of the beam, while the phase gradient in the azimuthal direction is retained. Therefore, the LIF spectrum obtained with this beam is expected to show an additional center frequency shift depending on the horizontal flow velocity. By tailoring the intensity distribution as desired, we can make the LIF spectrum sensitive to any direction perpendicular to the beam propagation direction. Since the translational Doppler shift is maintained, the LIF method with asymmetric optical vortex beams enables three-dimensional flow velocity vector determination with a single optical path. More details will be discussed in the presentation.

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References

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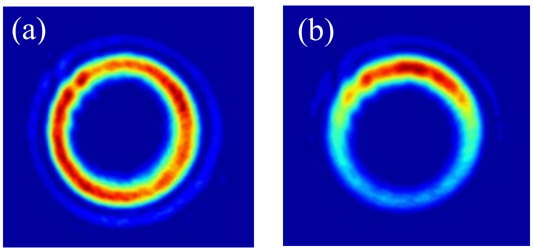

Figure 1 (a) Intensity distribution of an experimentally generated optical vortex beam ($l = 10$), (b) Intensity distribution of an experimentally generated asymmetric optical vortex beam, where the laser incident position to the hologram is intentionally misaligned.