Multi-ring Trap as a Reservoir of Cooled Antiprotons

T.Ichioka[A,C], H.Higaki[A], M.Hori[B], N.Oshima[C], K.Kuroki[D], A.Mohri[C], K.Komaki[A], Y.Yamazaki[A,C]

[A]*Institute of physics University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan*
[B]*Department of Physics University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[C]*Atomic Physics Laboratory RIKEN, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan*
[D]*National Research Institute of Police Science, 6-3-1 Kashiwanoha, Kashiwa-shi, Chiba 277-0882, Japan*

Abstract.

For the ASACUSA project, a new charged particle trap was designed and constructed. Like a Penning-Malmberg trap, static electric and static magnetic fields are used. Multi-ring electrode is exploited to generate a harmonic potential on the trap axis. It enables the confinement of a number of antiprotons and electrons for the electron cooling. Upon its design, plasma behavior of trapped particle clouds was taken into consideration.

As the first step, trap performances have been checked with electrons. Current status are presented.

INTRODUCTION

In ASACUSA project, experiments are planned to investigate initial formation processes of antiprotonic atoms, interaction between antimatter and matter etc., most of which require ultra-low energy antiproton beams [1–3]. At Antiproton Decelerator (AD ; at CERN), 10^7 antiprotons of 5 MeV will be at hand as a pulse of 250 ns with a repetition period of one minute. In our scheme, MeV-energy antiprotons from AD will have several tens of keV after passing through an RFQ, post decelerator. Those antiprotons enter a Multi-Ring Electrode(MRE) trap described in the following section. Then the well-known electron cooling technique will be applied. Dense cloud of antiprotons, together with electrons, are supposed to behave as a nonneutral plasma. Extraction method is being considered.

A MRE trap allows the utilization of axially long harmonic potential region. Advantages are :

(a) It ensures longer life times of plasmas than in the case of square potential [4].

(b) When the plasma radii are reduced, plasmas can freely accommodate themselves so that their axial lengths are longer, which can reduce a possibility of plasma heating up.

(c) It allows the plasma CM motion which can be used for diagnoses.

TRAP DETAILS

Design In designing the trap, following two points are especially considered :

1. Preparation of 10^{6-7} antiprotons with sub-eV energy within one minute (the value of which comes from the pulse interval at AD).
2. Extraction of cooled antiprotons from the trap which is located in the strong magnetic field.

As low energy charged particles tend to follow the field line, it is essential to make the position of the particles as close to the axis as possible for their extraction as a beam. One solution is the application of a rotational electric field, known as a "rotating wall method". Such a field can exert a torque on the plasma so that the plasma shape can be changed [5,6]. This method is thought to be effective in our application and one of the electrodes is segmented for the radial compression of the plasma.

When the plasma composed of electrons and antiprotons is axially compressed in this way, it stretches in the harmonic region. It can be noted that the square potential does not allow such an axial expansion. To reduce the space potential while keeping the cooling power high enough, central harmonic region is elongated in the axial direction so that the density will be optimum. Multi-ring structure [7,8] is exploited to generate such a harmonic potential.

Supposing that an antiproton cloud (density n_p, temperature T_p[K]) and an electron cloud (density n_e, temperature T_e[K]) are uniformly mixed at a time $t = 0$, simulations were done to estimate the time necessary for the electron cooling of antiprotons. Using cgs units, time evolution of T_p and T_e were determined by following set of equations

$$\frac{dT_p}{dt} = \nu_{pe}(T_e - T_p) \tag{1}$$

$$\frac{dT_e}{dt} = \nu_{ep}(T_p - T_e) - T_e A \tag{2}$$

where $A \simeq \frac{8}{B[\mathrm{T}]^2}$ is a synchrotron radiation cooling rate found experimentally [8]. Using Boltzmann constant(k), electronic charge(e), electron mass(m_e) and antiproton mass(m_p), equilibration rates (ν_{pe}, ν_{ep}) are given by

$$\nu_{pe} = \frac{8\sqrt{2\pi}e^4}{3k^{\frac{3}{2}}} n_e \lambda_{pe} \frac{m_p^{\frac{1}{2}} m_e^{\frac{1}{2}}}{(m_p T_e + m_e T_p)^{\frac{3}{2}}} \tag{3}$$

$$\nu_{ep} = \frac{8\sqrt{2\pi}e^4}{3k^{\frac{3}{2}}} n_p \lambda_{ep} \frac{m_p^{\frac{1}{2}} m_e^{\frac{1}{2}}}{(m_p T_e + m_e T_p)^{\frac{3}{2}}} \tag{4}$$

In FIGURE 1 and 2, result are shown. Realistic experimental conditions are assumed : $B = 5$[T], $T_p(0) = 5.8 \times 10^7$[K](= 5000[eV]), $T_e(0) = 4$[K] , Coulomb logarithm $\lambda_{ep} = \lambda_{pe} \sim 30$. For the calculation in FIGURE 1, $n_p = 10^8$[cm^3], $n_e = 10^8$[cm^3] were inputted and in the FIGURE 2, $n_p = 10^8$[cm^3], $n_e = 10^9$[cm^3] were used.

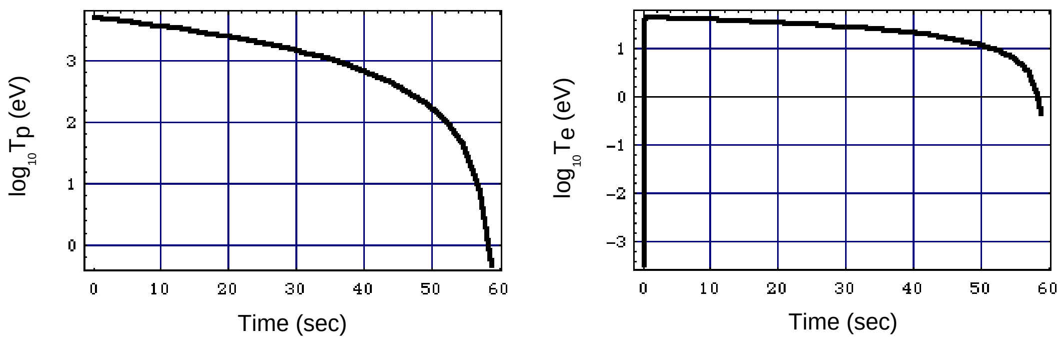

FIGURE 1. Simulation of electron cooling rate. ; $n_p = 10^8$[cm^3], $n_e = 10^8$[cm^3]

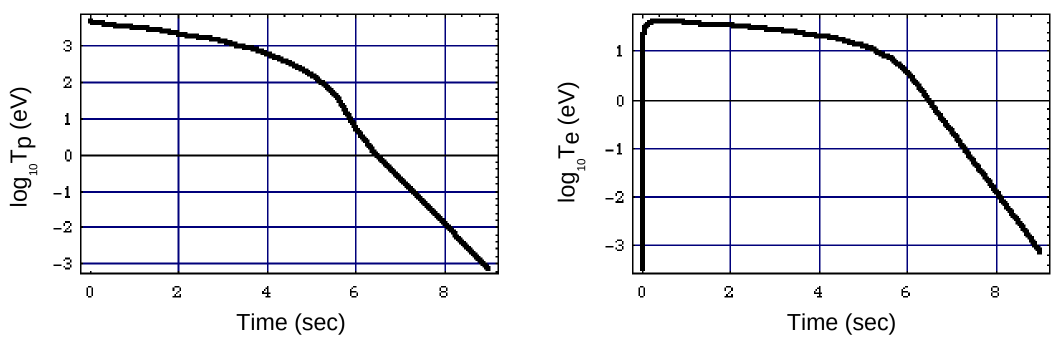

FIGURE 2. Simulation of electron cooling rate. ; $n_p = 10^8$[cm^3], $n_e = 10^9$[cm^3]

It is seen that electrons initially warmed up by incoming hot antiprotons lose their energy via synchrotron radiation and both antiprotons and electrons will be cooled below 1 eV within one minute. We may note that the cooling time will be longer if consider the anisotropy on the space and the temperature. Cooling time is thought to be optimized by adjusting the densities of two species.

Experimental Setup In FIGURE 3, shown are electrode configuration and schematic trap-cool-dump procedure. The ratio of the axial extent of the harmonic region to the radius of electrodes is about 5 times larger than that of a traditional Penning trap.

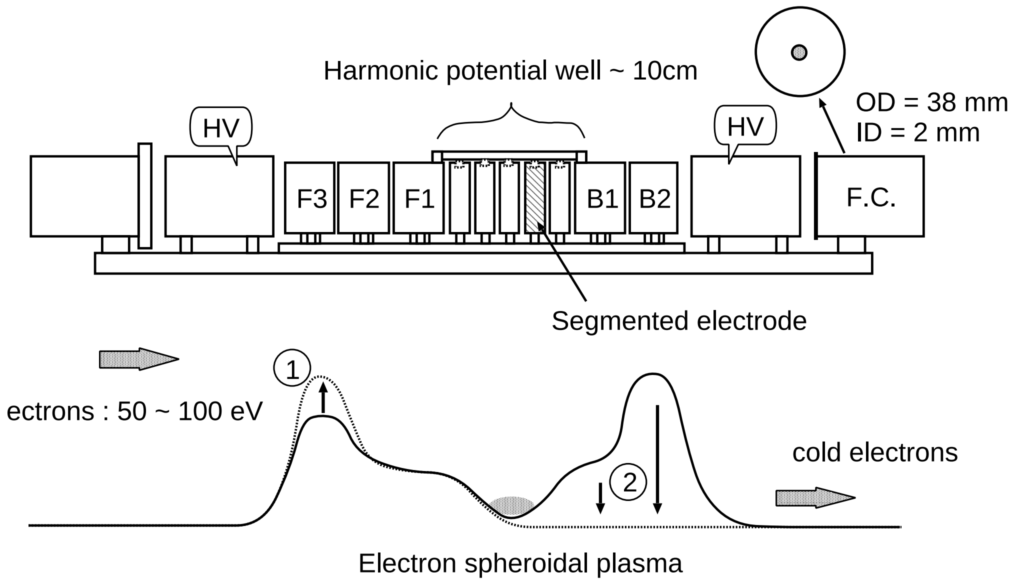

FIGURE 3. Configuration of trap electrodes. Inner diameter of cylindrical electrodes is 40 mm.

All the electrodes are made of OFHC copper with the machining precision of 10 μm and gold plated with the thickness enough to improve the surface property while the precision is tolerable. They are aligned on a base plate which is machined with the same precision. Insulation is done by pieces of AlN, which is known to be a good thermal conductor as well as an electric insulator.

For the application of rotational rf field, an electrode that is azimuthally segmented into four identical parts is located next to the one at the center. On one end of the trap there is a Faraday cup which serves as a destructive detector. It consists of two concentric parts as shown in FIGURE 3. In the future when the system is incorporated with the beam line, this part will be replaced by an grounded electrode. Two electrodes marked as HV are for the catching of energetic antiprotons.

All the system is installed in a superconducting solenoid. The uniformity of the magnetic field is better than $\pm 0.5\%$ within a region of 10 mm(D) $\times$ 1100 mm(L) and considered to be much better in the trapping region.

We also have a duoplasmatron ion source which can supply both proton and negative hydrogen ion beam. A negative hydrogen ion has a binding energy of 0.74 eV and can be used to simulate an antiproton in the low energy region. For tests like the injection of a high energy beam into the trap, protons will be used. A beam line which connects the ion source and the trap is already constructed and tested.

RESULTS

At first, electron trapping experiments were performed. A hot cathode located at the position 5cm off axis, in about 1 m from the center of the magnet (B-field strength $\sim$ 100G) is used to generate electrons. They were injected into the trap as a pulse train. Typical incident energy was 95 eV. Two HV electrodes were not used for electron trapping. Instead, two electrodes next to them (F3 and B2) were utilized for the initial confinement.

Trapping potential except the one for the entrance wall was formed beforehand(F2 - B2) and, by raising the potential height on the entrance(F3), confinement was completed(shown as 1 in the FIGURE 3). After a trapping period, electrons were dumped by changing the potential(shown as 2) and detected at the Faraday cup. Magnetic field strength was kept at 1 T during all the measurements.

The life time of electron plasmas was measured to be around 200 sec under the base pressure of 5×10^{-9} Torr.

In FIGURE 4, the effect of rotating electric field is shown. Sweep rate was set to be 2 MHz/min. There was shot-by-shot fluctuation in the number of electrons(about 10 %), which is not shown in the graph.

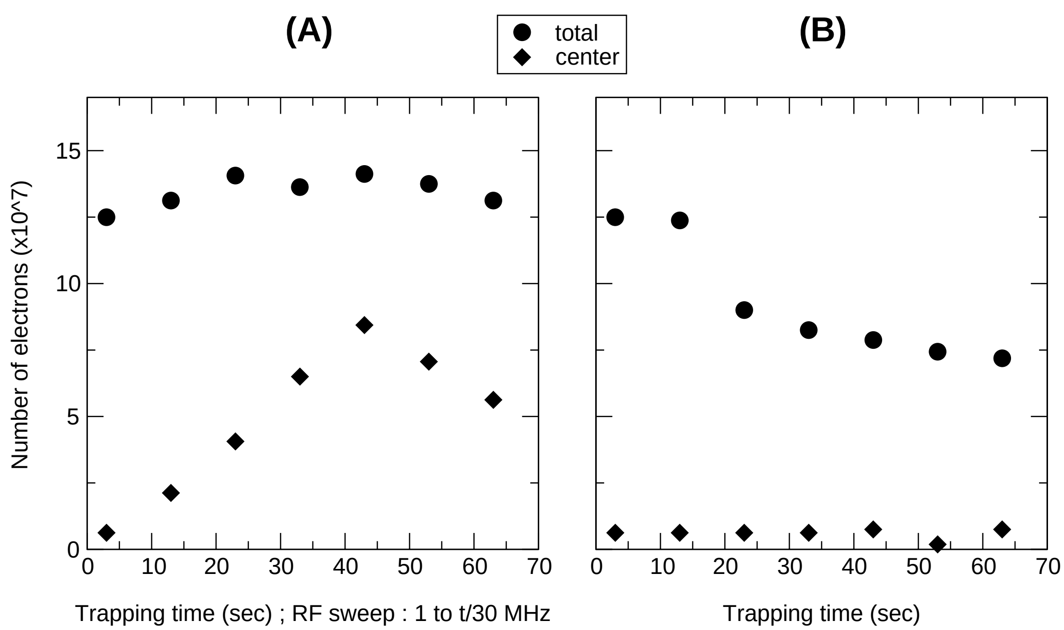

FIGURE 4. Effect of rotating electric field. (A) : with RF, (B) : without RF.

It was shown that the rotational electric field can compress the plasma and up to 60 % of the constituent particles was confined in a region of 2 mm in diameter. In addition, the life time of the plasma became longer. It can also be seen that the application of too high frequency reduces the fraction of electrons compressed radially. Since the effectiveness also depends on the sweep rate, optimization is still necessary. Generation of electrons by ionizing the residual gas was observed when the amplitude was too high.

Observation of radial and axial plasma modes by a spectrum analyzer has been also performed by picking signals up from the segmented electrode or one of the ring electrodes. When the rotational electric field was properly applied, (2,0) and (3,0) mode frequencies increased.

Injection of negative hydrogen beam was tried, though their plasma oscillations have not yet been observed. Electron cooling of them is in progress.

CONCLUSION

In a newly constructed Multi-Ring Electrode(MRE) trap, electrons were successfully trapped and electrostatic modes of plasmas are observed. The rotating wall method was applied and radial compression was achieved.

Simulation experiments are being performed with protons($\sim$50keV) and H^- ions($\sim$1keV) from a duoplasmatron ion source.

ACKNOWLEDGEMENTS

The work reported here is supported by the Grant-in-Aid for Creative Basic Research (10NP0101), Ministry of Education, Science, and Culture.

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