A new technique to measure the confinement time of the electron plasma in a Penning trap

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Introduction

We have developed a novel technique to measure the confinement time of an electron plasma trapped in a Penning trap and the corresponding residual air pressure inside the trap. The knowledge of the confinement time and the ambient pressure are required to determine the electron-neutral collision cross-section and the probability of recombination. The study of the non-neutral plasma is important in various fields of research starting from developing an improved atomic clock [1] to the formation and storage of the positron plasma [2] to cite a few examples. Some of these experiments are operated in an ambient pressure where the presence of the background neutrals changes the dynamical behavior and the confinement properties. Thus, it is important to understand the behavior of non-neutral plasma in different vacuum conditions.

In this work, an electron plasma was produced by bombarding an energetic electron beam with the background neutral gas and it was trapped in a Penning trap using a static quadrupolar electrostatic potential and a homogeneous magnetic field. The trapped particles underwent three independent eigen-motions: namely an axial motion with frequency ν_z, a cyclotron oscillation with frequency ν_+ and a magnetron oscillation with frequency ν_-. The axial oscillation of the charged particles induced a current on the trap electrodes and it was picked up by a resonant tank circuit. The stored electron plasma reached thermalization by resistive cooling and its temporal evolution was observed by looking at the axial oscillation of the center of mass of the electron cloud in the noise response of the tank circuit. Since the canonical angular momentum is a conserved quantity, inter-particle collisions cannot lead to an expansion of the stored electron plasma and would result in a confined thermal equilibrium of the trapped electron plasma. However, in reality, the expansion of the electron plasma occurs as the neutral gas molecules collide with the rotating electrons and the trapped electron plasma hit the wall of the electrodes of the Penning trap and get lost. The present work was carried out in the vacuum regime of 10^{-7}-10^{-8} mbar. In these regimes, the electron-neutral atom collision limits the confinement time [3]. A change in the direction of frequency shift was observed as the electron cloud was about to get lost in the radial direction and it has been observed for the first time in this work. This unique feature provides a tool to measure the confinement time. The experiments which are conducted with inject/hold/dump-detection cycle utilizing a Penning Trap [3] would require several cycles to get this information of confinement time and the result would rely on the shot to shot reproducibility of the identical experimental condition. Thus, the technique described in this work provide a single shot determination of the confinement time and could be utilized effectively in ion-atom / ion-ion collisions and recombination rate studies. Since the confinement time is directly related to the ambient pressure, the method additionally provides a new technique to measure the background pressure inside the Penning trap.

Experimental setup and results

The image current signal induced by the axial motion of the electron plasma stored in a Penning trap could be observed in the noise response of the detection circuit when suitable voltage V_0 is applied to the Penning trap electrode so that the axial frequency (ν_z) would be close to the resonance frequency of the tank circuit (ν_R). When $\nu_z \approx \nu_R$, a dip in the noise power was seen because the trapped electrons behaved as a series LCR circuit which tuned out the tank circuit's noise power at the resonance frequency. A mixed domain oscilloscope (Tektronix: Model No.

MDO3054) was used to observe the time correlated behavior of the electron plasma in the frequency domain and the entire frequency evolution of the electron plasma over the trapping period was recorded in a single pass. A screenshot is shown in Fig. 1 where the upper half shows the noise response in the frequency domain with a dip due to the stored electron plasma and the lower half shows the time domain signal. The current falling on the lower endcap after passing through the trap is shown by the triangular curve in the lower half. The number of the secondary electrons produced in the trap were controlled by the amount of primary current going through the trap. The primary current was passed through the trap for a certain time and then it was switched off. The confinement time is defined as the time for which the electron plasma remained stored in the trap from the end of electron loading time.

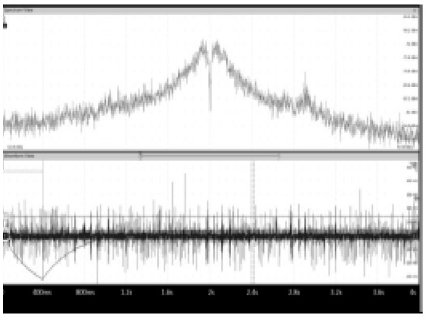

Fig. 1: An oscilloscope screenshot where the lower half shows the time domain signal and upper half shows the frequency domain response.

The frequency evolution of the electron plasma was observed at two different vacuum conditions of 1×10^{-7} mbar and 1×10^{-8} mbar. The temporal variations of the central frequency of the electron plasma in two different vacuum regimes have been plotted in Fig. 2. In these regimes, the confinement time of the electron cloud is mainly dominated by the electron-neutral collision transport [3]. It is seen in Fig. 2, that there is a downward shift of the axial frequency throughout the trapping time. This result has been understood by the change in the axial frequency with changing energy due to the presence of the trap imperfections as the electron cloud loses its energy and proceeds to attend a thermal equilibrium with the tank circuit. The energy of the stored secondary electrons comes down from a few eV to a few milli-eV by transferring its energy to the tank circuit. It can be observed that the reduction in axial frequency is similar for both the vacuum conditions indicating that the energy loss mechanisms of the plasma are similar and independent of the vacuum condition. However, the time taken for the energy loses defining the confinement time depends on the level of the vacuum.

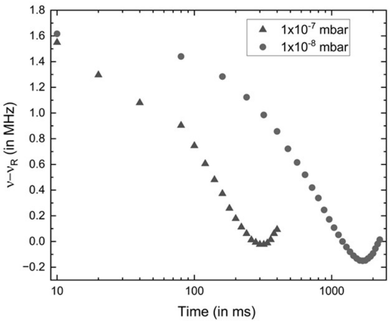

Fig. 2: Variations of the axial frequency of the center of mass with time at 1×10^{-7} mbar and 1×10^{-8} mbar pressure.

Fig. 2 shows that the axial frequency increases towards the end of the trapping time. This signature has been observed for the first time in this work. The time difference between the time at which the electron loading stopped and the time at which the upward shift in the axial frequency observed gives a good measure of confinement time. It is observed from Fig. 2 that the electron plasma remained confined for 300 milliseconds and 1.7 seconds at the ambient pressures of 10^{-7} and 10^{-8} mbar respectively. Alternatively, the residual air pressure in the trap could be inferred from the measured confinement time using its known relationship with the ambient gas pressure.
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