Journal of the Physical Society of Japan
Vol. 68, No. 12, December, 1999, pp. 3763-3765

Pulsed Evaporative Cooling for Trapped Highly Charged Ions

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(Received July 26, 1999)

We propose the application of pulsed evaporative cooling, which has been used successfully for Bose-Einstein condensation of neutral atoms, to highly charged ions. Practically, this cooling technique can be highly efficient and favorable for ions in an electron beam ion trap (EBIT). By computer simulation, we have numerically estimated the performance of this cooling scheme on the basis of the standard evaporation theory. The result is very promising; from the initial temperature of 500 eV, Kr^{+30} can be cooled to room temperature within a few seconds.

KEYWORDS: highly charged ion, evaporative cooling, electron beam ion trap

For the Bose-Einstein condensation of trapped atoms,[1-3] evaporative cooling[4] is an essential technique; one can expect several orders of decrease both in the temperature and the phase-space volume within a short time, which has never been achieved with other cooling methods. The present work is originally motivated by a naive question, "Is this cooling mechanism also valid for charged particles which are overflowing from electromagnetic ion traps via evaporation?"

For charged particles, the evaporation process should exhibit unique characteristics at low temperatures. Due to the long-range nature of the Coulomb interaction, the collision rate increases without limit as the temperature decreases; therefore the evaporation should be accelerated. Furthermore, we can safely ignore the undesirable inelastic collisions, the contribution of which decreases at lower temperatures. With respect to the charged-particle kinetics, therefore, evaporation via Coulomb force is interesting.

Concerning the experimental feasibility and practicality, the evaporation time appears to be formidably long for singly charged ions, judging from a crude order estimation. However, the situation seems very favorable for highly charged ions; the evaporation of ions having the charge number Z=30 should be enhanced by a factor of $30^4 \approx 10^6$, compared with singly charged ions (See eqs. (4) and (5)). This suggests a great practical advantage because there has been no easy way to cool highly charged ions. To obtain a cold U^{+92} ion, the most reliable method at present is considered to be the combined use of decelerators, an electron cooler and a resistive cooler.[5] By cooling highly charged ions, it will be possible to carry out the high-precision spectroscopy, as well as high-brightness and low-energy beam experiments. Compared with the above method, our idea is by far simpler and less expensive. Due to these possible advantages, even an order estimation of evaporative cooling via Coulomb collisions is of use and interest. In this note, we report numerical estimations based on scaling relationships and computer simulations, the results of which are very encouraging.

Specifically, the authors are aiming at the application to the ions produced and confined in an electron beam ion trap (EBIT).[6-8] This will be readily realized simply by lowering the electrostatic potential for trapping ions, thereby, controlling the evaporation rate. Actually, for an EBIT, the steady-state evaporation of lowly charged ions is already employed for cooling highly charged ions.[9] To distinguish our idea from this steady-state scheme, we call it pulsed evaporative cooling (PEC) throughout this note.

For the computer simulation, we introduce the model shown in Fig. 1. In our model, we consider only the axial escape of ions in a square-well electrostatic potential, and the charge $+Ze$ is assumed to be the same for the ions. For this virtual ensemble of highly charged ions, the flows of energy and ions are calculated using the rate equations, which is based on the conventional plasma-dynamical treatment[8,9] of the production and the confinement of highly-charged ions in an EBIT.

This is somewhat of a simplification of a real EBIT, but is still useful for two reasons. First, our main concern is the order estimation of the phenomena in general, not a detailed description of a too specific example. Second, what we really need is to formulate some 'guiding' principle, in a form of scaling relations between various quantities, so as to plan a successful cooling experiment.

Furthermore, we present only the simplest example; the electron beam is turned off at the beginning of the cooling process. Therefore, the heating of ions by the electron beam is completely ignored. However, this beam-off requirement is not essential for PEC with an EBIT. In fact, we have also obtained hopeful estimations even with electron-beam heating, which is briefly mentioned later.

Our numerical treatment is also in accordance with the standard evaporation theory[4] for Bose-Einstein condensation. In that theory, the most important factor for con-

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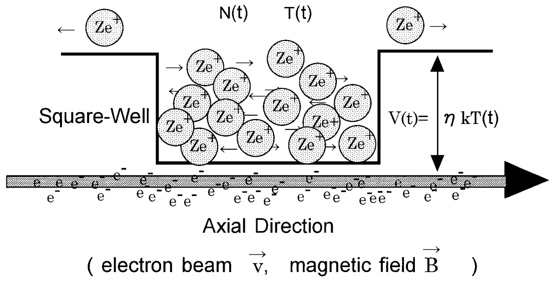

Fig. 1. Axial-escape and same charge-state model of pulsed evaporative cooling for highly charged ions in an EBIT.

trolling the cooling process is the truncation parameter η, namely, the ratio of the depth $V(t)$ of the axial-trapping potential to the thermal energy $kT(t)$ of trapped ions.

Specifically, the rate equations to describe the time evolution of the temperature $T(t)$ and the number $N(t)$ of ions remaining in the trap are, respectively,

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\frac{N}{\tau_{ev}}, \tag{1}$$

$$\frac{\mathrm{d}T}{\mathrm{d}t} = -\alpha\frac{T}{\tau_{ev}}, \tag{2}$$

where τ_{ev} is the time constant of evaporation, practically, the storage time in an EBIT, and α is a dimensionless parameter related to the energy balance;

$$\begin{aligned}\alpha &= \frac{\text{(the average energy of an escaping ion)}}{\text{(the average energy of a trapped ion)}} - 1\\ &= \frac{2}{3}\eta + \frac{1}{3}.\end{aligned} \tag{3}$$

The last line is the specific expression recommended for a one-dimensional axial trap, according to the equipartition law of thermodynamics. In fact, the efficiency of PEC is significantly enhanced even with only a slight increase of α; if α is constant in eq. (2), we find that $T \propto N^{\alpha}$. *For the better cooling performance, therefore, α (and η) should be kept as large as possible throughout the cooling process.*

However, if η is too large, the evaporation must take longer as fast particles are rarely produced by collisions. This is quantitatively shown by another dimensionless parameter λ, namely, the ratio of τ_{ev} to the relaxation time τ_{col} of the ion-ion collisions:

$$\begin{aligned}\lambda &= \tau_{ev}/\tau_{col}\\ &= \frac{\sqrt{2}}{3}\eta\ \exp(\eta).\end{aligned} \tag{4}$$

The last line in eq. (4), which is valid for $\lambda > 1$, is the specific expression for a one-dimensional axial trap, which results from the diffusive flux due to the Coulombic friction force.[8] For self-collisions,[10] the relaxation time is

$$\tau_{col} = \frac{6\sqrt{2}\pi^{3/2}\epsilon_0^2 M^{1/2}(kT)^{3/2}}{n(Ze)^4 \ln\Lambda}, \tag{5}$$

where ϵ_0 is the permittivity of free space, M is the mass of the ion, n is the number density of ions and $\ln\Lambda$ is the Coulomb logarithm. The evaporation time thus increases exponentially with η, which results inevitably from the principle of detailed balance.[4] *Eventually we need a trade-off between the cooling efficiency and the evaporation time,* which should be settled by the numerical integration of eqs. (1) and (2).

For the present simulation, we use the parameters listed in Table I, which represent a realistic operation of an EBIT.[8] Throughout the integration, $\eta = 4$. This is imposed to simplify the analysis of the numerical results; we automatically have $T \propto N^3$ and $V(t)$ is exactly proportional to $T(t)$. A typical result is shown in Fig. 2. The temperature decreases with almost a linear slope, which almost finishes at around $t = 1.3$ seconds. For the $N = 390$ remaining ions, the temperature reaches 30 meV. In contrast to the evaporation of neutral atoms, the escape of ions from the trap is thus accelerated toward the final phase of the evaporation. Without this distinct acceleration, the evaporation would take a formidably long time. On the contrary, when the decrease in the trap potential is too rapid, however, our numerical results also showed that most of the ions would escape the trap before a significant decrease in the temperature; once the truncation parameter η becomes too small during the cooling process, many low-energy ions are released from the trap without cooling the remaining ones.

Indeed this final burst of the evaporation is readily expected from eqs. (4) and (5);

$$\tau_{ev} = \lambda\tau_{col} \propto N^{-1}T^{3/2} \propto N^{3.5}, \tag{6}$$

if the radius $R(t)$ of the ion cloud is assumed to be constant at the final phase of evaporation. This assumption is justified by the numerical result shown in Fig. 3. Since the electron beam is turned off, there is no restoring force in the radial direction and the ion cloud should expand by collisions. (Actually the expansion by the ionic space-charge is negligible for the small number of ions considered here because the bending force by a few-Tesla magnetic field of an EBIT is much stronger.) Specifically, Fig. 3 is a numerical outcome based on the nonlinear diffusion theory,[11] the details of which will be published elsewhere. In a phenomenological manner, this theoretical result agrees well with the experimental observations;[12] the ion cloud shows some abrupt expansion immediately after the switch-off time but a majority of the ions still remain in the trap for several seconds. It is certain that a burst of the evaporation will happen in the end, even though the ion cloud is expanded as large as 1 mm in diameter. Since $R(t)$ is almost constant, the bursting bahavior is well described with our model. For Fig. 2, we have also considered the slowing-down of the evaporation due to the decreasing mean free path of escaping ions but the temperature continues to decrease significantly.

Even with the electron-beam heating, it is found from our numerical result, that PEC seems to work effectively up to temperatures as low as 1 eV. This success is attributed to the radial confinement of the ion cloud by the electronic space charge. At any rate, we have the freedom to choose the time for turning off the beam. Until this switch-off timing, the spatial expansion of the ion cloud can be delayed and so there is still a significant room for improving the cooling efficiency. Further-

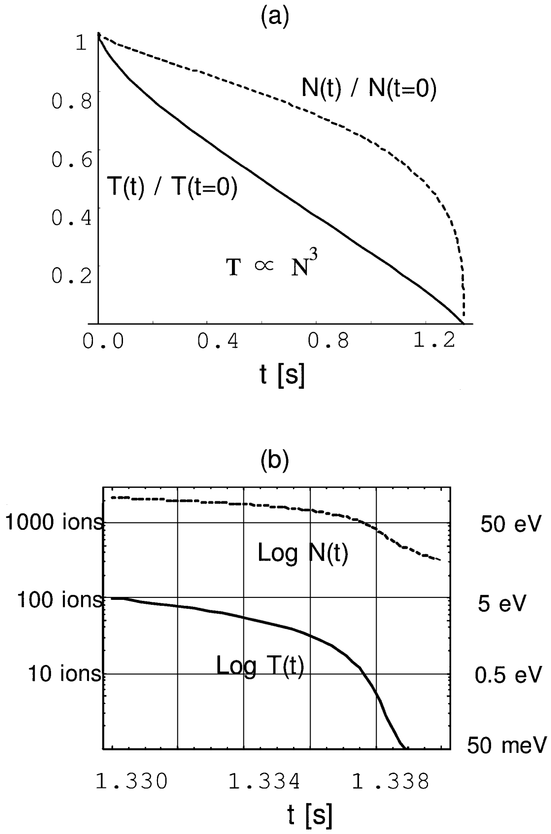

Fig. 2. Numerical result of the temperature $T(t)$ and the number $N(t)$ of ions remaining in the trap. (a) Plot for the entire cooling behavior. (b) Detail around the final phase of the evaporation.

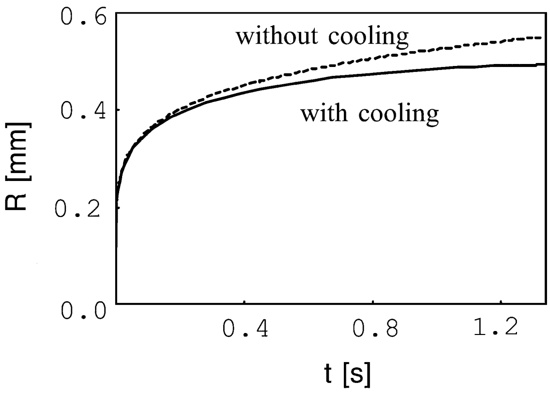

Fig. 3. Radius $R(t)$ of the ion cloud numerically obtained from the higher-order diffusion theory.

more, we ignored the extra cooling due to the evaporation of the lowly charged ions. So it is very likely that the present numerical result is an underestimation of the cooling phenomenon.

Using the Tokyo-EBIT,[13)] an experimental test is being prepared, with a computer-controlled voltage supply for decreasing the axial potential in a numerical manner.

The authors are grateful to the participants of the Eurotrap Workshop on Cooling of Highly Charged Ions in April 1999, for fruitful discussions.

Table I. Parameters used for the numerical computation.

Ion	Krypton	$Z = +30$
Initial Temperature	$kT(t=0)$	500 eV
Initial Number of Ions	$N(t=0)$	10^4
Initial Radius of Ion Cloud	$R(t=0)$	35 μm
Initial Relaxation Time	$\tau_{col}(t=0)$	0.3 msec
Coulomb Logarithm	$\ln\Lambda$	10
Truncation Parameter	$\eta = \frac{V(t)}{kT(t)}$	4
Trap Length	l	1 cm

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