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Advanced Laser-Doppler Spectroscopy with Twisted Wavefront for Plasma Flow Measurements

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Flow is an essential quantity for understanding transport phenomena and structure formation. Laser-induced fluorescence (LIF) Doppler spectroscopy is a non-intrusive and unperturbed diagnostic tool for accurately measuring the local flow velocity of ions and neutral particles, and has become a standard method in plasma research, especially for low-temperature plasmas. In the LIF method, which utilizes a tunable laser with a narrow bandwidth, the LIF spectrum obtained by sweeping the laser frequency provides the velocity distribution function directly. The flow velocity of ions and neutral particles is determined from the frequency shift of the LIF spectrum.

All previous LIF measurements have been performed using Gaussian beams (plane waves) as the probe beam. In the traditional method, the Doppler shift of the resonant absorption conditions of the target particles depends only on the velocity of the particles in the direction of beam propagation. Therefore, only the velocity component projected onto the optical axis can be determined, and flow perpendicular to the wavenumber vector cannot be detected. In other words, multiple optical paths are needed to determine the three-dimensional flow vector. However, the configuration of the equipment often limits the laser path. If an LIF method with sensitivity to the transverse flow is established, it expands the versatility of the method.

An optical vortex (OV), which carries orbital angular momentum, is a propagation mode characterized by a helical phase structure and a doughnut-shaped intensity distribution. Allen *et al.* determined that an atom moving in an OV beam experiences additional Doppler effects due to phase inhomogeneity. For a Laguerre-Gaussian beam with topological charge (TC), the resonant absorption frequency of a moving particle is modified by an additional Doppler shift, which is proportional to the TC [1]. Therefore, Doppler spectroscopy with OV beams has the potential to evaluate the flow velocity across the beam.

We have conducted the experiments to demonstrate the effectiveness of Doppler spectroscopy using OV beams. The suitability of twisted wavefronts for flow measurement was first shown by laser absorption spectroscopy [2]. Subsequently, we proposed the optical vortex beam-based LIF (OVLIF) method, which evaluates the flow velocity across the beam by analyzing the deformation of the LIF spectrum width [3]. More recently, a new method using asymmetric optical vortex beams with non-uniform intensity distributions (aOVLIF method) has been proposed and tested in proof-of-principle experiments to overcome some of the problems of the OVLIF method [4]. The beam intensity distributions and the interferograms (phase structure) of the OVLIF and aOVLIF methods are shown in Fig. 1. The aOVLIF method, which utilizes a beam with a crescent-like intensity distribution, has the potential to determine even three-dimensional flow vectors in a single optical path by changing the beam arrangement.

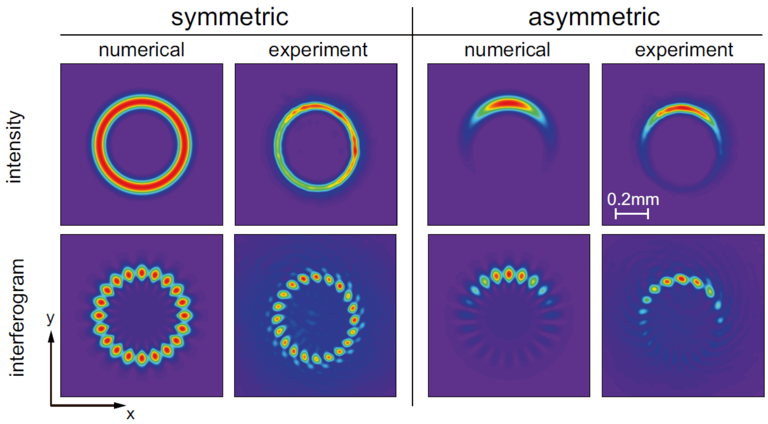

Figure 1. Intensity distributions and Interferograms of the symmetric OV beam (left) and the asymmetric OV beam (right). Large TC optical vortex beams are successfully generated. (reproduced from Ref. [4])

We have been conducting proof-of-principle experiments on ion and neutral flow measurements in several low-temperature plasmas, including an ECR plasma in a weakly diverging magnetic field and a magnetic sheath. In this conference, we will also discuss the recent progress in aOVLIF measurements.

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