The potential of an EBIT in assisting plasma diagnostics and progress at the Shanghai EBIT

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Abstract. In this paper, the potential of Electron Beam Ion Traps (EBIT) in assisting plasma diagnostics is reviewed. Examples of how EBITs have contributed to plasma diagnostic studies, including both magnetic fusion and inertial fusion plasmas, are shown. The progress of the instrumentation development at the Shanghai EBIT and ongoing research in the Shanghai EBIT laboratory are reported.

1. Introduction
Electron Beam Ion Traps (EBIT), initially developed at Lawrence Livermore National Laboratory (LLNL) [1], are sophisticated devices capable of acting both as highly charged ion (HCl) light sources and ion sources. As a HCl light source, they can basically provide light from emission states of any charge state of any element in the periodic table, hence almost unique for spectroscopic research. When an EBIT is operating, an electron beam is emitted by the cathode of an electron gun. This beam is accelerated by a high voltage, applied between the cathode and a drift tube assembly. The drift tube assembly provides a trap region for positively charged ions. On the way towards the trap region, the electron beam is compressed by a strong magnetic field provided by a pair of Helmholtz coils. The compression is made to increase the electron beam density, as the rates for all electron-ion collision processes are very dependent on the beam density. A strong compression, leading to three orders of magnitudes increase in the beam density, can be achieved by using superconducting Helmholtz coils. A cryogenic system is needed to maintain the superconduction, this also helps to produce a ultra high vacuum in the trap region. Such EBITs fall into the category of Cryogenic EBITs.

In an EBIT, a tenuous plasma can be formed from basically any element, as long as the element can be injected into the trap region. The way an EBIT works gifts it with the property of a tuneable mono-energetic electron beam. Unfortunately there is a small energy spread caused by the temperature of the emitting cathode and the electron beam space charge. The range the electron beam energy can be tuned can cover a few hundreds of eV to several tens of keV, in some cases even up to around 200 keV [2]. This property makes it possible to use EBITs for detailed studies of processes in hot plasmas, i.e. disentanglement studies of the various processes in hot plasmas and to assist plasma diagnostics for temperature, density, electromagnetic field, as well as ion motion.

After the groundbreaking developments at LLNL, EBITs have been set up in Oxford [3], NIST [4], Tokyo [5], Berlin [6], Freiburg [7] (now moved to Heidelberg), Dresden [8], Vancouver [9], Stockholm [10], Belfast [11] and Darmstadt [12]. To promote the above mentioned studies in China, the Shanghai EBIT project was launched in January of 2002, under a collaboration between Fudan...
University and the Shanghai Institute of Applied Physics. The design of the Shanghai EBIT puts it well into the category of so-called super EBITs, which means the electron beam energy should reach 100 keV or higher. There were already three members of the super EBIT category before the Shanghai EBIT was setup, they are the LLNL EBIT (super EBIT), the Tokyo EBIT (YEBISU) and the Heidelberg EBIT.

2. EBITs in assisting plasma diagnostics

Many laboratory and astrophysical plasmas involve a Maxwell-Boltzmann energy distribution of electrons colliding with an ensemble of ions. Understanding the behaviour of plasmas from their emission spectra needs accurate electron-ion collision rate coefficients, which include cross sections for various processes, such as excitations, ionizations, recombinations etc. The cross-sections are needed in the whole energy range at a certain plasma temperature. Theoretical calculations need to make approximations in almost all the cases. and may not always lead to accurate results. Experimental studies using laboratory plasma sources, like Tokamaks and 0 pinch devices, often suffer from limited accuracies caused by complications such as density effects, radiative transfer, ion abundance, field gradients and temperature effects etc. and combinations of all these effects [13].

At LLNL, a special setup was devised to simulate a Maxwell-Boltzmann electron distribution for a clean and optically thin EBIT plasma, in order to study collisions between ions of specific charge states with electrons of a Maxwell-Boltzmann energy distribution [14]. In their work, they developed a system to sweep the electron beam in energy and current as a function of time to simulate conditions in a hot plasma. The current is swept to keep the electron density constant during the energy sweep, so as to minimize differences caused by differing space charge distributions. While the energy sweeping is done by converting the number of electrons under the distribution to a time distribution, for example, for a higher fraction of electrons at a given energy the time duration at that energy was set to a longer value according to a Maxwell-Boltzmann distribution. The energy sweep covered most of the range of the electron energies at a given temperature, with a minimum and a maximum energy cut off according to their EBIT operation conditions. Because EBIT operating parameters can be easily changed, a wide range of temperatures can be simulated. Ion density effects are generally unimportant, as the EBIT plasma is optically thin. By measuring the emission photons at the same time as sweeping the electron beam energy and current, they could automatically integrate the collision cross sections with the desired electron distribution. The observed properties of ions in such experiments are directly dependent on the relevant rate coefficients [14].

Although it has been emphasized that X ray spectroscopy is important for ion temperature measurements in Tokamaks, the spectra of highly charged ions, in particular, He-like and Li-like ions, contain much more information than just the ion temperatures obtained from Doppler line broadening. The spectra show, in addition to the strong resonance lines, numerous satellites which are produced by dielectronic recombination and inner shell excitations. Since the intensity ratios between the resonance lines and their dielectronic satellites depend only on the electron velocity distribution, they are sensitive measures of electron temperature. In addition, the line intensity of an inner shell excited satellite is proportional to the density of the neighboring charge state. These satellites then provide information of charge balance and impurity ion transport. From the experimental point of view, the satellite spectra of He-like ions of medium Z elements are very attractive, because the separation between the resonance line and satellites are sufficiently large to allow for clean identifications. At the same time, the wavelength range of the spectrum is small enough, so that the sensitivity of the instrument is constant over the entire range. The measurements of the satellites-to-resonance line rations are therefore reliable.

In a work done at TEXTOR-94 [15], satellite spectra of He-like Ar from a discharge with auxiliary heating by neutral-beam injection was measured, as shown in Fig.2 in [14]. In that work, the intensity ratio of the line q, from the Li-like 1s2 2s 2S1/2 -1s2s2p 2P1/2 transition, over the line w, from the He-like 1s2 1S0 -1s2p 1P1 transition, was used to deduce the charge state ratio of Ar15+/Ar16+, believing that the satellite line q was produced by impact excitation of the ground state of Li-like Ar,1s2 2s 2S1/2
However, the result was about four times higher than theoretical predictions. A few years later the n=2-1 spectral emission pattern of He-like Ar, together with the associated satellite emission originating from Li-like Ar was measured with high-resolution x-ray spectroscopy at the Berlin EBIT [16]. In the Berlin work, a mono-energetic electron beam was ramped in energy between 1.9- and 3.9-keV (from below the resonance energy for dielectronic satellites to above the direct excitation threshold for n=1 to 2) to examine the He-like ions. In this way all the radiating processes of recombination and excitation could be studied with high-resolution spectroscopy. Hence, the satellites caused by dielectronic resonance are separated from those caused by direct excitations, as they appear at different electron energies. The results show that the line q could be caused by both direct excitation of the ground state of Li-like Ar and by dielectronic recombination to the ground state of He-like Ar. This questions the applicability of using the q/w line ratio to deduce the charge state ratio. X-ray emissions from He- and Li-like Ar ions are also used in diagnostics for inertial confinement fusion plasmas. Ar is usually added as a dopant to the solid fuel. The electron temperature is deduced from the intensity ratio of transitions between n=3 and 1 levels of H-like and He-like Ar, I_{H\beta}/I_{He\beta}; while the density is derived from Stark broadening of the K\beta line. But the satellites from Li-like 1s3lnl'-1s^2nl' transitions could distort the profile of the K\beta line. They can cause asymmetry of the line profile and broadening of the line width. This would mislead the temperature and density interpretation, if the satellite contributions were not properly taken into account. These contributions were usually estimated by theoretical models, with only the n=2 and 3 satellites being taken into consideration [17,18]. In 1995, the contributions of higher-n satellites to the K\beta line of He-like Ar were measured [19], using a high resolution crystal spectrometer to analyze the X-ray emission of the Ar ions trapped and excited in the LLNL EBIT. The electron beam energy was swept to hit the KLM, KMM, KMN and KMO dielectronic resonances, as well as through the excitation threshold of n=1 to 3. Their results showed that the resonance strength of n=4 satellites was larger than that of n=3, while the resonance strength of n=5 was nearly equal to that of n=3. That means the contribution of the satellites from n \geq 4 was considerably larger than expected from standard scaling procedure. This result has lead to reassessment of line profile calculations of the He-like K\beta line used in density diagnostics in Laser fusion.

In the past few decades, EBITs have been producing definite values of electron impact excitation, ionization and resonance excitation cross sections, as well as dielectronic resonance strengths. Some results have demonstrated shortcomings of theoretical data. For example, systematic measurements of n= 3 to 1 line emission from He-like ions at the LLNL EBIT [20] showed significant disagreement between the measured and the calculated ratios of the 1s3p ^3P_1 - 1s^2 1S_0 intercombination and the 1s3p ^3P_1 - 1s^2 1S_0 resonance line for low and medium Z ions. In [20], systematic disagreement was also reported for the measured and the calculated ratios of the 2p^3d ^3D_1 -2p^6 1S_0 intercombination and 2p^3d ^1P_1 -2p^6 1S_0 resonance line in the Ne iso-electronic sequence.

Table 1. Design parameters of the Shanghai EBIT.

| Parameter                        | Value  |
|----------------------------------|--------|
| Highest electron beam energy     | 200 keV|
| Highest electron beam current    | 200 mA |
| Electron beam radius             | 35 \( \mu \)m |
| Highest magnetic field           | 5 T    |
| liquid He consumption            | 0.5 L/h|
Hence EBITs have played an important role in producing accurate data for testing atomic theory, as well as in disentangling plasma processes and assisting plasma diagnostics.

3. Progress at the Shanghai EBIT
The Shanghai EBIT projected started at the beginning of the year of 2002. The conceptual design was done in around 6 months. The characteristic design parameters are listed in Table 1. The engineering design was finished by the end of 2003 while manufacturing the components took another year. The installation of the Shanghai EBIT took another half year and was completed by the end of 2004 [21]. In the May of 2005, the first X-ray spectrum was obtained. The electron beam energy was pushed to 100 keV by the end of 2005. Presently the Shanghai EBIT can be operated at electron beam energies spanning from 0.8 keV to 130 keV. The electron beam current depends on the beam energy, however at 130 keV the current has reached 160 milliamps. A picture of the main body of the Shanghai EBIT is shown in Fig.1. For machine diagnostics, a portable slit imaging system, together with sophisticated software for imaging processing was developed [22]. Through detailed imaging studies of the ion clouds in the Shanghai EBIT, upper limits for the electron beam diameter were obtained under various operating conditions. Table 2 lists some electron beam properties at 81 keV and for a 3 T magnetic field.

![Figure 1. A picture of the main part of the Shanghai EBIT.](image)

A metal vapour vacuum ion source, MEVVA, and a gas injection system have been installed for metal and gas element (also gas compound) injection. To give the Shanghai EBIT move flexibility in its variety of usable elements, a laser ion source and an atomic oven are under development. For spectroscopic studies of HCIs, we have set up three spectrometers covering the wavelength region of around 1 Å to above 10000 Å: a 1-meter normal incidence (McPherson 225) spectrometer for the wavelength region of 300 – 10000 Å, a flat-field grazing incidence spectrometer (home made) for the wavelength region of 30-300 Å, and a flat crystal spectrometer (home made) for 1–30 Å. A high purity Germanium detector is constantly attached to the Shanghai EBIT for X-rays measurements and monitoring.

| I(mA) | FWHM(μm) | Electron density(cm⁻³) |
|-------|----------|-----------------------|
| 120   | 76.2     | 7.1×10¹¹              |
| 100   | 74.8     | 6.5×10¹¹              |
| 80    | 68.5     | 6.8×10¹¹              |
While the diagnostic equipment was being developed, other highly related research projects were initiated at the Shanghai EBIT laboratory. These studies include: numerical simulation of the charge state distribution and temperature evolution of an EBIT plasma, angular distribution and polarization of photon emission from radiative recombination, studies of hyperfine interaction dependence of metastable state lifetimes, disentangle studies of hot plasma processes using EBIT, electron correlation and QED effects on atomic level structure. Some results from the above mentioned ongoing research projects are reviewed briefly in the following.

The work on numerical simulation of the charge state distribution and temperature evolution of an EBIT plasma was based on the work of Margolis [23], but substantial modifications and improvements were made. We assumed a Boltzmann distribution instead of a homogeneous radial distribution for the ion density and a Gaussian shape instead of a homogeneous radial distribution for the electron beam intensity. We also considered multiple charge exchange, up to four-electron transfer, instead of only single-electron transfer as in previous works. In this work, relativistic expressions for the electron energy and electron impact cross sections are employed, as the electron velocity is already a few tenths of light velocity even at modest electron beam energy (i.e. several tens of keV). Also in this work, the electron beam radius is calculated instead of being input as a fixed parameter. The computer code in our work was developed to handle two different experimental situations, one is for pulse injection and the other is for continuous injection [24]. In the project for hyperfine interaction effects on metastable lifetime, we have made theoretical studies along the iso-electronic sequences of Ni-, Zn-, Be- and Mg-like ions. For the Ni-like ions, interest was on the lifetime of the 3d^10 4s^3 3D_3 level. The focus of this work was to evaluate the importance of the hyperfine induced electric quadrupole channel of the 3d^{10} 4s^3 3D_3 transition for isotopes with nuclear spin. Result shows that hyperfine quenching is important along the whole iso-electronic sequence. At the low-Z end the hyperfine induced electric quadrupole transition channel dominates, being several orders of magnitude larger than the rate for the magnetic octupole transition channel, while for higher Z the two rates are of comparable size [25]. For Zn-like ions, our interest was on the lifetimes of the 4s^4p 3P_2 level. Our research reveals that the hyperfine-induced electric dipole transition contributes to the 4s 2 1S_0-4s^4p 3P_2 transition at about the same level as, or even higher than, the M2 transition whenever the nucleus has a spin. This is true all along the Zn-like sequence [26, 27]. The results of Be-like and Mg-like ions are under preparation for publication.

For experimental disentanglement studies of hot plasma processes, much effort was spent in studying KLL dielectronic recombination processes, both resonance strengths and resonance energies, for Xe ions [28, 29]. In this project, a stable and precise high voltage divider [30] was developed to meet the need to accurately determine the resonance energies. We could compare calculations by different theoretical methods at the precision level of 0.03 percent, on average, because of our accurately measured resonance energies. Under the project concerning electron correlation and QED effects on atomic structure, we studied the QED energy shift in the 1s^22s^1/2-1s^22p^3/2 x-ray transition in Li-like ^{208}\text{Pb}^{79+} as part of a collaboration with the Tokyo EBIT [31]. The contribution of QED effects to the transition was determined to be $-24.99\pm0.10$ eV. Data from the experiments on electron correlation studies are under analysing.

4. Conclusions
In this contribution, the application of EBITs in assisting plasma diagnostics is reviewed. The progress of machine development at the Shanghai EBIT, the related experimental setup, and the ongoing research projects together with some of their results are reported.

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