A new positron accumulator with electron plasma

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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 electromagnetic trap, which is mounted in a bore tube of a superconducting 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.,∗ 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 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 $B = 5 T$ 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 reemitted into the vacuum,1,12) which interact with the electron plasma. If the electron density is high enough and the positron kinetic energy is low enough, the
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 \(\beta^+\) 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.\(^{12}\)

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 (~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 ~ \(\mu\)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 \(\sim0.5\%\).\(^{15}\) The ratio of the number of extracted slow positrons to the number of \(\beta^+\) decays of the radioisotope. Slow positrons with an intensity of \(7 \times 10^6\) 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. 2. Schematic view of the positron accumulation scheme using an electron plasma.](image)

![Fig. 3. Drawing of the positron source assembly.](image)

<table>
<thead>
<tr>
<th>Table 1. Specifications of the encapsulated positron source.</th>
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<tbody>
<tr>
<td><strong>Positron source</strong></td>
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<tr>
<td><strong>Source lifetime</strong></td>
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<td><strong>Na compound</strong></td>
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<tr>
<td><strong>Specific radioactivity</strong></td>
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<td><strong>Source active diameter</strong></td>
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<td><strong>Source capsule window</strong></td>
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<table>
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<tr>
<th>Table 2. Specifications of the slow positron source.</th>
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<tbody>
<tr>
<td><strong>Positron source</strong></td>
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<tr>
<td><strong>Moderator</strong></td>
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<tr>
<td><strong>Expected moderation efficiency</strong></td>
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<tr>
<td><strong>Expected beam intensity</strong></td>
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<td><strong>Beam energy</strong></td>
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<tr>
<td><strong>Expected energy spread</strong></td>
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<tr>
<td><strong>Beam diameter</strong></td>
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</table>

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 \(\frac{1}{2}mv^2/L\), 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 (5 T). This indicates that \(E_\perp = \frac{1}{2}mv_\perp^2\) also increases by a factor of ~500. As \(E_\perp\) is known to be 0–2 eV,\(^{13}\) the positron energy must be higher than ~1 keV for them to be guided into the trap. Otherwise, a part of the positrons are reflected. In other words,
The branching ratio of each process is known to be almost
2) converted into positroniums, or 3) trapped at a surface.
A surface may be 1) reemitted into vacuum as slow positrons,
into W will return the incident surface. Positrons reached the
about 55nm. While the positron diffusion length in W is
of positrons in W when they are implanted with 1keV is
Der to reduce positron energy spread. The penetration depth
once into the remoderator, tungsten (W) single crystal, in or-
As described in the previous section, positrons are implanted
B
in the trap because the diameter is inversely proportional to
The radius of the positron beam, which is ∼2.5mm at the
moderator, is expected to be compressed down to ∼0.1mm
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 or-
order to reduce positron energy spread. The penetration depth
of positrons in W when they are implanted with 1keV is
about 20nm. While the positron diffusion length in W is
about 20nm. 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%.

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 1eV in the electron plasma, i.e.,
more than the energy spread of the beam, the potential dis-
tribution 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 10⁸ positrons are necessary to cool 10⁶
MCIs from ∼2keV/q down to ∼100K within a few seconds
at B = 5T. 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 7×10⁶e⁻/s, the re-
quired number of positrons (10⁸) for the MCI cooling can be
prepared within 100s.

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

Details of electron plasma
The density(nₑ⁻) 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 remod-
erated positron (∼1eV). In order to determine nₑ⁻ 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 Eₑ⁺, in an electron plasma was estimated by a
free electron gas model, in which the stopping power dE/dx
is calculated by

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

\[ \delta E(E_{e+}, b) = \left(1 - \frac{1}{(1 - (e^2/8\pi\epsilon_0E_{e+}b)^2)^2} \right), \]

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, \( \epsilon_0 \) the permittivity in vacuum,
and \( b_{\text{max}} \) the maximum impact parameter which is given by
the Debye shielding length of the plasma. Collisions with
\( b > b_{\text{max}} \) contribute to plasma excitations, which are neg-
ligibly smaller than the above two body collisions in the
present conditions. Figure 5 shows the two results of the cal-
culated stopping power of the positron in an electron plasma
of \( n_{e-} = 10^{17} \text{m}^{-3} \). The difference parameters in the two
calculations are electron plasma temperatures \( T_e \) (0.1eV and
1 eV), which affect Debye shielding length (\( b_{\text{max}} \)) by formula
\( b_{\text{max}} = (e_0 k T_e / e^2 n_{e-})^{1/2} \), where k is the Boltzmann
constant. There are no considerable difference between the two
results. At \( E_{e+} = 6 \text{eV} \), the stopping power is ∼2.2 eV/m,
hence, the necessary length of the electron plasma is about
25cm considering that the 6eV positrons pass through the
electron plasma two times before returning to the remoder-
ator 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.
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 \(L(0) = 2R_e\) is shown in Fig. 6 as a function of \(r/R_e\), where \(R_e\) 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 \(\sim 0.85\), 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 \(R_e\) 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\(^{(18)}\)

\[
V(r) = \frac{1}{4} \cdot m \omega_p^2 r^2 / e = \frac{1}{4} \cdot \frac{n_e^- e}{\epsilon_0} \cdot r^2,
\]

where \(\omega_p = (\epsilon^2 n_e^- / e_0 m)^{1/2}\) is the plasma frequency. In the case that \(n_e^-\) is \(10^{17} \text{e}^-/\text{m}^3\), \(V(r = 0.1 \text{mm})\) 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.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Total electron number, (N_e^-)</td>
<td>(&gt; 3.3 \times 10^{20}(= \sim 10^{20}))</td>
</tr>
<tr>
<td>Magnetic field flux, (B)</td>
<td>(5 \text{T})</td>
</tr>
<tr>
<td>Radius on (r) axis, (R_r)</td>
<td>(1.25 \times 10^{-1} \text{m})</td>
</tr>
<tr>
<td>Radius on (z) axis, (R_z)</td>
<td>(2 \times 10^{-4} \text{m})</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>500</td>
</tr>
<tr>
<td>Volume</td>
<td>(4.3 \times 10^{-8} \text{m}^3)</td>
</tr>
<tr>
<td>Density, (n_e^-)</td>
<td>(10^{17} \text{e}^-/\text{m}^3)</td>
</tr>
<tr>
<td>Cyclotron frequency, (\omega)</td>
<td>(8.8 \times 10^{11} \text{s}^{-1})</td>
</tr>
<tr>
<td>Plasma frequency, (\omega_p)</td>
<td>(1.8 \times 10^{10} \text{s}^{-1})</td>
</tr>
<tr>
<td>Bounce frequency (single particle)</td>
<td>(8.7 \times 10^{7} \text{s}^{-1})</td>
</tr>
<tr>
<td>Rigid rotation frequency</td>
<td>(1.8 \times 10^{8} \text{s}^{-1})</td>
</tr>
<tr>
<td>Debye length</td>
<td>(7.4 \times 10^{-6} \text{m}) (in case ((3/2)kT_e^- = 0.1) eV)</td>
</tr>
<tr>
<td>Brillouin Density limit</td>
<td>(1.2 \times 10^{20} \text{m}^{-3})</td>
</tr>
</tbody>
</table>

### 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 100s 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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References