X ray and EUV spectroscopic measurements of highly charged tungsten ions relevant to fusion plasmas

R Radtke[1], C Biedermann[1], P Mandelbaum[2] and J L Schwob[2]

[1]Institut für Physik, Humboldt-Universität zu Berlin, Lehrstuhl Plasmaphysik, D-12489 Berlin, Germany and Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-17491 Greifswald, Germany

[2]Racah Institute of Physics, The Hebrew University, 91904 Jerusalem, Israel

rainer.radtke@physik.hu-berlin.de

Abstract. Using high-resolution x ray and extreme ultraviolet (EUV) spectrometry, the line emission of W^{28+} - W^{50+} ions was measured at the Berlin Electron Beam Ion Trap (EBIT). Our study encompasses a wide range of wavelengths (5-800 Å) and includes the observation of electric and magnetic dipole lines. The results of our measurements are compared with predicted transition wavelengths from *ab initio* atomic structure calculations.

1. Introduction

As part of our program to generate atomic physics data in support of fusion work, the Berlin EBIT has been used to measure the radiation from highly charged tungsten ions. In future large fusion devices (e.g., the International Thermonuclear Experimental Reactor (ITER)) tungsten (Z=74) will be used for certain plasma-facing components because it exhibits excellent thermal properties and a long erosion lifetime to withstand the high power fluxes prevailing in reactor plasma conditions. However, historically tungsten has been regarded as detrimental to fusion experiments [1], due to its presence as an impurity in the plasma. Unlike lower-Z elements, such as carbon (Z=6), tungsten is not fully stripped in the hot plasma core (T_e=10-30 keV for ITER conditions) and has the effect of increasing the power losses by producing line emission in the x ray and EUV spectral ranges. This impurity radiation from tungsten limits the energy confinement in a fusion reactor and could quench the fusion reaction if tungsten ions in relative concentrations of about 10^{-5} reach the core [2]. It is important, then, to have information on the various ionization stages of tungsten and their x ray and EUV spectral fluxes in order to plan future fusion devices and predict the radiated power.

This study complements earlier work on the x ray and EUV spectra of tungsten performed at Tokamaks [1, 3-7] and Electron Beam Ion Traps [8-10]. Tokamak sources have been used extensively to provide tungsten spectra, but the spectral information in this case is strongly influenced by the radial profile of electron temperature and density. Moreover, the tungsten ions are usually in so many charge states that is often not feasible to identify individual spectra. In the present measurements, an EBIT is used which has the advantage over Tokamak sources that it provides almost complete control over the selection of charge states and excitation processes. By stepwise variation of the electron beam energy, it is possible to scan the ion inventory in the trap over an ionization threshold and produce spectra that differ by the contribution of a single charge state.
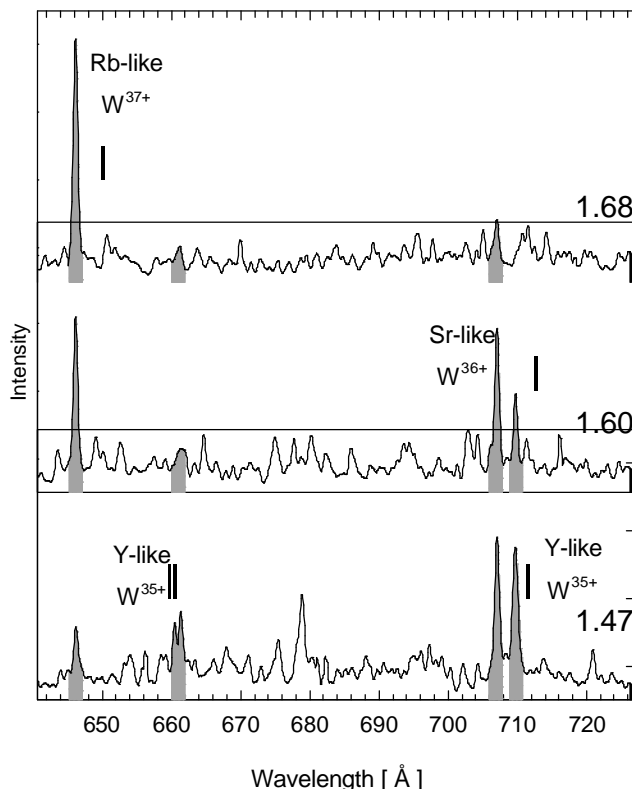
2. Experimental

The EBIT technique employs a monoenergetic electron beam originating from an electron gun which is accelerated and guided into the trap, a region of high magnetic field of roughly 4 cm in length. As the electrons pass through the trap region, the beam is compressed to a diameter of approximately 70 μm by a 3 Tesla magnetic field. The trap consists of an assembly of three drift tubes. Here voltages can be applied to axially confine the ions created by electron impact ionization. Radial confinement is achieved by the electrostatic attraction of the electron beam and the axial magnetic field. In addition to ionizing and trapping the ions, the beam also serves to excite the ions. Tungsten is introduced into the EBIT as a neutral carbonyl compound by directing a continuous flow of $W(CO)_6$ gas towards the trap. Compared to other techniques, a significantly greater amount of x ray and EUV emission is observed pointing to greater abundances of tungsten ions confined in the trap.

The radiation from the trapped tungsten ions is analyzed by high resolution x ray and EUV spectroscopy. A flat-crystal spectrometer is used to study soft x ray lines from the higher charge state ions of tungsten. Of particular interest is the wavelength range between 4 and 20 Å where many lines are predicted from Rb-like W^{37+} to Cr-like W^{47+} [11]. The EUV emission diagnostics were accomplished by means of a 2 m Schwob-Fraenkel grazing-incidence spectrometer. This instrument is specifically built for measurements with an EBIT and has extended our spectroscopic capabilities to the 30-1000 Å EUV region [9]. With this spectrometer we have undertaken a study of magnetic dipole (M1) lines from tungsten in Pd-like W^{28+} to Br-like W^{39+} charge states. The lines originate from transitions between ground term fine structure levels and appear in the wavelength band between 500 and 900 Å. All of our spectral measurements in the x ray and EUV regions are calibrated *in situ* by recording hydrogen- or helium-like reference lines whose wavelengths are accurately known.

3. Tungsten spectra

Spectra were obtained for a number of electron beam energies between 0.8 and 5.0 keV and recorded in the aforementioned wavelength regions, sampling radiation from W^{28+}-W^{39+} and W^{44+}-W^{50+} ions. As an example, figure 1 shows 1.47, 1.60, and 1.68 keV electron beam energy spectra recorded in the spectral range from 640 to 730 Å. Each spectrum is marked by the beam energy and the most abundant charge state in the trap (energies in keV are quoted with corrections for the space charge). There are five observed M1 lines in this region originating from Y-like W^{35+} (659.20 Å, 660.03 Å, and 710.46 Å), Sr-like W^{36+} (707.74 Å), and Rb-like W^{37+} (646.68 Å). The lines result from forbidden transitions between levels of the $4p^6 4d^n$ (n=3, 2, and 1 for W^{35+}-W^{37+}) ground state configurations. For the 12 tungsten ions, Pd-like W^{28+} through Br-like W^{39+}, a total of 48 individual M1 lines were registered and identified in the 500-900 Å wavelength region. A discussion of the data on these lines will be the subject of a forthcoming paper. To support our line identification,

Figure 1. EUV spectra of M1 lines from tungsten at three settings of the electron beam energy. The identified M1 lines are shaded in grey. Vertical marks indicate the wavelengths predicted by HULLAC.

wavelengths and intensities were calculated for each measured tungsten ion using the Hebrew University Lawrence Livermore Atomic Code (HULLAC) package [12] combined with a collisional radiative model. In calculating the population distribution among the levels of the $4p^6 4d^n$ ground configurations, the $4p^6 4d^{n-2} 4f^2$, $4p^6 4d^{n-1} 5s$, $4p^6 4d^{n-1} 5d$, $4p^4 4d^{n+2}$, and $4p^5 4d^n 4f$ excitation channels were included in the energy level calculations. In addition the two strongly mixing $4p^5 4d^{n+1}$ and $4p^6 4d^{n-1} 4f$ excited states were taken into account. The inclusion of the various excitation channels can have an important impact on the transition wavelengths calculated. However, in the present calculation there is no assurance that complete convergence was reached since the number of levels (more than 4000) quickly surpassed our computational means. From a comparison with the experimental values (figure 1), we infer that *ab initio* calculations for these lines can deliver results within about 1-3 % of the correct numbers depending on the transition. For Tokamak plasmas, the tungsten M1 lines can be considered as promising candidates for diagnostic measurements because they are intense and appear well isolated from other lines in a wavelength interval that is accessible with moderate instrumental effort.

In a second experiment, spectra of tungsten have been recorded in the 5 to 10 Å region. The most prominent lines in this wavelength range originate from 3d-4f transitions and are located near 5-6 Å.
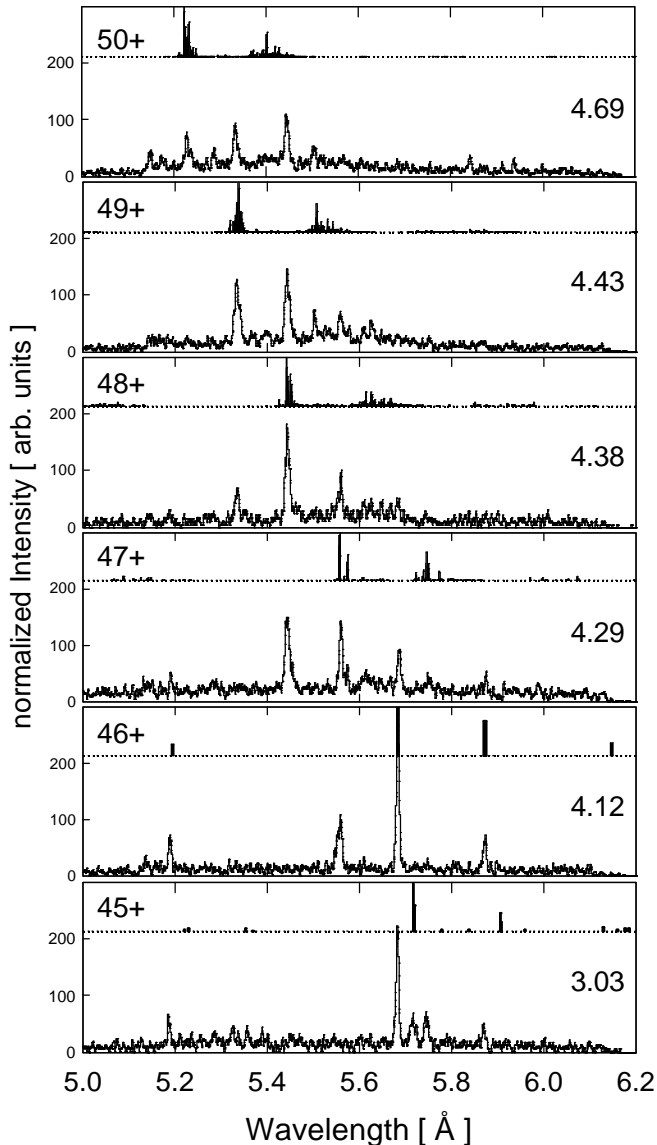
Data on these lines are essential for magnetic confinement fusion experiments as they serve as a monitor of tungsten impurities in the plasma [5]. Our measurements concentrated on soft x ray lines from Zn-like W^{44+} to Cr-like W^{50+} ions. As an example, figure 2 shows spectra obtained at six electron beam energies in the interval between 3.03 and 4.69 keV. The labels on the right of each panel indicate the energy of the beam in keV. The measured line intensities vary as a function of the beam energy and are enhanced considerably when the population of the emitting ion within the EBIT is at maximum. For the beam energies 3.03 and 4.12 keV, the most abundant tungsten ions in the trap are Cu-like W^{45+} and Ni-like W^{46+}. The dominating tungsten line at 5.673 Å is assigned as the $3d^{10}$-$3d^9 4f$ transition in Ni-like W^{46+}. At 3.03 keV beam energy a minor line emitted from W^{44+} at 5.746 Å is observed. As the beam energy progressively increases, the ion population in the EBIT is shifted to higher charge states. For the sequence following the 4.12 keV spectrum, we observe a weakening of the line at 5.673 Å in a manner that indicates the absence of W^{46+}

Figure 2. Measured and predicted soft x ray spectra of tungsten. The simulated spectra for W^{45+}-W^{50+} are based on calculations from Refs. [11, 13] and shifted vertically for clarity.

ions for beam energies above 4.2 keV. In the higher beam energy spectra multiplet lines from Co-, Fe-, Mn-, and Cr-like ions appear. The features from these ions are wider than expected for a single line since they incorporate contributions from a larger number of 3d-4f transitions. In addition to the measured spectrum, each panel in figure 2 displays a calculated spectrum for a single ion charge state from Cu-like W^{45+} through Cr-like W^{50+}. The simulated spectra are generated by *ab initio* calculations using the HULLAC package, and the relative populations for the levels of each ion are found by relying on collisional-radiative level population modelling [11, 13]. From a comparison of the experimental and theoretical spectra it is evident that the observations confirm the general pattern of the predicted spectra. All lines in the measured spectra also appear in the simulated data. The strongest isolated $3d^{10}$-$3d^{9}4f$ transition in Ni-like W^{46+} ($?_{exp}$=5.673 Å) is found to be calculated to better than 0.2 %. For the Co-like and higher charge state ions with the more complex spectra, no detailed comparison was made between observed and predicted wavelengths. Such comparison requires measurements with much a higher spectral resolution than that of the present experiment.

References
[1]   Isler R C, Neidigh R V and Cowan R D 1977 Phys. Lett. **63A** 295
[2]   Peacock N J, Barnsley R, Hawkes N C, Lawson, K D and O'Mullane M G 1996 in Diagnostics for experimental thermonuclear fusion reactors, edited by Stott P, Giuseppe G and Sindoni E (Plenum Press, New York) 291
[3]   Hinnov E and Mattioli M 1978 Phys. Lett. **66A** 109
[4]   Finkenthal M, Huang L K, Lippmann S, Moos H W, Mandelbaum P, Schwob J L, Klapisch M and the TEXT Group 1988 Phys. Lett. A **127** 255
[5]   Neu R, Fournier K B, Schlögl and Rice J 1997 J. Phys. B: At. Mol. Opt. Phys. **30** 5057
[6]   Asmussen K, Fournier K B, Lamig J M, Neu R, Seely J F, Dux R, Engelhardt W, Fuchs J C and the ASDEX Upgrade Team 1998 Nucl. Fusion **38** 967
[7]   Pütterich T, Neu R, Biedermann C, Radtke R and ASDEX Upgrade Team 2005 J. Phys. B: At. Mol. Opt. Phys. **38** 3071
[8]   Radtke R, Biedermann C, Schwob J L, Mandelbaum P and Doron R 2001 Phys. Rev. A **64** 012720
[9]   Biedermann C, Radtke R, Schwob J L, Mandelbaum P, Doron R, Fuchs T and Fußmann G 2001 Phys. Scr. **T92** 85
[10]   Utter S B, Beiersdorfer P and Träbert E 2002 Can. J. Phys. **80** 1503
[11]   Fournier K 1998 At. Data Nucl. Data Tables **68** 1
[12]   Bar-Shalom A, Klapisch M and Oreg J 1988 J. Phys. Rev. A **38** 177
[13]   Fournier K (private communication)