Application of Saturated Absorption Spectroscopy to Plasma Diagnostics

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Abstract. In this work, we utilized saturation spectroscopy to the Balmer-alpha line of atomic hydrogen in a linear magnetized plasma source with the intention of applying it to plasma diagnostics. The fine-structure of the Balmer-alpha line was observed clearly in weak magnetic field strength. Most of the peaks are assigned as transitions of the fine-structure of the Balmer-alpha line and its cross-over peaks. However, irregular cross-over peaks also observed and the population exchange among the 2s and the 2p states was suggested. Saturation spectra with Zeeman-splitting were also observed, however, the spectra became complicated with many small peaks.

1. Introduction

Saturation spectroscopy is a kind of laser absorption spectroscopy, and it achieves a Doppler-free spectral resolution. This technique is widely used in the field of fundamental spectroscopy for the precise determination of the wavelengths of transitions [1,2]. However, there are a few works of application of saturation spectroscopy to plasma diagnostics [3-5].

In this work, we developed a saturation spectroscopy system to investigate the basic properties of saturation spectrum at the Balmer-alpha line of atomic hydrogen in magnetized plasmas. This study intends to be applied to an analysis of spatial distribution of ionization in the Large Helical Device at the National Institute for Fusion Science. The Doppler-free spectral resolution is required for Zeeman-splitting analysis of high temperature hydrogen plasmas because the wider Doppler broadening masks the complex fine structure of the Zeeman-splitting spectrum [6], which carries information of the spatial distribution of ionization in the confinement magnetic field of helical devices [7]. In the following, we report the basic properties of the saturation spectrum of Balmer-alpha line with and without Zeeman-splitting in various conditions.

2. Experimental setup

The experimental apparatus is schematically shown in Figure 1. The plasma source was linear machine with a uniform magnetic field along the axis. The helical antenna was wound around a 1.6 cm inner diameter and 30 cm length quartz glass tube. The antenna was connected to an RF power supply at 13.56MHz via a matching circuit. One end of the quartz glass tube was connected to a diffusion chamber and the overall length of the plasma was 60 cm. The diffusion chamber was
evacuated by a turbo-molecular pump and was fed hydrogen gas via a mass-flow controller. The hydrogen gas pressure in the chamber was settled to 6.7 to 53 Pa (50 to 400 mTorr).

The light source for saturation spectroscopy was a tunable CW diode laser (New Focus Vortex II). The frequency of the laser was scanned over the range of 120 GHz in 25 ms. This frequency range was wide enough to cover the Doppler broadened Balmer-alpha spectrum. The main part of the laser beam was amplified by a diode laser amplifier, TOPTICA BoosTA, as a pump beam. The power of the pump beam was 110 mW at the optical window of the diffusion chamber. A half-wavelength plate was used to adjust the direction of polarization perpendicular to one of the probe beams to reduce influences of scattered pump laser light. The other part of the laser beam was divided into two laser beams, a probe beam and a reference beam. The power of the probe beam was 220 μW at the end of the quartz discharge tube. These beams passed axially through the plasma column. The probe beam and the pump beam were injected into the plasma from opposite directions and were overlapped with precision to obtain clear saturation signal. The reference beam also passed through the plasma column parallel to the probe beam, separated by the distance of 8 mm. It was used for compensation of temporal fluctuation of plasma density. The transmitted intensity of the probe beam and the reference beam were detected using avalanche photo diodes. A part of the master oscillator beam was picked up to measure the frequency scan using a Fabry-Pérot spectrum analyser. The signals from the avalanche photo diodes and spectrum analyser were recorded using a digital oscilloscope.

Figure 1. Experimental apparatus.
3. Results and discussion

3.1. Saturation spectrum with Zeeman-splitting

A typical result of absorption spectra with and without the pump laser beam is shown in Figure 2. The hydrogen gas pressure and applied RF power were 13 Pa (100 mTorr) and 750 W, respectively. The horizontal axis shows the frequency deviation from 656.2819 nm. The vertical axis shows the absorbance $\alpha_l$ which is obtained by the Lambert-Beer law $\alpha_l = -\ln(I_t/I_0)$ where $I_t$ and $I_0$ are the transmitted and the incident probe beam intensities, respectively. In Figure 2, the outer smooth curve with two broad peaks shows the absorbance without the pump laser beam. It shows good agreement with a spectrum calculated using theoretical transition coefficients of each fine-structure component of the Balmer-alpha line and assumed Doppler broadening at 500 K temperature. With the pump laser beam, the absorbance spectrum shown in Figure 2 has many sharp dips caused by saturation of absorption with the pump beam. The absorbance difference $\Delta \alpha_l = \alpha_{s,l} - \alpha_{0,l}$, where $\alpha_{s,l}$ and $\alpha_{0,l}$ are the absorbance with and without pump beam, respectively, shows fine resolution enough to separate the fine-structure of the Balmer-alpha line. In Figure 2, Zeeman-splitting is not found in this weak magnetic field, 6 mT (60 Gauss), since the expected separation of Zeeman-splitting is less than 200 MHz which is close to homogeneous line-width.

![Figure 2. Absorption spectra of Balmer-alpha line with and without pump beam. Theoretical spectrum is almost overlapped by the experimental spectrum without pump laser.](image)

The experimental result of saturation spectra with various magnetic fields are shown in Figure 3. The vertical axis shows relative absorbance difference $\Delta \alpha / \alpha_0$ which is approximately equal to $S/2$, where $S$ is called as saturation parameter. The hydrogen gas pressure and applied RF power were 6.7 Pa (50 mTorr) and 750 W, respectively. Figure 3 shows Zeeman-splitting fine-structure spectra of the Balmer-alpha line. Because the direction of magnetic field is parallel to the direction of propagation of the pump and the probe laser beams, only the $\sigma$ components of Zeeman-splitting are considered. The major peak at -2 GHz, the $2P_{3/2}-3D_{5/2}$ transition, shows clear split separation dependency to the magnetic field strength. However, in the case of relatively intense magnetic field, 130 mT (1300 Gauss), the saturation spectrum become complicated and shows many small peaks.
3.2. Assignment of saturation peaks

To understand the structure of these saturation spectra, the assignment of peaks of saturation spectrum without Zeeman-splitting was carried out. Figure 4 shows the saturation spectrum with weak magnetic field strength 6 mT (60 Gauss) and various hydrogen gas pressures. Thick vertical bars indicate the each transition frequency and relative magnitude of the $B$ coefficient of the fine-structure component. The fine-structure of the Balmer-alpha line consists of seven transitions shown in Figure 4 with labels of the upper and the lower energy levels. It is confirmed that five peaks can be assigned as these transitions ($2P_{3/2}-3D_{3/2}$, $2P_{3/2}-3D_{5/2}$, $2S_{1/2}-3P_{1/2}$, $2S_{1/2}-3P_{3/2}$, and $2P_{1/2}-3D_{3/2}$). The saturation peak of $2P_{3/2}-3S_{1/2}$ and $2P_{1/2}-3S_{1/2}$ cannot be recognized.

According to the theory of saturation spectroscopy [1], fictitious saturation peak, called as cross-over peak, should be considered. A cross-over peak arises at the midpoint frequency between two transition lines with common lower energy level and overlapping wings of Doppler-broadening. In Figure 4, the thin vertical bars indicate the expected frequency of cross-over peaks and some peaks are understood as the cross-over peaks. However, there are many irregular peaks which are pointed out by the down arrows in Figure 4. These irregular peaks are observed at the midpoint frequency between two transition lines, similar to the ordinary cross-over peak, but the lower energy levels of the two transition lines are different.

The lower energy levels of the Balmer-alpha line of atomic hydrogen are composed of three levels: $2S_{1/2}$, $2P_{1/2}$, and $2P_{3/2}$. All pairs of the lower energy levels show the irregular cross-over peaks. The ordinary cross-over peak is caused by sharing of the hole burning, which is population dip in the velocity space by the pump laser, on the velocity distribution function with two transitions. The irregular cross-over peaks suggest that the velocity distribution function of different two energy levels have common hole burnings. This means that the frequently population exchange or transfer without velocity change is occurred among the $2S_{1/2}$, $2P_{1/2}$ and $2P_{3/2}$ states. A possibly mechanism of this population transfer is electron impact transfer between $2s$ and $2p$ states. It is known that the electron impact transfer from the $2s$ state to the $2p$ state has significant rate coefficient [8]. In our analysis of the saturation parameter for each fine-structure of the Balmer-alpha line, the $2S_{1/2}$ state has significant relaxation frequency although the $2S_{1/2}$ state is metastable. This result suggests that the population of the $2S_{1/2}$ state is transfer to the other states. The details of the analysis of saturation parameter will be reported elsewhere.
4. Conclusion
We applied saturation spectroscopy to the Balmer-alpha line of atomic hydrogen in a linear magnetized plasma source with the intention of applying it to plasma diagnostics. We observed a clear saturation spectrum with high frequency resolution sufficient to resolve the fine-structure of the Balmer-alpha line with weak magnetic field strength. Saturation spectra with Zeeman-splitting also observed with the intense magnetic field up to 130 mT (1300 Gauss), however, the spectra became complex with many small peaks. Most of the peaks of the saturation spectrum without Zeeman-splitting are assigned as transitions of the fine-structure and ordinary cross-over peaks. However, irregular cross-over peaks also found. This suggests that a frequently population exchange or transfer without velocity change occurs among the 2s and 2p states.

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