Extraction of highly charged ions (up to 90+) from a high-energy electron-beam ion trap

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The extraction of high-Z high-charge-state ions up to U^{90+} from a high-energy electron-beam ion trap, the SuperEBIT at Lawrence Livermore National Laboratory, is reported. The SuperEBIT provides a 240 mA electron beam with up to 200 keV of energy. Depending on the operating conditions (pulsed, continuous) and charge state, the number of ions extracted from the SuperEBIT varies between 10^2 and 10^5 ions per second under the tested conditions. The ions produced in SuperEBIT are extracted at potentials ranging from 0.5 to 20 keV (continuously variable) to provide highly charged low-emittance ion beams with energies between a few keV and several MeV. The performance of the SuperEBIT as an ion source is described and aspects for future developments and potential applications are discussed. © *2002 American Institute of Physics.*
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I. INTRODUCTION

The electron-beam ion trap (EBIT) was developed[1] as an outgrowth of the original electron-beam ion source (EBIS) concept of Donets.[2] The first extraction of highly charged ions and the employment of an EBIT as an ion source was demonstrated in 1990 at the Lawrence Livermore National Laboratory (LLNL) EBIT, which has been in operation since 1989.[3] Subsequently, we have extended this capability to SuperEBIT and have extracted highly charged ions since 1996. The successful operation of an EBIT as an ion source, referred to hear after as EBIT/S, for very highly charged ions has been demonstrated and extensively utilized in a number of new experimental physics projects (see Refs. 3–5). Interactions between highly charged ions (charges of up to 90+) with low kinetic energy ($\leqslant$2 keV/amu) and solid surfaces have revealed new physical effects associated with the large Coulomb potential energy of such ions. At the LLNL EBIT/S facility we have investigated electron emission,[6] sputtering yields,[7] x-ray fluorescence,[8] and surface modifications,[9] following the impact of highly charged ions with solid surfaces. The quality of the highly charged ion beams with regard to their low emittance allows speculation on the application of new nanotechnology methods (i.e., surface analysis[10] and modification on a nanoscale).[11] The low emittance of EBIT/S or an EBIS-extracted ion beam makes their use as ion sources for ion traps attractive. The ''retrapping'' into a cryogenic Penning trap of highly charged ions from an EBIT/S has been demonstrated first by Schneider *et al.*[12] Other groups have established this capability or are in the process of doing so [University of Stockholm CRYSIS/SMILE (Ref. 13) and CERN EBIS/ISOLDE (Ref. 14)]. Sympathetic ion/ion laser cooling has been demonstrated to cool highly charged ions to very low temperatures ($\approx$1 K vs 10^5 K in EBIT) by the LLNL group.[15] This particular capability demonstrates possible schemes where ion traps are used to produce ultracold charged particle beams. The trapping of SuperEBIT ions would open up unprecedented possibilities of new physics studies involving up to H-like and bare high-Z ions.

This article describes the use of SuperEBIT as a source of highly charged ions. The first ion/surface test experiments were used to verify and diagnose the extracted ion species and to demonstrate the potential source capability. Since this provides the first demonstration of a highly charged ion source capable of producing slow uranium 90+ ions, several aspects for future ion source and accelerator technology can be addressed. We indicate here a few thoughts along this line. Because of the high charge states of the ions produced in SuperEBIT, ion beams with kinetic energy of a few MeV can easily be produced by increasing the extraction potential (i.e., 200 kV).[16,17]

It is noted that an EBIT/S could be an option for a post-accelerator scheme of compact size and low cost to accelerate heavy ions up to several MeV/amu as needed, for example, in proposed radioactive ion beam or medical accelerator facilities. In such a scheme a relatively low acceleration potential applied to the highly charged ions would fulfill the needed acceleration requirements. However, for such, and other applications (e.g., material analysis) higher ion intensities are required. They can be achieved by increasing the electron current, current density, and trap length (see Table I). A highly charged ion-beam intensity increase of a factor of 1000 would require an approximate increase in these quantities of a factor of 10 (parameters for a high-intensity EBIT are given by Marrs[18]).

The extracted ion yield depends on a variety of source parameters which need to be optimized for the desired ion species, charge state, and ion temperature. It varies from a few hundred per second for heavy highly charged ions up to a maximum of 10^5 per second for Xe^{44+} with the presently available source parameters and under current extraction

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TABLE I. Operating conditions for the U^{90+} ion beam ($\approx$2 keV/amu).

Electron-beam energy	159 keV
Electron gun potential (cathode)	−152 keV
Drift tube potential (top/mid/bottom)	7.00/6.95/7.50 keV
Collector potential	−150 keV
Electron-beam current[a]	50 mA
Electron-beam radius	40 μm
Central current density	10^4 A/cm^2
Total electron charges (in trap)	2×10^9
Magnetic field[a]	3 T
Confinement time	3 s
Extraction pulse length	20 ms
Trap length[a]	4 cm

[a]These quantities can be increased by a factor of 10; the trap length increase requires testing of the onset of possible plasma instabilities. To upgrade the present EBIT would require redesign including the cryogenic system.

conditions. The number of ions extracted from SuperEBIT is small when compared to the number of extracted ions from standard low-energy EBITs such as those at NIST (Refs. 19 and 20) and Livermore,[21] as is discussed below.

II. EXPERIMENT

From 1996 to 1998 we performed the first highly charged ion extraction tests on the LLNL SuperEBIT where fully stripped xenon (Xe^{54+}) and uranium ions with charge states up to 90+ (helium-like uranium) have been extracted. The first operational EBIT, as described in Ref. 1, had been extensively modified previously by Knapp *et al.*[22] to achieve higher electron beam energies (i.e., 200 keV). These modifications warranted a change in the designation of EBIT to SuperEBIT. SuperEBIT has been described in detail in Ref. 22. The most significant of these modifications was the increase of the electron–ion interaction energy brought about by the high-voltage configuration changes. The high-voltage modification consisted of placing the electron gun and collector on a high negative potential (i.e., −170 kV), which when combined with the high positive potential (i.e., +30 kV) of the drift tubes, yields the effective electron-beam energy. The drift tube mounting was modified to allow theoretical operation of up to 40 kV, however, to our knowledge it has not been run above 30 kV and we ran it at only 20 kV. The operation of an EBIT is based on successive ionization of atoms and ions nearly at rest by an energetic electron beam. The electron beam is focused along the magnetic-field axis of a 3 T superconducting magnet and through three drift tubes that form a longitudinal trap 4 cm in length. The electron beam is compressed to a small radius (37–47 μm) (Ref. 23) and very high current density (up to $\approx$6000 A/cm^2) by the magnetic field. The electron beam radially traps the positively charged ions to complete the three-dimensional trap. The source of the electron beam is a Pierce-type electron gun located about 50 cm below the trap. It is mounted on an iron plate with a magnet coil (bucking) wound around it such that the magnetic-field gradient can be nulled at the cathode surface.[1] At the present time the maximum current recorded is 240 mA,[24] and this current is not achievable at maximum potential. Since the maximum number of trapped ions is limited by the charge balance in the trap, higher electron-beam currents should allow for larger numbers of trapped ions. The electron-beam stop or collector has a magnet wound around it to reduce the current density of the electron beam at the collector surface. The collector is cooled with an inert liquid "Multitherm 503." The vacuum in the trap region ($\approx5\times10^{-12}$ Torr) is improved by the cryopumping generated by the cooling for the superconducting magnets.

Ion extraction is accomplished in one of two methods, pulse mode and leaky mode. Typical trapping potentials for both extraction modes on the drift tubes are: bottom tube = 7500 V, middle tube = 6800 V, and top tube = 7000 V. In the pulsed mode, ions are extracted from the trap by raising the potential of the middle drift tube above that of the top drift tube. The middle drift tube is ramped up to 7400 V in 50 ms to produce an ion pulse of about 20 ms duration. In the leaky mode, the drift tube potentials are held constant. As the ions are heated by the electron beam they gain sufficient energy to cross the potential barrier of the top drift tube and leak out of the trap. The leaky mode was not employed to collect the data presented here. Ions must be reintroduced into the trap periodically to replace the ions that are extracted. There are several methods of ion or neutral atom injection into the trap. The most widely used method is neutral gas injection through one of the two gas leak valves on the side ports of the superconducting magnet. A metal vapor vacuum arc (MEVVA) (Ref. 25) can also be used to inject low charged metallic ions (i.e., 1–3+) into the trap along the axis of the magnetic field.

A fundamental issue in all electron-beam–ion sources is that the electron beam heats the ions in the process of ionization.[26] This increase in temperature can lead to ion loss, thus reducing the net efficiency of the ion production. In order to produce high-Z highly charged ions, it is essential to provide evaporative cooling to compensate for the heating of the ions by the electron beam.[27] This is particularly critical at high electron beam energies.[1] The addition of light atoms into the trap through one of the gas injectors provides evaporative cooling of the heavy elements. The trapped ions are in thermal equilibrium, and since the trapping forces are directly proportional to the charge of the ions, the low charged ions (i.e., O^{q+},N^{q+}; $1\geqslant q\geqslant 8$) are not trapped as efficiently as the high charged ions (i.e., U^{q+}, Xe^{q+}; $q>20$). This results in the low charged ions leaking out of the trap at a higher rate than the high charged ions, which removes much of the kinetic energy that is added by the electron beam. This cooling process allows for the production during extended confinement times of very high charge states up to U^{92+} (see Ref. 28). The trapping potential, ionization time, and electron-beam current and density determine the temperature of the extracted ions.

The extraction of highly charged ions from SuperEBIT was made possible by the addition of an upgraded extraction beam line in 1996. Both LLNL EBIT ion extraction systems are similar to the system at the NIST EBIT.[19,20] The extraction beam line and SuperEBIT are depicted in Fig. 1. The extraction beam line components included an electrostatic 90° bender, einzel lenses, a 90° analyzing magnet, and a channel plate detector. After extensive modeling of the beam optics, using SIMION 3D, the beam transport was upgraded by the inclusion of electrostatic quadrupole lenses and cylindri-

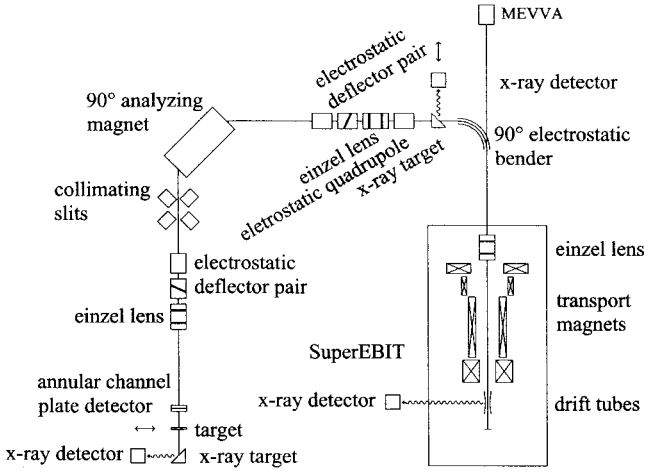

FIG. 1. SuperEBIT and extraction system.

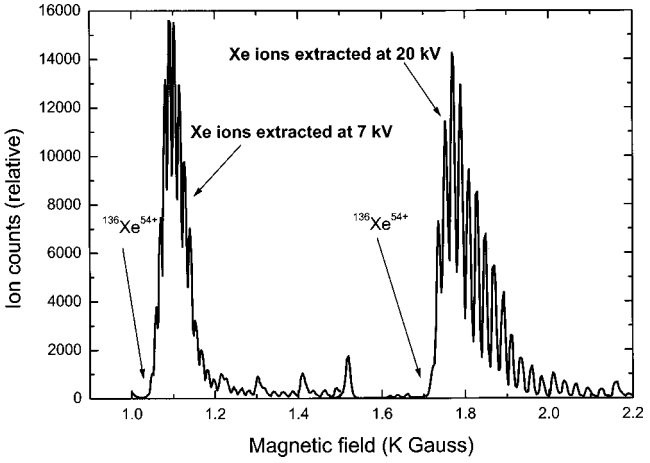

FIG. 3. Charge state analyzed extracted Xe spectra at 7 and 20 keV.

cally symmetric deflectors. With this upgrade the number of extracted Xe^{51+} ions was found to exceed 10^3 per second. The energy of the extracted ions was determined by the potential of the high-voltage power supply summed with the potential of the top drift tube, as is shown in Fig. 2.

We have extracted $^{136}Xe^{54+}$ ions at 7 and 20 kV and U^{86-90+} ions at 7 kV. At 20 kV extraction, the Xe^{54+} have 1.08 MeV of kinetic energy. The spectrum for momentum analyzed ^{136}Xe ions is displayed in Fig. 3. The xenon gas source sample that we used in this experiment was isotopically enriched to 90% ^{136}Xe. The gas atoms were injected through the gas inlet of SuperEBIT where they were ionized and trapped utilizing a 73 keV, 70 mA electron beam and a 200 V longitudinal trap potential. These ions were extracted after about 500 ms by ramping the potential of the middle drift tube above that of the top drift tube (see Fig. 2). In the case of uranium the ions were injected from the MEVVA, ionized and trapped utilizing a 159 keV, 50 mA electron beam and a 50 V longitudinal trap potential. The injection of the U ions from the MEVVA takes less than 5 ms of the total cycle time of 3 s. The U^{90+} ions were extracted after about 3 s of ionization time. The relative yield of extracted ions is about 1000 per second for Xe^{54+} and about 100 per second for U^{90+}. These rates agree favorably with predictions of the evolution of the ion charge state distributions within an EBIT/S that have been calculated by Penetrante *et al.*[27] Fully stripped U has been observed within the trap and the first direct ionization cross-section measurements of H-like U^{91+} to bare U^{92+} were performed on SuperEBIT operated with a

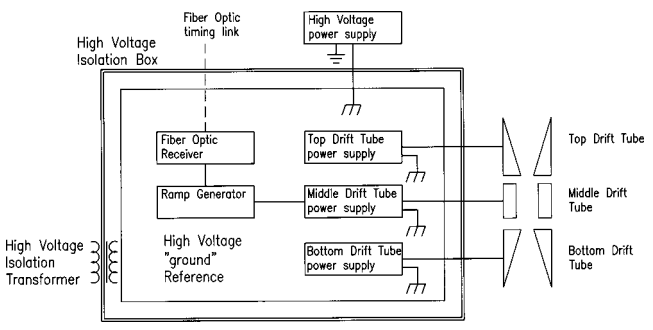

FIG. 2. Schematic representation of the floating high-voltage system.

198 keV, 200 mA electron beam and an ion confinement time of about 4 s by Marrs *et al.*[28]

A solid target positioned at 45° relative to the ion-beam axis right after the electrostatic bender and a Si(Li) detector was employed to look for x-ray emission following the radiative deexcitation of $U^{91+,92+}$ ions interacting with the surface. From the bare uranium ion production results reported by Marrs,[28] it can be estimated that less than a hundred 91+ and about ten 92+ ions per second would be produced at best in SuperEBIT at the given electron-beam energy. There is a large change in the potential energy as the two *K*-shell electrons from any ion are removed. At the electron-beam energies employed here, very few 91+ and 92+ ions are expected. Taking the poor extraction efficiency into account, one could expect only a few such ions to reach the target and create x rays with energies above 100 keV. However, none were observed after several hours of counting and only spurious indications for the production of these ions was indicated on the x-ray emission spectra from the SuperEBIT trap. We conclude that the low cross section for $U^{91+,92+}$ ion production, recombination, and beam transport inefficiencies made the extraction of such ions improbable at that time. However, the extraction of more than a hundred U^{90+} ions per second demonstrates that the EBIT/S ion source technology is certainly one way to provide such ions. It would, however, require substantial redesign and improvement of the extraction path in SuperEBIT to produce useful yields of $U^{91+,92+}$ ions.

The major difficulties that have been encountered in the operation of SuperEBIT as an ion source are the compromise between stable ion and electron-beam transport in the shared transport path (discussed below) and high-voltage stability. The latter requires conditioning for any high-voltage mode above ≈150 kV. The ion transport from the drift tube region to the electrostatic bender seemed to be correlated to the high voltage (i.e., breakdown and recombination from increased background electron emission). Due to intrinsic misalignment problems of these transport magnets it was necessary to reduce the electron-beam current to provide usable numbers of extracted ions.

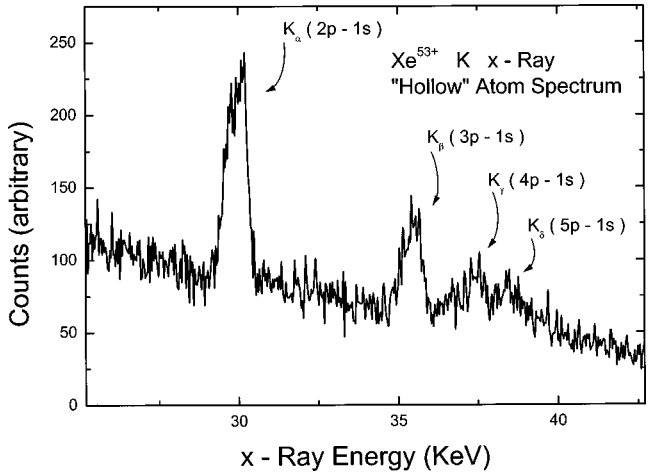

FIG. 4. Hollow atom x-ray spectra with Xe^{53+} $K\alpha$, $K\beta$, and $K\gamma$ lines from radiative deexcitation of Xe^{53+} ions on a surface are shown.

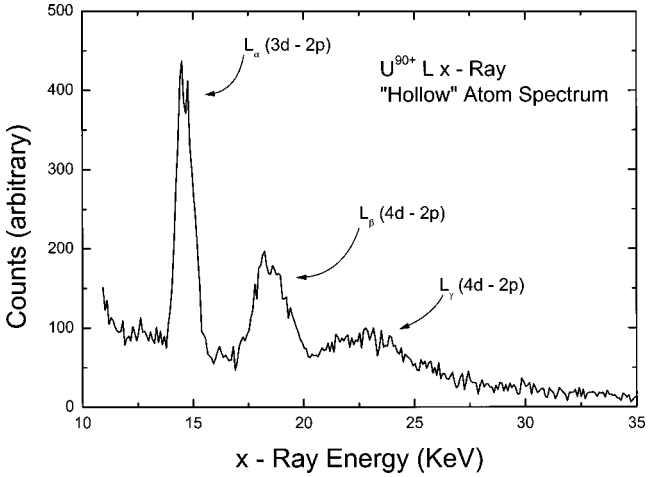

FIG. 5. Hollow atom x-ray spectra with U^{90+} $L\alpha$, $L\beta$, and $L\gamma$ lines from radiative deexcitation of U^{90+} ions on a surface are shown.

III. RESULTS AND DISCUSSION

The analysis of the extracted ions was performed in two ways. First, they were momentum analyzed by the 90° bending magnet and counted by a channel plate detector. Second, they were analyzed by collecting x-ray emission data following the interaction of $^{136}Xe^{53+}$ and U^{90+} on a Au surface at normal incidence. The former method is described above and the results are shown in Fig. 3 for the case of ^{136}Xe ions. The use of isotopically enriched source material helps to clearly identify the charge state distributions as demonstrated in the Xe extracted ion spectra. The extraction of relatively ''cold'' ions and, therefore, low emittance ion beams, also helps to separate the ion charge states in the momentum analyzed spectra after the analyzing magnet. The transverse momentum of the extracted ion beam can be further be reduced by lowering the electron-beam current, thereby reducing the electron-beam–ion heating effects. This procedure is limited by the trade-off between ion-beam emittance and the number of extracted ions. The rate of electron-beam heating must be taken into account in any new EBIT/S source design for higher-intensity electron beams. For estimates of the ion heating rate as a function of the electron-beam heating, we refer the reader to Penetrante *et al.*[27] It is noted that at very low electron-beam currents the achievable momentum resolution for the extracted ions possibly allows EBIT/S sources to be used for isotope analysis. For the case of the extracted U ions, the individual charge states could not be resolved due to isotopic contamination of the uranium used in the MEVVA. This could be improved by using isotopically enriched uranium metals in the MEVVA electrodes. We have used a Si(Li) detector to measure the x-ray emission following Xe and U ion impact on a surface. The spectra (FWHM$\approx$160 eV) are depicted in Figs. 4 and 5 for Xe and U, respectively. In the case of Xe^{53+} these spectra clearly show $K\alpha$, $K\beta$, and $K\gamma$ transitions. The presence of these transitions following radiative deexcitation confirms the charge state of the momentum analyzed hydrogen-like Xe^{53+} ions. In the case of U^{90+}, Fig. 5 shows $L\alpha$, $L\beta$, and $L\gamma$ transitions, where the centroid energies of these peaks confirms the presence of U^{90+} as the U ions approach the surface.[29] The centroid energies for the Xe and U peaks are in good agreement with transition energy calculations for the ''hollow atom'' configuration.[29] In the hollow atom formation scenario, electrons are drawn out of the solid surface due to the potential of the approaching highly charged ion. Some of these electrons are captured into high-n states of the approaching highly charged ion and partially screen its potential. Due to the short time the ion spends above the surface, on the order of a few femtoseconds, complete relaxation of the ion is not possible. The approaching ion may acquire sufficient electrons to completely neutralize its charge, but the inner shells remain vacant. It is the radiative deexcitation of these inner shells that occurs as the hollow atom penetrates the first layers of the surface that produce the characteristic inner shell transitions.[30] From the x-ray measurements ion yields of $\approx 10^3$ for Xe^{54+} and $\approx 10^2$ for U^{90+} per second are estimated.

In general, the number of lower charged ions (less than about 60+) that are extracted from an EBIT is small when compared to an electron cyclotron resonance (ECR) source, however, the situation is reversed at higher charge states (greater than about 60+). The performance of an ion source is often stated in terms of the emittance. In the simplest of terms, emittance is the ratio of transverse to longitudinal momentum of the ions in the beam. A small emittance implies that more of the ion beam that leaves the source gets to the target. We have estimated the emittance of the extracted ion beam.[8] Emittance is defined as $\epsilon = \pi r r'$, where r is the radius of the beam in mm at a waist and r' is its divergence angle in mrad. The emittance is then the area of the ellipse in phase space containing roughly 50% of the beam intensity. While the beam optics change the radius of the beam, the emittance is conserved. The expected emittance of an EBIT/S (or EBIS) can be calculated from the properties of the trapped ions. The normalized emittance is defined as $\epsilon_n = (v/c)\epsilon$, where v is the ion velocity, which is conserved and can be directly related to the ion temperature and volume of the trapped ions. The un-normalized emittance can be expressed as

$$\epsilon = \pi r_0 \sqrt{\frac{kT_i}{qU}},$$

where T_i is the temperature of the trapped ions, r_0 is the radius of their confinement volume, U is the ion acceleration potential, and q is the ion charge. Computer simulation estimates of the temperature of trapped ions in EBIT/S predict a temperature that is mainly determined by the trapping potential V_{well} (i.e., $kT_i \approx 0.1 q V_{\text{well}}$).[27] This prediction agrees well with temperature measurements performed on Ti^{22+} ions using *in situ* x-ray emission spectroscopy.[31] The radius for the ion plasma used here has been estimated as follows: Since kT_i/q is close to the 14 V space charge potential at the 35 μm electron-beam radius, we expect that the ion confinement radius is about the same as the electron-beam radius and set $r_0 = 35\,\mu$m. Furthermore, we assume that $kT_i/q \approx 0.1 V_{\text{well}} = 20$ eV for a 200 V well at the beginning of the extraction ramp and an extraction potential of 20 kV. With these assumptions, the expected emittance is $\epsilon \approx 1.1\,\pi$ mm mrad. This value is in good agreement with the experimentally deduced value using a two collimator system. For the case of the Xe^{44+} ions, the emittance was measured by focusing the ion beam through two collimators separated by 230 mm (see Fig. 1). The first collimator was an adjustable slit system set to 1 mm. The second collimator was a 3-mm-diam hole in an annular channel plate detector. The ions were focused onto a target and electrons emitted from the target were counted by the channel plate to measure the ion flux. This measurement sets an upper limit on the emittance of 1 π mm mrad on the ions that pass through both collimators. This crude measurement is considered valid since over half of the extracted ions can be made to pass through both collimators onto the detector. It should be noted that this measurement is performed at the end of the beam line and the extracted beam has been subjected to effective collimation by the upstream beam line components (see Fig. 1). No measurements of the total number of ions lost in transit from the trap to the detector have been made. The relationship between pulse width, the rate of the extraction, and emittance have not been measured on SuperEBIT thus far. The emittance dependence on trap parameters has been measured on EBIT II and the decrease of the emittance with decreasing ion temperature has been established mainly through reduction of the electron-beam current. It is, furthermore, noted that the intrinsic characteristic of the EBIT/S to produce low emittance ion beams can be improved by designing the top drift tube in such a way that it can act as an einzel lens during extraction and through better alignment of the primary electron-beam transport system between the trap and the electron collector (i.e., transport magnet alignment). The 20 kV extraction of Xe demonstrates the potential use of an EBIT/S as a table top accelerator or injector, and an EBIT/S on a 200 kV platform using 80+ ions would deliver beams of 16 MeV.

The ion extraction efficiency at SuperEBIT is limited because of the alignment of several axial magnet coils that guide the high-energy electron beam from the trap region to the collector over a distance of $\approx$1.5 m. These alignment issues include the necessity of transporting both the high-energy electron beam and the extracted ions simultaneously through common beam optics. The design of the electron-beam transport was not originally intended to transport the extracted ions and is, therefore, not optimized for ion transport. During ion extraction operation the electron-beam transport magnets must be adjusted such that a compromise between electron-beam transport efficiency and ion extraction efficiency are reached. This compromise limits the beam energy, current, and number of ions that can be extracted while maintaining stable operation with low bremsstrahlung radiation.

We have demonstrated the ability to produce low-emittance fully stripped Xe ion beams at MeV energies. We have also succeeded in extraction of beams of heavier ions up to helium-like uranium beams with low emittance. The possibility to produce and extract the highest charge state ion and the use of high electrostatic extraction potentials demonstrates a capability to readily produce low-emittance highly charged heavy-ion beams at MeV energies. These capabilities suggest the possibility of applications such as heavy-ion injection for high-energy accelerators or ion implantation schemes. Future development will focus on increasing the number of ions by applying more intense electron beams and higher current density to increase the radial space charge potential. However, a higher current density will lead to greater heating of the ions by the electron beam and a resulting increase in the emittance. In the current SuperEBIT the length of the trap is physically limited by the length of the field magnets.

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