The present status of the Tokyo electron beam ion trap

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Recent progress of the Tokyo electron beam ion trap (Tokyo-EBIT) project is described. The Tokyo-EBIT is of an original design and construction with several features different from other EBITs in the world. The maximum energy and current of the electron beam are designed to be 340 keV and 300 mA with a magnetic field of 4.5 T. The ongoing and planned physics experiments are described and the results for the initial stage of operation of the Tokyo-EBIT are given. © *1998 American Institute of Physics.* [S0034-6748(98)53702-1]

I. INTRODUCTION

Electron beam ion traps[1] developed at the Lawrence Livermore National Laboratory (LLNL) are versatile apparatus not only for spectroscopic studies of highly charged ions (HCIs) but also for studies on the interaction of HCIs with matter. Although about 6 EBITs[2–4] are in operation throughout the world at present, all EBITs have similar operational parameters, excluding the Super-EBIT[5] at LLNL and the Tokyo EBIT.[6–8] The maximum electron beam energy of the Tokyo EBIT is designed to be 340 keV while the Super-EBIT has achieved an energy of 210 keV. The operational parameters of the Tokyo EBIT promise many new experiments on HCIs. In this article, we present the recent progress and future planned experiments of the Tokyo EBIT project following a description of the design and the operational status of the device.

II. DESIGN AND OPERATION OF THE TOKYO EBIT

The Tokyo EBIT is of a new design, with several features which differ from other EBITs in the world. The electron gun was designed in house, while all other EBITs employ commercial ones. To optimize the electrostatic and the magnetic field inside the gun, a number of trajectory simulations were performed.[8] At present, total emission of up to 250 mA has been obtained in good agreement with the designed value of perveance. The trap region is also unique. The middle drift tube is divided into six electrodes. This makes it possible to trap the ions in the Penning trap[9] mode and excite the ion motion by applying rf to the electrodes. The temperature of the cryostat reaches 2.4 K by supercooling. This significantly improves the vacuum inside the trap because the vapor pressure of hydrogen molecules falls significantly ($\sim 10^{-15}$ Torr). For more details of the design, see recent papers.[6–8]

In the initial stage of the operation, an electron energy of 80 keV and a current of 250 mA have been achieved. At present the electron energy is limited by the insulation in the atmosphere outside the EBIT. The transmittance of the electron beam was measured to be $99.9^{+0.1}_{-0.2}\%$ for all electron energies and currents achieved.

A typical radiative recombination (RR) spectrum taken with a 75 keV–150 mA electron beam is shown in Fig. 1. The spectrum was obtained using a Ge detector (EURISYS, EGP500-15ER) placed at 350 mm away from the center of the trap. The acquisition time was about 70 min. During this observation, the trapped ions were periodically dumped once per 100 s. RR peaks to two dominant species of ions, Kr and Ba are seen in the spectrum. Kr was injected from the outside of the EBIT while Ba and W were evaporated from the cathode and ionized in the trap region. From the RR peaks around 118 keV, we can confirm that H like and bare Ba ions have been produced. The small peaks at 83 and 94 keV are considered to be RR processes to highly charged W ions.

We have also extracted highly charged ions from the trap. The present setup for the extraction line has been out-

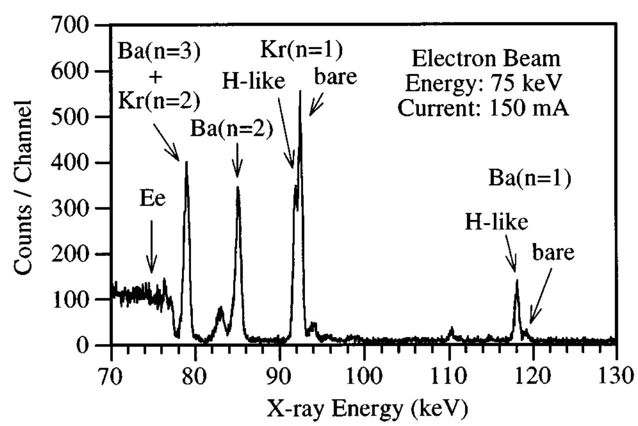

FIG. 1. A typical radiative recombination spectrum from the Tokyo-EBIT. The electron energy is represented as Ee.

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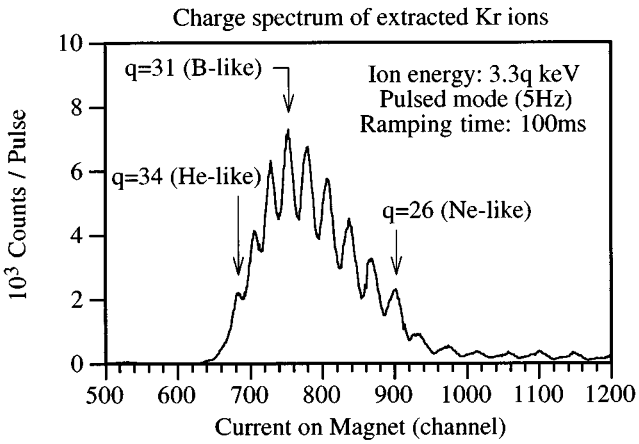

FIG. 2. Typical charge spectrum of Kr ions extracted from the Tokyo EBIT. The spectrum is taken with 48.2 keV–130 mA electron beam.

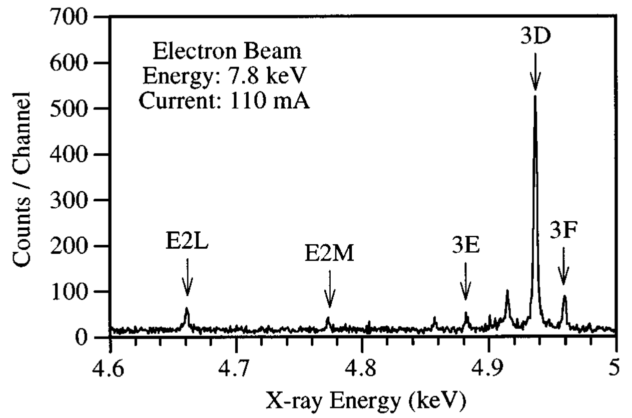

FIG. 3. High resolution x-ray spectrum of $(2l)^{-1}(3l)-(2p)^6$ transitions in Ne-like Ba (46+), taken with a flat crystal spectrometer. The notations in the figure represent initial states, E2L:$(2p_{5/2})(3p_{1/2})_2$; E2M:$(2p_{3/2})(3p_{3/2})_2$; 3E:$(2p_{3/2})(3d_{3/2})_1$; 3D:$(2p_{3/2})(3d_{5/2})_1$; 3F:$(2p_{1/2})(3s_{1/2})_1$.

lined in a previous paper.[10] Our extraction system is still undergoing tests to find the best conditions because there are many parameters to be adjusted for the extraction of trapped ions, e.g., voltage for the lenses and the deflectors, width and shape of the extraction pulse, the parameters of the EBIT itself, etc. A typical charge spectrum is shown in Fig. 2. The widths of the slits placed before and after the analyzing magnet were set to 2 mm. Krypton gas was introduced from a side port of the EBIT. Ions were extracted by a pulsed extraction mode. During dumping, the potential of the middle drift tube (DT2) was linearly changed from +3.2 to +3.4 kV with respect to laboratory earth during 100 ms, and then rapidly returned to +3.2 kV. This procedure was performed five times per second. Since the potential of the upper drift tube (DT3) was fixed to be +3.3 kV, the extracted ions may have an energy of 3.3q keV, where q is the charge state of the extracted ions. During trapping, the electron beam energy was set to be 48.2 keV and the current was about 130 mA. The extracted ions were counted while cutting off the contribution from continuous extraction. There is a peak in the charge state distribution at higher charge states, and the maximum is at Kr^{31+}.

III. ONGOING AND PLANNED EXPERIMENTS

As mentioned above, the present value of the maximum electron energy is limited by the insulation in 1 atm of air. An insulation system with 2 atms of SF_6 gas has been completed recently and the energy will increase in the very near future. We believe that a higher current of up to 300 mA can be easily achieved if a higher electron energy is achieved. At present we do not have a MEVVA[11] system to inject metal ions into the trap. We are constructing a MEVVA, which is similar to that of other EBITs, and this will be attached to the main EBIT in the very near future. The ion extraction line will also be improved. Especially, improvement of the transport system will make it possible to guide more ions through the line.

An EBIT can be used as an experimental tool for electron collision processes with highly charged ions because the electron beam always interacts with the ions in the trap. We have observed dielectronic recombination processes to Ne-like Xe and He-like Kr, and these results have been described in other papers.[12,13] These measurements will be expanded by measuring the charge-selected extracted ion yield as a function of electron energy to remove the uncertainty arising from mixing of other charge states.

An EBIT is very suitable for spectroscopic studies of highly charged ions because the charge state distribution inside the trap is very simple compared to any plasma source and the light source of an EBIT can be regarded as a slit. We have just started high resolution spectroscopic studies. Figure 3 shows one of the first results for $n=3-2$ transitions of Ne-like Ba taken with a flat LiF(200) crystal spectrometer with a position sensitive proportional counter. The Ne-like sequence has been well investigated both theoretically[14] and experimentally[15] because of its closed shell. However the Ne-like sequence still contains interesting physics. Theoretical calculations by Kagawa *et al.*[16] show that the order of excited levels changes between $(2p_{1/2})^{-1}(3s)_1$ and $(2p_{3/2})^{-1}(3d_{5/2})_1$ at the atomic number $Z\sim55$. It is considered that at this region of Z, the L-S coupling scheme gives place to the j-j coupling scheme as a proper representation of the system. The mixing of the wave functions between these states results in an increase of the oscillator strength of $(2p_{1/2})^{-1}(3s)_1$ state at $Z\sim55$. Systematical measurements of wavelengths and intensity ratios for $n=3$ excited states will then be important to check the theoretical treatment for relativistic manybody systems including strong mixing between levels.

At present we are designing two Bragg spectrometers, one of which is a flat crystal spectrometer with luminosity as high as a von Hámos spectrometer.[17] The other one is a Johann-type spectrometer which is suitable for absolute measurements of wavelength.[18]

Although transitions in highly charged ions dominate in the x-ray region, visible transition exists for specific transitions of specific ions. Examples are hyperfine transitions for the ground states of H-like ions[19] with $Z=65-85$, and $3d^4$ $^5D_2-^5D_3$ M1 transition of Ti-like ions[20] with $Z=54-92$.

We are designing an echelle type of spectrometer which is considered to be very useful for the survey of unknown transitions such as hfs transitions for H-like ions. After surveying these transitions, precise measurements by laser spectroscopy will be possible. Unlike laser spectroscopy with an accelerator in which resonance wavelength can be adjusted by Doppler shift, a laser which is used in laser spectroscopy with an EBIT should be tunable because trapped ions in an EBIT are at rest. We have an OPO laser (Spectra Physics, MOPO-700) which is tunable within the whole visible range, and an optical system to introduce the laser to the EBIT is in preparation.

Following the improvement of the ion extraction line we are planning to perform ion-surface collision experiments. In addition to conventional experiments, e.g., observation of the numbers, energies, and angles of secondary particles, we are interested in interaction with magnetic materials. Spin resolved experiments have not been performed yet for highly charged ions and surface collisions. We are planning to measure the spin distribution of secondary electrons using a Mott and/or diffuse scattering detector after a highly charged ion impact on the surface of a magnetic material.

IV. CONCLUDING REMARKS

The initial stage of operational testing for the Tokyo EBIT is now completed and routine operation is possible. Some of the physics experiments with the EBIT, e.g., observation of electron collision processes with trapped ions and high-resolution x-ray spectroscopy, are ongoing. In the next stage of operation, electron energies of up to 340 keV and currents of up to 300 mA will be achieved and additional experiments, e.g., visible and laser spectroscopy and ion-surface collision, will be performed.

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