Spatial distribution measurement of atomic radiation with an astigmatism-corrected Czerny-Turner-type spectrometer in the Large Helical Device

Motoshi Goto and Shigeru Morita
National Institute for Fusion Science, Toki 509-5292, Japan

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Emission lines in the visible/UV wavelength ranges are observed with 80 lines of sight which cover an entire poloidal cross section of the plasma in the Large Helical Device. The emitted light is received with optical fibers having 100 μm diameter and is guided into a 1.33 m Czerny-Turner-type spectrometer based on spherical mirrors for collimating and focusing. A charge-coupled device having 13.3×13.3 mm^2 area size is used as the detector and the spectra from all the lines of sight are recorded perpendicularly to the wavelength dispersion. The spectrometer is equipped with optics located in front of the entrance slit to correct the difference between the meridional and sagittal focal points, and thus the astigmatism, which otherwise causes severe cross talk between adjacent optical fiber images on the detector, is corrected. Consequently, simultaneous spectral measurement with 80 lines of sight is realized. The Zeeman splitting of a neutral helium line, λ667.8 nm ($2\,^1P$-$3\,^1D$), which is caused by the magnetic field for plasma confinement, is measured with the spectrometer. Though the obtained line profile is in general a superposition of several components on the same line of sight, they can be separated according to their different splitting widths. The two-dimensional poloidal distribution of the helium line intensity is obtained with the help of a tomographic technique. © *2006 American Institute of Physics.*
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I. INTRODUCTION

The Czerny-Turner-type imaging spectrometer is based on spherical mirrors for collimating and focusing so that point sources on the entrance slit are focused at different positions at the exit slit. A simultaneous multispectral measurement is thus realized. However, this type of spectrometer intrinsically suffers from an astigmatism; the sagittal and meridional focal points are different. As a result, the projected image of a point source at the entrance slit is generally elongated in the vertical direction at the exit slit when the wavelength resolution is optimized. In the case of a spatial distribution measurement where optical fibers are aligned along the entrance slit, for example, the spatial resolution could be deteriorated by cross talk between adjacent channels.

Many efforts have been made to correct such an astigmatism of the Czerny-Turner-type spectrometer.[1–5] Most of them are based on an elaborate rearrangement of optical components in the spectrometer. In our study, instead, the spectrometer is equipped with a set of optics in front of the entrance slit to adjust the different focal points on the sagittal and meridional planes. The adjustment is, however, optimized for the central optical axis. When a point source is displaced from the center, the focusing condition is changed due mainly to different optical path lengths between the entrance and exit slits. We replace the normal straight entrance slit with a circularly curved one so as to have the same path length irrespective of the point source position along the entrance slit.

Use of this astigmatism-corrected spectrometer for spectral measurements is made in the Large Helical Device (LHD), which has a rather complicated three-dimensional structure.[6] We observe the emitted light from the plasma with 80 lines of sight in total and their spectra are simultaneously obtained with a charge-coupled-device (CCD) detector.

Though the measurement is line integrated, the Zeeman effect due to the magnetic field for plasma confinement helps us to localize the emission location on the line of sight. In this article we focus our attention on an emission line of neutral helium, λ667.8 nm ($2\,^1P$-$3\,^1D$). Generally, emission lines of neutral helium show a small line broadening as compared to hydrogen lines and are preferable for the measurement of the Zeeman splittings.[7,8] A two-dimensional radiation map of the emission line is finally obtained with the help of a tomographic technique.

II. OBSERVATION SYSTEM

An entire poloidal cross section of the LHD plasma is covered with two optical fiber arrays, as shown in Fig. 1. Each array consists of 40 channels, and their field of view is focused with a set of lenses on the equatorial plane. The core and clad diameters of the optical fiber are 100 and 125 μm, respectively, and the spatial resolution on the equatorial plane is about 30 mm.

The collected light is introduced into the preoptics which project the images of the fiber end surfaces onto the entrance slit of the spectrometer. The spectrometer (McPherson model

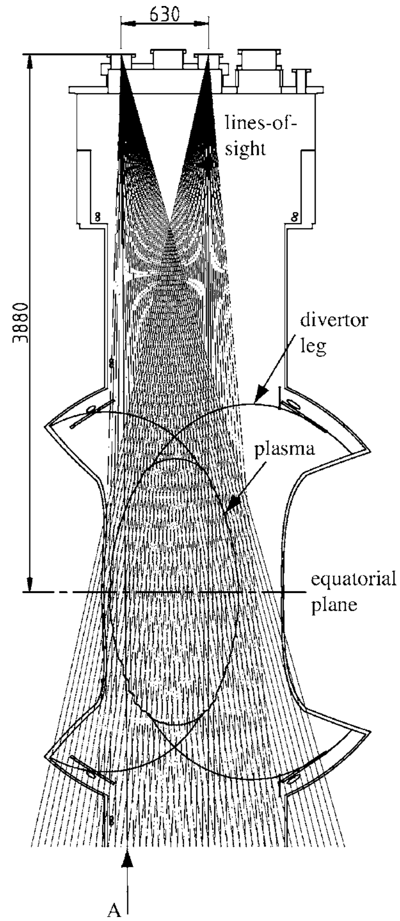

FIG. 1. Cross section of the vacuum vessel and the elliptical plasma for the observation. The major radius of the vacuum vessel center is 3.9 m. The plasma is observed with two arrays of optical fibers. Each array consists of 40 channels. The spectrum shown in Fig. 4 is obtained with the line-of-sight "A" in this figure.

209) has a focal length of 1.33 m and is equipped with a 1800 grooves/mm grating. The geometry of the preoptics is topologically similar to that of the spectrometer and the planes defined by their respective optical axes are perpendicular to each other, as shown in Fig. 2(a). The focal length of the collimating and focusing mirrors is 300 mm. Though a scale identical to that of the spectrometer would be ideal for the preoptics that is impractical, the present scale is found sufficient for our objective to avoid the overlapping between adjacent images.

The entrance slit lies on a circle, as shown in Fig. 2(b): its diameter is the distance between the entrance and exit slits. The end surfaces of the optical fibers are aligned similarly and thus their projected images are centered in the entrance slit at any position.

A CCD detector (Andor DV-435) is placed at the exit slit position and the spectra from all the lines of sight are measured simultaneously. The CCD is operated in the image-transfer mode; all of the electric charge accumulated during the exposure time is first transferred into the buffer area and then sequentially read out. The valid image area consists of 1024×1024 pixels and each pixel size is 13×13 μm^2. The vertical shift requires 16 μs/line and the readout (analog-to-digital conversion) time is 1 μs/pixel.

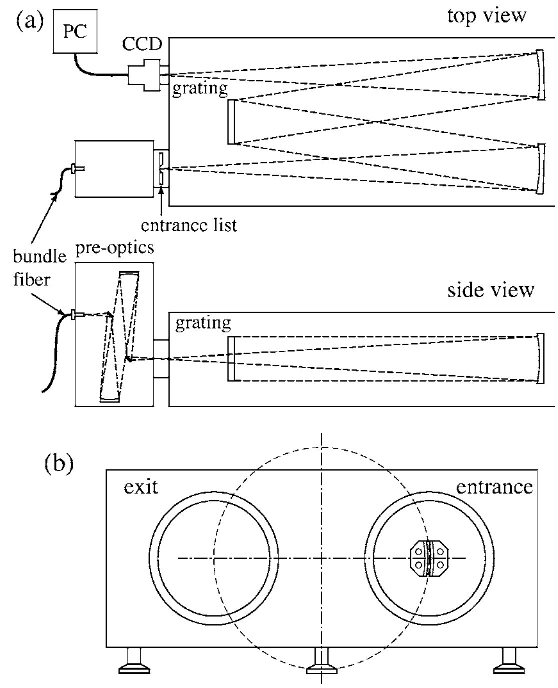

FIG. 2. Schematic geometry of (a) the spectrometer and preoptics and (b) the circulary curved entrance slit. The preoptics are topologically similar to the spectrometer: the focal length of the spherical mirrors is 300 mm, while it is 1.33 m for the spectrometer.

The reciprocal dispersion, which is necessary to derive the absolute Zeeman splitting width, is measured with a mercury lamp (HAMAMATSU L937) at several wavelengths. The results are fitted with a second-order polynomial function and then the dispersion for other wavelengths is readily obtained with accuracy.

The fibers are aligned closely and thus the interval between adjacent fiber centers is the same as the clad diameter of 125 μm. In principle, a measurement with 100 channels is possible with the present detector. Figure 3(a) shows an example of the recorded image of the fiber end surface, for which the entrance slit of the spectrometer is fully opened. Here, the λ253.7 nm line from the mercury lamp is used. The natural broadening and the Doppler broadening of the line are negligibly small under the present condition. The intensity distribution is almost symmetric with respect to the image center, and the full width at half maximum (FWHM) is about 7 pixels or 90 μm in both the horizontal and vertical directions as shown in the left and bottom panels in the figure.

Figure 3(b) shows the result of a test measurement for the LHD plasma. The Balmer-α line of neutral hydrogen is observed with all the lines of sight shown in Fig. 1. The CCD is operated in the full-image mode and the entrance slit width of the spectrometer is 30 μm. This measurement is made with no time resolution, i.e., the entire radiation during a discharge is accumulated. The extent in the direction of the wavelength dispersion is due mainly to the Zeeman effect and the Doppler broadening. The images from different channels are clearly isolated and cross talk between adjacent channels is negligible. In the actual measurement the vertical extent within a single channel is summed up and only the summation result is recorded.

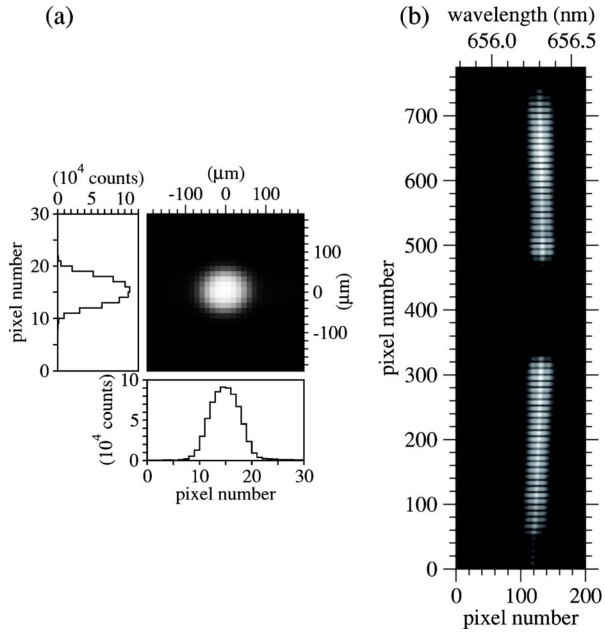

FIG. 3. (a) Projected image of the end surface of a 100 μm optical fiber at the exit slit position. The FWHM is about 90 μm (~7 pixels) in both the vertical and horizontal directions. (b) Example of the full-image mode measurement for the Balmer-α line of neutral hydrogen (656.3 nm) with all the 80 lines of sight. The faintly observed line at about 656.0 nm is He II (n =4–6). The wavelength shown along the upper axis is relative. The curvature is ascribed to the circularly curved entrance slit. The extent in the horizontal direction is due mainly to the Zeeman effect and the Doppler broadening.

The observation system is absolutely calibrated in the wavelength range between 350 and 750 nm. A plate which is coated with a chemical material, the so-called "white reflectance" (KODAK 6080), is irradiated with a tungsten standard lamp (Eppley Laboratory) and the reflected light is observed with the same optics as used in the actual measurement. This plate surface has a reflectivity of higher than 97% in the wavelength range of our interest and produces completely diffusive light in the reflection. The radiance on the plate surface is deduced from these characteristics of the optical components and then the absolute sensitivity of the system is obtained.

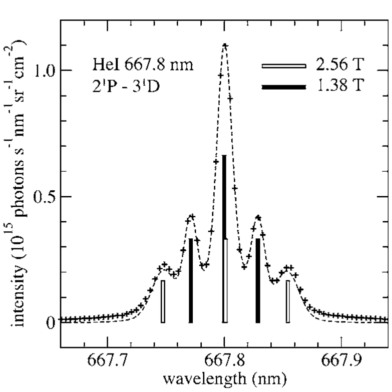

FIG. 4. Measured spectrum for the He I λ667.8 nm line with the line-of-sight "A" indicated in Fig. 1. The profile is well fitted with two Zeeman components and field strengths of 2.56 and 1.38 T are derived.

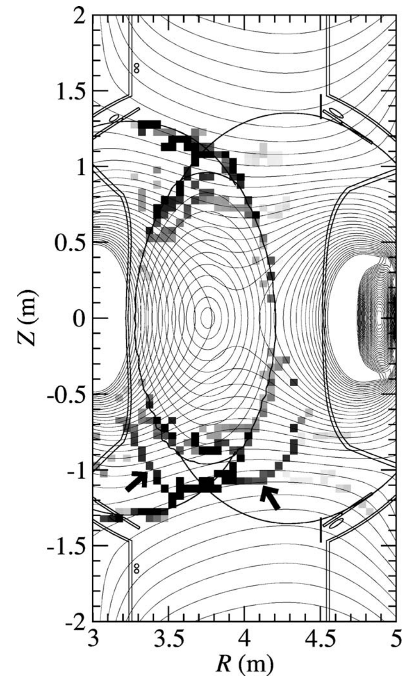

FIG. 5. Obtained Emission locations with all the lines of sight as a result of tomographic analysis. The darkness corresponds to the line intensity. The radiation regions indicated with the arrows seem to be ghosts which have wrongly survived the tomographic analysis.

III. RESULTS

The measurement is made for a discharge with a magnetic configuration of R_{ax}=3.75 m, where R_{ax} is the major radius of the magnetic axis. The magnetic field strength on the magnetic axis is 2.64 T. The plasma is sustained with hydrogen neutral beams and the electron density is controlled with the gas puff of helium. The λ667.8 nm line of neutral helium is observed as already mentioned. The entrance slit width is fixed to be 30 μm.

The spectra are taken every 250 ms (230 ms of exposure time and 20 ms of readout time), and the data over five frames are summed up to reduce the statistical errors. The line-averaged electron density and the center temperature are almost kept constant during the observation to be 2×10^{19} m^{-3} and 2.5 keV, respectively. Figure 4 shows the line profile obtained with the line-of-sight "A" indicated in Fig. 1. The profile is understood as a superposition of two Zeeman components having different splitting intervals. The magnetic field strengths of 2.56 and 1.38 T are deduced from a least-squares fitting. The fitting result is shown with dashed line in Fig. 4. The variation of the field strength along the line of sight is precisely known in LHD, and then the emission locations are determined from the obtained field strength values. In many cases, however, a single field strength gives two locations on the line of sight and in such cases unique determination of the emission location is difficult. Here, let us remind that we observe the plasma with two different angles as shown in Fig. 1 and a tomographic analysis might be possible. The observed area is divided into square cells having 50 mm side length and possible cells for the emission location are picked up according to the Zeeman splitting analysis. The intensity distribution over the candidate cells is then determined so that the following evaluation function $\varepsilon(f)$, where f represents the intensity distribution, has the minimum value,

$$\varepsilon(f) = \sum_i [I_i^{\mathrm{cal}}(f) - I_i^{\mathrm{obs}}]^2. \quad (1)$$

Here, $I_i^{\mathrm{cal}}(f)$ and I_i^{obs} are the line-integrated intensities in the calculation and in the observation with the ith line of sight, respectively. The summation is conducted over all the lines of sight. The result is shown in Fig. 5. The line emissions along the inboard-side divertor legs and around the X points are found to be considerably strong while in the regions near the inboard- and outboard-sidewalls they are hardly detected. This suggests that the dominant particle recycling takes place on the divertor plate rather than the vacuum vessel wall. The radiation regions indicated with arrows in Fig. 5 are unrealistic and are considered to be ghosts which have wrongly survived the tomographic analysis. The present evaluation equation has yet to be optimized and further improvement is necessary.

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