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光渦レーザー誘起蛍光法によるイオン流速計測
Ion Flow Diagnostics Using Optical Vortex Laser Induced Fluorescence Method

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Flow velocities of ions and neutrals are important parameters for characterizing weakly-ionized plasmas. We have been developing novel methods of flow-velocity measurement based on optical vortex laser Doppler spectroscopy. In addition to usual longitudinal Doppler effect, an atom moving in an optical vortex beam experiences azimuthal Doppler effect, which arises from azimuthal phase gradient around the phase-singularity point. Therefore, it is expected that the Doppler spectrum obtained by using optical vortex laser contain information on the flow perpendicular to the laser path.

We have so far studied optical-vortex laser absorption spectroscopy in which the transmitted laser intensity was recorded by a beam profiler so that the absorption spectrum was possible to be reconstructed at any positions on the cross-section of beam. This is because the magnitude of azimuthal Doppler shift depends on the distance from the singularity. This method, however, cannot be applied to ion-flow measurement, since the lower density of ions makes it impossible to detect the single path absorption. Here, we consider laser-induced fluorescence (LIF) measurements using optical vortex beams to expand the capability of optical vortex laser spectroscopy.

We have numerically calculated the shape of LIF spectrum obtained by optical vortex beam. The velocity distribution function (VDF) is given by

$$F(\upsilon_r,\upsilon_\phi,\upsilon_z)=\left(\frac{1}{2\pi V_t^2}\right)^{\frac{3}{2}}\exp\left[-\frac{(\upsilon_r-U_r)^2+\left(\upsilon_\phi-U_\phi\right)^2+(\upsilon_z-U_z)^2}{2V_t^2}\right]$$

in which V_t stands for the thermal velocity of ions and U the flow velocity. By considering the Doppler effect in optical vortex, $\delta_L \approx -k\upsilon_z - l\upsilon_\varphi/r$, the VDF can be integrated in all velocity space by change of variables, where l is the topological charge. In case that U has only x-component, the LIF spectrum at a position on the cross-section of the beam is given by the following expression:

$$F(\delta_L)=\left(\frac{1}{2\pi V_t^2}\right)^{\frac{1}{2}}\left(\frac{1}{\alpha^2+k^2}\right)^{\frac{1}{2}}\exp\left[-\frac{1}{2(\alpha^2+k^2)V_t^2}(\delta_L-\alpha U_x\sin\theta)^2\right]$$

in which $\alpha = l/r$. Then the following expression for LIF intensity at a position (r, φ) in a beam of which radius is w is obtained by assuming the proportionality to the laser intensity:

$$I_{\mathrm{LIF}}(r,\theta)\propto\left(\frac{2r^2}{w^2}\right)^{|\ell|}\left(\frac{r^2}{\ell^2+r^2k^2}\right)^{\frac{1}{2}}\left[L_0^{|\ell|}\left(\frac{2r^2}{w^2}\right)\right]^2$$

$$\times\exp\left[-\frac{r^2}{2(\ell^2+r^2k^2)V_t^2}\left(\delta_L-\frac{\ell}{r}U_x\sin\theta\right)^2-\frac{2r^2}{w^2}\right].$$

Finally, the LIF spectrum, which is to be observed in experiment, is obtained by numerical integration. Figure 1 shows some examples of the profile of LIF spectrum calculated for optical vortex beam (l = 10) and for plain wave (TEM_{00}) mode. Modification of LIF spectrum is remarkable only for extreme case. Some preliminary results of optical vortex LIF experiment will also be presented.

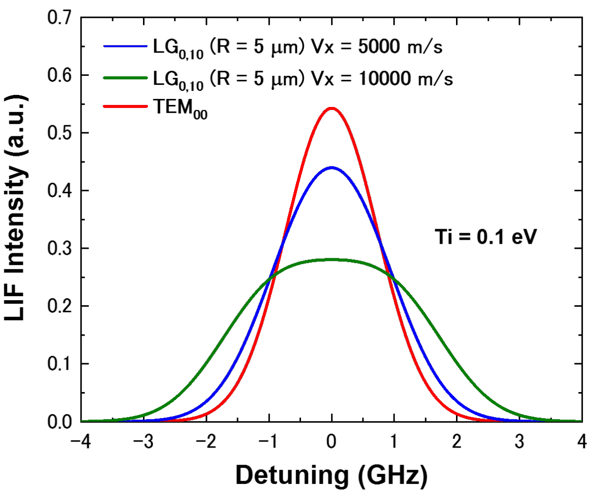

Fig. 1 Examples of modification of LIF spectrum due to azimuthal Doppler shift.