Thermal Plasma Diagnostics Using Tunable Dye Laser (Report III)†

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Abstract

With Doppler-free polarization spectroscopy, saturation behavior of the fluorescence was studied on the H_α line in a low density hydrogen plasma. Clear evidence of the saturation broadening was certified for the first in this spectroscopy and the result was compared with the one by the laser-induced fluorescence method.

KEY WORDS: (Thermal Plasma) (Tunable Dye Laser) (Power Broadening) (Doppler-free Polarization Spectroscopy) (Laser-Induced Fluorescence Method)

1. Introduction

In Report I[1] and II[2] we have studied on the spectral broadening of the H_α and the H_β line fluorescences at the saturation condition of absorption in a nearly thermal high density (n_e = $10^{14} - 10^{15}$ cm^{-3}) plasma of hydrogen produced by a high power CW microwave radiation with f = 915 MHz. This broadening was found to be "power broadening" or "saturation broadening", from which we could successfully extract the contribution of the Stark (homogeneous) effect in a line emission with a Voigt profile. It also enabled us to evaluate the electron density without measuring the Stark profile.

Originally the power broadening is of problem to an emission with a homogeneously broadened line shape. So that we aimed further at the Doppler-free spectroscopy[3)–5)] recently attracted much attention in the atomic physics. This method has also been applied[6)] to the plasma diagnostics, in which the Stark broadening was measured with a high accuracy in a low density plasma of $n_e \leqq 1 \times 10^{13}$ cm^{-3}. No attention was paid, however, to the problem of the power broadening, although the saturation condition of absorption was also satisfied in these studies.

We thus performed an experiment to study the saturation behavior in the Doppler-free polarization spectroscopy of a low density hydrogen plasma with $n_e \simeq 1 \times 10^{12}$ cm^{-3}. We also compared the result with the one by the laser-induced fluorescence method (LIFM). As the laser used was a pulsed high power one in this experiment, we expected to obtain a fully saturated behaviors in the spectral profiles of the H_α line in these two methods.

2. Experimental Set-up

The experimental set-up is similar to the one in the previous report. Only the plasma source was changed to a simpler one. A hydrogen plasma was produced in a quartz pipe of 20 mm in diameter at a filling gas pressure of 130 Pa by a CW microwave radiation with f= 2.45 GHz. The input power P_i was several hundred watts and the base pressure was about 5 Pa. The pumping laser was axially injected into the plasma column and the laser induced fluorescence was measured side-on to the quartz pipe. While the Doppler-free spectra were detected in the axial direction, which will be described in Section 3-b).

Typical plasma diameter is 20 mm and its length is 6–12 cm. The dye laser used (FL-2002E, Lambda Physik) has a spectral resolution of 0.056 cm^{-1} which is 0.024 A at the H_α line wavelength.

3. Result and Discussion

a) Laser-Induced Fluorescence

Figure 1 shows the H_α line fluorescence spectra obtained by the laser induced fluorescence method. Without laser pumping the H_α line emission was found to

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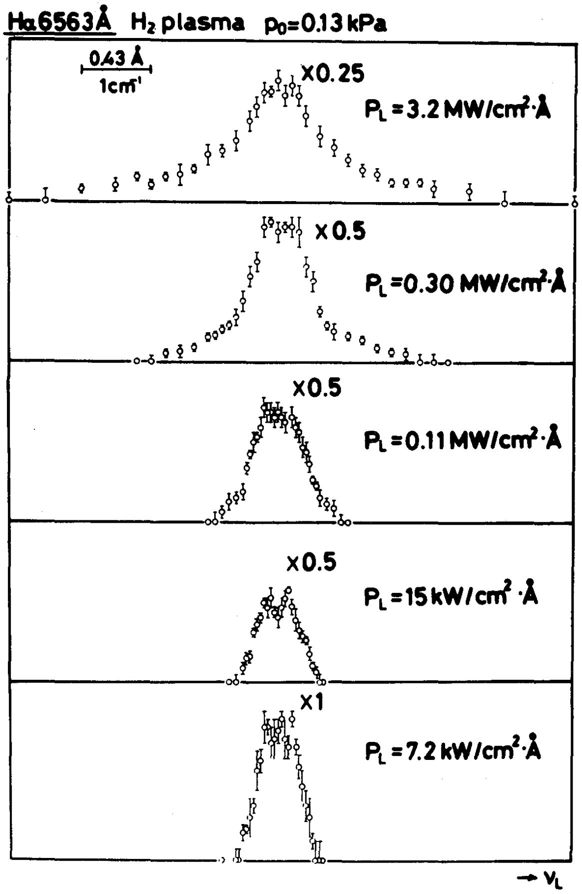

Fig. 1 The H_α line fluorescence spectrum for various laser power density P_L at p_0 = 0.13 kPa.

have a typical Doppler profile. As shown in the figure, the fluorescence spectrum is still governed by the Doppler broadening at the pumping power density P_L of 7.2 kW/cm^2·A. With the increase in P_L, the profile is transformed into the Lorentzian shape from the wing of the spectrum. It is the result of the convolution of Gaussian shape and Lorentzian one, and the latter smears out in the wing when each shape has the same half-width. At P_L = 3.2 MW/cm^2·A, the fluorescence profile becomes a typical Lorentzian shape. This tendency is the same as the one already found in refs. 1) and 2).

Figure 2 shows the saturation curve of the fluorescence. In the figure P_s is the saturation power density and circles

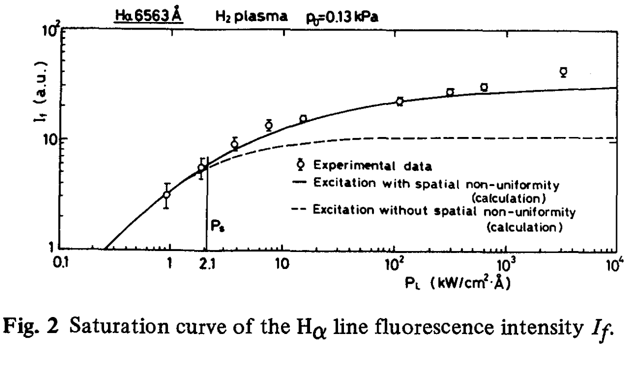

Fig. 2 Saturation curve of the H_α line fluorescence intensity I_f.

with error bars are experimental data. It is clear that the H_α line fluorescence intensity at the central wavelength does not show a full saturation even at a high value of P_L, in contrast to the result in the former reports. In the previous experiments the pumping laser had a radially uniform intensity distribution over the plasma radius. While in this experiment the spatial intensity distribution of the pumping laser has a Gaussian profile with a $1/e$ intensity diameter of 2 mm and the plasma diameter is 20 mm. So that in high power levels of the pumping satisfying the saturation condition, a spatially non-uniform pumping would occur over the plasma diameter. It is known[7] as the modification of the saturation behavior by the spatial variation of the excitation intensity. We have calculated the saturation curves with and without taking into this effect and the result is shown in the figure by solid and broken lines. The experimental result fits well with the calculation with the spatial variation of the excitation.

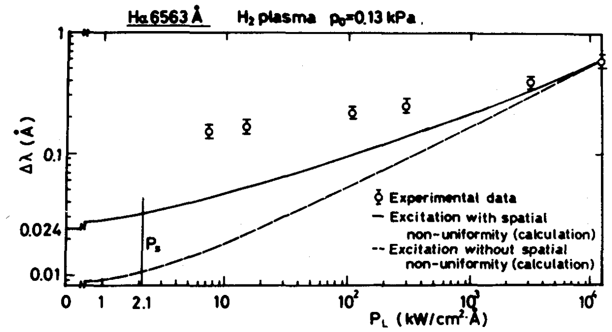

Fig. 3 Dependence of the FWHM $\Delta\lambda$ of the H_α line fluorescence spectrum on the laser power density P_L.

Figure 3 shows the dependence of the full-width at half maximum (FWHM) $\Delta\lambda$ of the fluorescence spectrum on the power density P_L. In the figure, the solid and the broken lines are the calculated curves of $\Delta\lambda$-P_L relation. The experimental data agree with the calculation only at very large value of P_L. We remark that the fine structure splitting of the H_α line is 0.15 A and it is subtructed from $\Delta\lambda$ in the figure to simplify the discussion hereafter. This splitting was also subtructed in the study in Report I or II.

It should be noticed that even at P_L = 13 MW/cm^2·A, $\Delta\lambda$ is only 0.59 A and the discrepancy between experiment and calculation comes from the fact that the original H_α line emission has a typical Doppler profile with FWHM of 0.16 A and the less broadened Stark component is hard to reveal its clear contribution to the power broadening.

Thus we have found that it is not so easy to evaluate the contribution of the Stark component from the power broadening by LIFM in a line almost completely governed by the Doppler profile.

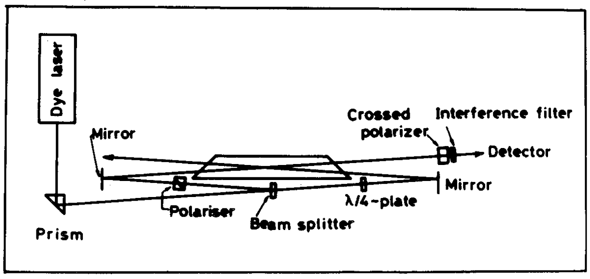

Fig. 4 Schematic diagram of the optical system of the Doppler-free polarization spectroscopy.

b) Doppler-Free Spectra

Figure 4 shows the optical system of the Doppler-free polarization spectroscopy. It is essentially the same as in ref. 5), but the pumping dye laser is a pulsed high power one. We took care in the arrangement so that the probe beam crosses the saturation beam at the plasma center simultaneously. Using an intracavity polarizer in the dye laser system and adding a commercially available camera polarizer to Glan-Thompson prism in front of the detector, we achieved the extinction ratio of the probe beam of 10^{-6} and obtained a good S/N ratio of the detected Doppler-free signal.

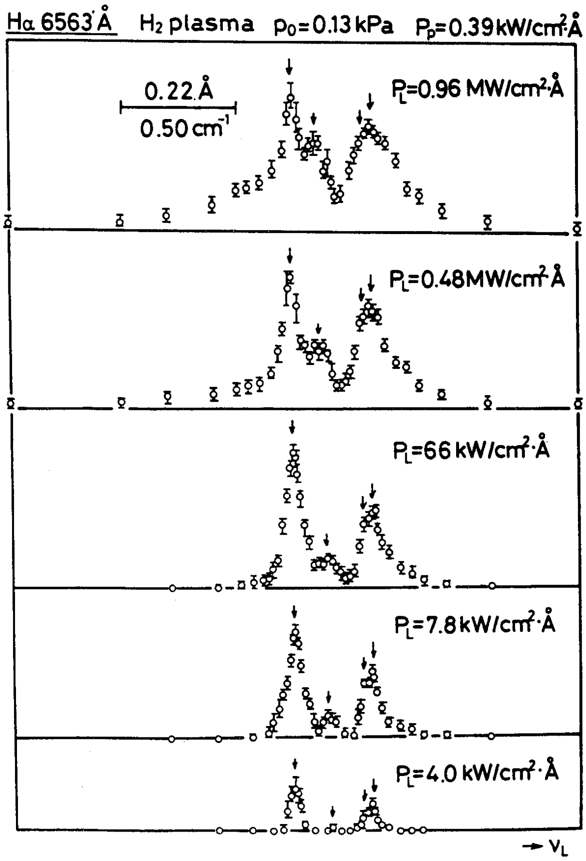

Fig. 5 The H_α line Doppler-free spectrum for various laser power density P_L at p_0 = 0.13 kPa.

Figure 5 shows the Doppler-free H_α line spectra obtained for various intensities of the saturation beam. We can clearly find that the fine structures of the H_α line are separated with a good S/N ratio and that the spectral profile is broadened from the wing of the line with the increase in P_L. The intensity of the individual fine structure line shows the same saturation behavior. This is the first observation of the power broadening in the Doppler-free polarization spectroscopy. We here demonstrate that the power broadening is an essential phenomenon to be observed in the saturation spectroscopy with a tunable dye laser, though quite little attention has been paid until now.

Moreover we remark that the Doppler-free signal is a stimulated emission as the result of the interaction between the saturation and the probe beams, in contrast to the spontaneous emission in case of LIFM. This difference

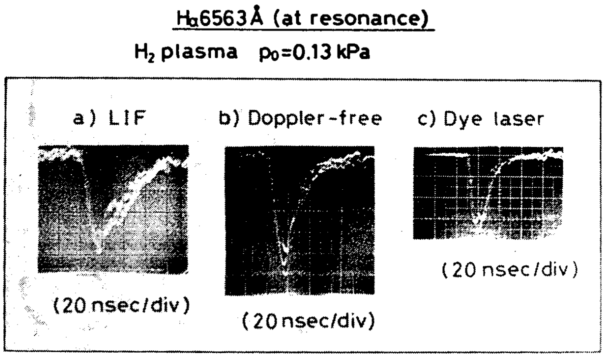

Fig. 6 Oscillogram of laser-induced fluorescence and Doppler-free signal with that of the pumping laser.

is clearly found in **Fig. 6**. In the LIFM time variation of the detected signal follows a decay curve longer than the laser pulse in correspondence with the transition probability A_{32} of the spontaneous emission ($1/A_{32}$ = 22.7 nsec.) While in case of the Doppler-free spectroscopy the detected signal has quite the same form in its time variation with the pumping laser reflecting the fact that it is a stimulated emission.

Figure 7 shows two saturation curves experimentally obtained by LIFM and Doppler-free spectroscopy. In the figure abcissa is the saturation parameter S which is defined to be P_L/P_S. The intensity I_f by the Doppler-free spectroscopy is brought from the most intense one by the transition of $2P_{3/2} - 3D_{5/2}$. From the figure it is clear that I_f by the Doppler-free spectroscopy shows a simple saturation at a certain value of S in contrast to the case of LIFM. As stated earlier, in the latter case the effect of the spatially non-uniform pumping gave a gradually increased intensity even at a high value of S. While in the former case the fluorescence is obtained as a stimulated emission from a very small region where the saturation beam and

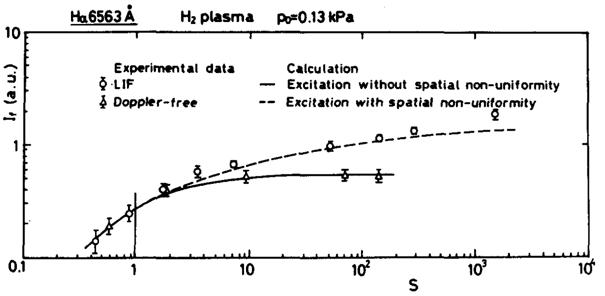

Fig. 7 Saturation curves of the H_α line fluorescence intensity I_f obtained by LIFM and Doppler-free polarization spectroscopy.

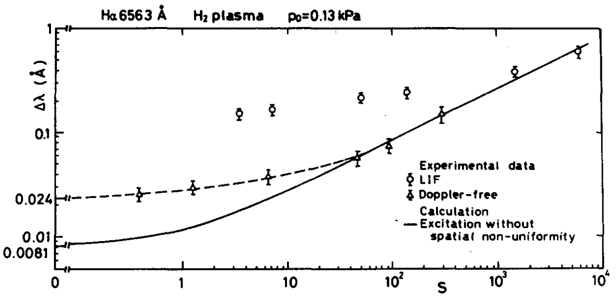

Fig. 8 Dependence of the FWHM $\Delta\lambda$ of the H_α line fluorescence on the saturation parameter S obtained by LIFM and Doppler-free polarization spectroscopy.

the probe beam crosses each other. Indeed the signal is brought as quite a local information and no effect of non-uniform pumping should occur. So that the saturation curve of the Doppler-free signal coincides with the calculated one without the spatially non-uniform pumping effect.

Figure 8 shows the comparison of the dependence of $\Delta\lambda$ (FWHM) on S by the two methods. Of course the width $\Delta\lambda$ by the Doppler-free spectroscopy becomes smaller than that by LIFM, and at $S \geqq 45$ it agrees well with the theoretical curve of $\Delta\lambda = \Delta\lambda_0 \sqrt{1+S}$, where $\Delta\lambda_0$ is the FWHM of the homogeneously broadened line shape. The discrepancy at $S \leqq 45$ is due to the limited spectral bandwidth of the dye laser which is equal to 0.024 A as we can find at $S = 0$. But we could estimate $\Delta\lambda_0$ at $S = 0$ to be 0.0081 A with a good reliability. This is equivalent to a value of n_e of about 1×10^{12} cm^{-3} by the calculation of ref. 8).

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