The Asymmetric Optical Vortex Laser-Induced Fluorescence Method for Measuring Flow in Plasma–Solid Materials Boundary

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Understanding ion and neutral particle transport in the boundary regions between plasmas and solid materials such as walls, substrates, and electrodes is important not only for fundamental plasma physics, but also for a wide range of plasma applications. For example, in plasma-based microfabrication, the energy and angular distribution of ions incident on the substrate are among the most critical parameters that determine etching precision. In addition, in magnetically confined plasma devices for fusion research, ion and neutral particle transport in the divertor region is known to influence the formation and stability of detached plasmas, which are essential for reducing thermal loads on material surfaces.

Laser spectroscopy, an optical and non-intrusive diagnostic method, is well suited for in situ flow measurements in such boundary regions. However, conventional plane-wave-based laser spectroscopy can detect the Doppler shift only for the velocity component along the direction of light propagation. As a result, it has been fundamentally impossible to measure flows perpendicular to the boundary surface without physical modifications such as drilling a hole to secure the optical path.

To overcome this limitation and enable in situ measurement of flows perpendicular to boundary surfaces, we have developed a novel laser spectroscopic method that exploits the azimuthal Doppler effect induced by optical vortex beams, specifically Laguerre-Gaussian (LG) modes [1]. Using this approach, we have already achieved high-precision measurements of metastable argon atom flows in RF discharge plasmas over a velocity range of 50–150 m/s, employing laser absorption spectroscopy with optical vortex beams with a topological charge of $l = \pm 10$ [2].

More recently, our numerical simulations have demonstrated that introducing asymmetry into the intensity profile of an optical vortex beam enables detection of spectral shifts in the laser-induced fluorescence (LIF) signal due to the azimuthal Doppler effect [3]. In addition, we have shown that, by carefully tailoring the asymmetry and conducting a set of measurements, it is possible to reconstruct the full three-dimensional flow vector using only a single line of sight.

In this workshop, we will present an overview of the asymmetric optical vortex LIF method, including recent proof-of-principle experimental results.

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