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Positron accumulation and manipulation for antihydrogen synthesis

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Abstract. Our group ASACUSA-MUSASHI has established an efficient way for accumulating antiprotons in the cusp trap, a combination of an anti-Helmholz superconducting coil and a multi-ring electrode trap. The last piece for synthesizing antihydrogens in the cusp trap is positron. We have developed a compact system to effectively accumulate positrons based on N_2 gas-buffer scheme with a specially designed high precision cylindrical multi-ring electrode trap. Millions of positrons were accumulated in the pre-accumulator just using polycrystalline tungsten moderators. The accumulated positrons were transported as a pulsed beam via three guiding coils and caught in the cusp trap under cryogenic and ultra high vacuum conditions without serious loss. Confinement of two kinds of numerous antiparticles, e.g., 10^8 positrons and 10^7 antiprotons, in the cusp trap becomes feasible.

1. Introduction

Antihydrogen is one of the most attractive systems involving positron because it is an ideal system for testing CPT invariance. Ever since cold antihydrogens were successfully produced [1, 2], a priority was "confinement of ground-state antihydrogen" for its high-precision spectroscopy. Several research groups are pursuing that with various approaches [2, 3]. We ASACUSA-MUSASHI group has developed a unique electro-magnetic trap for synthesizing and confining antihydrogen, the "cusp traph, which is a combination of a multi-ring electrode trap (MRT) and an "axially-symmetrich anti-Helmholtz magnetic field [5, 6, 7]. We established an efficient way [8, 9] to accumulate antiprotons in this trap; millions of antiprotons, about 10^2 times larger than those in other groups, were stably confined. A remaining major difficulty for producing antihydrogen in the cusp trap was the preparation of positrons. The expected recombination mechanisms of antihydrogen are radiative and three-body one. The two mechanisms lead to different quantum state populations of antihydrogen, and the reaction rate have different dependencies on the positron plasma density and temperature, n and $T^{-0.63}$ for the radiative [10], n^2 and $T^{-9/2}$ [11] for the three-body, respectively. In order to produce a large amount of antihydrogens via recombination in the cusp trap it is required to have cold and highdensity positrons available. For the purpose of this, we have developed an exceptionally compact





Figure 1. A Cross-sectional view of the trapping region of the positron pre-accumulator and the electrical potential along the axis of the trap and the moderators.

gas

and high-efficient positron pre-accumulator based on N_2 gas-buffer scheme [12] applicable to the cusp trap.

2. Positron pre-accumulator and transport line to cusp trap

The positron pre-accumulator is an instrument for trapping and cooling a continuous beam of slow positrons generated by moderating β^+ particles from a 50-mCi ²²Na radioactive source. In our new apparatus, all of the required components, i.e., the radioactive source enclosed a tungsten shield, polycrystalline tungsten moderators, a N₂ gas-buffer cell and a high-precision cylindrical MRT, were situated in a superconducting solenoid (2.5 T). Such all-in-one system in the strong magnetic field has several advantages. A stable trapping by suppressing the diffusion (\propto (L/B)²) and a rapid cooling of positrons by synchrotron radiation (\propto 1/B² [13]) can be expected in the strong magnetic field. A beamline complex between the source and the trapping region was avoided because half of positrons emitted from the source are automatically guided to the main trapping region along magnetic field lines. Also, pre-accumulated positrons in the strong magnetic field can be easily transported to the cusp trap without the reflection due to the magnetic mirror.

A cross-sectional view of the trapping region is shown in Fig. 1. We used two annealed polycrystalline tungsten foil moderators (4 μm for transmission moderator and 25 μm for reflection moderator in thickness) to make slow positron beams. A fraction of positrons into the foil are thermalized within a few picoseconds and isotropically diffuse. Some of the positrons reach the surface and are emitted with the energy around 3 eV depending on the work function for positrons ϕ_+ . In this way about ~0.1% of the irradiated positrons directly from the radioactive source emerge from the tungsten surface. The physical dimensions of the N_2 buffer cell and the MRT are designed to allow an efficient pressure gradient to be formed in the small trapping region. The inner pressure of the entrance side of the N₂ buffer cell is maintained to 10^{-3} Torr while the exit side of the trapping region is around 10^{-6} Torr. An efficient differential pumping with the capillary structure ($\phi=6 \text{ mm}$, 400 mm in length) is accomplished. The emitted slow positrons moderated in the tungsten foil lose energy dominantly via the electronic excitation of a N_2 molecule and then trapped. The trapped positrons further collide with N₂ molecules in a MRT and simultaneously accumulated. The MRT has 22 channels of the gold-coated aluminum-ring electrodes which can form flexible potentials for trapping, confining and extracting positrons. We used PEEK (poly-ether-ether-ketone) rings for the



Figure 2. Schematic view of the transport line between the positron pre-accumulator and the cusp trap.

electrical insulation of the electrodes. Two channels of them are segmented in quarter, making it possible to compress or decompress the positrons in the trap by applying rotating electric fields. An outstanding feature of the MRT is the excellent cylindricity, which is important for stable trapping of positrons. The cylindricity of 15 μ m involving the segmented electrodes was achieved by utilizing several advanced processing techniques, wire-electrical discharge machining and horning.

We need to transport the positrons after trapping in the pre-accumulator to the cusp trap $(\sim 3 \text{ T})$ under cryogenic and ultra high vacuum conditions where the positrons are mixed with the antiprotons. The specially designed transport line with three guiding coils was developed (Fig. 2). After the accumulation in the pre-accumulator, the vacuum separation valves (GV1 and GV2) are opened and the transfer magnet is energized (500 Gauss) for 3 second. The positrons accumulated in the pre-accumulator are extracted as a low-energy ($\sim 100 \text{ eV}$) pulsed beam and transported to the cusp trap via two aperture (AP1 and AP2) for a differential pumping. The transported pulsed positrons are caught in the MRT of the cusp trap by opening and closing a gate electrode. We found in the particle trajectory calculations that such low-energy positrons can be transported along the magnetic field lines and re-trapped in the cusp trap without serious loss. Two kind of detectors were placed between the positron pre-accumulator and the cusp trap for monitoring the extracted positrons: @(1) A combination of a micro-channel plate and a phosphor screen to get information about the number and the x-y distribution of positrons. (2) NaI and plastic scintillation detectors to detect the positron annihilation signal providing information about the time-of-flight and the z distribution of the pulsed positrons. The whole experimental operations including source opening and closing, moderator movement, potential manipulation of MRTs, detector movement, the data acquisition from the detectors and gating the gate values are automated to make it possible to run the experiment remotely.

3. Results and discussion

We performed the adjustment and the optimization of the accumulation and transportation process of positrons. The parameter space for them was vast, e.g., trapping potential, buffer gas pressure, moderator treatments, axis adjustment between the MRTs and the magnetic field lines, variety of positron manipulation in both the pre-accumulator and the cusp trap. The optimization of the trapping potential and the gas pressure were especially essential for the trapping efficiency. One of the optimized trapping potential is shown in Fig. 1. Because the length of the trapping region was quite limited in our all-in-one system compared with the conventional positron accumulators [12], the pressure gradient of the buffer gas in the MRT are sharper. The pseudo-harmonic potential for confining positrons is made at the exit side of the MRT where positrons have the lifetime of around 100 s when a proper amount of

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the buffer gas present. The optimized path energy around ~9 eV, which is the energy of the moderated positrons passing through the gas buffer cell, is consistent with that reported elsewhere [12, 14]. During the measurements we have been able to trap about 2×10^6 e⁺ within 30 s accumulation time. Although direct measurements to know our moderator efficiency still not be performed, the expected trapping efficiency referring typical efficiency of the polycrystalline tungsten moderator [15] is more than 25%, which is favorably comparable with the values for conventional "largeh accumulators. About 90% of the positrons in the pre-accumulator are transported and successfully re-trapped in the cusp trap. We are continuing the development works for the manipulation techniques of positrons required for the antihydrogen synthesis in the cusp trap. In the preliminary tests, we have shown that the effectiveness of the stacking of positrons and the positron compression technique for making high-dense positron plasma in the cusp trap.

4. Summary and future prospect

In summary, we have successfully developed the compact positron pre-accumulator applicable for the cusp trap and prepared a significant amount of positrons for \overline{H} synthesis in the cusp trap. The experiment for synthesizing antihydrogen is undergoing. Fine adjustment and further improvement of the positron pre-accumulator are still under developing. The moderator, especially, leave much to be improved. A mesh tungsten moderator [16, 17] or field assisted moderator [18] are possible candidate for the high-efficiency moderators.

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