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# Activities at the Tokyo EBIT 2010

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# Activities at the Tokyo EBIT 2010

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ABSTRACT: In this paper, we present recent activities at the Tokyo EBIT after giving an overview of the present status of the devices. We have been studying dielectronic recombination processes by means of several techniques. In addition to X-ray observations and charge abundance observations, 2-photon observations have been recently used to study DR processes which emit two photons successively (but practically simultaneously). Recent efforts on spectroscopic work are mainly concentrated on Fe and W ions, which are relevant to astrophysical and fusion plasmas.

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Several spectrometers that can cover a wide range of wavelength, such as visible, EUV, and X-rays, were used for accumulating useful data for plasma diagnostics applications. HCI-surface collision processes were studied using ions extracted through the beam line, that has recently been modified. Very highly charged ions up to $Bi^{81+}$ were used for studying the effect of huge potential energy.

KEYWORDS: Low-energy ion storage; Ion sources (positive ions, negative ions, electron cyclotron resonance (ECR), electron beam (EBIS))

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## 1 Introduction

We are using two electron beam ion traps (EBITs) for studying the structure and the atomic processes of highly charged ions. One of them is a high-energy EBIT, called the Tokyo-EBIT [1–3], that was built in 1995 and has been being stably operated ever since. Another is a low-energy EBIT, called CoBIT [4], that was built recently for efficiently studying moderate charge state ions. The complementary use of these two EBITs allows us to study ions over a wide range of charge state. In this paper, we present recent activities with these EBITs.

## 2 Present status

Parameters of the two EBITs in Tokyo are shown in table 1. The maximum electron beam energy and current of the Tokyo-EBIT achieved so far are 180 keV and 330 mA respectively, while typical

**Table 1**. Operational parameters of the Tokyo-EBIT and CoBIT.

| | Tokyo EBIT | CoBIT |
|---|---|---|
| Max. electron energy (keV) | 180 | 2.5 |
| Max. electron current (mA) | 330 | 20 |
| Max. magnetic field (T) | 4.5 | 0.2 |
| Cryostat temperature (K) | $\leq$4.2 | 77 |
| Coolant | Liq. He | Liq. $N_2$ |
| Height (m) | $\sim 4$ | $\sim 0.4$ |

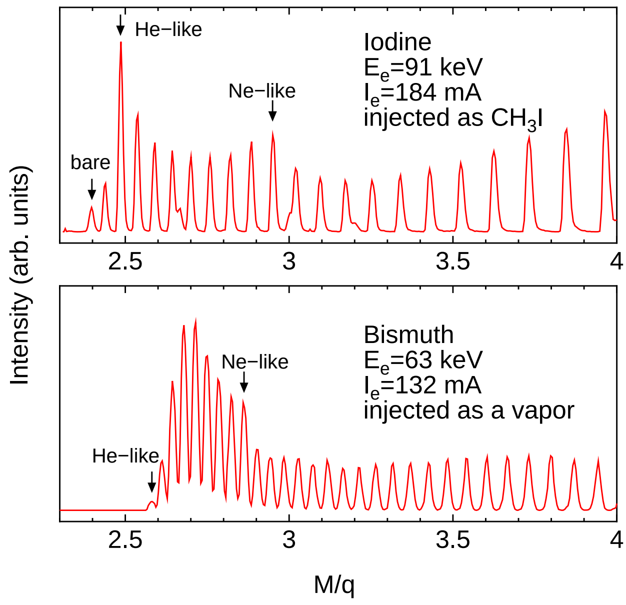


**Figure 1**. Typical charge state spectra of highly charged ions extracted from the Tokyo EBIT.

operational parameters are in the range of 10-90 keV with 100-150 mA. Highly charged ions produced with such a high-energy, high-current electron beam can be not only stored for spectroscopic studies but also extracted for collision experiments. Typical charge state spectra of extracted ions are shown in figure 1. As shown in the figure, very highly charged ions up to $Bi^{81+}$ can be used for collision experiments [5]. The intensity of the HCI beam with a cross section of 1 $mm^2$ is $10^{3-5}$ counts per second, depending on charge state. Recently, the beam line has been modified with the aim of increasing the intensity. In the previous system [6], an electrostatic bender has been used before a charge analyzing magnet. On the other hand in the present system, the electrostatic bender has been omitted and the analyzing magnet is placed just above the EBIT. As a result, the path length between the EBIT and the collision chamber has been much shortened and simplified. The performance of the modified line is currently being tested.

Although the Tokyo EBIT has been operated with lower electron energies such as 1 keV or less, the stability in such operation is not so good that an electron current of only a few mA is available. Thus we built the compact device CoBIT for effectively studying moderate charge state ions that can be produced with an electron energy of 1 keV or less. Not only the electron energy but also the electron current and the magnetic field are rather small compared with the Tokyo-EBIT as shown in the table; such parameters allowed us to downsize the device. Diagnostics using EUV and visible spectrometers proved that CoBIT is a powerful device to produce and study moderate charge state ions that are important for the application in the plasma physics and so on. The details of CoBIT and the results of recent operation are shown in elsewhere in this volume.

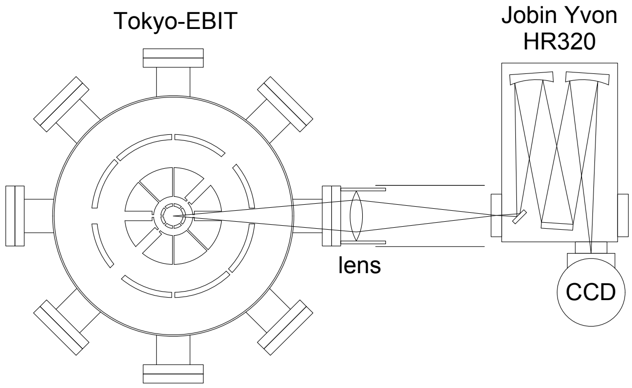


**Figure 2**. Setup for visible spectroscopy.

## 3 Spectroscopic studies

### 3.1 Spectroscopy of tungsten ions

Since tungsten is a major candidate for the divertor material of ITER, its spectroscopic data are strongly needed for diagnosis and control of the high temperature plasma in ITER. By using the two EBITs, we are systematically measuring spectra of highly charged tungsten ions with a wide range of charge states over a wide range of wavelength. In particular, we are currently interested in the visible region because a lot of effort has already been paid for the shorter wavelength range such as VUV and X-rays at several EBIT facilities [7–9]. Figure 2 shows the typical setup for visible spectroscopy [10], which is used both for the Tokyo-EBIT and for CoBIT although the focal length and the size of the lens are changed depending on the ion source used. Tungsten is injected into the EBIT as a vapor of $W(CO)_6$ through a gas injection system. To distinguish the lines of tungsten from those of carbon and oxygen, spectra were also observed while injecting CO and $O_2$ and compared with the spectra obtained with $W(CO)_6$ injection. The charge state of the tungsten ion responsible for the observed line can be identified from the appearance energy by observing electron energy dependence although the comparisons with theoretical calculations are needed for the detailed identification. Resent results will soon be published elsewhere.

### 3.2 Spectroscopy of iron ions

For the diagnostics of the solar corona with the solar physics satellite Hinode, spectroscopic data of highly charged iron ions with charge states around 10+ are needed. Under the collaboration with the Hinode project, the EUV spectra of iron ions has been being studied for a wavelength range of 10-30 nm. One of the most important subjects is to observe the electron-density dependence of line intensity ratios to test the collisional radiative models used in the density diagnostics [11, 12]. Although the electron density can be controlled by changing the electron beam current or the central magnetic field (or both), it is generally difficult to know the absolute density. Recently, we have installed a slit near the electron beam in the EBIT to obtain the image of the electron beam based on the principle of a pin-hole camera. From the observed image of the electron beam, the radius and thus the density of the electron beam can be obtained [13–15].



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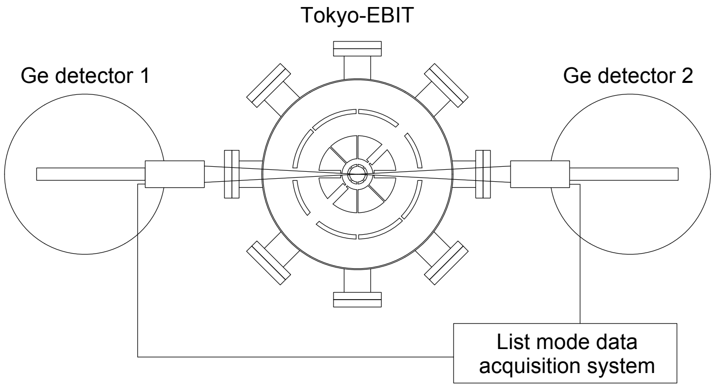


**Figure 3**. Setup for two photon observation.

## 4 Dielectronic recombination measurements

Dielectronic recombination (DR) of highly charged ions is one of the most important processes in plasmas. An EBIT is a useful device for studying DR processes of highly charged heavy ions since it has a (quasi-)monoenergetic electron beam whose energy can be easily and rapidly controlled [16, 17]. By using the Tokyo-EBIT, we have been studying DR processes through both X-ray observations [18] and ion abundance measurements [19, 20]. The former has the advantage that absolute cross sections can be obtained by normalizing the X-ray intensity of DR to that of radiative recombination (RR), for which reliable theoretical cross sections can be obtained. On the other hand, it has the disadvantage that it is difficult to resolve the charge states mixed in the EBIT due to the intrinsic energy resolution of a solid state Ge detector. In contrast, the latter has the advantage that charge-state resolved measurements are possible although it is difficult to obtain absolute cross sections. The ion abundance measurement is thus suitable for open shell systems for which it is difficult to concentrate the abundance on a single charge state.

In the previous X-ray measurements, a single detector was used at an observation angle of 90 degrees with respect to the electron beam. In the stabilization of the intermediate doubly excited state, however, two photons are generally emitted successively (but quasi-simultaneously). For example, two $K$ X-rays can be emitted in $KLL$ DR of a H-like ion:

$$\begin{aligned} \mathrm{e}+\mathrm{A}^{q+}(1s) &\rightarrow \mathrm{A}^{(q-1)+**}(2l2l') \\ &\rightarrow \mathrm{A}^{(q-1)+*}(1s2l') + h\nu_1 \rightarrow \mathrm{A}^{(q-1)+} + h\nu_2. \end{aligned}$$

In the experiments with a single detector, one of these two photons has been observed. Recently, we have been measuring these two photons in coincidence using a pair of Ge detectors. One of the motivations for this coincidence measurement is to obtain the angular correlation between these photons. A few theoretical studies have demonstrated the correlation [21], but it has never been confirmed experimentally so far.

Figure 3 shows the typical setup for the two-photon observation. Signals from two Ge detectors were recorded with a multi-parameter data acquisition system (IWATSU A3100). Both the pulse height (X-ray energy) and the arrival time of each signal were stored in the list mode. The system is currently being tested through the coincidence measurement of K and L X-rays emitted in the KLM-DR process of Ba ions.

## 5 Interaction of HCIs with surfaces

A highly charged ion has so huge potential energy that a single ion impact can induce drastic changes on a surface even if it has no kinetic energy at all (e.g. see [22] and references therein). For example, it is known from previous studies that a nano-structure is created with a quantum efficiency of unity for various kinds of surfaces [23]. The size and the shape of the structure are found to be strongly dependent on the charge state of the incident ion, the physical properties of the surface and so on [24, 25], but the detailed mechanism is still unclear so that further studies are needed. Microscopic observations is ongoing with a scanning tunnelling microscope directly connected to the beam line of the Tokyo-EBIT.

## 6 Summary and outlook

The complementary use of the high-energy and low-energy EBITs allows us to study highly charged ions over a wide range of charge state. Spectroscopic studies over a wide range of wavelength are ongoing using various types of spectrometers. In addition, by using the ion extraction system of the Tokyo-EBIT, the collision processes of highly charged ions with electrons and surfaces are studied. For further studies, new spectrometers and a coincidence system for two photon observation has been developed. An ion extraction system for CoBIT is also currently being developed.

## Acknowledgments

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## References

[1] F.J. Currell et al., *A New Versatile Electron-Beam Ion Trap*, *J. Phys. Soc. Jpn.* **65** (1996) 3186.

[2] H. Watanabe et al., *Characteristics of the Tokyo Electron-Beam Ion Trap*, *J. Phys. Soc. Jpn.* **66** (1997) 3795.

[3] N. Nakamura et al., *The present status of the Tokyo electron beam ion trap*, *Rev. Sci. Instrum.* **69** (1998) 694.

[4] N. Nakamura, H. Kikuchi, H.A. Sakaue and T. Watanabe, *Compact electron beam ion trap for spectroscopy of moderate charge state ions*, *Rev. Sci. Instrum.* **79** (2008) 063104.

[5] C. Yamada et al., *Injection of metallic elements into an electron beam ion trap using a Knudsen cell*, *Rev. Sci. Instrum.* **77** (2006) 066110.

[6] N. Nakamura et al., *Recent activities at the Tokyo EBIT 2006*, *Can. J. Phys.* **86** (2008) 315.

[7] R. Radtke, C. Biedermann, J.L. Schwob, P. Mandelbaum and R. Doron, *Line and band emission from tungsten ions with charge 21+ to 45+ in the 45–70Årange*, *Phys. Rev.* **A 64** (2001) 012720.

[8] J. Clementson, P. Beiersdorfer and M.F. Gu, *X-ray spectroscopy of E2 and M3 transitions in Ni-like W*, Phys. Rev. **A 81** (2010) 012505.

[9] Y. Ralchenko, J. Reader, J.M. Pomeroy, J.N. Tan and J.D. Gillaspy, *Spectra of* $W^{39+}-W^{47+}$ *in the 12-20 nm region observed with an EBIT light source*, J. Phys. **B 40** (2007) 3861.

[10] H. Watanabe et al., *Magnetic dipole transitions in titaniumlike ions*, Phys. Rev. **A 63** (2001) 042513.

[11] G.Y. Liang et al., *Experimental investigations of ion charge distributions, effective electron densities, and electron-ion cloud overlap in electron beam ion trap plasma using extreme-ultraviolet spectroscopy*, Astrophys. J. **702** (2009) 838.

[12] H. Chen et al., *Electron Impact Excitation Cross Section Measurement for* $n=3$ *to* $n=2$ *Line Emission in* $Fe^{17+}$ *to* $Fe^{23+}$, Astrophys. J. **646** (2006) 653.

[13] J.V. Porto, I. Kink and J.D. Gillaspy, *UV light from the ground term of Ti-like ytterbium, tungsten, and bismuth*, Phys. Rev. **A 61** (2000) 054501.

[14] D.A. Knapp et al., *A high-energy electron beam ion trap for production of high-charge high-Z ions*, Nucl. Instrum. Meth. **A 334** (1993) 305.

[15] Y. Zou and R. Hutton, *The potential of an EBIT in assisting plasma diagnostics and progress at the Shanghai EBIT*, J. Phys. Conf. Ser. **185** (2009) 012060.

[16] D.R. DeWitt et al., *Dielectronic recombination cross sections of fluorinelike xenon*, Phys. Rev. **A 47** (1993) R1597.

[17] A.J.G. Martínez et al., *State-Selective Quantum Interference Observed in the Recombination of Highly Charged* $Hg^{75+\ldots78+}$ *Mercury Ions in an Electron Beam Ion Trap*, Phys. Rev. Lett. **94** (2005) 203201.

[18] H. Watanabe et al., *The measurement of the dielectronic recombination in He-like Fe ions*, J. Phys. **B 34** (2001) 5095.

[19] H. Watanabe et al., *Dielectronic recombination of He-like to C-like iodine ions*, Phys. Rev. **A 75** (2007) 012702.

[20] N. Nakamura et al., *Evidence for Strong Breit Interaction in Dielectronic Recombination of Highly Charged Heavy Ions*, Phys. Rev. Lett. **100** (2008) 073203.

[21] S. Zakowicz, W. Scheid and N. Grün, *Dielectronic recombination into hydrogen-like heavy ions with emission of two photons*, J. Phys. **B 37** (2004) 131.

[22] F. Aumayr and H.P. Winter, *Potential sputtering*, Phil. Trans. Roy. Soc. Lond. **A 362** (2004) 77.

[23] N. Yoshiyasu et al., *Demonstrative experiment for single ion implantation technique using highly charged ions*, Jpn. J. Appl. Phys. **45** (2006) 995.

[24] M. Tona et al., *Nano-crater formation on a Si(1 1 1)-(7* $\times$ *7) surface by slow highly charged ion-impact*, Sur. Sci. **601** (2007) 723.

[25] M. Tona et al., *Some characteristics in the interaction of slow highly charged Iq+ ions with a Si(1 1 1) 1* $\times$ *1-H surface*, Sur. Sci. **600** (2006) 124.