



Simultaneous cooling of highly charged ions with electrons and positrons

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Abstract

A new scheme to effectively and quickly cool highly charged ions (HCIs) is presented. The key item is the combination of high density electron plasma and cold positron plasma, which enables to realize a quick cooling (~ 1 s) and at the same time the HCI loss due to recombination with electrons and residual gases is largely suppressed.

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1. Introduction

The positron cooling of HCIs is a reversed scheme of the electron cooling of antiprotons [1,2]. Charged particles in a strong magnetic field lose their kinetic energies via synchrotron radiation, the rate of which is inversely proportional

to the particle mass cubed, i.e. the rates for positrons and electrons are more than 10^{10} times faster than those of heavy particles like ions and antiprotons. Actually, only electrons and positrons can be cooled via synchrotron radiation within some reasonable time for a magnetic field available on earth. Heavy particles can accordingly be cooled sympathetically if they are stored simultaneously with electrons and/or positrons in a strong magnetic field. In principle, positrons are better than electrons because HCIs are not lost due to recombination during the cooling procedure. On the other hand, the number of electrons ($N_e \sim 10^9 - 10^{10}$) in a trap [3] can be practically a few orders

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of magnitude larger than the number of positrons ($N_p \sim 10^7\text{--}10^8$) [4], and the electron cooling scheme has a large advantage with respect to the cooling time and accordingly the loss due to recombination with residual gases.

In order to selectively pick up the favorable features of positrons and electrons and suppress disadvantages, a new scheme to cool HCIs is considered utilizing electrons and positrons simultaneously. Our simple evaluation showed that the required cooling time of ~ 10 keV/q HCIs with the new scheme could be 10 times faster than that by pure positron cooling, and therefore, the loss of HCIs due to recombination with residual gases can be reduced by one order of magnitude.

2. Numerical evaluation of pure positron cooling scheme

The cooling time of HCIs with positrons and loss probabilities of HCIs during the cooling due to collisions with residual gases is evaluated under the assumption that

- (1) positrons are stored in a 5 T magnetic field,
- (2) the trap (the environmental temperature) is at $T_0 = 1$ meV,
- (3) the residual gas density is $n_g \sim 10^5$ H₂ cm⁻³ ($\sim 10^{-10}$ Pa),
- (4) positrons and HCIs are trapped in a volume of ~ 0.1 cm⁻³ (10 cm × 0.1 cm × 0.1 cm) [3,5],
- (5) the number of stored positrons are $N_p \sim 10^7\text{--}10^8$,
- (6) $\sim 10^6$ Ne¹⁰⁺ or U⁹²⁺ ions ($N_i \sim 10^6$) are assumed as sample HCIs injected at ~ 10 keV/q in the trap [6].

The energy of an HCI during the positron cooling is evaluated by solving the following rate equations [7,8],

$$\begin{aligned} \frac{dT_i}{dt} &= -\frac{1}{\tau_{\text{eq}}} (T_i - T_p), \\ \frac{dT_p}{dt} &= \frac{N_i}{N_p} \frac{1}{\tau_{\text{eq}}} (T_i - T_p) - \frac{1}{\tau_s} (T_p - T_0), \end{aligned} \quad (1)$$

where T_i and T_p are the energies of the HCIs and positrons, $\tau_s \sim 0.2$ s is the time constant of the synchrotron radiation of positrons, and τ_{eq} is the time constant representing the coupling between HCIs and positrons, which is given by

$$\tau_{\text{eq}} = \frac{3\sqrt{2}\pi^{3/2}\epsilon_0^2 M m_p}{n_p q^2 e^4 L} \left(\frac{T_p}{m_p} + \frac{T_i}{M} \right)^{3/2}, \quad (2)$$

where L is the Coulomb logarithm [7,9], n_p the positron density, e the positron charge, ϵ_0 the permittivity of the vacuum, M the HCI mass, m_p the positron mass.

Fig. 1(a) shows the energy variations of Ne¹⁰⁺ (the dotted lines) and U⁹²⁺ (the solid lines) ions obtained by solving Eq. (1). HCIs can be cooled from ~ 10 keV/q down to ~ 0.1 eV/q within several second (several tens s) for $N_p = 10^8$ (10^7) positrons assuming HCIs are not lost due to collisions with residual gases. The fraction of HCIs lost due to charge transfer reactions with the residual H₂ gas ($n_g \sim 10^5$ cm⁻³) during cooling is calculated using the spherical absorption model [10,11], which is shown in Fig. 1(b). It is seen that a considerable fraction of the HCIs is lost during cooling. If the residual gas density can be reduced one more order, i.e. $n_g \sim 10^4$ cm⁻³, the loss fraction can be kept at 10% level for $N_p = 10^8$, the vacuum condition of which is however rather difficult to achieve.

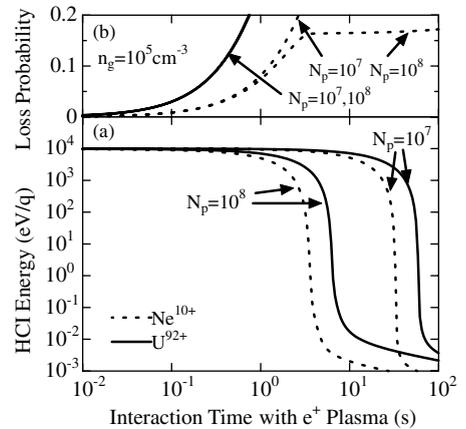


Fig. 1. (a) HCI (Ne¹⁰⁺ and U⁹²⁺) energies and (b) loss probability of HCIs as a function of the interaction time with positrons. HCI initial energies are 10 keV/q.

Table 1
Characteristics of the cooling methods applied for HCIs (see text)

Coolant	Required time for		Required vacuum for ~ 0.1 eV/q
	~ 1 eV/q	~ 0.1 eV/q	
$10^7 e^+$	~ 10 – 100 s	~ 10 – 100 s	$< 10^{-11}$ Pa
$10^8 e^+$	~ 1 – 10 s	~ 1 – 10 s	$< 10^{-10}$ Pa
$10^9 e^-$	~ 0.1 – 1 s	Impossible	
$10^{10} e^-$	~ 10 – 100 ms	Impossible	
$10^{11} e^-$	~ 1 – 10 ms	Impossible	
$10^9 e^-$ ($T_0 = 1$ eV)	~ 0.1 – 1 s	~ 1 s	$\sim 10^{-10}$ Pa
$10^7 e^+$ and $10^9 e^-$	~ 1 – 10 s	~ 1 – 10 s	$\sim 10^{-10}$ Pa
$10^8 e^+$ and $10^{10} e^-$	~ 0.1 – 1 s	~ 0.1 – 1 s	$< 10^{-9}$ Pa

Some characteristics parameters are summarized in Table 1.

It is noted that the charge transfer cross-section in the energy range in question is a weakly increasing function of energy, and accordingly the reaction rate is an increasing function of energy, i.e. it is essential to cool HCIs as quickly as possible to suppress the loss fraction.

3. Simultaneous cooling scheme of HCIs with electrons and positrons

When a large number of electrons are used together with positrons, the time necessary to cool HCIs is reduced drastically, which helps to suppress the HCI loss due to recombination with the residual gas. If then the cooling is taken over by positrons, the recombination loss with electrons can also be suppressed. Before discussing the details of this co-cooling scheme, let us consider how quickly HCIs are cooled in a large number of electrons and how quickly HCIs are lost due to the recombination with electrons.

Fig. 2(a) shows that the numerical solution of Eq. (1) for $N_e \sim 10^9$ – 10^{11} . The loss probabilities of HCIs during the electron cooling are shown in Fig. 2(b), where the charge transfer reaction with H_2 , and the radiative- and three body recombination processes with electrons are taken into account [12]. It is seen that (1) HCIs can be cooled down to ~ 1 eV/q within ~ 1 ms– 1 s with the loss fractions less than $\sim 10\%$ and (2) the loss fractions increase abruptly once the energy of HCIs gets less than ~ 1 eV/q or lower depending on the electron

density. The abrupt increases of the loss fractions can be attributed to three body recombination processes, which could be suppressed by heating the electron plasma temperature at certain level because this reaction rate strongly depends on the electron energy ($\propto T_e^{-4.5}$) [12]. Typical characteristics of the electron cooling are listed in the Table 1.

A possible procedure of the simultaneous cooling of HCIs with electrons and positrons is schematically drawn in Fig. 3(a) and (b): (a) HCIs are injected into a multi-ring trap (MRT) [13] and cooled down to ~ 1 eV/q in the electron plasma (10^9 – 10^{10}). (The procedure to prepare electron and positron plasmas are described elsewhere [3,5].) (b) HCIs are guided to the positron trapping region by opening the potential barrier between the electron and positron traps. If e.g. the positron

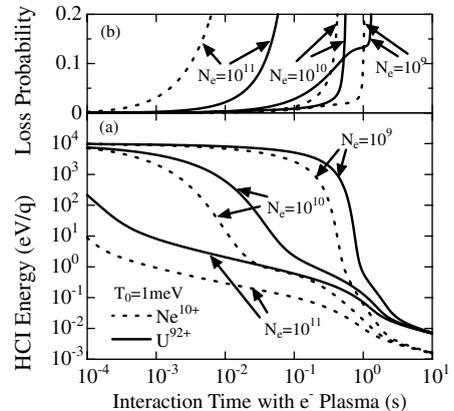


Fig. 2. (a) HCI (Ne^{10+} and U^{92+}) energies and (b) loss probability of HCIs as a function of the interaction time with electrons. HCI initial energies are 10 keV/q.

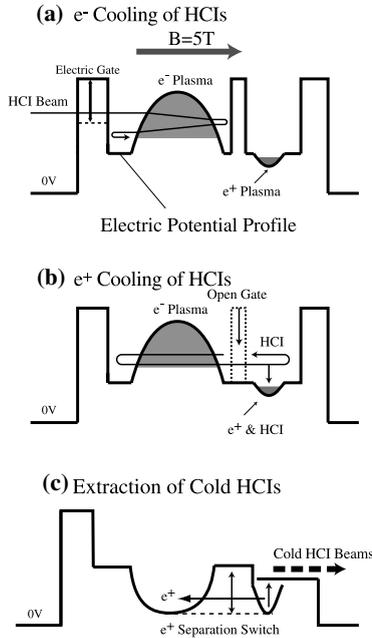


Fig. 3. (a–c) Schematic descriptions of the simultaneous cooling scheme of HCIs with electrons and positrons.

plasma potential is adjusted $\sim 10^2$ V lower than the electron plasma potential, HCIs can be injected into the positron plasma with energy of $\sim 10^2$ eV/q. A stopping power of HCIs in the positron plasma ($T_p \sim 1$ meV) is order of ~ 1 – 10 eV/q/m [9]. Therefore, after ~ 1 – 10 trips of the HCIs within the MRT, they lose more than ~ 1 eV/q in the positron plasma and finally accumulate into the positron well, hence, they are separated from the electron plasma completely. In this picture, after the opening the electric gate between the electron and positron plasma, HCIs continue interaction with electron plasma for ~ 1 ms. HCl loss probability due to the recombination with electrons is, accordingly, negligibly small. HCIs merged with positrons with energy of ~ 100 eV/q after the electron cooling were further cooled down to ~ 0.1 eV/q within a few hundred ms for $N_p = 10^8$ (a few s for $N_p = 10^7$) (see Fig. 4). The total cooling time of this simultaneous cooling scheme could be 1/10 of the pure positron ($N_p \sim 10^7$ – 10^8) scheme and at the same time, the loss fraction due to recombination and charge transfer reaction with residual gases is also 1/10 of other schemes. The

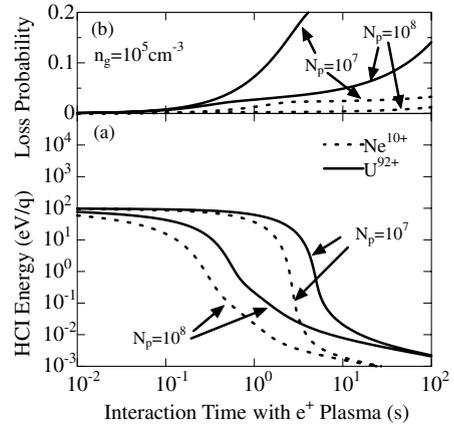


Fig. 4. (a) HCl (Ne^{10+} and U^{92+}) energies and (b) loss probability of HCIs as a function of the interaction time with positrons. HCl initial energies are 100 eV/q.

characteristics of these features are summarized in Table 1.

After the cooling of HCIs down to ~ 0.1 eV/q, positrons can be separated and reserved for reuse in the next cooling cycle of HCIs (Fig. 3(c)). Computational simulation has shown that if cold HCIs are confined within a diameter of 1 mm in the MRT, they can be extracted as low energy beam out of the magnetic field [14].

4. Summary

An efficient and quick scheme to cool HCIs from ~ 10 keV/q down to ~ 0.1 eV/q is presented, in which trapped electrons and positrons are used as energy absorbers of HCIs. The usage of the large number of electrons helps to cool HCIs quickly $< \sim 1$ s so that the fraction of HCIs lost due to collisions with residual gases can be suppressed considerably ($\text{H}_2 \sim 10^{-10}$ Pa).

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References

- [1] G. Gabrielse, X. Fei, L.A. Orozco, R.L. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells, *Phys. Rev. Lett.* 63 (1989) 1360.
- [2] Y. Yamazaki, *Phys. Scr. T* 110 (2004) 286.
- [3] N. Oshima, T.M. Kojima, M. Niigaki, A. Mohri, K. Komaki, Y. Iwai, Y. Yamazaki, *Nucl. Instr. and Meth. B* 205 (2003) 178.
- [4] R.G. Greaves, M.D. Tinkle, C.M. Surko, *Phys. Plasmas* 1 (1994) 1439.
- [5] N. Oshima, T.M. Kojima, M. Niigaki, A. Mohri, K. Komaki, Y. Yamazaki, *Phys. Rev. Lett.* 93 (2004), Art. No. 195001.
- [6] W. Quint et al., *Hyperfine Interact.* 132 (2001) 457.
- [7] L. Spitzer, *Physics of Fully Ionized Gases*, Interscience Publishers, New York, 1962.
- [8] S.L. Rolston, G. Gabrielse, *Hyperfine Interact.* 44 (1988) 233.
- [9] D.V. Sivukhin, in: M.A. Leontovich (Ed.), *Rev. of Plasma Physics*, Vol. 4, Consultant Bureau, New York, 1966, p. 93.
- [10] R.E. Olson, A. Salop, *Phys. Rev. A* 14 (1976) 579.
- [11] S. Kravis, H. Saitoh, K. Okuno, K. Soejima, M. Kimura, I. Shimamura, Y. Awaya, Y. Kaneko, M. Oura, N. Shimakura, *Phys. Rev. A* 52 (1995) 1206.
- [12] Y. Hahn, *Rep. Prog. Phys.* 60 (1997) 691.
- [13] A. Mohri, H. Higaki, H. Tanaka, Y. Yamazawa, M. Aoyagi, T. Yuyama, T. Michishita, *Jpn. J. Appl. Phys.* 37 (1998) 664.
- [14] M. Niigaki, N. Oshima, T.M. Kojima, Y. Yamazaki, *ICPEAC Abstr.* 22 (2001) 689.