J. Plasma Fusion Res. SERIES, Vol. 5 (2002) 442–445

Measurement of Bremsstrahlung Profile with a High-Spatial Resolution on LHD

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(Received: 11 December 2001 / Accepted: 27 August 2002)

Abstract

Measurements of the bremsstrahlung emission profile have been made in order to measure the effective charge (Z_{eff}) profile in Large Helical Device (LHD). The main diagnostic system consists of a 84 optical fiber array, an interference filter and 84 photomultipliers, which gives a spatial resolution of 5 cm at the plasma center. To evaluate the contribution of impurity line radiation, the wavelength spectrum was measured by a visible spectrometer with a CCD camera. Analysis of the emission was performed using data from the two diagnostics during the quasi-steady phase of NBI-heated discharges. Based on the profiles obtained from the two diagnostics, the effect of line radiation from the edge plasma is discussed. As the results, it was found that the contribution of line radiation to the total radiation from ρ=–0.9 to ρ=0.9 is 20~30 %.

Keywords:

bremmstrahlung, effective charge, X-point, edge plasma, ergodic layer

1. Introduction

The effective charge, (Z_{eff}), profile is used to analyze the behavior of impurities/fuel ions and the state of discharges [1,2]. However, reports of such measurements in helical devices are very limited. A measurement of the bremsstrahlung emission profile has been attempted in LHD. In LHD, the sight lines viewing the plasma center generally pass through the X-point region. Furthermore, the main plasma is surrounded by an ergodic region and radiation by many visible line is emitted from the low-temperature, high-density plasma in this region. Therefore, it is very important to evaluate the contribution of line radiation emitted from the X-point and ergodic regions. For this purpose, an array with an interference filter and a spectrometer were used. In this paper, we report the result of our analysis to determine the contribution of line radiation based on data from the two diagnostics and an Abel inversion method in which the finite β-effect is taken into account.

2. Experimental Setup

LHD is a helical device with a magnetic field of 3 T, major and average minor radii of 3.6 m and 0.6 m, respectively [3]. The ranges of plasma parameters are electron density $n_e \leq 15.0\times10^{19}$ m^{-3}, electron and ion temperatures $T_e \leq 10$ keV and $T_i \leq 4.0$ keV and stored energy $W_p \leq 1.0$ MJ.

The profile of visible bremsstrahlung is measured by a system consisting of an array of 84 optical fibers with a core diameter of 300 μm, an interference filter and 84 photomultiplier tubes (PMTs). Focusing lenses

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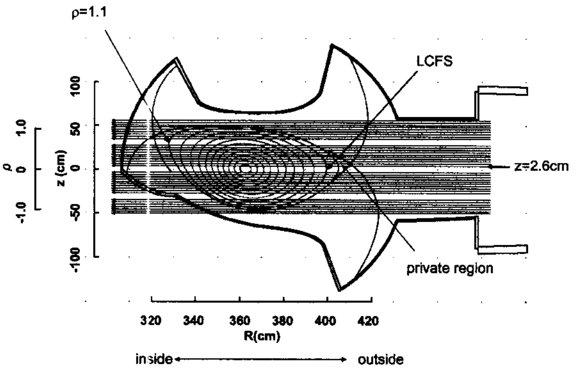

Fig. 1 Parallel viewing chords, magnetic surfaces and the separatrix.

set in front of each fiber make 84 parallel viewing chords along the z-direction on slightly different two poloidal cross-section, where z denotes the vertical distance from the equatorial plane, and the fiber in length of about 100 m transmits visible emissions from the LHD diagnostic port to the diagnostic room. The transmission coefficient measured at He-Ne laser wavelength (633 nm) is about 70 %. The viewing chords cover the whole geometry (z_{max}-z_{min} ~ 900 mm) of the plasma at a horizontally elongated cross section, including the ergodic region. Figure 1 shows the parallel viewing chords relative to the flux surfaces. The spatial resolution of 50 mm in the z-direction is determined by focal length of the lens (30 mm) and the size of the fiber. The time response of the PMT is 10 ms. The central wavelength of the interference filter is 521.5 nm with a FWHM of 5 nm, chosen to avoid regions with strong line emissions. The relative sensitivity among the 84 channels was calibrated using a tungsten lamp and a rotating chopper (1800 rpm). The signal cross talk between channels was negligible, typically less than 1 %.

A second system is a visible spectrometer with a CCD camera. An array of 44 optical fibers with a core diameter of 100 μm is arranged in the vertical direction. The 44 parallel viewing chords observe the plasma at a slightly different toroidal angle (~0.4 degree) from the viewing chords for the array with an interference filter. The exposure time of the CCD camera is 160 msec and the simultaneously observable wavelength range is from 400 nm to 700 nm.

3. Experimental Results

Figure 2 shows a typical spectrum at z=2.6 cm taken with the visible spectrometer, when the line-averaged density was 5.5×10^{19} m^{-3}. Since the

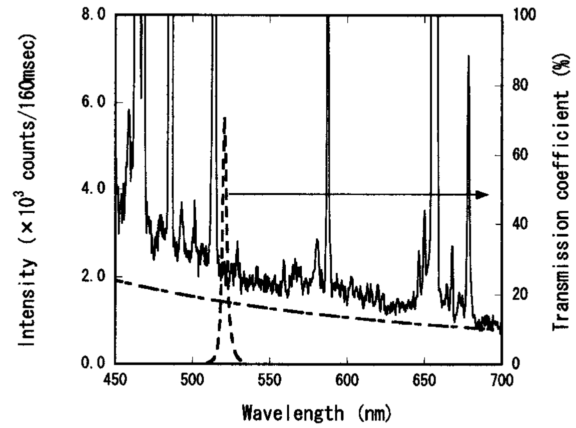

Fig. 2 Visible spectrum measured along a chord at z=2.6 cm (solid line), a curve fit for the continuum level (dash-dot line), and transmission coefficient of the interference filter (dashed line).

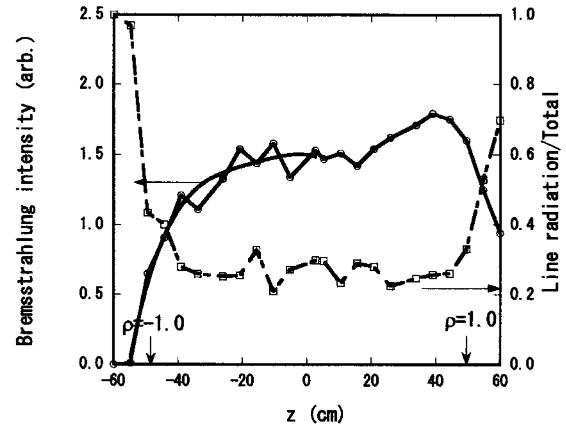

Fig. 3 Chord-integrated bremsstrahlung profile in the z-direction derived from continuum emission and the fitting curve (solid line) and the ratio of line radiation to total radiation (dash-dot line). Data are taken from the spectrum shown in Fig. 2.

bremsstrahlung emission is proportional to λ^{-2}, it can be written as follows ;

$$\frac{\Delta P_{ff}}{\Delta\lambda}=\frac{1.89\times10^{-36}\,n_e\sum_i n_i\,Z_i^2\,\bar{g}_{ff}}{T_e^{1/2}\lambda^2}\exp\left(-\frac{1240}{T_e\,\lambda}\right)\quad[\mathrm{W\cdot m^{-3}\cdot nm}]\ (1)$$

where the units of n_e, n_i, T_e and λ are m^{-3}, m^{-3}, eV and nm, respectively. Since the background noise of the CCD detector is less than a few counts per pixel and is negligible, the continuum emission can be fitted by a curve, as shown with the dashed line. The bremsstrahlung emission profile obtained in this way is shown in Fig. 3. The asymmetric profile of bremsstrahlung originates from the vertical asymmetry in the flux surface geometry at the poloidal cross-section of the measurement. Considering the transmission coefficient of the interference filter, the fitted curve of the continuum emission and the measured spectrum, the fraction of line radiation to the total radiation can be derived. This is also shown in Fig. 3. From $z = -40$ cm to $z = 40$ cm, the ratio of line radiation to the total radiation is estimated to be 20~30 %.

In order to obtain the radial emission profile from the line-integrated measurements using Abel inversion,

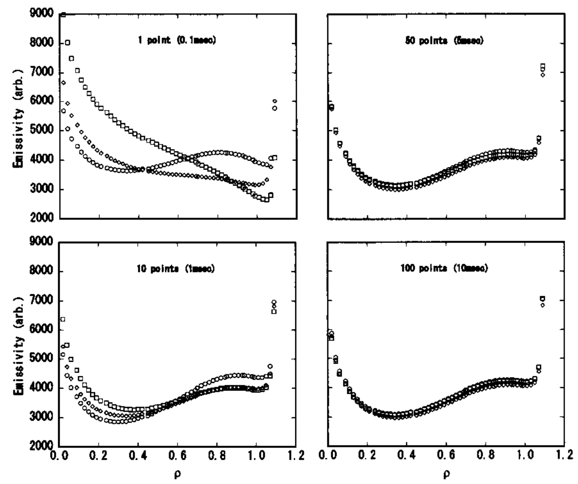

Fig. 4 Convergence of each radial emissivity profile based on time-averaged results with interference filter measurements after Abel inversion.

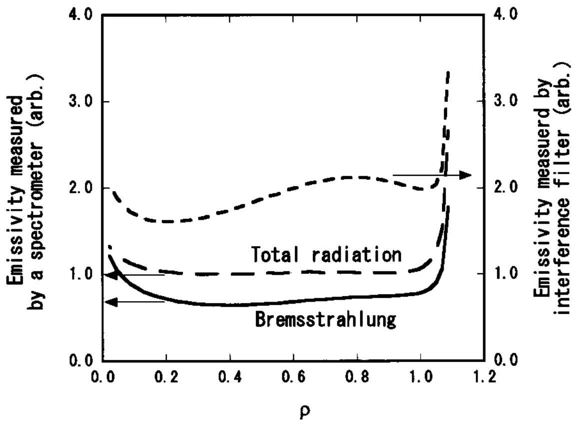

Fig. 5 Radial emission profiles measured with interference filter and bremsstrahlung, and total radiation profiles measured with visible spectrometer. Emissivities are obtained from Abel inversion.

it is important to check the change of the profile with a noise of the measurement system and difficult to evaluate an error bar in conjunction with the calculation of Abel inversion and a measurement noise. The radial emissivity profile was calculated using only lower half of the plasma, because emission from the edge region is very strong in the upper half of the plasma (see Fig. 3). This is probably caused by line emissions from the high density, low temperature region near the inboard X-point. In this Abel inversion, since the signal in the z-direction is zero at $z = 55$ cm (ρ=1.12), the point is used as the boundary condition. To obtain the stable emissivity profile, an effective time resolution of 5 msec at maximum is needed by a time-averaged operation, which corresponds to 50 points due to a sampling time of 0.1 msec. As known in Fig. 4, the convergence of the profiles is saturated from more than 50 points. The three profiles are individually measured by plasma of a same condition, which have the electron density of $n_e = 2.0\times10^{19}$ (m^3). The bremsstrahlung profile measured using the array with the interference filter is presented by the dashed line in Fig. 5, compared to the total radiation profile and the bremsstrahlung profile deduced from the visible spectrometer. These profiles are obtained assuming that the boundary of emission is located at ρ=1.1. The emission increases at the plasma center ($\rho\leq0.2$) in all cases. It suggests that the emission from the vicinity of the X-point is strong and the accumulated error in Abel inversion would appear inside

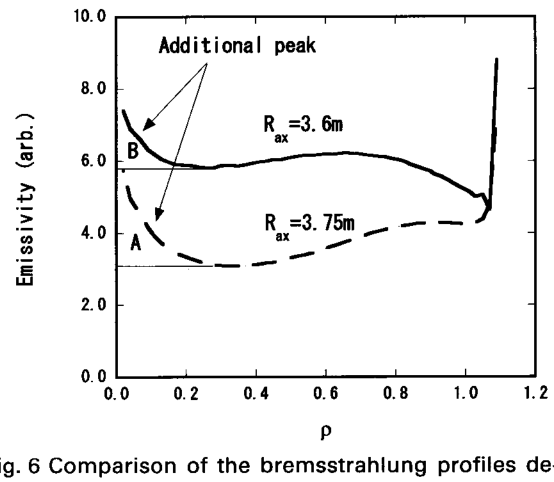

Fig. 6 Comparison of the bremsstrahlung profiles deduced from interference filter measurement between R_{ax}=3.6 m (n_e=2.3×10^{19} m^{-3}) and 3.75 m (n_e=2.0×10^{19} m^{-3}) configurations. Areas indicated by A and B denote integration of the additional emission at $\rho\leq0.3$.

ρ=0.2 because the local emissivity is calculated from the edge of the plasma to the center by turns to solve a matrix equation. In the measurement with the interference filter, the profile has more radial structure than the measurement with the spectrometer. The reason for this difference probably arises from the line radiation contribution. A more complete calibration and more detailed investigation are necessary. In LHD plasmas, the volume of the private region depends on the axis position R_{ax} [4,5]. Path-lengths of the private region in the R_{ax} = 3.6 m and 3.75 m configurations are 13 cm and 20 cm, respectively, at the horizontally elongated cross section. As shown in Fig. 6, the additional peak for the R_{ax} = 3.75 m case is larger than that for the R_{ax} = 3.6 m case. The two reason that these additional peaks appear inside ρ=0.2 can be considered. Firstly, the accumulated error in Abel inversion contributes as noted above. Secondary, as known in Fig. 1, emissions from the private region (inside ρ=0.2) are also detected and the contribution is not taken into account in Abel inversion at present. The ratio of the integrated additional peak at the plasma center, A/B, is usually 1.93 and different from the ratio (20/13~1.54) of path-lengths between the R_{ax} = 3.75 m and 3.6 m configurations. Even if each additional peak includes the accumulated error in Abel inversion, it can be concluded that the cause for the peak is the contribution from the emission in private region. The region has an electron density to some extent and is not understood in the magnetic structure.

4. Summary

Visible bremsstrahlung emission has been measured by two diagnostics in NBI-heated discharges of LHD. The contribution of line emissions was estimated to be 20~30 % by separating the continuum emission in the visible spectrum measured by the spectrometer. The aim of the diagnostic using the interference filter is to study the transport of impurity in combination with impurity pellet injection within the time-scale of several millisenonds and to complete Z_{eff} profile measurement. In the near future, the boronization is planned in LHD to suppress metallic impurities [6]. The contribution of line radiation can be investigated in more detail, since it is expected that the line contribution would be reduced by boronization.

The authors thank Prof. H. Yamada (NIFS) for his help on magnetic surface calculation programs and all members of the LHD experimental group for their supported.

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