Design of a dynamic orthogonalized Penning trap with higher order anharmonicity compensation

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Introduction

A Penning trap uses a strong and uniform magnetic field and an electrostatic quadrupole potential to confine and manipulate charged particles. Penning traps with cylindrical electrodes have the advantage of machining to better surface finish and also provides the accessibility for particle loading and rejection, laser beams and microwaves [1]. A set of compensation electrodes can be introduced to tune out the anharmonicity of a Penning trap to first order. The concept of an orthogonalized Penning trap was introduced for a trap with special geometries such that the trapping well depth and the trapped particle axial oscillation frequency were independent of the tuning of anharmonicity.

In our present work, we present a design technique of a double compensated cylindrical Penning ion trap which includes the effect of realistic gap. By varying the length of the electrodes, we have been able to make the trap orthogonal and tuned out anharmonicity to a higher degree for a wide range of radius of the trap and gap length which was previously possible only for certain special geometries.

Present work

In trap geometry as shown in Fig. 1, if V_0 is the voltage applied between the ring and the endcaps, then the electric potential close to the centre of the trap can be written as

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

where d is the characteristic dimension of the trap, defined as $d=1/2(Z_0^2 + r_0{}^2/2)$. In the expression, it is assumed that the trapped ions have no effect on the potential field and the centre of the ring electrode is considered as origin. In order to generate an ideal quadrupole trapping field, it is required that C_2 is as close as possible to one with all other C_k ($k > 2$) should approach zero. We know that the axial oscillation frequency of a particle with mass *m* and electric charge *q* in the harmonic potential well is given by

$$\omega_Z = \sqrt{\frac{q\,V_0}{m\,d^2} C_2} \qquad (2)$$

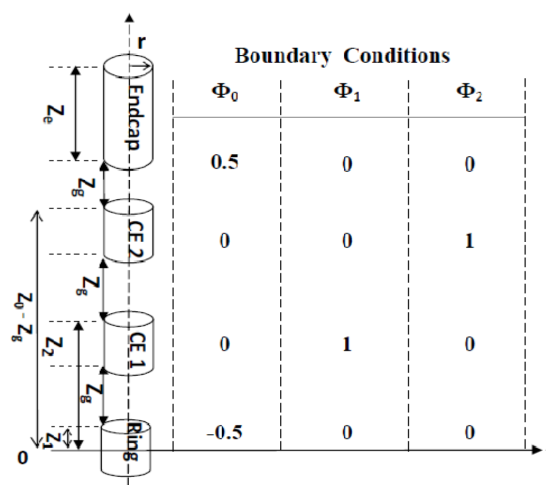

Fig. 1.Half part of cylindrical Penning trap with two set of compensation electrodes with specified boundary conditions of Φ_0, Φ_1 and Φ_2

If we apply a potential V_0 between the endcaps and the ring, V_1 to the inner compensation electrodes(CE1), and V_2 to the outer compensation electrodes(CE2),the superimposed potential [2] inside the trap (since the potential is additive) is

$$V = V_0\Phi_0 + V_1\Phi_1 + V_2\Phi_2 \qquad (3)$$

where

$$\Phi_0 = \frac{1}{2} \sum_{\substack{k=0 \\ even}}^{\infty} C_k^{(0)} \left(\frac{r}{d}\right)^k P_k(\cos\theta) \qquad (4)$$

$$\Phi_1 = \frac{1}{2} \sum_{\substack{k=0 \\ even}}^{\infty} D_{1k} \left(\frac{r}{d}\right)^k P_k(\cos\theta) \qquad (5)$$

and

$$\Phi_2=\frac{1}{2}\sum_{\substack{k=0\\even}}^{\infty} D_{2k}\left(\frac{r}{d}\right)^k P_k(\cos\theta) \quad (6)$$

are solutions of the Laplace equation with the boundary shown in Fig 1. and $C_k^{(0)}$, D_{1k} and D_{2k} are the coefficients which depend crucially on the length of trap electrodes. The detailed expression of these coefficients can be obtained from the literature [3] where the gap is considered as semi – infinite which is applicable only when Z_g is much smaller than the electrode thickness and r>>Z_g .Under this assumption, the potential within the gap when V_α is applied to lower electrode and V_β to upper electrode can be written as [3]

$$V\left(\frac{\sigma}{Z_g}\right)=\frac{1}{2}\left(V_\alpha - V_\beta\right)\left[\frac{(V_\alpha+V_\beta)}{(V_\alpha-V_\beta)}-\left(\frac{\sigma}{Z_g}\right)^{2/3}+\left(1-\frac{\sigma}{Z_g}\right)^{2/3}\right] \quad (7)$$

The gap potential for different boundary conditions as specified in Fig. 1. are fitted with fifth order polynomial and the coefficients are used accordingly [3]. Thus, the total electrostatic potential polynomial expansion coefficient C_k can be expressed as

$$C_k=C_k^{(0)}+\frac{V_1}{V_0}D_{1k}+\frac{V_2}{V_0}D_{2k} \quad (8)$$

The dynamic orthogonalized harmonic trap with leading anharmonic term C_4 = 0 and C_2=$C_2^{(0)}$ (which is independent of compensation potentials V_1 and V_2) can be realized by adjusting V_1 and $V_2$to satisfy equations

$$\frac{V_1}{V_0}D_{12}+\frac{V_2}{V_0}D_{22}=D_2=0 \quad (9)$$

and

$$C_4^{(0)}+\frac{V_1}{V_0}D_{14}+\frac{V_2}{V_0}D_{24}=0 \quad (10)$$

For a given gap (Z_g/Z_0), radius (r/Z_0) and (Z_2/Z_0), we can adjust the length of the ring electrode to make the next higher order anharmonic term C_6 = 0 in addition. The various lengths of electrodes required to satisfy this conditions are plotted in Fig.2. for four different gap-length.

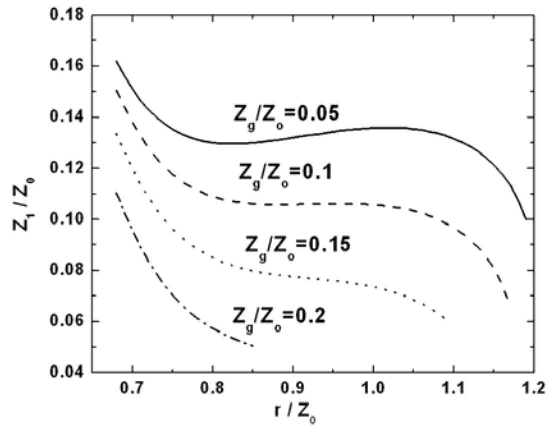

Fig. 2. Variation of Z_1/Z_0 with r/Z_0 which satisfy all the conditions mentioned

Dicussion

This work provides a method of designing a cylindrical trap with double compensation electrodes having quadrupolar potential over appreciable region near the trap centre for a wide range of cylindrical trap geometries including the effect of realistic gap. Two sets of compensation electrodes were used to make oscillation frequency independent of anharmonic tuning voltages and drive out C_4 term (the largest non-quadrupole term). Next higher order coefficients (C_6) is tuned out with proper geometry selection for a wide range of trap dimensions. The coefficients obtained from the analytical solution matches very well with that obtained from standard code SIMION8 [4]. This work will be useful for designing trap for several different applications.

References

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