§21. Development of Plasma Diagnostics Based on Doppler-free Spectroscopy

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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, it was confirmed that the LHD plasma was optically thin for the Balmer-alpha line of atomic hydrogen to apply the conventional absorption spectroscopy. In this year, we tried to apply the frequency modulated absorption spectroscopy, which is sensitivity-enhanced absorption spectroscopy, with the saturation spectroscopy to detect the fine structure of the Balmer-alpha line of atomic hydrogen.

The hydrogen plasma was generated in a inductively-coupled plasma source with an internal antenna, filled with 50 mTorr hydrogen gas, and fed 1 kW, 13.56 MHz RF power. The light source was a tunable cw diode laser (NewFocus Vortex II), which is able to scan the whole range of the Balmer-alpha line of atomic hydrogen without mode-hopping. The output laser light was divided into two parts. The main part of the laser beam (8.5 mW) was used as a pump beam, and the other part (0.42 mW) was used as a probe beam. These beams were injected into the plasma through the facing optical windows of the plasma source on the same chord but opposite directions to each other. The optical path length in the plasma was approximately 25 cm. The probe beam transmitted through the plasma was picked up by a beam sampler and was detected using a photodiode. The frequency of the laser was scanned over the whole range of the Balmer-alpha line of atomic hydrogen with a 0.5 Hz triangle waveform. In addition, a frequency modulation by a 1 kHz sinusoidal waveform was superposed.

The absorption of the probe beam was not observed. According to the theory of the frequency modulated absorption spectroscopy, when the laser wavelength is modulated by a certain frequency, the second harmonic component of the detected signal is proportional to the second derivative of the absorption spectrum. This second harmonic component (2f signal) is able to be detected by using a phase sensitive amplifier system with high sensitivity. Figure 1 shows the obtained 2f spectra with various frequency modulation widths, in the case of without the pump beam. Each spectrum was subtracted by the spectrum without plasma in the same condition. These spectra well agreed with the 2f spectra estimated with the Doppler broadening of 900 K atomic temperature.

Figure 1 also shows that the intensity of the 2f spectra were roughly proportional to the frequency modulation width. In the case of the frequency modulation width of less than 1 GHz, the signal intensity and the signal to noise ratio were reduced. However, when the pump beam was switched on, the 2f spectra had clear peaks with the narrow frequency modulation widths as shown in figure 2. The pump beam caused the Lamb dips on the absorption profile at the center of the fine structure component by the configuration of the saturation spectroscopy. The peaks shown in figure 2 were able to be assigned as the major fine structure components of the Balmer-alpha line of atomic hydrogen and their cross-over signals. Figure 2 also shows that the 2f spectrum concerned with the Lamb dips were detected selectively with the narrow frequency modulation width because the width of Lamb dips was a few hundreds MHz while the Doppler width was approximately 20 GHz. This result shows that the combination of the saturation spectroscopy and the frequency modulated spectroscopy is useful to apply the Doppler-free spectroscopy for optical thin plasmas.

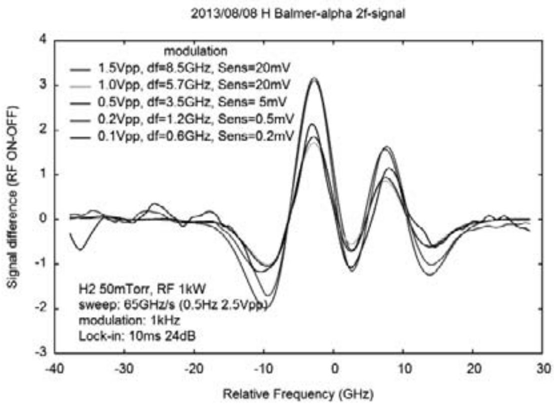

Fig. 1. 2f spectra of the Balmer-alpha line of atomic hydrogen with Doppler broadening.

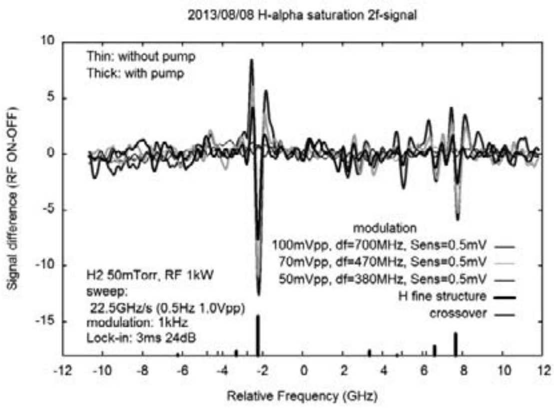

Fig. 2. 2f spectra of Doppler-free fine structure of Balmer-alpha line of atomic hydrogen.