A miniature EBIT with ion extraction for isolating highly charged ions

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Abstract. A room-temperature miniature electron beam ion trap (EBIT) is being developed for the production of charge states with a relatively low ionization threshold. A unitary Penning trap is modified slightly to provide the magnetic field and electric potential necessary for ion production via electron impact in this compact EBIT. This design allows radial access for in-EBIT spectroscopy as well as extraction of highly-charged ions for isolation at low energy to investigate proposed experiments. A fast micro-channel plate is used as a time-of-flight detector to study the initial production of helium and neon ions. Planned work would also involve the use of a Wien filter to select a single charge state to be isolated in a secondary ion trap for various studies. For instance, fully stripped ions can be captured for recombination experiments to form one-electron ions in high-angular momentum Rydberg states.

1. Introduction
Recent theoretical studies have reported special features in some highly charged ions that could potentially be useful for improved atomic clocks [1, 2], quantum information processing [1], measurements of fundamental constants [3, 1, 4], and tests of quantum electrodynamics [3]. Exploration or realization of these atomic systems requires the production of ions with low ionization threshold, as well as isolation in ultra-high-vacuum (UHV) for manipulation at low energy. We are developing a miniature electron beam ion source/trap (EBIS/T) that could be useful for exploring some of these possibilities. For instance, an ion source that fully strips atoms with $Z < 11$ could facilitate the production of one-electron ions in high-angular-momentum Rydberg states, with optical electric-dipole transitions which are well-suited for an independent measurement of the Rydberg constant [3, 5].

2. Highly charged ions in compact Penning traps
Recent work at the National Institute of Standards and Technology (NIST) has used a unitary Penning trap [6, 7] to capture highly charged ions extracted from an EBIT. An analyzing magnet in the existing ion-extraction beam-line of the NIST EBIT was used to select a single-charge state for isolation in this secondary ion trap, which has been made very compact by integrating NdFeB magnets into the electrode structure [6]. Since the trapping volume is relatively small in a unitary Penning trap, ion capture efficiency relies greatly upon beam focusing, ion pulse-width compression, proper timing of the capture trigger, and energy matching between the EBIT and unitary Penning trap. With careful optimization, roughly $10^3$ ions have been captured with an initial energy spread of $\approx 5$ eV, which is about 60 times lower than in the ion source [7].
interesting feature is that the low energy is obtained within 1 ms of ion capture. This can be useful in experiments for which the time constants of known cooling mechanisms are too long. An illustration is provided in the recent lifetime measurement of the $3d^2D_{5/2}$ metastable spin state in Kr XVIII, a relativistic Rydberg ion [8]. On a longer time scale, lower temperature may be attainable via other mechanisms, such as evaporative cooling [9]. Additional work is underway studying cooling and electron-capture processes of ions isolated in a unitary Penning trap.

3. A miniature electron beam ion source/trap
Compact electron beam ion sources and traps have been constructed using rare-earth permanent magnets in various configurations [10, 11]. The system being developed at NIST uses a two-magnet unitary Penning trap [6], but with its three electrodes shorted together as a single central drift tube that also provides the magnetic field. In this prototype, a simple annular disk is added to each end as end-cap electrodes in order to generate the electrostatic potential required for axial confinement of highly charged ions. The resulting miniature EBIS/T is illustrated in figure 1, located in the main six-way-cross chamber. The electron beam is provided by a magnetically shielded Pierce gun. The electron gun is mounted on a translation stage to assist with focusing the electron beam into the EBIT and optimizing the production of charge states with relatively
Figure 2. Observation of initial ion extraction signals using the TOF detector, corresponding to the ionization of injected helium gas (left) and injected neon gas (right). The same EBIT operating conditions were used in each case.

low ionization thresholds. A gas injector is mounted below the main chamber, with its nozzle aligned radially into one of the four equidistant holes in the mid-plane of the EBIT to serve as the initial source of atoms selected for electron-impact ionization. The remaining three holes are available for in-EBIT spectroscopy. Highly charged ions can also be extracted in pulses for further study. A retractable Faraday cup or a fast multi-channel plate time-of-flight (TOF) detector, located downstream, can be selected to analyze the extracted ion pulses. A diagram of the full apparatus is shown in figure 1.

Multiple charge states are created by electron-impact ionization inside the EBIT. When ejected to the TOF detector, higher charge states have shorter transit times to the detector. Figure 2 shows some early TOF signals corresponding to the initial extraction of helium ions (left) and neon ions (right), under the same EBIT operating conditions. The production and pulsed extraction of ions in various conditions is under study.

4. Planned work

We are interested in using the miniature EBIS/T for studies involving low ionization energy or isolation of fully stripped ions for experiments to produce one-electron ions in high angular momentum states. A Wien filter and additional ion beam optics will allow for selection of a single-charge state and better control of the extracted ions to optimize capture in a secondary ion trap. Planned charge exchange experiments with extracted ions stored in a secondary ion trap will utilize a rubidium beam oven apparatus [12], currently in development, that provides a beam of Rydberg rubidium atoms via laser excitation.

Some metastable states of interest have very long lifetimes (see, e.g., Ref. [1]). On the other hand, the storage lifetime of ions isolated in a secondary trap is dependent on the background gas pressure. For instance, ion storage lifetimes in a unitary Penning trap are less than 1 s at the pressures typically achievable in room-temperature UHV systems [6]. In order to increase the ion storage lifetime for studying very-long-lived metastable states, we plan to incorporate a Gifford-McMahon-type cryocooler into the apparatus, which would substantially lower the background gas pressures in the ion capture trap.
5. Summary
Theoretical studies have unveiled highly charged ions with special properties that can contribute to significant advances in several areas of precision measurements and atomic physics [1, 2, 3, 4]. Recent work at NIST used a unitary Penning trap to store highly charged ions at relatively low energy for precise measurements [6, 7, 8]. Initial extraction of ions from a miniature EBIS/T has been observed. Work is underway to optimize ion production and to capture the extracted ions in a secondary trap. An interesting application would be to produce one-electron ions in high angular momentum states [3]. Other possible applications include exploratory studies of highly charged ions that are potentially useful for ultra-precise atomic clocks [1, 2], quantum information processing [1], or new measurements of possible time-variation of the fine structure constant [1, 4].

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