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Real-time detector for plasma diagnostic in antimatter experiment

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ATHENA Collaboration

Abstract

In the ATHENA experiment, which has recently produced and detected cold antihydrogen, the antiatoms formation is performed by mixing two cold (meV) charged clouds of positrons and antiprotons. The antihydrogen production is strictly dependent on positron plasma parameters. For this purpose we developed a new system to investigate such properties in a non-destructive way. The method is based upon the measurement of the plasma response under a frequency sweep RF excitation and its subsequent analysis. Plasmas trapped in Penning trap exhibit typical resonant collective modes characterized by frequencies, amplitudes and widths dependent on the particle number, density, spatial extent and temperature. With this system it is so possible to have a real-time monitor of the plasma during antihydrogen production.
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The ATHENA collaboration recently produced and detected cold antihydrogen atoms [1] at the CERN Antiproton Decelerator (AD) [2].

The antihydrogen was made by mixing low-energy antiprotons with a cold, dense positron plasma in a nested Penning trap [3]. Therefore, a knowledge of the characteristics of the positron plasma is important. The most likely antihydrogen formation mechanisms depend on both the density and the temperature of the positron plasma [4]. Moreover, control and simultaneous monitoring of the positron plasma temperature allow the antihydrogen formation reaction to be effectively turned off while maintaining an overlap between antiprotons and positrons.

Here we describe a system which provides a non-destructive diagnostic based on the measurements of the first two axial modes of a finite temperature positron plasma. The diagnostic has no discernable effect on the normal evolution of the plasma, so it can be used during antihydrogen production.

The harmonically confined one-component plasmas at temperatures close to absolute zero are known to form spheroids of constant charge density [5]. In our case the shape is a prolate ellipsoid characterized by the aspect ratio $\alpha = z_p/r_p$, where z_p and r_p are the semi-major axis and semi-minor axis, respectively. A theory [6] relating the frequencies of the low-order plasma modes to the density and the aspect ratio of spheroidal plasmas was confirmed experimentally [7,8].

As an extension to the above work, we have developed a model in which the plasma length can be extracted from the shape of the resonance when the dipole mode is excited [9]. We considered the plasma as an equivalent RLC circuit where the inductance L is related to the plasma length $L = 3m\alpha^2 r_w^2/\pi n q^2 z_p^3$, where q and m are the positron charge and mass, respectively, n is the particle density and r_w is the electrodes radius. α and n are determined independently by the frequency analysis of the modes and the inductance L is calculated fitting the frequency response of the first mode (dipole mode). Thus, the aspect ratio, density, and length can be measured and the radius and positron number obtained.

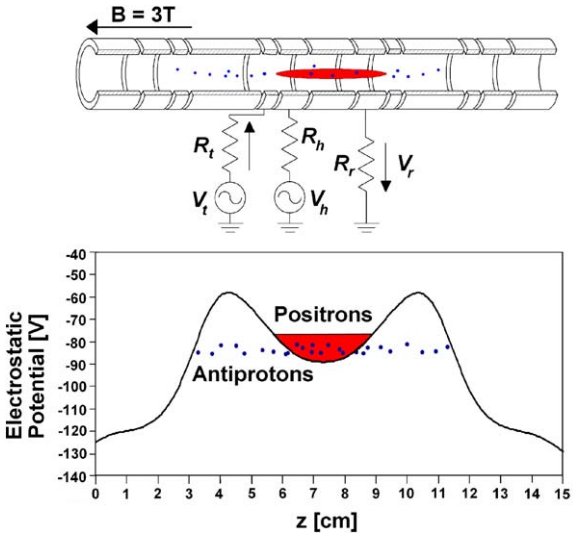

Fig. 1. (a) Trap electrodes with the heating and mode detection electronics. The shape of the positron plasma prolate ellipsoid is shown schematically. (b) The axial potential of the ATHENA nested trap is shown and the ranges of axial motion of the positrons and the antiprotons indicated schematically.

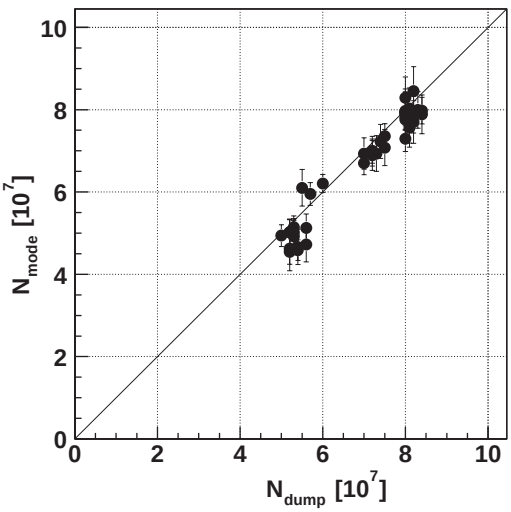

Fig. 2. The total number of positrons, during different mixing cycles, obtained using the modes diagnostic is plotted against the number measured extracting the positrons to a Faraday cup.

The setup is shown in Fig. 1. A sinusoidal drive obtained by a generator having an electromotive force $V_t = v_t e^{j\omega t}$ is applied to one electrode, the oscillation of the plasma induces currents on the

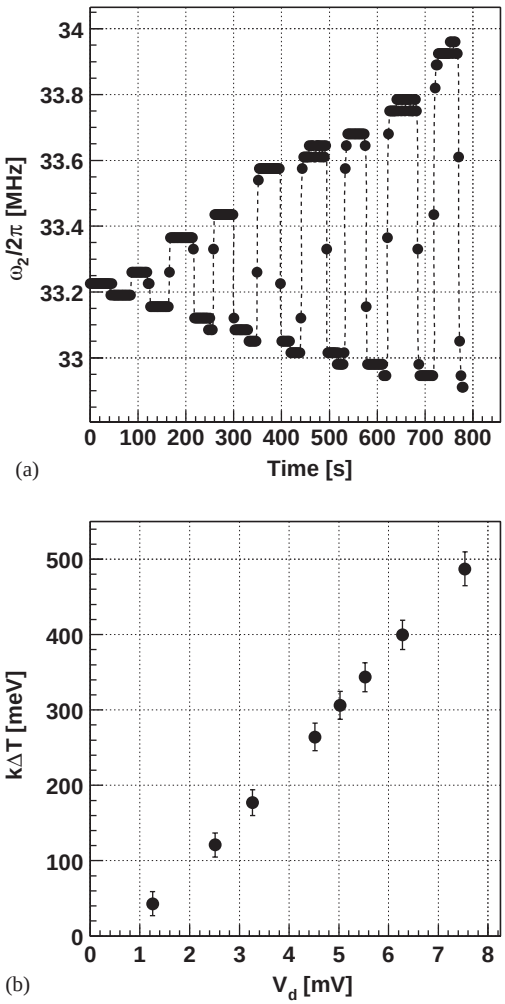

Fig. 3. (a) Time evolution of the quadrupole mode frequency during a heating off-on cycle, different frequency shifts correspond to different heating amplitudes V_d (proportional to V_h of Fig. 1). The drift of the frequency in the unperturbed intervals is due to the plasma expansion and it is consistent with the normal evolution of the unperturbed plasma. (b) Dependence of the temperature variation on radio-frequency signal amplitude for the same cycle.

various electrodes and a voltage $V_r(t) = v_r(\omega)e^{j\omega t}$ is detected across the resistance R_r. Experimentally we measure the ratio $T_L = v_r(\omega)/v_t$ as a function of the driving frequency ω. An example of the results of the implemented diagnostic is shown in Fig. 2.

Because of the importance of temperature in antihydrogen production, we have also investigated whether this diagnostic system can be used to detect changes in the plasma temperature. Previous authors have demonstrated, with work on similar plasmas, that temperature changes manifest themselves in frequency shifts of the second mode (quadrupole mode) [10,11]. It is also possible to monitor the plasma temperature changes measuring the shift in the quadrupole frequency (see Fig. 3). We induced a plasma heating by applying an excitation near the dipole frequency ($\approx$21 MHz) to one of the trap electrodes. Off-resonance heating pulses were not effective. For the ATHENA collaboration it was possible to study the antihydrogen formation vs. temperature by heating and at the same time monitoring the plasma during antiprotons–positrons mixing.

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