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

Yoshiaki ARATA*, Shoji MIYAKE and Hidesato MATSUOKA*****

Abstract

Laser-induced fluorescence spectra were measured on the H_α and H_β lines in a thermal plasma produced by a high power microwave radiation. Saturation behavior of the fluorescence was made clear for both lines. Special attention was paid to the check of power broadening using two dye lasers with different spectral bandwidths. It was demonstrated again that the broadening was an important phenomenon in a high density plasma under study and we could estimate the Stark width of the line emission having Voigt or almost Doppler profiles without de-convolution technique. By this active spectroscopy it was also possible to decide the electron density in agreement with the one obtained from the emission spectroscopy.

KEY WORDS: (Thermal Plasma) (Tunable Dye Laser) (Power Broadening) (Laser-Induced Fluorescence)

1. Introduction

In Report I[1)] laser-induced fluorescence spectrum was studied on the H_α line of hydrogen in a nearly thermal high-density plasma produced by a high power CW microwave radiation. Strong broadening of the fluorescence spectrum was observed with an increase in the pumping laser power, and the phenomenon was attributed to "power broadening" or "saturation broadening"[2)] of the fluorescence.

In that experiment, however, the spectral profile of the dye laser used was not good and so broad due to a misalignment in the optical system (Lambda Physik, FL 2000), and it remaind unsolved that the observed broadening might occur due to the pumping of the H_α line by photons at a wing of the incident laser spectrum at a high power level satisfying the saturation condition[2)] of the absorption.

We have rearranged the laser system to obtain the spectral width of 1A. Moreover, we have prepared a new-type dye laser system (Lamba Physik, FL 2002E) having a very narrow bandwidth below 0.1 A at the H_α line wavelength. We checked and certified again that the broadening of the fluorescence spectrum was due to "saturation broadening" as we expected in Report I.

In this report, experimental results are shown on the examination of the power broadening by using the refined and a new-type laser systems with narrower bandwidths than that used in Report I. Besides the H_α line resonance fluorescence, the H_β line fluorescence was also measured and the same broadening phenomenon was clarified again indicating that "power broadening" is of remarkable importance in the study of laser-induced fluorescence in a high density plasma spectroscopy.

2. Pumping on the H_α Line

Figure 1 shows semi-logarithmic plots of the intensity distribution I_L of the dye laser tuned to wavelengths of the H_α and H_β lines. They are the optimum spectra obtained by the rearrangement of the optical system of the dye laser. The spectral width in fullwidth at half-maximum intensity (FWHM) is largely improved compared to the former report and equal to or lower than 1A for both lines.

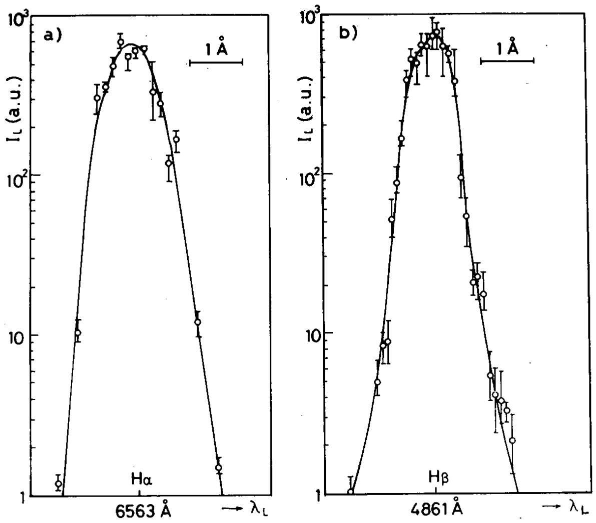

Fig. 1 Intensity distributions of the dye laser tuned to wavelengths of the H_α and H_β lines.

Figure 2 shows a typical spectra of the H_α line fluorescence for different dye laser power density P_L. In this case the electron density n_e was decided to be 1.0 ×

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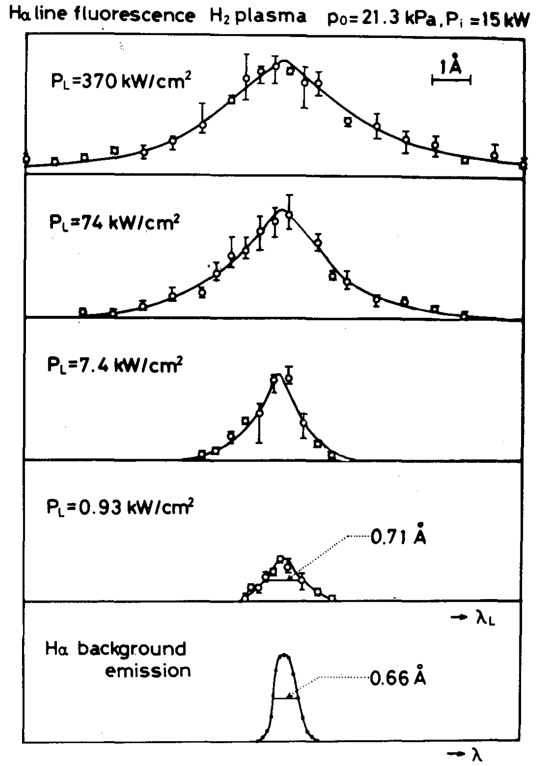

Fig. 2 Typical dependence of the H_α fluorescence spectrum on the laser power density P_L.

$10^{14}\,cm^{-3}$ from the Stark broadening of the H_γ line emission at $\lambda = 4340A$. At a low P_L of $0.93\,kW/cm^2$, the FWHM of the fluorescence spectrum is nearly equal to that of the background H_α line emission and to the laser bandwidth of about 1A. While at $P_L = 370\,kW/cm^2$ of fully saturated condition, the fluorescence spectrum is widely broadened to about 4A having a typical Lorentzian profile.

Figure 3 shows the saturation curves of the fluorescence intensity I_f at three different experimental conditions. In the figure, the data at $p_0 = 48$ kPa was brought from Report I. It is known experimentally[3] that the difference in microwave power P_i results in little change in plasma parameters. So that this figure indicates the fact that the saturation power density P_s decreases with the

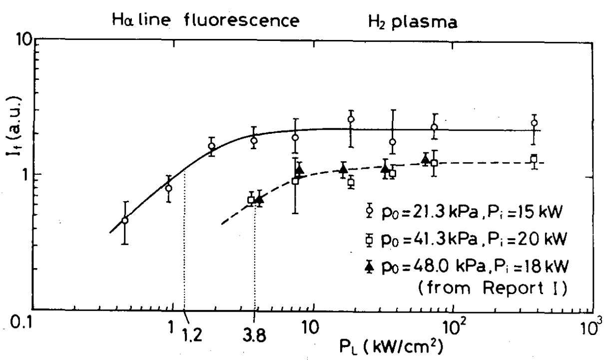

Fig. 3 Saturation curves of the H_α fluorescence intensity I_f for various gas pressures.

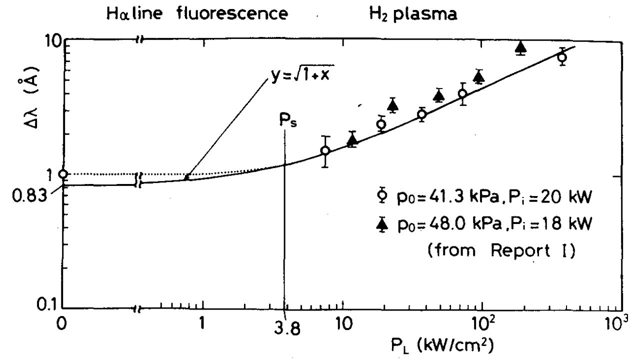

Fig. 4 Dependence of the full-width at half-maximum (FWHM)Δλ of the H_α fluorescence on the laser power density P_L at two different experimental conditions.

gas pressure p_0.

Figure 4 shows full-logarithmic plots of the dependence of the FWHM Δλ of the fluorescence spectrum on the dye laser power density P_L. The data at $p_0 = 48$ kPa was brought again from Report I. In this figure, as well as in Fig. 3, it is clear that there is little difference between the data at $p_0 = 41.3$ kPa and 48.0 kPa. The difference of about 14% in p_0 and it gives a change of 20% in n_e at the maximum, when the electron density varies in proportion to p_0 as stated in Report I. While in Report I the fluorescence spectra showed a very broad and flat distribution at a fully saturated condition in correspondence with the broad laser bandwidth. So that there we subtracted the flat part in estimating the power broadening. It might bring about errors of 10 to 20% in Δλ quite easily. Thus we may conclude that the data in Report I well certifies the occurrence of the power broadening within the experimental error.

At $P_L = 370\,kW/cm^2$ of fully saturated condition, the experimental data at $p_0 = 41.3$ kPa gives $\Delta\lambda = 7.5A$. As stated in the introduction, there is a possibility that photons at a wing of the spectral profile of the incident laser may pump the H_α line at the resonance condition, when the laser power is increased to satisfy the saturation condition. Here the lowering of P_L by two orders gives $3.7\,kW/cm^2$, and it is nearly equal to P_s. As shown in Fig. 1 a), however, the dye laser bandwidth is increased only to about 3A even at $I_L = 1$, which is smaller by about three orders than the maximum I_L of 6.5×10^2 in arbitrary unit. So that it is clear that the observed broadening of the fluorescence is never due to the above mentioned possibility of the pumping at the wing of the laser spectrum.

The data at $p_0 = 41.3$ kPa fits well with a theoretical curve of $y = \sqrt{1+x}$, where x and y are normalized values of Δλ and P_L divided by $\Delta\lambda_0$ and P_s, respectively and $\Delta\lambda_0$ gives the FWHM of a homogeneously broadened half-width of a line emission from the background plasma.

From this curve we can estimate $\Delta\lambda_0$ to be 0.83A by the value given at $P_L = 0$. When $\Delta\lambda_0$ corresponds to the Stark with of the H_α line, it gives the electron density n_e of $1.2 \times 10^{15}cm^{-3}$ from a well-known calculation[4]. It agrees well with that from the measurements of the Stark width of H_β or H_γ lines emitted from the background plasma.

The plasma temperature is known to be about 8000K[3] and the Doppler-broadened half-width $\Delta\lambda_d$ on the H_α line gives 0.42A. Knowing $\Delta\lambda_0$ and $\Delta\lambda_d$ we made a convolution of the line profile using calculated data by Davis and Vaughan[5]. **Figure 5** a) shows the resultant Voigt profile compared with the background H_α line spectrum at $p_0 = 41.3$ kPa. Experimental data agrees well with the calculated prifile. While Fig. 5 b) shows the spectral profile of the measured fluorescence line. It coincides well with a typical Lorentzian line shape drawn in the figure.

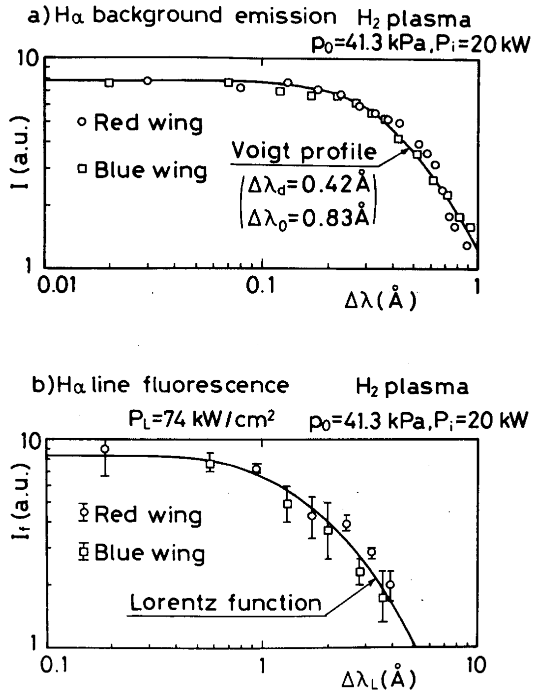

Fig. 5 Spectral profilies of the fluorescence and the background emission of the H_α line.

We have mentioned in the introduction that we have applied a new-type dye laser having a spectral bandwidth below 0.1A to further check the observation of the power broadening. The result is shown in **Fig. 6**. Data with circles are obtained by the laser system with the bandwidth of about 1A as in Figs. 1 to 5. While triangles are the data by the high-resolution laser with the bandwidth of 0.1A at the H_α line wavelength. For the latter laser, only a part of the excited-state particles at the level n = 2 is pumped as the spectral width of the background emission is 0.66A and larger than the laser's. Both data irrespectively fit with the theoretical curve of $y = \sqrt{1+x}$.

From these results it is clear that broadening by a high-

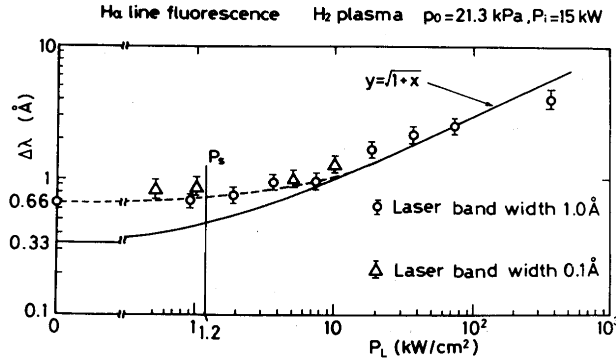

Fig. 6 Dependence of the FWHM $\Delta\lambda$ of the H_α fluorescence spectrum on the laser power density P_L measured by dye lasers with different bandwidth.

intensity laser pumping observed in Report I and this paper is certified again to be "power broadening" or "saturation broadening" and we can estimate the Stark (homogeneous) width of the emission line having Voigt or almost Doppler profiles, making use of this phenomenon.

In Fig. 6 the Stark width estimated from the curve of $y = \sqrt{1+x}$ becomes 0.33A. In this case, however, it should be noted that the fine-structure splitting of 0.15A of the line has remarkable influence[6] to the Stark broadening and the estimation has various problems to be solved further.

3. Pumping on the H_β Line

Figure 7 shows typical dependence of the H_β line

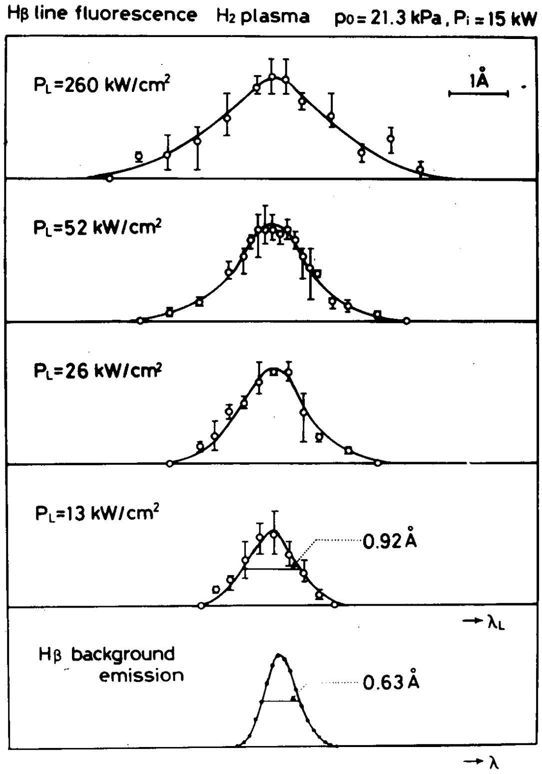

Fig. 7 Typical dependence of the H_β line fluorescence spectrum on the laser power density P_L.

fluorescence spectrum on P_L at p_0 = 21.3 kPa. It is clear that we can obtain the fluorescence spectrum with a good S/N ratio and observe a similar broadening with the increase in the incident laser intensity.

Figure 8 shows the dependence of the fluorescence I_f on P_L at p_0 = 21.3 kPa. Saturation power density P_s for the H_β line is shown to be larger by one order than for the H_α line due to the strong quenching by the electron-impact processes. This tendency coincides with the theoretical estimation by Burges et al.[7]

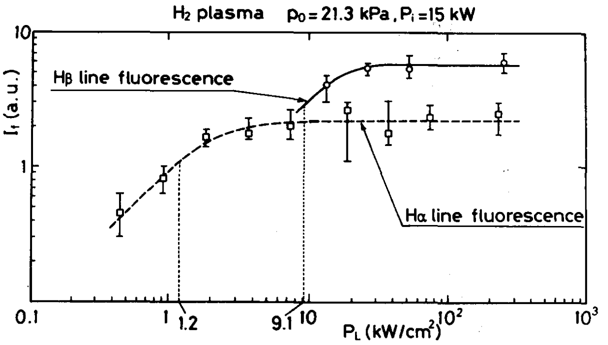

Fig. 8 Saturation curves of the H_α and H_β fluorescence intensity I_f at p_0 = 21.3 kPa.

Figure 9 shows the dependence of $\Delta\lambda$ on P_L at p_0 = 21.3 kP. We estimate again $\Delta\lambda_0$, the Stark width of the background emission. The value of $\Delta\lambda_0$ is found to be 0.5A. The half-width $\Delta\lambda_d$ of the Doppler broadening for the H_β line emission is calculated to be 0.3A at T = 8000K. We made a convolution of the spectrum with $\Delta\lambda_0$ and $\Delta\lambda_d$ and obtained a calculated half-width to be 0.67A. The experimental half-width of the H_β line emission without laser pumping is measured to be 0.63A. Both value are in good conformity as well as for the case of the H_α line. The electron density n_e decided from this estimation gives

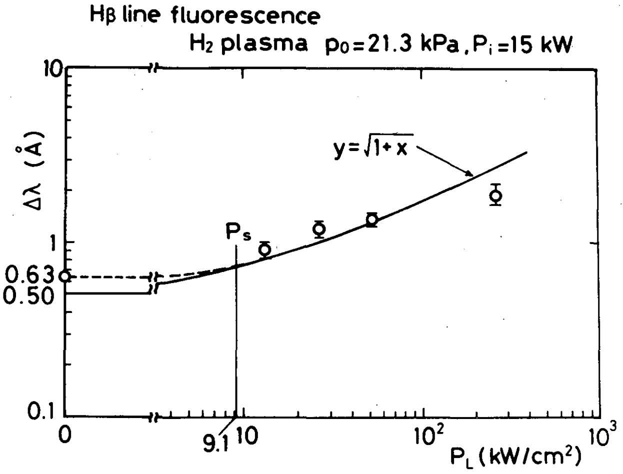

Fig. 9 Dependence of the FWHM of the H_β fluorescence spectrum $\Delta\lambda$ on the laser power density P_L.

$1.0 \times 10^{14} cm^{-3}$, which agrees with the one from the measurement of the half-width of the H_γ line emission having a typical Stark profile in this experimental condition.

Figure 10 shows fluorescence spectra of the H_β line at two different experimental conditions. The profile in the upper part of the figure corresponds to the case n_e = = $1.0 \times 10^{14} cm^{-3}$ and the data in the lower part to $n_e = 1.0 \times 10^{15} cm^{-3}$. Although S/N ratio of the data is not so good for the latter case, a flat spectral profile of the fluorescence is clearly obtained near the center of the line corresponding with the profile of the background emission. To study in more detail this observation is very interesting in connection with the influence of the laser field to the particles under plasma microfield.

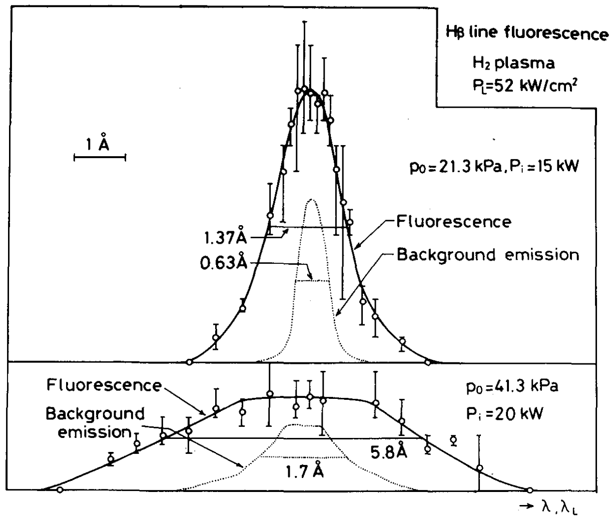

Fig. 10 Fluorescence spectra for the H_β line at two different electron densities.

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