An ion trap for cooling MCIs with cold positrons

Takao M. Kojima,[*1] Nagayasu Oshima,[*1] Dana Dumitriu,[*1] Hitoshi Oyama,[*1] Akihiro Mohri,[*1] and Yasunori Yamazaki[*1,*2]
[*1] *Atomic Physics Laboratory, RIKEN*
[*2] *Institute of Physics, University of Tokyo*

An electro-magnetic trap for cooling multi-charged ions (MCIs) with cold positrons has been designed and is now under construction. A 5-tesla superconducting solenoid in which the trap will be installed has been constructed and installed in the experimental hall. The cooling scheme of MCIs is as follows: 1) loading electrons in the trap on which an electric harmonic potential is applied, 2) cooling of trapped electrons via emission of orbital radiation of cyclotron motion, 3) injection and trapping of positrons through collisions with the pre-loaded electrons and then cyclotron radiation, 4) injection and trapping of MCIs followed by cooling with positrons. The cooled MCIs will be extracted as a low energy MCI beam with well-defined energy, which allows ultra-slow collision experiments with mono-energetic MCIs.

1. Introduction

The physics with multi-charged ions (MCIs) has been the subject studied most intensively in the last two decades of the 20th century. Vigorous investigations revealed many interesting features of MCIs. In the field of atomic collision physics, however, experimental studies have been performed mainly with "high-energy" ($\geq$ 1 keV) ions. Slow collision processes including MCI has not yet been studied enough because of the difficulty to prepare and control well-defined low-energy ($\leq$ 10 eV) MCI beams.

To realize such "low-energy" MCI beams for slow collision experiments, we have started a new project to make very cold MCIs in an electro-magnetic trap.[1)] The cooling method of MCIs is the same as that of electron cooling of antiprotons.[2,3)] In the case of MCIs, positrons are employed instead of electrons to avoid recombination loss of MCIs. The project consists of fol, lowing four parts of development: 1) production of high-intensity slow positron beam and its transport, 2) positron accumulation and cooling with an electron plasma, 3) positron cooling of MCIs, 4) extraction and transport of MCIs from the trap.

Detailed description of the first two parts is given elsewhere. [4,5)] This report discusses 3), *i.e.* the concept of positron cooling of MCI and current status of the apparatus.

2. Scheme of positron cooling of MCIs

A multi-ring electrode electro-magnetic trap [6)] is used for accumulating and cooling positrons and MCIs. The trap is mounted in the bore of a superconducting solenoid which makes strong collinear magnetic field along the beam axis. Injected charged particles are trapped axially by the electric potential of the multi-ring electrodes and confined radially by a strong magnetic filed. Figure 1 shows a sketch of the trap. Overall procedure to obtain cold MCIs is as follows: 1) loading $\sim 10^{10}$ electrons in the trap on which an electric harmonic potential is applied; 2) cooling of trapped electrons via emission of orbital radiation of cyclotron motion due to strong magnetic field; 3) injection and trapping of $\sim 10^8$ positrons through collisions with the pre-loaded electrons and then cyclotron radiation; 4) injection and trapping of MCIs followed by cooling with the trapped positrons; 5) extraction of MCIs as a cold beam. In this procedure , the trapped electrons are kept through extraction of MCIs. Since the electron-ion recombination cross section is very small at high energies, the trapped cold electrons are effective to cool MCIs at the beginning of the cooling process. Once MCIs have been cooled down to $\sim$ 1 eV, they are automatically separated from electrons and merged into positrons by electric potentials, so the recombination loss of MCIs is evaded. In such a complex plasma, however, even very small disorder of a plasma component or potentials can easily cause an instability. To avoid such an instability, we also consider an optional scheme where the trapped electrons are kicked out from the trap after cooling of positrons. A schematic diagram of the procedure including electron kick-out option is shown in Fig. 2. The mechanisms and methods of positron accumulation and cooling, *i.e.* 1)–3) above, are described elsewhere.[4,5)]

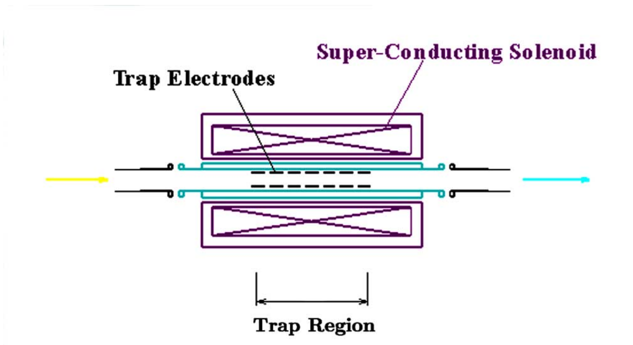

Fig. 1. Schematic diagram of the multi-ring electrode trap. The trap vacuum vessel is settled inside the solenoid.

2.1 Injection of MCIs

Multi-charged ions produced at the CAPRICE ECR ion source are transported and injected into the trap (see Fig. 3).[7)] Closing the electric potential gate at the entrance and exit of the trap, a certain amount of MCIs are confined in

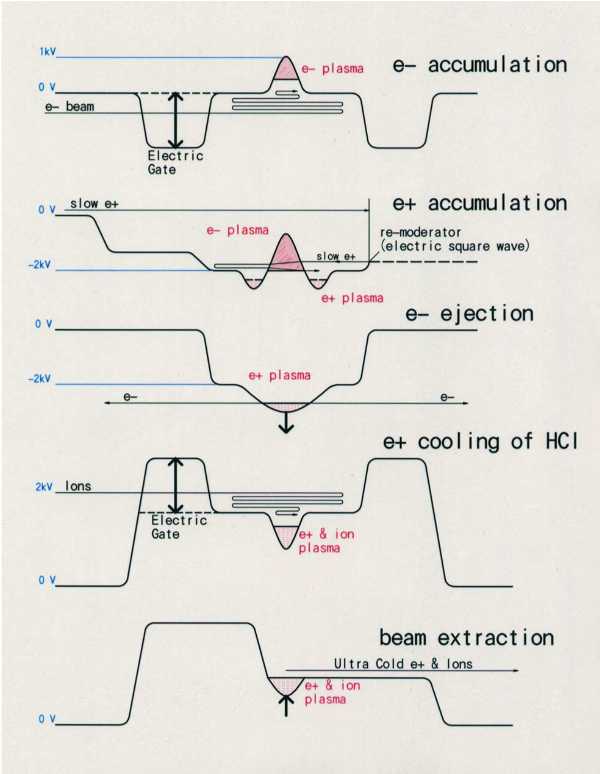

Fig. 2. Scheme of the procedure to obtain cold MCIs in the trap.

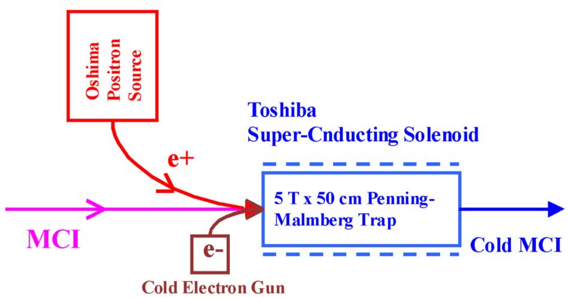

Fig. 3. Sketch of the project facility which consists of the high-intensity slow positron source (see Ref. 4, 5), an electron gun, the linear Penning trap inside the 5-tesla superconducting solenoid, and beam transport optics. Multi-charged ions (MCIs) are produced at an CAPRICE ECR ion source (see Ref. 7) and injected into the trap.

the trap. The number of trapped ions, N_i, can be estimated by

$$N_i = 4.49 \times 10^{12} I_\mathrm{i} L \sqrt{\frac{M}{q^3 V}} \qquad (1)$$

where I_i is the beam intensity in A, L the trap length in cm, M the ion mass in amu, q the ion charge state, and V the ion acceleration voltage at the ion source in V. In the case of 2-μA Ar^{8+} (M=40) beam with 2-kV acceleration (*i.e.* the total ion energy of 16 keV) confined in a trap of 50-cm long, N_i is estimated to be 2.8×10^6.

The trapped MCIs are cooled and thermalized by the pre-loaded positron plasma. During the cooling, the MCIs will be lost through charge-exchange collisions with residual gas molecules. The loss rate, γ, is given by

$$\frac{dN_\mathrm{i}}{dt} = -\gamma N_\mathrm{i} = -k n_\mathrm{g} N_\mathrm{i} = -\sigma v n_\mathrm{g} N_\mathrm{i} \qquad (2)$$

where k is the charge-exchange rate coefficient, n_g the number density of residual gas molecule, σ the charge-exchange collision cross section, and v the collision velocity. Since the energy of MCI decreases several orders of magnitude during the cooling process, the cross section σ also varies widely. As is show in the next subsection, the mean energy of MCIs injected at a few keV/q stays around the injected energy for a while, then drastically decreases to ≤ 100 meV. Therefore, the charge-exchange loss of MCIs can be estimated separately for the two energy regions.

In the first "hot" period where the ion energy is $\sim$keV, one-electron capture cross section σ is $\sim 10^{-15}$ cm^2. By using the ion energy E in eV, collision velocity is written as

$$v = 1.39 \times 10^6 \sqrt{E/M} \qquad [\mathrm{cm \cdot s^{-1}}]. \qquad (3)$$

Since the ion energy is being reduced by the positron cooling, let us assume an "average" energy of the hot period as 10 keV. Then, in case of multi-charged Ar injection, $v = 2.20 \times 10^7$ cm·s^{-1}. The charge-exchange rate coefficient for a moment just after injection is roughly estimated as $k = \sigma v \simeq 2.20 \times 10^{-8}$ cm^3·s^{-1}. With the set-up we designed, reachable vacuum pressure is considered to be in the range of 10^{-11} Torr. Assuming a vacuum pressure $p = 5.0 \times 10^{-11}$ Torr at room temperature, *i.e.* $n_\mathrm{g} = 1.78 \times 10^6$ cm^{-3}, ion loss rate is estimated as $\gamma = k \times n_\mathrm{g} = 3.90 \times 10^{-2}$ s^{-1}. This means that the lifetime of the trapped MCIs is $\gamma^{-1} = 25.6$ s.

Since k is proportional to v, charge exchange rate coefficient becomes smaller as energy decreases. Therefore, once MCIs have been cooled down to ~ 1 eV or less, charge-exchange loss rate is expected to be one or two order of magnitude smaller than that estimated above. For long-time storage and stacking of ions, *i.e.* further accumulation of MCIs by repeating additional injection and cooling, however, even small loss rate can not be negligible. In ion-atom/molecule collisions below 1 eV, the dominant long-distance interaction is charge-induced polarization force which causes so-called "orbiting" collisions. The cross section of orbiting collision, which is often referred as "Langevin cross section", is given by

$$\sigma_\mathrm{L} = 1.69 \times 10^{-16} q \sqrt{\alpha / E_\mathrm{CM}} \qquad [\mathrm{cm^2}] \qquad (4)$$

$$E_\mathrm{CM} = \frac{1}{2}\mu v^2 = \frac{\mu}{M} E \qquad (5)$$

where α is the dipole polarizability of gas molecule in Å^3, and μ is the reduced mass in amu. In most cases of MCI-atom/molecule collisions, charge-exchange process is exothermic, so that charge exchange occurs with a large probability during orbiting. Therefore, the Langevin cross section σ_L can be used as the charge exchange cross section. It is worth noting that Langevin cross section becomes larger as energy E decreases, as is seen in Eq. (4). Using Eqs. (3)–(5), charge exchange rate coefficient is given by

$$k_\mathrm{L} = \sigma_\mathrm{L} v = 2.35 \times 10^{-10} q \sqrt{\alpha/\mu} \qquad [\mathrm{cm^3 s^{-1}}] \qquad (6)$$

which shows that the Langevin collision rate does not depend on the ion energy. Again, let us consider the case of Ar^{8+} in vacuum of 5.0×10^{-11} Torr (*i.e.* $n_g = 1.78 \times 10^6\,\mathrm{cm^{-3}}$). In such ultra-high vacuum environment, the dominant residual gas is usually H_2. The polarizability of H_2 is 0.807 Å^3, and the Ar–H_2 reduced mass $\mu = 1.90$ amu. Then, the rate coefficient is estimated as $k_L = 1.23 \times 10^{-9}\,\mathrm{cm^3 s^{-1}}$, and ion loss rate $\gamma = k_L \times n_g = 2.19 \times 10^{-3}\ \mathrm{s^{-1}}$. In this case, the lifetime $\gamma^{-1} \simeq 460$ s. In an ion stacking procedure, the step 4) of the overall procedure, *i.e.* injection and cooling of MCIs, is repeated several times, and this requires $\sim 10^2$ s of storage time. To make the ion stacking procedure feasible, the vacuum pressure should be $\sim 10^{-11}$ Torr or better.

2.2 Positron cooling

When MCIs are injected and confined in the trap where there is a cold positron plasma, they are cooled through collisions with positrons, and finally, the ion temperature T_i and positron temperature T_{e+} are equilibrated. The relaxation time constant for equilibration is given by

$$\tau_{ie+} = \frac{3 \cdot 2^{1/2} \pi^{3/2} \varepsilon_0^2 m_i m_{e+} k_B^{3/2}}{n_{e+} q^2 e^4 \ln \Lambda} \left(\frac{T_{e+}}{m_{e+}} + \frac{T_i}{m_i} \right)^{3/2} \quad (7)$$

where ε_0 is the vacuum dielectric constant, m_i and m_{e+} are the mass of ion and positron, respectively, k_B the Boltzmann constant, n_{e+} the positron number density, e the elementary electric charge, $\ln \Lambda$ the Coulomb logarithm.[8] Here Λ is defined as the ratio of the Debye length of the positron plasma to the closest approach, which is given by

$$\Lambda = \frac{4\pi}{qe^3} (\varepsilon_0 k_B)^{3/2} \left(\frac{T_{e+}}{n_{e+}} \right)^{1/2} \times \left(T_{e+} + \frac{m_{e+}}{m_i} T_i + 2\sqrt{\frac{m_{e+}}{m_i} \cdot T_i T_{e+}} \right). \quad (8)$$

During equilibration, positrons colliding with "*hot*" MCIs are heated up, while they lose their energy by emitting radiation due to cyclotron motion. For a single charged particle case, the time constant of radiative relaxation is given by

$$\tau_c = 3\pi\varepsilon_0 m^3 c^3 / q^4 e^4 B^2 \quad (9)$$

where m is the mass of the particle, c is the velocity of light, and B is magnetic flux density. (For positrons, we use the notation $\tau_{c_{e+}}$ instead of τ_c.). Although the radiative relaxation occurs only for the motion perpendicular to B, parallel component is also relaxed through mutual collisions in the plasma.

Using Eqs. (7)–(9), the time evolution of the temperatures of ions and positrons can be calculated by the following two equations:

$$\frac{d}{dt} T_i = -\frac{1}{\tau_{ie+}} (T_i - T_{e+}) \quad (10)$$

$$\frac{d}{dt} T_{e+} = \frac{N_i}{N_{e+}} \frac{1}{\tau_{ie+}} (T_i - T_{e+}) - \frac{2}{3 \cdot \tau_{c_{e+}}} (T_{e+} - T_0) \quad (11)$$

where N_i and N_{e+} are the total number of ions and positrons sharing the same volume, respectively, and T_0 is the environmental temperature.

Now, it is the time to consider how to realize this scheme. As discussed in the previous subsection, vacuum pressure is one of the critical parameters. Vacuum of 10^{-12} Torr or less is enough but it is very hard to achieve, while 10^{-11} Torr

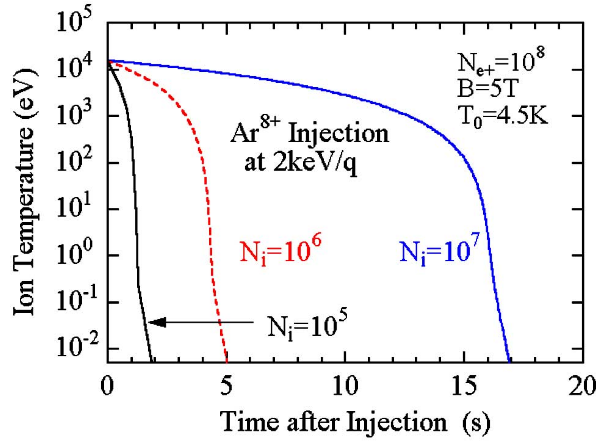

Fig. 4. Calculated time dependence of average ion energy in the cooling process for 16-keV Ar^{8+} injection. N_i denotes the total number of trapped Ar^{8+}. Assumed parameters are as follows; total number of positrons $N_{e+} = 10^8$, magnetic flux density $B = 5$ T, and environmental temperature $T_0 = 4.5$ K.

is more likely to be realized. With vacuum of 10^{-11} Torr, life time of trapped MCIs in "hot" energy region is expected as some tens seconds. This requires that MCIs should be cooled down to ≤ 1 eV in a few seconds. To realize effective cooling of MCIs by positrons, it is required that $\tau_{c_{e+}} \ll \tau_{ie+}$, *i.e.* $\tau_{c_{e+}} \sim 0.1$ s or less. According to Eq. (9), this can be satisfied by taking the magnetic filed $B \sim 5$ T or larger, so we have designed the trap solenoid to make 5 T of magnetic field. In this condition, collisionally heated positrons are almost immediately cooled.

Examples of the calculation of Eqs. (10) and (11) are shown in Fig. 4 and in Table 1. In the cases of $N_i \leq 10^6$, trapped MCIs are cooled down to 100 K in a few seconds for $q \geq 8$. Since the relaxation time constant is proportional to q^{-2} as is seen in Eq. (7), cooling efficiency is expected to be better for higher charge states.

Table 1. Calculated cooling time for 2-keV/q MCIs down to 100 K. Total number of positrons $N_{e+} = 10^8$, magnetic flux density $B = 5$ T, and environmental temperature $T_0 = 4.5$ K are assumed.

Species	Total number N_i	Required time (s)
Ar^{8+}	10^7	16.8
	10^6	4.9
	10^5	1.7
Ar^{12+}	10^6	4.6
	10^5	1.7
Ne^{8+}	10^6	3.9
	10^5	1.5

3. Apparatus

The non-coolant type superconducting solenoid has been constructed and installed in the experimental hall (see Figs. 5 and 6). The ultra-high vacuum (UHV) chamber, the inner diameter of which is 9.6 cm, is inserted inside the bore of the solenoid. The vacuum chamber is thermally insulated

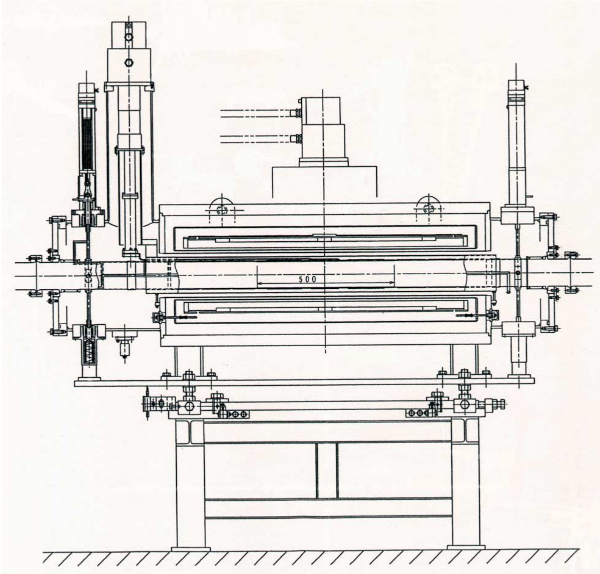

Fig. 5. The Toshiba-made non-coolant type superconducting solenoid. It equips two refrigerators; one for superconducting solenoid itself and the other for UHV vacuum vessel in which the trap electrodes will be settled.

from the solenoid and has another refrigerator, so that it can be baked keeping the solenoid at superconducting condition. The properties of the solenoid are summarized in Table 2.

The length of the trapping region is 50 cm. The trap itself consists of 27 cylindrical electrodes which makes it possible to confine electrons/positrons/MCIs in harmonic potentials. Two of the electrodes are divided into 4 symmetric arcs,

Table 2. Properties of the superconducting solenoid.

Parameters	
Magnetic filed B	5 Tesla
Expected trap region	ϕ4 mm$\times L$500 mm
Uniformity $\Delta B/B$ in trap region	$\leq 10^{-3}$
UHV vessel inner diameter	96 mm
Inner wall temperature of UHV vessel	$\geq$6 K

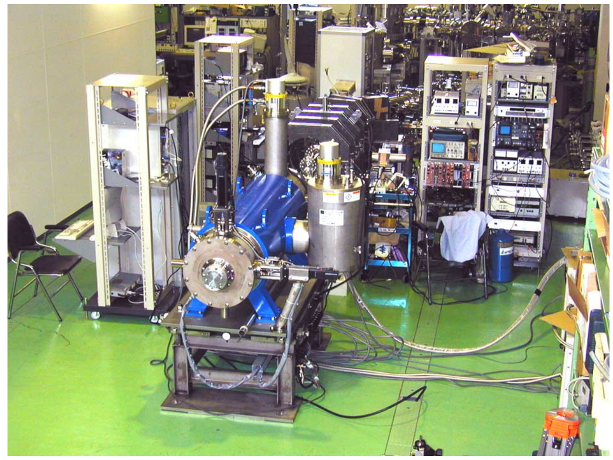

Fig. 6. Photograph of the Toshiba-made superconducting solenoid installed in the experimental hall. View from downstream of the beam line.

which are used for compression[9] and diagnosis of trapped plasmas.

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