Spectroscopic data of highly charged tungsten ions obtained with an electron beam ion trap

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INTRODUCTION

An electron beam ion trap (EBIT)[1] is a powerful device to obtain the atomic data of highly charged ions needed for understanding and controlling high temperature plasmas, such as fusion plasmas and the solar corona. It can trap highly charged ions interacting with a monoenergetic electron beam for many hours. It is thus regarded as a well-defined simple plasma consisting of unidirectional monoenergetic electrons and trapped ions with a narrow charge state distribution. Consequently the EBIT plasma is an unique and ideal source for high resolution spectroscopic studies of highly charged ions. Spectra from an EBIT are useful to survey and identify previously unreported lines, and also to provide benchmark for plasma models. An EBIT can also be used as a device to study the interactions of electrons with highly charged ions. Such spectroscopic and collisional data can be obtained for ions over wide ranges of charge state and atomic number; any ion of any element can practically be studied. Interaction energy between ions and electrons can also be varied over a wide range, such as 100 eV to more than 100 keV.

In this paper, we introduce two types of EBITs at the University of Electro-Communications; one is a high-energy EBIT called the Tokyo-EBIT[2] and another is a low-energy, compact EBIT called CoBIT[3]. Recent results with them are also presented.

ELECTRON BEAM ION TRAP (EBIT)

An EBIT[1] was developed at the Lawrence Livermore National Laboratory based on the principle of an electron beam ion source (EBIS)[4] developed at Joint Institute for Nuclear Research in Dubna. Figure 1 shows the schematic principle of an EBIT. An EBIT consists of a Penning-like ion trap and a high-energy, high-density electron beam going through the trap. Its main components are an electron gun, a drift tube (ion trap), an electron collector, and a superconducting magnet. The drift tube is composed of three (or more) successive cylindrical electrodes where a well potential is applied for trapping ions axially. Radial ion trap is achieved by the combination

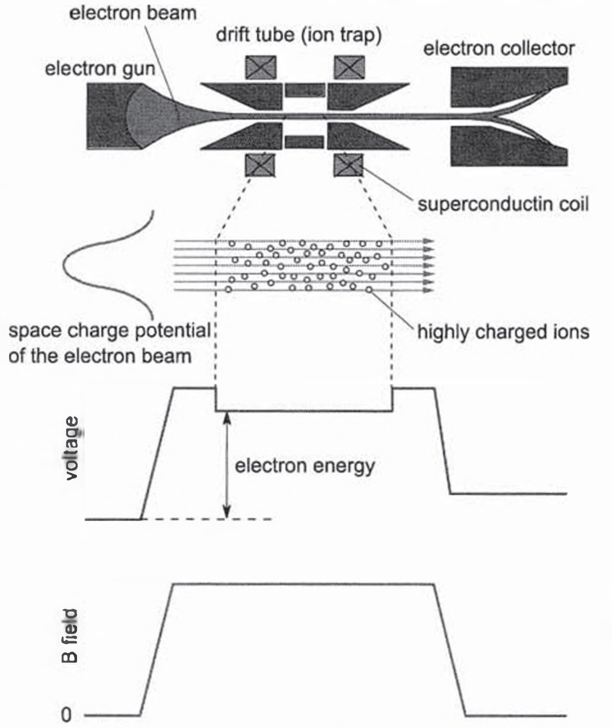

Fig. 1 Schematic principle of an electron beam ion trap.

of the strong axial magnetic field produced by the magnet and the space charge potential of the high density electron beam compressed by the magnetic field. Highly charged ions are produced by successive electron impact ionization of the trapped ions. Emission of highly charged ions excited by the electron beam can be studied spectroscopically through a slit opened at the middle of the drift tube. Since the trapped ions are produced and excited by an (quasi-)monoenergetic electron beam, an EBIT has following advantages over plasma sources. (1) A narrow charge state distribution can be obtained with a dominant charge state controlled by the electron energy. (2) Electron energy dependent emission processes, such as resonant excitation, can be studied. (3) There is no Doppler shift and less Doppler broadening. (4) Polarization of radiation excited by a unidirectional electron beam can be studied. We have developed a high-energy EBIT called the Tokyo-EBIT[2] in 1995 and a compact low-energy EBIT called CoBIT[3] in 2007. The former can be operated with electron energies of 1 to 200 keV, and the latter can be operated with electron energies of 0.1 to 2 keV. The complementary use of them enables spectroscopic studies of tungsten ions with a wide range of charge state.

An element of interest is usually introduced through the slit on the drift tube as a molecular beam. Not only rare gases and molecular gases, compounds which have a relatively high vapor pressure can also be used. For example, for producing tungsten ions, tungsten hexacarbonyl ($W(CO)_6$) are used respectively.

TUNGSTEN SPECTRA IN VISIBLE RANGE

Tungsten is considered to be the main impurity in the ITER plasma, and thus spectroscopic data of tungsten ions are necessary to diagnose and control the high temperature plasma in ITER[5]. In particular, there is strong demand for emission lines in the visible range in the diagnostics of the edge plasmas[6]. Since efficient optical components, such as mirrors, lenses, optical fibers, etc., are available, efficient and effective diagnostics can be expected with the visible range. Until recently, however, only one visible emission line[7] has been reported for tungsten ions with a charge state higher than two. Survey and identification of previously unreported visible lines of tungsten ions are thus in strong demand. An EBIT is a suitable device for such a purpose. As an example, tungsten spectra obtained with CoBIT are shown in Fig. 2. As seen in the figure, observed lines revealed strong dependence on electron energy, i.e., they appeared at a certain threshold energy and their intensity became weak when the

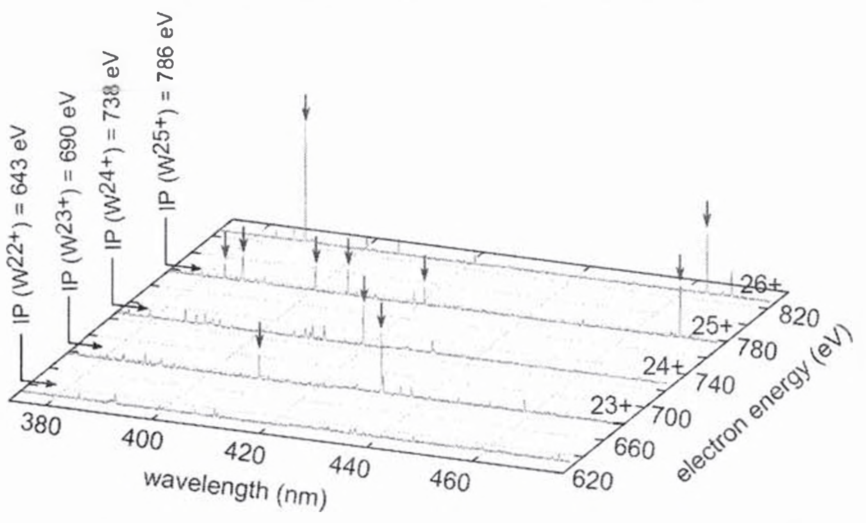

Fig. 2 Visible spectra of highly charged tungsten ions observed with CoBIT. IP(W^{q+}) represents the ionization potential of W^{q+}.

energy was further increased. This strong dependence reflects the charge distribution in the trap. For example, after the electron energy was changed from 630 eV to 675 eV, production of W^{23+} became available because the ionization energy of W^{22+} is 643 eV[8]. The lines at around 409 and 432 nm, appeared at 675 eV, are thus considered to be emission lines from W^{23+}. When the energy was further increased to 725 eV, which is higher than the ionization energy of W^{23+} (690 eV), the intensity of these lines became small because the number of W^{23+} was decreased due to further ionization, and the line from W^{24+} appeared at around 419 nm. The validity of such identification based on the appearance energy has been confirmed through several previous experiments[9]. Consequently, the lines indicated by arrows in the figure are assigned to be the transition of tungsten ions shown in each spectrum. Since transitions between different electronic configurations in highly charged heavy ions should fall in shorter wavelength range, such as EUV and x-ray, transitions in the visible range can be assigned as M1 transitions between fine structure levels. The detailed identification of the fine structure levels should be done through comparison with theoretical calculations. Although it is rather difficult to calculate fine structure splitting precisely for many electron heavy ions, some lines in Fig. 2 have been identified through the comparison with detail calculations[10]. Survey of previously unreported lines is also possible with plasma sources, but observation of spectra excited by a mono-energetic electron beam in an EBIT is quite useful for the identification of the responsible charge state as shown here.

TUNGSTEN SPECTRA IN X-RAY RANGE

Collisions of highly charged ions with electrons are the most important atomic process in hot plasmas. Various parameters and behavior of plasmas are modeled based on the cross sections for electron collisions, such as excitation, ionization, recombination, etc. For the most simple example, the ion density ratio at the ionization equilibrium is determined from the ratio between ionization and recombination rates. However, even for this simple example, different theories sometimes give quite different results[11]. It is thus obviously important to measure cross sections experimentally and examine the theories with them. In an EBIT, a quasi-monoenergetic electron beam interacts with trapped highly charged ions. Collision processes, such as excitation[12] and ionization[13] can thus be studied by observing emission from an EBIT or charge state distribution in an EBIT. In particular, resonant processes, such as dielectronic recombination

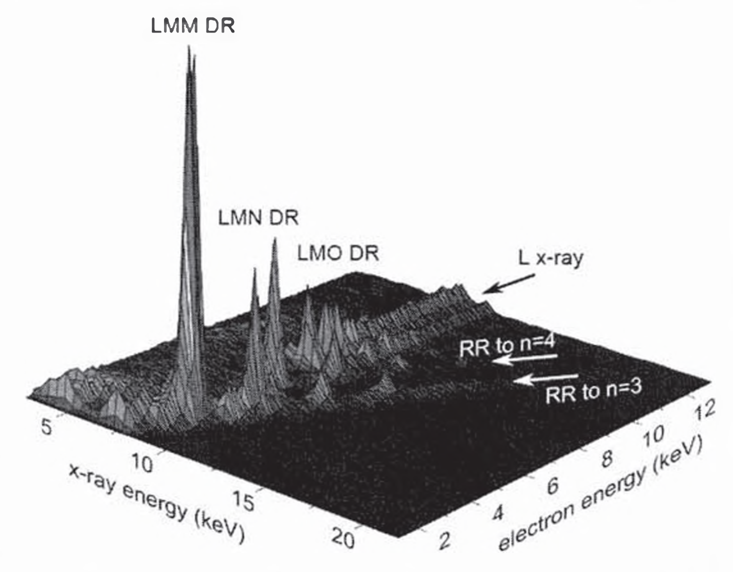

Fig. 3 X-ray spectra of highly charged tungsten ions observed with the Tokyo-EBIT while scanning electron energy between 1.5 and 14 keV.

(DR) can be studied efficiently by observing the dependence on electron energy. For example, Fig. 3 shows the x-ray spectra of tungsten ions observed with a Ge detector while scanning electron energy between 1.5 keV and 14 keV. As seen in the figure, x-ray intensity is prominently enhanced due to DR at some electron energies. For example, at an electron energy of ~3 keV, *L* x-rays are enhanced by the *LMM* DR resonance. *LMM* represents the process where a doubly excited state is produced by capturing the incident electron into the *M* shell while exciting a *L* shell electron to the *M* shell. For heavy ions, since the doubly excited state decays by emitting x-ray with a probability near unity, x-ray intensity is enhanced at the resonant energy. On the other hand, x-rays whose energy increases with the gradient of unity as a function of electron energy are due to non-resonant recombination (radiative recombination: RR). DR resonant strengths can be obtained by normalizing the x-ray intensity from DR to that from RR, for which reliable cross section can be calculated because there is no need to include electron correlation. For example, so far such a method was used to obtain DR resonant strengths for H-like Kr[14], He-like Ti[15], etc.

SUMMARY

As shown in this paper, an EBIT is an unique and versatile device for studying spectra and collision processes of highly charged ions. Three EBITs (the Tokyo-EBIT and two CoBIT) in Japan and over ten EBITs in the world are currently in operation for accumulating the atomic data of highly charged ions relevant to hot plasmas. Spectroscopic data of tungsten ions over a wide range of charge states have been accumulated under the IAEA Coordinated Research Projects “Spectroscopic and Collisional Data for Tungsten from 1 eV to 20 keV” for making a contribution to the future diagnostics of the ITER plasma. An EBIT is a powerful device also for studying collisional processes of highly charged ions, and the monoenergeticity of the electron beam enables ones to study resonant processes, such as dielectronic recombination which strongly affects the ionization balance and the emission of plasmas.

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