PRODUCTION OF ULTRA-SLOW HCI BEAMS SYMPATHETICALLY COOLED BY A COLD POSITRON PLASMA

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A system of producing ultra-slow beams of Highly-Charged Ions (HCIs) has been developed in RIKEN. HCIs, produced in ECR ion source, are once confined in a trap in a UHV vessel, cooled down sympathetically by a cold positron plasma without a fear of recombination, and then extracted as a slow HCI beam. In order to maintain UHV conditions during a positron plasma formation, a gas-free positron accumulation technique has been developed, which utilizes a high-density electron plasma as a damper of positrons. Using an electron plasma of $3 \times 10^{11} \text{ cm}^{-2}$, about $3 \times 10^5 \text{ e}$, are trapped, marking 1% of trapping efficiency. The detail of the scheme is described below.

1. Introduction

In the last two decades, interaction between slow Highly-Charged Ions (HCIs) and solid targets has been intensively studied [1, 2]. Main purpose of such experiments is to investigate how large potential energy of HCIs is deposited on the targets. However, because of difficulty in producing HCI beams of ultra-slow energy ($\approx 1 \text{ eV/q}$), their kinetic energy often came to be a disturbance in such experiments.

In order to realize slow and mono-energetic HCI beams, a system of producing ultra-slow beams of HCIs has been developed in RIKEN [3 – 8]. HCIs are cooled down by a cold positron plasma in our Multi-Ring Linear Penning Trap (MRT) in an UHV vessel (the detail of MRT is described in the next section). This procedure allows cooling of HCIs without a fear of recombination, as long as vacuum pressure is kept at $10^{-10} \text{ mbar}$ or better. Therefore, we have been developing a gas-free positron accumulation method, which utilizes electrons as a damper of positron beams.

Production of HCI beams will be realized as follows: a) form a positron plasma in MRT in the gas-free method, b) inject hot HCI beams produced in the ECR ion source, then they are cooled down sympathetically by a cold positron plasma, c) extract HCIs as cold and mono-energetic beams. To date, development is on the stage a), and here we report resent success in positron accumulation as a first step toward production of slow HCI beams.

2. Experimental

Schematic description of MRT and trap potential profile is on Fig.1. This 50cm-long MRT consists of coaxially aligned 21 cylindrical electrodes, each of which is 20mm long, 38mm in inner diameter. These electrodes are biased to prepare two harmonic potential wells one is for electrons and the other is for positrons/HCIs. MRT is placed in a 5T uniform magnetic field formed by a super-conducting solenoid. Charged particles are confined radially by the magnetic field, axially by electric barriers of a potential well. The center of MRT is cooled down to 10K, keeping a vacuum pressure at $10^{-10} \text{ mbar}$ or better.

Fig.2 shows the set up of the whole system. At the upper stream of MRT, ECR ion source and slow positron source are installed, and they are connected to MRT by beamlines. At the very beginning of the beamline is ECR ion source, from which hot HCIs with energy spread of several 10s eV are supplied. Slow positron source contains a $^{22}\text{Na}$ capsule with a moderator.
(solid-Ne, transmission geometry) positioned in a 100G magnetic field. About $3 \times 10^6 e+/\text{sec}$ is extracted as slow positrons, 30% of which can actually enter MRT overcoming the magnetic-mirror effect. Electrons, necessary for a positron plasma formation, are supplied by an electron gun installed at the entrance of vacuum vessel.

A positron re-moderator, made of tungsten single crystal (W(100), backscattering geometry), is installed at the exit of MRT. This re-moderator is held in a movable holder so that it will be removed when charged particles are extracted downstream. For diagnosing charged particles, Faraday-Cup and phosphor screen are installed at the end of the UHV vacuum vessel.

The accumulation of positrons is performed as follows: 1) inject electron beams (1µA) into MRT for about 30sec to form an electron plasma, 2) positrons with energy spread of $\sim 1\text{keV}$ in MRT are injected into re-moderator, 3) some of them are re-emitted and injected into the electron plasma with less energy spread ($\sim 1\text{eV}$), 4) positrons are decelerated inside the electron plasma by Coulomb collisions, until they cannot reach re-moderator any longer, 5) these positrons go back and forth in MRT for a while, and finally accommodated in the potential well as a cold positrons by emitting synchrotron radiations. Density of the electron plasma is estimated combining the information on the total particle number and plasma diameter. The total number of particles in the electron plasma is deduced by collecting them at the positively biased Faraday-Cup or re-moderator, giving the integral of total charge amount. The plasma diameter is estimated from its image on the phosphor screen attached on the back of the Faraday-Cup. Assuming the electron plasma to be spheroidal, these results enable us to calculate its aspect ratio and density. For an estimation of the total number of positrons trapped in the above method, they are extracted downstream, collected by the negatively biased (-3.5kV) Faraday-Cup, and 511keV gamma-rays are detected by a NaI scintillation counter as signals of accumulated positrons. In order to achieve high trapping efficiency, it is important to finish the process 4) within (and not more than) one round trip of positrons in the electron plasma, since multiple injections into re-moderator cause considerable decrease of emitted positrons entering the electron plasma. Therefore, large stopping power for positrons in the electron plasma is required, which demands high surface density of the electron plasma $\sigma = n \cdot L$ (n and L are number density and

Fig.1 Schematic description of MRT and potential profile on trap axis.
length, respectively), and low injection energy (into the electron plasma) of re-emitted positrons. In the present system, an electron plasma of $3 \times 10^{11} \text{cm}^{-2}$ ($1 \times 10^{10} \text{cm}^{-3}$, 30 cm-long) was achieved.

Injection energy of re-emitted positrons is estimated roughly as $K = e(V_{\text{Re-mod}} - V_{\text{e-plasma}}) + \delta E$, here $e$ is elementary charge, $V_{\text{Re-mod}}$ is the bias of re-moderator, $V_{\text{e-plasma}}$ is the electrostatic potential in the electron plasma, $\delta E$ (\textasciitilde a few eV) is the contribution to axial energy from negative work function for positrons. For efficient deceleration of re-emitted positrons, $K$ should be minimized \textasciitilde nearly equal to zero, but still enables re-emitted positrons to enter the electron plasma. Since $\delta E$ has the ambiguity of \textasciitilde 0.5 eV, $K$ can be minimized to \textasciitilde 1 eV by setting $V_{\text{Re-mod}}$ nearly equal to $V_{\text{e-plasma}}$.

Fig. 3 shows the positron trapping efficiency as a function of the bias of re-moderator $V_{\text{Re-mod}}$. Peak corresponds to the bias matching condition, $V_{\text{Re-mod}} \approx V_{\text{e-plasma}}$. For further increase of the trapping efficiency, surface density of the electron plasma should be enhanced. Stopping power calculation shows that electron plasma with surface density $6 \times 10^{12} \text{cm}^{-2}$ is required for deceleration of all the positrons with injection energy of $0 \sim 1 \text{ eV}$.

Another important point for this positron accumulation method is to ensure that positrons are gathered into the potential well after they are damped by the electron plasma (process 5). In our case, $\sim 10^6$ of positive ions that exist in the potential well for positrons are considered to play an important role, changing the axial component of positron momentum to radial by Coulomb collisions. Since radial component will be consumed in $\sim 0.1 \text{sec}$ by synchrotron radiations, these positrons are automatically cooled down. These positive ions are created by ionization of residual gas molecules during the injection of electron beams (process 1). Measurement of bounce frequency of ion plasma in the potential well suggested that main component of these ions are $\text{H}_2^+$. It is a reasonable result, considering that hydrogen molecules are the main component of the residual gas in MRT that is kept at 10K.
3. Summary
Positron accumulation in a gas-free method was succeeded, where positrons re-emitted from re-moderator are decelerated in an electron plasma which acts as a damper of positrons. H$^+$ ions are considered to play an important role, helping confinement of positrons inside a potential well. About 1% of trapping efficiency was achieved. Further improvement is now on progress.

3. References