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System of Slow Highly Charged Ion Beam Generation Using a Cold Positron Plasma Trap at RIKEN

Akihiro Mohri*, Takao M. Kojima*, Nagayasu Oshima*[†],
Megumi Niigaki*[†] and Yasunori Yamazaki*[†]

** Atomic Physics Laboratory, The Institute of Physical and Chemical Research (RIKEN),
Wako 351-0198, Japan*

*[†] Institute of Physics, Graduate School of Arts and Sciences, University of Tokyo,
Tokyo 153-8902, Japan*

Abstract. A system to generate ultra-slow beams of highly ionized ions (HCIs) is under construction at RIKEN for studying collision processes of slow HCIs with atoms, molecules and surfaces. HCIs beams produced with an ECR ion source are transported to a multi-electrode trap, which can include several local harmonic potential wells enabling to confine different nonneutral plasmas of oppositely charged particles. Injected HCIs are decelerated by a dense electron plasma and then, to evade their recombination with electrons, cooled further with a positron plasma under cyclotron radiation cooling. This electron plasma also works as the damper of slow positrons at their loading into the trap. The cold HCIs are finally extracted from the trap as an ultra-slow beam with well-defined energy and used for slow collision experiments.

INTRODUCTION

Production of highly charged ions (HCIs) of ultra low velocities is expected to give an effective means for studies of interaction processes of slow HCIs with matter [1]. A new project to generate very slow HCI beams by using a nonneutral plasma trap has been started at RIKEN. Since different nonneutral plasmas as electrons, positrons and HCIs should be manipulated in the trap, a multi-ring electrode trap [2] is adopted, which can produce a variety of axially symmetric configurations of electric field.

The following is a rough sketch to generate a cold HCI beam using the trap. A dense electron plasma is formed in the trap for a start. Subsequently, slow positrons are injected into the trap and stacked subject to collisional damping by the electrons. Non-adiabatic process employed here is Coulomb collisions between electrons and positrons. At that phase, the electron plasma and the positron plasma are simultaneously confined in different regions of the trap and they are cooled by cyclotron radiation. An HCIs beam is then transported from an ECR ion source to the trap and captured in it by changing its potential barrier. The trapped HCIs are mainly

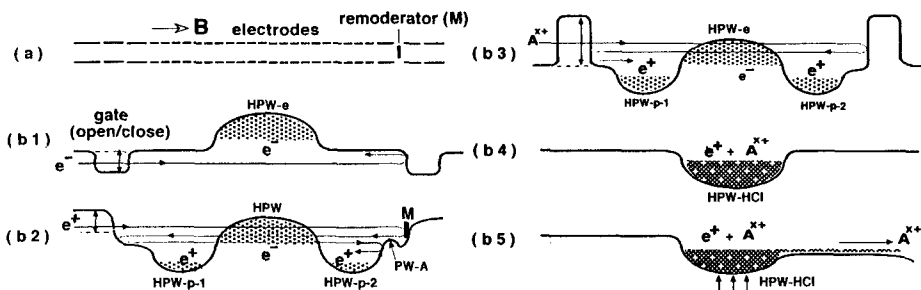


Figure 1. (a) Alignment of electrodes of the trap. (b1 - 5) Potential configurations in operational stages. (b1) Loading of electrons, (b2) Stacking of positrons, (b3) Injection and deceleration of HCl beam, (b4) Positron cooling of HCl, (b5) Extraction of an ultra-slow HCl beam.

HPW indicates the portion of a harmonic potential well, and PW-A is a low potential hill.

cooled down by the electrons at the beginning. When the energies of HCl's become lower, they are separated from the electrons to fall into the positrons, evading recombination loss of HCl's. After the HCl's thermally equilibrate with the cold positrons, they are extracted as a cold beam with a well-defined energy.

This report discusses the fundamental procedure mentioned above, in addition to a brief description of the trap.

Trap

A sketch of the trap is shown in Fig.1(a). Twenty seven ring electrodes of 3.8 cm inner diameter are aligned in the bore of a superconducting solenoid, which generates uniform magnetic field of 5 T over the axial length of 50 cm. Installation of many electrodes enables to form different configurations of electrostatic potential necessary for the manipulation. Two of the electrodes are cut into 4 sectors to be used for compression and diagnosis of trapped plasmas. All beams of electrons, positrons and HCl's are injected into the trap from the one side. On the down stream side, a removable tungsten plate of single crystal is installed to remoderate the incoming positrons.

HCl's of the charge state q are injected into the trap with energies of about 3 keV/ q and then cooled. To avoid their charge-exchange losses with residual gas molecules, the vacuum pressure of the trap is required to be 10^{-9} Pa or lower [3]. This ultra-high vacuum is realized by keeping the trap at the temperature less than 10 K. Such a environment also helps the radiation cooling of electrons and positrons.

Stacking of Electrons and Positrons

An electron gun is set at an off-axial position outside the trap to ensure the axial beam paths of positrons and HCl's. The emitted electron beam launches onto the axis

making $E \times B$ drift motion, which is induced by applying an electric field perpendicular to the leaked magnetic field from the main SC-solenoid. The beam electrons are stacked by raising the gate potential as shown in Fig.1(b1). They finally settle in the central harmonic potential well (HPW-e) and become colder due to cyclotron radiation cooling. This cold electron plasma is spheroidal, characterized by the parameters as the radius a , the half axial length of b and the density n_e . Although there are a lot of choices of these parameters, later discussions will be made using a spheroidal electron plasma with $a=0.25$ mm, $b=10$ cm and $n_e=1 \times 10^{11}$ cm $^{-3}$. After the electron plasma is formed, the potential distribution is rearranged to add two harmonic wells: HPW-p-1 and HPW-p-2 to trap positron plasmas on the both sides of the electron plasma (Fig.1(b2)).

A slow positron beam is produced by combining a solid Ne moderator with a positron source of 40 mCi ^{22}Na [4,5]. The attainable beam intensity is about 10^7 e $^+$ /s. It is guided toward the trap with a magnetic duct. On reaching the SC-solenoid, the beam is once accelerated up to ~ 1 keV to get over the magnetic mirror present there. In the trap, the beam radius is $r_{e^+}=0.1$ mm, and its energy parallel to the magnetic field spreads to ~ 1 keV. To reduce this energy spread, the beam positrons are implanted into the tungsten remoderator shown in Fig.1(b2). About 30 % of the implanted positrons are expected to emerge backward from the remoderator with the energy of 2~3 eV. Before this implantation, the beam once passes through the electron plasma but the caused energy loss is small because of high beam energy.

Figure 2 shows energy decay of positrons through the electron plasma of $n_e=1 \times 10^{11}$ cm $^{-3}$ as a function of their penetrated depth d . Here, the decay is estimated from the longitudinal momentum change of positrons moving in the electron plasma [6], since the loss of longitudinal energy is essential when we consider the axial motion in the potential well. The hatched lines in the figure indicate one path length of positron

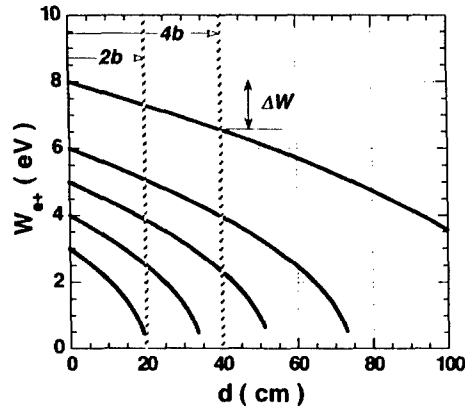


Figure 2. Decrease of positron beam energy W_{e^+} as a function of penetration depth d for $n_e=1 \times 10^{11}$ cm $^{-3}$.

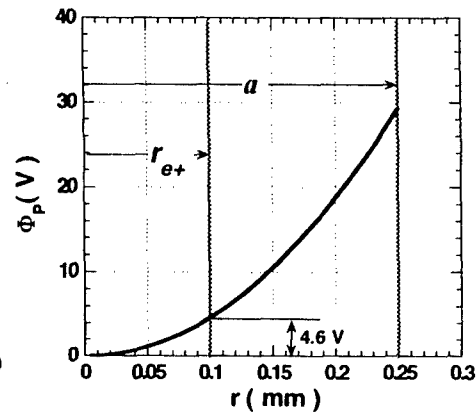


Figure 3. Internal potential of the plasma on the midplane $\Phi_p(r)$ for the case $a=0.25$ mm and $n_e=1 \times 10^{11}$ cm $^{-3}$.

through the plasma $2b=20$ cm and the double one $4b=40$ cm. The plasma potential radially increases, as is shown in Fig.3. We express this variation as $\Phi_p(r)$, where $\Phi_p(0)=0$. Let the potential of the remoderator and the energy of re-emitted positron be Φ_M and W_M , respectively, then the incident positron energy into the plasma is written by $W_{IN}(r)=\Phi_M+W_M-\Phi_p(r)>0$. Incident positrons returning back after twice passes through the plasma lose their energies by ΔW . If $\Delta W>W_M$, the positron is kept off from re-entering the remoderator. Reduction of ΔW may relax requirements for n_e and b of the electron plasma. When a low potential hill Φ_A (PW-A in Fig.1) is added just in front of the remoderator such that $\Phi_M<\Phi_A<(\Phi_M+W_M)$, ΔW is reduced by $(\Phi_A-\Phi_M)$, so that $\Delta W>W_M-(\Phi_A-\Phi_M)$.

For the exemplified electron plasma, Φ_p varies from 0 to 4.6 V within the radius of the incident positron beam r_{e+} (Fig.3). Also, W_M is 2-3 eV as mentioned above. When we set $\Phi_A=4.5$ V and $\Phi_M=2.6$ V, all re-emitted positrons can pass the potential hill PW-A, since $\Phi_A<(\Phi_M+W_M)$. In this case, W_{IN} is distributed in a range of 0-5.6 eV. As is seen in Fig.2, incident positrons of 5.6 eV return back with the energy ~ 3 eV and they are reflected by PW-A. They are again damped by the electron plasma. In this way, all of the re-emitted positrons are either sufficiently slowed down or stopped in the plasma. They are expected to finally settle in the harmonic wells: HPW-p1 and HPW-p2 in Fig.1. The positrons with the total number $N_{e+}\approx 1\times 10^8$ are estimated to be stacked within 100 s.

The harmonic wells for positrons are formed by applying allocated voltages on the electrodes through resistors with high impedances, so that the electrodes work as a resistive wall. Besides, once some slow positrons accumulate in these wells, they damp positrons incoming later. Such a damping mechanism and application of rf field may contribute to make the positron stacking more efficient [7].

Cooling of HCIs

Deceleration of HCI beam by Electron Plasma

We shall start our discussions from the situation that HCIs of charge state q are just trapped between the potential barriers set on the both ends of the main trap as shown in Fig.1(b3). The dense electron plasma interacts with the HCIs through Coulomb collisions. Let the beam energy, the density and the total number of HCIs be W_{HCI} , n_{HCI} and N_{HCI} , respectively. The ratio of $2b$ to the length of the HCI trap is noted by α . The HCIs lose their energies by heating the electrons, while the electrons are cooled by cyclotron radiation. The cooling time used here is empirically obtained from experiments on ASACUSA-Trap [8] which is now in operation at CERN [9]. This

time is expressed as $\tau_R \approx 6/B^2$ s where B is in Tesla. Neglecting interactions among HCIs, we formulate the rates of change in W_{HCl} and electron temperature T_e as [6]

$$\frac{dW_{\text{HCl}}(t)}{dt} = -\alpha F(n_e, T_e(t), q, W_{\text{HCl}}(t), \beta), \quad (1)$$

$$\frac{dT_e(t)}{dt} = \frac{2}{3} \frac{N_{\text{HCl}}}{k_B N_e} \alpha F(n_e, T_e(t), q, W_{\text{HCl}}(t), \beta) - \frac{T_e(t)}{\tau_R}, \quad (2)$$

where β and k_B are the reduced mass and Boltzmann constant. The function F includes Coulomb logarithm and velocity of HCl, which are all given by the denoted variables. Solving these equations, we can find the time evolutions of W_{HCl} and T_e .

The case of Ar^{8+} is taken as an example. The initial condition at $t=0$ is set as follows; $B=5$ T, $N_e=2.7 \times 10^9$, $n_e=1 \times 10^{11} \text{ cm}^{-3}$, $T_e=0.01$ eV, $N_i=1 \times 10^7$, $W_{\text{HCl}}=10$ keV, and $\alpha=0.2$. Figure 4 shows the results. Immediately after the start of damping, the beam energy decreases fast, while T_e rapidly rises. Then, T_e reaches its peak of 18 eV and smoothly decreases with time. On the other hand, W_{HCl} continuously gets lower toward $k_B T_e$. The deceleration of 10 keV Ar^{8+} is almost finished within 0.3 s.

The HCl beam also heats up the positrons which are being cooled by cyclotron radiation. However, the coupling is weak since the positron density n_{e+} is much lower than n_e . Here dominates the radiation cooling. When the positron total number is $N_{e+}=10^8$, the positron temperature T_{e+} rapidly rises but it saturates at 2.7 eV.

When both of W_{HCl} and T_e decrease to a few eV, the electrons are exhausted from the trap by changing the potential profile as shown in Fig.1(b4). This electron emoval is necessary to evade HCl-electron recombination at lower T_e . By this potential change,

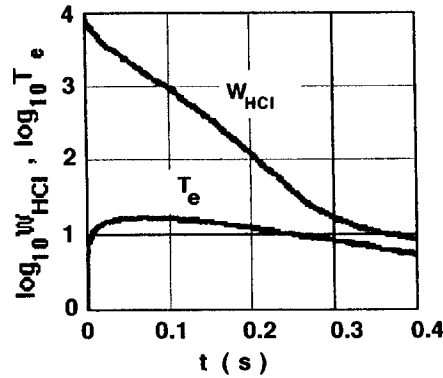


Figure 4. Time evolutions of W_{HCl} and T_e during the deceleration of HCIs in the electron plasma of $n_e=1 \times 10^{11} \text{ cm}^{-3}$. Energy is in eV.

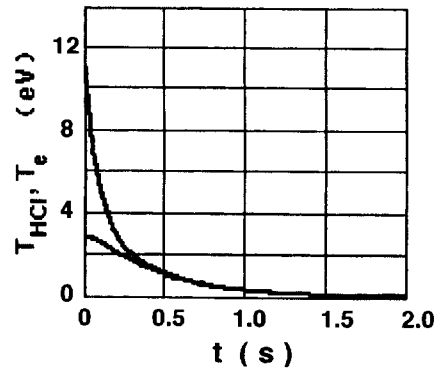


Figure 5. Time variations of W_{HCl} and T_{e+} of the mixed plasma, where $N_{\text{HCl}}=1 \times 10^7$, $T_{\text{HCl}}=12$ eV, $n_{e+}=1 \times 10^9 \text{ cm}^{-3}$, and $T_{e+}=2.7$ eV at $t=0$.

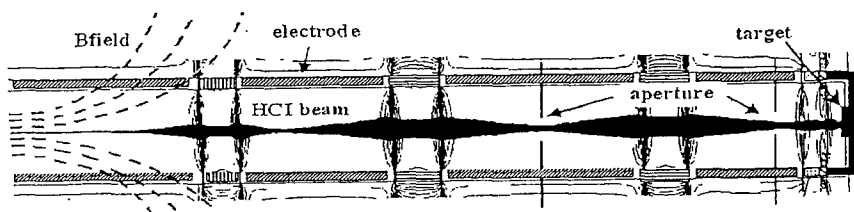


Figure 6. Beam line consisting of Einzel lenses for extraction of ultra-slow beams.

the HCIs and the positrons are mixed in the newly formed trap: HPW-HCI shown in Fig.1.

Positron Cooling and Extraction of HCIs

The HCIs in HPW-HCI becomes colder through the temperature equilibration with the positrons which are under cyclotron radiation cooling. The time evolution of the HCI temperature T_{HCI} is easily estimated by adding a radiation loss term to usual temperature relaxation equations. To clearly demonstrate the cooling, we choose the initial T_{HCI} to be somewhat as high as $T_{\text{HCI}}=12$ eV. The other parameters are $B=5$ T, $N_{e^+}=1 \times 10^8$, $T_{e^+}=2.7$ eV, $n_{e^+}=1 \times 10^9 \text{ cm}^{-3}$ and $N_{\text{HCI}}=1 \times 10^7$. These values correspond to the situation at 0.2 s in Fig.4. The estimated time variations of T_{HCI} and T_{e^+} are shown in Fig.5. Temperature equilibration between the HCIs and the positrons finishes within 0.3 s and, after then, the equilibrated temperature decreases to that determined either by the environmental noise temperature or by the wall temperature. Thus, there are produced cold HCIs.

The cold HCIs are finally extracted as an ultra-slow beam from the trap set in 5 T magnetic field [10]. A beam line consisting of Einzel lenses is used for the extraction. Figure 6 shows the arrangement of lenses and the HCI beam trajectories in the line. Two lenses at the exit of the trap accelerate HCIs to suppress the spatial beam divergence caused by the strong magnetic field gradient. The other lenses take parts to make nodes of the trajectories and also to decelerate and focus the beam. Disks with small apertures are installed at these node positions, which enable differential pumping of gas which is coming back from the region of atomic collision experiments.

Present Status and Examination of Scenario

A scenario to generate ultra-slow HCIs has been described and the system is near completion at RIKEN. Realization of the scenario has been checked at each stage of

the assembling. The SC magnet stably works to generate 5 T and the trap housed in the inner bore can be cooled down to 9 K. To increase the production efficiency of a slow positron beam, several different structures near the ^{22}Na positron source have been examined experimentally [11]. At present, the HCI source is supplying HCI beams to the other experimental devices for atomic physics.

A dense electron plasma is requisite for damping remoderated slow positrons in order to realize the scenario. When a spheroidal electron plasma is slim enough, its density can be high with the small total number of electrons. No deep harmonic potential well is necessary in this case and also image charge effects caused by the surrounding walls are small. Formation of such a plasma was experimentally checked at $B=5\text{ T}$. A long harmonic potential well of 46 cm length and 60 V well depth was made in the central region of the trap. Very slender plasmas were formed in the well. Their typical parameters were $N_e=1.9\times10^8$, $a\sim0.07\text{ mm}$, $2b\sim25\text{ cm}$ and $n_e\sim7\times10^{10}\text{ cm}^{-3}$. The confinement time was about 8 hours. These results suggest that the electron plasma of $n_e=1\times10^{11}\text{ cm}^{-3}$ in the example mentioned above, is easily producible. However, very fine adjustment of the plasma parameters is necessary since we have to accurately set a small potential difference between the plasma and the tungsten remoderator. To make the adjustment easier, alternative potential configurations and operational schemes are now under study.

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