Recent status of A Positron-Electron Experiment (APEX)

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Abstract. A project is underway to generate an electron-positron plasma by using the NEPOMUC positron source at the FRM-II facility combined with a multicell-type Penning trap (PAX) and a superconducting dipole magnetic field trap (APEX). In the APEX project, proof-of principle experiments are proposed for the development of efficient injection methods of positrons by using a small dipole magnetic field trap with a permanent magnet. Plans for the APEX project and its recent status are reported.

1. Introduction

There has been growing interest in the formation of an electron-positron plasma in a laboratory [1]. Conventional plasmas are characterized by large mass differences between electrons and ions. Many plasma phenomena, such as wave propagation and stability properties, are strongly related to the mass asymmetry and differences in the mobility of electrons and ions. Unlike conventional plasmas, the electron-positron plasma is in the class of pair plasmas, plasmas consisting of equal-mass particles. It is theoretically predicted that pair plasmas exhibit unique physical properties. According to theoretical studies and recent observation in γ-ray astronomy, formation of a large amount of electrons and positrons is predicted in pulsar magnetospheres and active galactic nuclei. Thus the experimental understanding of the electron-positron plasma is also important for astrophysics.

Although theoretical studies have been conducted intensively, there are very few experiments to generate an electron-positron plasma. This is mainly because of (1) the difficulty in the simultaneous confinement of electrons and positrons as plasmas, and (2) the availability of strong positron sources. (1) Concerning the confinement configurations, stable confinement of non-neutral pure electron plasmas has been demonstrated in a toroidal stellarator [2] and in a dipole magnetic field trap [3]. One can confine plasmas at any degree of non-neutrality in the toroidal geometries in principle. Based on these experiments, we will construct A Positron-Electron Experiment (APEX) for the confinement of the electron-positron plasma. (2) The positron source, NEPOMUC [4] at the FRM-II facility is the brightest DC moderated source in the world, with a rate in the order of 10^9 positrons s^{-1}. Moreover, the development of a Positron Accumulation Experiment (PAX) is underway for the accumulation and fast extraction of a large amount of cold positrons. PAX consists of a multicell-type Penning trap and is designed to trap of the order of 10^{11} positrons and extract them in a few milliseconds.

We plan to generate an electron-positron plasma in combination with the NEPOMUC, PAX, and APEX facilities [1]. In this report, we focus on the APEX project and present its plans and recent status. While excellent confinement properties are expected in the closed toroidal geometry, it is not

straightforward to transport positrons from the source to the trap region. For this purpose, two methods have been proposed [1]. One is to use external electric fields and the other is to use positronium as intermediate particles, which are generated on single crystal surfaces [5] hit by the DC positron beam. Prior to the pair plasma experiment to be conducted in a superconducting dipole field trap, we plan to conduct proof-of-principle experiments to test the injection methods by using a small dipole field trap with a permanent magnet. The required parameters for the pair plasma formation and plans for the small trap experiment are described in the following sections.
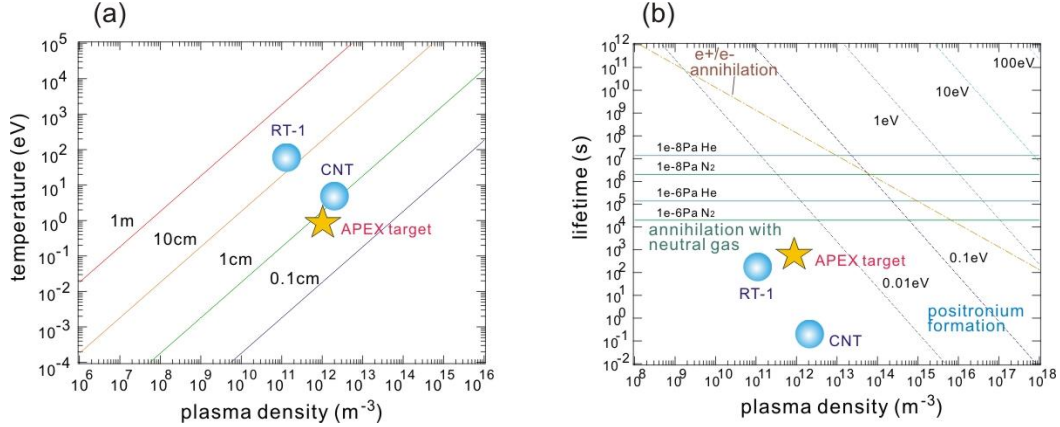

Figure 1. (a) Debye length and (b) life times of positrons set by neutral collision, annihilation with electrons, and positronium formation for various number density and temperature [6].

2. Required parameters for pair plasma production and proof-of-principle experiments

2.1. Target parameters for pair plasma production in APEX

In order to observe collective plasma phenomena of a charged particle cloud, the scale length a of the cloud must be larger (preferably $a > \sim 10\lambda_D$) than the Debye length $\lambda_D = \sqrt{k_B T_e / n_e e^2}$, a typical length of electrostatic shielding [1]. The key techniques are (1) efficient injection methods of a large amount of low temperature positrons into a confinement region with small volume and (2) excellent confinement properties during injection, confinement, and mixing phases. Because the condition $a \sim 10\lambda_D$ is achieved when temperatures $T_e = 1$ eV and a number density $n_e = 10^{12}$ m^{-3} for a realistic scale of $a \sim 10$ cm, we set these parameters as a target (Fig. 1 (a)). By using the DC positron beam, the required confinement time of the trap is ~ 10 s when the confinement region volume $V \sim 10^{-2}$ m^{-3}. Although the maximum confinement time of a toroidal pure electron plasma exceeds this value, it is difficult to realize such a long confinement by using the relatively weak DC positron beam, clearly showing the importance of the PAX development. The total efficiency (after transport, cooling, and mixing with electrons) above 10% is needed for the injection of 10^{11} positrons from PAX to APEX.

As an antimatter plasma, the effects of (1) annihilation with neutral particles, (2) pair-annihilation with electrons, and (3) positronium formation processes should be considered as well as confinement properties of the trap system. We estimate the lifetimes τ of positrons set by these effects according to Ref. [6] for the above target parameters. (1) As shown in Fig. 1 (b) with solid lines, positron annihilation on neutral gas is negligible in clean UHV environments. For nitrogen gas, $\tau = 2 \times 10^4$ s at pressure 10^{-6} Pa, which is routinely obtained with a standard vacuum system. (2) When mixed with positrons, the dominant two photon annihilation time $\tau[s] \sim 10^{20}/n_e[\text{m}^{-3}]$, and the annihilation effects are again negligible for low density plasmas, as plotted with a chain line in the figure. (3) Lifetimes set by the three body recombination process are plotted with dot lines for different electron and positron temperatures. It is likely that this effect will not be a problem but may cause significant loss of plasmas at very cold (<0.01eV) and high-density (>10^{14} m^{-3}) cases. In addition to these effects, it is possible that instabilities and enhanced turbulent transport emerge due to the two fluid effects, which should be investigated when positrons are mixed with electrons in future experiments.
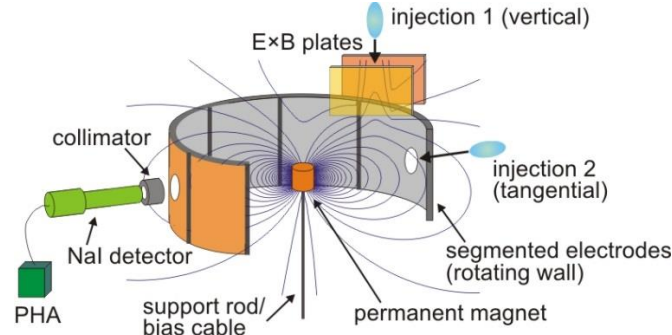
Figure 2. Schematic drawing of a proof-of-principle experiment, including the supported neodymium magnet, E×B plates for vertical injection, rotating wall for tangential injection, and diagnostics.

2.2. Proposed proof-of-principle experiments in a small dipole field trap

As a first step experiment, we will develop appropriate injection schemes of positrons (1) by using the effects of external electric fields, and (2) by using the positronium reemission process on solid materials in this proof-of-principle experiment [1,5] . These experiments will be conducted in a small dipole magnetic field illustrated in Fig. 2. The dipole field is generated by a mechanically supported neodymium magnet and the typical field strength in the confinement region is 0.05T.
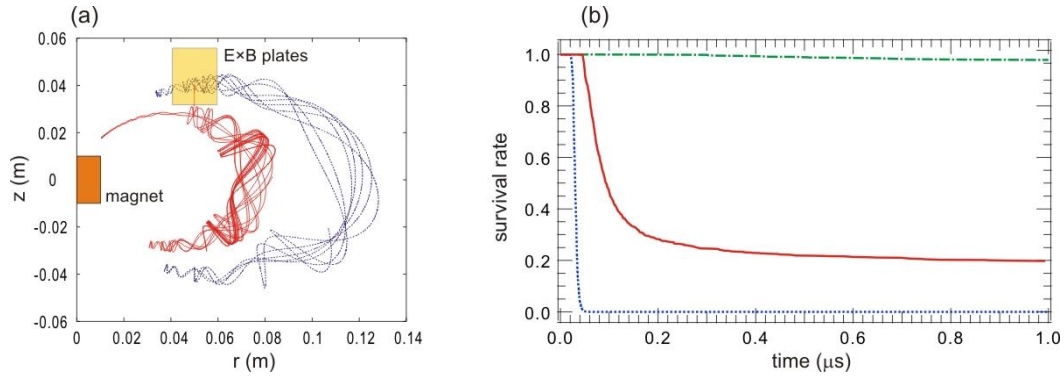

Figure 3. (a) Typical positron orbit projected onto the *r-z* cross section when the electric field is applied (solid line) and not applied (dot line). Electric field of $\mathbf{E} = 1 \times 10^3$ V/m was applied in the marked region from t=0 to 0.1μs. (b) Ratios of remaining positrons after injection without $\mathbf{E}$ (dot line), with the application of $\mathbf{E}$ (solid line), and when the magnet was also biased (chain line).

In order to inject positrons from the guiding field of the beam line into the confinement region, positrons must be transported across closed field lines. As injection methods by using external electric fields, we plan to test two procedures. The first one is a vertical injection scheme by using the $\mathbf{E} \times \mathbf{B}$ drift motion induced by a local crossed electric field. As shown in Fig. 2, the positron beam is vertically guided to the peripheral region of the dipole field, where a local electric field is applied in the perpendicular direction. Figure 3 (a) shows the typical orbits of a positron with a kinetic energy of 10 eV. Without the application of $\mathbf{E}$, the guiding centre motion is trapped on the location of the initial field line (the dot line in the figure). After reflection motions of finite times between the mirror points, positrons are reflected back to the beam line. By applying $\mathbf{E}$, positrons are radially transported into the confinement region (the solid line in the figure). Figure 3 (b) shows the calculated remaining ratio of 3086 positrons with vertical energy of 10 eV and perpendicular energy of 0 to 3 eV. When $\mathbf{E}$ is not applied, as plotted with the dot line, positrons are immediately lost after injection by hitting the $\mathbf{E} \times \mathbf{B}$ plates. By applying $\mathbf{E} = 1 \times 10^3$ V/m from t=0 to 0.1μs, as shown by the solid line, the loss on the $\mathbf{E} \times \mathbf{B}$ plate is suppressed and approximately 20 % of the injected positrons survived at *t*=1μs. The main loss channel in this case is the magnet surface, and it is further suppressed by positively biasing the magnet (the chain line), realizing the remaining rate of 98 %. The second scheme with external electric

fields is to use a rotating wall (a technique to generate field asymmetry by using segmented electrodes [7]) with tangential positron injection. A charged particle in a poloidal dipole field undergoes a toroidal rotation due to the grad B and curvature drifts. The typical rotation frequency for a 10 eV positron in the present configuration is in the order of MHz. By applying an azimuthal electric field by using segmented electrodes (Fig. 4 (a)) in the dipole field, effective radial transport is induced. Figure 4 (b) shows the typical orbits of a positron. When the rotating wall frequency is synchronized with the rotation frequency of the positron, positrons are effectively transported to the confinement region. After transported inward, positrons are expected to relax into an equilibrium state in the dipole field. For the diagnostics of the injected number of positrons, finally the magnet is negatively biased so that trapped positrons are dumped onto the magnet surface. The γ rays from annihilation are counted by a scintillator detector with a pulse height analysis system.
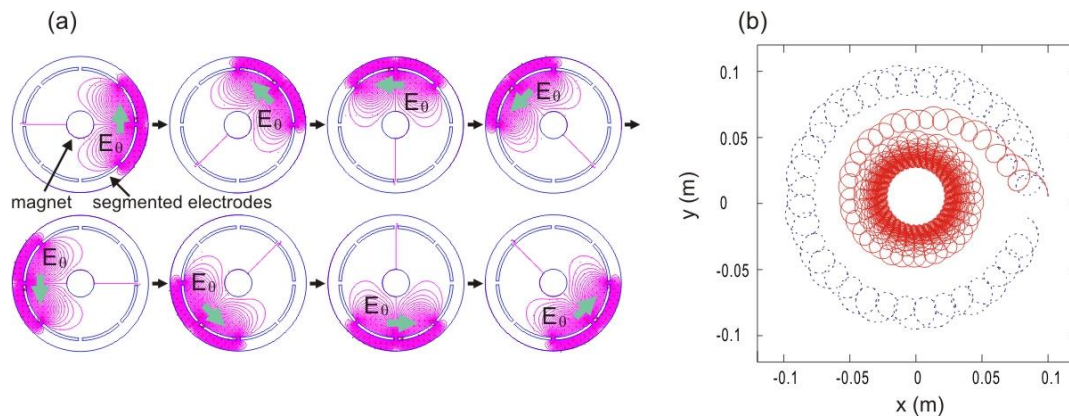

Figure 4. (a) Schematic view of a rotating wall and equipotential contours generated by the segmented electrodes. (b) Typical positron orbits with (dot line) and without (solid line) the rotating wall.

As a second positron injection method [1], positrons are guided to solid state materials and converted into positronium atoms [5]. The neutral positrons are freely transported into the confinement region, where they are photo ionized to generate an equal amount of electrons and positrons. We will study the formation ratio of positrons by injecting the positron beam from NEPOMMUC and access the feasibility for the electron-positron plasma formation. As well as lifetime measurements, a coincident Doppler-broadening spectroscopy will be applied for the measurements [8].

3. Summary and outlook
Aiming for the electron-positron plasma experiment, we have started the APEX project and plan to develop injection methods of positrons by using a small-scale dipole magnetic field trap with a permanent magnet. Based on these proof-of-principle experiments to investigate the injection efficiency of positrons scheduled to be carried out in 2014, we plan to construct a superconducting levitated dipole field trap and simultaneously confine positrons and electrons as a future experiment.

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