Extraction of ultra-slow antiproton beams and their physics application

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Abstract.
The Trap group of ASACUSA collaboration has decelerated and confined millions of cooled antiprotons in an electromagnetic trap, 50 times more efficiently than conventional methods. They were then extracted out of the magnetic field of 2.5 T and transported at 10–500 eV. This unique ultra-slow antiproton beam from our apparatus named MUSASHI is expected to open up a new field of atomic and nuclear physics.

Keywords: antiproton, Antiproton Decelerator (AD), RFQD (Radio Frequency Quadrupole Decelerator), Multi-Ring electrode Trap (MRT), ultra-slow antiproton beam
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INTRODUCTION

Antiproton, as an exotic particle with infinite lifetime, is an interesting and ideal probe in atomic physics, as well as in nuclear physics. Having the same mass as the proton but with opposite charge, it acts as a "heavy electron" or as a "negative nucleus". With the aim of producing a mono-energetic antiproton beam at a low energy comparable to the Rydberg energy, we developed a system consisting of a RFQ Decelerator, an electromagnetic trap and an extraction beamline.

DECELERATION OF ANTIPROTON BEAM

At CERN, antiprotons are produced by collision of protons at 26 GeV/c with an Ir target. They are cooled and decelerated to 5.3 MeV in the Antiproton Decelerator (AD) ring, before being extracted to experimental zones as a pulsed beam of typically 3×10^7 antiprotons in a bunch of 100–200 ns. Thus produced antiproton beam, though already lower in energy by 3 orders of magnitude than at production, needs further deceleration for them to be captured in vacuo electrostatically. A conventional method using thick degrader foils inevitably caused considerable broadening of the energy spread, and only 0.01%–0.1% of antiprotons could be captured in the prepared potential [1, 2].

In order to decelerate antiprotons efficiently, the ASACUSA collaboration [3] developed a Radio Frequency Quadrupole Decelerator (RFQD) [4] in collaboration with the CERN PS group. RF wave was applied to the cavities in such a way as to decelerate

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microbunches of the antiproton beam at 5.3 MeV down to 63 keV with an efficiency of 30%. Since the RF cavities can be biased ± 60 keV, the output antiproton energy can be varied 10–120 keV.

The output beam from the RFQD was injected into an electromagnetic trap in a strong magnetic field of 2.5 T produced by a superconducting solenoid. The beam was focused to a diameter of 3–4 mm on a thin Mylar i.e. PET (polyethylene terephthalate) double-layered foil of 90 μg/cm^2 for each layer, used to isolate ultrahigh vacuum of 10^{-12} Torr inside the trap. Ten strips of silver electrodes had been evaporatively plated onto each layer of the foil. Passage of antiprotons through the foil caused emission of secondary electrons, and the signals from each strip were amplified and read out. This allowed for the first time non-destructive two-dimensional monitoring of the antiproton beam profile at low energies [5].

Taking into account the energy loss in the foil, we set the bias voltage of the RFQD to 110 kV so as to maximize the number of antiprotons captured, with their transverse energy less than 10 keV after penetration through the foil.

CONFINEMENT AND COOLING

Antiprotons were then captured and confined in the trap. We used a Multi-Ring Trap (MRT) [6] consisting of 14 cylindrical electrodes placed coaxially along the magnetic field line. A favorable feature of the MRT compared with a normal Penning trap and a trap with a well-type potential is that a harmonic electric potential can be prepared in a wide region near the trap axis by application of appropriate voltage on each electrode, which enables extremely stable confinement of a large number of charged particles.

Figure 1 shows sequential steps for antiproton capture, cooling and extraction. The pulse of incident antiprotons were reflected backward at the DCE electrode floated at -10 kV. By the time the pulse returned after its round trip of typically 500 ns back to the UCE, the trap was closed by a fast switch which biased the UCE to -10 kV, confining a major part of the antiprotons. The antiprotons were then cooled by a plasma of typically 3×10^8 electrons preloaded in the harmonic potential [*]. Antiprotons lost their energy by transferring it to electrons, while the heated electrons cooled by themselves by emission of synchrotron radiation in the magnetic field of 2.5 T, until the antiprotons were trapped in the bottom of the harmonic potential of 50 V depth. We then opened one side of the potential for 550 ns to selectively release electrons: lighter and thus faster electrons escaped within this short period, while heavier and much slower antiprotons remained inside. This release of electron was necessary for efficient extraction of antiprotons. The antiproton cloud were then given torque by a rotating electric field to be compressed radially. For this purpose, one of the electrodes was segmented azimuthally into four parts, and an RF voltage was applied to each segment with a phase difference of $\pi/2$ next to each other [7].

With this trap, we successfully confined 1.2×10^6 cooled antiprotons until the end of our trap cycle of 1–5 minutes. Typically 1 million antiprotons were trapped for each AD shot. We then accumulated antiprotons for several AD shots. This technique of "stacking" also worked fine, and we trapped 4.8×10^6 antiprotons simultaneously for stacking of 5 AD shots, the largest number of antiprotons ever accumulated.

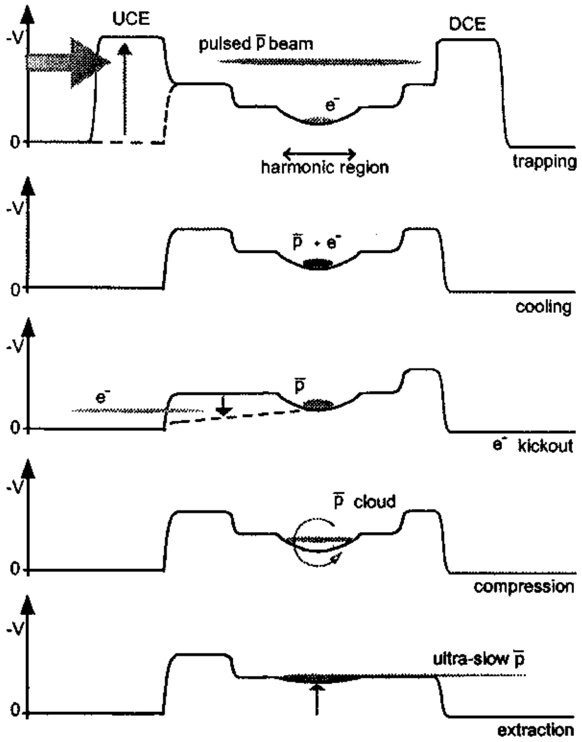

FIGURE 1. Sequential procedures of antiproton capture, cooling and extraction.

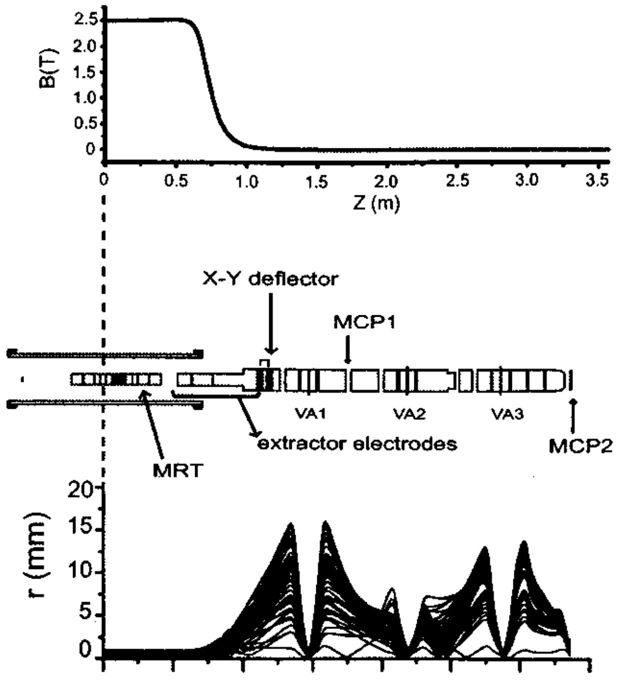

FIGURE 2. Schematic of the extraction beamline and calculated trajectories of ultra-slow antiproton beams, together with a graph of magnetic field strength.

EXTRACTION AND BEAM TRANSPORT

The antiprotons were then released from the trapping potential as it was gradually shallowed, and were extracted as an ultra-slow continuous beam of 10–500 eV. Since the antiprotons tend to expand in radial direction when they follow the strongly diverging magnetic field line, it was essential that the antiproton cloud be well compressed radially in the trap [7]. Precise alignment of the magnetic field axis, electric trap axis, and the beam transport axes was also important in efficient extraction.

The extraction beamline was designed to transport antiproton beams over a length of 3 m, at variable energies ranging from 10 to 1000 eV. The antiproton beams were refocused three times by sets of Einzel lenses at the position of apertures, as shown in Fig. 2. These variable apertures allow differential pumping of 6 orders of magnitude along the beamline, which was necessary to keep the trap region at an extremely high vacuum better than 10^{-12} Torr so as to avoid antiproton annihilation, while the end of the beamline will be exposed to atomic or molecular gas jets of up to 10^{-6} Torr [8].

The MRT, the superconducting solenoid and the transport line for the ultra-slow beam are jointly known as "MUSASHI", or the Monoenergetic Ultra-Slow Antiproton Source for High-precision Investigations. MUSASHI opens a new research field ranging from atomic physics to nuclear physics [9, 10, 11, 12], including our near-future project of antihydrogen synthesis in a cusp trap [13].

Especially, atomic formation and ionization processes by low-energy antiprotons can be studied under single collision conditions for the first time. We are now preparing a supersonic gas-jet target for atomic collision experiments planned in the next years. The target is aimed to achieve a density of 3×10^{13} cm^{-3} with a gas-jet cross section of 0.5 cm × 1 cm [14], which will be crossed with the ultra-slow antiproton beams to produce antiprotonic atoms.

SUMMARY AND ACKNOWLEDGMENTS

With the combination of a RFQD and a MRT, we have successfully decelerated antiprotons from 5 MeV to less than 10 keV, confined them and cooled them down to sub-eV energies. Out of 30 million antiprotons delivered from the AD, 1.2 million antiprotons were trapped stably for a cycle of a few minutes, which was 50 times more efficient than the conventional method of using thick degrader foils for deceleration. Antiprotons were extracted at energies of 10–500 eV, and this ultra-slow antiproton beam will be a powerful tool for the study of atomic collision dynamics and formation of antiprotonic atoms including antihydrogen, as well as nuclear physics.

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