ELSEVIER

Journal of Nuclear Materials 313–316 (2003) 716–719

journal of nuclear materials

www.elsevier.com/locate/jnucmat

# High resolution measurements of the $H_\alpha$ line shape in LHD plasmas

H. Kawazome [a,*], K. Kondo [a], K. Ida [b], K. Takiyama [c], M. Goto [b], S. Morita [b], N. Tamura [d], N. Ohyabu [b], S. Sudo [b], The LHD experimental Group

[a] Graduate School of Energy Science, Kyoto University, Gokasho, Uji 611-0011, Japan
[b] National Institute for Fusion Science, Toki, Gifu 509-5292, Japan
[c] Graduate School of Engineering, Hiroshima University, Higashi-Hiroshima 739-8527, Japan
[d] Graduate University for Advanced Studies, Toki, Gifu 509-5292, Japan

**Abstract**

The shift and fine line shape of $H_\alpha$ emissions in large helical device (LHD) plasmas have been analyzed by a high resolution spectroscopic system. The minimum detectable velocity for hydrogen atoms is $10^3$ m/s. This is confirmed by a newly developed light source with a magnetic field of 1.13 T. In a long-pulse NBI plasma of LHD, hydrogen atoms move toward the plasma from the divertor with velocity of $10^4$ m/s. Fine spectral profile of $H_\alpha$ was measured with a linear polarizer and it shows an asymmetric structure. The spectrum consists of cold component shifted to the blue side and tail extended to 656.0 nm. The energy corresponding to the tail is from 8 to 100 eV.


*PACS:* 32.30.−r
*Keywords:* LHD; Fine profile of $H_\alpha$; Recycling; Plasma flow

## 1. Introduction

In magnetically confined plasmas, it is important to understand the behavior of neutral hydrogen and deuterium for controlling recycling process and obtaining good confinement plasmas. The most essential parameters for understanding the neutral hydrogen and deuterium atoms are their velocity distribution function and the flow velocity. Spectroscopic methods with high-resolution are powerful one to measure above parameters. In recent experiments of tokamaks, the velocity distribution functions of hydrogen and deuterium atoms were measured by spectroscopic methods [1–5].

In helical systems, it is also very interesting to measure the velocity distribution function in the edge plasmas, especially in the ergodic layer and the divertor leg. However these measurements have not been performed yet.

In this paper, development of a high-resolution spectroscopic system and the first measurements of the fine spectroscopic profiles of $H_\alpha$ in large helical device (LHD) [6] plasmas are presented. In Section 2, the experimental setup is shown. The fine spectral profiles of $H_\alpha$ in long-pulse NBI plasmas are shown in Section 3. Summaries are presented in Section 4.

## 2. Experimental setup

The LHD is a toroidal helical magnetic confinement device with a major radius of Rax = 3.5–4 m, an average minor radius of 0.6 m and magnetic field 0.5–3 T. The magnetic field is created by superconducting coil currents and has two X-point and intrinsic divertor legs. In

* Corresponding author. Tel.: +81-774 38 4442; fax: +81-774 32 9397.
*E-mail address:* kawazome@center.iae.kyoto-u.ac.jp (H. Kawazome).

0022-3115/03/$ - see front matter 
PII: S0022-3115(02)01454-X

order to measure the shift of central wavelength and velocity distribution function of neutral hydrogen atoms in LHD long-pulse plasmas, a high-resolution spectroscopic system has been developed. It consists of a collecting optics, optical fibers, a visible spectrometer with an echelle grating and a CCD detector. The spatial resolution of the collecting optics is 20 mm in the edge plasma, and 50 points are focused on the optical fibers with 200 μm core diameter. The focal length of the spectrometer is 1.2 m and the order of the diffraction is 93rd for $H_\alpha$ measurement. The pixel size of the CCD detector (Roper Scientific Co. TE/CCD-1024SB) is 24 μm, and the active detection area is $1024 \times 512$ pixels. The data is transferred by frame transfer mode. The minimum time resolution is 150 ms. The absolute wavelength and the dispersion were calibrated by a hollow cathode discharge in the magnetic field strength of 1.13 T. The hydrogen and deuterium plasma were produced and six spectral lines, σ and π components, of $H_\alpha$ and $D_\alpha$ were used to calibrate the absolute wavelengths in a narrow wavelength region from 656.0 to 656.3 nm. Fig. 1 shows the $H_\alpha$ and $D_\alpha$ spectral profiles measured with a linear polarizer. This $H_\alpha$ spectrum is used as a reference to determine the shift of central wavelength. From this calibration the reciprocal dispersion is 0.0024 nm/pixel and the spectral resolution is 0.016 nm. The minimum detectable velocity for this system is estimated as $10^3$ m/s.

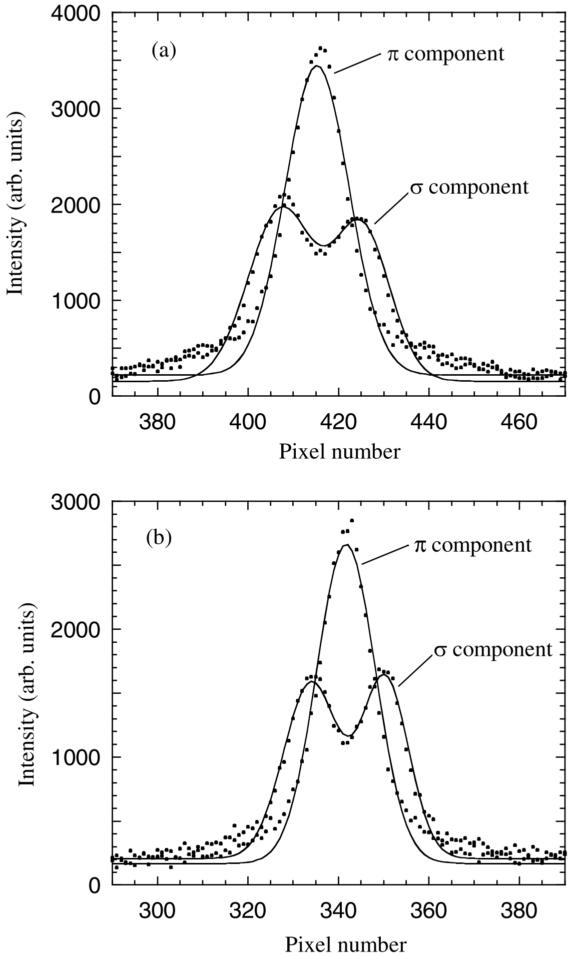


Fig. 1. $H_\alpha$ (a) and $D_\alpha$ (b) spectral profiles measured in a hollow cathode discharges. Two polarized components, σ and π, are obtained with a linear polarizer.

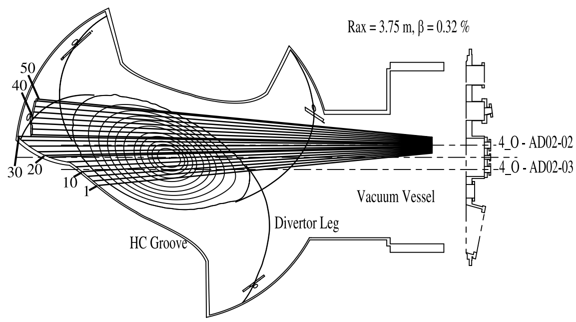


Fig. 2. The poloidal cross-section of LHD and lines of sight.

Fig. 2 shows a poloidal cross-section of LHD and lines of sight. The lines of sight view the inner side of the torus from the outer side. Sight lines #31–50 are viewing the inner divertor plate. The spatial resolution is 20 mm and the distance between the successive lines is 40 mm at the inner divertor plate. Other sight lines are viewing the inner wall. Usually seven sight lines are selected for simultaneous measurements. The lights collected by optics are transferred via quartz fiber bundle to the entrance slit of the spectrometer located in a diagnostic room.

## 3. Fine spectral profiles of $H_\alpha$ in long-pulse NBI plasmas

The spectral profile of $H_\alpha$ were measured in NBI long-pulse plasma. The magnetic axis was 3.6 m and the magnetic field was 2.75 T. The hydrogen plasma was initiated by ECH with 1.2 MW and further heated by neutral beams with 0.7 MW injection power. The pulse duration was 36 s. The average electron density was $3.3 \times 10^{19}$ m$^{-3}$ in the steady state phase. Fig. 3 shows the spectral profile measured on the sight line #25 at 24 s. The width of the entrance slit was 200 μm and the time resolution was 1 s. The reference spectrum of $H_\alpha$ in the hollow discharge is also shown. The shift of the peak to the blue side is clearly observed. The shift is seven pixels, which corresponds to the velocity of $8.0 \times 10^3$ m/s.

Fig. 4 shows the time evolution of the shift of central wavelength for five sight lines and the electron density. As shown in Fig. 2, sight lines #1, #9 and #17 view the wall, and #25 and #33 view near the divertor plate. The

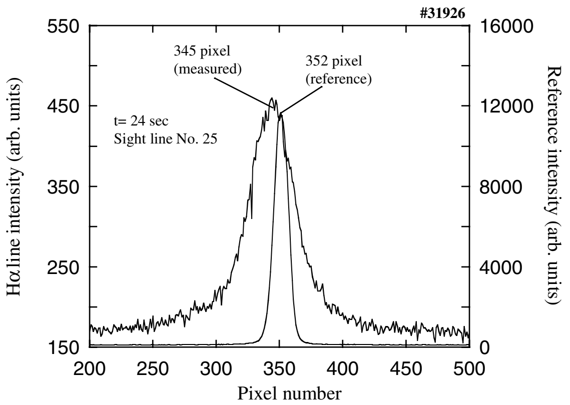


Fig. 3. The spectral profile of $H_\alpha$ observed in the NBI long-pulse discharge. The reference $H_\alpha$ profile by hollow discharge is also shown. The shift of the $H_\alpha$ spectrum in the NBI plasma is seven pixels from the reference line, which corresponds to the velocity of $8.0 \times 10^3$ m/s.

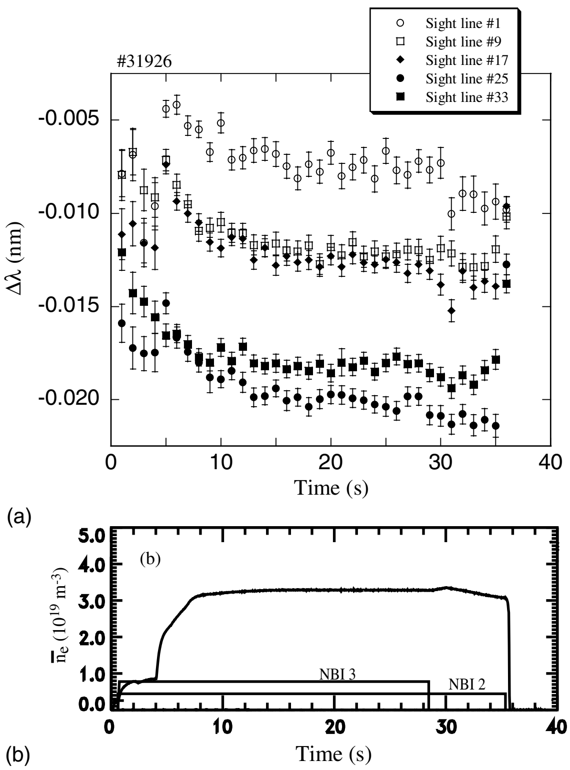


Fig. 4. Time evolution of the shift of central wavelength for several sight lines (a) and the electron density (b).

shift increase as the electron density increases for 10 s. After the electron density reaches to $3.3 \times 10^{19}$ $m^{-3}$, the shift keeps also constant values. The velocity component along the line of sight of $1.0 \times 10^4$ m/s is estimated in the sight line #25.

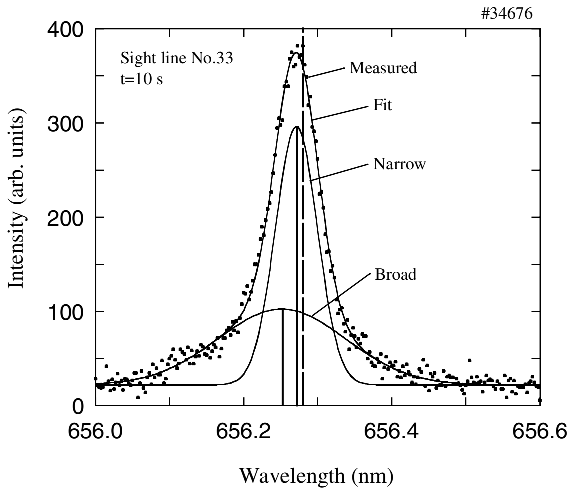


Fig. 5. The spectral profile of $H_\alpha$ measured with a linear polarizer. The profile is fitted to a sum of two Gaussian components. The shoulder in the blue wing is clearly distinguished from 656.0 to 656.2 nm. The corresponding energy region is from 8 to 100 eV.

In order to reject σ-components and separate outer and inner emissions, a linear polarizer is inserted. The angle between the magnetic field line and the line of sight is nearly perpendicular. The field lines at the outer and inner region have different angles to the horizontal plane. The maximum intensity was obtained as the polarizer was set parallel to the inner field lines. Thus emissions were located mainly at the inner part. Fig. 5 shows the spectral profile of π-component. The sight line is #33 and time is 10 s. The time resolution and the width of entrance slit are 2 s and 75 μm, respectively. The hydrogen plasma was heated by neutral beam injection of 1.2 MW and the electron density was $3 \times 10^{19}$ $m^{-3}$. The magnetic axis was 3.6 m and the magnetic field was 1.5 T. The spectrum has an asymmetric feature extended to the blue side. In Fig. 5, the measured spectrum is decomposed into broad and narrow Gaussian profiles. The half widths of the broad and narrow component are equal to the Doppler width of hydrogen atoms at temperature 2 and 18 eV, respectively. The shoulder in the blue wing is clearly distinguished from 656.0 to 656.2 nm. The corresponding energy region is from 8 to 100 eV.

Fig. 6 shows the intensities of narrow and broad components for six sight lines at $t = 20$ s. For the broad component, the intensity of sight line #31 is the largest among them. The intensities from the sight lines around #30 viewing the inner divertor plate are higher than that from sight lines viewing the inner wall. These results are consistent with the simulation of the divertor particle fluxes [7]. The simulation shows that the flux concentrates at inboard side of the torus in the configuration of Rax = 3.6 m. In Fig. 6, the shadow area indicates sight

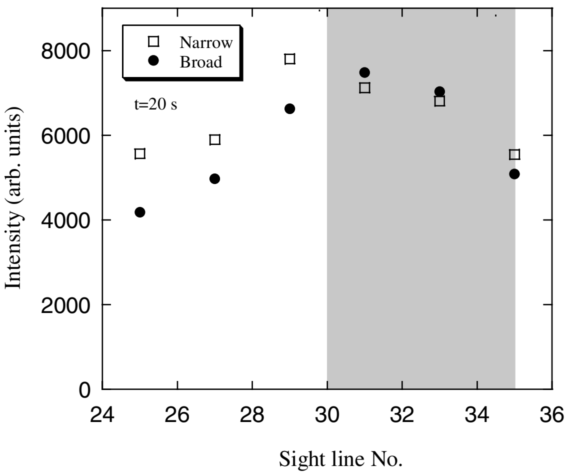


Fig. 6. The intensities of narrow and broad component for six slight lines. The intensities from the sight lines around #30 viewing the inner divertor plate are higher than that from sight lines viewing the inner wall. The shadow area indicates sight lines viewing the region in which the particle flux is concentrated.

lines viewing the region in which the particle flux is concentrated. In a determination of the line emission locations using the Zeeman effect, it is also observed that He I line intensity emitting at near the inner X-point is greater than at the outer X-point [8]. The broad component is due to charge exchange and reflection [9]. But more precise discussion will be given after a simulation code is completed to identify the atomic processes for the broad and narrow components.

## 4. Summaries

The fine spectral profile of $H_\alpha$ has been measured in the long-pulse NBI plasmas of LHD. The blue shift of the measured profile increased in the increasing phase of the electron density. After the electron density reaches to the steady state, the maximum shift of 0.02 nm was observed. The fine profiles of $\pi$-component of $H_\alpha$ are measured with a linear polarizer in the NBI plasma. The spectrum has an asymmetric profile extended to the blue side and the shoulder in the blue wing. The corresponding energy of this component is 8–100 eV. The atomic processes contributing to the line shape will be discussed in future work.

## Acknowledgements

The authors are grateful to the LHD experimental group for their excellent and helpful support and Y. Suzuki for the magnetic field calculation. The collaboration program of LHD experiment supports this study.

## References

[1] U. Samm, H.L. Bay, P. Bogen, H. Harwig, E. Hintz, et al., Plasma Phys. Control. Fusion 29 (1987) 1321.
[2] D. Reiter, P. Bogen, U. Samm, J. Nucl. Mater. 196–198 (1992) 1059.
[3] H. Kubo, H. Takenaga, T. Sugie, S. Higashijima, S. Suzuki, A. Sakasai, N. Hosogane, Plasma Phys. Control. Fusion 40 (1998) 1115.
[4] T. Loarer, L.D. Horton, H. Kubo, C.F. Maggi, P.D. Morgan, M.F. Stamp, M. von Hellermann, JET Report JET-R(99)05.
[5] A. Kumagai, H. Kubo, H. Takenaga, S. Shimizu, N. Asakura, M. Shimada, Plasma Phys. Control. Fusion 42 (2000) 529.
[6] O. Motojima, H. Yamada, A. Komori, N. Ohyabu, K. Kawahata, O. Kaneko, et al., Phys. Plasma 6 (1999) 1843.
[7] T. Morisaki, S. Masuzaki, M. Goto, S. Morita, A. Komori, et al., Contrib. Plasma Phys. 42 (2–4) (2002) 321.
[8] M. Goto, S. Morita, Phys. Rev. E 65 (2002) 02640.
[9] D.P. Stoler, C.H. Skinner, R.V. Budny, A.T. Ramsey, et al., Phys. Plasma 3 (1996) 4084.