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Trapped Highly Charged Ion Plasmas

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Abstract. Electron Beam Ion Trap (EBIT) devices and their special features are reviewed with attention to applications in highly charged ion plasma research. EBIT properties are presented based on information extracted from a variety of experiments reported in the literature. Topics discussed include typical parameters (Debye length, Wigner-Seitz radius, Coulomb coupling parameter, density, temperature, etc.), magnetic trapping mode, ion cloud shape, rotation, and evaporative cooling. We conclude that the quantitative understanding of highly charged ion plasmas inside an EBIT requires improved modeling and advanced diagnostic techniques.

INTRODUCTION

Heavy ions with dozens of electrons removed, so-called highly charged ions, have a wide range of potential applications. Imagine an atomic system that is stripped to its core, with only a few electrons remaining at most. The electronic binding energy that must be overcome to further ionize such a system can be over a thousand times higher than that in ordinary ions or atoms. Even more striking, the potential energy liberated when such a highly charged ion re-neutralizes itself can be nearly a million times larger than that of a conventional ion.

Because many atomic properties scale with high powers of the nuclear charge, ions along an isoelectronic sequence (ions with different nuclear charges, but the same number of electrons) quickly enter exotic regimes where conventional intuition fails. Forbidden electronic transitions can become stronger than those allowed by electric dipole selection rules, and energy levels can become strongly affected by the structure of the vacuum [1,2].

The enormous amount of free potential energy and ultra-compact size that highly charged ions possess is as unique as their exotic atomic structure. When such ions approach surfaces, their strong electrostatic pull on bulk electrons can be felt many atomic diameters away. As a result, highly charged ions are very effective in modifying or breaking chemical bonds and crystal structures on the nanometer length scale [3].

The natural curiosity to study such exotic ions in the extreme strong field limit was one of the driving forces to build a device, such as an Electron Beam Ion Trap (EBIT), that can be accommodated in a small laboratory. The first EBIT was put into operation at the Lawrence Livermore National Laboratory [4,5] almost fifteen years ago. Shortly after this, the National Institute of Standards and Technology (NIST) became the

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second place in the world to have a working EBIT [6,7], followed by new constructions in several other laboratories [8-12].

EBITs are not the only machines that can create ions in high charge states, but certainly they are one of the most versatile, offering great control over the experimental conditions in which highly charged ions are produced. The success of the EBIT is proven by the numerous widely-cited experiments that have been carried out by since its inception [4,5,13-18].

Although the device is still in the process of rapid evolution, the fact that current small-scale EBITs can already produce millions of highly charged ions per second suggests that applications that take advantage of the unusual properties of very highly charged ions should be pursued. Some of the basic scientific studies which will underlie applications of such exotic ions are being carried out by the highly charged ion community, while more immediate applications are being pursued by industrial entrepreneurs [19] (and references contained in [2]).

As EBIT devices may one day be capable of producing much larger numbers of highly charged ions, it is interesting to survey the capabilities and properties of the present machines to help further the development of possible future designs. The basic mechanisms of ion production and operation of the EBIT is theoretically understood; the evolution of the charge states and the dynamical ionization and recombination balance between the neighboring charges can qualitatively be accounted for with model calculations [20-23]. However, there are indications in several experiments that a quantitative understanding remains to be developed.

Detailed understanding of EBIT properties is hampered by the fact that only a limited number of experiments have been performed that specifically target the properties of the highly charged plasma inside an EBIT. There is, however, a large database of indirect information contained in other types of measurements. In the present paper, we will attempt to put these pieces of information together in a coherent manner to provide a general experimental overview of the detailed operation and features of an EBIT. We will also point out some discrepancies that have accumulated in the fifteen years of experience with the device that might point to a better understanding of its operation and that could possibly even be exploited in future applications. We hope that with this summary we will stimulate people from the broader scientific community to contribute to a cross-disciplinary attack on some of the problems, and in particular to put forward advanced diagnostic and modeling ideas that will ultimately help to realize new applications for highly charged ions.

HIGHLY CHARGED ION BEAMS AND CLOUDS

Most of the applications that take advantage of highly charged ions require large numbers ions in the form of high quality clouds or beams. EBITs, in this sense, already qualify as one of the best devices to study. The source region is rather simple and well controllable, and is qualitatively similar to the precision controlled traps that the non-neutral plasma community uses. Understanding the basic properties of these traps can serve as a foundation for designing new, innovative highly charged ion devices. However, as in atomic structure, it might well be that conventional plasma

properties have to be rethought in the highly charged ion regime, in which case existing EBITs could be used as test-beds for these ideas.

Some members of the conventional non-neutral plasma community have argued that highly charged ions could offer some attractive possibilities for the study of strongly coupled systems at relatively high temperatures [24]. Some of the advantages of using highly charged ions in quantum information schemes have also been discussed [25]. One of the first steps towards these goals was the experimental realization of a highly charged ion crystal in a precision trap that was filled with ions from an EBIT [26,27]. Some of the cooling schemes applicable to highly charged ions have already been put into operation in an EBIT [28-30].

Another interesting possibility is related to the quest for crystalline ion beams with high center-of-mass energies (>1 MeV, but with small relative energy <1 eV). These beams would provide the unprecedented quality and brightness sought in many applications [31-33]. The idea of creating crystalline ion beams in storage rings was proposed more than fifteen years ago [34]. Despite some promising results [35,36], the experimental realization in high-energy devices appears to be still lacking [32].

An alternative approach to the crystalline ion beam problem [37] was recently experimentally realized [32] in a small-scale storage ring. The idea is to first create a crystalline ion cloud at rest using methods and tools that are applied in strongly coupled ion cloud studies, and then to accelerate it to high energies without destroying the ordered structure. The experiment, which used singly charged ions and laser cooling to create the ion crystals at rest, was able to demonstrate acceleration to about 1 eV energy [32]. It is believed that scaled-up versions of this scheme can be used as high-energy storage rings.

Direct laser cooling of highly charged ions is problematic because of the scarcity of visible transitions. It has recently been demonstrated, however, that sympathetic laser cooling can be equally effective [38]. This alternative cooling technique has also been shown to be very effective for highly charged ions [26,27]. In addition, there may be other, non-laser based cooling schemes that have yet to be fully developed [45,46].

One of the major differences between Penning traps and EBITs is the presence of a monoenergetic, high-energy, high-density electron beam at the center of the trap. Some groups, however, have modified their Penning traps to include an electron beam [39-42]. These works are not motivated by the desire to create highly charged ions, but rather to create better confinement conditions and more dense plasmas for applications such as alternative nuclear fusion devices. The dense electron beam creates a steep spatial ion density gradient that helps to locally overcome the density limitations posed by the Brillouin limit [39,40]. Similar gradients have been observed in recent EBIT experiments [43,44]. Furthermore, typical ion densities found in EBITs (see below) are already above the Brillouin limit.

The possibility of creating high ion cloud densities and high brilliance beams using present EBITs without auxiliary laser cooling may not be that far-fetched. Recent model calculations [45,46] suggest that evaporative cooling could be significantly enhanced under certain conditions, and thus even the strongly correlated regime might be achievable this way.

ELECTRON BEAM ION TRAPS

The basic operational principle and the details of the EBIT components can be found in several recent reviews [47,48]. These papers give a design and modeling point of view of the operation of the present-day EBITs. In the present work, we would like to review a few experiments that determined some of the important operating parameters of the machine. In some cases these results were not even the main goal of the particular experiment, but rather a byproduct. Since these experiments were done with different machines, using different types of ions, and different experimental techniques, their direct comparison might not be justified in all cases. However, a semi-comprehensive review of the data might help to shed some light on the capabilities of EBITs and to give a general feel for the operating parameter ranges.

Operation

The creation of highly charged ions in an EBIT is based on the interactions of ions with a high density electron beam of about 1 keV to 30 keV energy. The electron beam is produced by a commercial electron gun and is highly compressed by a pair of superconducting magnets producing homogenous field of about 3 T in the center of the machine. Neutral atoms or singly charged ions are injected into a three element Penning trap and then are stripped of most of their bound electrons during consecutive interactions with the electron beam. The average ionization stage in equilibrium can be selected by properly choosing the energy of the electron beam. Radially the ions are confined by both the electric field of the electron beam and the high magnetic field. The effect of the magnetic field dominates only for large distances from the electron beam. Once the ions of the desired charge state are produced, the electron beam can be used for exciting electronic transitions for spectroscopic studies, or it can be turned off completely, leaving the axial confinement solely to the magnetic field [49,50]. Details of the modeling of ion creation [47] and the trapping dynamics [48] are described elsewhere. The NIST EBIT is also equipped with a highly efficient ion extraction and transport system, with a built-in charge-to-mass ratio separator. This system can be used for diagnostic purposes to infer charge state distributions inside the trap, or as a facility for ion-surface and ion-gas collision experiments.

In the following paragraph we summarize the typical plasma parameters of EBIT ion clouds. The measurements that provided the input for these determinations will be presented in later sections.

Typical plasma parameters

Plasma conditions created in EBITs are similar to those of the solar corona. Electron densities are around 10^{12} cm^{-3} and electron energies are approximately equal to (or above) those found in 10 million Kelvin temperature plasmas. One distinctive difference is that in the EBIT the electron energy is monoenergetic, with a width of only about 16 eV [70] to 70 eV [71]. A typical relative energy spread, $\Delta E/E$, is under

1 %. The narrow energy spread is the key to creating a charge state distribution that only includes a few ionization stages. In the case of ions with closed shell electronic configurations, close to 100 % charge state purity can be achieved [77]. In a more typical case, there would be a distribution of charge states present. The charge-to-mass spectrum of extracted ions [72,73] can be used to monitor the degree of charge state purity.

Typical measured densities of particular charge states in multi-component EBIT ion clouds range from 5×10^8 cm^{-3} to 1×10^{10} cm^{-3} [7,61]. Local ion densities can be higher than these values because of the steep gradient in the space charge potential of the electron beam. Typical measured ion temperatures are between 70 eV [65] and 700 eV [66, 64], increasing as the ion charge increases.

The Debye length for typical ion densities (n) and temperatures (T) inside an EBIT,

$$\lambda_D = \sqrt{\frac{\varepsilon_0 kT}{nq^2}} \qquad (1)$$

is around 20 μm to 60 μm. This value is relatively small mainly because of the high charge (q) of the ions. The size of the ion cloud is 2 to 20 times this value.

The average distance between ions of a particular charge state is given by the Wigner-Seitz radius,

$$a = \sqrt[3]{\frac{3}{4\pi n}} \qquad (2)$$

about 3 μm to 8 μm. These Debye lengths and Wigner-Seitz radii are similar to those for typical singly charged ion plasmas, but other parameters that scale with the ion charge can be very different. One such parameter that scales quadratically with ion charge is the average potential energy between neighboring ions:

$$V_a = \frac{q^2}{4\pi\varepsilon_0 a} \qquad (3)$$

For ions of high charge-states this can be 3 or 4 orders of magnitude higher than for singly charged systems. It can be more than 1 eV in absolute value. This leads to another strongly scaling quantity, the Coulomb coupling parameter:

$$\Gamma = \frac{q^2}{4\pi\varepsilon_0 akT} \qquad (4)$$

Because of the high ion charge, even at temperatures close to 1 million Kelvin Γ is more than 0.01. If the cloud could be cooled to room temperature, Γ would be around 50, which is well into the range where liquid phase behavior is predicted [60].

EXPERIMENTAL CHARACTERIZATION OF EBITS

Although there have been over 300 EBIT publications since the first one in 1988, relatively few experiments have been performed to date that determine the parameters described in the previous section. In the following subsections, we discuss these few experiments, and point to corresponding theoretical work.

Electron beam

The spatial distribution of the electron beam has been measured using a variant of an x-ray pinhole camera [5, 74, 75], and using Thomson scattering [76]. The x-ray imaging experiments rely on the fact that excited state lifetimes in highly charged ions are so short that x-rays are emitted essentially instantaneously at the location that they interact with the electron beam. A map of the x-ray emission from the ions, therefore, reflects the electron beam density distribution directly. The measurements are in rough agreement with predictions based on Herrmann theory [51], although there have been some discrepancies on the order of 20 %. Generally, it has been assumed that the electron beam spatial distribution is Gaussian, with a radius r_H containing 80 % of the electron beam given by,

$$r_H = \frac{r_B}{\sqrt{2}} \sqrt{1 + \sqrt{1 + 4(\frac{8mkT_c r_c^2}{e^2 B^2 r_B^4} + \frac{B_c^2 r_c^4}{B^2 r_B^4})}} \tag{5}$$

where B_c is the magnetic field in the electron gun cathode region; T_c is the temperature of the cathode; r_c is the radius of the cathode; B is the magnetic field at the central drift tube; m is the rest mass of the electron; k is the Boltzmann constant; r_B is the Brillouin radius:

$$r_B = \sqrt{\frac{I_c \sqrt{E_c}}{4.74 \cdot 10^5 \cdot \pi B^2}} \tag{6}$$

determined by the electron current, I_e, and the electron energy, E_e.

In order to understand the presence of the parameter B_c in the above expression, it is useful to consider some further details of the EBIT design. The electrons are emitted from a heated cathode in a Pierce-type electron gun configuration [4,5,48] located in the fringing field region of the main trap magnet. The electrons are accelerated towards a positively biased drift tube region (the trap center) by a series of guiding electrodes. It has typically been assumed that the maximum current density is achieved by minimizing the radius in expression (5), implying that the field at the cathode should be zero. In this case, however, the trap magnet acts as a magnetic mirror, and a significant number of electrons will be reflected back away from the trap. We have shown that theoretically the optimum field is actually a few tenths of a mT (a few gauss) [52]. The control of the magnetic field is aided by a steel plate placed above

the electron gun, and a coil built into a sealed chamber that surrounds the electron gun [5,52]. The magnitudes of the various EBIT parameters ($r_c \sim 1.5$ mm, $T_c \sim 1000$ K, for example) allow one to simplify expression (5) considerably to,

$$r_H \approx \left(\frac{8mkT_c r_c^2}{e^2 B^2} \right)^{1/4} \qquad (7)$$

On its way towards the drift tubes, the electron beam is compressed by the increasing magnetic field. Model calculations show that the 3 T magnetic field in the trap region is homogenous over the 3 cm long ion trap region to better than 0.05 % [44].

Magnetic trapping

The early EBIT papers stated that the ions were trapped in the radial direction by the electrostatic field provided by the electron beam (see, for example [5]). The magnetic field was presented as a technical detail needed to adiabatically compress the electron beam to high densities at the trap center. From the onset of our work [7,50], however, we have taken a somewhat different view, which emphasizes the direct effect of the magnetic field on the ion confinement. With this point of view, we first reported an experiment that demonstrated that an EBIT can be used to measure some properties of highly charged ions (excited state lifetimes, for example) more efficiently when the electron beam is turned off [50]. This work was stimulated by some related work on ion cloud diagnostics at Livermore [53-57]. Both the atomic lifetime measurements and the cloud diagnostic studies showed that after an initial expansion, the ion cloud stabilized after the electron beam was turned off. Only trap losses like cross-field diffusion and charge exchange with the background gas then lead to a decrease of the ion signal. Similar issues have been studied more thoroughly outside of the EBIT community e.g. [24, 60]. We suggest that using an EBIT to produce highly charged ions, and then switching to the "magnetic trapping mode" of operation might be particularly interesting for many advanced plasma studies.

Ion cloud shape

It is only recently that an image of the measured ion cloud shape has been reported [2]. Most of the experiments have simply used the EBIT as a light source or as an ion source for atomic physics or ion-surface studies, with relatively little effort allocated to study the macroscopic properties of the ion cloud itself. Ironically, much of the work that *has* been published rests on assumptions about the spatial distribution of the ions in the cloud.

The first systematic study of the ion cloud shape was published recently [43]. This work used a CCD camera and an optical lens system. Data was collapsed along the axis of the electron beam to produce a 1-dimensional cross sectional image with improved signal-to-noise ratio. Complimentary data, taken under rather different EBIT

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operating conditions, have been reported in the PhD thesis of M. Tarbutt [44]. Both of these works were predated by some spatial information that was obtained by Serpa *et al.* [50] in connection with the measurement of excited-state atomic lifetimes. In this work, the entire spectrometer table was mounted on sliding rails and was moved perpendicular to the EBIT observation direction by piezoelectric translators, allowing the transverse distribution of light at the entrance slit of the spectrometer to be mapped out. Some earlier unpublished work using CCD imaging was briefly described in a Livermore annual report [58].

The lack of any work in imaging the ion cloud immediately after the first EBIT came online can be partly understood by realizing that it was quite a few years before the first visible-light spectroscopy was done on an EBIT [18]. The reason for this is that the scaling laws cause most of the transition energies to shift into the x-ray energy range as the ion charge is increased. There are a few unusual transitions, however, that stay in the visible range, because of a fortuitous energy-level crossing. One of these transitions has been predicted [59] and found [18] in the Ti-like isoelectronic sequence. There are also transitions that during their rapid scaling to shorter wavelengths from the infrared or microwave range, pass through the visible range at a particular charge state or narrow range of charge states. Notable examples of the latter are visible hyperfine transitions in high Z elements.

Another requirement for cloud imaging is that the line should have a lifetime that is long compared to the time it takes the ion to complete several cycles of its motion (the cyclotron frequency varies from 1.2×10^7 s^{-1} to 1.3×10^8 s^{-1} for ions ranging from U^{10+} to Ar^{18+}). This condition is necessary, because electron impact excitation can only take place inside the electron beam. As mentioned above, if the emitting transition has a short lifetime (like in most of the x-ray lines), the image only reflects the product of the electron and ion densities, not the full ion cloud shape.

The cloud imaging experiments of Porto *et al.* [43] used Ar^{13+}, Xe^{31+}, and Xe^{32+} ions and the experiments of Tarbutt [44] used Ar^{10+} ions for the measurements. Both experiments concluded that the ion cloud has a density distribution that sharply peaks in the center of the EBIT. Porto et al. assumed thermal equilibrium for the ion cloud to model the shape of the measured distribution in the self-consistent field of the electron beam and the ion clouds. The fits suggest that the ions may indeed be close to thermal equilibrium. The temperatures obtained from the fits fall within expected values [43]. At lower trapping voltages, the experimentally obtained widths became wider than what is expected for even the maximum possible temperatures, which was interpreted as a signature that the ion cloud is non-thermal.

Ion cloud rotation

The possible collective rotation of the ion cloud has not been taken into account in any of the previous work with EBITs. Clouds of highly charged ions in thermal equilibrium in a pure magnetic field with densities close to the Brillouin limit should rotate collectively at half the cyclotron angular frequency [60]. How this situation is modified by the presence of the electron beam has yet to be studied in detail.

Ion number and density

The ion densities can be measured by detecting x-rays originating from processes with well-known cross sections, assuming the electron density is known. One of these is the so-called radiative recombination, which can be calculated to better than few percent accuracy [13]. This method was used by Gillaspy et al. [7] and by Margolis et al. [61] to determine the number Ba^{46+} ions in the trap ($3.1x10^5$) or, with fewer assumptions, the ion density ($1.0x10^8$ cm^{-3} – $1.1x10^9$ cm^{-3}). Margolis et al. [61] also measured densities of $1.3x10^{10}$ cm^{-3} and $0.7x10^{10}$ cm^{-3} for Ar^{16+} and Ar^{17+} ions respectively using the same method.

A different technique was used by Schweikard et al. [54] to determine the number of ions inside the EBIT. In [54] electrical probes were inserted into the EBIT to detect ion cyclotron resonance (ICR) signals induced by the ions. From the induced currents, the number of ions is inferred to be 10^5 to 10^6 for high charge state Kr ions (Kr^{34+}, Kr^{35+}, and Kr^{36+}). Using these numbers and assuming approximately 10^{-3} cm^3 for the volume of the ion cloud, we infer 10^8 cm^{-3} - 10^9 cm^{-3} for the average ion densities, in reasonable agreement with the results of the x-ray method.

It should be noted that the estimated densities using the ICR method are averages over the entire ion cloud, whereas the x-ray method samples only the region where the electron beam overlaps with the ion cloud. Because of the density gradient, the x-ray method should yield higher values than the average density. A better determination of the local ion densities could be performed by combining either of these methods with imaging techniques.

Charge state distribution

The evolution of the charge state distribution when the electron beam is on is determined by a set of coupled differential equations including source and loss terms for each charge state [20]. Once equilibrium is reached, recombination with electrons to produce lower charge states and re-ionization keep a balance between the neighboring charge states. Model calculations can account for the qualitative behavior of the time dependence, however discrepancies have been reported in several cases [62,63]. One of the critical issues that comes up in many experiments is the overlap factor between the electron beam and the ion cloud [20,63]. The modeling of this parameter relies on the knowledge of the properties of the ion cloud. As it has been shown in the imaging experiments [43,44], this can be very complicated, especially if non-thermal clouds are present. Further understanding calls for advanced modeling of the highly charged ion cloud.

Ion temperatures

A routine procedure in spectroscopy to determine ion temperatures is the measurement of the Doppler broadening of spectral lines. This method assumes that the emitting ions are in thermal equilibrium, a condition that might not be satisfied in some cases as suggested by the direct imaging results. Collective ion cloud rotation

could also cause spectral line broadenings, which might explain why the experiments have not indicated very low temperatures, even in cases where the axial potential barrier was very small. Nevertheless, the broadening of a relatively narrow spectral line, measured by high-resolution instruments, gives a general idea about the temperature ranges that highly charged ions are subjected to in EBITs.

The NIST EBIT group [7,64] used a Fabry-Perot spectrometer to measure the width of a visible magnetic dipole transition in Ba^{34+}. The experimental results indicated an ion temperature between 500 eV and 1000 eV. These values are much less than what the depth of the potential trap would allow, which for such a high charge-state amounted to about 17 keV (the reason for this reduced temperature is given in the next section). Similar conclusions were drawn from the x-ray line-width measurements of Beiersdorfer et al. [65,66] using Ti^{20+} ions. In these cases, the measured widths indicated equilibrium temperatures of 70 eV - 700 eV. Although the temperatures showed a dependence on the axial trap depth, the measured values were generally smaller than the possible temperatures Ti^{20+} ions were allowed to take, similarly to the observation of the NIST group using Ba^{34+} ions. Neither of the measurements took into account the possible collective rotation of the ion cloud, so the actual ion temperatures could have been even lower than those inferred from the measurements.

Evaporative cooling

The interaction of the ions with the dense and energetic electron beam continuously pumps energy into the cloud via inelastic collisions at a rate of a few keV/s [20]. At this rate of heating, most of the ions would quickly boil out of the trap. However, evaporative cooling of the higher charge state ions by elastic collisions with lower charge state ions that preferentially escape the trap strongly modifies this situation. Evaporative cooling of heavy ions can be even more efficient using lighter ions purposely injected into the trap. These lighter ions can be rapidly stripped bare, after which their charge state evolution is truncated.

Evaporative cooling of highly charged gold (Au^{69+}, Au^{68+}, Au^{67+}, etc.) by low charge state Ti ions (maximum Ti^{22+}) was successfully demonstrated by Schneider et al. [67]. Using this method, trapping times of several hours have been observed, demonstrating the presence of a strong cooling mechanism. Model calculations of the effect [69] predicted that highly charged heavy ions can be trapped for indefinitely in this way.

Conventional evaporative cooling in an EBIT [67-69], as described above, differs from evaporative cooling in neutral atom taps in that there is no time-dependence of the trap potentials. This cooling is not lossy because it depends on collisions with lower charge state ions that "see" a different trap depth. There have been two recent model investigations [45,46], which propose improved evaporative cooling schemes for an EBIT using time-dependent potentials. Because of the long-range nature of the strong Coulomb interaction, evaporative cooling works very differently in the case of highly charged, compared to the neutral atom case. At low temperatures, instead of getting weaker, the evaporative cooling mechanism can be accelerated, leading to very low achievable temperatures.

REFERENCES

[1] I. Martinson, *Reports of Progress in Physics* **52** (1989) 157.

[2] J.D. Gillaspy, *Journal of Physics B: Atomic, Molecular and Optical Physics* **34** (2001) R93.

[3] R. Minniti, L.P. Ratliff, J.D. Gillaspy, *Physica Scripta* **T92** (2001) 22.

[4] M.A. Levine, R.E. Marrs, J.R. Henderson, D.A. Knapp, and M.B. Schneider, *Physica Scripta* **T22** (1988) 157

[5] M.A. Levine, R.E. Marrs, J.N. Bardsley, P. Beiersdorfer, C.L. Bennett, M.H. Chen, T. Cowan, D. Dietrich, J.R. Henderson, D.A. Knapp, A. Osterheld, B.M. Penetrante, M.B. Schneider, and J.H. Scofield, *Nuclear Instruments and Methods in Physics Research B* **43** (1989) 431.

[6] J.D. Gillaspy, J.R. Roberts, C.M., Brown, and U. Feldman, *Proceedings of the VIth International Conference on the Physics of Highly Charged Ions, eds. P. Richard, M. Stockli, and C.D. Lin, (AIP press, New York, 1993), AIP Conference Proceedings* **274** (1993) 682.

[7] J.D. Gillaspy, Y. Aglitskiy, E.W. Bell, C.M. Brown, C.T. Chantler, R.D. Deslattes, U. Feldman, L.T. Hudson, J.M. Laming, E.S. Meyer, C.A. Morgan, A.I. Pikin, J.R. Roberts, L.P. Ratliff, F.G. Serpa, J. Sugar and E. Takács, *Physica Scripta* **T59** (1995) 392.

[8] J.D. Silver, A.J. Varney, H.S. Margolis, P.E.G. Baird, I.P. Grant, P.D. Groves, W.A. Hallett, A.T. Handford, P.J. Hirst, A.R. Holmes, D.J.H. Howie, R.A. Hunt, K.A. Nobbs, M. Roberts, W. Studholme, J.S. Wark, M.T. Williams, M.A. Levine, D.D. Dietrich, W.G. Graham, I.D. Williams, R. Oneil, and S.J. Rose, *Review of Scientific Instruments* **65** (1994) 1072.

[9] C. Biedermann, A. Forster, G. Fussmann, and R. Radtke, *Physica Scripta* **T73** (1997) 360.

[10] F.J. Currell, J. Asada, K. Ishii, A. Minoh, K. Motohashi, N. Nakamura, K. Nishizawa, S. Ohtani, K. Okazaki, M. Sakurai, H. Shiraishi, S. Tsurubuchi, and H. Watanabe, *Journal of the Physical Society of Japan* **65** (1996) 3186.

[11] T. Werner, G. Zschornack, F. Grossmann, V.P. Ovsyannikov, and F. Ullmann, *Nuclear Instruments and Methods in Physics Research B* **178** (2001) 260.

[12] J.R.C. Lopez-Urrutia, B. Bapat, I. Draganic, A. Werdich, and J. Ullrich, *Physica Scripta* **T92** (2001) 110.

[13] R.E. Marrs, M.A. Levine, D.A. Knapp, and J.R. Henderson, *Physical Review Letters* **60** (1988) 1715.

[14] P. Beiersdorfer, S. Vongoeler, M. Bitter, E. Hinnov, R. Bell, S. Bernabei, J. Felt, K.W. Hill, R. Hulse, J. Stevens, S. Suckewer, J. Timberlake, A. Wouters, M.H. Chen, J.H. Scofield, D.D. Dietrich, M. Gerassimenko, E. Silver, R.S. Walling, and P.L. Hagelstein, *Physical Review* A **37** (1988) 4153.

[15] J.R. Henderson, P. Beiersdorfer, C.L. Bennett, S. Chantrenne, D.A. Knapp, R.E. Marrs, M.B. Schenider, K.L. Wong, G.A. Doschek, J.F. Seely, C.M. Brown, R.E. LaVilla, J. Dubau, and M.A. Levine, *Physical Review Letters* **65** (1990) 705.

[16] D. Schneider, D. Dewitt, M.W. Clark, R. Schuch, C.L. Cocke, R. Schmeider, K.J. Reed, M.H. Chen, R.E. Marrs, M. Levine, and R. Fortner, *Physical Review A* **42** (1990) 3889

[17] R.E. Marrs, S.R. Elliott, and D.A. Knapp, *Physical Review Letters* **72** (1994) 4082

[18] C.A. Morgan, F.G. Serpa, E. Takács, E S. Meyer, J.D. Gillaspy, J. Sugar, J.R. Roberts, C.M. Brown and U. Feldman, *Physical Review Letters* **74** (1995) 1716.

[19] G. Borsoni, N. Bechu, M. Gros-Jean, M.L. Korwin-Pawlowski, R. Laffitte, V. Le Roux, L. Vallier, N. Rochat, and C. Wyon, *Microelectronics Reliability* **41** (2001) 1063.

[20] B. M. Penetrante, J. N. Bardsley, D. DeWitt, M. Clark, and D. Schneider, *Physical Review A* **43** (1991) 4861.

[21] B. M. Penetrante, D. Schneider, R. E. Marrs, and J. N. Bardsley, *Review of Scientific Instruments* **63** (1992) 2806

[22] H.S. Margolis, *D.Phil. Thesis, Oxford University*, 1994.

[23] I.V. Kalagin, D. Küchler, V.P. Ovsyannikov, and G. Zschornack, *Plasma Sources in Science and Technology* **7** (1998) 441.

[24] X.P. Huang, J. J. Bollinger, W.M. Itano, J.N. Tan, B. Jelenkovic, T.B. Mitchell, and D.J. Wineland, *Hyperfine Interactions* **115** (1998) 41.

[25] D.J. Wineland, C. Monroe, W.M. Itano, D. Leibfried, B.E. King, and D.M. Meekhof, *Journal of Research of the National Institute of Standards and Technology* **103** (1998) 259.

[26] L. Gruber, J.P. Holder, J. Steiger, B.R. Beck, H.E. DeWitt, J. Glassman, J.W. McDonald, D.A. Church, and D. Schneider, *Physical Review Letters* **86** (2001) 636.

[27] J.P. Holder, L. Gruber, H.E. DeWitt, B.R. Beck, D.A. Church, and D. Schneider, *Physica Scripta* **T92** (2001) 158.

[28] B. M. Penetrante, J. N. Bardsley, M. A. Levine, D. A. Knapp and R. E. Marrs, Physical Review A **43** (1991) 4873.

[29] B. M. Penetrante, M. A. Levine, and J. N. Bardsley, *Proceedings of the International Symposium on Electron Beam Ion Sources and their Applications, ed. A. Herschovitch (AIP press, New York, 1989),* AIP Conference Proceedings **188** (1989) 145.

[30] R. E. Marrs, *Review of Scientific Instruments* **67** (1996) 941.

[31] T. Schatz, U. Schramm, and D. Habs, *Hyperfine Interactions* **115** (1998) 29.

[32] T. Schatz, U. Schramm, and D. Habs, *Nature* **412** (2001) 717.

[33] J. Beebe-Wang, N. Elander, and R. Schuch, *Physica Scripta* **57** (1998) 36.

[34] J. P. Schiffer and P. Kienle, *Zeitschrift fur Physik A, Atoms and Nuclei* **321** (1985) 181.

[35] M. Steck, K. Beckert, H. Eickhoff, B. Franzke, F. Nolden, H. Reich, B. Schlitt, and T. Winkler, *Physical Review Letters* **77** (2001) 3803.

[36] R.W. Hasse, *Physical Review Letters* **83** (2001) 3430.

[37] R. Blumel and P.E. Smaldino, *Physics Letters A* **260** (1999) 495.

[38] P. Bowe, L. Horneaker, C. Brodersen, M. Drewsen, J. S. Hangst, and J. P. Schiffer, *Physical Review Letters* **82** (1999) 2071.

[39] D.C. Barnes, R.A. Nebel, and L. Turner, *Physics of Fluids B* **5** (1993) 3651.

[40] G. Zhuang, W. Liu, C. Yu, J. Zheng, C. Fu, J. Xie, K. Zhao, B. Bai, X. Liang, S. Zhao, and J. Chi, *Physics of Plasmas* **7** (2000) 3912.

[41] R.G. Greaves, M.D. Tinkle, and C.M. Surko, *Physical Review Letters* **74** (1995) 90.

[42] M. H. Holzscheiter, *Physica Scripta* **T59** (1995) 69.

[43] J.V. Porto, I. Kink, and J.D. Gillaspy, *Review of Scientific Instruments* **71** (2000) 3050.

[44] M.R. Tarbutt, *D.Phil. Thesis, Oxford University*, 2000.

[45] R.E. Marrs, *Nuclear Instruments and Methods in Physics Research B* **149** (1999) 182.

[46] T. Kinugawa, F.J. Currell, and S. Ohtani, *Journal of Physical Society of Japan* **68** (1999) 3763.

[47] F.J. Currell, *Trapping Highly Charged Ions: Fundamentals and Applications ed. J.D. Gillaspy (New York: Nova Science)*, 2001.

[48] G. Fussmann, C. Biedermann, and R. Radtke, *Advanced Technologies Based on Wave and Beam Generated Plasmas eds. H. Schluter and A. Shivarova (Kluwer Academic Publishers)*, 1999, 429.

[49] L. Schweikhard, P. Beiersdorfer, G. V. Brown, J. R. Crespo Lopez-Urrutia, S. B. Utter, and K. Widmann, *Nuclear Instruments and Methods in Physics Research B* **142** (1998) 245.

[50] F.G. Serpa, C.A. Morgan, E.S. Meyer, J.D. Gillaspy, E. Trabert, D.A. Church, and E. Takács, *Physical Review A* **55** (1997) 4196.

[51] G.J. Hermann, *Journal of Applied Physics* **29** (1958) 127.

[52] E. Takács, E. S. Meyer, J. D. Gillaspy, J. R. Roberts, C. T. Chantler, L. T. Hudson, R. D. Deslattes, C. M. Brown, J. M. Laming, J. Dubau, and M. K. Inal, *Physical Review A* **54** (1996) 1342.

[53] P. Beiersdorfer, B. Beck, S. Elliott, and L. Schweikhard, *Rapid Communications in Mass Spectrometry* **8** (1994) 141.

[54] L. Schweikhard, J. Ziegler, P. Beiersdorfer, B. Beck, St. Becker, and S. Elliott, *Review of Scientific Instruments* **66** (1995) 448.

[55] P. Beiersdorfer, St. Becker, B. Beck, S. Elliott, K. Widmann, and L. Schweikhard, *Nuclear Instruments and Methods in Physics Research B* **98** (1995) 558.

[56] P. Beiersdorfer, B. Beck, St. Becker, and L. Schweikhard, *International Journal of Mass Spectrometry and Ion Process* **157/158** (1996) 149.

[57] P. Beiersdorfer, L. Schweikhard, J. Crespo Lopez-Urrutia, and K. Widmann, *Review of Scientific Instruments* **67** (1996) 3818.

[58] Electron Beam Ion Trap, *Annual Report 1994, Lawrence Livermore National Laboratory, ed. D. Schneider, UCRL-ID-121572*, 1995.

[59] U. Feldman, P. Indelicato, and J. Sugar, *Journal of the Optical Society of America B* **8** (1991) 3.

[60] T.M. O'Neil, *Physica Scripta* **T59** (1995) 341.

[61] H. S. Margolis, A. J. Varney, R. A. Jarjis, and J. D. Silver, *Nuclear Instruments and Methods in Physics Research B* **98** (1995) 562.

[62] N.J. Peacock, R. Barnsley, M.G. O'Mullane, M.R. Tarbutt, D. Crosby, J.D. Silver, and J.A. Rainnie, *Review of Scientific Instruments* **72** (2001) 1250.

[63] E. Takács, Z. Berényi, Cs. Szabó, J.D. Gillaspy, and A.G. Calamai, *to be published*, 2001.

[64] H. Adler, E.S. Meyer, F.G. Serpa, E. Takács, J.D. Gillaspy, C.M. Brown, and U. Feldman, *Nuclear Instruments and Methods in Physics Research B* **98** (1995) 581.

[65] P. Beiersdorfer, V. Decaux, and K. Widmann, *Nuclear Instruments and Methods in Physics Research B* **98** (1995) 566.

[66] P. Beiersdorfer, V. Decaux, S. R. Elliott, and K. Widmann, *Review of Scientific Instruments* **66** (1995) 303.

[67] M.B. Schneider, M.A. Levine, C.L. Bennett, J.R. Henderson, D.A. Knapp, and R.E. Marrs, *Proceedings of the International Symposium on Electron Beam Ion Sources and their Applications, ed. A. Herschovitch (AIP press, New York, 1989)*, AIP Conference Proceedings **188** (1989)158.

[68] B. M. Penetrante, J. N. Bardsley, M.A. Levine, D.A. Knapp, and R.E. Marrs, *Physical Review A* **43** (1991) 4873.

[69] D. Schneider, M.W. Clark, B.M. Penetrante, J. McDonald, D. DeWitt and J. N. Bardsley, *Physical Review A* **44** (1991) 3119.

[70] D. DeWitt, D. Schneider, M.H. Chen, M.W. Clark, J.W. McDonald, and M.B. Schneider, *Physical Review Letters* **68** (1992) 1694.

[71] R.E. Marrs, M.A. Levine, D.A. Knapp, and J.R. Henderson, *Electronic and Atomic Collisions, eds. H.B. Gilbody, W.R. Newell, F.H. Read, and A.C.H. Smith (Elsevier Science Publishers B.V.)*, 1988.

[72] A.I. Pikin, C.A. Morgan, E.W. Bell, L.P. Ratliff, D.A. Church, and J.D. Gillaspy, *Review of Scientific Instruments* **67** (1996) 2528.

[73] L.P. Ratliff, E.W. Bell, D.C. Parks, A.I. Pikin, and J.D. Gillaspy, *Review of Scientific Instruments* **68** (1997) 1998.

[74] D.A. Knapp, R.E. Marrs, S.R. Elliott, E.W. Magee, and R. Zasadinski, *Nuclear Instruments and Methods in Physics Research A* **334** (1993) 305.

[75] S.B. Utter, P. Beiersdorfer, J.R.C. Lopez-Urrutia, and K. Widmann, *Nuclear Instruments and Methods in Physics Research A* **428** (1993) 276.

[76] H. Kuramoto, I. Yamda, H. Watanabe, M. Sawasaki, C. Yamada, and S. Ohtani, *Physica Scripta* **T92** (2001) 351.

[77] S. Chantrenne, P. Beiersdorfer, R. Cauble, and M.B. Schneider, *Physical Review Letters* **69** (1992) 265.