§1. High Density Plasma Experiment: HYPER-I

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High Density Plasma Experiment-I (HYPER-I) is a linear plasma device for basic plasma collaboration research and development of novel plasma diagnostics[1]. HYPER-I has been in operation for 20 years since 1996 (Fig. 1). The plasma is produced by the electron cyclotron resonance (ECR) discharge using a right-handed circularly polarized 2.45 GHz microwave injected parallel to the device from the higher-field end, which enables to generate overdense plasma easily because of the lack of density cutoff in the dispersion relation of electron cyclotron wave[2]. A variety of diagnostic tools are provided, e.g. electric and magnetic probes, a spectrometer, an ICCD camera, a dye laser and external cavity diode lasers.

The main topic of the HYPER-I experiment in this fiscal year is the development of novel laser diagnostics utilizing a Laguerre-Gaussian (LG) beam which is frequently referred to as *optical vortex*. Usual laser spectroscopy utilizes a conventional plain-wave mode, or a Hermite-Gaussian (HG) mode, of which wave front is perpendicular to its propagation vector. Because the inner product of flow velocity and the propagation vector determines the Doppler shift, the conventional laser measurement is essentially one-dimensional. On the other hand, the LG beam has a helical wave front, which represents that the phase on a plain perpendicular to the propagation vector varies in azimuthal direction. Due to this three-dimensional phase structure, the Doppler effect experienced by an atom moving in the LG beam is also three-dimensional. The goal of our research is to establish a novel laser measurement method which can detect the atomic flow in perpendicular to the laser propagation vector. This research subject has been adopted as two JSPS KAKENHI Grants, a LHD project collaboration research in NIFS and a young scientists' collaboration program for cross-disciplinary study in NINS in this fiscal year.

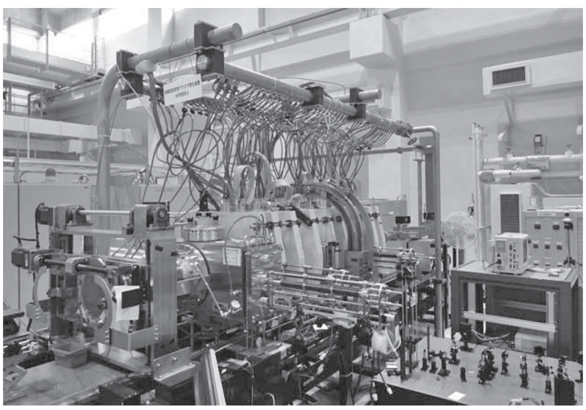

Fig. 1: The HYPER-I device

In order to perform a proof-of-principle experiment for the optical vortex laser spectroscopy, we have focused attention on the azimuthal Doppler shift that is a characteristic effect of LG beam. The dominant terms in the Doppler shift for an atom moving in the LG beam is given by

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

where k is the wave number of LG beam, V the corresponding component of atomic flow velocity, m the topological charge, and r the distance from the beam axis[3]. The second term in the right-hand side is the additional azimuthal Doppler shift. Since the magnitude is a function of the position in the beam, the dependence of frequency shift can be detected by two-dimensional measurement of absorption spectra. Moreover, it is expected that when the atomic flow in the LG beam is regarded as constant, the frequency shifts of absorption spectra reconstructed on a circumference of the circle centered at the beam axis show sinusoidal dependence.

We have performed the laser absorption spectroscopy experiment with the HYPER-I device in which the target particles are metastable argon neutrals whose resonant absorption wavelength is 696.735 nm in vacuum. The argon gas pressure was 20 mTorr, and the microwave power 40 W. The LG beam was generated by holographic method using a spatial light modulator. The transmitted laser light intensity was measured by a beam profiler which has spatial resolution of 4.4 μm per pixel. Images of transmitted laser light were taken by sweeping laser frequency by which the absorption spectrum at any position in the beam can be reconstructed.

The dependence of frequency shift on position (angle that determines the position on the circumference) and on the topological charge is shown in Fig. 2. For plain-wave mode case (m = 0), there is no position dependence. On the other hand, the frequency shifts for $m = \pm 1$ clearly show sinusoidal dependence, which agrees qualitatively to our prediction for the azimuthal Doppler shift of LG beam.

1) S. Yoshimura et al.: J. Plasma Phys. **81** (2015) 3481024.
2) M. Tanaka et al.: J. Phys. Soc. Jpn. **60** (1991) 1600.
3) L. Allen et al.: Opt. Commun. **112** (1994) 141.

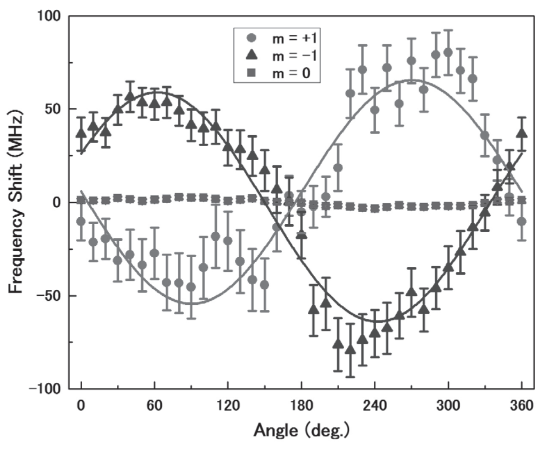

Fig. 2: Spatial dependence of peak frequency shift of absorption spectra for different topological charge.