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学 位 論 文 題 目	A study on radial profile of impurity line emissions using EUV spectrometer in LHD
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論文内容の要旨

A space-resolved flat-field extreme ultraviolet (EUV) spectrometer working in 60- 400 Å ranges has been developed to observe impurity emission profiles in core and edge plasmas of large helical device (LHD). A flat focus is made for plane surface detector by use of a varied line spacing (VLS) holographic grating with an angle of incidence of 87°. An excellent spectral resolution slit of 0.22 Å at 200 Å is obtained after careful adjustment of the optical components. Two entrance slits of 30 and 100μm in width are tested. The result shows that spectral resolution is less than 5 pixel channels for both slits in the whole wavelength range of 60- 400Å . The vertical resolution is also checked by three space-resolved slits of 0.2, 0.5 and 1mm in width. The 100μm entrance slit and 0.5mm space-resolved slit are finally selected for the present study considering the intensity and spatial resolution. In the profile measurement of the LHD plasmas the toroidal resolution is important as well as the vertical resolution, because the magnetic surfaces of LHD quickly change when the observation chord is tilted at a slightly different toroidal location. Horizontal dispersion is therefore selected for the present spectrometer. As a result, the toroidal resolution of 75 mm is achieved at the plasma position. An enough radial resolution of 10 mm is also obtained at spatial-resolution slit width of 0.2 mm, which is defined as full width at half maximum (FWHM) in the radial profile of edge impurities. In order to measure the full radial profile of LHD plasmas the spectrometer is placed at a distance of ~9200 mm away from the plasma center and a back-illuminated charge coupled device (CCD) with size of 6.6 × 26.6 mm^2 is set vertical to the horizontal dispersion. Due to the size of CCD detector, half of the LHD plasma, i.e., ~50 cm, can be measured along the vertical direction at horizontally elongated plasma cross-section. The CCD is usually operated in the binning mode with time resolution of 200ms, in which five pixels are summed and converted into one channel. A full vertical profile can be obtained by changing the vertical angle of the EUV spectrometer. A wavelength interval of 35 to 65 Å can be simultaneously observed, which varies according to the wavelength to be measured.

Radial profiles of impurity ions of carbon, neon and iron are measured from LHD plasmas using the space-resolved EUV spectrometer in wavelength range of 60-400Å. The low-Z impurities are usually located at the plasma edge, whereas the medium- and high-Z impurities are widely distributed over the entire plasma volume. The radial positions of the impurity ions are investigated at magnetic axis position of R_{ax}=3.60m with the local electron temperature, T_{eZ}, defined by the electron temperature at radial location where the impurity ion exists. The result is compared with the ionization energies, E_i. It is found that the impurity ions with $0.3 \le E_i \le 1.0$keV are always located in the outside of plasmas, i.e., $0.7 \le \rho \le 1.0$, and those with $E_i \le 0.3$keV exist in the ergodic layer, i.e., $1.0 \le \rho \le 1.1$, with a sharp peak edge. Here, ρ is the radial position normalized to the plasma radius. The result also reveals that the T_{eZ} is approximately equal to the E_i for the impurity ions with $E_i \le 0.3$keV, whereas the T_{eZ} is roughly half to the E_i for the impurity ions with $0.3 \le E_i \le 1.0$keV. It is known that the T_{eZ} is considerably smaller than the E_i in the plasma edge and becomes equal to the E_i in the plasma core. Therefore, this result is seemed to originate in the difference of the perpendicular transport between the plasma edge at $\rho \le 1.0$ and the ergodic layer at $\rho \ge 1.0$. The perpendicular transport is studied with impurity transport simulation code. As a result, it confirms that the difference appeared in the impurity radial positions can be qualitatively explained by different values of the diffusion coefficient, e.g., D=0.2 and 1.0m^2/s, as the typical index of the perpendicular transport.

Vertical profiles of edge impurity emissions have been measured in upper half region of elliptical plasmas at horizontally elongated plasma cross section in LHD. The vertical profiles near upper O-point located just below helical coil are analyzed to study the plasma edge boundary of the ergodic layer consisting of stochastic magnetic field lines with connection lengths of $30 \le L_c \le 2000$m. As a result, C^{3+} ion emitting CIV spectrum is identified as the ion existing in the farthest edge of the ergodic layer. The peak position of CIV (312.4Å: $1s^2 3p\ ^2P_{1/2,3/2}$-$1s^2 2s\ ^2S_{1/2}$) vertical profile is investigated as a function of electron temperature at last closed flux surface (LCFS: ρ=1), T_e(ρ=1), in magnetic axis positions of R_{ax}=3.60m, 3.75m and 3.90m. Result shows that the CIV peak position does not change at all in a wide temperature range of $150 \leq T_e(\rho=1) \leq 400$eV, whereas it moves inside the ergodic layer when T_e(ρ=1) is reduced below a threshold temperature, e.g., 130eV at R_{ax}=3.75m. The edge temperature dependence of CIV peak position is also verified by the Langmuir probe measurement. The comparison of CIV peak position with L_c shows that the C^{3+} ion exists at the boundary between ergodic layer and open magnetic filed layer at which the L_c distributes in lengths of 5 to 30m. The result indicates that the edge boundary near the O-point in LHD is determined by a starting point of the open filed layer, where a tokamak-like steeper edge temperature gradient is formed, although the edge boundary is quite obscure at the X-point region. The fact is also supported from the analysis on the ionization lengths of carbon ions and the collision frequency. It is also found that no plasma exist between the edge boundary and the vacuum vessel. The CIV profile at the O-point is simulated using a three-dimensional edge transport code of EMC3-EIRENE in which the magnetic field structure in vacuum is used for the ergodic layer. A clear discrepancy of 8mm is found in the peak positions of CIV between measurement and simulation for magnetic configurations with thick ergodic layer, i.e., R_{ax}=3.90m, while only a small discrepancy of 3mm is observed for those with relatively thin ergodic layer, i.e., R_{ax}=3.75m. The CIV profiles simulated with different particle diffusion coefficients, input power and carbon sources show similar CIV peak position to the original simulation result. The discrepancy is possibly caused by a modification of the magnetic filed due to the presence of plasma pressure.

The radial profile of bremsstrahlung continuum radiation is clearly recorded in the EUV spectrum observed from high-density discharges with hydrogen pellet injection, characterized by central-peaked profile as well as the visible bremsstrahlung continuum. A new method for the absolute intensity calibration of the EUV spectrometer has been developed based on the EUV bremsstrahlung profile measurement. Wavelength intervals available for the absolute intensity calibration of the space-resolved EUV spectrometer system are listed with dominant line emissions which are useful as a wavelength marker.

A precise absolute intensity calibration of the flat-field space-resolved EUV spectrometer is done using the new calibration technique based on radial profile measurement of the bremsstrahlung continuum. A peaked vertical profile of the EUV bremsstrahlung continuum has been observed in high-density plasmas ($n_e \geq 10^{14}cm^{-3}$) with hydrogen ice pellet injection. The absolute calibration is carried out by comparing the EUV bremsstrahlung profile with the visible bremsstrahlung profile of which the absolute value has been already calibrated using a standard lamp. For the purpose the line-integrated profile of the visible bremsstrahlung continuum is converted into the local emissivity profile considering a magnetic surface distortion based on the plasma pressure. For direct comparison with the EUV bremsstrahlung profile measurement the line-integrated profile of the EUV bremsstrahlung continuum is calculated from the visible bremsstrahlung emissivity profile by taking into account the electron temperature profile. The absolute intensity calibration factor is thus obtained as a function of wavelength. As a result, it is found that the grating reflectivity of EUV emissions is constant along the direction perpendicular to the wavelength dispersion. The result shows the uncertainty of the calibration factor is significantly improved compared with conventional method.

Finally, the density of iron is analyzed from its radial profile using the absolute intensity calibration factor determined from EUV bremsstrahlung continuum profile. The radial profiles of FeXV, FeXVI, FeXX and FeXIV are used for the analysis. The chord-integrated intensity profiles are converted into the local emissivity profiles by considering the deformation of magnetic surfaces followed by the change in chord length between neighboring magnetic surfaces. The emission rate coefficients for such spectral lines are accurately calculated using collisional-radiative model. The density profile of the iron ions is thus evaluated by taking into account the electron temperature and density profiles in addition to the emission rate coefficient. As a result, the iron densities of Fe^{23+} at plasma center indicate almost 10^6-10^7 orders of magnitude smaller than the electron density. The radiation power of iron in LHD typical discharges estimated from the emissivity profiles is negligibly small compared to the total input power. As the application of the iron density profile measurement to the impurity transport study, the FeXXIV profile is simulated by one-dimensional transport code. The present new method on the impurity transport study strongly suggests that the diffusion coefficient and convective velocity can be separately determined with their radial structures.

博士論文の審査結果の要旨

核融合プラズマのエネルギー収支を議論する上で重要となる不純物に起因する放射損失やプラズマ特性に大きな影響を与える不純物輸送を研究するためには不純物スペクトルの空間分布を定量的に計測する必要がある．出願者は多くの不純物スペクトルが集中している極端真空紫外（EUV）領域における詳細な空間分布計測を目的として研究を開始した．

多価に電離した不純物イオンが放射するスペクトル線は主に30-500Åの波長領域に集中している．これらスペクトル線を観測するためにLHDではEUV分光法の確立を目指し研究を進めている．最近開発された平面結像型ホログラフィック回折格子（入射角：87.0°，非等間隔溝回折格子：1200本/mm）や背面照射型CCD検出器の採用により格段に明るく分解能に優れた分光性能を達成した．出願者はこのEUV分光器に用いられている回折格子の大きな曲率（曲率半径：5600mm）に着目し，新たに空間分解スリットを入口スリットに近接して設置することにより空間分布計測の可能性を探求した．2台の拡大望遠鏡を用いた高精度回折格子設置角度調整法を採用し，空間分解スリット，入口スリット及びCCD検出器運転モード等を最適化した結果，明るい分光器感度の確保と高い空間分解能の同時達成に成功し，磁場閉じ込め核融合装置では初めてEUVスペクトルの空間分布計測を実現した．

LHD ではダイバータ板に炭素材を使用しているため炭素イオンからのスペクトル線が強く発光する．出願者は炭素をはじめ多くの不純物スペクトル線の空間分布を丹念に調べ，CIV（312.4Å）が LHD プラズマの最も外側，つまりプラズマエッジ境界に位置していることを突き止めた．これを指標としてヘリカルコイル直下の高磁場側に位置するプラズマエッジ境界の振舞いを調べた結果，最外殻磁気面での電子温度がある閾値（例えば 130eV）以上ではプラズマエッジ境界は変化せず，その閾値以下ではプラズマエッジ境界がプラズマ内側へ移動していく様子を観測した．閾値以上で固定されるプラズマエッジ境界の空間位置は磁力線がトロイダル方向からポロイダルダイバータ方向へ向きを変え，短い磁力線連結長（Lc=5-30m）となる開磁力線領域と一致しており，LHD のプラズマエッジ境界はこの領域で決定されていることを実験的に検証した．周辺プラズマ輸送コード（EMC3-EIRENE）を用いて実験データを解析した結果，エルゴディック層の薄い磁場配位では観測した CIV 径方向位置はシミュレーション結果と比較的良い一致を示すが，エルゴディック層がより厚くなる磁場配位では実験データが最大 8mm 程度外側へ移動していることが分かった．シミュレーション結果は拡散係数，加熱入力及び不純物源の位置の違いには大きく依存せず，間欠的密度バースト（Blob），対流速度及び荷電交換反応等の物理機構を考慮しても両者の違いを説明できないことから，出願者はエルゴディック層内磁力線構造のプラズマ圧力による再構成の可能性を原因として指摘すると共に統計的磁場の圧力効果に関する研究の重要性を喚起した．

更に出願者は，可視及びEUV領域の制動放射分布を同時観測することにより今までにはない高精度で分光器の絶対感度較正を行うことに初めて成功した．CCD検出器の計数率を放射強度に変換することが可能となり，磁気面変形を考慮した磁気面座標を採用することにより観測した視線積分不純物分布放射強度から信頼性の高い不純物局所放射強度分布を得た．その結果，不純物空間密度分布を高精度で求めることが可能となった．特に鉄不純物については衝突輻射モデルを用いて不純物スペクトル放射係数を精度良く求め，LHDプラズマにおける鉄不純物の定量化を高精度で行った結果，電子密度に対して10^{-7}以下という非常に少ない混入量であることを突き止めた．これはLHDのエルゴディック層が有する重要な物理特性の一つである不純物遮蔽効果が真空容器壁材料に対しても有効であることを明瞭に示しており，今後のLHDを用いた核融合研究に対して大きな意義を持つ実験結果となった．

以上のように，申請者は EUV 分光器を用いた空間分布計測法の開発とそれを用いて得られた研究結果に関し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．

８月２日の論文審査では書類上の資格審査を行い，問題がないことを確認した後口述試験を実施した．試験は出願者本人による論文内容の説明を受けながら適宜質疑応答を行う形式とした．論旨をより明快にし，内容をより平易に理解できるよう努力した出願者の工夫が見られた．審査委員から平面結像型 EUV 分光器を用いた空間分布計測の基本原理，視線位置の絶対値に関する誤差評価，不純物の価数分布と電子温度分布の関係，不純物輸送コードにおける拡散係数や対流速度の物理的意味，プラズマ圧力効果による楕円プラズマの磁気面変形やアーベル変換に関する計算原理，不純物量決定における誤差評価等，研究の基礎知識について質問が出された．出願者は磁気面構造やエルゴディック層内磁力線構造等の図面を用いて具体的な事柄に言及した上でそれぞれの質問に対して的確に返答した．また，EUV 分光器の迷光やノイズの要因，従来の感度較正法との比較，スペクトル線強度の電子温度・密度依存性等，実験研究の詳細に関する質問にも機器較正実験での経験を交えながら実験結果や計算結果を提示することにより的確に答え，基礎から専門に至る十分な知識を備えていることを示した．8 月 30 日に行われた公開発表会においても出願者は指定時間内に内容を要領よくまとめ，EUV 分光計測に関する質問や不純物輸送に関する物理的な質問に対しても的確に答えた．

出願者が第一著者となっている査読付英文論文は４編が既に学術雑誌から出版され，２編が投稿中である．また，出願者は全ての審査会における発表と議論を英語で行い，英語発表における十分な意見交換が可能であることを示した．従って審査委員会は出願者の英語学力についても十分と判断した．以上の結果から、審査委員全員一致で試験を合格とした．