Two-Dimensional Distribution of Electron Temperature in Ergodic Layer of LHD Measured from Line Intensity Ratio of CIV and NeVIII*)

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Two-dimensional distribution of impurity lines emitted from ergodic layer with stochastic magnetic field lines in Large Helical Device (LHD) has been observed using a space-resolved extreme ultraviolet (EUV) spectrometer. The two-dimensional electron temperature distribution in the ergodic layer is successfully measured using the line intensity ratio of Li-like NeVIII 2s-3p ($^2S_{1/2}$-$^2P_{3/2}$: 88.09 Å, $^2S_{1/2}$-$^2P_{1/2}$: 88.13 Å) to 2p-3s ($^2P_{1/2}$-$^2S_{1/2}$: 102.91 Å, $^2P_{3/2}$-$^2S_{1/2}$: 103.09 Å) transitions emitted from radial location near Last Closed Flux Surface (LCFS). The intensity ratio analyzed with ADAS code shows no dependence on the electron density below 10^{14} cm^{-3}. The result indicates a little higher temperature, i.e., 220 eV, in the poloidal location at high-field side near helical coils called O-point compared to the temperature near X-point, i.e., 170 eV. The electron temperature profile is also measured at the edge boundary of ergodic layer using the line intensity ratio of Li-like CIV 2p-3d ($^2P_{1/2}$-$^2D_{3/2}$: 384.03 Å, $^2P_{3/2}$-$^2D_{5/2}$: 384.18 Å) to 2p-3s ($^2P_{1/2}$-$^2S_{1/2}$: 419.53 Å, $^2P_{3/2}$-$^2S_{1/2}$: 419.71 Å) transitions. The intensity ratios analyzed with CHIANTI, ADAS and T.Kawachi codes show a slightly higher temperature near O-point, i.e., 25 eV for CHIANTI, 21 eV for ADAS and 11 eV for T.Kawachi's codes, compared to the temperature at X-point, i.e., 15 - 21 eV for CHIANTI, 9 - 15 eV for ADAS and 6 - 9 eV for T.Kawachi codes. It suggests that the transport coefficient in the ergodic layer is varied with three-dimensional structure.

Keywords: line intensity ratio, electron temperature, Li-like CIV and NeVIII, EUV spectrometer

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1. Introduction

Line intensity ratio between two different transitions in the same ionization stage is an essential tool to measure the electron temperature and density in astrophysical plasmas [1]. In order to measure the electron temperature the ratio of 2s $^2S_{1/2}$-3p $^2P_{3/2}$ to 2s $^2S_{1/2}$-2p $^2P_{3/2}$ transitions for Li-like ions is generally used because both lines are very strong and the ratio is sufficiently sensitive to the electron temperature, e.g. CIV (312.4 Å/1548 Å) and NeVIII (88.1 Å/770.4 Å) [2]. However, it is difficult to measure the line pair simultaneously using a single spectrometer. It may introduce a large uncertainty if the intensity ratio is measured with two different types of spectrometers having a different observation volume and a different accuracy in the absolute sensitivity calibration. Therefore, the intensity ratio using closely existing two lines is desired to analyze the data accurately because those lines can be simultaneously measured with a single spectrometer and the spectrometer sensitivity is practically the same between the two lines.

For the purpose the line ratio of Li-like CIV 2p-3d ($^2P_{1/2}$-$^2D_{3/2}$: 384.03 Å, $^2P_{3/2}$-$^2D_{5/2}$: 384.18 Å) to 2p-3s ($^2P_{1/2}$-$^2S_{1/2}$: 419.53 Å, $^2P_{3/2}$-$^2S_{1/2}$: 419.71 Å) transitions and NeVIII 2s-3p ($^2S_{1/2}$-$^2P_{3/2}$: 88.09 Å, $^2S_{1/2}$-$^2P_{1/2}$: 88.13 Å) to 2p-3s ($^2P_{1/2}$-$^2S_{1/2}$: 102.91 Å, $^2P_{3/2}$-$^2S_{1/2}$: 103.09 Å) are selected in the present experiment. These lines can be simultaneously measured using a space-resolved extreme ultraviolet (EUV) spectrometer installed in Large Helical Device (LHD) and the line ratios are only sensitive to the electron temperature at $n_e \leq 10^{14}$ cm^{-3} in which the electron density of ergodic layer in LHD ranges. In this paper, the two-dimensional measurement of electron temperature in the ergodic layer is attempted based on the NeVIII line ratio. In order to measure the electron temperature profile at edge boundary of the ergodic layer, the CIV line ratio is also analyzed with T.Kawachi [3], ADAS [4] and CHIANTI codes [5, 6] All of these codes use the collisional-radiative model to calculate the line ratios. The intensity ratio used in this paper is indicated by a ratio in photo numbers between relevant two spectral lines.

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2. Experimental Setup

In LHD, the magnetic field for plasma confinement is basically produced by a pair of helical coils with poloidal and toroidal pitch numbers of $l = 2$ and $m = 10$, respectively. The ergodic layer consisting of stochastic magnetic field lines with lengths from 10 to 2000 m is formed surrounding the main plasma with elliptical poloidal cross section defined by the last closed flux surface (LCFS). The heat and particle transports in the ergodic layer are strongly affected by the ergodicity of stochastic field lines [7]. The elliptical plasma poloidally rotates five times during one toroidal turn. The plasma cross section is traced in Fig. 1 with different toroidal angles denoted by φ, which is defined as horizontal angle of the EUV spectrometer. The space between the two arrows in each figure indicates the observation range for vertical profile measurement.

The thickness of ergodic layer is a function of the magnetic axis position, R_{ax}, and poloidal angle. The minimum thicknesses of ergodic layer is given at the O-point, e.g., 2 cm for R_{ax} = 3.60 m and 10 cm for R_{ax} = 3.9 m. Typical plasma parameters of the ergodic layer range in 10^{13} cm^{-3} < n_e < 10^{14} cm^{-3} and 10 eV < T_e < 500 eV. Four divertor legs connecting to divertor plates made of carbon are also intrinsically formed as a specific character of LHD. Carbon is therefore the most dominant impurity in LHD.

The space-resolved EUV spectrometer working in 30 - 650 Å is set with horizontal dispersion to observe the vertical profile at horizontally elongated plasma cross section, as seen Fig. 1. The spectrometer is recently graded up by adding a horizontal scanning mechanism with a stepping motor to measure the two-dimensional distribution of line emissions. It is then possible to scan the spectrometer horizontally during a stable discharge. The minimum time interval necessary for the horizontal scan is 6 s. The horizontal range for the scanning is limited by the rectangular spectrometer port and diamond LHD diagnostic port [8].

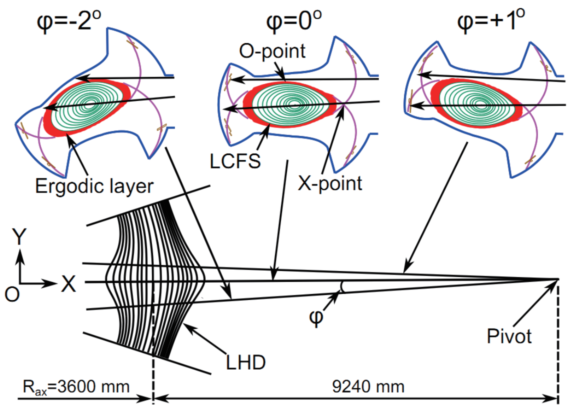

Fig. 1 Cross sections of LHD plasma at toroidal angles of $\varphi = -2°$, $\varphi = 0°$ and $\varphi = +1°$. Two arrows indicate the observation range of space-resolved EUV spectrometer. The toroidal angle is defined as an angle from X-axis at the pivot of spectrometer. The vertical and horizontal spatial resolutions are ΔZ = 10 mm and ΔY = 80 mm, respectively.

A back-illuminated charge-coupled detector (CCD) with 1024 × 255 pixels (26.6 × 6.6 mm^2) is used for the spectrometer. The vertical profile of line emissions is measured along the long axis of CCD, while the short axis is given as the wavelength dispersion. Therefore, the observable wavelength interval, $\langle\lambda\rangle$, defined by the short axis size (6.6 mm) of CCD is narrow at present, e.g., $\langle\lambda\rangle$ = 40 Å at λ = 100 Å and $\langle\lambda\rangle$ = 60 Å at λ = 300 Å. We then select the line pairs for the temperature measurement having a wavelength difference within the wavelength interval such as CIV 2p-3d/2p-3s (384 Å/420 Å) and NeVIII 2s-3p/2p-3s (88 Å/103 Å) in order to delete the uncertainty based on shot-to-shot reproducibility. The CCD position can be moved by a stepping motor along the wavelength dispersion to change the wavelength. The spectral resolution is $\Delta\lambda$ = 0.22 Å at λ = 200 Å in full image mode of CCD which corresponds to 4 - 5 pixels at the foot position of spectral line. In practice, the CCD is operated in the binning mode to shorten the sampling time. Five pixels are usually summed into one channel and the sampling time is set to 200 ms. The spectrometer sensitivity is absolutely calibrated using bremsstrahlung continuum [9].

Since the CCD is operated in the binning mode of 5 pixels, the number of vertical observation chords is 204. Several tens of upper observation chords can observe only the region near upper O-point in all different poloidal cross section, as shown in Fig. 1, while lower observation chords observe the region near both inboard and outboard X-points. The vertical position of all observation chords is calibrated using a toroidal slit with rectangular-corrugated edge installed between LHD and EUV spectrometer [8].

3. Results and Discussion

Two-dimensional distribution of impurity line emissions is generally measured from steady discharges maintained by electron cyclotron heating (ECH) and ion cyclotron resonance heating (ICRH). In the present study the two-dimensional distributions of NeVIII 2s-3p (88 Å) and 2p-3s (103 Å) are obtained from the ECH discharge in magnetic axis position of R_{ax} = 3.6 m. The pulse length is 10 s with sufficient steady phase and neon gas is supplied through gas puffing during 30 ms at the beginning phase of discharges, as seen in Fig. 2. The electron temperature at LCFS measured by Thomson scattering changes a little during the discharge over 10 s, i.e., from 300 eV at t = 1 s to 350 eV at 10 s. The space-resolved EUV spectrometer is horizontally scanned from 1 s to 10 s, i.e., from Y = 210 mm to Y = −520 mm with a pivot point near the entrance slit, as seen in Fig. 3. The total scanning time to record the full two-dimensional distribution is 9 s at the speed of 80 mm/s.

The line intensities shown in Figs. 3 (a) and (b) de-

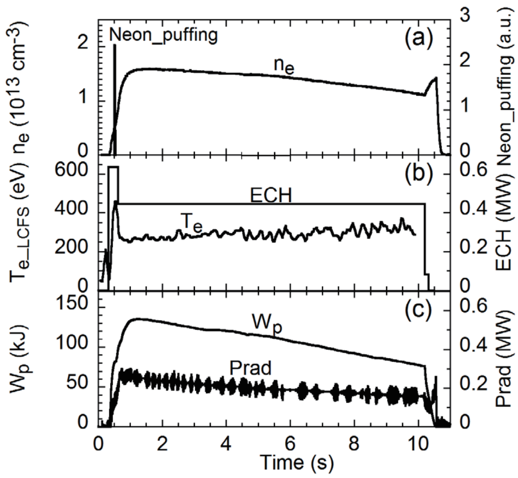

Fig. 2 Waveforms of plasma parameters: (a) line-averaged density and neon puff, (b) T_e at LCFS and ECH power and (c) Stored energy, W_p and radiation power, P_{rad}.

crease as a function of time during the scan from Y = 200 mm to −400 mm, since the electron density gradually decreases during the discharge (see Fig. 2). The plasma range in the two-dimensional distribution is indicated by dash line. The observation chord from Y = −400 mm to −520 mm is hided by the spectrometer port and the plasma is absent at upper region above roughly Z = 500 mm. The strong intensity of NeVIII near Y = 200 mm and Z = 500 mm is due to the Ne gas puffing at the beginning of ECH discharges. The NeVIII is located near the LCFS at all poloidal positions. The two-dimensional distribution of line intensity ratio, NeVIII 2s-3p/2p-3s, calculated from Figs. 3 (a) and (b) is shown in Fig. 3 (c). Although a considerably large nonuniformity is seen in the two-dimensional intensity distribution (see Figs. 3 (a) and (b)) based on the parameter change during the discharge, it can be deleted when the intensity ratio is calculated.

The line intensity ratio of NeVIII 2s-3p (88 Å) to 2p-3s (103 Å) is not sensitive to the electron density. The intensity ratios calculated by ADAS at electron densities of $n_e = 1 \times 10^{11}$ cm^{-3} and $n_e = 1 \times 10^{13}$ cm^{-3} are shown in Fig. 4. The line intensity ratios calculated at different densities are nearly the same in the temperature range of 10 - 400 eV.

The two-dimensional distribution of electron temperature is calculated from Fig. 3 (c) and Fig. 4. The result is shown in Fig. 5 (a). Although the electron temperature evaluated from NeVIII intensity ratio distributes in range of 130 - 170 eV in most of the region, it tends to increase when the radial position moves to the region near O-point. In order to make clear the temperature distribution in the edge plasma, the vertical profiles are plotted in Fig. 5 (b) at three different toroidal positions of φ = −2°, 0° and +1°. The observation chord of three toroidal positions is indicated in Fig. 1. The temperature profile in the ergodic layer can be clearly seen at the region near O-point, i.e., $480 \leq Z \leq 560$ mm at $\varphi = -2°$, $440 \leq Z \leq 500$ mm at $\varphi = 0°$ and $480 \leq Z \leq 520$ mm at $\varphi = +1°$. We can understand from the profile that the temperature gradient in the ergodic layer is steeper depending on the thickness of the ergodic layer, when the observation chord moves from X-point to O-point. It also indicates that the temperature in the ergodic layer has a similar value even if the poloidal

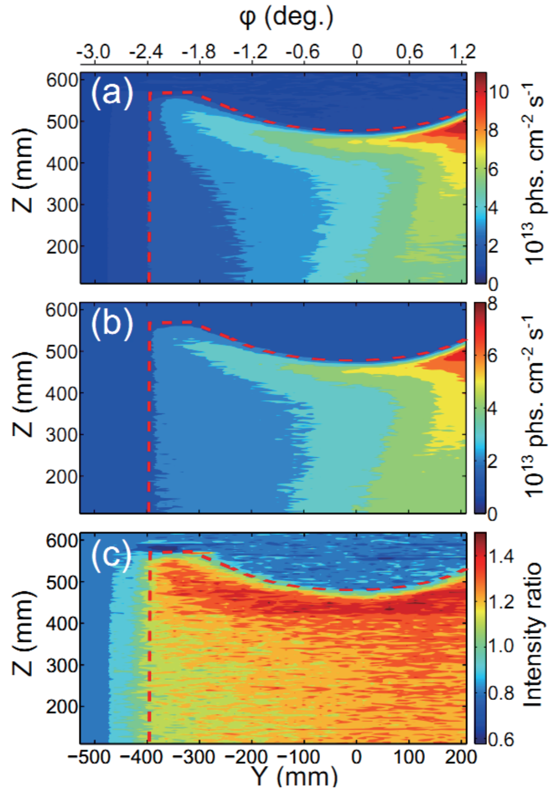

Fig. 3 2-dimensional distributions of NeVIII (a) 2s-3p: 88 Å, (b) 2p-3s: 103 Å and (c) line intensity ratio of 2s-3p/2p-3s.

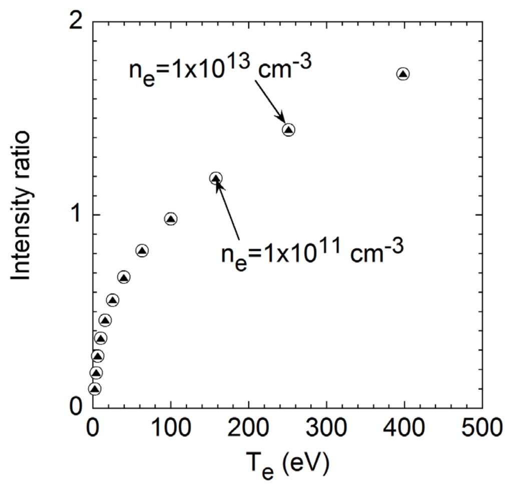

Fig. 4 Line intensity ratio of NeVIII 2s-3p (88 Å) to 2p-3s (103 Å) calculated by ADAS at electron densities of $n_e = 1 \times 10^{11}$ cm^{-3} (solid triangles) and $n_e = 1 \times 10^{13}$ cm^{-3} (open circles).

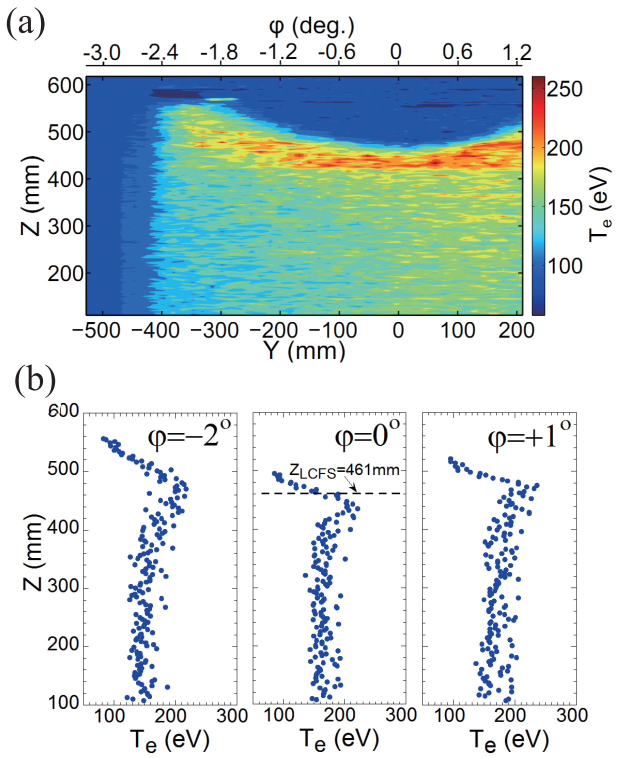

Fig. 5 (a) 2-dimensional distribution of edge T_e measured from NeVIII line intensity ratio and (b) vertical profiles of edge T_e at different toroidal positions of $\varphi = -2°$, 0° and +1°. Position of LCFS is denoted with dashed line at $\varphi = 0°$.

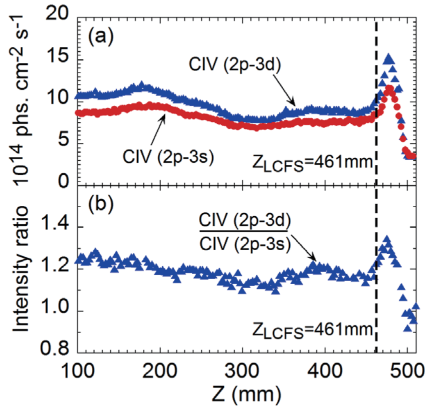

Fig. 6 Vertical profiles of (a) CIV 2p-3d (384 Å) and 2p-3s (420 Å) at $\varphi = 0°$ and (b) CIV line intensity ratio of 2p-3d/2p-3s. Position of LCFS is denoted with dashed line.

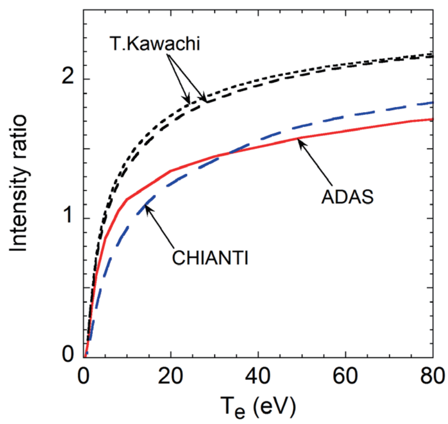

Fig. 7 Line intensity ratio of CIV 2p-3d (384 Å) to 2p-3s (420 Å) calculated by ADAS and CHIANTI at electron density $n_e = 1 \times 10^{13}\,\mathrm{cm}^{-3}$ and T.Kawachi at $n_e = 1 \times 10^{11}\,\mathrm{cm}^{-3}$ (long dash) and $n_e = 1 \times 10^{13}\,\mathrm{cm}^{-3}$ (short dash).

position is different, at least in the vicinity of O-point. The temperature profile at O-point gives the maximum value at the radial location where the observation chord positions a little inside the LCFS. On the contrary, the temperature in the vicinity of X-point, i.e., $100 \leq Z \leq 400$ mm at $\varphi = -2°$, 0° and +1°, is constant against the vertical position whereas the structure of stochastic magnetic field entirely different along the vertical observation chord. Therefore, a clear toroidal structure of the electron temperature is not seen in the vicinity of X-point at present. The result suggests that, although the magnetic structure of ergodic layer at different poloidal positions is completely different, the Ne^{7+} ions distributions in different poloidal position of ergodic layer are the same.

The line intensity ratio of 2p-3d/2p-3s (384 Å/420 Å) in Li-like CIV is observed to measure the electron temperature profile in edge boundary of the ergodic layer. It is examined that the C^{3+} ions with ionization energy of $E_i = 64$ eV are located in the farthest edge in LHD plasmas [10]. The vertical profiles of CIV emissions are shown in Fig. 6 (a) measured from another discharge heated by NBI. It is clear that the two CIV emissions have a very similar profile both in the vicinities of X- and O-points. In particular, the profile near X-point changing its intensity along vertical direction reflects the structure of stochastic magnetic field in the ergodic layer. The vertical profile of CIV line intensity ratio calculated from Fig. 6 (a) is shown in Fig. 6 (b). The ratio showing variation from 0.9 to 1.4 has a good accuracy compared to NeVIII case because of the strong intensity.

The line intensity ratios are calculated by T.Kawachi, ADAS and CHIANTI codes as a function of electron temperature, as plotted in Fig. 7. The ratios of CIV also have no density dependence at the density range seen in the edge plasma of LHD, as shown in the result by T.Kawachi. The line intensity ratio from the ADAS code gives lower temperature compared to the CHINTI code in range of $T_e \leq 30$ eV, whereas it gives higher temperature in the range of $T_e \geq 30$ eV.

The vertical profiles of electron temperature evaluated from the CIV ratios in Fig. 7 are shown in Fig. 8. The vertical profiles of electron temperature evaluated from CHIANTI, ADAS and T.Kawachi codes show a similar structure, although the absolute values are different. The electron temperature near X-point shows a lower value,

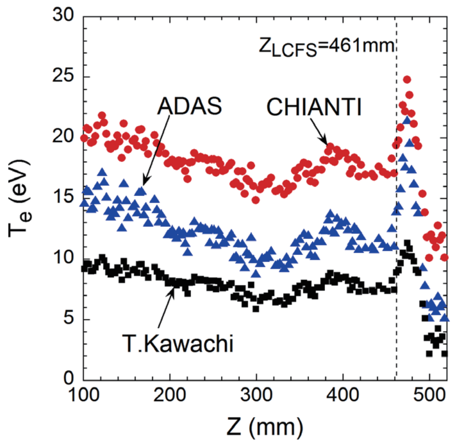

Fig. 8 Vertical profiles of electron temperature at edge boundary of ergodic layer evaluated from ADAS, CHIANTI and T.Kawachi codes. Position of LCFS is denoted with dashed line.

i.e. 20 eV for CHIANTI, 15 eV for ADAS and 9 eV for T.Kawachi codes, while the electron temperature near O-point shows a higher value, i.e., 25 eV for CHIANTI, 16 eV for ADAS and 11 eV for T.Kawachi codes. Since the edge boundary at the O-point near $Z = 480$ mm where the CIV is located is connected to the divertor plate with short magnetic field lines around 10 m, the CIV temperature at the O-point can be correlated with the temperature on the divertor plate. The electron temperature on divertor plates measured by electric probes ranges from 15 to 25 eV [11]. Therefore, it seems that the electron temperature analyzed from CHIANTI and ADAS codes can give a reasonable result.

4. Summary

Electron temperature profiles in the ergodic layer of LHD have been measured using line intensity ratio from Li-like NeVIII and CIV. Two-dimensional electron temperature distribution in the edge plasma has been successfully obtained from stable discharges in LHD. The result indicates a little higher temperature in the vicinity of O-point compared to the vicinity of X-point. The electron temperature profile in the edge boundary of ergodic layer is measured from the line intensity ratio of CIV 2p-3d/2p-3 s. The result also shows a little higher temperature in the vicinity of O-point in addition to a clear temperature structure in the vicinity of X-point. These results will be compared with ones from the three-dimensional edge simulation code to make clear the relation with magnetic field structure in ergodic layer.

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