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論文内容の要旨
Summary of thesis contents

Development of two-dimensional EUV spectroscopy for study of impurity behavior in ergodic layer of LHD

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A space-resolved extreme ultraviolet (EUV) spectrometer has been upgraded to study the impurity transport in the edge ergodic layer of large helical device (LHD) by observing the two-dimensional distribution of impurity line emissions. The ergodic layer composing of stochastic magnetic field lines with three-dimensional structure maintains a low-temperature ($10 \leq T_e \leq 500$eV) and relatively high-density ($n_e < 10^{13}$cm^{-3}) plasma. The space-resolved EUV spectrometer consists of a space-resolved slit placed in front of an entrance slit, a gold-coated varied-line-spacing (VLS) holographic grating (1200grooves/mm) and a back-illuminated charge-coupled device (CCD) with 1024 x 255 pixels (26.6μm/pixel). The two-dimensional measurement becomes possible by adding two stepping motors and scanning the observation chord horizontally and vertically. Since the EUV spectrometer observes the LHD plasma with 50cm long vertical image, the measurement at three different vertical angles is required to record the full vertical plasma image. The spatial resolution in the vertical direction is determined by a vertical width of the spatial resolution slit. Since the spatial resolution slit of 0.2mm in width is usually used, the EUV spectrometer system possesses a sufficient spatial resolution of 10mm which roughly corresponds to one hundredth of the full vertical length at horizontally elongated plasma cross section of the LHD plasma.

The two-dimensional distribution of impurity line emissions can be observed by scanning the horizontal angle of the EUV spectrometer with a constant speed during a relatively long stable discharge at a fixed vertical angle. Therefore, the spatial resolution in the horizontal direction is a function of the scanning speed in addition to the original spatial resolution of 75mm determined by the grating size and the focal length. Since the scanning speed is usually set to 3mm/s, the horizontal spatial resolution is 90mm at major radius of R=3.6m. Although the horizontal observation range is limited by a rectangular spectrometer port and a diamond LHD port, the upgraded EUV spectrometer system secures a sufficient image area with vertical and horizontal lengths of 1.2x0.8m^2 to study the impurity transport in the ergodic layer. Furthermore, the wavelength range of the EUV spectrometer for measuring impurity line emissions has been also extended from 50-500Å to 30-650Å by adding the second stage, which enables to expand a stroke for the CCD movement in the wavelength dispersion direction from 45mm to 75mm. As a result, the radial profile of several line emissions such as CV at 40.3, CVI at 33.7 and OV at 629.7 can be newly measured after the improvement of the spectrometer system. For the positional calibration of the observation chords a toroidal slit with one meter long was installed between the spectrometer and LHD post. The toroidal slit has a rectangular-corrugated edge with a variety of opening sections of which the width is

periodically changed from 2mm to 9mm. When the toroidal slit is closed remaining the opening sections of the rectangular edge, the resultant vertical intensity profile of line emissions reflects a projection of the opening sections. Thus, the vertical position of observation chords can be accurately calibrated by considering the geometrical relation among the space-resolved slit, the opening section of the rectangular edge and the LHD plasma. The horizontal position is also calibrated basically with the same method. The uncertainties in the vertical and horizontal positions are estimated to be 4mm and 10mm, respectively. The intensity of line emissions is absolutely calibrated by comparing the bremsstrahlung continuum between visible and EUV ranges in high-density discharges of LHD, since the absolute value of the visible bremsstrahlung intensity is already known by use of integrated sphere as the standard lamp.

Vertical profiles of edge impurity line emissions of He II and C IV have been measured at different toroidal locations of LHD by changing the horizontal angle of the EUV spectrometer shot by shot to observe the edge impurity poloidal distribution. The radial location of HeII with ionization energy of E_i=54.4eV reflects the penetration depth of neutral helium and the radial location of CIV with E_i=64.5eV expresses the index on the plasma edge boundary position in the ergodic layer of LHD. The result indicates that the radial location of HeII is positioned at inner side compared to that of CIV, whereas the ionization energy of HeII is smaller than that of CIV. It is found that the distance between HeII and CIV radial positions is nearly constant, i.e., 4mm, not depending on poloidal positions of the elliptical LHD plasma. The penetration depth of helium is analyzed for comparison with the measurement. The analysis shows a good agreement with the measurement when the room temperature of 300K is assumed as an energy of the neutral helium. It suggests that the neutral helium mainly enters the plasma as the residual gas in the vacuum vessel, but not as the recycling particle from the vacuum vessel or divertor plates. The full vertical profile of HeII is also measured at horizontally elongated plasma cross section to compare the intensity between the top and bottom O-points. The result shows an asymmetric profile indicating that the HeII intensity at the bottom O-point is two times stronger than that at the top O-point. This asymmetric intensity profile can be also seen in the CV vertical profile, while it is not seen in the vertical profile of CVI locating inside the last closed flux surface (LCFS). The reason still remains an open question at present.

Two-dimensional measurement of electron temperature in the ergodic layer is of crucial importance to study the transport in the edge plasma of LHD. Until now, however, there was no diagnostic method of measuring such the two-dimensional edge temperature distribution in the fusion research. In the present study a diagnostic method based on the intensity ratio between two line emissions is attempted to measure the two-dimensional electron temperature distribution in the ergodic layer of LHD. For the purpose the line intensity ratio of Li-like CIV and NeVIII has been adopted in the two-dimensional EUV spectroscopy, since the C^{3+} (E_i=64.5eV) and Ne^{7+} (E_i=239eV) ions are located at edge boundary and deep inside near LCFS of the ergodic layer, respectively. The use of such Li-like ions in the intensity ratio measurement exhibits an important advantage that a pair of two spectral lines is closely emitted in an adjacent wavelength. The two spectral lines can be then measured in the same CCD position. Since the intensity ratio is recorded as a function of time in a single discharge, any uncertainties based on the shot-to-shot reproducibility error in plasma discharges can be avoided from the temperature analysis. The CIV line intensity ratio of 2p-3d (384Å) to 2p-3s (420Å), of which the wavelengths are close, is calculated from ADAS atomic code. The result shows that the ratio is sufficiently sensitive to the electron temperature but entirely insensitive to the electron density. The vertical profile of electron temperature at the edge boundary of ergodic layer measured from the CIV line ratio ranges in 13-16eV in the vicinity of X-point except for the plasma edge near O-point. Since the edge boundary at O-point near helical coils is connected to the divertor plate with short magnetic field lines around 10m, the CIV temperature at O-point can be correlated with the temperature on the divertor plate. The electron temperature on divertor plates measured by Langmuir probe ranges around 10eV. Therefore, the temperature from the CIV intensity ratio shows a good consistency with the divertor temperature.

The line intensity ratio of NeVIII 3p-2s (88.08Å+88.12 Å) to 3s-2p (102.9Å+103.9Å) is used to measure the electron temperature at a deep inside of the ergodic layer. The vertical electron temperature distribution evaluated from ADAS ranges in 100-130eV. The electron temperature measured with Thomson scattering diagnostic shows 120eV at LCFS. The electron temperature profile is also simulated with three-dimensional edge transport code, EMC3-EIRENE, and the result indicates the electron temperature of 100eV at LCFS showing a good agreement with the measurement.

The two-dimensional electron temperature distribution in the ergodic layer is measured at upper half of LHD plasmas using the NeVIII intensity ratio. The electron temperature profile is analyzed against different horizontal angles. The result indicates that the electron temperature from NeVIII intensity ratio in the ergodic layer does not show any specific non-uniformity in the most part of LHD plasma. However, the electron temperature at the top plasma edge shows a higher temperature of 210-220eV in all toroidal locations, whereas the electron temperature in the vicinity of X-point shows lower temperature around 150-180eV. Although further detailed analysis is necessary for understanding the difference in the electron temperature, the observed relatively flat temperature profile is in a good agreement with result from the three-dimensional simulation code, EMC3-EIRENE.

The CIV vertical profiles near X-point at horizontally elongated plasma cross section are studied with magnetic field structure in the ergodic layer. In low-density range less than $2x10^{13}cm^{-3}$ the profile is almost flat. When the density increases, the two peaks newly begin to appear near X-points in addition to usual edge peaks at O-point, whereas such peaks do not appear in the profile of CVI locating near LCFS. Those peaks become very clear at high-density range of $n_e \geq 8x10^{13}cm^{-3}$. All these behaviors on the CIV profile are almost the same, even if the plasma axis position is changed. The carbon profile is also analyzed with three-dimensional edge transport code. The simulated result well explains the basic change in the profile. In low-density discharges, the C^{3+} ions move upstream and widely expand in the ergodic layer due to the presence of thermal force originated in the temperature gradient along magnetic fields, which leads to the flat CIV profile. Increasing the density, the friction force based on collisions between impurity and background plasma ions becomes dominant and the impurity ions are going to move downstream, so-called "impurity screening". The C^{3+} ions begin to stay in the vicinity of the X-point, where the magnetic field lines are directly connected to divertor plates. Thus, the two peaks near X-point are formed by the increasing C^{3+} density. As a result, the presence of the impurity screening, of which the effect can be dominantly enhanced in the ergodic layer consisting of stochastic magnetic field lines, has been experimentally certificated through the present study with clear evidence.

The two-dimensional CIV distribution is analyzed among configurations with different plasma axes. It is found that the CIV intensity becomes considerably strong along the poloidal trajectory of X-points. In addition, the CIV diagonal trace can be replaced from inboard X-point trajectory to outboard X-point trajectory, when the plasma axis, R_{ax}, is changed from 3.60m to 3.75m. In the simulation, however, the CIV trajectory is always enhanced at outboard X-point despite the position of magnetic axis. In discharges with R_{ax}=3.6m configuration a strong particle recycling is usually observed at the inboard side. An increased neutral density at the inboard side can enlarge the density gradient and enhance the friction force along magnetic fields. As a result, the present result strongly suggests that the impurity transport at the inboard side may be modified due to the localized neutral density.

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博士論文の審査結果の要旨

Summary of the results of the doctoral thesis screening

Development of two-dimensional EUV spectroscopy for study of impurity behavior in ergodic layer of LHD

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磁場による環状プラズマ閉じ込め研究において, エルゴディック層と呼ばれる周辺磁場構造がコアプラズマの閉じ込めに果たす役割の理解が非常に重要な研究課題となっている．大型ヘリカル装置（LHD）においても，閉じ込め磁場は外部導体コイルのみで容易に生成される一方，プラズマ周辺部に統計的磁場で構成される磁力線領域が同時に形成される．最近のLHD実験の成果により，この周辺統計的磁場はダイバータへの熱負荷軽減を目指したデタッチプラズマの安定維持や不純物遮蔽等，不純物の輸送に関連した重要な役割を担うことが明らかになりつつあり，3次元統計的磁場構造を有するエルゴディック層での不純物輸送に関する研究が注目されている．3次元統計的磁場構造を有するエルゴディック層での不純物輸送を研究するには少なくとも2次元計測が必要となる．そこで，出願者は不純物線スペクトルがエルゴディック層で主に支配的となる極端真空紫外（EUV）領域における新たな2次元空間分布計測法の研究開発を進めた．

出願者は非等間隔溝ホログラフィック回折格子（入射角：87度，1200本/mm）を用いた水平分散型平面結像EUV分光器に複数のステッピングモーターを付加することにより分光器の視線を縦・水平に自由に掃引できるよう改造した．次に，ホログラフィック回折格子の高い反射率と背面照射型CCDの高い検出効率を利用し，空間分解スリットを最適化することにより，高い縦方向空間分解能と明るい光学系を同時に達成した．更に，放電中に水平方向へ視線を掃引することにより2次元分布計測を可能とした．分光器とLHDの間に設置した長さ1m，幅20mmの矩形型スリットを用いてプラズマ中心から約10mの距離に位置する分光器の視線位置を決定することにより，LHDプラズマから発光するEUV領域不純物スペクトルの2次元分布を高精度で観測することに成功した．

スペクトル線強度比を用いた電子温度計測法を今回開発した分光手法に適用し, エルゴディック層内電子温度の1次元および2次元分布観測を行った. 利用可能なEUVスペクトルの組み合わせを波長, スペクトル混合及び電子温度依存性等の観点から丹念に解析し, 最終的にCIV (2p-3d : 384Å, 2p-3s : 420 Å）及びNeVIII（2s-3p：88.1Å，2p-3s：102.9 Å）というリチウム様イオンスペクトル線強度比の組み合わせが最適であることを突き止めた. 計測結果はスペクトル線強度及び電子温度共に平坦な分布を示し，トムソン散乱や静電プローブで別途計測されている電子温度と良い一致を示した．開発した2次元電子温度計測法は上述したデタッチプラズマ等の生成機構の解明に貢献するものとして期待される．

次に出願者はプラズマ上端から下端までの1次元CIV線強度分布を電子密度の関数として解析した．密度を上昇させると，それまで平坦であった分布に新しく2つのピークがセパラトリックスX点近傍に出現することを見出した．3次元周辺プラズマ輸送コード（EMC3-EIRENE）でCIV分布を解析したところ，低密度領域ではポロイダル方向に一様な分布が，密度上昇と共に，よりダイバータ側へ不純物が輸送され結果としてX点近傍に2つのピークが出現することが分かった．磁力線に沿って働く摩擦力の増大に基づいた統計的磁場領域における不純物遮蔽現象をより直接的な手法を用いて観測し，その存在を実証した．また，不純物発光スペクトルの2次元分布を観測した結果，X点の軌跡に

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沿って不純物が強く発光し，磁気軸位置をトーラス外側へ移動させると，その強い発光領域がトーラス内側X点近傍からトーラス外側X点近傍へ移動することを発見した．これらの実験観測と3次元輸送コード解析との比較により，非均一な水素密度分布の違いが摩擦力分布を変化させ，結果として磁力線方向に沿った不純物輸送に変化を与えている可能性を指摘した．

以上のように，出願者はEUV分光器を用いた2次元分光計測法を確立し，それを用いたエルゴディック層における不純物の振舞いについて多くの成果を挙げると共に，周辺プラズマ物理の進展に大きな貢献をした．よって本論文の内容は学位（理学）の授与に十分値すると判断した．