Polarization measurement of hydrogen Lyman-α in the Large Helical Device

N Ramaiya\textsuperscript{1}, M Goto\textsuperscript{1,2}, T Oishi\textsuperscript{1,2} and S Morita\textsuperscript{1,2}

\textsuperscript{1} Department of Fusion Science, SOKENDAI (The Graduate University for Advanced Studies), Toki 509-5292, Japan
\textsuperscript{2} National Institute for Fusion Science, Toki 509-5292, Japan

E-mail: nilam.nimavat@nifs.ac.jp

Abstract. We have investigated the polarization of the Lyman-α line due to anisotropic electron collisions in the Large Helical Device (LHD). Optical components provided by the CLASP (Chromospheric Lyman-Alpha Spectro-Polarimeter) project [Kano R 2017 ApJL 839 L10] team have been incorporated into a VUV spectrometer so that linearly polarized light spectra at different angles can be obtained sequentially. The steady-state phase of an ECH (electron cyclotron heating) discharge has been analyzed, and it is confirmed that the Lyman-α line is polarized. From a temporal variation analysis of the intensity, integrated over the line profile, the polarization degree is evaluated to be 3.4%. A simple theoretical model calculation shows that this polarization degree can be explained by approximately 10% anisotropy in the electron temperature between the parallel and perpendicular directions with respect to the magnetic field.

1. Introduction

In magnetic confinement fusion plasmas, electrons are considered to have an anisotropic velocity distribution function (VDF) because the confinement characteristics are different depending on their velocity pitch angle with the magnetic field. Although knowing the anisotropy in the VDF of electrons is important for the study of plasma confinement, no well established method exists to determine it accurately. On the other hand, it is well known that emission lines from atoms or ions excited by the electrons having an anisotropic VDF are generally polarized and such characteristics of the emission lines can be used to obtain information regarding the anisotropy in the electron VDF [1].

In the Large Helical Device (LHD), the study of the polarization of the Lyman-α line has been initiated. A high-sensitivity polarization measurement is realized with optical components developed by the CLASP (Chromospheric Lyman-Alpha Spectro-Polarimeter) [2, 3] team. In this paper, we describe the principle of the polarization-resolved measurement with an initial result obtained for a typical LHD discharge.

2. Experimental setup

The LHD is a heliotron-type magnetic confinement fusion experimental device. A normal incidence VUV spectrometer having a focal length of 3 m is used for acquiring polarization resolved spectra of the Lyman-α line at $\lambda = 121.56$ nm. Figure 1 shows a schematic drawing of the viewing geometry with the vacuum chamber and magnetic surfaces for the plasma axis.
Figure 1. Viewing geometry of the present measurement for the plasma axis position at $R_{ax} = 3.75$ m.

Figure 2. Optical arrangement of the high-reflectivity mirror and the polarization analyzer in the spectrometer.

at $R_{ax} = 3.75$ m, where $R_{ax}$ is the major radius of the magnetic axis. The field-of-view of the spectrometer is indicated with the dashed lines.

The spectrometer is equipped with additional optics, which consists of a high-reflectivity mirror, a polarization analyzer, and a half-waveplate developed by the CLASP [2, 3] team for the polarization resolved measurement. Figure 2 shows the arrangement of the high-reflectivity mirror and the polarization analyzer. The mirror works to guide the diffracted light from the grating to the polarization analyzer and has a reflection efficiency of 80% at $\lambda = 121.56$ nm. The polarization analyzer, based on Brewster’s angle reflection, only reflects linearly polarized light in the direction vertical to the CCD (charge coupled device) detector (Andor model DO435-BN).

The half-waveplate is placed just behind the entrance slit in the spectrometer and it is continuously rotated during a discharge. Although the detector always receives the linearly polarized light in the vertical direction as mentioned above, the direction of the corresponding linearly polarized light at the emission location changes depending on the optical axis angle of the rotating half-waveplate. During the measurement, the cycle time of the Lyman-$\alpha$ line spectral observation is 50 ms with an exposure time of 16 ms, and the period of the half-waveplate rotation is 1.6 s. Under such conditions, linearly polarized light at every 22.5 degree angle is monitored.

3. Results and discussion

The measurement has been made for an ECH (electron cyclotron heating) discharge having a steady-state phase of about 1 s. Figure 3 shows an example of the measured Lyman-$\alpha$ line spectrum, where both the hydrogen and deuterium lines are observed. In the present analysis, only the integrated intensities of the hydrogen and deuterium lines are considered.

The background subtracted spectrum is integrated over the entire wavelength range shown in Fig. 3 for each time frame and the result is plotted as a function of time, $t$, with open circles in Fig. 4. In the same figure, the angle of the observed linearly polarized light, which is defined here as the polarization angle, is also shown with the dashed line. The polarization angle is measured in the counter-clockwise direction seen from the plasma with reference to the vertical axis. The intensity shows a modulation which is synchronized with the half-waveplate rotation period. This result clearly indicates that the Lyman-$\alpha$ line is polarized.

For evaluating the polarization degree, the steady-state phase of the discharge, i.e., from $t = 3.6$ s to $t = 4.5$ s, is considered so that it can be assumed that the polarization state
Figure 3. The measured Lyman-$\alpha$ line spectrum which includes both the hydrogen and deuterium peaks.

Figure 4. Temporal variation of the Lyman-$\alpha$ line intensity (open circles) and the angle of measured linearly polarized light (dashed line). The solid line is the fitting result.

is unchanged during this period of time. Here, the polarization degree is defined as $P = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}})$, where $I_{\text{max}}$ and $I_{\text{min}}$ stand for the maximum and minimum intensities, respectively. The least-squares fitting is performed on the temporal variation of the intensity, $I(t)$, with a function like

$$I(t) = f(t)[1 + P \sin(\omega t + \theta)],$$

where $f(t)$ represents the global intensity variation, which is here expressed by a second order polynomial, $\omega$ is fixed at $5\pi$ in the present case, $P$ is the polarization degree, and $\theta$ is the phase offset. As a result of this fitting, $P = 3.4\%$ is obtained. The fitting result is shown with the solid line in Fig. 4.

For a quantitative analysis of the derived polarization degree, a theoretical model called the population-alignment collisional-radiative model [1], is under development. A preliminary result of the model calculation suggests that the present polarization degree can be explained by an anisotropy of approximately 10% in the electron temperature between the parallel and perpendicular directions with respect to the magnetic field.

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