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論文内容の要旨

Summary of thesis contents

A space-resolved extreme-ultraviolet (EUV) spectrometer has been developed to study the edge impurity transport by measuring two-dimensional intensity (2-D) distribution of impurity spectral lines emitted from stochastic magnetic field layer in which all the impurity ions have a non-uniform density distribution. The 2-D intensity distribution can be observed by horizontally scanning the space-resolved EUV spectrometer during a discharge with long pulse length of 6-8s. The full top-to-bottom 2-D intensity distribution of impurity line emissions is completed by superimposing a few 2-D distributions measured at a different vertical position. In Large Helical Device (LHD), however, high-performance plasmas have been produced with high-power negative-ion-source-based neutral beam injection (n-NBI) at short-pulse operation of 2 s. A major upgrade of the space-resolved EUV spectrometer system was then required for the study of three-dimensional (3-D) structures of impurity ion distribution in stochastic magnetic field layer of LHD. The performance improvement of the EUV spectrometer system has been carried out by installing a high-frame-rate charge-coupled detector (CCD) and a polyethylene terephthalate (PET) filter, increasing the horizontal scanning speed and adopting an intensity normalization method.

Since the high-frame-rate CCD can be operated with a relatively short sampling time of 50 ms for the 2-D measurement, the horizontal spatial resolution is significantly improved. With the increase in horizontal scanning speed, the 2-D intensity distribution measurement is applicable to NBI discharges with short pulse length. The intensity normalization method is adopted for data analysis of the 2-D image of impurity line emissions based on a rapid temporal behavior of those line emissions measured with another fast time-response EUV spectrometer. A blurred image influenced by the temporal intensity variation during a discharge and shot-to-shot intensity variation among two or three discharges can be almost eliminated from the full 2-D image after applying the intensity normalization method. A 0.5-μm-thick PET filter is installed in front of the entrance slit of the space-resolved EUV spectrometer to reduce the spike noise induced by high-energy neutral particles in NBI discharges. The PET filter can perfectly block the neutral particles originating in 40 keV positive-ion-source-based NBI (p-NBI) and also slightly change the direction of neutral particles originating in 180 keV n-NBI. As a result, the spike noise is almost eliminated from the EUV spectrum in NBI discharges. Thus, the 2-D intensity distribution of impurity line emissions located in the stochastic magnetic field layer is excellently observed with a good signal quality for helium, carbon and iron. The present upgraded system has shown a sufficient performance for the study of 3-D structure of impurity ion distributions in the stochastic magnetic field layer. In addition, the upgraded space-resolved EUV spectrometer is absolutely calibrated on the basis of the profile measurement of visible and EUV bremsstrahlung continua, and the calibration factor is obtained as a function of wavelength in the range of 60 – 440 Å. The calibration factor of the present upgraded system is comparable to that of the original system indicating similar detection efficiency between old and new CCDs.

The poloidal distribution of the impurity line emissivity has been evaluated by analyzing the 2-D intensity distribution against magnetic flux surfaces calculated with a 3-D plasma equilibrium code, VMEC. The inner and outer boundaries of edge impurity locations are estimated by analyzing the vertical profile of each impurity line emission measured at different toroidal positions. The observation chord length passing

through an emission contour is calculated from radial thickness of the impurity emission location. The poloidal distributions of CIV, CVI, FeXV and FeXVIII with different ionization energies are thus reconstructed from their 2-D intensity distributions. A non-uniform poloidal distribution has been clearly observed for CIV, whereas the FeXVIII emissivity distribution is almost a function of the magnetic surface. It is experimentally confirmed that the poloidal distribution becomes gradually uniform as the ionization energy of impurity ions increases and the radial position of impurity ions changes from the ergodic layer toward the plasma core. The non-uniform poloidal distribution of the CIV emissivity is well explained by a simulation with 3-D edge plasma transport code, EMC3-EIRENE.

The detached plasma has been achieved in LHD without external impurity gas feed by supplying the resonance magnetic perturbation (RMP) field with m/n = 1/1 mode at outwardly shifted plasma axis position of $R_{ax}$ = 3.90 m where the magnetic resonance exists in the stochastic magnetic field layer. Impurity carbon radiation has been studied to clarify the physical mechanism triggering the RMP-assisted detachment. Resonance lines of CIII (977.02 Å, $2s2p–2s^2$), CIV (1548.2 Å, 2p–2s), CV (40.27 Å, $1s2p–1s^2$), and CVI (33.73 Å, 2p–1s) measured by vacuum ultraviolet (VUV) and EUV spectrometers are used to estimate the radiation power from $C^{2+}$–$C^{5+}$ ions because carbon is the most abundant impurity element in LHD. The partial carbon radiation at each ionization stage of $C^{2+}$ to $C^{5+}$ ions, $P_{rad}$ ($C^{q+}$), is estimated for attached and detached plasmas by calculating the ratio of the partial carbon radiation to the resonance line based on ADAS atomic code. It is found that the $P_{rad}$ ($C^{3+}$) localized near a radial location of $\iota/2\pi = 1$ in the stochastic magnetic field layer is much stronger than $P_{rad}$ ($C^{2+}$), $P_{rad}$ ($C^{4+}$) and $P_{rad}$ ($C^{5+}$) for both the attached and detached plasmas. The $P_{rad}$ ($C^{3+}$) is extremely enhanced during the plasma detachment with 6-O island, i.e. $P_{rad}$ ($C^{3+}$)/$P_{rad}$~40%, while it is only 8% to the $P_{rad}$ in the attached plasma. Therefore, the $P_{rad}$ ($C^{3+}$) plays a key role in the enhancement of edge radiation during the RMP-assisted detached plasma.

In order to understand the role of edge impurity radiation in triggering the plasma detachment, the vertical profile of edge impurity ions has been measured during the plasma detachment with the space-resolved EUV spectrometer. It is found that the radial position of the top and bottom edge peaks appeared in both the CIII and CIV vertical profiles shifts radially inside after the detachment transition and the change in the radial position is different between the top and bottom edges, while the CV and CVI positions do not radially change at all during the detachment transition. The sudden change in the top edge peak ($\Delta Z_{Top}$) is much larger than that of the bottom edge peak ($\Delta Z_{Bottom}$), i.e. $\Delta Z_{Top}$ ~ 70 mm and $\Delta Z_{Bottom}$ ~ 20 mm. The difference between $\Delta Z_{Top}$ and $\Delta Z_{Bottom}$ observed here indicates a clear evidence of newly appeared m/n = 1/1 magnetic island in the plasma edge during the plasma detachment. The result concludes that a big magnetic island can be created by the RMP field given in LHD even if the magnetic resonance exists in the stochastic magnetic field layer.

Vertical intensity profiles and 2-D intensity distributions of edge impurity carbon emissions of CIII to CVI have studied during the RMP-assisted plasma detachment. The 3-D structure of carbon line emissions has been carefully analyzed with 3-D magnetic field structure in the stochastic magnetic field layer based on the 2-D intensity distribution measurement. As a result, it is found that the CIII and CIV emissions located in the stochastic magnetic field layer are drastically increased near the island O-point and in the vicinity of both the inboard and outboard X-points during the RMP-assisted detachment, while those emissions are enhanced only in the vicinity of the outboard X-point in attached plasmas without RMP. The result clearly indicates an enhancement of edge carbon radiation and a considerable change in the magnetic field lines connecting to the divertor plates due to the appearance of the temperature flattening and the big magnetic island. In contrast, the CVI emission located radially inside the m/n=1/1 island entirely weakens the intensity during the detachment, suggesting an enhancement of the impurity screening based on the density gradient force along magnetic field lines. The measured carbon 2-D intensity distribution is also analyzed with EMC3-EIRENE for attached plasmas without RMP. It is found that the impurity trajectory along edge X-point and its width are sensitive to the cross-field impurity diffusion coefficient, $D_{Z\perp}$. As a result, the value of $D_{Z\perp}$ for $C^{3+}$ ions is evaluated to be 20 times larger than that of the bulk ions in the $R_{ax}$ = 3.90 m configuration. The 3-D structure of carbon ions along edge X-point is also well explained with the structure of m/n=1/1 magnetic island quickly expanded with appearance of the plasma detachment.

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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

環状プラズマの定常維持のためのダイバータ熱負荷制御を目的として，非接触プラズマの研究が精力的に進められている．通常外部から不純物ガスを導入し，その放射損失を利用して非接触プラズマを生成しているが，安定な放電維持が大きな課題となっている．一方，LHDでは周辺磁場に適合した共鳴摂動（RMP）磁場を用いて非接触プラズマの発生に成功しており，定常維持への可能性が検討されている．しかし，非接触プラズマのエネルギー収支や周辺部の特徴である統計的磁場下での不純物輸送・磁気島形成過程等，解明すべき課題も多く指摘されている．そこで，出願者は極端真空紫外（EUV）領域における不純物スペクトルの2次元発光分布計測法による非接触プラズマの研究を開始した．これまでの計測手法では2次元分布観測に6秒程度の時間が必要であり，パルス幅が2秒程度に制限される高出力中性粒子ビーム入射（NBI）加熱を必要とする非接触プラズマ放電の観測は不可能であった．出願者は，高速2次元分布計測の確立を目指し，高速動作CCD検出器の新規整備，NBIに起因した高エネルギー中性粒子による雑音信号除去のための0.5μm厚ポリエステル薄膜フィルターの導入，ステッピングモータドライバー改造による分光器掃引速度の高速化，放電特性の時間変化に起因する2次元解像度劣化を補正するための信号強度の規格化等を行った．これにより，データの質を格段に向上させ，2秒程度で計測が完了するシステムの構築に成功した．また，制動放射連続光を用いた2次元分布計測用EUV分光器の絶対感度較正とレーザーによる2次元分光視野の高精度位置較正を行い，システム変更に伴う機器特性の変化を正確に補正した．これによって放電時間が制限される高出力加熱時においても2次元発光分布観測を可能とし，非接触プラズマの研究を進展させた．

観測した2次元炭素イオン発光分布を，3次元磁場計算を基にして解析した結果，非接触プラズマが発現する前に磁気セパラトリックスX点近傍の磁力線構造が変化し始め，その後磁気島が成長し，磁気島幅が最大になった時点で非接触状態に移行することを明らかにした．また，CIIIやCIVの低価数炭素イオンの発光強度は非接触プラズマ移行前に大きく増加し，その主な発光位置はRMP磁場による磁気島形成位置とほぼ一致した．移行後にはその2次元分布形状は磁気島O点の位相角度の違いに応じて変化し，磁気島形成に伴う磁力線構造の変化を強く反映していることが分かった．一方，非接触プラズマが形成されると，磁気島より内側のプラズマコア部に存在する不純物イオンの密度が大きく減少することを見出した．統計的磁場領域の拡大と磁力線に沿った密度勾配の増大による摩擦力の増加がその原因と考えられる．RMP磁場により形成された非接触プラズマは，周辺放射損失の増大とコア部の不純物減少という放電の定常維持にとって望ましい特性を有していることを実証した．

さらに，観測した2次元CIV分布の外側X点に沿った発光軌跡を磁力線に垂直方向の分布に再構成し，3次元シミュレーションコード（EMC3-EIRENE）で解析した．その結果，統計的磁場中の$C^{3+}$イオンの磁場に垂直方向の拡散係数（$D_{\perp z}=4m^2/s$）は周辺プラズマの径方向温度分布から評価した水素バルクイオンの拡散係数（$D_{\perp}=0.2m^2/s$）の20倍程度になっていることが判明した．出願者は，バルク水素イオンに対する低価数炭素イオンのより大きなラーマー半径，プラズマ圧力による統計的磁場領域の磁力線構造の変形及び異常

輸送等を輸送係数の増大要因として指摘した．

以上のように，出願者はEUV波長領域での高速2次元空間分布計測法を開発し，非接触プラズマで発光する不純物スペクトル線強度の2次元空間分布を初めて取得した．この観測の分析から，非接触プラズマ中での周辺不純物イオンの振る舞いを明らかにし，統計的磁場領域での不純物輸送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．