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論文内容の要旨
Summary of thesis contents

A space-resolved extreme ultraviolet (EUV) spectrometer working in the wavelength range of 10-130Å has been developed to measure vertical profiles of line emissions of heavy impurities and bremsstrahlung continuum at horizontally elongated plasma cross section in the Large Helical Device (LHD). The spectrometer has a spectral resolution of 0.15Å at 30Å when an entrance slit with 100μm width is used. The spatial resolution in the vertical direction is sufficiently good, i.e. approximately 30mm, when a spatial-resolution slit with 1mm width is used. The spatial resolution in the toroidal direction is also good, i.e. 22mm. The value is enough to measure the radial profile of impurity line emissions with good spatial resolution avoiding the effect on a quick poloidal turn of LHD elliptical plasmas.

The spectral intensity of the present system is absolutely calibrated as a function of wavelengths based on the profile measurement of visible and EUV bremsstrahlung continua. The calibration factor is also examined along the grating groove in the spectrometer with horizontal wavelength dispersion. A constant reflectivity of EUV emissions observed along the grating groove can validate the present vertical profile measurement. These results obtained here indicate a sufficient performance of the present space-resolved EUV spectrometer system for the profile measurement.

A large amount of spike noise caused by neutral particles with high energies (≤180keV) has been observed with the EUV spectrometer in NBI discharges of LHD. These high-energy neutral particles originating in fast ions from neutral beam injection (NBI) bring a serious problem to the EUV spectroscopy, especially in low-density discharges at which the slowing down time of the fast ion is very long. A holographic grating used in the present spectrometer causes more spike noises compared to a ruled grating. It is probably due to a geometric difference in the groove structure, i.e. rectangular shape for the holographic grating and triangle shape for the ruled grating. The pulse height distribution analysis on the spike noise using signal counts of charge-coupled detector (CCD) definitely concludes that the spike noise is composed of high-energy neutral particles attributed to 180keV n-NBIs and 40keV p-NBIs.

Three filters of 0.5μm thick polyethylene terephthalate (polyester, PET), 3.3μm thick polypropylene (PP) and 11μm thick beryllium (Be) have been tested to block the spike noise. The 11μm Be and the 3.3μm PP filters entirely eliminate all the spike noise, but the signal intensity is also significantly reduced. The 0.5μm PET filter fully eliminates the low-energy neutral particles originating in the p-NBIs, while the high-energy neutral particles originating in the n-NBIs cannot be sufficiently blocked. However, a small amount of the spike noise remaining in the EUV spectrum can be erased by computer software programing. The 0.5μm PET is thus selected as the best filter in the present EUV system.

Based on the good spectral and spatial resolutions, the Fe n=3-2 L_α transition array consisting of FeXVII to FeXXIV is excellently observed with their radial profiles. The

transition array is distributed in narrow wavelength range of 10 to 18 Å, the radial profile from all the charges states of FeXVII to FeXXIX can be simultaneously measured as a function of time. Therefore, the transition array is used as a new technique for the impurity transport study. The result is mentioned later. Each transition in the L_α array can be accurately identified with its radial profile. Through the analysis a spectral line observed at 17.62Å is newly identified as FeXVIII transition.

Ne-like FeXVII n=3-2 L_α transitions ($2p^5 3d$ or $3p^5 3s$ to ground state: $2p^6\ ^1S_0$) denoted with labels of 3C ($3d^1P_1$), 3D ($3d^3D_1$), 3E ($3d^3P_1$), 3F ($3s^3P_1$), 3G ($3s^1P_1$) and M2 ($3s^3P_2$) have been observed from LHD plasmas along with the radial intensity profile. The measured line-integrated radial intensity profile is reconstructed to the radial emissivity profile of FeXVII transitions by means of Abel inversion, and the emissivity ratio among the FeXVII transitions is analyzed. A collisional-radiative (CR) model specially developed for the Fe ions is applied for analyzing the data. Although the emissivity ratios of $\varepsilon_{3D}/\varepsilon_{(3G+M2)}$ and $\varepsilon_{3F}/\varepsilon_{(3G+M2)}$ well agree with the CR model calculation, the emissivity ratio of $\varepsilon_{3C}/\varepsilon_{(3G+M2)}$ shows a clear discrepancy by 25%-40%. The result indicates that the discrepancy is not caused by the chord-integrated effect in the measured intensity. It seems that the theoretically calculated excitation cross section of 3C transition is an overestimate due to uncertainty of the atomic wave function used in the calculation. The effect of electron density on the emissivity ratio of $\varepsilon_{3F}/\varepsilon_{(3G+M2)}$ is also examined. It is found that that the ratio is also sensitive to the electron density in addition to the electron temperature.

Two types of coaxial pellets, i.e. tungsten inserted into PE tube (polyethylene) and tungsten inserted into C tube (graphite carbon), have been designed and tested in LHD for the tungsten spectroscopy and transport study. Experimental results show the W-in-PE pellet can avoid plasma collapse, whereas the W-in-C pellet usually terminates the discharge. The reason is clearly explained by the analysis of pellet deposition profile based on pellet ablation spectroscopy with interference filters. Since the graphite carbon has a high sublimation energy, the tungsten pellet can be delivered into deeper radial location (ρ = 0.43). It leads to a huge energy loss by the tungsten ions in the plasma core including radiation and ionization losses. In case of the W-in-PE pellet, on the contrary, the energy loss is much smaller due to a shallower penetration (ρ = 0.7), suggesting some of evaporated tungsten ions are not well confined in the plasma. The plasma can then survive from the tungsten pellet injection. As a result, the W-in-PE pellet can excellently produce sufficient emissions from highly ionized tungsten ions in LHD.

Several tungsten spectra are measured with the W-in-PE pellet. Radial emissivity profiles are also obtained for WXXV (32.3Å), WXXVI (30.9Å) and WXXVII (29.6Å). Based on the emissivity profile measurement of tungsten ions in different ionization stages, the rate coefficient of ionization and recombination can be experimentally derived. Therefore, the present result is greatly helpful not only for the atomic modeling of tungsten spectra but also for the tungsten transport study in fusion devices with tungsten divertor.

The bremsstrahlung profile has been successfully observed without spike noise at low-density discharges, e.g. $2.9\times10^{13}cm^{-3}$, as well as high-density discharges, by installing the PET filter and optimizing the entrance and space-resolved slit widths. The Z_{eff} profile has been also obtained in the plasma core ($\rho < 0.75$) from the measured EUV bremsstrahlung radial distribution. Recombination radiation can give a significant effect on the bremsstrahlung profile, in particular, in the edge region ($\rho > 0.75$), since the energy of EUV bremsstrahlung is relatively high, e.g. 100-600eV. In the plasma core ($\rho < 0.75$), on the other hand, the emissivity profile is basically free of the recombination radiation because the radiative recombination rate drastically decreases with increasing electron temperature T_e. The time behavior of Z_{eff} profiles analyzed in low-density NBI discharges with carbon pellet injection suggests a strong relation between Z_{eff} and T_i. The value of Z_{eff} decreases with increasing electron density n_e in both the NBI- and ICRF-heated discharges, while it has no obvious correlation with n_e in ECH discharges.

The Fe n=3-2 L_α transition array is of great advantage because the transition array consists of emissions from several charge states of Ne-like Fe^{16+} through Li-like Fe^{23+} ions. Radial profiles of all the charge states can be simultaneously measured with the EUV spectrometer developed in the present study. Therefore, the radial structure of transport coefficients, i.e. diffusion coefficient D and convection velocity V can be analyzed basically without any assumption because the iron line emissions in the transition array distribute over the whole radial location. The time behavior of the Fe transition array is examined by injecting the impurity pellet. It is found that the intensity decay time of FeXX is longer than that of FeXVII and the decay time increases with n_e. It suggests the impurity confinement time is longer when n_e increases. The impurity transport analysis is attempted to discharges with different density profiles. In the case of centrally peaked n_e profile, the radial structure of the inward convection velocity seems to be similar to the n_e profile, suggesting the importance of the density gradient. In the hollow n_e profile, on the contrary, a large outward convection velocity is observed in the plasma center. The convection velocity changes from outward to inward at certain radial location in the peripheral region where the n_e gradient changes the sign, i.e. from positive to negative. These results indicate that the convection velocity strongly correlates with the density gradient. It also shows a good agreement with the neoclassical theory.

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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

核融合プラズマの実効電価数（Z_{eff}）は燃料水素の純度を示す重要なプラズマパラメータの一つであり，不純物量やプラズマ粒子の衝突周波数を求める上でも大事な指標となっている．また，重元素不純物はプラズマ中心に集中する傾向（不純物蓄積）があり，その大きな放射損失はプラズマ性能を劣化させる．本研究は高温低密度領域におけるZ_{eff}空間分布と重元素不純物輸送の理解に大きな進展を与える重元素多価イオン群の詳細な空間分布を世界で初めて実験的に求めたものである．

多価に電離した重元素不純物イオンが放射するスペクトル線は主に10-100 Åという短波長極端紫外（EUV）領域に集中しており，制動放射連続光は波長が短くなるほどその強度を増す．出願者黄贤礼氏はLHDにおいて，この波長領域のスペクトル線や制動放射連続光の空間分布を観測するために，平面結像型ホログラフィック回折格子（入射角：88.6°，非等間隔溝回折格子：2400本/mm）及び背面照射型CCD検出器を採用したEUV分光器の開発を進めた．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，空間分布計測を試みたが，プラズマを維持し加熱するために入射される中性粒子ビーム（NBI）に起因した高エネルギー中性粒子が回折格子で反射されて直接CCD検出器に到達し，大きなノイズ信号を発生するという斜入射分光器特有の問題に遭遇した．これを克服するため黄氏は多くの薄膜フィルターを試験し，最終的に0.5μm厚ポリエステル薄膜フィルターを使用することにより，EUV制動放射強度を減衰させることなく高エネルギー中性粒子の遮断に成功した．同時に短波長EUV領域では初めてとなる詳細な空間分布計測を達成した．特に，高エネルギーイオンの減衰時間が長くなり，結果としてノイズ信号が極端に増大する低密度放電においてこの手法は非常に有効に機能した．更に黄氏は入口及び空間分解スリット幅及び形状を最適化してより明るい分光光学系を構築し，プラズマ周辺部からの再結合放射の寄与を考慮することにより，$1.5\text{-}2.0\times10^{13}cm^{-3}$の低密度放電でコア部（$0\le\rho\le0.75$）の$Z_{eff}$空間分布計測を世界で初めて成功させた．この結果，低密度領域で観測されるイオン温度の上昇とZ_{eff}値の相関を解析することが可能になり，イオン温度とZ_{eff}値の間に正の相関があることを見出した．

また,黄氏は本分光器を用いて代表的な不純物重元素である鉄イオンの振舞いを調べた．10-20Å領域に存在するFeXVII-XXIV n=3-2 Lα遷移の空間分布を観測し，プラズマ全域に渡る鉄イオン価数密度の分布解析を行った．分布計測に当たってはレーザーを用いた観測視線の位置較正を慎重に行い，分布解析に当たってはプラズマ圧力を考慮した磁気面形状を採用することによりデータ解析の精度を向上させた．こうして得られた分布データを基に黄氏は不純物の輸送解析を試みた．LHDのプラズマ放電に於いてはNBI加熱入力を抑制した時に不純物蓄積が生じることが分かっている．そこで，NBI放電を解析対象として加熱入力や電子密度依存性に着目して同上の計測を行い，輸送コードを用いて鉄イオンの拡散係数と対流速度の評価を行った．輸送コードに使用する鉄イオンの電離・再結合係数と遷移係数には最新のデータを反映させた．その結果，電子密度分布が急峻な勾配を有する領域で不純物蓄積を誘起する大きな内向き対流速度が発生し，電子温度勾配には大きな相

関がないことを明らかにした．これらの輸送解析に於いて，必要となる各価数のイオン密度分布が実験的に得られたことにより，輸送係数評価の信頼性が著しく向上したことは本研究の大きな成果である．

以上のように，黄氏は EUV 波長領域の空間分布計測法を開発し，Z_{eff} や不純物イオン密度の空間分布を初めて得ることで，高温プラズマ中の不純物イオンの振る舞いを明らかにし，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．