A TANK CIRCUIT MONITORING A LARGE NUMBER OF ANTIPROTONS IN MUSASHI *

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Abstract

For the production of low energy antiproton beams with the energy of 100 to 1000 eV, it is desirable to accumulate a larger number of antiprotons in a large Penning trap, where a tank circuit signal can be used as a nondestructive measurement of more than 10^6 antiprotons. This is similar to Schottky signals used to monitor beams in accelerators.

INTRODUCTION

In Antiproton Decelerator (AD) at CERN, unique low energy antiproton ($\bar{p}$) beams of 5.6 MeV have been delivered for physics experiments. Furthermore, the RFQ decelerator (RFQD) dedicated for Atomic Spectroscopy And Collisions Using Slow Antiprotons (ASACUSA) collaboration enables the use of 100 keV pulsed $\bar{p}$ beams for experiments. What is more, Mono-energetic Ultra Slow Antiproton Source for High-precision Investigations (MUSASHI) in ASACUSA can produce $\bar{p}$ beams with the energy of 100 to 1000 eV. Since the successful extraction of 250 eV $\bar{p}$ beams reported in 2005 [1], continuous improvements on beam quality and equipments have been conducted [2].

Here, some properties observed with a tank circuit attached to MUSASHI are reported. Signals from a tank circuit provide information on the trapped antiprotons, as Schottky signals do for high energy beams in accelerators. In fact, it is known that this kind of trap-based beams [3] are physically equivalent with those in a FODO lattice [4, 5]. Monitoring a tank circuit signal will be useful for handling the low energy antiproton beams from MUSASHI.

THEORETICAL BACKGROUND

Here, the analogy between a non-neutral plasma in a solenoid trap and a charged particle beam in a FODO lattice is reviewed based on the ref.[3]. When charged particles (mass : m, charge : e) are confined with an infinitely long uniform magnetic field B in z direction, the Hamiltonian H_{sol} of a test particle, which describes the motion in $x-y$ plane, becomes as follow.

$$H_{sol} = \frac{1}{2m}\left[\left(p_x + \frac{eBy}{2}\right)^2 + \left(p_y + \frac{eBx}{2}\right)^2\right] + e\phi_{sc}$$

The potential, ϕ_{sc} denotes the electric potential due to the space charge. When the system is observed in the rotating frame of reference around the z-axis (with the angular rotation frequency of $eB/2m$), the Hamiltonian is transformed to $\tilde{H}_{sol}$ below.

$$\tilde{H}_{sol} = \frac{\tilde{p_x}^2 + \tilde{p_y}^2}{2} + \frac{1}{2}K_3(\tilde{x}^2 + \tilde{y}^2) + \frac{e}{mc^2}\tilde{\phi_{sc}} \quad (1)$$

The energy and momentum are normalized by mc^2 and mc, respectively and $K_3 = (eB/2mc)^2$. The quantities with tilde mean that these are observed in the rotating frame.

Since the Hamiltonian H_{beam} of a test particle in a periodic focusing channel can be approximated with

$$H_{beam} \approx \frac{p_x^2 + p_y^2}{2} + \frac{1}{2}K_1(z)(x^2 - y^2) + \frac{e}{p_0\beta_0 c\gamma_0^2}\phi_{sc},$$

it is seen that there is a correspondence between two systems. Under the smooth focusing approximation of the periodic focusing channel, both systems are physically equivalent.

Assuming the Kapchinsky-Vladimirsky distribution for the charged particles, of the circular cross section with the radius a and the density n, the self field potential $\tilde{\phi_{sc}} = -\frac{en}{4\epsilon_0}(\tilde{x}^2 + \tilde{y}^2)$ can be substituted into eq.(1) to give

$$\tilde{H}_{sol} = \frac{\tilde{p_x}^2 + \tilde{p_y}^2}{2} + \frac{1}{2}\left(K_3 - \frac{K_s}{a^2}\right)(\tilde{x}^2 + \tilde{y}^2) \quad (2)$$

with $K_s = \frac{\pi a^2 ne^2}{2\pi\epsilon_0 mc^2}$. And the the radius a satisfies the envelop equation given by

$$a'' + K_3 a - K_s/a - \epsilon^2/a^3 = 0$$

with the beam emittance ϵ. Then, the space-charge limit is achieved when $K_3 - K_s/a^2 = 0$ and given by $n_{lim} = \epsilon_0 B^2/2m$. Also, the bare tune σ_0, space-charge depressed tune σ, and the tune depression of the solenoid system are described as below.

$$\sigma_0 = \frac{eB}{2mc}, \quad \sigma = \sqrt{K_3 - \frac{K_s}{a^2}}, \quad \eta = \frac{\sigma}{\sigma_0} = \sqrt{1 - \frac{n}{n_{lim}}}$$

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Although the above formulation is valid for an infinitely long plasma column, it is also applicable for a uniform density spheroidal plasma confined in a harmonic potential.

EXPERIMENTAL SETUP

A schematic of the experimental setup is shown in Fig.1. Typical procedure to obtain low energy $\bar{p}$'s is almost the same with the one reported before [6]. At first, electrons are injected from the movable electron gun at downstream side of the multi-ring electrode trap. About 4×10^8 electrons are accumulated inside the harmonic potential $\phi_{ex} \propto (r^2 - 2z^2)$ provided with multi-ring electrodes. The inner diameter of the electrodes is 4 cm and the harmonic potential extends to more than 12 cm along the trap axis. A unique feature of the MUSASHI is that the trap can form the axially long harmonic potential, which is necessary for the reasonable cooling time for a large number of high energy $\bar{p}$'s ($\geq 10^6$) . These ring electrodes can be also used to excite or detect axial oscillations of confined charged particles. In addition, one of ring electrodes is azimuthally segmented into four pieces, so that the sideband cooling [7] or rotating electric field [8, 9] can be applied. In fact, injected electrons are radially decompressed to have the larger cross section with high energy $\bar{p}$'s.

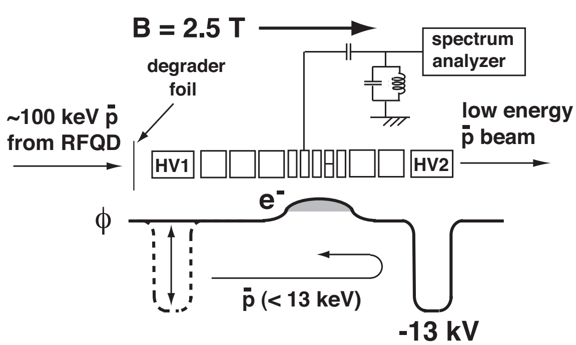

Figure 1: A schematic of the multi-ring electrode trap in a uniform magnetic field. Electrons are confined in a harmonic potential. Then, high energy antiprotons are cooled with the electrons to be extracted as a low energy beam. A tank circuit is attached to a ring electrode to observe a signal of antiprotons in MUSASHI.

The accumulated electrons are cooled to less than 0.1 eV via synchrotron radiation, which is possible due to the strong magnetic field of 2.5 T. Then, a pulsed $\bar{p}$ beam with the energy of $\sim$ 100keV from RFQD, which contains about 10^7 antiprotons is injected into MUSASHI. The polyethylenterephtalat (PET) foils located 70 cm upstream of the trap center are used as degrader foils and also as a beam profile monitor [10]. Since the high voltage of -13 kV is applied to the electrode HV2 after electron injection, $\bar{p}$'s with the energy less than 13 keV are reflected back at the position. Before the reflected $\bar{p}$'s escape from the trap, the potential at the electrode HV1 is switched from 0 V to -13 kV as shown by the dashed line in Fig.1.

The electron cooling of more than 10^6 $\bar{p}$'s takes about 30 s under the present experimental condition. The cooling process can be monitored by observing the electrostatic oscillations of the confined electrons [1, 11]. After 30 s of electron cooling, high voltages are switched off and the electrons are discarded by quickly grounding the harmonic potential. The duration of the potential change should be short enough so that the cooled $\bar{p}$'s have no time to move out of the trap. More than 10^6 low energy $\bar{p}$'s can be confined per AD shot, which is about 50 times larger compared with other experiments without RFQD. If necessary, several AD shots can be accumulated to increase the number of antiprotons $N_{\bar{p}}$ (or to increase the intensity of the low energy $\bar{p}$ beam). Then, rotating electric field is applied for 300 s to have the smaller radial distribution of $\bar{p}$'s inside the trap. This is important for the better quality of the low energy $\bar{p}$ beam since the $\bar{p}$'s are extracted from the strong magnetic field to the field free region, where the experiments are performed. So, the radial compression of the trapped particles results in the higher density in the phase space of the extracted beam. Finally, the trap potential is controlled to provide a pulsed beam or quasi continuous beam with a fixed energy.

Since the beam intensity is an important parameter, it should be measured somehow. So far, track detectors aligned along the trap and extraction beam line [12] have been used for measurement. However, it is desirable to have a nondestructive measurement as a Schottky signal monitors a beam. The fact that $\bar{p}$'s are confined in a harmonic potential makes it possible to use the well developed tank circuit technique [13, 14]. Here, a tank circuit composed of a variable capacitor and an inductor is attached to a ring electrode [15]. The amplified signal is monitored with a spectrum analyzer as shown in Fig.1. Monitoring the tank circuit signal, $N_{\bar{p}}$ or the beam intensity can be inferred nondestructively.

EXPERIMENTAL RESULTS

Shown in Fig.2 (a) is an example of a signal from track detectors placed along MUSASHI, where 3 AD shots were accumulated as a demonstration. The AD cycle in this case was about 100 s. Three large annihilation signals observed before 400 s means that a part of high energy $\bar{p}$'s from RFQD annihilate when they were injected into MUSASHI. Then, electrons were kicked out and the rotating electric field was applied for 300 s. In case of the trap system, which is closed by cryogenic environment, it is claimed that the vacuum pressure is better than 10^{-16} torr and the confinement time of $\bar{p}$ is more than 3 months [16]. However, MUSASHI is an open system, because low energy $\bar{p}$ beams have to be extracted from the trap. Therefore, the confinement time of $\bar{p}$'s is finite and is about 2000 s. It is seen that a small amount of trapped $\bar{p}$'s annihilate during the radial compression. It is thought that a small amount of electrons were accumulated inside the trap through the annihilations of $\bar{p}$'s with the background neutral particles

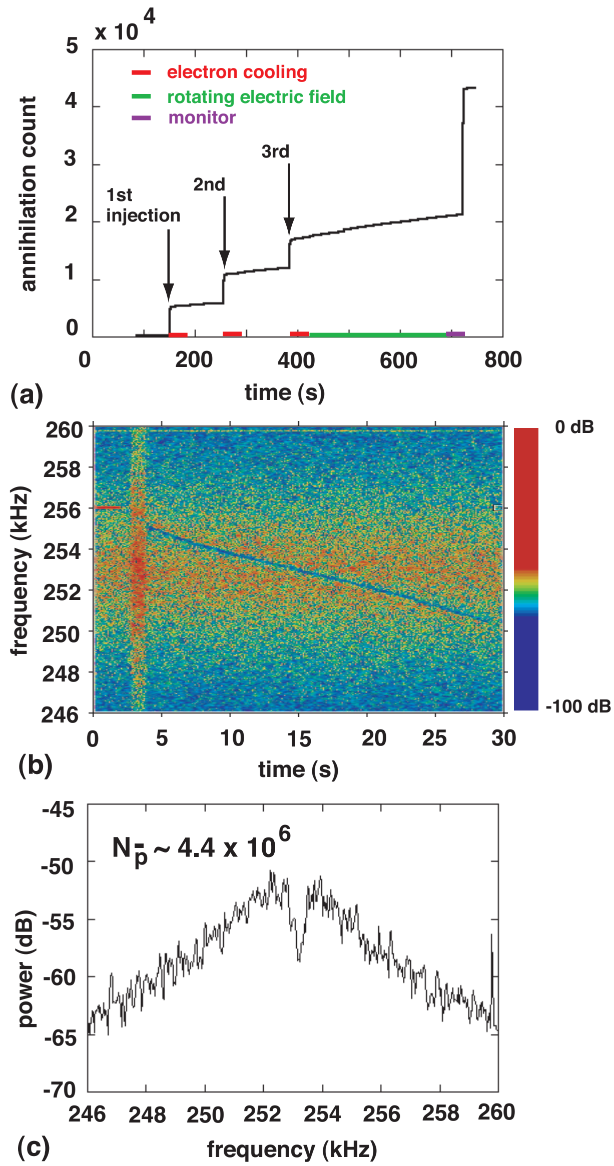

Figure 2: (a) A signal of the track detectors aligned along MUSASHI, where 3 AD shots were accumulated. (b) A signal observed with the spectrum analyzer after electrons were kicked out by applying white noise to a ring electrode for 1 s. (c) A spectrum of tank circuit with 4.4×10^6 antiprotons in MUSASHI.

(mainly H_2). To observe the tank circuit signal of $\bar{p}$, white noise was applied to a ring electrode for 1 s to kick out electrons completely. Then, to confirm $N_{\bar{p}}$, $\bar{p}$'s were extracted slowly towards degrader foils. The large annihilation signal observed after 700 s indicates the number of confined low energy $\bar{p}$'s. Here, $N_{\bar{p}}$ is about 4.4×10^6.

After rotating electric field is applied with the frequency of 256 kHz, the tank circuit signal is observed with the spectrum analyzer for 30 s, which is shown in Fig.2(b). The noise observed around 3 s is due to the applied white noise. It is clearly seen that a dip appeared in the spectrum. The spectrum at 15 s is shown in Fig.2(c). The resonance frequency corresponds to the axial harmonic oscillation frequency of $\bar{p}$ in the MUSASHI and the width of the dip reflects $N_{\bar{p}}$. The wider dip means the larger $N_{\bar{p}}$.

It is also seen that the resonance frequency shifts from 255 kHz to 250 kHz within 25 s. Since the number of $\bar{p}$'s annihilated during this period is about 6.6×10^4, it is thought that a similar amount of electrons were created and shifted the resonance frequency. When a plasma instability occurred during the accumulation of AD shots, it was observed that the dip became smaller and the resonance frequency shifted much lower after the white noise was applied. The resultant $N_{\bar{p}}$ was much lower than that without an instability.

In summary, a tank circuit was attached to the MUSASHI to observe a large number of trapped antiprotons more than 10^6. With the tank circuit signal, the number of antiprotons extracted as a low energy beam can be inferred nondestructively before the extraction. Thus, it may be possible to improve the beam quality before extraction, even if there is an instability. It is beneficial for the effective use of low energy antiproton beams.

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