

Investigation of Ne and He Buffer Gases Cooled Ar⁺ Ion Clouds in a Paul Ion Trap

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Abstract : In this article, we examine the influences of Ne and He buffer gases under confined Ar⁺ ion cloud in a homemade Paul ion trap in various pressures and confinement times. The trap is of small size ($r_0 = 1$ cm) operating in a radio frequency (rf) voltage only mode, and has limited accuracy of 13 V. The electron impact and ionization process take place inside the trap and a Faraday cup has been used for the detection. Although the experimental results show that the Ar⁺ ion FWHM with Ne buffer gas is wider than the He buffer gas at the same pressure (1×10^{-1} mbar) and confinement time is about 1000 μ s, nevertheless, a faster cooling was found with He buffer gas with 500 μ s. ultimately, the obtained results performed an average cloud temperatures reduced from 1777 K to 448.3 K for Ne (1000 μ s) and from 1787.9 K to 469.4 K for He (500 μ s)

Keywords : Paul ion trap, rf only mode, impact electron ionization technique, buffer gas cooling ions.

Introduction

The confinement of ions in a quadrupole Paul ion traps are well known process and has outstanding applications in sciences and technology.¹⁻⁴ Since the Paul ion trap was employed as a mass spectrometer, cooling (damping) process has become very important as successful damping improves the sensitivity and resolution of the ion trap performance.⁵⁻⁸ As we deal with the confinement of a non-neutral plasma in a Paul ion trap, buffer gas cooling becomes significant.⁹

Theoretically, the damping force F is assumed to be proportional to the velocity v of the confined ion such as $F = -m\gamma v$, where m denotes the ion mass, and γ depends on the mobility of particular gas and has unit of s^{-1} . In general, for non-energetic confined ion (up to few eV) the mobility is approximately constant.¹⁰ Under the damping force, the Mathieu differential equations¹¹ should be modified and in the u direction, r or z , may be written;

$$\frac{\partial^2 u(\xi)}{\partial \xi^2} + 2C \frac{\partial u(\xi)}{\partial \xi} + (a_u - 2q_u \cos(2\xi))u(\xi) = 0$$

and the stability parameters a_u , and q_u are defined

$$a_z \frac{-4eU}{mz_0^2 \Omega^2} = -2a_r, \quad q_z \frac{-2eV_{0 \rightarrow p}}{mz_0^2 \Omega^2} = -2q_r$$

and $2\xi = \Omega t$, where $\Omega = 2\pi f$ is radio-frequency (rf). At low buffer gas pressure down to 10^{-4} mbar, the ratio $c = \gamma/\Omega = 1$.

The influence of damping force on the ion motion has been studied using two q_z values, $q_z = 0.45$ and $q_z = 0.908$; one is near the adiabatic region and other is at the limited of the stability diagram. However, for Ar⁺ ion of mass $m = 40$ amu and $f = 650$ kHz, the corresponding rf voltages will be $V_{rf} = 77$ V, and $V_{rf} = 156$ V, respectively. Figure 1 shows the obtained numerical computations for the initial ion displacement of $z(\xi_0) = 1$ mm, and a damping time of 200 μ s. The Figure shows a very strong shift in the damping time as the q_z value moves to the stability limits (e.g. 0.908). This can be attributed to the energetic ion.

The existence of the buffer gas in the Paul ion trap causes the ion cloud to move to the central region of Paul ion trap and increase in the ion signal detections. The purpose of this work is to show experimentally the effect of cooling (damping) ions with buffer gases in a homemade Paul ion trap. All components of the trap including the rf generator, the electron gun, trap electrodes, the detection system and timing system are made in our Lab.

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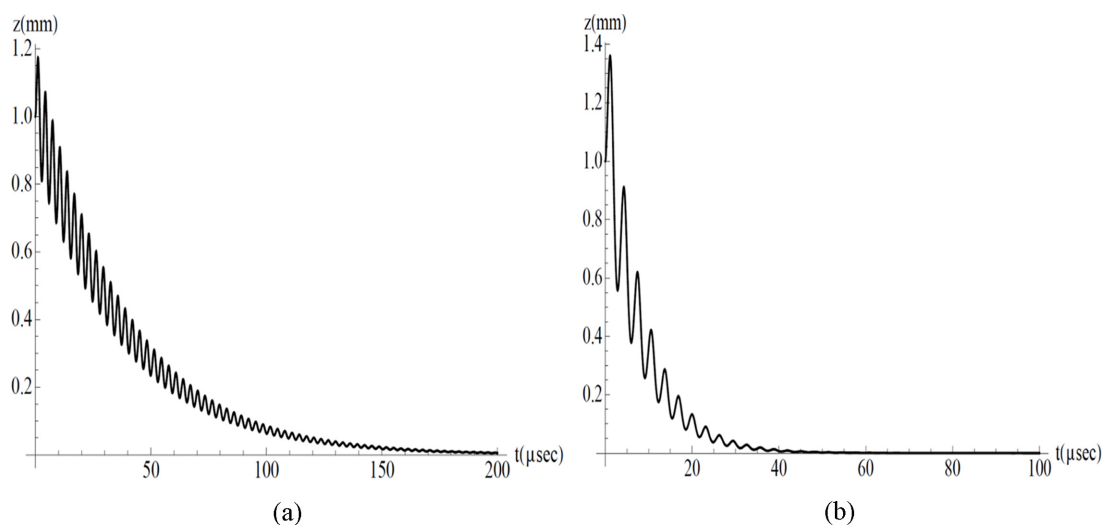


Figure 1. The confined 40Ar^+ ion damping displacement as a function of damping time; (a) $q_z = 0.45$, with $V_{rf} = 77$ V, and (b) $q_z = 0.908$, with $V_{rf} = 156$ V, and $f = 650$ kHz. The initial displacement $z(\xi_0) = 1$ mm, $C = 1$, and $a_z = 0$.

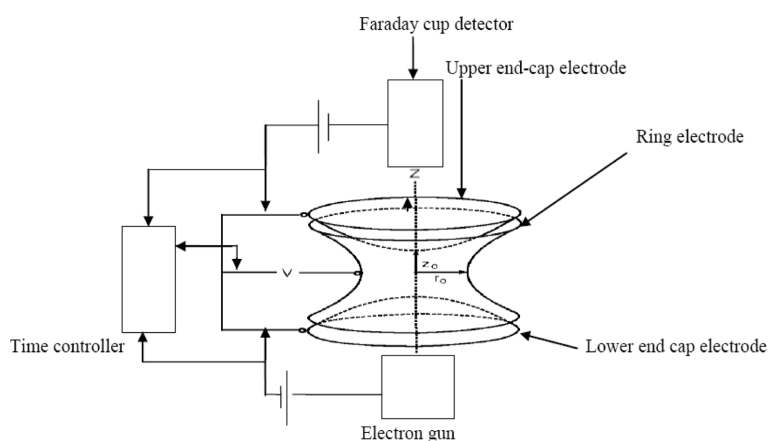


Figure 2. A schematic diagram of experimental set up.

Experimental Methods

The Paul ion trap electrodes are made of stainless steel 316, Figure 2. The $z_0 = 0.707$ cm is one-half of the shortest separation of the endcap electrodes, and $r_0 = 1$ cm is the ring electrode radius. The ring electrode has three meshes of 9 holes, each 0.1 mm in diameter and placed around circle in which 120 degrees are apart for gas entrance. The gas flowed through three small stainless steel tubes, 0.5 mm in diameter, puff through the meshes in to the ionization volume. This situation effectively provides a better ionization efficiency.

The lower and upper end-cap electrodes have 6 small holes, each 0.1 mm in diameter pass the electrons into the ionization volume and then ions get through the detector, respectively, see Figure 3. The ion trap geometry is stretched hyperbolically to have higher confinement efficiency. The truncation of the electrodes has been made at $3r_0$. Therefore, the relationship

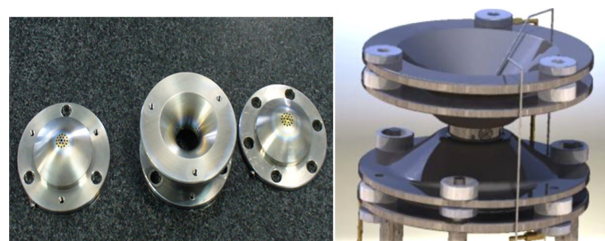


Figure 3. A ring and two hyperbolic end-cap electrodes of a Paul ion trap up.

$r_0^2 = 2z_0^2$ will be true for $3r_0$ with 2.8% error.

The trap is set up in a vacuum chamber of volume 0.0147 m³ and pumped with a turbo-pack up to pressure 10^{-5} mbar. The rf voltage is connected to the ring and end-cap electrodes in the mass-selective instability mode. An electron gun supplied the flow of the electrons is situated below the lower end-cap electrode. The Tungsten filament

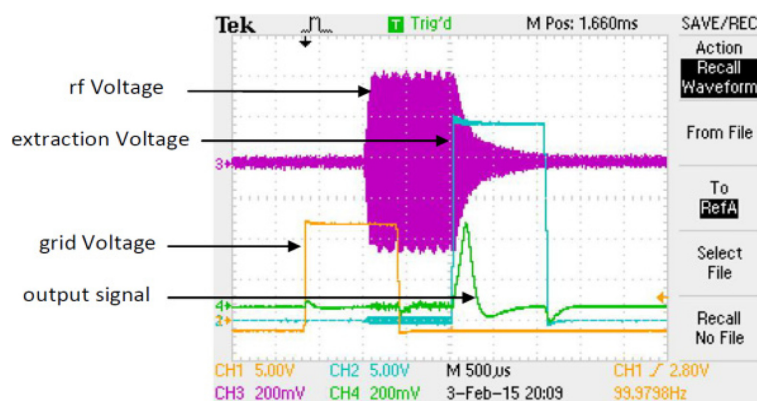


Figure 4. A typical confined Ar^+ ions signal with rf voltage, electron acceleration (grid voltage), and extraction voltage.

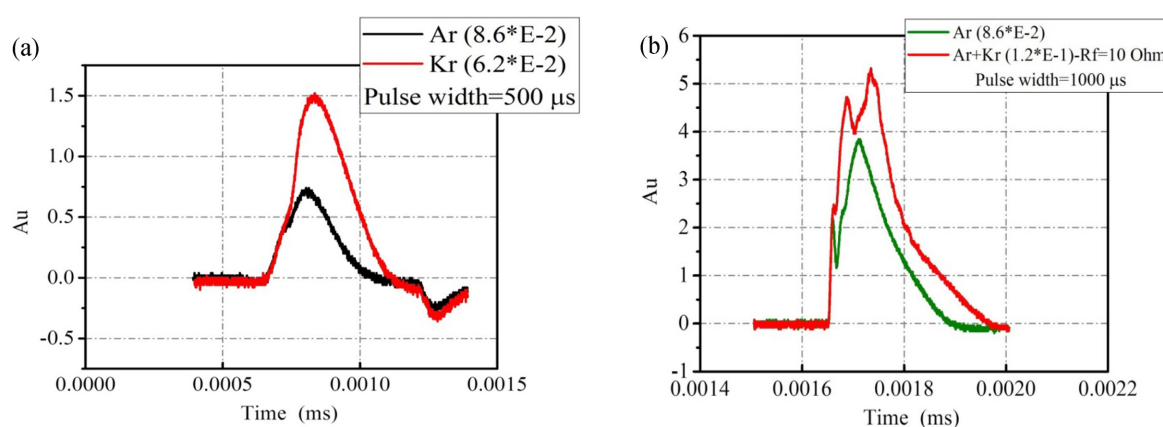


Figure 5. Buffer gas He cooled Ar^+ , and Kr^+ ion signals, (a) scanned separately, (b) a mixed scanned.

uses 0.46 A, and 9 V and a constant current circuit generates a constant follow of electrons. The acceleration of electron is made by -110V with respect to lower end-cap electrode. The ejection voltage applied between Faraday-cup and the upper end cap is up to -300 V, chosen in a way that during ejection phase ions sees fairly same voltage.

The variable time delay of the duty cycle depends on the experiments. Here, a delay time of 50-1000 μs is used in the experiments. The rf voltage can produce up to 350 V0 \rightarrow p (zero to pick) with 650 kHz and more. It is important to indicate that the times; electron acceleration time, the time of confinement and the ejection times can be adjusted through a 10 canals circuit with LVTTTL controled by Labview program. The output signals from the detector can be visualized and memorized by oscilloscope providing 2500 data on the Excel software can be used for Origin-pro software.

Figure 4. displays a typical Ar^+ ion together with rf signals, electron accelerations voltage (grid voltage), and ejection voltage, respectively. The ion signal depends on some parameters including the ejection time and voltage amplitude.

For a more comprehensive ions signal, one should trigger the ejection voltage, whenever, the rf confinement voltage is nearly stopped, see figure 4.

Results and discussion

Shown in Figure 5 is a He buffer gas cooled ion scanned signals; (a) separated Ar^+ , Kr^+ and (b) a mixed Ar^+ + Kr^+ scanned, respectively. As seen, at separately scanned masses, one easily obtains ion trapping and an acceptable signal. At mixed scanned, one observes a low resolution, caused by Paul ion trap rf voltage accuracy (13 V), which the limit of stability diagram of ions might be missed for ejection.

Some experiments with the goals of comparing He and Ne buffer gases cooled Ar^+ ions are carried out. Shown in Figure 6 (a) and (b) is a signal from Ar^+ cooled by a He buffer gas.

At 500 μs time of confinement, one easily obtains fast cooling; while, at higher 1000 μs time of confinement one observes the amplified Ar^+ ion signal. These amplifications can be due to Ar^+ ion reorganization towards the trap center.

At the pressure of 7.4×10^{-2} mbar, and a time of confinement of 500 μs , the average Ar^+ ion cloud temperature 1787.9 K, using the relationship $\frac{1}{2}mv^2 = \frac{3}{2}kT$ is calculated, where v is ion velocity, k is Boltzman constant. At the mixed He with Ar^+ pressure of 1×10^{-1} mbar, the average ion cloud temperature reduces to 469.4 K.

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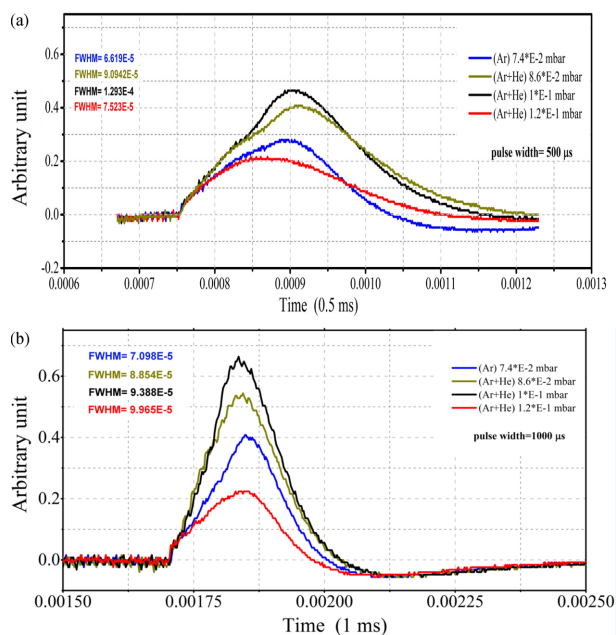


Figure 6. The He buffer gas cooled Ar⁺ ion signals at different pressures and confinement times (a) 500 μs, and (b) 1000 μs.

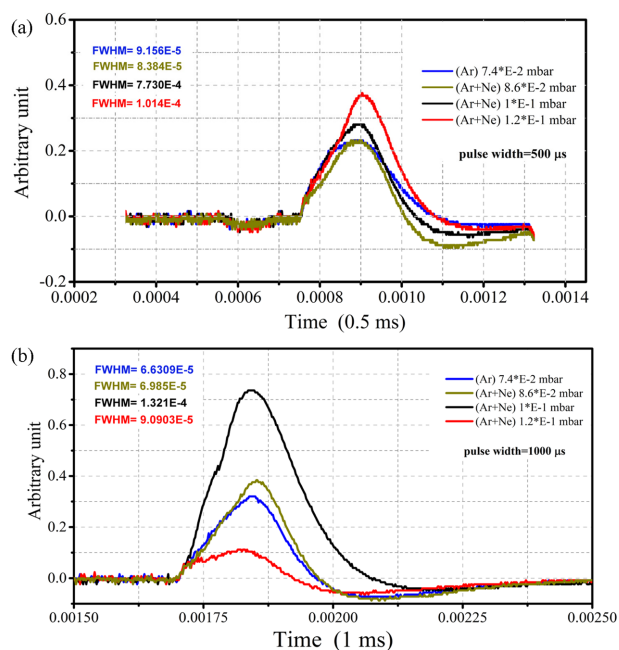


Figure 7. The Ne buffer gas cooled Ar⁺ ion signals at different pressures and confinement times (a) 500 μs, and (b) 1000 μs.

The same experiment is carried out with Ar⁺ ions cooling with heavier Ne buffer gas at 1000 μs confinement time. The acquired results are depicted in Figure 7 (a) and (b). Here, for Ar⁺ ions pressure of 7.4×10^{-2} mbar, the average ion cloud temperature is 1774 K and alternatively, for the mixed Ar⁺ + He pressure of 1×10^{-1} mbar, the average cloud temperature reduces to 448.3 K.

Conclusion

The observation of the results for Ne cooling buffer gas can quantitatively be understood, as Ne has a heavier mass than the He buffer gas, a better ion signal is obtained; the longer time of confinement, the higher number of collisions occurs, so a better damping will arise. He is a good buffer gas for a fast cooling process, tens of μs confinement time, nevertheless, for a good quality signal, one should consider a higher confinement time for ions to reorganize themselves toward the trap center. Finally, the experimental results for the mixed gases acquire low resolution due to lower precision in rf voltage, i.e. a minimum of 13 V. However, satisfactory results were found for the scanned signals of the sample, the damping process can be done successfully.

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