First results from the Stockholm Electron Beam Ion Trap

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Abstract. A new laboratory for highly charged ions is being built up at Stockholm university. An electron beam ion trap (EBIT) (3 T magnet, \leq 30 keV electron beam) was installed. It is used for spectroscopic studies, precision mass measurements, electron ion collisions, and highly-charged ion surface studies. Here we report about a fast ion-extraction scheme from EBIT and first results using a time-of-flight detection as well as a LABVIEW based operational system of EBIT.

1. Introduction

Electron Beam Ion Trap/Sources EBIT/EBIS are very efficient tools to produce and trap highly charged ions. Injected atoms or molecules are ionized by an intense electron beam and longitudinally trapped by electrostatic potentials provided by drift tubes. The electron beam is compressed by a strong magnetic field. Both, the electron beam and magnetic field provide radial trapping. Often an EBIS is build with a longer trapping region with the purpose to yield large quantities of highly charged ions [1, 2]. EBIS devices with drift tubes of up to 1.5 m were built [4]. The long transport region of the compressed electron beam gave rise to modes of plasma oscillations and other instabilities. The design of the EBIT differs fundamentally in the length of the drift tubes and of the magnet. The center drift tube which defines the electrostatic well is typically 2 cm long. By this most of the instabilities can be avoided. The EBIT has instead of a solenoid a magnet in the Helmholtz geometry. There are ports with access to the trapping region. This makes the EBIT a tool with which spectroscopic studies can be performed under well controlled conditions. The first EBIT was developed by Levine \textit{et al} [3] in Livermore. From this EBIT the super-EBIT has been developed which is capable of delivering highly charged ions up to bare uranium [5].

In these machines the superconducting magnet was cooled by having liquid He and liquid N$_2$ in cryostats. The next generation EBITs are refrigerated (cryogenic) systems where cold heads keep the magnets and heat screens on the respective temperatures. Such an EBIT [6] has been acquired and was build up in our laboratory. We changed the operational system of this EBIT to complete LabView control of the relevant parameters as well as basic data acquisition routines. A fast extraction system of the ions from EBIT and a time-of-flight (TOF) mass spectrometer for analysing the charge abundances of the ions in the trap has been developed. This allows a
fast and convenient adjustment of the machine and efficient studies of electron-ion processes in the trap.

2. Description of the system

The EBIT produces and traps the ions by an intense electron beam. The typical electron beam currents run up to around 150 mA. In the trap region the electron beam is compressed to a diameter of 70 μm by the magnetic field of 3 T produced by the superconducting Helmholtz coils. This gives a central current density of up to 4 kA/cm². Contrary to other EBITs the coils are cooled to 4 K by a cold head and are screened by a 60 K cold head shroud, which are connected to two separate compressors having a closed Helium circuit. This means no refilling of liquid nitrogen or helium is required. This EBIT design [6] excels in terms of its startup time, power consumption, and convenience. From the startup it takes 12 h until the temperature of the superconducting magnet reaches 4 K. The total power consumption is less than 15 kW/h.

The ions are trapped radially by the space charge of the electron beam and axially by applying higher positive potentials to the outer two of three drift tubes. The length of the central tube is 2 cm and has 8 ports. These can be used to observe radiation, inject laser beams and the gas atoms/molecules. The gas is injected as an atomic beam, collimated in a differentially pumped drift region. The final aperture, formed by an injection needle is movable using a micrometer manipulator so that the atomic beam can be pointed directly on the electron beam. Gas can be injected into the buffer volume by a leak valve or a pulsed valve. They can also be used simultaneously to mix a cooling gas. To inject metallic ions a SPARK (Metal Vapor Vacuum Arc) ion source is installed (see Fig. 1). The mainly singly charged ions produced from that source are injected into the EBIT where they are further ionized. Currently spectroscopy has been done using a Si(Li) x-ray detector. So far a solid state x-ray detector and a spectrometer for visible light has been installed on two of the ports of the EBIT.

The ions can be extracted from the EBIT for further analysis. The extracted ions are focused and momentum analyzed in a 90° analyzing magnet according to their charge to mass ratio. They can be detected using an electron-multiplier tube or Farady cup. From there they can be transported to the experiments, currently in two beamlines. At one of them a Penning ion-trap has been built up to cool ions. From there ions can be extracted for feeding them into the Penning trap SMILETRAP [7] used for precision mass measurements. The other beam line has been built up for measurements with nano-capillaries [8]. The ions can be delivered in two different modes. In leaky mode a continuous ion beam can be provided by setting the trapping
voltage of the drift tube on the extraction side to a value between zero and a few volts. This mode can, however, only be used for low charge states. The other mode is pulsed extraction. The pulse length can be varied between 0.1 $\mu$s and many ms. The extraction energy can be set independently of the ionization energy. On the zero degree extraction line from the EBIT the ion optics and electron-multiplying detector for time of flight (TOF) measurements is installed. As described below, we successfully measured the charge state distribution of single extracted pulses with this detector.

A new LABVIEW program has been developed to control the EBIT with a PC containing the appropriate cards for analog output and input. Via a user-friendly graphical interface all parameters of the EBIT and the whole beamline can be controlled. The program continuously monitors the temperature of the superconducting coils, the vacuum, the emission and collector current, the anode current and the power consumption of the high voltage power supply. It allows to set limits for these values. If these are exceeded the electron beam current is immediately lowered by reducing the anode voltage until all values are within the given limits. In case these can not be reached, the anode voltage is turned off.

The LABVIEW operational system also allows data taking and EBIT operation for experiments that are done directly at the EBIT, such as recombination studies. The electron beam energy can be scanned and the connected x-ray spectra can be stored. The analyzing magnet scans are operated and the charge state spectra are stored and analyzed in LABVIEW.
3. Time-of-flight measurements

For tuning the EBIT a fast diagnostics of the charge distribution is of advantage. In experiments that count ions in the trap and especially those that are sensitive to charge-state ratios, such as recombination and ionization/excitation studies, a simultaneous detection of all charge states extracted from the trap is essential. For this purpose we implemented a TOF system at our EBIT. The critical condition is a short extraction time of less then a micro-second of most of the ions from the trap. Chopping the ion pulse was considered, but found to possibly create false results for the different charge states in an ion counting experiment. Therefore we experimented with schemes to get a fast extraction of all ions from the trap. First experiments were made using Neon and Argon ions. The depth of the trap was set to 20 V. The ions were extracted by lowering the trapping potential of the drift tube on the extraction side below the potential of the middle drift tube in a time interval of \( \approx 50 \) ns. The length of the pulse is limited by the fact that the ions are extracted from a 2 cm long trap. The extraction potential was set to 1700 V. We estimate a time interval of \( \approx 100 \) ns for emptying the trap. This can still be improved by manipulating the other drift-tube potentials during extraction. The ions travel a distance of 3.1 m from the trapping region to the time of flight (TOF) detector. An electron-multiplier tube is used to detect the ions. The top plot on figure 2 shows the TOF measurement for neon ions. The first ions arrive at the detector after 9 \( \mu \)s. The difference in the time of flight for the adjacent charge states \( ^{20}\text{Ne}^{10+} \) and \( ^{20}\text{Ne}^{9+} \) is 500 ns. It increases for lower charge states. The double peak structure of the most intense Ne and Ar peaks is due to saturation effects in our detector. The plot in the bottom of figure 2 shows the corresponding magnet scan. In figure 3 the results for Argon are shown. Here the difference in the charge to mass ratio is smaller than in the case of neon and hence the difference in the flight time for adjacent charge states decreases. Still we clearly resolve all charge states in the TOF up to \( \text{Ar}^{18+} \).

This scheme will allow fast and direct measurements of the ionization process during charge breeding. We plan to combine the TOF measurements with the x-ray detection in recombination measurements. For every value of the electron energy a TOF spectrum will be taken. It will allow us to see changes in the charge state distribution as we cross the dielectronic recombination resonances. This information can be used to obtain absolute recombination rate for differential channels in the x-ray spectrum.

4. Conclusions and Outlook

The Stockholm EBIT is fully operational. First experiments have been done with highly charged Ne, Ar, as well as Si ions. We have developed a system to continuously monitor the charge state distribution for such measurements by TOF for each extraction pulse. For that we were able to reach a fast extraction of the trapped ions with about 100 ns. A new LABVIEW based program has been implemented for controlling the EBIT and for data acquisition. We have also started to use the EBIT as an ion source for measurements on nano-capillaries by a continuous beam of \( ^{8+}\text{Ne} \) ions. For testing the new ion trap, used to cool ions for SMILETRAP, short ion pulses of less then 1 \( \mu \)s length were extracted from the EBIT. Preparations to mount an EUV spectrometer in cooperation with the university of Uppsala are made.

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