氏　　　名	Malay Bikas Chowdhuri
学位（専攻分野）	博士（理学）
学 位 記 番 号	総研大甲第 1191 号
学位授与の日付	平成２０年９月３０日
学位授与の要件	物理科学研究科　核融合科学専攻 学位規則第６条第１項該当
学 位 論 文 題 目	Development of flat-field EUV spectrometers with absolute calibration and study of impurity behavior in edge plasmas on LHD
論 文 審 査 委 員	主　査　教授　山田　弘司 教授　森田　繁 教授　居田　克巳 教授　蓮尾　昌裕（京都大学） 主幹研究員　杉江　達夫（日本原子力研究開発機構）

論文内容の要旨

Two flat-field extreme ultra violet (EUV) spectrometers for measuring 10–500Å ranges have been developed to improve the technical basis on the spectroscopic diagnostics and to study the edge impurity transport in high-temperature plasmas of Large Helical Device (LHD). This wavelength range contains many spectral lines from low to high Z impurities typically seen in fusion plasmas such as B, C, O, Ar, Ti, Fe, Mo and W. The EUV Spectrometers with varied-line-spacing 1200 (named as 'EUV_Long') and 2400 grooves/mm (named as 'EUV_Short') gratings cover each wavelength range of 50–500Å and 10–130Å ranges, respectively. Spectral characteristics of newly developed laminar-type holographic gratings used for both EUV spectrometers have been studied by comparing with conventional ruled gratings.

Comparison between ruled and holographic gratings for EUV_Long spectrometer shows that both spectral resolutions (FWHM) are excellent for the spectroscopic use and a very similar spectral resolution is obtained for both (e.g. $\Delta\lambda\sim$ 0.24Å at λ=200Å). However, only the holographic grating can sufficiently suppress the higher order light. For example, the second order light of CV (40.3Å) is only about 18% to the first order for the holographic grating, whereas the second order light is nearly equal to the first order light for the ruled grating.

Relative sensitivity of the EUV_Long spectrometer was determined using a new technique of EUV bremsstrahlung continuum measurement. As a result, it was found that the sensitivity of the ruled grating quickly deteriorates at wavelengths lower than 150Å, but the holographic grating constantly keeps a high sensitivity against the wavelength. The holographic grating was therefore finally selected for the EUV_Long spectrometer. The absolute calibration has been done using a combination of the bremsstrahlung continuum and the branching ratio technique with two CIV spectral lines in EUV (3p-3s: 312.4Å) and visible (3p-2s: 5810Å) ranges. The absolute calibration curve is obtained continuously against the wavelength. This technique could be an excellent alternative to overcome a large uncertainty against the wavelength dependence seen in the conventional absolute calibration method using only the branching ratio.

In case of the EUV_Short spectrometer, both ruled and old holographic gratings effectively suppress higher order light, but the ruled grating shows better spectral resolution ($\Delta\lambda$=0.083Å at λ=18.97Å) than the old holographic grating ($\Delta\lambda$=0.130Å at λ=18.97Å). Relative sensitivity was also determined from the EUV bremsstrahlung continuum and the absolute calibration was done by comparing the overlapping wavelength range (50–130Å) with absolutely calibrated EUV_Long spectrometer. It was found that the holographic grating is three times brighter than the ruled grating. A new holographic grating has been developed in Shimadzu Co. Ltd. very recently with modified grating parameters. This new holographic grating was also checked instead of the old holographic grating. We thus found that the new grating improved the spectral resolution at lower wavelengths of ≤40Å ($\Delta\lambda$=0.900Å at λ=18.97Å). As a result, the EUV spectroscopy was clearly progressed at shorter wavelength range, at least in 10–30Å range, where Δn=1 transitions of medium-Z impurities (Ar, Ti, Fe etc.) and many EUV spectral lines of high-Z impurities (Mo, W etc.) closely exist.

EUV spectra from Mo and W in 20–500Å range have been observed using double-structure impurity pellet injected into LHD plasmas. From the data analysis many spectral lines have been successfully identified and compared with previous experimental results and also with calculated values. Especially, The Δn=1 transitions of WXXII-WXXVI ($4d^9 4f^k 5p$–$4d^{10} 4f^k$, $4f^{k-1} 5g$–$4f^k$: k=3-7) in 25–40Å range are newly identified with the help of calculated values. The Δn=1 (n=3-2) transitions of Ti and Fe in 10–30Å range have been measured using the EUV_Short spectrometer. The spectra from Ne-like TiXIII (FeXVII) to Li-like TiXX (FeXXIV) have been also newly observed simultaneously with a good spectral resolution.

Impurity transport of edge plasmas with ergodic layer in LHD has been studied using CIII to CVI emissions. For this purpose, four resonance transitions of CIII (977Å: 2s2p $^1P_1$–$2s^2$ $^1S_0$), CIV (1550Å: 2p ^2P–2s ^2S), CV (40.27Å: 1s2p $^1P_1$–$1s^2$ $^1S_0$) and CVI (33.73Å: 2p ^2P–1s ^2S) have been observed using EUV_Short spectrometer and two VUV monochromators. The ionization energies of CIII (50eV) and CIV (68eV) are clearly separated from CV (392eV) and CVI (495eV). These carbon emissions can be then divided into two groups, i.e., CIII+CIV and CV+CVI. Here, the CIII+CIV indicates the influx of the carbon at plasma edge and the CV+CVI indicates the carbon fraction after transport in the ergodic layer. The ratio of CV+CVI to CIII+CIV has been observed in a variety of magnetic configurations and plasma parameters.

The ratio of CV+CVI to CIII+CIV decreases in two orders of magnitude with increasing ne in the range of 1–$8\times10^{19}m^{-3}$. This reduction with n_e comes mainly due to monotonically increased CIII+CIV emissions and constant CV+CVI emissions. This result suggests enhanced impurity screening by the presence of the ergodic layer. On the other hand, the edge impurity transport parallel to the magnetic fields is mainly dominated by the ion thermal force due to ion temperature gradient and the friction force due to proton-impurity collision. The modeling of the edge impurity transport with EMC3+EIRENE code strongly suggests the importance of the friction force in high-density range, which means the appearance of the impurity screening. The density dependence of the measured ratio is in good agreement with the modeling result.

The ratio has been also examined by shifting the plasma axis and changing the thickness of the ergodic layer. The ratio decreases with changing the ergodic layer thickness under similar line-averaged densities. The edge density in the ergodic layer normalized to the core density becomes higher with increasing ergodic layer thickness. As a result, the effect of the impurity screening can be enhanced in thicker ergodic layer.

The carbon emissions have been also observed changing the radial position of externally supplied m/n=1/1 island. The ratio considerably decreases when the island exists in the ergodic layer. This result evidently indicates that the modification of magnetic field structure in the ergodic layer changes the edge impurity behavior.

論文の審査結果の要旨

外部導体コイルのみによって閉じ込め磁場を形成できる大型ヘリカル装置（LHD）ではエルゴディック層と呼ばれるカオス磁力線領域がプラズマ周辺部に本来的に具備されており，それがコアプラズマ閉じ込めに果たす役割を明らかにすることは非常に重要な研究課題となっている.そこで,Chowdhuri 君はエルゴディック層での不純物輸送に着目し、LHD における代表的な不純物である炭素イオンを対象として、自ら開発した極端紫外領域分光器を用いて研究を行った.

多価に電離した炭素イオンが放射するスペクトル線は主に極端紫外（EUV）領域に分布しているため，まず 10-130Å（入射角：87.0°，非等間隔溝回折格子：1200 本/mm）及び 50-500Å（入射角：88.7°，非等間隔溝回折格子：2400 本/mm）領域を観測できる 2 台の EUV 分光器を開発した．異なった波長を有する各スペクトル線の結像が平面座標上に得られる平面結像型斜入射分光器を選定し，機械切り回折格子とホログラフィック回折格子の特性の違いを丹念に調べた．また，従来から用いられていたレーザー光軸調整法に換えて 2 台の拡大望遠鏡を用いて回折格子設置角度精度の向上を図った結果，ホログラフィック回折格子を採用した場合に迷光や高次光の非常に少ない分光器特性を得た．従来の機械切り回折格子と比較して 3－5 倍程度明るい分光光学系も達成可能となった．検出器として背面照射型 CCD 検出器を採用した結果，検出器ノイズも 1 カウント/チャンネル以下に軽減することに成功し，スペクトル線とともに得られる連続光がプラズマ制動放射に由来していることを発見した．そこでこの制動放射を用いた分光器の新しい較正法を考案し，EUV 分光器の波長に対する感度較正を精度良く行なうことに成功した．分岐線比較正法を併用することにより分光器の絶対較正も同時に行った.

次にこれらの分光器を用いて LHD から放射される CIII-CVI 線を計測した．各荷数にある炭素イオンがコアプラズマ周辺部やその外側に広がるエルゴディック層の異なる径方向位置に分布していることを利用して，その相対強度変化よりエルゴディック層における炭素不純物の輸送を研究した．通常 CIII や CIV はエルゴディック層表面付近に，CV や CVI はコアプラズマ周辺部（最外殻磁気面近傍）もしくはエルゴディック層深部に分布している．つまり，CIII や CIV は炭素不純物の流入量を表し，CV や CVI はエルゴディック層での輸送を経た流入量を示す．そこでこれら炭素スペクトル線の強度比 (CV+CVI)/(CIII+CIV)がエルゴディック層での不純物輸送の度合いを表す指標となることに着目して実験を行い，データを解析した．その結果，電子密度の増大につれて比が減少することを突き止め，エルゴディック層での不純物遮蔽効果の実在を実験的に初めて確証した．また，この不純物遮蔽効果はエルゴディック層を厚くすることによってその効果をより顕著に出来ることも確認した．これらの実験結果はエルゴディック層における粒子輸送を対象とした 3 次元シミュレーション計算でも再現されており，磁力線に沿って運動している不純物イオンと背景イオンとの衝突に起因した不純物イオンに作用する力の違いによって主に説明できることが明らかとなりつつある.

以上のように，Chowdhuri 君は丹念な EUV 分光器の開発と新しい発想に基づく分光器の感度較正等の実験機器に関する十分な知見に立脚して,LHD のエルゴディック層における炭素不純物遮蔽に関する実験的研究を行い，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．