Progress at the Shanghai EBIT

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Abstract. In this report, a brief description of the progress of the Shanghai EBIT project is presented. This is followed by short discussions on the X ray spectra at several electron beam energies and the ion densities in the EBIT at a specific running condition.

1. Introduction
Electron Beam Ion Traps (EBIT), initially developed at Lawrence Livermore National Laboratory [1], are sophisticated devices capable of acting as both highly charged ion (HCI) light sources and ion sources. Because the HCIs produced in an EBIT are moving at much lower velocities compared to those produced in heavy ion accelerators, the spectra suffer much less from Doppler shifts and spectral line broadening. These are very good characteristics for spectroscopic research. Secondly, because of the flexibility in producing various ions with an EBIT, such devices are very powerful tools for studies along iso-electronic and iso-nuclear-charge sequences aimed to reveal the underlying physics behind many physical properties.

To promote HCI related physics research in China the Shanghai EBIT project was launched in January of 2002. Since then the Shanghai EBIT has made rapid progress to the status at which it stands today. The design parameters of the Shanghai EBIT put it well into the class of so-called super-EBITs, i.e. electron beam energies up to 200 keV at a current of 200–250 milliamps and compressed to a current density of around 5000 A/cm\textsuperscript{2} by a magnetic field of up to 5 Tesla.

Presently our EBIT can be operated with a minimum of effort at electron beam energies spanning from 1.5 to 130 keV. The electron current depends somewhat on the beam-energy, however at 130 keV the current has reached 160 mA. The performance of the Shanghai EBIT is steadily increasing towards the design parameters.

The principle features of an EBIT are: an electron gun to produce an electron beam; a pair of superconducting Helmholtz coils to produce a strong magnetic field for compressing the electron beam to a high current density; a cryogenic system to maintain the super-conductivity and to produce an ultra high vacuum in the trap region; drift tubes to produce a potential well for axial trapping of ions and a high voltage (relative to the cathode of the electron gun) to accelerate the electron beam to the required energy; the electron beam to provide radial trapping of the ions.
and at the same time ionize and excite the ions by successive collisions and finally an electron collector to collect the electrons after they have finished their job [2].

In the trap region, ions undergo numerous collisions with electrons, other ions and residual gas atoms. In collisions with electrons the main processes that can occur are dielectronic recombination (DR), radiative recombination (RR), impact excitation (IE), ionization and a temperature increase due to energy gained from collisions with the electrons. Collisions with other ions lead mainly to transfer of kinetic energy among the collision partners. Collisions with residual gas atoms will lead to charge transfer (CX) from the residual atoms to the ions, lowering the overall charge state balance of the ions of interest. Out of all the collision processes, impact ionization, including direct ionization and excitation-ionization, works in the direction of raising the ion charge state distribution. Other processes, like DR, RR, CX all work to decrease the ion charge state distribution.

2. Progress at the Shanghai EBIT

2.1. X-ray spectra

Figure 1 shows an example of the first X-ray spectra recorded at the Shanghai EBIT. These spectra were taken at electron beam energies of 10 and 15 keV and show the L X-rays of Ba and W. These elements are inherent constituents in the electron gun cathode material. Ba and W atoms are sputtered and subsequently injected into the EBIT trap region. Figure 2 shows Ba and W K X-rays along with X-rays emitted from RR to Ba $n = 2$ and W $n = 3$. This spectrum was recorded using an electron beam with the energy of 100 keV. All the X-ray spectra presented in this work were measured using a High-Purity Germanium (HPGe) detector.

![Figure 1](image1.png)

**Figure 1.** This shows examples of the first X-ray spectra recorded at the Shanghai EBIT. These spectra were taken at electron beam energies of 10 and 15 keV and show the L X-rays of Ba and W.

2.2. Ion density

For testing EBIT operation, we injected Kr gas with the following operating parameters: beam energy of 40 keV, beam current 80 mA, trapping voltage 100 V, and dumping every 3 seconds. The measured X-ray spectrum recorded under these conditions is shown in Fig. 3(a). From this spectrum, we were able to deduce the ion densities of bare and hydrogen-like (H-like) Kr in the trap region.
Figure 2. This shows Ba and W K X-rays along with X-rays emitted from RR processes to Ba \( n = 2 \) and W \( n = 3 \). This spectrum was recorded using an electron beam with an energy of 100 keV.

Figure 3. (a) A spectrum taken at a beam energy of 40 keV, beam current of 80 mA, trap depth of 100 V, the trapping time is 3s and Krypton injection; (b) fitting result of the RR line to K shell of H-like and bare Kr.

The Bare and H-like Kr densities were determined by analyzing the peak intensities for RR into the \( n = 1 \) levels of bare and hydrogen-like Kr ions. The count rates of the RR events can be written as:

\[
R[s^{-1}] = n_e n_i \sigma_{RR} \frac{A(P)}{4\pi} v S L \Omega T \varepsilon
\]

\[
= \frac{[A]}{e}[cm^{-3}] \sigma_{RR} \frac{A(P)}{4\pi} [cm^2 sr^{-1}] L[cm] \Omega[sr] T \varepsilon,
\]

where, \( n_e \) and \( n_i \) are the electron and ion number density respectively, \( \sigma_{RR} \) is the total cross sections for the RR processes, \( v \) is the velocity of the electrons relative to the ions; \( S \) and \( L \) are separately the area and length of the light source; \( \Omega \) and \( \varepsilon \) are the solid angle and quantum
Figure 4. (a) This figure shows a recording of a spectral line $3s^23p^5(2P_{3/2})4s - 3s^23p^5(2P_{3/2})5p$ in Ar I from the EBIT plasma; (b) the intensity distribution of the image shown in (a). This is obtained by summing vertically along the CCD channels.

efficiency of the detector used in the experiment, $T$ is the transmission of the X-ray photon; $A(P)$ is the angular distribution factor, which is unity if the emission is isotropic.

The effective detector area is 200 mm$^2$, and the distance between the detector and the center of the EBIT is 1009 mm. Hence the solid angle $\Omega$ is close to $2 \times 10^{-4}$ sr. $T$ and $\varepsilon$ are close to 100%. $L$ is 1.8 cm in our case. The total cross section for RR to the K shell of bare Kr is $2.76 \times 10^{-23}$ cm$^2$ [3] at this electron energy, and the value for H-like Kr RR cross section is $2.2 \times 10^{-24}$ cm$^2$, this is derived from the scaling law presented in [4]. $A(P)$ is 1.5 for RR to all s orbitals in the non-relativistic case [5].

The count rate following RR to the K shell of bare and H-like Kr, are measured to be 0.01622 s$^{-1}$ and 0.04674 s$^{-1}$ respectively. The fitting results are shown in Fig. 3(b). From these results we could determine the density of bare and H-like Kr ions to be around $3 \times 10^7$ cm$^{-3}$, and $7 \times 10^7$ cm$^{-3}$ respectively.

2.3. Electron beam size

We recorded an image of the ion cloud with a cooled CCD detector attached to a one meter grating spectrometer working in the visible spectral region, the magnification of this instrument is 1:1. This image was recorded with totally opened entrance slits (4 mm). The recorded image is shown in Fig. 4(a). The column summed intensity distribution is shown in Fig. 4(b), along with a Gaussian fitting of the image. The fitting leads to a FWHM of 130 $\mu$m, which is an upper limit of the electron beam diameter.

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