§1. Development of Doppler-free Spectroscopy for Plasma Diagnostics

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A requirement for diagnostics in LHD experiments is the development of high-resolution spectroscopy at the Balmer-α line of atomic hydrogen. If the high-resolution spectrum of the Balmer-α line with Zeeman splitting is measured, one can estimate the place of electron impact excitation of atomic hydrogen with the help of the knowledge of the distribution of the magnetic field strength. The place of electron impact excitation roughly represents the place of electron impact ionization. The knowledge on the place of electron impact ionization is helpful for investigating the particle balance in LHD. However, the Zeeman-split spectrum of the Balmer-α line is masked by the Doppler broadening. The goal of this work is to develop a technique of Doppler-free spectroscopy (saturation spectroscopy) at the Balmer-α line of atomic hydrogen, with the intention of applying it to LHD experiments.

In this year, we carried out in-depth analysis of the saturation spectrum observed in a linear plasma source. The plasma source had a uniform magnetic field along the cylindrical axis. The system of saturation spectroscopy employed an oscillator-amplifier system of diode lasers, which yielded tunable, single-mode, cw radiation with a power of 200 mW. A part of the laser beam obtained from the master oscillator was picked up using a beam splitter and was used as the probe beam. The other part of the master oscillator beam was injected into the amplifier to obtain the intense pump beam. The probe and pump beams were launched into hydrogen plasmas from the counter axial directions. The probe and pump beams were overlapped carefully.

Figure 1 shows the saturation spectra observed at various hydrogen gas pressures. The widths of the peaks in the spectra are less than 500 MHz, indicating the wavelength resolution that is much finer than the Doppler width (Doppler-free spectroscopy). The magnetic field strength in this experiment was 60 G, where the magnitude of Zeeman splitting is less than the widths of the peaks, and the spectra are almost the same as those observed in unmagnetized plasmas. As indicated in the figure, some peaks are assigned as the fine-structure components of the Balmer-α line of atomic hydrogen. The peaks with no labels and arrows are understood as the cross-over signals, which appear at the center between two transition lines with the common lower energy level in saturation spectroscopy. In addition to the aforementioned understandable peaks, the spectra shown in Fig. 1 have several peaks which are pointed out by the arrows. These anomalous peaks are observed at the center between two transition lines, but the lower energy levels of the two transition lines are different. Therefore, they are different from the normal cross-over signals.

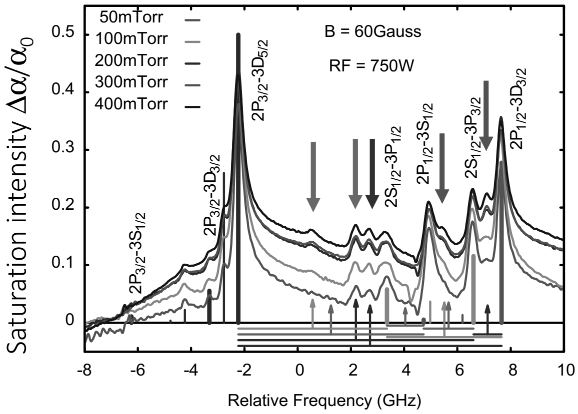

Fig. 1: Saturation spectra of the Balmer-α line of atomic hydrogen observed in a magnetic field of 60 G.

The $n = 2$ state of atomic hydrogen is composed of three levels: $2^2S_{1/2}$, $2^2P^o_{1/2}$, and $2^2P^o_{3/2}$. The $2^2P^o_{1/2}$ and $2^2P^o_{3/2}$ states are radiative, while the $2^2S_{1/2}$ state is metastable. Although the $2^2P^o_{1/2}$ and $2^2P^o_{3/2}$ states are radiative, they can have significant populations due to strong radiation trapping at the Lyman-α line. However, it is noted that the effective (reduced) transition probability of the Lyman-α line due to radiation trapping does not correspond to the relaxation frequency of the 2p state in saturation spectroscopy, since the 2p state populated by radiation trapping cannot keep the hole burning in the velocity distribution function. This means the relaxation frequency of the 2p state in saturation spectroscopy is greater than 10^8 s^{-1}. On the other hand, the lifetime of the $2^2S_{1/2}$ state is determined by electron impact transfer to the 2p state ($H(2s) + e \rightarrow H(2p) + e$), which has a rate coefficient of 2×10^{-6} cm^3/s.[1)] Hence, in the plasma with an electron density of 10^{11} cm^{-3}, the relaxation frequency of the $2^2S_{1/2}$ state is less than 10^6 s^{-1}.

The anomalous peaks are explained by the same mechanism as that of the cross-over signal, if the velocity distribution functions of the $2^2S_{1/2}$, $2^2P^o_{1/2}$, and $2^2P^o_{3/2}$ states have similar hole burnings. This means very frequent interchanging between the 2s and 2p states. However, according to the relaxation frequencies described in the previous paragraph, it is difficult to imagine the population transfer between the 2s and 2p states with keeping the hole burnings. Therefore, the anomalous peaks observed in the saturation spectrum of the Balmer-α line possibly suggest a larger rate coefficient for the electron impact transfer between the 2s and 2p states. A larger relaxation frequency than 10^6 s^{-1} is also suggested by the height of the $2^2S_{1/2}$–$2^2P^o_{1/2}$ and $2^2S_{1/2}$–$2^2P^o_{3/2}$ peaks.

1) R. K. Janev, W. D. Langer, K. Evans, Jr., and D. E. Post, Jr., *Elementary Processes in Hydrogen-Helium Plasmas* (Springer, 1987).