Trapping of highly charged ions with an electrostatic ion trap

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Abstract. In the current contribution, we present our first results with an electrostatic ion trap which has been constructed at LKB (Laboratoire Kastler Brossel) in collaboration with the Weizmann institute. The electrostatic ion trap is composed of two coaxial electrostatic mirrors, working for charged particles in the same way as a Fabry-Perot interferometer works for light in the optical regime. The trap has been attached to the beamline of SIMPA (Source d’ions Multichargs de Paris) an Electron Cyclotron Resonance Ion Source (ECRIS) at LKB (Laboratoire Kastler Brossel) and INSP (Institut des NanoSciences de Paris). The trap is foreseen to be applied for various studies on highly charged ions; as measurements of the life times of metastable states, mass spectroscopy etc. First results for trapping highly-charged ions are presented and simulations in order to explain the observed behavior are discussed.

1. The experimental setup

The developments and applications of ion traps and heavy-ion storage rings has had a significant impact on many branches of physics. These devices enable storing of ions for a relatively long time, with meV to eV kinetic energies, in ion traps and to GeV kinetic energies, in heavy-ion storage rings. Therefore, they provide unique experimental conditions for a broad range of experimental investigations. Ion traps are able to trap charged particles for a long time, and they have been successfully applied in several areas of physics. Recently, a novel class of ion traps has been developed [1, 2], in which ions oscillate between a pair of electrostatic mirrors, much like photons in an optical resonator. The trapped ions have kinetic energies of a few keV in the central part of the trap while inside the mirrors they have only a few meV near their turning points, where they are also subject to radial focusing forces. Several experiments have already been performed with these devices, such as lifetime [3, 4] as well as studies of charge exchange [5].

Following a design from the Weizmann Institute [1], we have constructed an electrostatic trap and attached it to the beam line of "SIMPA" (Source d’ions Multichargs de Paris) an Electron Cyclotron Resonance (ECR) ion source at LKB (Laboratoire Kastler Brossel) and INSP (Institut des NanoSciences de Paris). The experimental setup including the ECR ion source, the beamline and the trap is presented in Fig. 1. A schematic drawing of the trap together with a photography is displayed in Fig. 2. The ion trap consists of two coaxial electrostatic mirrors, each composed of a stack of eight cylindrical electrodes. The configuration of the trap is characterized by the
potentials on five of these electrodes, V1, V2, V3, V4, Vz (see Fig. 2), the other three being grounded. Provided that the field generated by these potentials fulfills certain criteria, ions can be trapped oscillating between the two mirrors [1]. The vacuum system of the ion trap includes an ionic pump and a Ti getter pump that can reach low pressures down to $\sim 10^{-11}$ mbar. Injection of an ion bunch into the trap is performed by grounding all the entrance electrodes. The electrodes on the other side are kept at high potential so that the bunch is reflected toward the entrance. Before the ion bunch returns to the entrance mirror, the potentials of its electrodes are rapidly ($\sim 100 - 200$ ns) raised and the ion bunch is thus confined between the mirrors.

The highly-charged ions are produced in the SIMPA ECR ion source and are extracted and accelerated by the extraction voltage of 4.2 kV. Then, the ions are focused and analyzed by a solenoid and a dipole magnet downstream to the ion source before injection into the trap (see Fig. 1). In addition, steering of the ions between the dipole magnet and the ion trap can be done with the help of two electrostatic deflectors. An electrostatic chopper located before the first magnet was used to create bunches of ions with a temporal extension of 0.05 - 1 $\mu$s. The evolution of ion bunches during storage was monitored with a cylindrical pickup electrode made with a length of 7 mm and inner diameter of 18 mm located at the center of the trap (see Fig. 2). The amplified pickup signal was recorded on a digital oscilloscope and a spectrum analyzer.

2. The experimental data and simulations

With the help of the pick-up electrode in the linear center of the trap we have proved trapping for tens of milliseconds in the case of a variety of high charge states of O, Ar, Kr and Xe ions (up to O$^{5+}$, Ar$^{13+}$, Kr$^{21+}$ and Xe$^{20+}$). Using a low (< 20V) radio frequency voltage with frequencies close to the oscillation frequency of the ions in the trap we were able to observe trapping times up to 50 ms. Running the ion trap in the so called “bunching” or synchronization mode [6] in the time domain of the pickup signal we observed a strange oscillation on the millisecond scale superposing the ion oscillation in the trap on the microsecond scale. This is shown in Fig. 3 for
Figure 2. The schematic view and a photography of the electrostatic trap at the Laboratoire Kastler Brossel.

Figure 3. Data from the pick-up electrode, for \( \text{Ar}^{8+} \) trapping, on the ms time scale (green), a zoom on the \( \mu \)s time scale (yellow) and FFT of the 20 ms range of data from pick up (pink).

Our goal is to explain the observed oscillations with computer simulations. We mainly use two types of simulations for this purpose. The first one is based on the 1D model by Pedersen et al [7] where behavior of a test ion close to a bunch of ions in the trap is investigated. The estimate for the bunch size dynamics can be obtained from observing variation of the distance between the test ion and the ion cloud as function of time. This is shown in Fig. 4 where millisecond scale oscillation of the bunch size is clearly visible. This could in principle be considered as a possible reason for the observed oscillations in the experiment because the change in the bunch size could affect the pickup signal. In addition to the 1D model, we are developing an N-particle 3D simulation code where we include the interaction between the ions fully and observe dynamics...
of all the particles in the potential of the trap. First results of this simulation are shown in fig 4. Here, we show that if there is a slight misalignment during the injection of the ion beam in the trap, the radial velocity given to the bunch leads to radial oscillations of the packet. These radial oscillations could perturb the signal on the pickup as well because it depends on the distance from the ions. Further checks for various effects and consistency are underway. After successfully trapping highly-charged ions, we plan, as a next step, to utilize the ion trap for measurement of the life times of metastable states in highly charged ions.

![Figure 4](image-url)

**Figure 4.** Top: 1D simulation showing variation of the distance between the test ion and the ion cloud as function of time (bunch-size dynamics); Bottom: N-particle 3D simulation of the bunch radial position as function of time.

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