Effect of excitation on the temporal evolution of electron cloud in Penning trap

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Introduction

According to the AME 2020 Atomic Mass Table [1-2], which includes over 3550 nuclide masses, Penning traps have become indispensable tools for measuring precisely both short- and long-lived nuclide masses, advancing atomic and nuclear research. Storing electrons or positrons in a Penning trap is an excellent method for studying non-neutral plasma. This plasma configuration is crucial for creating antihydrogen [3], the simplest form of antimatter, consisting of a positron and an antiproton. In a planar trap geometry, a confined electron [4] is a promising candidate as a qubit in quantum computing.
In a Penning trap, radio frequency excitation is typically used to align the phase for accurate cyclotron frequency determination in both Pulse 'N' Phase (PnP) [5] and Pulse 'N' Amplify (PnA)[6] methods. Moreover, quadrupolar excitation [7] is necessary for high precision mass measurements using time-of-flight as well as Phase Imaging- Ion Cyclotron resonance (PI-ICR) methods. For magnetron cooling [8] of trapped charged particles, such excitation is also applied. In VECC Penning trap, we studied the effect of different excitation amplitudes on the temporal evolution of the axial oscillation frequency of the centre of mass of electron cloud. This study provides insight into how the electron cloud responds to applied excitation, revealing changes in its motion dynamics under different excitation levels.

Experiment and Discussion

In the VECC Penning trap, the image charge signal induced by the trapped electron cloud is recorded nondestructively using the noise dip detection technique, as detailed in Ref. [9]. This method provides a single-shot detection capability to monitor the motion of the electron cloud throughout the trapping period. A tank circuit with a loaded frequency of $\omega_R = 2\pi \times 40.95\, MHz$ is used to track the axial frequency of the cloud's center of mass. As the cloud undergoes radial expansion due to interactions with residual gases, the overall magnetron radius changes, leading to a continuous variation in the axial frequency.

In each cycle, the primary electron beam is passed for a set duration, leading to the generation of secondary electrons upon collision with background gases, which are subsequently stored in the trap. During noise dip detection, the initial signal is observed after a delay from beam stoppage, and this delay increases as the vacuum condition improves. This suggests that the electron cloud requires some time to synchronize and gain strength at the center-of-mass axial oscillation frequency. This phenomenon is found to be vacuum-dependent.

We also observed that the signal becomes undetectable at vacuums better than 2×10^{-8} mbar using the noise dip technique. This is because fewer secondary electrons are generated as the vacuum improves. Moreover, the axial frequencies of these few electrons are distributed over a broad frequency range, making them undetectable above the noise floor. To enhance the signal, these dispersed electrons must be centered, which can be achieved through magnetron cooling. This technique reduces the magnetron radius by applying dipolar excitation, similar to methods used to center positrons in previous work [8].

Magnetron cooling requires a substantial amount of time, approximately 20 minutes, so a trapping duration of more than 20 minutes is necessary. This extended trapping time can be achieved at a vacuum level better than 5×10^{-10} mbar. However, to observe the effect of applied excitation on the dynamics of the electron cloud using the noise dip technique, we conducted the experiment at a vacuum level of 2×10^{-7} mbar, where the confinement time is approximately 1200-1600 ms.

So, in this work, the stored electron cloud is subjected to axial excitation by applying an RF field to the upper electrode of the Penning trap. Applying excitation at ω_R would cause the output voltage of the low-noise amplifier in the detection electronics to saturate even at low power levels. Thus, the excitation is applied at 43 MHz, which is far away from the influence zone of the tank circuit.

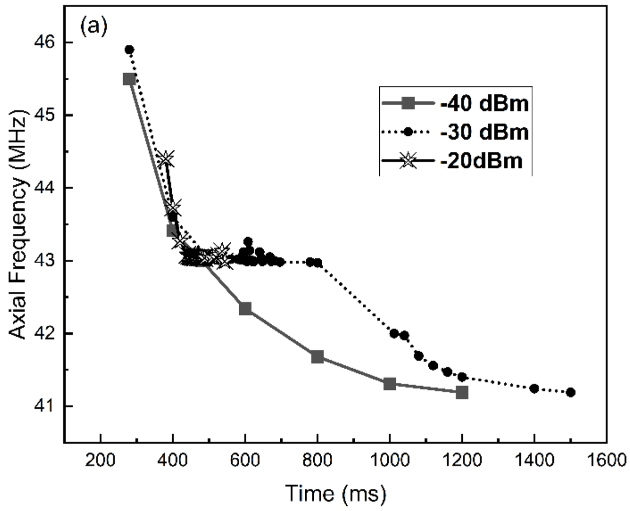
The motion of the center of mass of the electron cloud in the Penning trap in the presence of an additional rf-excitation and considering some damping mechanism due to presence of detection circuit, characterized by a damping constant γ is given as

$$M\ddot{Z} + \gamma\dot{Z} + M\omega_z^2 Z = F_0 Z\cos(\omega t) \qquad (1)$$

where, M is the total mass of the electron cloud and F_0 is the amplitude of the radiofrequency excitation at frequency ω. The variation of axial oscillation frequency over time for different level of excitations (F_0) is shown in Fig. 1(a).

As seen in Fig. 1, when the excitation level is below -40 dBm, no effect is observed at the applied frequency of 43 MHz. The motion of the electron cloud remains unchanged, similar to the case without excitation [9]. However, at an excitation level of -30 dBm, a plateau is observed around 43 MHz for a duration of 330 ms, where the evolution of the cloud appears to temporarily freeze. This excitation power is sufficient to increase the energy (E_z) of the trapped particles in the axial direction. As the oscillation amplitudes increase, the anharmonic terms cause an increase in the axial frequency, as given below in [11]

$$\frac{\Delta f_z}{f_z} = \frac{3}{2}\frac{C_4}{C_2^2}\frac{E_z}{qV_0} + \frac{15}{4}\frac{C_6}{C_2^3}\left(\frac{E_z}{qV_0}\right)^2 \qquad (2)$$



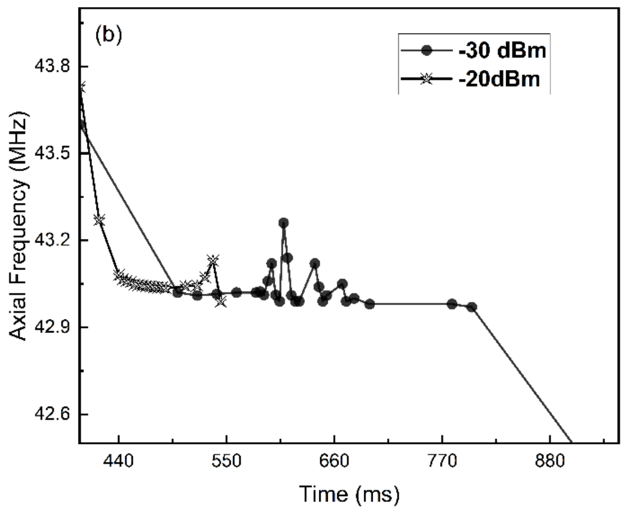


Figure 1: Temporal evolution of electron cloud under different excitation amplitude at frequency 43 MHz (a) Total Evolution. (b) Zoomed view in the temporal regime where axial frequency nearly freezes at 43 MHz.

As mentioned in Eq. 2, the axial frequency shift due to -40 dBm excitation in the axial direction is small compared to the shift resulting from changes in the magnetron radius caused by collisions with background gas [9]. However, at -30 dBm, both the excitation effect and the varying magnetron effect contribute, resulting in a prolonged observation of the axial frequency at the applied frequency. In this plateau region, the signal strength gradually decreases due to particle loss. Thus, this excitation amplitude should be applied for detecting signals from low number of stored electrons.

At an excitation power of -20 dBm, the axial excitation becomes so pronounced that the high-amplitude oscillation causes particles to escape from the trapping region. Consequently, after this plateau, the signal disappears, and the trapping signal is observed only up to 550 ms. At even higher power levels, the electron cloud is lost as soon as the axial frequency matches the applied frequency.

In this work, the temporal evolution of electron clouds was studied under different excitation amplitudes. At relatively higher excitation power, a plateau was observed in the temporal evolution around the excitation frequency. This phenomenon is attributed to a combination of dipolar excitation and changes in the magnetron radius. This study provides insights into the changes in the dynamics of stored particles under applied excitation.

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DATA AVAILABILITY
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Reference

1. W. Huang, *et. al.*, Chinese Physics C **45** (2021) 030002.
2. M. Wang, *et. al.*, Chinese Physics C **45** (2021) 030003.
3. G. B. Andresen, *et.al.*, Nature **468** (2010) 673–676.
4. P. Bushev, *et.al.* Eur. Phys. J. D, **50** (2008) 97–102.
5. Eric A. Cornell, et.al., Phys. Rev. Lett. **63** (1989) 1674.
6. S. Sturm, Ph.D. thesis, Johannes Gutenberg University of Mainz, Germany, (2011).
7. Klaus Blaum, Physics Reports **425** (2006) 1-78.
8. L. D. Haarsma, Ph.D. thesis, Harvard University, (1994).
9. J.Nandi, *et.al.*, Rev. Sci. Inst. **95** (2024) 043202.
10. K.A. Farrar, Nucl. Instrum. Meth. A **485** (2002) 780.
11. M.S. Ebrahimi, *et.al.* Phys. Rev. A **98** (2018) 023423