A tandem linear Paul trap as an ion source

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Abstract. Argon ions were produced by electron impact ionization in a linear Paul trap and confined there directly. The ions with a specific charge state (Ar$^+$ and Ar$^{2+}$ in this report) were successfully extracted as a pulsed beam by using another linear Paul trap as a mass filter. In principle, this technique is applicable for various highly charged ions generated and trapped in an ion source. The tandem linear Paul trap described here can also be employed, with the help of laser cooling, to produce nano-ion beams.

1. Introduction
Linear Paul traps have been widely employed nowadays for various purposes. For example, they work as a compact mass spectrometer. Applying the laser cooling technique, we can study frequency standards [1] and quantum computations [2] with ultra-cold ion ensembles in a Paul trap. It is also possible to use those confined one-component plasmas for the experimental study of charged-particle beam dynamics because the beam motion is physically almost equivalent to the plasma motion [3, 4].

Some techniques were previously reported of confining highly charged ions in a Kingdon trap [5] and a Penning trap [6]. It was also demonstrated that Ne$q^+$ ($3 \leq q \leq 8$) ions could be confined in a Paul trap [7]. Among these ion traps, a linear Paul trap is relatively advantageous to extract a particular ion species with a particular charge state. In comparison with other types of ion sources, such as electron cyclotron resonance ion sources (ECRIS) and electron beam ion sources (EBIS, EBIT), the present tandem linear Paul trap (TLPT) is quite compact and inexpensive. Neither intense magnetic fields nor microwaves are necessary to produce ions in TLPT, therefore it can be useful in many practical applications where a high ion current is not required.

In the following, we report on the application of TLPT as a highly charged ion source. Ar ions were employed to explore the basic properties of TLPT experimentally. The obtained data are compared with a rough estimate from the rate equation. Ca$^+$ ions were also confined in another linear Paul trap to make Coulomb crystals for nano-beam generation.

2. Experimental setup
A schematic diagram of TLPT is shown in Fig.1(a). This apparatus is basically the same as the one used in the previous study of resonant plasma instability [8, 9]. As illustrated in Fig.1, each electrode rod is axially divided into three pieces. The three sets of quadrupoles, which we call Ion Source (IS), Gate, and Experiment Region (ER), are electrically isolated, so that we can manipulate the plasma with various AC and DC voltages. By biasing the central Gate...
Figure 1. (a) A schematic diagram of a tandem linear Paul trap. (b) Stability boundaries for Ar\textsuperscript{q+} (1 ≤ q ≤ 3) and ionized residual gas (N\textsubscript{2}\textsuperscript{+} : red line and H\textsubscript{2}O\textsuperscript{+} : orange line) at the radio frequency Ω/2π of 1 MHz. The solid circle (blue) indicates the operating point of IS where both Ar\textsuperscript{+} and Ar\textsuperscript{2+} can be confined. The solid triangle (red) and square (green) correspond to the operating points of ER to extract Ar\textsuperscript{+} or Ar\textsuperscript{2+}.

Electrodes, it is possible to separate IS from ER. All electrodes have the diameter of 11.5 mm and are placed 5 mm apart from the trap axis. The axial lengths of IS, Gate, and ER are L\textsubscript{IS} = 5 cm, L\textsubscript{G} = 1 cm, and L\textsubscript{ER} = 10 cm, respectively. The typical vacuum pressure is 1.5 × 10\textsuperscript{-7} Pa. When we introduce an Ar gas into the chamber, the vacuum is worsened to 5 × 10\textsuperscript{-5} Pa corresponding to the Ar density of n\textsubscript{0} ∼ 1.3 × 10\textsuperscript{10} cm\textsuperscript{-3}. Then, an electron beam is injected into IS to ionize Ar atoms. The typical energy of the electrons is 135 eV (i.e., average velocity v\textsubscript{e} ∼ 6.8 × 10\textsuperscript{8} cm/s), which is capable of producing Ar\textsuperscript{6+}. The electron beam current, measured by a Faraday cup placed under IS, was kept at about 6 µA.

Radial confinement of ions in the trap is accomplished by sinusoidal RF voltages of the form ±(U + V cos Ωt), where U and V represent the constant bias and the RF amplitude, respectively, and Ω is the RF frequency. Not only V but also the bias U are necessary to select specific ion species [10]. When we choose Ω/2π to be 1 MHz, the stability regions of various ion species are changed as shown in Fig.1(b). The RF amplitudes of the IS and Gate were fixed at V\textsubscript{IS} = V\textsubscript{G} = 35.6 V. The corresponding operating point is indicated by the solid circle in Fig.1(b), where we can confine both Ar\textsuperscript{+} and Ar\textsuperscript{2+}. The end plate □ Cap A □ and Gate electrodes were biased at φ\textsubscript{capA} = φ\textsubscript{G} = 6 V in order to achieve axial confinement of ions in IS. In addition, we biased the IS electrodes to φ\textsubscript{IS} ∼ 2.5 V for axially accelerating ions toward the Faraday cup. After a short accumulation of ions in IS, the bias voltage φ\textsubscript{G} on the Gate electrodes is switched off to release the ions. They are then filtered in ER, depending on their charge states, and finally detected by a Faraday cup. The RF amplitude and bias voltage of ER were set at V\textsubscript{ER} = 70 V and U\textsubscript{ER} = 0 V for Ar\textsuperscript{+} extraction while V\textsubscript{ER} = 35.6 V and U\textsubscript{ER} = 5 V to obtain Ar\textsuperscript{2+} ions. These operating points are also shown in Fig.1(b) with the solid triangle and square, respectively.

3. Results and discussions

After a certain period of ionization time (t\textsubscript{i}), we shut down the electron beam and confine produced ions for a certain period (t\textsubscript{c}) in IS. Then, the ions are released toward the Faraday cup by switching off the bias φ\textsubscript{G}. Fig.2(a) shows the number of measured Ar\textsuperscript{q+} (q = 1,2) ions plotted as a function of t\textsubscript{i}. We see that the number of Ar\textsuperscript{+} ions (N\textsubscript{Ar+}) and that of Ar\textsuperscript{2+} ions (N\textsubscript{Ar2+}) have reached about 6 × 10\textsuperscript{6} and 6 × 10\textsuperscript{4}, respectively, when the ionization time is sufficiently long. In both cases, the number of ions rapidly increases with t\textsubscript{i} and comes to a plateau after t\textsubscript{i} > 2 s.

The lifetime τ\textsubscript{q} of a confined plasma can be measured by changing t\textsubscript{c}. The number of Ar ions that survive after a specific confinement period is plotted in Fig.2(b) where the ionization time
has now been fixed at $t_i \sim 6$ sec. The solid squares and the circles correspond to measurement data of Ar$^+$ and Ar$^{2+}$, respectively. We recognize that in the case of Ar$^+$, the ion loss somewhat slows down in the region $t_c > 300$ ms where the plasma confinement is limited mainly by collisions with residual gas atoms and RF heating [11]. The cause of the fast ion loss is suspected that it is due to the loss of trapped higher temperature ions which are created in the peripheral region around the electrodes. According to exponential fittings of these results, i.e. the solid lines in the figure, the lifetimes of the Ar plasmas under the present experimental conditions are about 300 ms for Ar$^+$ and 65 ms for Ar$^{2+}$. The lifetime of the Ar$^{2+}$ plasma is considerably shorter than that of Ar$^+$, which is probably due to charge exchange collisions with the Ar gas.

If we can assume that the neutral gas was ionized only by collisions with electrons, the density $n_q$ of Ar$q^+$ ions in IS can be estimated from the rate equations

$$\begin{align*}
\frac{dn_1}{dt} &= \frac{j}{e} \left( n_0 \sigma_0 - n_1 \sigma_1 \right) - \frac{n_1}{\tau_1} \\
\frac{dn_2}{dt} &= \frac{j}{e} \left( n_0 \sigma_0' - n_2 \sigma_2 \right) - \frac{n_2}{\tau_2}
\end{align*}$$

where $j$ is the current density of electrons, $e$ is the elementary charge, $\sigma_q$ represents the cross section to generate Ar$(q+1)^+$ by electron impact on Ar$q^+$, and $\sigma_q'$ is the cross section of multiple ionization that produces an Ar$q^+$ ion from an Ar atom. These cross sections are about $\sigma_0 \sim 2.7 \times 10^{-16}$, $\sigma_1 \sim 6.5 \times 10^{-17}$, $\sigma_2 \sim 3.6 \times 10^{-17}$, and $\sigma_0' \sim 1.8 \times 10^{-17}$ cm$^2$ according to Refs.[12, 13]. In the equilibrium state after $t_i \sim 2$ sec, the left hand side of the rate equations becomes zero. The ion densities are estimated to be $n_1 = 3 \times 10^7$ and $n_2 = 4 \times 10^5$ cm$^{-3}$. According to past experimental results [14], the radial extent of an Ar plasma is typically about 2 mm in diameter. Assuming that the ion distribution is roughly uniform, the calculated number of Ar$^+$ and Ar$^{2+}$ ions agrees fairly well with the observed number.

Assuming that the lifetime of Ar$^{3+}$ ions is equal to that of Ar$^{2+}$ in a proper operating point, $N_{Ar^{3+}}$ in IS is estimated to be $1.5 \times 10^3$. However, Ar$^{3+}$ ions were not detected with a simple Faraday cup and an amplifier at the moment. Therefore, a multi-channel plate will be installed to confirm production of Ar ions in higher charge states.

The TLPT system can also be a good candidate for an ultra-low emittance ion beam source because it is straightforward to reduce the temperature of an ion plasma to near the absolute zero by employing the laser cooling technique. As is well-known, laser cooled ions eventually
form an ordered configuration referred to as a Coulomb crystal. Laser-induced fluorescence signals from Coulomb crystals generated in one of our Paul traps are depicted in Fig.3 where each bright dot represents a $^{40}\text{Ca}^{+}$ ion. Various crystalline structures can be formed depending on the line densities of ion plasmas. As pointed out previously [15], it is theoretically possible to extract a linear Coulomb crystal of nano-meter spot size. Additionally, the crystal can be accelerated without major heating. Note also that we can sympathetically cool various highly charged ions with an ultra-cold $\text{Ca}^{+}$ plasma in TLPT. The precise measurement of cold highly charged ions will be made easier with the use of a tandem linear Paul trap.

4. Conclusion

$6 \times 10^4 \text{Ar}^+$ ions and $6 \times 10^4 \text{Ar}^{2+}$ ions were successfully produced within a few seconds in TLPT and extracted as a pulsed beam of particular charge state. The obtained results are well explained by the rate equations. In addition to the Ar ions, other ion species with higher charge states will probably be obtainable although the possible current is limited. Therefore the TLPT system is useful as HCI source of table-top-size. The system can also be a nano-ion beam source with the use of the laser cooling technique.

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