A new positron accumulator with electron plasma

Nagayasu Oshima,[*1] Takao M. Kojima,[*1] Dana Dumitriu,[*1] Akihiro Mohri,[*1] Hitoshi Oyama,[*1] Tadashi Kambara,[*1] Yasuyuki Kanai,[*1] Yoichi Nakai,[*1] Michiharu Wada,[*1] and Yasunori Yamazaki[*1,*2]
[*1] *Atomic Physics Laboratory, RIKEN*
[*2] *Institute of Physics, Graduate School of Arts and Sciences, University of Tokyo*

A new positron accumulation scheme with an electron plasma is presented. The electron plasma will be used as an energy absorber of positrons like a buffer gas. A unique feature of the scheme is an ability to accumulate a large number of positrons still keeping the whole system under ultra high vacuum (UHV) environment. The accumulation efficiency, which is defined as the ratio the number of the injected positrons into the accumulator to that of the accumulated positrons, is expected to be 20–30%. This accumulation efficiency is expected to be comparable to that of the nitrogen buffer gas technique which is known to be the most effective technique to accumulate positrons at present.

Introduction

It is known that multi-charged ions (MCIs) supplied from an EBIS (electron beam ion source) and ECRIS (electron cyclotron resonance ion source) have energy spreads around 10 eV/q or more, which is caused by, *e.g.*, a heat-up during sequential ionization and a finite potential distribution in the area where ionization takes. In order to expand the energy range of available MCIs much below the above limits, we have started a new project to produce ultra cold MCIs with a positron cooling technique.[1–3)]

The production scheme of cold MCIs is similar to that of cold antiprotons.[4–7)] Charged particles are stored in an electro-magnetic trap, which is mounted in a bore tube of a super-conducting solenoid. They lose their kinetic energy *via* synchrotron radiation, the rate of which is inversely proportional to the mass cubed. Hence light charged particles, namely electrons and positrons, would be useful coolants for heavy particles if they are stored simultaneously in a strong magnetic field. The reason to use positrons instead of electrons as coolants is to avoid recombination loss of MCIs.

In order to make this scheme feasible, a large number of positrons have to be accumulated in the trap. Up to now, the most efficient technique to accumulate positrons is the one developed by Surko *et al.*,[8,9)] where nitrogen gas is used as a buffer to absorb the kinetic energies of positrons, which are eventually captured in a potential valley of the trap.

The electro-magnetic trap, where ions and positrons are stored together, is cooled down to ∼6 K to realize an ultra high vacuum environment, because MCIs are lost through collisions with residual buffer gases.[3)] Hence, it is concluded that the positron accumulation technique using buffer gas is not applicable to the above scheme and we have to develop a new technique of positron accumulation where no buffer gas is necessary.

Here, a new positron accumulation scheme is proposed with an electron plasma. In the new scheme, an electron plasma works as an energy absorber instead of buffer gas, where the whole system could be held under a UHV condition.

A scheme of a positron accumulation

The electro-magnetic trap[10)] consists of 30 ring electrodes, which is installed in a 2 m long bore of a superconducting solenoid. The solenoid can yield magnetic field flux $B = 5\,\mathrm{T}$ in the central volume of 0.8 m in length and 4 mm in diameter. A brief sketch of the electro-magnetic trap is shown in Fig. 1. The detailed design parameter of the trap and the solenoid are described elsewhere.[3)]

The scheme of positron accumulation is schematically shown in Fig. 2. At first, an electron plasma, which is the energy absorber of positrons, is prepared (Fig. 2 (a)). Electrons are injected into the trap and are captured by ramping the electron trap gate. The electrons lose their energy through synchrotron radiation and are accumulated at the top (saddle point) of the electric potential because of their negative charge.

After a cold electron plasma is formed, positrons are injection into the trap and implanted into a removable remoderator (tungsten single crystal) prepared on the other side of the trap (Fig. 2 (b)). It is known that 20–30% of the implanted positrons are reemited into the vacuum,[11,12)] which interact with the electron plasma. If the electron density is high enough and the positron kinetic energy is low enough, the

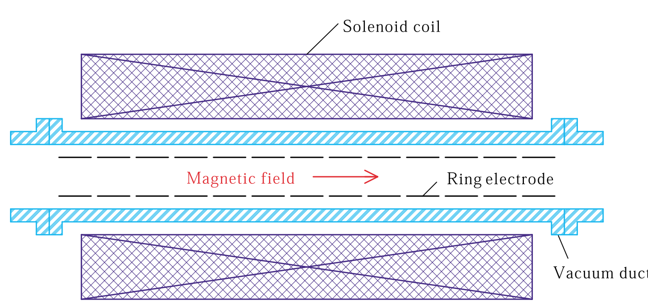

Fig. 1. Schematic drawing of the electro-magnetic trap used for positron accumulation. Charged particles can be trapped axially by an electric field and radially by a magnetic filed in the trap.

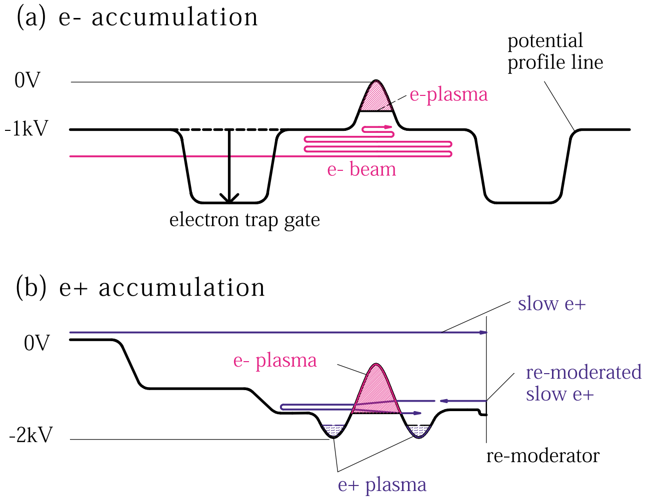

Fig. 2. Schematic view of the positron accumulation scheme using an electron plasma.

positrons lose considerable amount of energy and are eventually trapped. The trapped positrons will further lose their energy through synchrotron radiation and a positron plasma is formed on both sides of the electron plasma.

In the following sections, the slow positron source and the required electron plasma for the above scheme are described in detail.

Slow positron production and its manipulation

Slow positrons[11)] are produced through moderation of fast positrons which are emitted from a β^+ decay radioisotope. The energy spread of slow positrons so prepared are typically a few eV. In our study, the combination of a ^{22}Na radioactive source (44 mCi) and a solid neon (Ne) moderator is used.[13)]

Rare gas solids, especially solid Ne, are well known to be efficient moderators for positrons.[11,14,15)] Fast positrons injected into a moderator lose their energy *via* collisions till their energies reach the lowest electronic excitation energy of Ne ($\sim$16 eV). Bellow this energy, the energy loss rate drastically decreases because only phonon excitation processes can contribute to the energy loss. Because of this, the diffusion length of these positrons get as long as $\sim \mu$m and a considerable fraction of them are ejected into the vacuum as slow positrons.[16)] A typical efficiency of the solid Ne moderator is $\sim$0.5%,[15)] which is defined by the ratio of the number of extracted slow positrons to the number of β^+ decays of the radioisotope. Slow positrons with an intensity of 7×10^6 e^+/s are expected to be available with a 44 mCi ^{22}Na positron source.[15)]

Figure 3 shows a drawing of the positron source assembly. An encapsulated ^{22}Na positron source is mounted on a cold-head of a refrigerator and is cooled down to 5 K so that a solid rare gas moderator is formed on the front surface of the ^{22}Na source. Slow positrons are accelerated with the electrodes in front of the source and then guided magnetically to the cooling trap. Specifications of the encapsulated ^{22}Na positron source and the slow positron source are given in Tables 1 and 2, respectively.

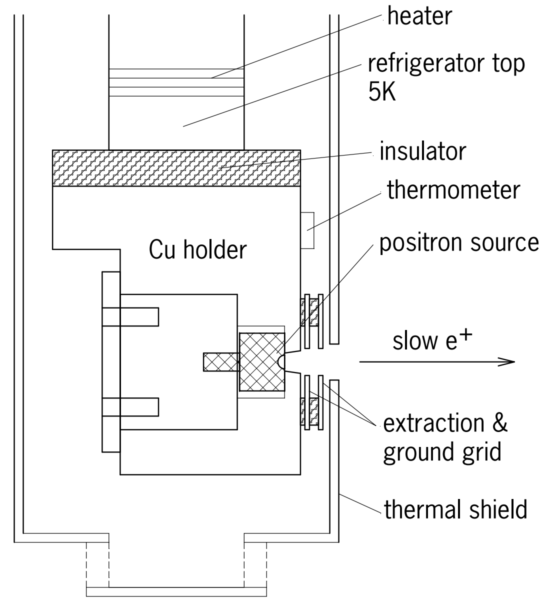

Fig. 3. Drawing of the positron source assembly.

Table 1. Specifications of the encapsulated positron source.

Positron source	^{22}Na (44 mCi)
Source lifetime	2.6y
Na compound	Sodium acetate
Specific radioactivity	1100 mCi/mg
Source active diameter	3 mm
Source capsule window	Ti 13 μm

Table 2. Specifications of the slow positron source.

Positron source	^{22}Na (44 mCi)
Moderator	Solid Ne
Expected moderation efficiency	5×10^{-3}
Expected beam intensity	7×10^6 positrons/s
Beam energy	0–200 eV
Expected energy spread	2 eV
Beam diameter	5 mm

A schematic drawing of the positron beam line is shown in Fig. 4. The coils installed along the beam line yield a magnetic field of about 10 mT and guide the slow positrons to the trap. To eliminate fast positrons, a bending solenoid was prepared on the beam line. The positron beam line merges with an MCI beam line and is connected to the solenoid.

When a charged particle is adiabatically guided in a magnetic field, the magnetic moment, which is defined by $\frac{1}{2}mv_\perp^2/B$, is constant, where m is the mass of the particle and $v_\perp$ the velocity of the particle perpendicular to B.[17)] B increases by a factor of 500 while the positrons travel from the positron source (10 mT) to the solenoid (5T). This indicates that $E_\perp = \frac{1}{2}mv_\perp^2$ also increases by a factor of $\sim$500. As $E_\perp$ is known to be 0–2 eV,[15)] the positron energy must be higher than $\sim$1 keV for them to be guided into the trap. Otherwise, a part of the positrons are reflected. In other words,

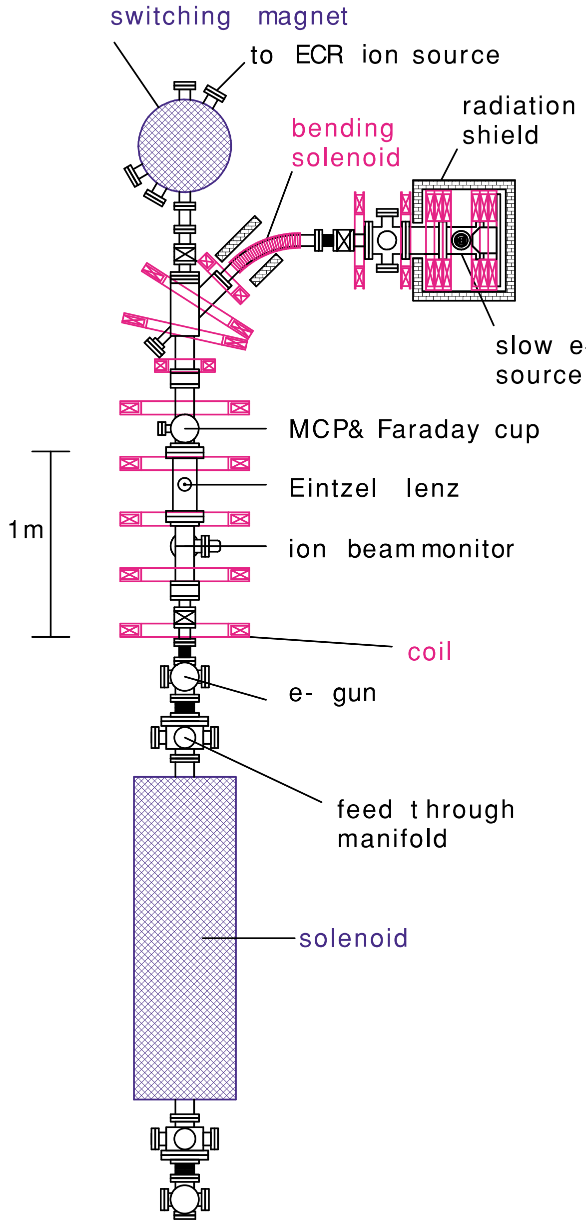

Fig. 4. Brief sketch of the beam line. The beam line is still under construction.

the kinetic energy of positrons in the solenoid inevitably have energy spread of ∼1 keV parallel to the magnetic field.

The radius of the positron beam, which is ∼2.5 mm at the moderator, is expected to be compressed down to ∼0.1 mm in the trap because the diameter is inversely proportional to $B^{1/2}$.

As described in the previous section, positrons are implanted once into the remoderator, tungsten (W) single crystal, in order to reduce positron energy spread. The penetration depth of positrons in W when they are implanted with 1 keV is about 20 nm. While the positron diffusion length in W is about 55 nm.[12)] Therefore, almost all the implanted positrons into W will return the incident surface. Positrons reached the surface may be 1) reemitted into vacuum as slow positrons, 2) converted into positroniums, or 3) trapped at a surface. The branching ratio of each process is known to be almost the same, *i.e.*, about 30%.[11,12)] The kinetic energy of the reemitted positrons is 2–3 eV, *i.e.*, the energy width of the positron beam is ∼1 eV.

Such slow positrons are injected into the pre-loaded electron plasma (see Fig. 2 (b)), and lose their kinetic energy. If the positrons lose more than 1 eV in the electron plasma, *i.e.*, more than the energy spread of the beam, the potential distribution of the trap can be arranged so that all of them do not return the remoderator and are captured in the trap. Such positrons lose energy further by synchrotron radiation.

It is expected that 10^8 positrons are necessary to cool 10^6 MCIs from ∼2 keV/q down to ∼100 K within a few seconds at $B = 5$ T. The overall trapping efficiency of positrons by the new method is expected to be 20–30%. Then if slow positrons are injected into the trap with intensity of $7\times10^6 e^+$/s, the required number of positrons (10^8) for the MCI cooling can be prepared within 100 s.

In the next section, the details of electron plasma, which is required for the positron accumulation, are discussed.

Details of electron plasma

The density(n_{e^-}) and length(L) of the electron plasma should be large enough so that the energy loss of the slow positron beam is larger than the energy spread of the remoderated positron (∼1 eV). In order to determine n_{e^-} and L, the stopping power of a positron in an electron plasma has to be evaluated. The stopping power of a positron, which has kinetic energy E_{e^+}, in an electron plasma was estimated by a free electron gas model, in which the stopping power dE/dx is calculated by

$$\frac{dE(E_{e^+})}{dx} = n_{e^-} \cdot \int_0^{b_{\max}} \delta E(E_{e^+}, b) 2\pi b db,$$

$$\delta E(E_{e^+}, b) = \left(1 - \frac{1}{\{1 - (e^2/8\pi\epsilon_0 E_{e^+} b)^2\}^2}\right),$$

where $\delta E(E_{e^+}, b)$ is the energy loss of the positron during a collision with an electron at its impact parameter b, e the elementary electric charge, ϵ_0 the permittivity *in vacuum*, and $b_{\max}$ the maximum impact parameter which is given by the Debye shielding length of the plasma. Collisions with $b > b_{\max}$ contribute to plasma excitations, which are negligibly smaller than the above two body collisions in the present conditions. Figure 5 shows the two results of the calculated stopping power of the positron in an electron plasma of $n_{e^-} = 10^{17}\,\mathrm{m}^{-3}$. The difference parameters in the two calculations are electron plasma temperatures T_e(0.1 eV and 1 eV), which affect Debye shielding length ($b_{\max}$) by formula $b_{\max} = (\epsilon_0 k T_e/e^2 n_{e^-})^{1/2}$, where k is the Boltzmann constant. There are no considerable difference between the two results. At $E_{e^+} = 6$ eV, the stopping power is ∼ 2.2 eV/m, hence, the necessary length of the electron plasma is about 25 cm considering that the 6 eV positrons pass through the electron plasma two times before returning to the remoderator as shown in Fig. 2 (b).

It is known that if a harmonic electric potential is formed along the z axis, the lifetimes of plasmas get longer.[10)] As

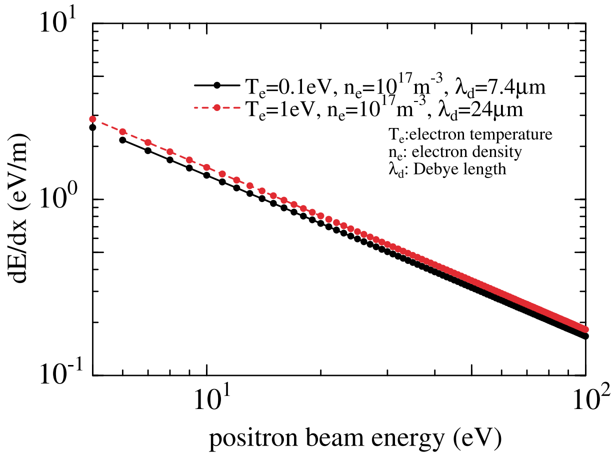

Fig. 5. Calculated positron stopping power in free electron gas. The difference parameter between two calculations are plasma temperatures, $T_e = 0.1$ eV, and 1 eV.

shown schematically in Fig. 1, the electro-magnetic trap used in our project consists of multi ring electrodes, which allows to accumulate a large number of charged particles stably, because a precise harmonic potential can be formed over all large area. The shape of the plasma in the harmonic electric potential is known to be spheroidal.[10,18] If positrons are injected into the spheroidal electron plasma, the interaction length of the positrons, L, in the plasma depends on the radial position, r. The ratio of $L(r)$ to $L(0) = 2R_z$ is shown in Fig. 6 as a function of r/R_r, where R_z and R_r are radii of the spheroid in the z and r directions, respectively. In case the allowable $L(r)/L(0)$ is set to be ∼0.85, the radius of the electron plasma should be twice that of the positron beam. As the positron beam radius is expected to be 0.1 mm as described in the previous section, the electron plasma radius R_r is to be tuned 0.25 mm.

There is no electric potential gradient along the magnetic field, because electrons can move freely parallel to the field and they screen the potential gradient. However, the potential gradient perpendicular to the magnetic field exists. The shape of the required electron plasma is very long and its aspect ratio is almost 500. The electric field in the plasma is straight perpendicular to the magnetic field and so the equipotential line is parallel to the magnetic field, which is shown schematically in Fig. 7. The r dependent potential $V(r)$ is given by[18]

$$V(r) = \frac{1}{4} \cdot m\omega_p^2 r^2/e = \frac{1}{4} \cdot \frac{n_{e-}e}{\varepsilon_0} \cdot r^2,$$

where $\omega_p = (e^2 n_{e-}/\epsilon_0 m)^{1/2}$ is the plasma frequency. In the case that n_{e-} is 10^{17}e$^-$/m^3, $V(r = 0.1\,\mathrm{mm})$ is 4.5 V higher than $V(r = 0)$, *i.e.*, the energy of positrons in the plasma at $r = 0$ mm is 4.5 eV higher than that at $r = 0.1$ mm even when monoenergetic positrons are injected. Because the stopping power is inversely proportional to the injection energy, positrons injected at large r lose energy quickly, which partly compensate for the short plasma length.

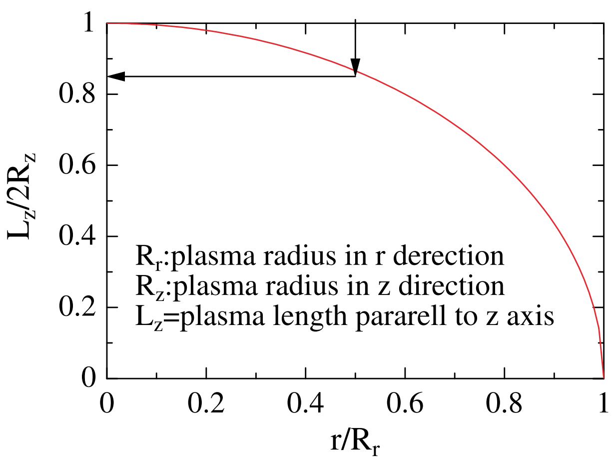

Fig. 6. Dependence of the spheroid plasma length along to z axis on r position.

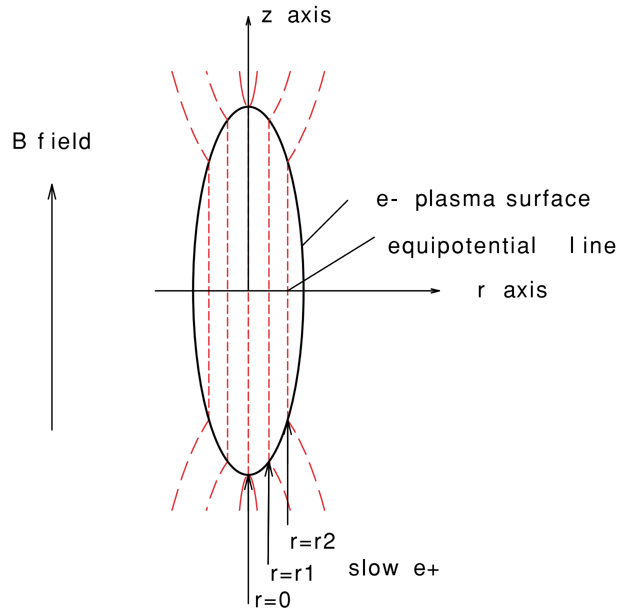

Fig. 7. Image drawing of the equipotential line in a plasma (not scaled).

Parameters of the electron plasma required for the positron accumulation are summarized in Table 3.

Table 3. Parameters of electron plasma.

Total electron number, $N_{e-} > 3.3 \times 10^9 (=\sim 10^{10})$
Magnetic field flux, $B = 5$ T
Radius on r axis, $R_r = 1.25 \times 10^{-1}$ m
Radius on z axis, $R_z = 2 \times 10^{-4}$ m
Aspect ratio = 500
Volume = 4.3×10^{-8} m^3
Density, $n_{e-} = 10^{17}$ m^{-3}
Cyclotron frequency = 8.8×10^{11} (s^{-1})
Plasma frequency = 1.8×10^{10} (s^{-1})
Bounce frequency (single particle) = 8.7×10^7 (s^{-1})
Rigid rotation frequency = 1.8×10^8 (s^{-1})
Debye length = 7.4×10^{-6} m (in case (3/2)kT_{e-} = 0.1 eV)
Brillouin Density limit = 1.2×10^{20} m^{-3}

Conclusion

A new positron accumulation scheme using an electron plasma is briefly introduced. The trapping efficiency of positrons with this method is expected to be 20–30%, which is determined by the remoderation efficiency of the remoderator in the trap. If $\sim 7\times 10^6 e^+$/s slow positrons are available by combining a Ne moderator and a ^{22}Na (44 mCi), we can obtain the necessary number of the positrons (10^8) within 100 s of accumulation. The new accumulation scheme is expected to have a comparable accumulation rate as the nitrogen buffer gas technique, and, at the same time, is expected to be operative under UHV condition which is essential in the MCI cooling scheme. It is noted that the present technique will also be a potential tool to produce antihydrogen.

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