DEVELOPMENT OF MUSASHI, A MONO-ENERGETIC ULTRA-SLOW ANTIPROTON BEAM SOURCE*

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Abstract

The ASACUSA collaboration developed an ultra-slow antiproton beam source, named MUSASHI, Mono-energetic Ultra-Slow Antiproton Source for High-precision Investigation, consisting an electromagnetic trap housed in an liquid He free superconducting solenoid and low energy antiproton beam transport line. The MUSASHI confined more than 1×10^7 of antiprotons and extracted them as ultra-slow antiproton beams with energy of 250 eV and various bunch lengths.

INTRODUCTION

The preparation of a large number of antiprotons at extremely low energy is an important step on the road to synthesizing antihydrogen atoms [1, 2] and antiprotonic atoms. The studies of these exotic atoms can reveal collision process at low energy region and test elemental theorem such as CPT theorem and weak equivalent principle [3]. On the other hand, such exotic atoms can only be efficiently synthesized from component particles at the eV and lower energy scale, and this is far below the mandatory GeV scale of accelerator-produced antiprotons ($\bar{p}$).

This energy gap has been partially bridged by the CERN Antiproton Decelerator (AD), which decelerate $\bar{p}$ beam with GeV-scale kinetic energy to 5.3 MeV, and re-ejects them every 2 min in 150 ns long pulses, containing 3×10^7 particles. This beam energy is still far above the 10 keV range at which $\bar{p}$ can readily be captured and cooled in electro-magnetic traps [4, 5, 6, 7].

APPARATUS

Overview

Usual antiproton catching trap systems working at the AD especially designed for production of antihydrogen atoms use typically $\sim$ 70 000 $\mu\text{g/cm}^2$ degrader foils to reduce the $\bar{p}$ energy further from the MeV scale to the keV scale [4, 5, 6, 7]. Many incident $\bar{p}$s stop and annihilate within such foils, while others emerge with too high an energy to be captured in the potential well of any trap located downstream. We replaced these simple degrader foils by a radio frequency quadrupole decelerator (RFQD) with MUSASHI (see Fig. 1). The RFQD, 3.5 m in length, reduced the 5.3 MeV AD beam energy between 10 and 120 keV. Some of $\bar{p}$s, typically 30% of single AD shot, fulfilled the phase condition required by the acceptance of and deceleration by the RFQD, the remainder being transmitted without deceleration [8].

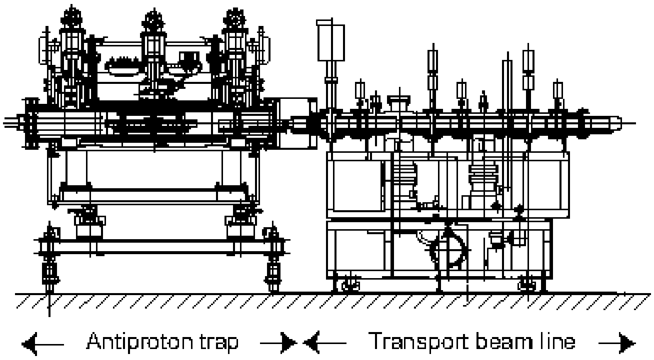

Figure 1: Cross sectional view of MUSASHI.

The RFQD and MUSASHI were bridged via a low energy beam transfer line (LEBT). The $\bar{p}$ beam was steered and focused passing through the LEBT. The captured $\bar{p}$s were cooled to sub-eV via collisions between preloaded electrons in a multi-ring electrode trap (MRT) of MUSASHI. The cloud of $\bar{p}$ after the cooling was radially compressed by a rotating wall technique [9]. Thus compressed $\bar{p}$ cloud were extracted and transported as an ultra-slow beam via a beam line to an experimental apparatuses [10].

Superconducting Solenoid with an UHV Bore

The MUSASHI superconducting magnet was cooled by a Gifford-McMahon (GM)-type cryocooler. The magnetic

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field strength was chosen to set 2.5 T for better trapping efficiency and at the same time for better focusing of low energy beams from strong magnetic field to non magnetic field region. The uniformity of the magnetic field in the UHV bore was designed and achieved to less than 0.1% for stable confinement.

The UHV bore made by nonmagnetic stainless steel clad by Cu strips was kept at around 4 K by also two GM-type cryocoolers which thermally connected through oxygen-free high thermal conductivity copper mesh. The temperature difference between the center and the both ends where GM-cryocoolers were connected was 0.2 K.

Since the $\bar{p}$s spent a long time in the trap, more stringent vacuum conditions were required there to avoid annihilation on residual gas atoms [5] than in the RFQD, through which they passed only once. Two 90 $\mu\mathrm{g/cm}^2$ (0.65 μm thickness) polyethylenterephtalat (PET) foils located 70 cm upstream of the MRT were therefore used to isolate the trap and RFQD vacuum systems, at 10^{-12} mbar and 10^{-9} mbar, respectively.

Since these foils were some 800 times thinner than those used at the entrance of the traps described in Ref.[4, 6, 5] of 99.9% in total stopping direct beam from the AD at 5.3 MeV by thick degrader foils, only 30-40% of decelerated $\bar{p}$s were lost at the foil.

Multi-ring Electrode Trap

The MRT comprised of 14 ring electrodes lying perpendicular to the beam and on the axis of a superconducting solenoid. For confinement of charged particles, 5 of the electrodes and both side of those were used. By applying a proper voltage on each electrode, an electrostatic potential

$$\phi(\rho, z) = -V_0 \frac{\rho^2 - 2z^2}{2L^2 + R^2} + \delta, \qquad (1)$$

was produced, described in the cylindrical coordinate, where the radius of ring electrode is $R = 20$ mm, the axial length of the trap region is $2L = 125$ mm, the potential difference is $V_0 = \phi(0, L) - \phi(0, 0)$, the offset from the surface potential on the center electrode is δ.

Before the injection of $\bar{p}$ beam, electrons as a coolant were injected from the downstream side of the MRT. They were emitted from a barium dispensed cathode on a pneumatic type linear feed-through, which was retracted during the extraction procedure of ultra-slow $\bar{p}$ beams. The typical number of stored e^- was 4×10^8. The radial size of the e^- plasma was adjusted to its of incoming $\bar{p}$ beam by a rotating wall technique with the segmented electrode for better cooling efficiency of $\bar{p}$.

Figure 2 shows the experimental procedure of antiproton capture, cooling, manipulation, and extraction from the MRT. In Fig.2(a), a potential, -13 kV, was applied to an electrode, DCE, for the reflection of pulsed $\bar{p}$ beam. The potential of UCE was increased until the pulse came back.

In Fig. 2(b), collisions between $\bar{p}$ and e^- plasma takes important role to cool the $\bar{p}$ beam. Electrons soon lose their energy by synchrotron radiation because of strong magnetic field. It took about 30 s to settle in a thermal equilibrium state.

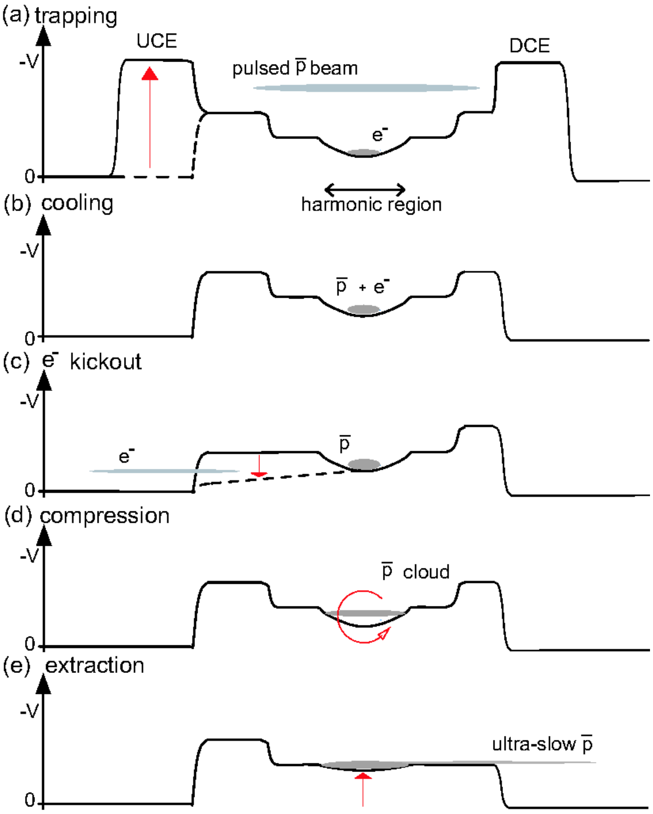

Figure 2: Antiproton trapping, cooling, electron kick-out, compression, and extraction procedures.

Then, in Fig. 2(c) the trapped e^-s were removed during the time when the trapping potential was turned off, which was enough short to keep $\bar{p}$ cloud in the trapping region but long for e^-s to escape from there. In our case, it was important to remove e^- from the trapping region before $\bar{p}$ cloud extraction for better extraction [11].

In Fig. 2(d), the segmented electrode was also used to compress $\bar{p}$ cloud for better focusing [9].

Finally, as shown in Fig. 2 (e), the trapping potential well depth was gradually decreasing, that is to say, ramp up, for slow extraction, meanwhile the barrier potential was remained to the same. The extraction energy of $\bar{p}$ beam was chosen to 250 eV during the following experiments.

Transport Beamline

The beam line for the transportation of slow $\bar{p}$ from the MRT to an experimental chamber was also developed [10]. The beam line was equipped with a three-stage differential pumping system in order to maintain a pressure lower than 10^{-12} mbar in the MRT while having a pressure of around 10^{-6} mbar in the chambers using for atomic collision experiment with gaseous target [12].

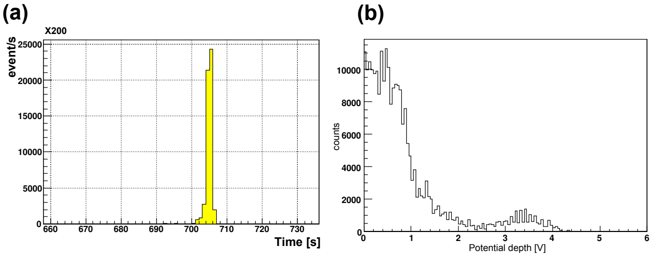

Figure 3: (a) The number of stored $\bar{p}$s after 7 AD shots accumulation. (b) The number of extracted $\bar{p}$ against potential depth of the MRT.

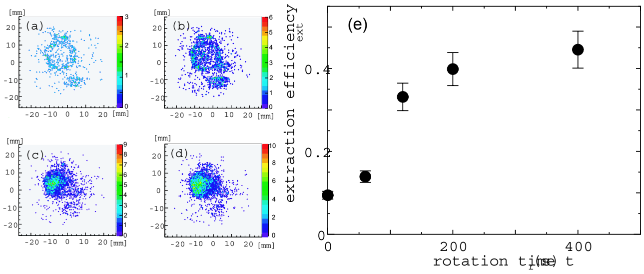

Figure 4: (a)–(d) The PSD images of extracted $\bar{p}$ for t_r =0, 60, 120, and 200 s. (e) The transport efficiency $\varepsilon_{\mathrm{exp}}$ as a function of the rotation time t_r. The rotation frequency was f =247 kHz with its peak-to-peak amplitude V_r =0.56 V.

EXPERIMENTAL RESULTS

The MRT stored 1.5×10^6 among captured $\bar{p}$s after the cooling by collisions with e^- plasma. The life time of $\bar{p}$ cloud was at least a few tens minutes, although $\bar{p}$s were usually ejected earlier. Accumulation of several AD shots enabled us to store more $\bar{p}$s. Figure 3 (a) shows the results of 7 AD shots accumulation took 700 s. There were unavoidable initial annihilation at every $\bar{p}$ beam injection. Some of $\bar{p}$s which survived the initial annihilation were stored in the harmonic potential and then ejected, which number was 10^7 $\bar{p}$s, the largest number of $\bar{p}$s ever stored and cooled in such traps.

Thus stored $\bar{p}$ cloud would be extracted by gradually decreasing the depth of the trapping potential. In order to determine the extraction energy the barrier potential was kept during this extraction procedure, while the trap potential was gradually ramped up for 80 s. Figure 3 (b) shows spilled $\bar{p}$ number against the well depth, which corresponds to relative energy distribution at the extraction energy, 250 eV. Though some hot $\bar{p}$s remained at 3-4 V depth which was less than 10% of total numbers, most of $\bar{p}$ started to escape from the trap region when the potential depth came at around 1 V. The energy width of the extracted cold component of $\bar{p}$ cloud would become around 1 eV. This long bunched $\bar{p}$ beam, ca. 30 s length, applied to atomic collision experiments [12]. On the other hand, a 2 μs short bunch beam obtained by a quick ramp down of the barrier was transported to an antihydrogen recombination trap [13].

In order to increase the extracted number of $\bar{p}$ from the MRT in the strong magnetic field, a rotating wall technique was applied. Compression of $\bar{p}$ after e^- removal without strong resonant structures was observed for a range of frequencies from the sideband frequency of 200 kHz to 1000 kHz.

Figure 4(a)–4(d) show the PSD images of extracted $\bar{p}$ beams for the time of applying rotating electric field $t_r = 0$, 60, 120, and 200 s, respectively. Without the rotating field as shown in case (a), the image is dim with low intensity and shows a hollow like depopulated region in its center. This hollow gradually fills up as the field is applied, as in the cases (b), (c), and (d). The cloud of $\bar{p}$ was therefore effectively being compressed by the rotating field, then the measured transport efficiency $\varepsilon_{\mathrm{exp}}$, defined as the ratio of the number of detected $\bar{p}$ by the PSD to the number of trapped $\bar{p}$ as shown in Fig. 4(e). The efficiency $\varepsilon_{\mathrm{exp}}$ monotonically increased from 0.08 for $t_r = 0$ to more than 0.4 for $t_r > 200$ s. The maximum number of transported $\bar{p}$ to the end of the beam line was $\geq 5 \times 10^5$. From a trajectory simulation assuming a $\bar{p}$ cloud having a superposition of two Gaussian distribution, we concluded that the cloud of $\bar{p}$ after radial compression had a compressed thin component,ρ =0.25 mm, and a halo component [9]. It is noted that the self field potential became ~ 1 V for the cloud of $\bar{p}$ for ρ =0.25 mm which corresponds to the results shown in Fig.3 (b).

In summary, MUSASHI stored 1.5×10^6 $\bar{p}$s per 1 AD cycle and accumulated 10^7 $\bar{p}$s by stacking several AD spills. Such amount of $\bar{p}$ was cooled by e^-s and extracted as 250 eV slow beam with various bunch lengths after the radial compression.

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