Optimization and characterization of Penning Trap at room temperature

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Introduction

Penning trap is a device to trap charged particles under the combined application of a strong homogenous magnetic field and weak quadrupolar electric potential. It is generally required to generate a perfect harmonic potential near trap centre which should be free from any undesirable electric field imperfections for high precision mass and g-factor measurements. Cylindrical electrodes could be used to generate a weak quadrupolar potential near the trap centre with a high degree of harmonicity by the judicious choice of trap electrode geometry and applied electrostatic potential. This optimization procedure to create a perfect harmonic potential was done earlier by trapping one or a few charged particles in a cryogenic Penning Trap [1]. However, this optimization procedure is very time consuming to perform in a cryogenic trap, because it would take a long time to implement any modifications and test it again. In this work, we present an optimization procedure that could be done at room temperature using a cloud of electrons. The optimization procedure could be implemented by observing the noise dip signal of the trapped electrons at room temperature. This noise dip detection technique was applied earlier to observe the signal of single or a few charged particles trapped in a cryogenic Penning trap. Due to excellent performance of our detection circuit, the noise dip detection technique could be applied to observe a cloud of electrons trapped in a Penning Trap at room temperature. This paper represents the optimization and characterization of Penning Trap utilizing noise dip detection technique at room temperature.

Theory

Let V_0 is the voltage applied between the ring and the endcap electrode. The electric potential close to the centre of the trap can be written as

$$V(r,\theta) = \frac{1}{2} V_0 \sum_{\substack{k=0 \\ even}}^{\infty} C_k \left(\frac{r}{d}\right)^k P_k(\cos\theta) \quad (1)$$

where d is the characteristic dimension of the trap [2]. In order to generate an ideal quadrupole trapping field, it is required that $C_2 \rightarrow 1$ with all other C_k ($k > 2$)$\rightarrow 0$. The axial oscillation frequency of a particle with mass m and electric charge q in a harmonic potential well is given by

$$\omega_Z = \sqrt{\frac{qV_0}{md^2} C_2} \quad (2)$$

If we apply a potential V_0 between the endcap and the ring electrodes, and V_c to the compensation electrodes, the superimposed potential [2] inside the trap is given by

$$V = V_0\Phi_0 + V_c\Phi_c \quad (3)$$

where,

$$\Phi_0 = \frac{1}{2} \sum_{\substack{k=0 \\ even}}^{\infty} C_k^{(0)} \left(\frac{r}{d}\right)^k P_k(\cos\theta) \text{ and}$$

$$\Phi_c = \frac{1}{2} \sum_{\substack{k=0 \\ even}}^{\infty} D_{1k} \left(\frac{r}{d}\right)^k P_k(\cos\theta) \quad (4)$$

are solutions of the Laplace equation with the boundary conditions given in ref. [2]. The coefficients $C_k^{(0)}$ and D_k depend crucially on the length of trap electrodes. The total electrostatic potential polynomial expansion coefficient C_k can be expressed as

$$C_k = C_k^{(0)} + \frac{V_c}{V_0} D_{1k} \quad (5)$$

A good harmonic trap requires leading anharmonic term $C_4 \rightarrow 0$ which can be realized by adjusting V_c to satisfy the following relationship:

$$C_4^{(0)} + \frac{V_c}{V_0} D_4 = 0 \quad (6)$$

Due to the presence of electric field imperfections, the axial frequency is shifted by

$$\frac{\Delta\omega_z}{\omega_z} = \frac{3C_4}{2C_2^2} \frac{E_z}{qV_0} \quad (7)$$

where E_z is the axial energy of the trapped electrons.

Experimental Optimization

In the noise dip detection technique, the electron signal appears as a peak when the electron oscillation frequency (ν_z) is far away from tank circuit's resonance frequency (ν_R) and appears as a dip when both the frequency matches i.e. $\nu_z = \nu_R$ as shown in Fig. 1.

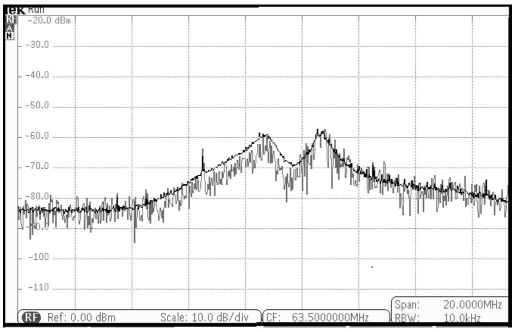

Fig. 1: Noise response of detection circuit for $\nu_z = \nu_R$.

According to eqn. (2) & (7), the axial oscillation frequency varies with the change in the applied voltage V_0 between the ring and endcap electrodes.The tuning ratio ($T_r = \frac{V_c}{V_0}$) is the ratio of compensation voltage V_c with the applied voltage V_0 between ring and endcap electrode.

Table 1: Slope and intercept for the variation of ω_z^2 with the applied voltage V_0 obtained for different values of the tuning ratio.

Tuning ratio(T_r)	Slope (x10^{12})	Intercept (x10^{12})
0.3	4212.1± 211.9	55985.7± 4862.9
0.31	4161.7±224.1	57991.5± 5040.9
0.32	5358.1± 185.0	31334.0± 4116.1
0.33	5724.4±487.1	23807.1±10730.3
0.34	5264.9± 487.1	34218.5± 3981.6
0.35	5320.1±211.0	33712.4± 4653.5
0.37	5233.2± 491.8	35188.3±10798.2
0.4	4742.0±306.9	48134.4± 6631.9

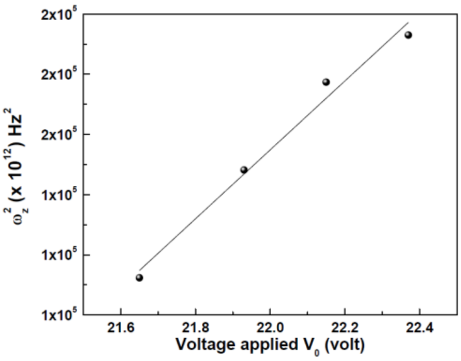

Fig. 2: Variation of ω_z^2 with V_0 for tuning ratio T_r= 0.33.

Since C_4 term is usually responsible for broadening the axial line shape by coupling the axial energy E_z to the axial frequency ω_z, the dip signal becomes the narrowest and deepest when $C_4 \rightarrow 0$. We plotted V_0 versus ω_z^2 for different tuning ratios ($T_r = \frac{V_c}{V_0}$) and obtained linear fit for each case. A typical example for T_r= 0.33 is shown in Fig. 2. The slope and intercept obtained for different values of T_r have been tabulated in Table 1. At $T_r = 0.33$, we find the minimum intercept and maximum slope parameters. We think that this condition would provide the narrowest and deepest electronic dip signal and it would be verified experimentally. Thus, our procedure would give a method to optimize the trap at room temperature using a cloud of electrons.

Conclusions

This work provides a new technique to optimize the Penning Trap at room temperature by tuning out the dominant anharmonic term and characterize it by observing the trapping signal in the noise response of the tank circuit.

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References

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