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(Form 3)

Summary of Doctoral Thesis

Name in full

LIU Yang

Title

Experimental study on tungsten EUV spectroscopy in LHD for high-temperature plasma diagnostics

ITER (International Thermonuclear Experimental Reactor), which is now under construction at Cadarache in France, is a next-generation tokamak device for fusion research aimed at carrying out D-T burning plasma experiments and the first operation is now scheduled in 2025. Materials for plasma-facing components (PFCs) in ITER must have a good capability of tolerating an extremely large thermal heat load, in addition to capabilities of reducing the erosion and tritium retention rates. Then, tungsten with a large atomic number of 74 is used as the most suitable material for the PFCs in the ITER tokamak instead of carbon materials which have been used for many years in toroidal devices. However, the line radiation loss from tungsten ions is very huge because of the large atomic number. Once the tungsten concentration exceeds a certain threshold level in the core plasma, the plasma performance is significantly degraded. In addition, heavy impurities such as tungsten tend to accumulate in the central plasma region due to the neoclassical effect. In the ITER operation, therefore, the tungsten density, n_W, must be maintained at a low level against the electron density, n_e, e.g., $n_W/n_e<10^{-5}$. The tungsten transport study is extremely important for controlling the tungsten accumulation in the plasma core and the tungsten influx in the plasma edge.

On the other hand, the tungsten diagnostics is also important for controlling the tungsten buildup and accumulation. At present, however, understanding of the tungsten spectrum, which can provide unique information for the tungsten diagnostics and transport study, is still insufficient, while the spectrum and related atomic data for medium-Z impurities such as iron are well understood in conducting the impurity diagnostics based on numerous past works which have been done in both fields of plasma spectroscopy and atomic physics. Thus, the study on tungsten spectroscopy has been motivated in Large Helical Device (LHD) with graphite divertor plates and stainless steel first wall. Since the LHD discharge is totally tolerant for the impurity buildup due to the absence of the plasma current, the LHD experiment is possible over a wide range of tungsten concentrations. It resultantly leads to a high-brightness plasma source of tungsten line emissions. In LHD, the tungsten spectrum is observed by injecting a coaxial graphite pellet with a narrow tungsten wire because the use of a traditional laser-blow-off method is difficult due to the presence of a thick stochastic magnetic field layer surrounding the core plasma, by which the impurity screening is largely enhanced in the plasma peripheral region and the impurity flux toward the main plasma is reduced.

As a basis of the present thesis, tungsten spectra in extreme ultraviolet (EUV) range of 10-500 Å have been observed in LHD to identify the line emissions. All the tungsten spectra in the present thesis have been measured in neutral-beam-heated discharges using two grazing incidence EUV spectrometers called EUV_Short and EUV_Long working in wavelength ranges of 10-130 Å and 30-500 Å, respectively. A lot of tungsten lines from low-ionized ions of W^{4+}, W^{6+} and W^{7+} are observed for the first time in the toroidal device in addition to tungsten lines from highly ionized ions of W^{41+} - W^{45+}. Measured line emissions are carefully identified based on the NIST (National Institute of Standards and Technology) atomic spectra database and the wavelengths are accurately determined. The result is summarized in a table with information on line intensity and blended lines which is obtained by measuring the radial profile and analyzing the shape and peak position of the radial profile. The wavelength determined in the present study shows a good agreement with the NIST atomic spectra database.

Two space-resolved EUV spectrometers, called EUV_Short2 and EUV_Long2, have been utilized to observe the full vertical profile of tungsten line emissions by simultaneously measuring the vertical profile at upper- and lower-half plasmas of LHD, respectively. The radial profile of local emissivity is reconstructed from the measured vertical profile in the overlapped wavelength range of 30-130 Å. Up-down asymmetry is then examined against the local emissivity profiles of WXXVIII existing in the unresolved transition array (UTA) spectrum. The result shows a nearly symmetric profile, suggesting a good availability in the present diagnostic method for the impurity asymmetry study, while the up-down and in-out asymmetries have been observed for argon, nickel, tungsten, etc., in JET and Alcator C-mod tokamaks. It is obviously confirmed from the observation of symmetric tungsten line emission profiles that the tungsten profile data obtained in LHD can be analyzed as a function of magnetic surfaces.

A series of experiments on tungsten spectroscopy have been carried out in LHD with tungsten pellet injection to study the tungsten spectra and to develop a method for the tungsten diagnostics. In particular, pseudo-continuum tungsten spectra called unresolved transition array (UTA) are very important for the diagnostics and transport study of tungsten ions in edge plasmas of ITER. However, understanding of the UTA spectra is still insufficient due to the complicated spectral structure. For the purpose, EUV spectra of UTA observed in the wavelength range of 15 Å to 70 Å are observed and analyzed at two different wavelength ranges of 15-45 Å and 45-70 Å, which mainly consist of $\Delta n = 1, 2$ and $\Delta n = 0$ transitions for $n = 4$ partially ionized tungsten ions, i.e. W^{18+}-W^{45+}, respectively. At first, the UTA line intensity is analyzed against central electron temperature at temperature recovery phase after the pellet injection to examine the presence of blended lines. Next, vertical profiles measured with two space-resolved EUV spectrometers are analyzed against electron temperature profiles for further precise investigation of the UTA spectra. For the analysis the local emissivity profiles are obtained from the measured vertical intensity profiles with Abel inversion method based on magnetic surface structures calculated by VMEC (Variational Moments Equilibrium Code) code. It is then possible to investigate the ionization stage of tungsten ions composing the UTA. As a result, it is found that the wavelength intervals of 49.24 Å $\leq \lambda \leq$ 49.46 Å, 48.81 Å $\leq \lambda \leq$ 49.03 Å and 47.94 Å $\leq \lambda \leq$ 48.15 Å, which are identified as

W^{27+}, W^{26+} and W^{24+}, respectively, are applicable to the tungsten diagnostics. The result of the line component analysis on the tungsten UTA is summarized in tables.

Based on the radial profile measurement of W^{24+} (32.16-33.32 Å), W^{25+} (30.69-31.71 Å) and W^{26+} (29.47-30.47 Å) of which the wavelength interval is composed of only a single ionization stage, the ion density is evaluated. In order to evaluate the ion density, a photon emission coefficient for the W^{24+}, W^{25+} and W^{26+} ions is calculated using a collisional-radiative (CR) model. The chord-integrated radial profile of UTA lines is converted to the local emissivity profile based on Abel inversion technique. The tungsten density profile of W^{24+}, W^{25+} and W^{26+} ions is thus obtained from the local emissivity profile and the photon emission coefficient in addition to the temperature and density profiles. A detailed analysis of the obtained profile is done for the W^{24+} ion by investigating dependences on the electron density and the number of tungsten particles injected by the pellet. A total tungsten ion density, n_W, near $\rho = 0.7$ where the W^{24+} ion locates is also estimated from the W^{24+} ion density based on the fractional abundance in ionization equilibrium calculated with ADAS (Atomic Data and Analysis Structure) code. The tungsten density calculated with the photon emission coefficient from the present CR model is roughly five times bigger than the tungsten density estimated from the pellet size, while the density calculated from a CL version of ADAS code is fairly close to the density estimated from the pellet size, i.e. difference within two times. A cascade process from higher excited levels may enhance the photon emission coefficient in the ADAS code calculation and resultantly the tungsten density calculated with the ADAS code is smaller.

As the supplement study, effects of neutrons and γ-rays on charge-coupled device (CCD), which is widely used as a detector of vacuum spectrometers in fusion devices, have been examined in deuterium plasma experiments of LHD. Totally 3.7×10^{18} neutrons have been yielded with energies of 2.45 MeV (D-D neutrons) and 14.1 MeV (D-T neutrons) during the deuterium experiment over four months. Meanwhile, the γ-rays are radiated from plasma facing components and laboratory structural materials in a wide energy range, i.e. 0.01-12.0 MeV, through the neutron capture. It is well known that these neutrons and γ-rays bring serious problems to the CCD system. Then, several CCDs of vacuum ultraviolet (VUV) / EUV / X-ray spectrometers installed at different distances from LHD plasma center are examined to study the effect of neutrons and γ-rays on CCD. An additional CCD placed in a special shielding box made of 10 cm thick polyethylene contained 10% boron and 1.5 cm thick lead is also used for the detailed analysis. As a result, it is found that the CCD has no damage in the present neutron yield of LHD, while the background signal noise integrated for all pixels of CCD largely increases, i.e. $1\text{-}3\times10^{8}$ counts/s. The data analysis of CCD in the shielding box shows that the background signal noise caused by the γ-ray is a little smaller than that caused by the neutron, i.e. 41% from γ-rays and 59% from neutrons. It is also found that the signal noise can be partly removed by an accumulation of CCD frames or a software programming.

In conclusion, EUV spectra from low-ionized tungsten ions, i.e. W^{4+}, W^{6+} and

W^{7+}, are newly found in wavelength range of 260-500Å and tungsten UTA spectra are qualitatively and quantitatively investigated in detail. It is found that the wavelength interval of 32.16-33.32 Å, 30.69-31.71 Å and 29.47-30.47 Å is composed of a single ionization stage of W^{24+}, W^{25+} and W^{26+}, respectively. Tungsten density of these ions is demonstratively evaluated based on the radial profile measurement at the wavelength interval. Evaluated tungsten ion densities shows a good agreement with the tungsten density estimated from the pellet size. The result on tungsten spectroscopy in EUV range obtained through the present thesis study makes a valuable contribution to the edge tungsten diagnostics in ITER.

Results of the doctoral thesis screening

博士論文審査結果

氏　名（Name in Full）　LIU Yang

論文題目（Title）　Experimental study on tungsten EUV spectroscopy in LHD for high-temperature plasma diagnostics

2025 年に稼働が予定されている国際熱核融合実験炉（ITER）では，高熱負荷への対策やトリチウムリテンション・ダスト等の軽減を目的として，タングステンダイバータが採用される。高原子番号のタングステンは放射損失が大きく容易に不純物蓄積を引き起こすため，タングステンの輸送と制御に関する研究が重要な課題となる。必然的にタングステン診断法の確立も重要になるが，高温プラズマ中でのタングステン不純物の定量的な挙動を正確に診断するための分光学的手法は未だ確立されていない。タングステンダイバータでのプラズマ壁相互作用研究の定量解析には，中性タングステン原子が放出する可視スペクトル（WI：4009Å）が広く利用されてきた。しかし，タングステンイオンの定量解析にはイオンスペクトルが主に放射される極端真空紫外（EUV）領域の空間分布計測が必須要件であり，タングステンイオンの定量研究はこれまでのところ全く進展していない。また，ITER の周辺プラズマに相当する数 keV 程度の電子温度領域では，タングステンイオンはその外殻軌道に未だ多くの束縛電子を有する。放出されるスペクトルは非常に複雑な構造を示し，個々のイオン価数におけるスペクトル線の正確な同定と定量解析は困難であった。そこで，出願者はタングステンイオンが放出する EUV スペクトルの空間分布計測を主な実験手法として，タングステン分光診断法の研究を進めた。

出願者は円筒型グラファイトにタングステンワイヤー細線を装着した同軸型タングステンペレットを製作し，LHD プラズマに入射することでタングステンスペクトル観測を開始した。計測した 10-500Å 領域のタングステンスペクトルを詳細に解析した結果，これまであまり注目されていなかった長波長側で W^{4+}，W^{6+}及び W^{7+}イオンからのペクトル線が強く発光することを初めて発見した。また，W^{6+}イオンスペクトルには 4f 電子に関する内殻励起遷移も観測され，低電離タングステンイオンの電子密度効果を含む励起機構のより深い理解に向け，貴重なデータを提供した。これらのスペクトル線は ITER のダイバータ部のタングステン輸送研究に役立つものと期待される。

一方，ITER の周辺プラズマに存在すると予想される W^{10+}~W^{45+}イオンからの大半のスペクトル線は UTA（Unresolved Transition Array）と呼ばれる疑似連続光を形成する。6g-4f，5g-4f，5f-4d，5g-4f，4f-4d，4d-4p 等多くの遷移が同じ波長領域に存在するため非常に複雑なスペクトル線構造を形成しており，通常の分光計測では詳しい同定や定量解析を行うことは不可能であった。そこで，出願者は空間分解スリットを装着した EUV 分光器による空間分布計測を UTA スペクトルの研究に適用し，20-70Å 波長域に存在する UTA スペクトルを 0.1-0.2Å という狭い波長領域に分離して空間分布を観測するという新しい実験手法を採用した。電子温度分布を基にスペクトル空間分布解析を行った結果，

W^{24+}，W^{25+}及び W^{26+}イオンの情報を選択的に特定の波長領域（29.47-33.32Å）で精度よく得ることに成功した。内殻励起を考慮した衝突輻射モデルや配位平均（configuration average）を基にした ADAS 原子分子コードを用いてその波長領域に放射される UTA スペクトル強度計算を行い，アーベル変換後の UTA スペクトルの局所強度分布からそれらイオンの密度分布を求めた。得られたタングステン密度を入射したペレットサイズを基に算出したタングステン密度と比較した結果，良い一致を得た。より精度の高い定量解析を行うためには, W^{24+}-W^{26+}イオンの 5g-4f 遷移に関する内殻励起の寄与を正確に取り入れる必要があることも判明した。これらの研究成果は ITER の周辺プラズマにおけるタングステンイオンの定量評価を初めて可能にすると共に，今後のタングステン不純物の輸送研究に大きく貢献する。

出願者は，タングステン分布の非対称性や CCD 検出器の中性子・γ線影響に関する研究も行っており，博士論文の骨格をなす成果はすでに複数の論文誌に掲載されている（掲載済３編，掲載予定２編）。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。