

Measurement of Anisotropic Electron Velocity Distribution Function in LHD by Polarization Spectroscopy^{*)}

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Polarization of the hydrogen Lyman- α line is detected in the Large Helical Device. It is the first observation of a polarized atomic emission line in magnetically confined fusion plasma devices. With the help of an atomic model simulation, the anisotropy in the electron velocity distribution function (EVDF) in terms of T_{\parallel}/T_{\perp} is evaluated, where T_{\parallel} and T_{\perp} represent the electron temperature in the parallel and perpendicular directions regarding the magnetic field, respectively. The results show that T_{\parallel}/T_{\perp} has a tendency to decrease and deviate from unity with decreasing electron-electron collision frequency, which qualitatively agrees with an intuitive understanding of the anisotropic EVDF in the plasma boundary.

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1. Introduction

Anisotropy in the magnetically confined fusion plasma is thought to play an important role for characterizing the plasma confinement. The so-called density clamping can be attributed to the difference in characterizations of trapped and passing electrons [1]. The radial electric field formation in the plasma edge stochastic region is thought to be related to the anisotropy in the velocity distribution function (VDF) of electrons (EVDF) [2]. No diagnostic method, however, has been established for the anisotropic EVDF to date. The plasma polarization spectroscopy is a promising technique for that purpose.

When atoms are excited by collisions with electrons unidirectionally moving, resulting line radiation is generally polarized with respect to the direction of the colliding electrons. The polarization degree depends on the energy of the colliding electrons. In a plasma, atoms are excited by electrons having a certain velocity distribution function. If the EVDF has an anisotropy, emission lines from such excited atoms can be polarized. In this paper, we report our attempts to understand the polarization in the Lyman- α line of neutral hydrogen observed for the LHD plasma.

The measurement in LHD is based on the same technique as used in CLASP (Chromospheric Lyman-Alpha SpectroPolarimetry) [3, 4], which aims at observing polarization in the Lyman- α line in the solar atmosphere. For analyzing the measurement results, a simulation model re-

garding the relation between the anisotropic EVDF and the polarization degree of the Lyman- α line is developed following the method formulated by Fujimoto *et al.* [5]. The anisotropy in EVDF is evaluated so that the simulation gives a polarization state consistent with the measurement results.

2. Polarization due to Anisotropic Collisions

The polarization observed in emission lines is ascribed to a population imbalance among magnetic sublevels in the upper state. The hydrogen Lyman- α consists of two fine structure lines, i.e., $1^2S_{1/2} - 2^2P_{1/2}$ and $1^2S_{1/2} - 2^2P_{3/2}$, and the polarization states of these two lines are individually treated.

Figure 1 shows all the magnetic sublevels involved in the Lyman- α line emission. The lines connecting the upper and lower states show all the allowed transitions between magnetic sublevels. The $\Delta m_J = 0$ transitions shown with the vertical solid lines correspond to linearly polarized lights in the quantization axis direction (π -light). The $\Delta m_J = +1$ and $\Delta m_J = -1$ transitions by oblique dashed lines respectively correspond to the right- and the left-handed circularly polarized lights with respect to the quantization axis (σ^+ - and σ^- -lights).

The numbers given next to the transition lines show relative magnitude of the spontaneous transition probability, i.e., Einstein A coefficient. For each of the $1^2S_{1/2} - 2^2P_{1/2}$ and $1^2S_{1/2} - 2^2P_{3/2}$ groups, it is confirmed that when

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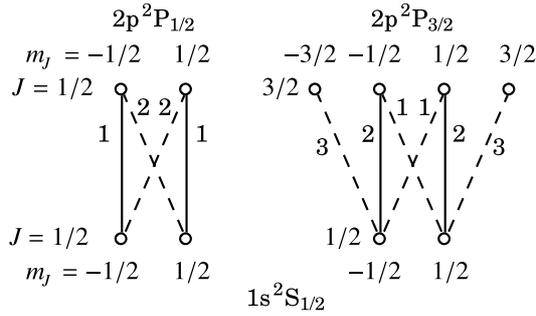


Fig. 1 Kastler diagram for the Lyman- α line. The solid and dashed lines correspond to the $\Delta m_J = 0$ and $\Delta m_J = \pm 1$ transitions, respectively. The numbers next to the lines indicate the relative line intensities when the population in the upper state is equally distributed over all the magnetic sublevels.

the population is equally distributed over all the magnetic sublevels in the upper state, all the π -, σ^+ -, and σ^- -light intensities are identical, i.e., the emission line is unpolarized, otherwise it is polarized.

Here we assume an axisymmetry with respect to the quantization axis which will be later taken in the direction of the magnetic field. In that case, the magnetic sublevel populations have a “mirror symmetry”, i.e., populations of the $\pm m_J$ sublevels are identical in each of the $2^2P_{1/2}$ and $2^2P_{3/2}$ states. Under such a restriction, the $1^2S_{1/2} - 2^2P_{1/2}$ group is never polarized. Because our measurement cannot resolve the two fine structure lines, we first evaluate the polarization state of the $1^2S_{1/2} - 2^2P_{3/2}$ line and then take into account the influence of the unpolarized $1^2S_{1/2} - 2^2P_{1/2}$ line.

For deriving the polarization state of the emission line $1^2S_{1/2} - 2^2P_{3/2}$, we evaluate a quantity “alignment” $a(p)$ besides the population $n(p)$, where p stands for the state $2^2P_{3/2}$. The relative alignment $a(p)/n(p)$ can be translated into the observable polarization degree. We employ a simple atomic model, the so-called “corona equilibrium,” for evaluating $n(p)$ and $a(p)$.

Under the corona equilibrium, the population $n(p)$ is assumed to be formed so that the excitation by electron collisions is balanced with the spontaneous radiative decay. This condition can be expressed as

$$C^{0,0}(1, p)n_e n(1) = \sum_s A(p, s)n(p), \quad (1)$$

where $n(1)$ stands for the ground state population, $C^{0,0}(1, p)$ is the excitation rate coefficient due to electron collisions from the ground state to the state p , $A(p, s)$ is the Einstein A coefficient for the transition from the state p to the state s , and n_e is the electron density.

As for the alignment $a(p)$, a similar equilibrium condition can be considered as

$$C^{0,2}(1, p)n_e n(1) = \left[\sum_s (A(p, s) + C^{2,2}(p, p)n_e) \right] a(p), \quad (2)$$

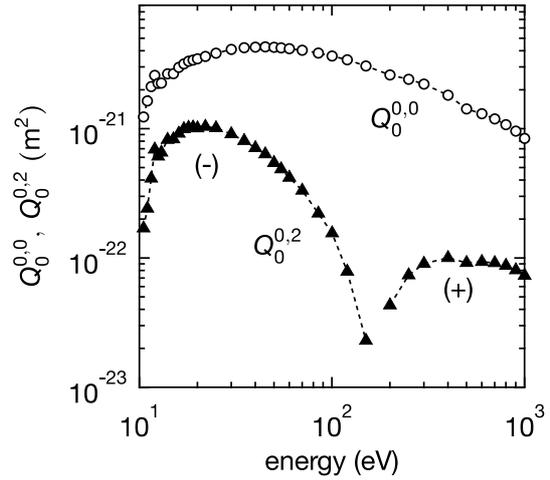


Fig. 2 Cross sections for the excitation $Q_0^{0,0}$ [6] and alignment creation $Q_0^{0,2}$ [7] for calculating their rate coefficients $C^{0,0}(1, p)$ and $C^{0,2}(1, p)$, where p stands for the state $2^2P_{3/2}$. The label (-) indicates that true values take negative sign.

where $C^{0,2}(1, p)$ is the alignment creation rate coefficient accompanying the excitation from the ground state to the state p , and $C^{2,2}(p, p)$ is the alignment destruction rate coefficient of the state p . From Eqs. (1) and (2), $n(p)$ and $a(p)$ can be written as

$$n(p) = \frac{C^{0,0}(1, p)n_e}{\sum_s A(p, s)} n(1),$$

and

$$a(p) = \frac{C^{0,2}(1, p)n_e}{\sum_s A(p, s) + C^{2,2}(p, p)n_e} n(1), \quad (3)$$

respectively.

The rate coefficients $C^{0,0}(1, p)$ and $C^{0,2}(1, p)$ are calculated under a certain EVDF [5] from the cross section data of the excitation $Q_0^{0,0}$ and alignment creation $Q_0^{0,2}$ which are shown in Fig. 2. The excitation cross section is taken from Ref. [6], and the alignment creation cross section is evaluated from polarization degree data due to electron beam collisions [7] following the scheme in Ref. [5]. We employ an axisymmetric EVDF having non-equilibrium electron temperatures between in the parallel and perpendicular directions with respect to the quantization axis or the magnetic field direction, which are here denoted as T_{\parallel} and T_{\perp} , respectively [5].

The alignment destruction process corresponds to the relaxation of the population imbalance among the upper state magnetic sublevels due to electron collisions. This process is known to have some correlation with the Stark broadening [8]. The alignment destruction rate coefficient is evaluated as

$$C^{2,2} = w_s/n_e, \quad (4)$$

where w_s is the full width at half maximum of the Stark

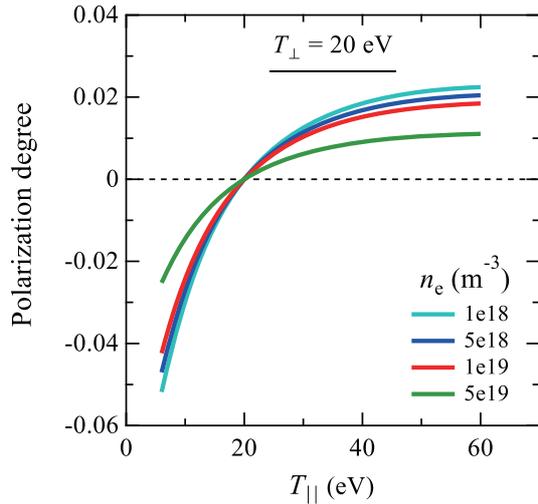


Fig. 3 Simulation results for the polarization degree as a function of T_{\parallel} under a fixed T_{\perp} at 20 eV. The influence of the unpolarized line $1^2S_{1/2} - 2^2P_{1/2}$ is included.

broadening profile. We use the Stark broadening data by Stehlé *et al.* [9] for w_s .

Figure 3 shows the polarization degree P as a function of T_{\parallel} when T_{\perp} is fixed at 20 eV for several n_e values. The results take into account the influence of the unpolarized line $1^2S_{1/2} - 2^2P_{1/2}$. The observation line-of-sight is assumed to be perpendicular to the quantization axis, and P is evaluated as

$$P = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}}, \quad (5)$$

where I_{\parallel} and I_{\perp} are the intensities of linearly polarized light components in the parallel and perpendicular directions regarding the quantization axis, respectively. It is seen that $T_{\parallel} < T_{\perp}$ gives negative polarization degrees, i.e., $I_{\parallel} < I_{\perp}$, and the other way around with the opposite condition. It is also confirmed that the polarization is relaxed with increasing n_e due to enhancement of the polarization destruction process.

3. Experimental Setup

The measurement has been made for LHD with a normal incidence VUV spectrometer having a focal length of 3 m. Figure 4 shows the line-of-sight of the present observation. Line emissions of hydrogen atoms are expected at the plasma boundary, approximately at $r_{\text{eff}} = 0.67$ m [10, 11] as shown by crossing points between the line-of-sight (horizontal dashed line) and the magnetic surface of $r_{\text{eff}} = 0.67$ m (solid curve) in Fig. 4.

Figure 5 shows a schematic drawing of the spectrometer. Some optical components have been supplementary installed in the spectrometer for the polarization measurement. The light dispersed by the grating is reflected 90 degrees into a CCD detector by two mirrors. The mirror in front of the detector is placed at Brewster's angle so that

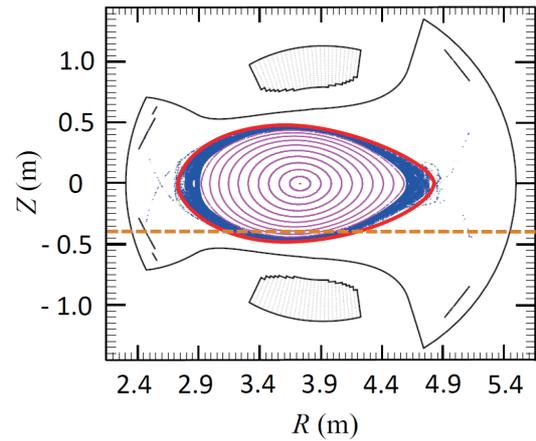


Fig. 4 Cross section of the plasma for the observation and the field of view.

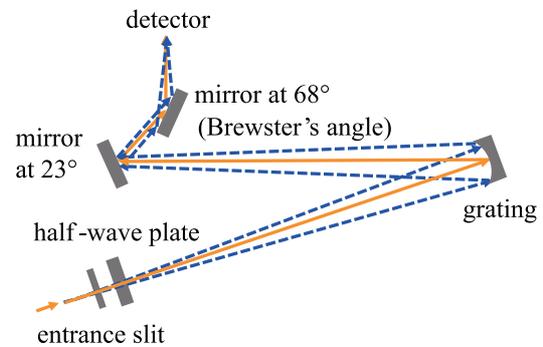


Fig. 5 Schematic drawing of the spectrometer. Two mirrors and a half-wave plate are supplementary installed for the polarization measurement.

the linear polarized angle in the vertical direction is only reflected. The purpose of the second mirror is adjusting the light path angle. These two mirrors have been developed in CLASP so that the reflection efficiency is optimized at the Lyman- α line wavelength.

Another optical component is a rotatable half-wave plate placed between the entrance slit and the grating. Although the linearly polarized light in the vertical direction is always detected at the detector, the corresponding linearly polarized light in the plasma can have angles different from the vertical depending on the rotation angle of the half-wave plate. By rotating the half-wave plate during a steady-state of discharge, we can obtain linearly polarized light components at all angles as a time series.

In the actual measurement, spectra are taken every 50 ms and the rotation speed of half-wave plate is adjusted such that the angle of the linearly polarized light to be observed is rotated 22.5 degrees for every measurement in the counter-clockwise direction observed from the plasma. Figure 6 shows an example of the discharges which the measurement has been made. The magnetic axis position and the magnetic field strength at the magnetic axis are $R_{\text{ax}} = 3.75$ m and $B_{\text{ax}} = 2.64$ T, respectively, for all the dis-

charges used in the present study. The plasma is sustained by the electron cyclotron heating in this case as shown in the top panel in Fig. 6. The bottom panel shows the Lyman- α line intensity which is derived as an integral over the entire measured spectrum. The intensity clearly shows a modulation synchronized with the half-wave plate rotation which indicates that the Lyman- α line is polarized.

We here assume that the polarization state is unchanged during a quasi-steady-state of the plasma and fit the temporal variation of line intensity $I(t)$ with a function,

$$I(t) = f(t) [1 + P_{\text{abs}} \cos(\omega t + \theta)], \quad (6)$$

where P_{abs} is the absolute polarization degree, ω is the angular frequency of the polarized light rotation to be observed, θ is the phase offset. The function $f(t)$ expresses a general temporal variation except the sinusoidal oscillation. The polarization degree P_{abs} is defined as

$$P_{\text{abs}} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}, \quad (7)$$

where I_{max} and I_{min} correspond to the maximum and minimum of the oscillating intensity. The line intensity is well fitted by Eq. (6) with $P_{\text{abs}} = 0.035$. The fitted curve is shown with the red solid line in Fig. 6.

The value I_{min} is recorded at the angle of 55.5 degree which is measured in the clockwise direction from the vertical upward axis when observed from the spectrometer position. On the other hand, according to the magnetic equilibrium database TSMAP [12], the angle of the magnetic field direction at the Lyman- α line emission, i.e., $r_{\text{eff}} = 0.67$ m, on the line-of-sight is 56.1 degree at the inboard side and 108.5 degree at the outboard side. This result suggests that the polarization has a correlation with anisotropy in EVDF regarding parallel and perpendicular

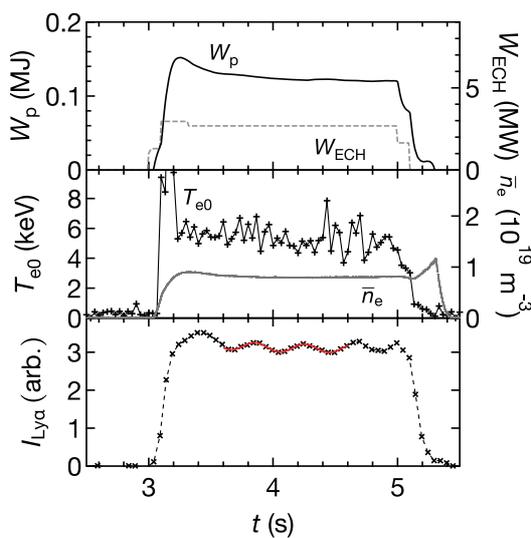


Fig. 6 Example of discharge for the measurement: (a) ECH power and stored energy, (b) line-averaged electron density and central electron temperature, and (c) Lyman- α line intensity of the present observation.

directions to the magnetic field and that the polarization is mainly made at the inboard side rather than at the outboard side. Under such a condition, I_{max} and I_{min} correspond to I_{\perp} and I_{\parallel} in Eq. (5), respectively, and therefore P takes negative values as $P = -P_{\text{abs}}$.

4. Results and Discussion

We have obtained P for a number of discharges including some different plasma heating conditions. Figure 7 shows the results against the line-averaged electron density \bar{n}_e . It is found that P shows a tendency to decrease with increasing \bar{n}_e , while no clear dependence on the heating conditions is seen.

We attempt a derivation of the EVDF anisotropy in terms of T_{\parallel}/T_{\perp} for each P in Fig. 7 with the help of the atomic model introduced above. The n_e and T_e data by Thomson scattering diagnostic are used as the local parameters at the emission location which is assumed to be fixed at $r_{\text{eff}} = 0.67$ m for all the cases [10, 11]. Because the Thomson scattering system in LHD dominantly measures the perpendicular temperature with respect to the magnetic field, T_e data by Thomson scattering are taken as T_{\perp} in the atomic model. The parallel temperature T_{\parallel} is then derived such that the model gives the same polarization degree P as the measurement with the fixed T_{\perp} and n_e .

The results are shown in Fig. 8 where T_{\parallel}/T_{\perp} is plotted against the electron-electron collision frequency ν at the expected emission location. It is observed that T_{\parallel}/T_{\perp} decreases or the anisotropy becomes larger with lowering ν .

This result is qualitatively understandable when the confinement characteristics difference between the trapped and passing particles are taken into account. Particles hav-

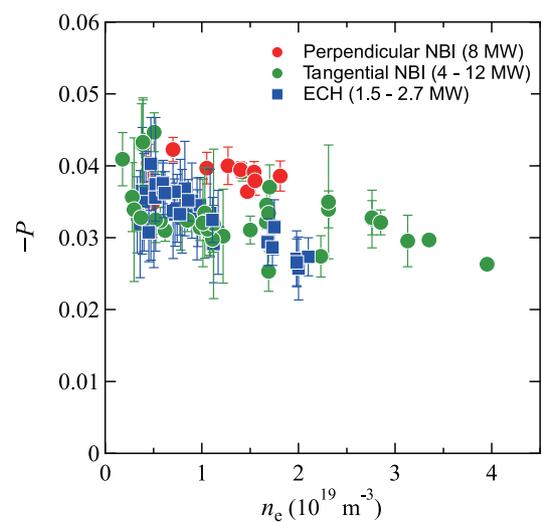


Fig. 7 Measurement results of the polarization degree plotted against \bar{n}_e for some different heating conditions. The red and green circles show results with the perpendicular NBI and tangential NBI, respectively, and the blue squares show results with the ECH.

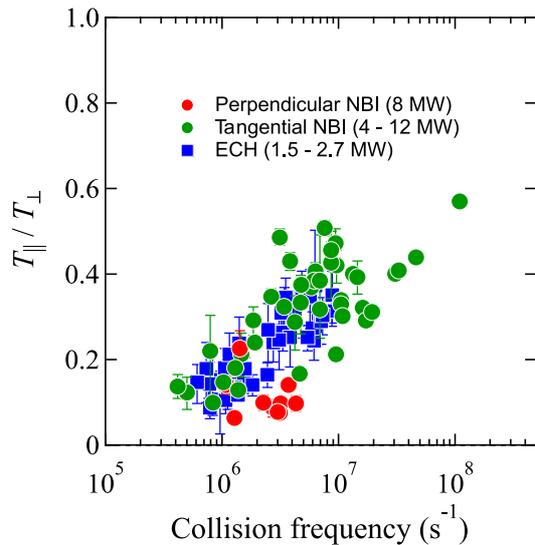


Fig. 8 Anisotropy in terms of T_{\parallel}/T_{\perp} plotted against the electron-electron collision frequency at the expected emission location $r_{\text{eff}} = 0.67$ m.

ing a large velocity component in the direction perpendicular to the magnetic field are called the trapped particles because they are apt to be trapped in the magnetic field ripples due to the mirror effect. On the other hand, particles moving in parallel with the magnetic field are not influenced by the magnetic field ripples and called the passing particles. In the region where the Lyman- α line emissions take place, the magnetic field is open so that the passing electrons are expected to be led to the divertor plates immediately while trapped electrons could remain longer.

It is still an open question why an anisotropy is only observed in the inboard side. A possible explanation is that the line emission observed is actually dominated by the line emission at the inboard side. The neutral flux generally has a poloidal asymmetry in LHD following an inhomogeneous divertor flux, and a previous study of ours demonstrated that the inboard side line emissions are larger in the case of the present magnetic configuration [13]. It is also possible that the anisotropy is smaller at the outboard

side even though line emissions at the outboard side significantly contribute to the observed line intensity. There is actually some difference in the connection length structure between at the inboard side and at the outboard side, and this could cause different anisotropic states in these regions.

Although further investigations are necessary for a clear understanding of the obtained results, the observation of polarized emission line itself is assured, and the present results should be of significance in the study of anisotropy in the magnetically confined fusion plasma.

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