§25. Doppler-free Spectroscopy of Deuterium Balmer-alpha Line for Plasma Diagnostics

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In the LHD experiments, the particle balance in the plasma edge region is important for the study of the high-performance confinement. Since the magnetic field strength and direction vary with the position and are known in the LHD plasma, the Zeeman-splitting of spectral lines carries the information of the position of excitation, which is almost the same as that of ionization. This information is helpful for investigating the particle balance in LHD. In the case of hydrogen plasma, however, the structure of Zeeman-splitting is masked by the Doppler broadening. For that reason, we developed a system of "Doppler-free" saturation spectroscopy at the Balmer-alpha line of atomic hydrogen. In our previous study, the precise phenomena of saturation spectrum of the atomic hydrogen Balmer-alpha line with and without Zeeman-splitting were investigated. Since the LHD plasma will be switched to deuterium plasma, we have investigated the saturation spectrum of atomic deuterium Balmer-alpha line in this year.

The plasma source was a helicon wave discharge machine installed in Hokkaido University. The discharge part consisted of a 16 mm inner diameter and 300 mm length quartz tube wound a helical antenna. The quarts tube was connected to a vacuum chamber, of which depth was 300 mm. The vacuum chamber and the quarts tube was filled with 7.2 Pa deuterium gas and the rf power fed to the helical antenna was 250 W continuously. The discharge was maintained without external magnetic field. The light source for saturation spectroscopy was a tunable diode laser with an external cavity (TOPTICA DL100pro). The laser beam was injected to the deuterium plasma as a pump beam. The transmitted laser beam was attenuated by a ND filter and was reflected by a mirror to be reentered to the plasma on the same chord as a probe beam. The intensity of the pump beam and the probe beam were 9.2 mW and 0.4 mW, respectively. The absorption length was approximately 30 cm. The transmitted probe beam was picked up by a beam sampler and detected by a photo diode.

Figure 1 shows the observed absorption spectrum and calculated absorption spectrum based on the Einstein's A coefficients of the deuterium Balmer-alpha line listed on the NIST Atomic Spectra Database. The horizontal axis shows the relative frequency from the $2P_{3/2}$-$3D_{5/2}$ (656.1067 nm) transition. The calculation was carried out with Doppler-broadening at the temperature of 650 K. The experimental and calculated spectrum showed good agreement except Lamb dips on the experimental spectrum. It was confirmed that the Doppler-broadening was narrower than the hydrogen plasma that generated similar condition. Figure 1 also shows calculated absorption spectra of the individual fine structures. The frequencies of the Lamb-dips of the experimental spectrum showed good agreement with the center of each absorption peaks. The Assigned transitions were labeled in Fig. 1. The dip at 7.21 GHz also found but this dip was slightly different frequency of weak $2P_{1/2}$-$3S_{1/2}$ (6.98 GHz) absorption. This dip can be explained as a crossover dip which observed at the midpoint of two adjacent transitions with a common lower level by the saturation spectroscopy. In this case, $2S_{1/2}$-$3P_{1/2}$ (5.57 GHz) and $2S_{1/2}$-$3P_{3/2}$ (8.86 GHz) are the related transitions. This crossover dip was observed clearly while other crossover dip could not be found. The obvious crossover signal between $2S_{1/2}$-$3P_{1/2}$ and $2S_{1/2}$-$3P_{3/2}$ transitions was also found in the hydrogen saturation spectrum.

The saturation parameter S_0 can be derived from the relative depth of the Lamb dips by the equation,

$$S_0 = (1-\Delta\alpha/\alpha_0)^{-2} - 1,$$

where $\Delta\alpha$ is the depth of Lamb dip and α_0 is the peak absorption of the each fine structure. Derived saturation parameters are listed in Table I. The saturation parameter is proportional to the spectral energy density of pump beam ρ, Einstein's B coefficient, and inverse of the effective relaxation frequency of the upper and the lower levels $1/R^*$,

$$S = B_{12}\rho / R^*.$$

The differences of saturation parameters between each transition reflect these parameters.

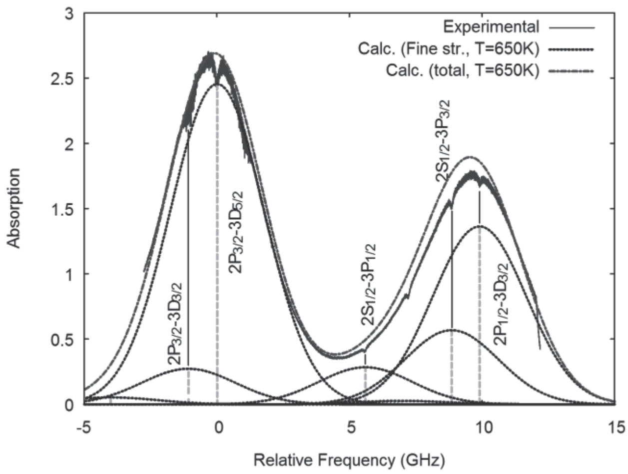

Fig. 1: Absorption spectrum of atomic deuterium Balmer-alpha line with Lamb dips (experimental) and calculated absorption spectrum (total and each fine structure).

Table I: Saturation parameters of observed Lamb dips

Transition	B_{ik}(arb.unit)	$\Delta\alpha$	α_0	S_0
$2P_{3/2}$-$3D_{5/2}$	9.7	0.25	2.4	0.25
$2S_{1/2}$-$3P_{1/2}$	2.2	0.03	0.27	0.25
$2S_{1/2}$-$3P_{3/2}$	4.5	0.08	0.54	0.36
$2P_{1/2}$-$3D_{3/2}$	10.8	0.06	1.30	0.1