B-I10

1st Asia-Pacific Conference on Plasma Physics, 18-22, 09.2017, Chengdu, China

Inevitable Limitation of Plane Wave Laser Spectroscopy, and a Solution by Using Optical Vortex

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In the past decades, a lot of extreme laser diagnostics techniques have been developed, and most of them are based on the control of the laser parameter in time-domain, frequency-domain, or spatial resolution. On the other side, the topology of laser parameters in spatial-domain has not been so much utilized so far. Recently the topological light sources have been developed by controlling the spatial structure of the phase and polarization of the laser beam. By using the spatial structure, the topological lasers can potentially add new functions to the traditional laser applications. In this study, in order to detect the beam crossing gas flow in plasma, we apply the optical vortex (OV), which is one of the topological laser light, to the Doppler spectroscopy.

The Doppler shift is caused by the additional phase change by the movement of an observer in the wave field. As shown in Fig. 1 (a), the plane wave, which is commonly used for the traditional laser spectroscopy, has the flat wave front. Therefore, the induced Doppler shift is limited in the propagating direction of the laser beam, and the movement perpendicular to the wave propagation is not detectable. On the other side, since the OV has twisted wave front (see Fig.1 (b)), the motion in the light field causes the Doppler shift in all the three-dimensional directions [1]. It is described as follows:

$$\delta_{LG} = -\left[k + \frac{kr^2}{2(z^2+z_R^2)}\left(\frac{2z^2}{z^2+z_R^2} - 1\right) - \frac{(2p+|l|+1)z_R}{z^2+z_R^2}\right]V_Z - \left(\frac{krz}{z^2+z_R^2}\right)V_R - \left(\frac{l}{r}\right)V_\phi \quad (1)$$

,where V_Z, V_R, and V_ϕ are the axial, radial and azimuthal velocity components of the atom, l is the topological charge, r is the distance from the beam center (phase singularity). Our current study aims to detect the azimuthal Doppler shift, which is undetectable by the traditional Doppler spectroscopy, by using the OV laser.

Figure 2 shows the experimental setup for the OV laser spectroscopy. Inductively coupled plasma is generated by a spiral antenna with applied RF power at 13.56 MHz. An external cavity diode laser (ECDL) was tuned at 697nm for the excitation of an argon metastable generated in the plasma. The laser beam is separated into the pump laser and the probe laser. The probe laser is converted to OV by a computer generated hologram displayed on the spatial light modulator (SLM). The beam crossing gas flow is generated by introducing the gas along the discharge tube. The typical gas flow velocity was 200 m/s in this experiments. The images of the OV probe laser were recorded while the wavelength of the ECDL was scanned. The Doppler absorption spectroscopy and the saturated absorption spectroscopy were performed.

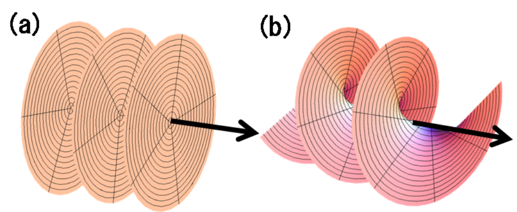

Fig.1 Phase front of (a) plane wave and (b) optical vortex.

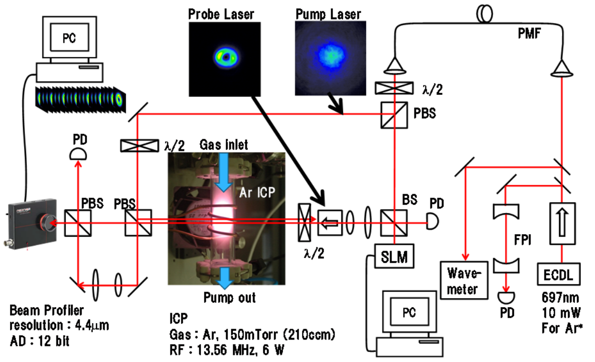

Fig.2 Experimental setup for optical vortex Doppler spectroscopy.

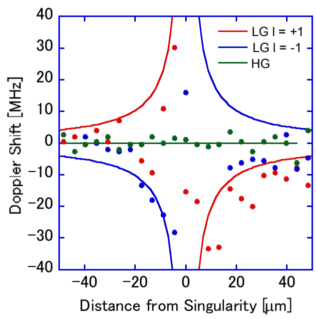

Fig.3 Dependence of the transverse Doppler shift on the distance from the phase singularity. Red : $l = +1$, blue : $l = -1$, green : $l = 0$.

Figure 3 shows the transverse Doppler shift of the Doppler absorption spectra along with theoretically calculated lines at 200 m/s gas flow. As expected, the transverse Doppler shifts of the OV ($l = \pm 1$) were inversely proportional to the distance from the phase singularity, and depended on the sign of the topological charge. On the other side, the transverse Doppler shift of the plane wave was nearly zero. The experimental results were qualitatively agree with the theory, however, the improvement of the accuracy in the Doppler shift detection is required for the quantitative estimation of the beam crossing gas flow velocity. The concept of optical vortex spectroscopy and some results of the Doppler spectroscopy and the saturated absorption spectroscopy will be presented.

References

[1] L. Allen, et al.: Opt. Comm. 112 (1994) 141-144.