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Injection and trapping of pulsed positrons in dipole magnetic field toward pair-plasma creation

Haruhiko Saitoh[1], Jens von der Linden[2], Adam Deller[2], Hiroyuki Higaki[3], Koji Michishio[4], Toshihiko Hori[4], Nagayasu Oshima[4], Stefan Nissl[2], Eve V. Stenson[2]

[1] Department of Advanced Energy, The University of Tokyo, [2] Max Planck Institute for Plasma Physics, [3] Division of Advanced Science and Engineering, Hiroshima University, [4] National Institute of Advanced Industrial Science and Technology

e-mail (speaker): saito@ppl.k.u-tokyo.ac.jp

Plasmas composed of equal-mass charged particles are called pair plasmas and are theoretically predicted to exhibit unique properties of wave propagation and instabilities. Pair plasmas consisting of electrons and their antiparticles, positrons, are believed to exist widely around high-energy celestial bodies such as pulsars. Understanding electron-positron plasmas is crucial not only for basic plasma physics but also for studying the fundamental processes of astrophysical phenomena. However, the confinement of a large number of positrons together with an equal number of electrons that satisfy the plasma conditions is challenging, resulting in only a few experimental studies on electron-positron plasmas.

We utilize a magnetospheric dipole field geometry and slow positron beams for creating and investigating electron-positron plasmas. The dipole field generated by a magnetically levitated superconducting coil is one of the so-called innovative confinement concepts for fusion plasmas. The RT-1 experiment [1] of the University of Tokyo has successfully achieved stable confinement of high-beta plasmas suitable for advanced fusion and non-neutral (pure electron) plasmas, demonstrating the capability to confine both positrons and electrons in principle. In the final plan of the electron-positron plasma project, a large number of positrons ($>10^9$) are accumulated in a linear trap with strong field (5T), using an intense positron source and a buffer gas trap [2]. These positrons are then extracted as a pulsed beam, injected, and trapped in a small-volume levitated dipole [3] with electrons that satisfy the pair-plasma state.

Efficient (~100%) injection [4] and relatively long (~1s) trapping [5] of the positron beam have been achieved in a prototype dipole trap at the NEPIMUC positron facility in the Technical University of Munich. In the DC beam experiments at NEPOMUC so far, the number of positrons stored in the trap has been less than 10^3.

In order to realize the plasma state of positrons and induce collective phenomena, a significant increase in the trapped particle number is needed, which is achieved through the utilization of pulsed positron beams [2,6]. In this study, prior to the accumulation of a large number of positrons in the 5T trap, we conducted experiments using pulsed positron beams supplied from a linac-based system with a buffer gas trap [2] and a prototype permanent magnet dipole. The use of pulsed positron source allowed the separation of particle injection period and stable confinement period of the dipole field trap, leading to an improved number of positrons. This will provide new insights into the behavior of positrons after injected into the dipole magnetic field.

Orbit calculations showed that injected positrons of $\sim 10^4$ become uniformized in the toroidal direction in ~100us (Fig.1), due to the finite temperature spread of ~1eV. This process, along with the predicted temporal variation of annihilation rate of positrons at different toroidal positions (Fig.2), is consistent with the observations of annihilation gamma rays. Once an almost uniform toroidal positron cloud is generated, more than 96% of positrons are trapped in a volume of $\sim 170\mathrm{cm}^3$. However, the averaged number density and the Debye length of positrons in this region are $\sim 10^8\ \mathrm{m}^{-3}$ and on the order of meters, respectively, indicating that the positron cloud does not currently satisfy the plasma conditions. Further increase of the trapped positron number using the high-field accumulator will be conducted in the future.

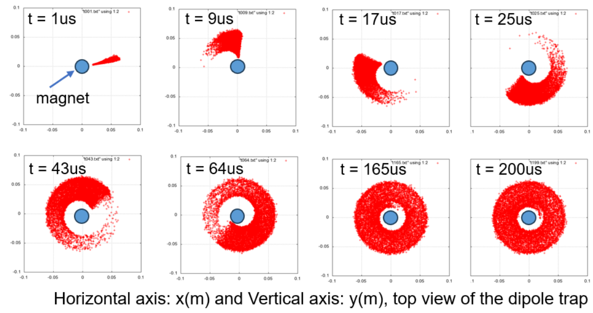

Fig.1 Temporal evolutions of the spatial profile of positrons after injected into permanent magnet dipole.

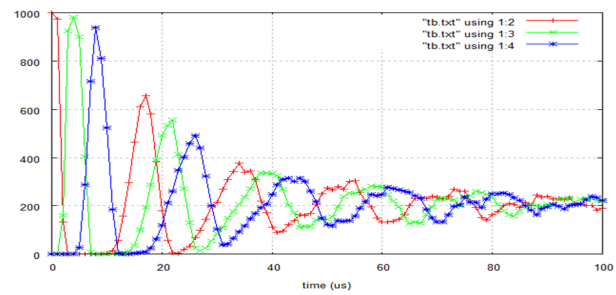

Fig.2 Expected annihilation rate (a.u.) of positrons near three gamma-ray detectors at different toroidal positions.

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