Project to Produce Cold Highly Charged Ions using Positron and Electron Cooling Techniques

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Abstract. A project to cool highly charged ions (HCIs) with positron and electron cooling techniques is under way. Trapped $10^{10}$ electrons and $10^7$ positrons in a multi-ring trap are used as energy absorbers for HCIs. The detail of the cooling procedure is reviewed.

INTRODUCTION

It is well known that highly charged ions (HCIs) produced by an electron beam ion source (EBIS) and an electron cyclotron resonance ion source (ECRIS) have energy spreads order of $\sim 10$ eV/q, which caused by a heat-up during sequential ionization by electron impacts and a finite potential distribution in the area where ionization takes. In order to expand the energy range of available HCIs much below the above limits, a project to cool HCIs by positron and electron cooling techniques is under way [1-7].

The electron/positron cooling technique has been applied for the cooling of antiprotons [8-10] and protons [11]. Charged particles stored in a strong magnetic field lose their energies by a synchrotron radiation, the rate of which is inversely proportional to the cube of the particle mass, i.e., the rates for positrons and electrons are more than $10^{10}$ times faster than those of ions [1, 4]. This indicates that if light and heavy particles are stored in a strong magnetic field simultaneously, the light particles are useful coolants for the heavy particles. In our project, both light particles, namely electrons and positrons, are used for the cooling of HCIs. At first, HCIs are injected into a dense electron plasma, in which almost all energies of HCIs are lost by Coulomb collisions. Before changing the charge state of HCIs due to the recombination with electrons, HCIs are guided into the positron plasma and then cooled down to environmental temperature.

In this report, a scheme for a production of a low energy ion beam using positron and electron cooling techniques is presented.

SCHEME OF COLD HCIS PRODUCTION

Positron and electron cooling techniques to produce cold HCIs are being developed, which is schematically drawn in Figs. 1(a) - (d). (a) A non-neutral plasma consisting of
FIGURE 1. The production scheme of the cold HCI beam using positron and electron cooling techniques.

∼ $10^{10}$ electrons and a cloud consisting of ∼ $10^7$ ions are prepared in a multi-ring trap (MRT) [12,13] which confines charged particles radially by a strong magnetic field (B = 5 T) and axially by an electric field. The $10^7$ ions ($H_2^+$) are created by the ionization of the residual H$_2$ gas by the electron impact [14] during the injection of electrons into the MRT. The electron plasma is automatically cooled down to its environmental temperature via synchrotron radiation in the strong magnetic field. The radiation cooling time constant is order of ∼ 0.1 s in case of B = 5 T [1, 4]. (b) A positron beam of $10^6$-$10^7$ e$/$s is injected into the MRT, where they are once accelerated to avoid reflection due to the magnetic mirror effect. The positrons are first implanted into a re-moderator (tungsten single crystal plate), and then re-emitted as slow positrons with small energy spread (a few eV) with a typical efficiency of 10-30% [15-17], which interact with the pre-loaded electron plasma. The column density (plasma density times plasma length) of the electron plasma is large enough, so that the positrons lose their energy through Coulomb collisions with electrons. The existence of $H_2^+$ ions helps capturing positrons effectively due to the further energy loss through Coulomb collisions [18]. Eventually, they are guided into the bottom of the potential. After trapping, they are cooled via synchrotron radiation like in the case of electrons. This stage lasts when ∼$10^7$ positrons are accumulated. (c) After ejection of positive ions ($H_2^+$), HCIs ($10^5$-$10^7$) are injected and trapped in the MRT by switching the entrance electric gate, which are then cooled with the electron and the positron plasmas. Almost all energies of HCIs are lost by Coulomb collisions with $10^{10}$ electrons in a short time of ∼10 ms. Before changing of HCI charge state due to the recombination with electrons, HCIs are loaded into the positron plasma and then cooled down to environmental temperature within ∼ 1 s. (d) Positrons and HCIs are separated from each other by a time of flight technique and
only cold HCIs are extracted from the MRT by ramping the potential valley as a cold HCl beam. The cold HCl beam is guided to the out of the magnetic field with suitable electrostatic lenses [19] and used for various experiments.

SYSTEM FOR COLD HCIS PRODUCTION

In order to realize the above scheme, we have built a system which consists of four main apparatus i.e., MRT [4, 7], a slow positron source [3], an electron cyclotron resonance ion source (ECRIS) [2, 5], and a beam line connected to them each other [3]. Each apparatus are briefly presented in this section.

Multi-Ring Trap (MRT)

A trap called by multi-ring trap (MRT) developed by Mohri et al. [12, 13] is adopted for trapping of three different particles i.e., electrons, positrons and HCIs, because it can flexibly prepare various harmonic wells, where a large number of positively and/or negatively charged particles are stably confined simultaneously. Schematic view of the MRT is shown in Fig.2 [4, 7].

The superconducting solenoid (NbTi) provides a magnetic field as high as 5 T. The uniformity of the field near the center of the solenoid bore is better than $10^{-3}$ in the volume of $4 \text{ mm } \times 500 \text{ mm}$ where charged particles are confined. An electrochemically polished ultra-high vacuum (UHV) vessel 1940 mm long is inserted in the solenoid. The vacuum in the MRT should be kept at $10^{-8}$ Pa or better to prevent charge transfer reaction between HCIs and residual gas atoms/molecules during HCI cooling processes which take a few seconds [20]. Therefore, the vessel is thermally insulated from the beam line with two bellows so that the vessel can be baked and cooled down to $\approx 10 \text{ K}$ to realize an UHV environment.

An electrode assembly consists of 21 ring electrodes is installed around the center of the UHV vessel to form the potential distribution. The assembly is 50 cm in length, each electrode is 38 mm in inner diameter and 20 mm in length and electrodes of 160 mm long are added on both ends. The electrodes are made of gold-coated oxygen free copper. Aluminum nitride is adopted as the insulating material to support electrodes, because of its high thermal conductivity, which is essential to cool the electrodes effectively by the cold vessel still keeping electrical insulation. The positron re-moderator made of a tungsten single crystal is positioned at the downstream side of the ring electrodes. The re-moderator is on the movable holder so that it is removable when particles are extracted from the MRT. A Faraday cup (FC) is mounted at the end of the MRT which is used to measure the number of trapped electrons. The end cap of the FC is made of an aluminum coated phosphor on an Indium-Tin-Oxide glass plate. The radial distribution of the electron plasma in the MRT is determined by observing the image on the phosphor screen with a CCD camera. A NaI and a CsI scintillation counters near the FC detect annihilation radiations to measure the number of positrons arriving at the FC.
Slow Positron Source

Slow positrons are generally produced by a moderation of fast positrons which can be obtained by a $\beta^+$ decay of radioisotopes or a pair production using an accelerator. Fast positrons injected into a moderator lose their energy via inelastic collisions and a considerable fraction of them are ejected into vacuum as slow positrons. The energy spread of slow positrons are typically a few eV, hence, slow positrons are controllable as a beam with beam optics [15].

In our study, a $^{22}$Na positron source is used together with a solid Ne moderator. Rare gas solids, especially solid Ne, are well known to be efficient moderators for positrons. Fast positrons injected into a moderator lose their energy via collisions till their energies reach the lowest electronic excitation energy of Ne ($\sim$16eV). Below this energy, the energy loss rate drastically decreases because only phonon excitation process can contribute to the energy loss. Therefore, positron can flight/diffuse long distance and a re-emission probability into vacuum increases [21, 22]. Typical efficiency of the solid Ne moderator is 0.5% which is defined by the ratio of the number of the extracted slow positrons to the number of $\beta^+$ decays emitted from the radioisotope [23]. Figure 3 shows a drawing of the positron source assembly [3]. An encapsulated $^{22}$Na positron source (20 mCi) is mounted on a cold-head of a refrigerator and is cooled down to $\approx$5 K so that a solid Ne moderator is formed on the front surface of the source. Slow positrons with intensity of $\sim 2 \times 10^6$ e$^+$/s are extracted and then guided magnetically to the MRT.

**FIGURE 2.** Schematic drawing of the multi-ring trap (not scaled). Charged particles are trapped axially by an electric field and radially by a magnetic field in the trap.
FIGURE 3. Drawing of the slow positron source assembly.

Beamline

A slow positron source, an electron gun and an ECRIS are connected to the upstream side of the trap. Brief sketch of the beamline is shown in Fig. 4. The coils form magnetic field along to the beamline from the positron source to the MRT. The mean magnetic field is $\approx 10$ mT which is enough to confine slow positrons radially during their transport. To eliminate fast positrons which are not moderated completely in the moderator, a bending part was set on the beam line. Fast positrons are not guided in the bending part with such a low field (10 mT), then they collide inner wall and annihilate. The positron beam profile is observed by a micro-channel plate (MCP). The positron beam diameter was about 5-10 mm. A gamma ray detector (CsI) is located close to the MCP to evaluate positron beam intensity by measuring count rate of the positron annihilation radiation. Since the downstream beamline after the bending part guides not only positrons but also HCIs, an electrostatic lens and a profile monitor for HCIs are also installed there.

An electron gun is placed at 25 mm off axis from the center of the beamline. An electron beam is guided on the magnetic center of the MRT across the magnetic field with the $E \times B$ deflector. Typical electron beam current measured in the MRT is $\approx 1 \mu A$ [7].

HCIs are produced with a 14.5 GHz ECRIS and are transported to the MRT with energy of 1-2 kV/q. An HCI ($Ar^{8+}$) beam with intensity of $\approx 40$ nA was successfully transported to the MRT with energy of 1.5keV/q.
STATUS OF THE HCI COOLING PROJECT

We have succeeded in trapping of electrons in 2002 [7] and positrons in 2003 [18]. Trapped number of electrons was $\approx 1.8 \times 10^{10}$ with density of $\approx 10^{11} \text{ cm}^{-3}$. The behavior of such high density plasma is in itself an interesting subject and is being studied [24]. Present positron accumulation rate into the UHV normalized by the intensity of $^{22}\text{Na}$ positron source is $\approx 360 \text{ e}^+/\text{s/mCi}$ which is the highest one in the UHV compatible positron accumulation schemes so far reported [18]. Trapped cold positrons would be used not only for cooling of HCIs but also for cold positron beam production, antihydrogen production and mono-energetic positronium beam production. We have recently decelerated HCIs ($\text{Ar}^{8+}$) successfully with an electron plasma in 2004 [20]. The experimental study for the positron cooling of HCIs schematically shown in Fig.1 (c) is in progress.

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