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EUV Spectroscopy and Atomic Model of Highly Charged Ions of High Z Elements Using LHD Plasmas
LHDプラズマを用いた高Z元素多価イオンのEUV分光と原子モデルの構築

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We have extensively investigated extreme ultraviolet (EUV) spectra from highly charged ions of high Z elements in the Large Helical Device (LHD) experiments in the last few years. In particular, spectral feature of tungsten ions around 2–3 nm and 5 nm have been analyzed well using compact electron beam ion trap (CoBIT) and theoretical calculations. The atomic models improved in this work satisfactorily reproduce the measured spectra. Distinct temperature-dependent spectra have been observed for a number of elements in a wide range of Z, which leads to the new identifications of the spectral lines as well as the derivation of quasi-Moseley's law for the peak position of the quasicontinuum band structure.

1. Introduction

Studies on extreme ultraviolet (EUV) spectra of highly charged ions of high Z elements in plasmas have recently been stimulated in terms of growing interests in a variety of fields. Since tungsten has been chosen as one of the plasma facing materials in the International Thermonuclear Experimental Reactor (ITER), spectral data of tungsten ions have become indispensable for simulating impurity behaviors in plasmas. In semiconductor industries, EUV lithography at 13.5 nm using tin plasmas is now under development, and lanthanide ions are potentially considered as a light source around 6–7 nm [1]. A number of heavy elements such as bismuth are being investigated as candidate materials for a light source in water window (2.3–4.4 nm) and carbon window (4.4–5.0 nm) regions for high-contrast biological imaging [2].

Based on the backgrounds mentioned above, spectroscopic studies on high Z elements have extensively been promoted in the Large Helical Device (LHD) experiments in the last few years. LHD plasmas are considered to be appropriate for benchmarking atomic models of highly charged ions of high Z elements, not only because of low opacity and high-temperature, but also because of the availability of reliable diagnostics of plasma parameters. In this paper, we review some remarkable results on EUV spectroscopy and atomic models of high Z ions in LHD plasmas.

2. Tungsten Spectroscopy

We extrinsically introduce tungsten into LHD plasmas for spectroscopic studies using pellet injection systems. In EUV region, tungsten spectra in typical temperature (around 1 keV) plasmas mainly comprise strong emission of unresolved transition array (UTA) around 5 nm and weaker emission of UTA with separate peaks in the 2–3 nm region. The latter has been analyzed using a compact electron beam ion trap (CoBIT) [3] and an atomic model constructed based on HULLAC code [4]. Figure 1 shows two spectra measured in CoBIT with different beam energies and a spectrum measured in LHD. As a result of comparisons

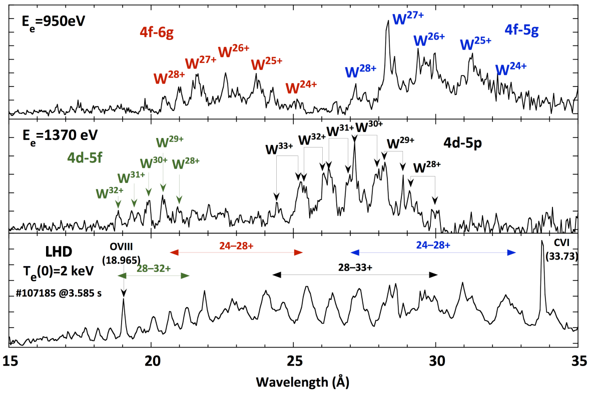

Fig. 1. Spectra form tungsten ions in the 2–3 nm region measured in CoBIT and LHD.

among them, we have successfully identified almost all of the peaks in the LHD spectrum as UTAs of n=4–5 or n=4–6 transitions of W^{24+}–W^{33+} [5].

The primary UTA emission around 5 nm is due to n=4–4 transitions, which results in overlapped contributions from a number of charge states. This feature usually accompanies weaker peak around 6 nm. We tried to improve the atomic models using HULLAC and FAC [6] codes based on the experiments. Consequently, much more levels such as inner shell excited states, which are ignored in earlier works, should be included in the models to correctly reproduce the measured spectra.

3. Atomic Number Dependence

We have also studied a number of elements with a wide range of Z in terms of the needs for the industrial applications to EUV light sources as well as basic atomic physics. In LHD, we can realize a state in which the electron temperature along the line of sight is extremely low (below 500 eV) due to the formation of hollow plasmas [7]. This allows us to observe drastic variations in spectral feature, for example, as shown in Fig. 2 for terbium. When the hollow plasma is formed, the UTA bandwidth of n=4–4 transitions is extremely narrowed, and the doublet peak of Ag-like ions appears in the longer wavelength side, as shown in Fig. 2 (d). When the core electron temperature is much higher (typically above 1.3 keV), on the other hand, the UTA feature disappears as shown in Fig. 2 (a), and spectral lines of Cu- and Ni-like ions can be identified. Some of the lines were identified for the first time in this work [7].

The position of the UTA generally moves to shorter wavelength with increasing Z. Recently, the Z dependence of the UTA peak position measured in LHD and laser-produced plasmas is formalized as a simple Quasi-Moseley's law, analogous to classical Moseley's law for X-ray emission [8]. It would be useful for finding an appropriate material for the future development of light sources in the wavelength of consideration.

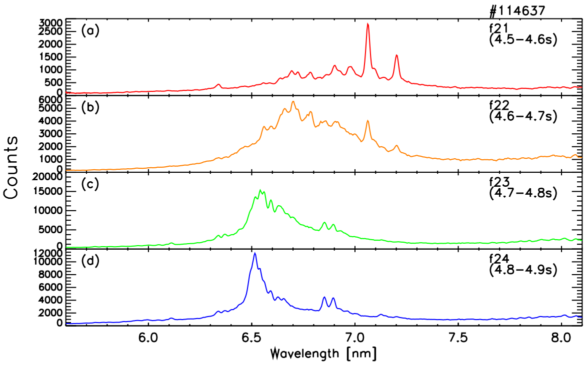

Fig. 2. Variation of Tb Spectra in LHD with changing electron temperature.

Acknowledgments

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