Influences of optical elements on the polarization measurement

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abstract

An emission line of HeI λ 667.8 nm is observed in the Large Helical Device (LHD) with a polarimeter, with which two linearly polarized components of the light from the same line of sight is simultaneously measured. The emission line exhibits splittings due to the normal Zeeman effect and the π and two σ lights are respectively observed. The results indicate the polarization state of emission lines is different from our expectation. From two measurement, for the second of which the polarimeter is rotated 45 degrees from the first, the polarization ellipses of all the three polarized lights are determined. Some observations for a reversed magnetic field plasma operation, for different emission lines of different ions, and also for operations with some different magnetic field strengths suggest that the distortion of the polarization state originates not in the atomic radiation itself or the plasma condition, but in the optical window at the observation port of the vacuum chamber.

1 Introduction

In the plasma polarization spectroscopy, which aims at quantitative determination of the anisotropy of electron velocity distribution function in plasma, a high precision measurement of the polarization state of emitted light is required. If the polarization state is distorted by some reasons other than the anisotropic electron collisions, the reason of the distortion must be made clear and its affection must be removed experimentally or in the analysis.

Some polarization measurements have been carried out in the Large Helical Device (LHD) and we have found a distortion of polarization state which is not ascribed to the anisotropic electron collisions. This article introduces the method we have employed to determine the polarization state of the observed emission lines from a limited number of experimental results and seeks the origin of the distortion.

We mainly use an emission line of HeI λ 667.8 nm (2^1P–3^1D). This line clearly exhibits a normal Zeeman effect and is split into three components which respectively have different polarization states: one of them is the linearly polarized light along the magnetic field direction (*pi* light) and others are the right- and left-handed circularly polarized light on the plane perpendicular to the field direction (*sigma* light). This feature is quite useful for the present study because different types of polarization state can be simultaneously measured.

In LHD whole the magnetic field is stationary formed irrespective of plasma state. Owing to this characteristic, at the end of a discharge most of the ions and electrons in the plasma quench through volume recombination processes rather than dissipation [2] and finally show an intensive radiation on the magnetic axis. This study exploits such a strong and spatially localized radiation is used.

2 Experimental setup

Figure 1 shows a schematic top view of LHD and the line of sight which is on the equatorial plane. From the geometrical relation between the line of sight and the magnetic field direction on the magnetic axis, the polarization ellipses [1] of the π and two σ lights of the Zeeman-split HeI λ 667.8 nm line are expected to have such shapes as shown in Fig. 2. In this case, the spectrum to be observed is shown in Fig. 3. We denote the σ light having a shorter wavelength of the two as σ^+ and the other as σ^- throughout. In the same figure, actually observed data are also drawn with crosses and they show a good agreement with each other.

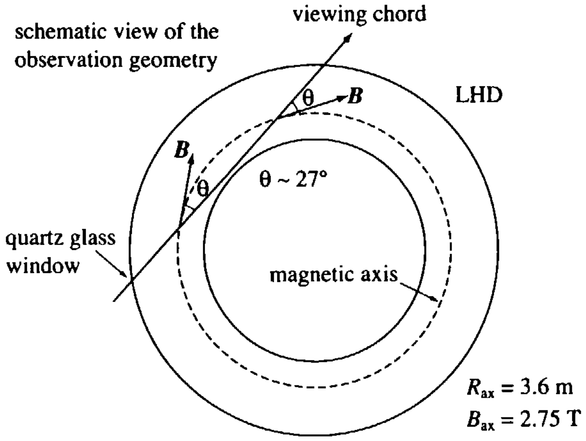

Figure 1: Schematic top view of LHD and the line of sight which is on the equatorial plane. ***B*** indicates the direction of the magnetic field for normal operations.

The magnetic field strength determines the wavelength shift of σ^+ and σ^- lights from the unshifted π light, and the angle between the line of sight and the field direction determines the intensity ratio of π to σ light. The good agreement in Fig. 3 indicates that our assumption that the line emission is localized on the magnetic axis is reasonable.

For the polarization measurement, such an optical system as shown in Fig. 4 is employed. With this polarimeter, two orthogonal components of linearly polarized light from the same viewing chord is simultaneously measurable. In addition to that, the angle of the axes of the linearly polarized light with respect to the equatorial plane can be changed by rotating the polarimeter.

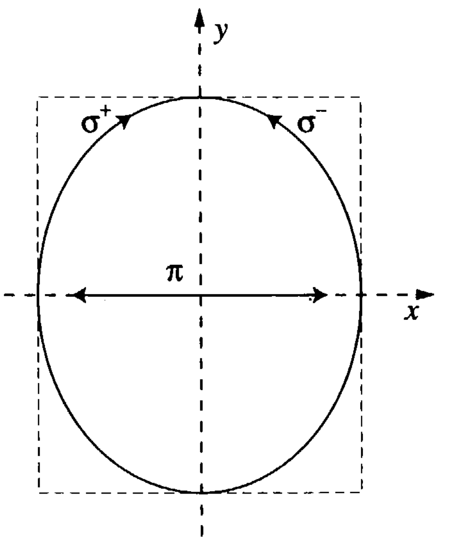

Figure 2: Expected polarization ellipses for the π and two σ lights.

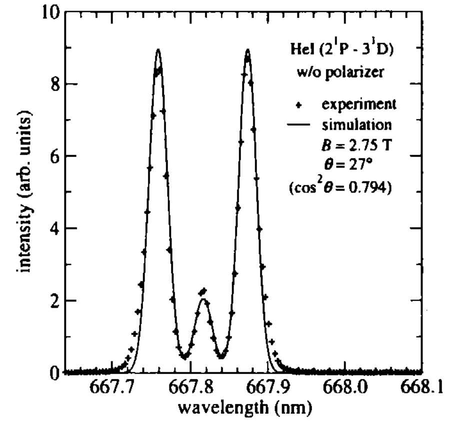

Figure 3: Observed profile of the HeI λ 667.8 nm line. Expected profile based on the polarization ellipses in Fig. 2 is also shown.

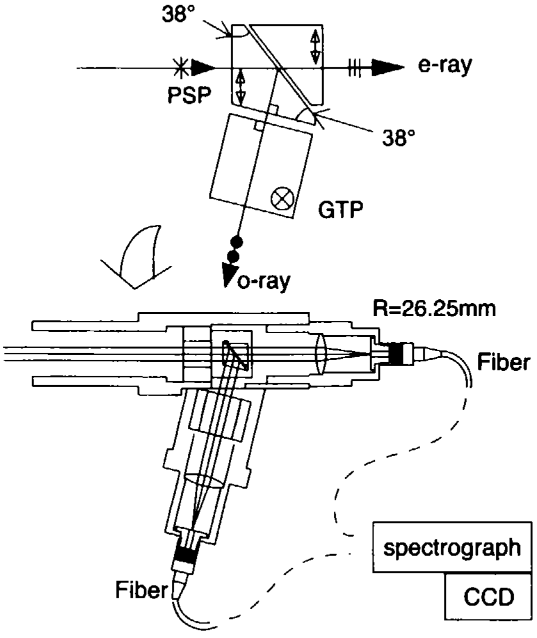

Figure 4: Optical system used for the present measurement. The axes of the linearly polarized lights to be measured can be arbitrarily determined.

3 Results

We have tried a measurement of the same emission line through a polarimeter in Fig. 4. When the two orthogonal axes of the polarimeter are aligned in the horizontal (x) and vertical (y) directions, respectively, the expected spectra are shown in Fig. 5 which is based on the polarization ellipses in Fig. 2. The x component of the π light is denoted as π_x and similarly for others in the following.

From the polarization ellipses in Fig. 2 the π light is expected to appear only in the x component. As for the σ lights the x component should be a little weaker than the y component because the line of sight has a finite angle with the magnetic field direction on the horizontal plane. What should be noted here is that there is no reason which gives rise to differences between σ^+ and σ^- lights.

The results of an actual observation, however, contradict our expectation. They are shown in Fig. 6. In the x component, the intensity of σ_x^- is higher than that of σ_x^+ and vice versa in the y component. The intensities in the x and y components in Fig. 6 can be directly compared because the relative sensitivity including the transmittance of the polarimeter is calibrated. The calibration is carried out as follows. As shown in Fig. 3, σ^+ and σ^- show equal intensities without the polarimeter. This means the summation of σ_x^+ and σ_y^+ is equal to that of σ_x^- and σ_y^-. This is written as

$$I(\sigma_x^+) + \frac{I(\sigma_y^+)}{\alpha} = I(\sigma_x^-) + \frac{I(\sigma_y^-)}{\alpha}, \qquad (1)$$

where $I(\sigma_x^+)$ and others stands for the observed intensities of the respective line components, and α is the relative sensitivity of the y to x components. The coefficient α is then obtained as

$$\alpha = \frac{I(\sigma_y^-) - I(\sigma_y^+)}{I(\sigma_x^+) - I(\sigma_x^-)}. \tag{2}$$

As for π light, the x component predominates over the y component in the actual observation, and this seems reasonable here. More detailed analysis about the π component is carried out later.

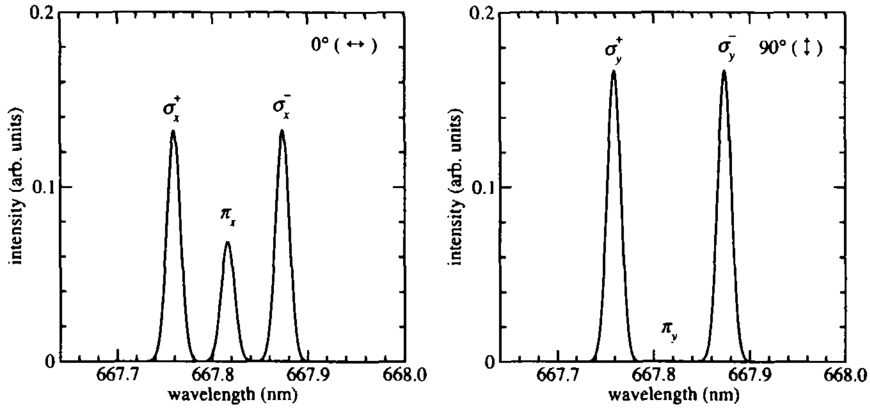

Figure 5: Expected spectra of HeI λ 667.8 nm from the polarization ellipses in Fig. 2 when the axes of the polarimeter is aligned in the horizontal (x) and vertical (y) directions, respectively.

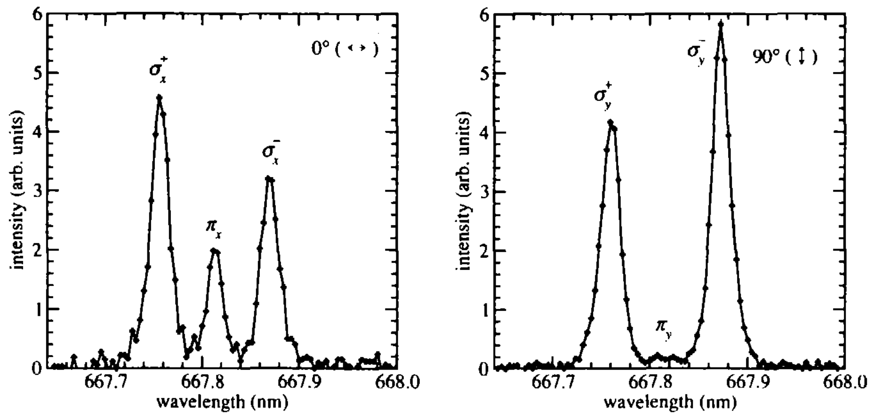

Figure 6: Observed HeI λ 667.8 nm line with the polarimeter, the polarization axes of which are aligned in the horizontal (x) and vertical (y) directions, respectively.

Then we consider the meaning of these asymmetric σ intensities. For this purpose, the polarization ellipses are also helpful. For each of the ellipses, a unique envelope rectangle is drawn, the sides of which are parallel to either the x or y axis. The different σ intensities in the x component indicate that the length of the envelope rectangle in the x axis direction is different between for σ^+ and σ^- lights. The different y component intensities can be considered similarly. These results indicate that the two polarization ellipses, which correspond to σ^+ and σ^-, respectively, have different shapes as schematically shown in Fig. 7, though they are not yet uniquely determined at this moment. The ellipses drawn in Fig. 7 are only examples.

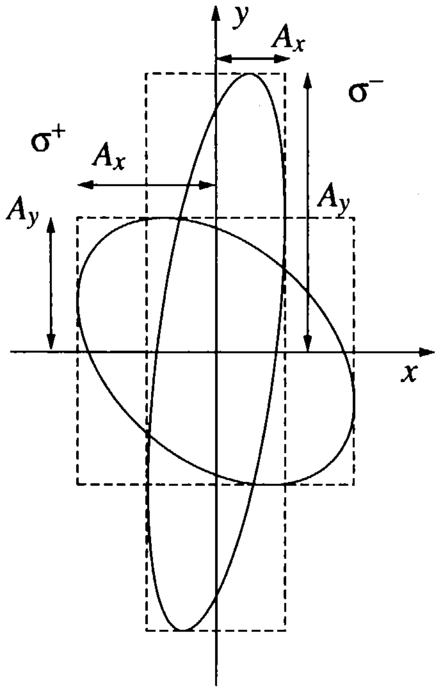

Figure 7: Relations between the observed line intensities and the polarization ellipses or the envelope rectangles when the axes of the polarimeter are aligned in the x and y directions. This figure is only for an explanation and the real observation results are not reflect on it.

In order to identify the polarization ellipses, we have rotated the polarizer 45 degrees and measured the same emission line. If the true polarization ellipses are the ones in Fig. 2, the ξ and η components should be identical as shown in Fig. 8. Figure 9 shows the result of an actual observation. In this case the intensities of the σ^+ and σ^- lights are almost the same in both of the ξ and η components. Therefore we denote their intensity just as $I(\sigma_\xi)$ or $I(\sigma_\eta)$ here.

The results in Fig. 9 are also relatively calibrated. However, a similar calibration method as in the previous case is unavailable because the two σ components have the same intensity. Instead we give attention to the intensity ratio of the σ to π lights. It is readily noticed that the ratio is different between in the ξ and η components. Since the

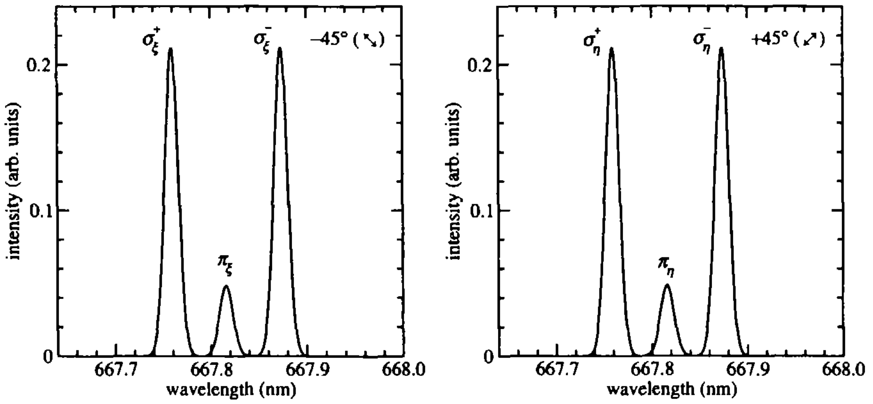

Figure 8: Expected spectra of HeI λ 667.8 nm from the polarization ellipses in Fig. 2 when the axes of the polarimeter is aligned in the −45 degrees (ξ) and +45 degrees (η) directions, respectively.

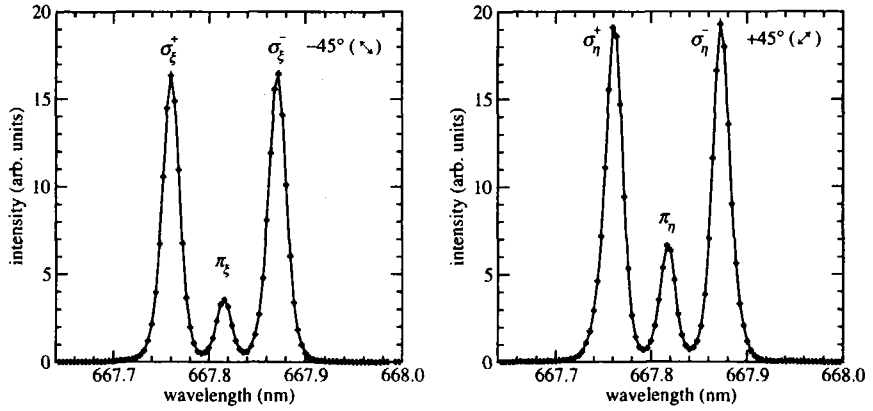

Figure 9: Observed HeI λ 667.8 nm line with the polarimeter, the polarization axes of which are aligned in the −45 degrees (ξ) and +45 degrees (η) directions, respectively.

ratio of the summation of true intensities should be equal to that of Fig. 3, the following equation must hold true,

$$\frac{I(\pi_\xi) + I(\pi_\eta)/\beta}{I(\sigma_\xi) + I(\sigma_\eta)/\beta} = \frac{I(\pi)}{I(\sigma)}, \tag{3}$$

where β is the relative sensitivity of the η to ξ components. The ratio $I(\pi)/I(\sigma)$ is the value without polarimeter. The sensitivity β is obtained as

$$\beta = \frac{I(\pi_\eta) - \frac{I(\pi)}{I(\sigma)} I(\sigma_\eta)}{\frac{I(\pi)}{I(\sigma)} I(\sigma_\xi) - I(\pi_\xi)}. \tag{4}$$

Though the two σ lights have equal intensities respectively in the ξ and η components, $I(\sigma_\xi)$ and $I(\sigma_\eta)$ are different. This contradicts our expectation. $I(\pi_\xi)$ and $I(\pi_\eta)$ are also different and it is confirmed that the polarization condition of the π light is also different from our expectation.

We again try to understand these results with the help of polarization ellipses. Here, the intensities of the two σ lights in the ξ component are identical. This indicates that the length of the envelope rectangle in the ξ axis direction of the two σ lights is the same. η components can be understood similarly. That is to say the two envelope rectangles corresponding to the two σ lights coincide with each other. The situation is schematically drawn in Fig. 10. The ellipses drawn in the figure are, however, again just examples and they are not uniquely determined yet.

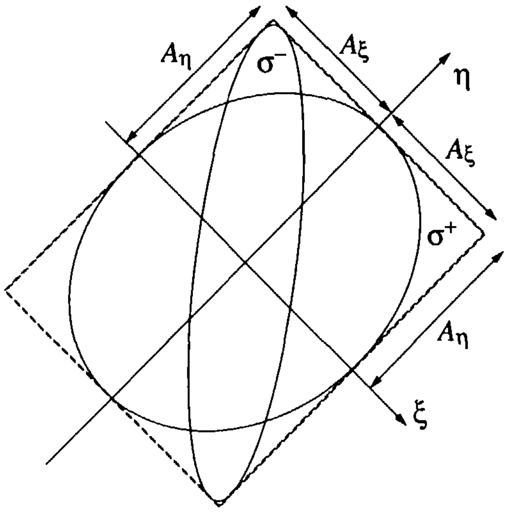

Figure 10: Similar to Fig. 7 but when the axes of the polarimeter is aligned in the ξ and η directions.

So far, for each of the π and two σ lights the shapes of two envelope rectangles for which the axes are rotated 45 degrees from each other, are determined. The relative intensity or the relative scale of the rectangles between in the x-y and ξ-η coordinates is, however, not determined. Since both the measurements are carried out for different discharges, they cannot be compared directly. We normalize them with the total intensity for the moment and this presumes that the relative sensitivity of the system has no dependence on the rotation angle of the polarimeter. The normalization factor γ is therefore derived from a relation

$$I(\sigma_x^+) + I(\sigma_y^+) = \gamma[I(\sigma_\xi^+) + I(\sigma_\eta^+)]. \tag{5}$$

Finally, the two envelope rectangles for each of the π and two σ lights are completely determined.

The polarization ellipse which simultaneously correspond to the two envelope rectangles uniquely exists and it is determined as follows. Any elliptically polarized light is mathematically expressed in the x-y coordinate as

$$x = A_x \cos(\omega) \tag{6}$$

$$y = A_y \sin(\omega + \Delta). \tag{7}$$

Here, A_x or A_y is the the electric field amplitude of the light in the axis denoted by the subscript. The square of this value corresponds to the observed intensity. The relative phase difference Δ is the only unknown quantity in the expression at this moment and is derived as follows. The ξ component of the same light is expressed as

$$\xi = \frac{\sqrt{2}}{2}\left\{A_x \cos(\omega) + A_y \sin(\omega + \Delta)\right\} \tag{8}$$

$$\equiv A_\xi K \sin(\omega + \phi), \tag{9}$$

with

$$A_\xi = \frac{\sqrt{2}}{2}\sqrt{\left\{A_x + A_y \sin(\Delta)\right\}^2 + \left\{A_y \cos(\Delta)\right\}^2}, \tag{10}$$

and

$$\tan\phi = \frac{A_x + A_y \sin(\Delta)}{A_y \cos(\Delta)}. \tag{11}$$

From eq. (10)

$$\sin(\Delta) = \frac{A_\xi^2 - A_\eta^2}{2A_x A_y} \tag{12}$$

is obtained where

$$A_x^2 + A_y^2 = A_\xi^2 + A_\eta^2 \tag{13}$$

is used. There are two candidates for Δ even if the range is subtended from 0 to 2π. They correspond to the right-handed and left-handed elliptically polarized lights and hence the shape is at least uniquely determined. The polarization ellipses for the π and two σ lights which are determined similarly are shown in Fig. 11.

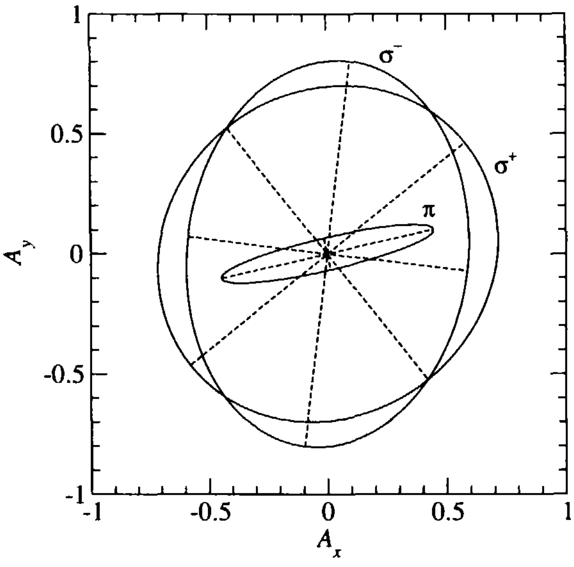

Figure 11: Polarization ellipses for the observed π and two σ lights.

4 Discussion

In the previous section we have shown how to determine the polarization ellipse of the observed light. However, it has not been confirmed whether the light is intrinsically distorted when it is emitted or the emitted light is somehow distorted in the medium. It is generally difficult to intuitively understand the transformation of polarization ellipses, and we usually resort to matrix theories such as Jones and Muller calculi [1], under which a polarization state and an affection to it are expressed as a vector and a matrix, respectively. Though in principle the operator matrix can be determined by observing a required number of transformations for different polarization states, our data is not enough for that purpose. Instead, we guess the reason of the distortion through some characteristics of the phenomena.

First, the same observation is attempted for a discharge with a reversed magnetic field, which means that the filed direction is reversed while other characteristics like the strength are intact. The result is shown in Fig. 12. As compared with Fig. 5, the normal field direction case, it is readily noticed that the asymmetry of the σ^+ and σ^- light intensities is reversed. Under the normal direction field, σ^+ and σ^- lights correspond to the right-handed and left-handed polarized lights from the observer, respectively. When the field direction is reversed, these relations are also reversed. This result implies that the observed distortion of the polarization is not an intrinsic effect on the atomic emission itself but an effect on the emitted light.

Other emission lines are also observed. Figure 13 shows the results for the Zeeman profile of the CIII 3^3S–3^3P lines. Here also shown are the expected profiles under an assumption that the same effect as on the neutral helium case works on this case. The

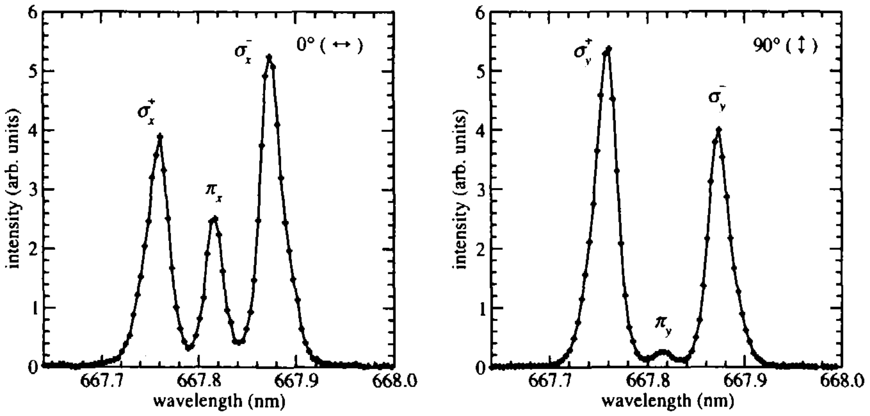

Figure 12: Similar to Fig. 6 but for a discharge of reversed magnetic field.

effect of the magnetic field, however, is not be expressed as a linear effect such as the normal or anomalous Zeeman effect. We have instead solved a problem of general cases of the Zeeman effect and have calculated all the transition components between the magnetic sublevels. We have finally had a good agreement with the experiment as seen in Fig. 13. A similar observation and simulation are carried out for the CII 2s2p(^{3}P^o)3s^{4}P^o–2s2p(^{3}P^o)3p^{4}P lines. The results are shown in Fig. 14 and a good agreement between the experiment and simulation is again obtained. It is inferred from these results that the effect on the polarization state depends on neither the angular momentum states of the energy levels nor the wavelength of the observed emission line, and this make certain our provisional conclusion that the effect works on the emitted light.

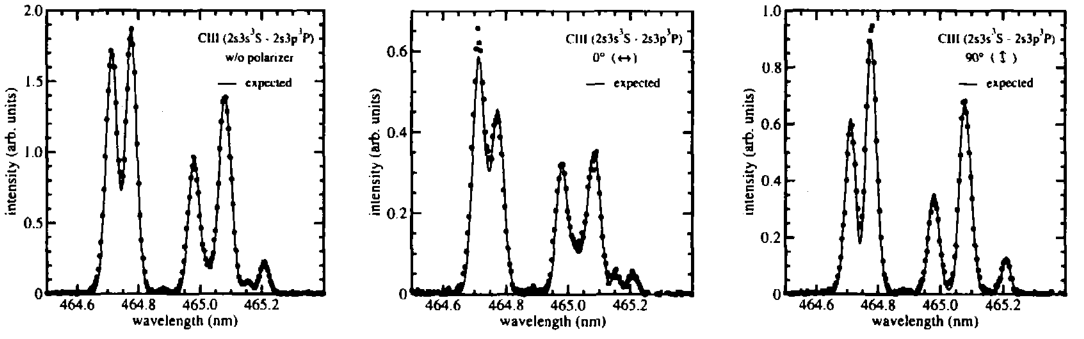

Figure 13: Spectra of the CIII 3^3S–3^3P lines measured with the polarimeter. Synthetic Zeeman spectra with B = 2.75 T and based on the same polarization states as the helium line are also shown.

Finally, the dependence of the effect on the magnetic field strength is investigated. Figure 15 shows the observed y-axis component of the Balmer-α line of neutral hydrogen for three different $B_{\rm ax}$ discharges and no $B_{\rm ax}$-dependence is observed.

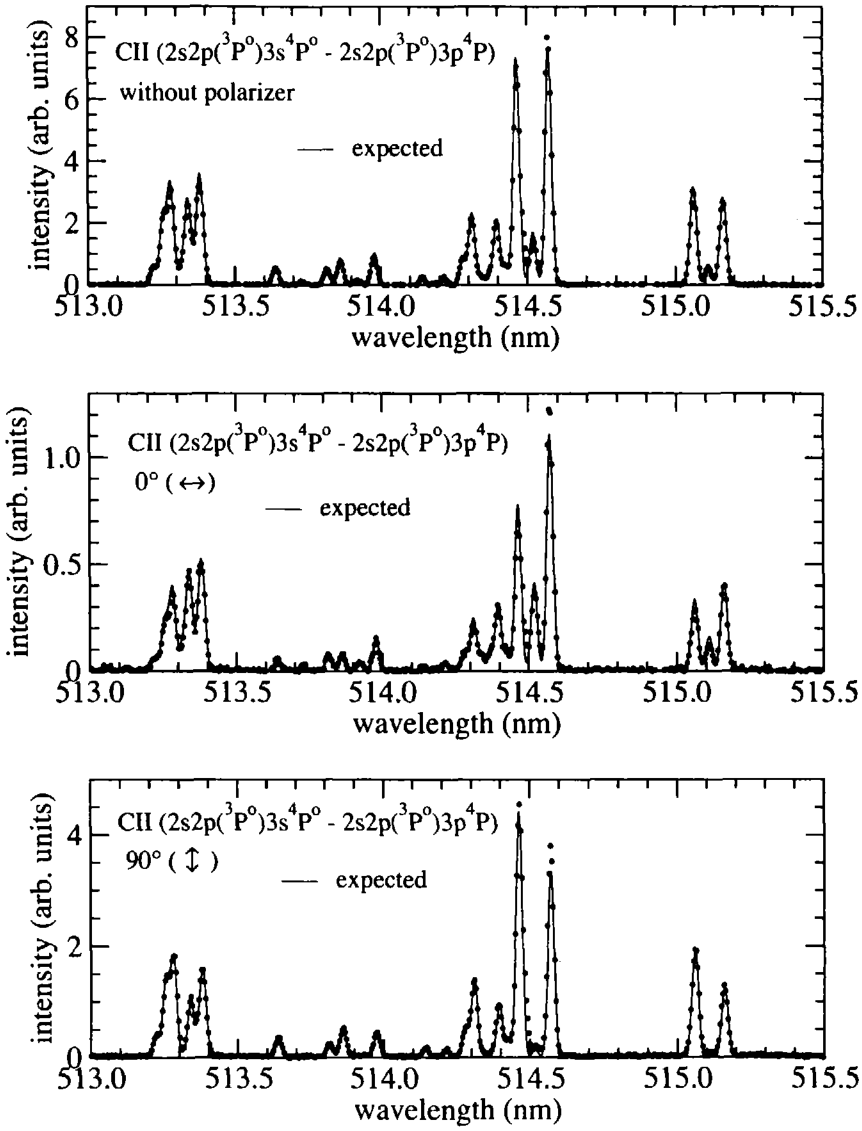

Figure 14: Similar to Fig. 13 but for the CII $2s2p(^3P^o)3s\,^4P^o$–$2s2p(^3P^o)3p\,^4P$ lines.

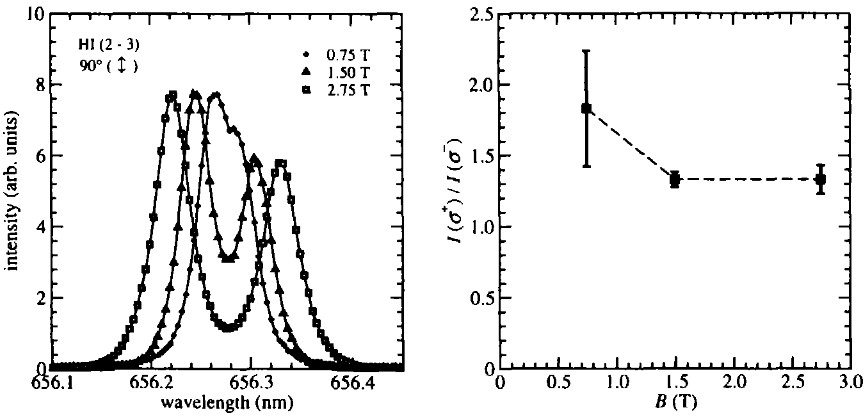

Figure 15: Dependence on the magnetic field of (a) the hydrogen Balmer-α line profile and (b) the intensity ratio of two σ lights.

The comprehensive understanding of the effect from these evidences is that the effect has nothing to do with the plasma and the magnetic field and might be appeared by the photoelasticity of the optical window.

References

[1] D. S. Kliger, J. W. Lewis, and C. E. Randall, *Polarized Light in Optics and Spectroscopy* (Academic Press, Inc., San Diego, 1990).

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