Observation of Azimuthal Doppler Effect by Optical Vortex

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We have been developing a novel spectroscopic method to measure particle flow velocity using a Laguerre-Gaussian (LG) mode laser beam, which is called as an *optical vortex*. In contrast to a Hermite-Gaussian (HG) mode laser beam, which has planar phase fronts perpendicular to the beam axis, the optical vortex has helical phase fronts around the beam axis and an on-axis singularity. The wave vector of the optical vortex has a finite azimuthal component depending on the spatial structure of the phase. When the optical vortex is used in laser absorption spectroscopy measurement, the main terms of the Doppler shift in frequency is given by

$$\delta_{LG} \approx -kV_z - \left(\frac{m}{r}\right)V_\phi, \qquad (1)$$

where k, m, r, V_z, V_ϕ are the wave number, the topological charge characterizing the helical structure of the phase, the distance from the beam axis, the velocity components of a moving atom in the beam axis direction and that in the azimuthal direction, respectively [1]. The second term in the right-hand side of eq. (1) shows the contribution of the Doppler shift in the azimuthal direction, which depends on both the topological charge "m" and the distance from the beam axis "r". Therefore we can evaluate the particle velocity component perpendicular to the laser beam from this additional azimuthal Doppler shift.

The experiment to observe the azimuthal Doppler effect was carried out with the high density plasma experiment (HYPER-I) device at NIFS [2]. The plasma was generated by electron cyclotron resonance (ECR) heating with the microwave power of 40W and the Ar gas pressure of 10mTorr. The optical vortex was generated with the holographic method using a spatial light modulator (SLM). In order to evaluate the azimuthal Doppler shift of the absorption spectra of metastable argon neutrals in the plasma, laser absorption spectroscopy experiments were performed. The two-dimensional profile of the beam intensity transmitted through the plasma was measured by a beam profiler with a high spatial resolution. 1100 frames of two-dimensional data were obtained during the frequency sweeping from which the absorption spectra were reconstructed. The Doppler shifts of the absorption spectra were evaluated at points on the circumference of circles with three different radii. The results obtained in this experiment are summarized as follows:

i) The frequency shift of absorption spectra on the circumference of a circle centered at the singular point shows a sinusoidal dependence.
ii) The frequency shift decreases with the distance from the singular point.
iii) The sign of the frequency shift changes by changing the sign of the topological charge.

These experimental results are qualitatively consistent with the azimuthal Doppler effect of the optical vortex given by eq. (1). This is a promising achievement, and our next work is to calibrate the absolute particle flow velocity.

[1] L. Allen et al., Opt. Commun. **112**, 141 (1994).
[2] S. Yoshimura et al., J. Plasma Phys. **81**, 345810204 (2014).