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A planar Penning trap with tunable dimensionality of the trapping potential

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ABSTRACT

The coplanar-waveguide Penning trap developed at the University of Sussex is modified by enclosing it in a rectangular microwave cavity and adding two “side electrodes”. These permit to expand the range of useful trapping positions, where the linear fluctuations of the axial frequency with the axial energy – caused by electrostatic anharmonicities – are eliminated. That is the critical condition for the accurate measurement of the eigenfrequencies of a single trapped electron – or ion – as required for quantum computation or mass spectrometry applications. The side electrodes also allow for adjusting the dimensionality of the potential. The trap can be driven into the “ultra elliptical”, regime, where the magnetron motion vanishes and the particle is confined within a quasi two-dimensional potential. Furthermore, we calculate the deviations of the eigenfrequencies caused by the gradient and curvature of the magnetic field. The obtained frequency shifts matrices have universal validity for all Penning traps. They include those obtained for conventional traps, i.e. with cylindrical symmetry, as a particular case.

1. Introduction

Different planar Penning traps have been designed [1–4], mainly motivated by potential quantum applications with electrons [5–7] or with ions [8]. At the University of Sussex we have developed the *coplanar-waveguide Penning trap* or CPW-trap [9]. Its sketch is shown in Fig. 1. In contrast to all other surface trap models, the CPW-trap has the magnetic field parallel to the surface of the chip. As shown in the figure, this delivers a symmetric axial (= along z) potential well. Furthermore, all experiments and proposals on planar Penning traps employ or assume an unscalable “room-size”; superconducting solenoid. We follow a different approach. We aim at implementing the magnetic field source and the trap's electrodes in a single, scalable chip. This idea has been introduced in [10,11]. We call our new device *Geonium Chip*, inspired by H. Dehmelt, who used the expression geonium atom to name a single electron captured in a Penning trap [12].

We have expanded the capabilities of the CPW-trap by adding two “side electrodes”, to the original design presented in [9]. These are described in detail in this article. In particular, we discuss the adjustable dimensionality of the trapping potential and show how the particles can be captured within a finite plane in free space. Moreover, we derive the fluctuations of the eigenfrequencies caused by the gradient and curvature of the magnetic field at the position of the particle. The obtained formulas have general validity for all Penning traps; they include those derived for conventional three-dimensional traps [13] as a special case. The achievable magnetic homogeneity will define the capacity of the envisaged Geonium Chip technology, for applications in mass spectrometry, quantum computation and plasma physics. The discussion is focused upon electrons, the objects of our experimental work. Its generalisation to other charged particles is straightforward.

2. Boxed CPW-trap

The basic CPW-trap consists of five flat rectangular electrodes. These are patterned on the surface of a dielectric substrate. As shown in Fig. 1, the electrodes are: the “ring”, two “correction (or compensation) electrodes”; and two “end caps”.

The electrodes' dimensions and the applied voltages are given in Fig. 2(a). The voltages applied to the ring, correction electrodes, end caps and side electrodes are denoted by V_r, V_c, V_e and V_g, respectively. The symbols l_i denote the different electrodes' lengths. S_0 represents the width of the central electrodes and η_1 is the small insulating gap between them. The total length of the trap is $L_0 = l_r + 4\eta_1 + 2l_c + 2l_e$. The length of the side electrodes is also given by L_0. Furthermore, S_1 represents the width of each side electrode and η_2 is the gap between these and the central electrodes. Other important symbols are the *tuning ratio*, $T_c = V_c/V_r$, the end cap-to-ring voltage ratio, $T_e = V_e/V_r$ and the side electrode-to-ring voltage ratio, $T_g = V_g/V_r$. These three ratios define the electrostatic potential.

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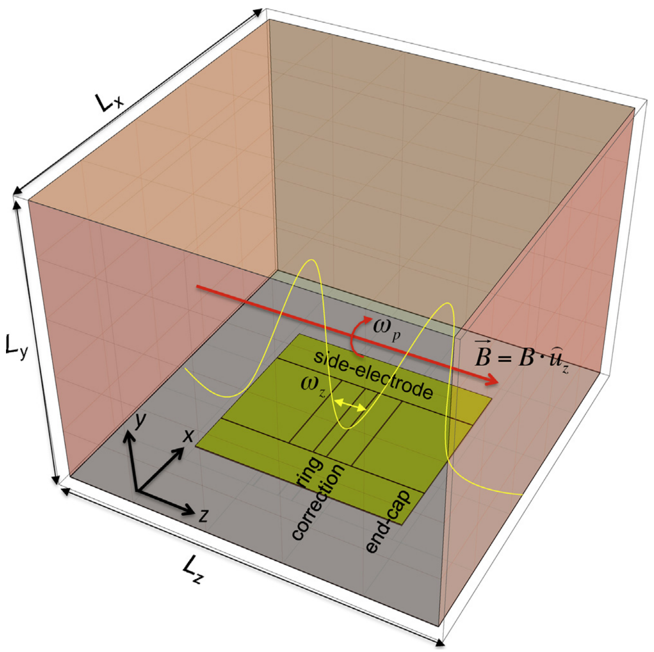

Fig. 1. Sketch of the CPW-Penning trap in a closed metallic box. The walls of the box and the metallic surface around the trap's electrodes are assumed to be at zero dc-voltage.

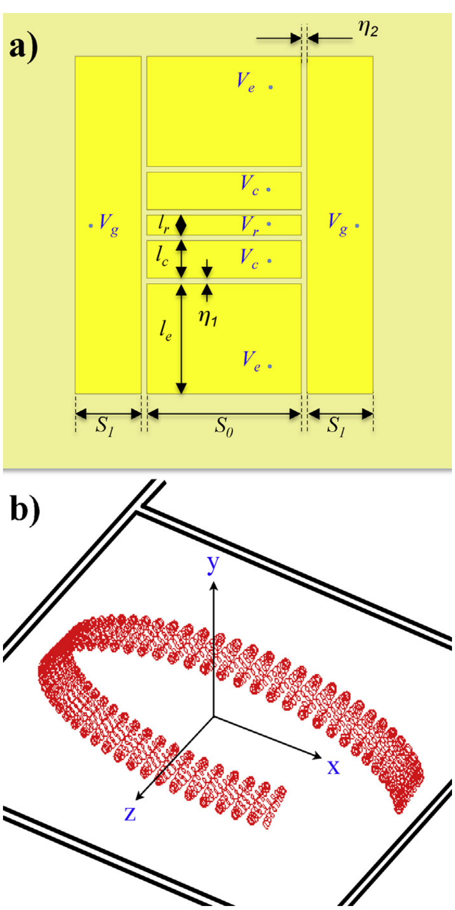

Fig. 2. (a) Sketch of the CPW Penning trap. The coordinates' origin, (0, 0, 0), is the centre of the ring. The rest of the chip's surface, beyond the trap's electrodes, is also metallic and dc-grounded. (b) Plot of the ideal motion of a trapped particle above the ring.

2.1. Ideal boxed CPW-trap

The basic voltage configuration is: $T_e > T_c \simeq 1$, with $T_g = 0$. The ring voltage will be negative for trapping electrons and positive for positively charged particles. This voltage configuration creates a potential minimum at some equilibrium position, $(0, y_0, 0)$, above the ring. The charged particle is captured and performs a periodic motion around $(0, y_0, 0)$.

In the CPW-trap the curvature of the electrostatic potential along $\hat{u}_x$ is, in general, different to the curvature along $\hat{u}_y$. Due to the distinguishability between x and y, the CPW-trap falls within the general category of *elliptical Penning traps*. Elliptical Penning traps have been discussed by Kretzschmar [14]. The ideal quadrupole potential of the CPW-trap is given by the following expression [9]:

$$\phi_{\text{quad}} = C_{002}\left\{\left(z^2 - \frac{x^2 + (y - y_0)^2}{2}\right) + \frac{\epsilon}{2}\cdot(x^2 - (y - y_0)^2)\right\} \quad (1)$$

In Eq. (1) the coefficient C_{002} represents the curvature of the potential well along the z-axis at $(0, y_0, 0)$. We have introduced the *ellipticity parameter* ϵ. This is defined as $\epsilon = (1 - \xi)/(1 + \xi)$, where $\xi = C_{200}/C_{020}$ is the ratio of the curvature of the potential along x (C_{200}), versus the curvature along y (C_{020}). Penning traps with cylindrical symmetry have these two curvatures identical and, therefore, ϵ vanishes. In a CPW-trap, in general, we have $\epsilon \neq 0$. Moreover, for vanishing energies the motion of a trapped particle is governed by the general quadrupole potential of Eq. (1). The ideal motion is plotted in Fig. 2 **b)**. It is described by the following equations:

$$\begin{aligned} x(t) &= \xi_p \cdot A_p \cos(\omega_p t) + \xi_m \cdot A_m \cos(\omega_m t) \\ y(t) &= y_0 - \eta_p \cdot A_p \sin(\omega_p t) - \eta_m \cdot A_m \sin(\omega_m t) \\ z(t) &= A_z \cos(\omega_z t) \end{aligned} \quad (2)$$

The motion is the superposition of three oscillators: the reduced cyclotron motion, with frequency ω_p ($=2\pi\nu_p$), the axial motion, with characteristic frequency ω_z ($=2\pi\nu_z$), and the slow magnetron motion with frequency ω_m ($=2\pi\nu_m$). The frequencies in an ideal elliptical trap, i.e. with the quadrupole potential of Eq. (1), have been calculated analytically [14]. They are given by the following formulas:

$$\begin{aligned} \omega_z &= \sqrt{2\,C_{002}\frac{q}{m}}, \\ \omega_p &= \sqrt{\frac{1}{2}(\omega_c^2 - \omega_z^2) + \frac{1}{2}\sqrt{\omega_c^2\,\omega_1^2 + \epsilon^2\,\omega_z^4}}, \\ \omega_m &= \sqrt{\frac{1}{2}(\omega_c^2 - \omega_z^2) - \frac{1}{2}\sqrt{\omega_c^2\,\omega_1^2 + \epsilon^2\,\omega_z^4}}, \\ &\text{with} \quad \omega_c = \frac{q}{m}B_0; \quad \omega_1 = \sqrt{\omega_c^2 - 2\,\omega_z^2}. \end{aligned} \quad (3)$$

In Eq. (3) the symbols q, m represent the charge and mass of the trapped particle, respectively. The free cyclotron frequency is denoted by ω_c, where B_0 is the strength of the magnetic field along $\hat{u}_z$ at y_0. Furthermore, the motion's amplitudes are given by:

$$\begin{aligned} A_p &= \frac{1}{\omega_p}\sqrt{\frac{2E_p}{\gamma_p\,m}}, \quad \gamma_p = 1 - \frac{\omega_z^2}{2\,\omega_p^2} \simeq 1. \\ A_m &= \sqrt{\frac{2\,E_m}{(\omega_m^2 - \omega_z^2/2)\,m}}. \\ A_z &= \frac{1}{\omega_z}\sqrt{\frac{2\,E_z}{m}}. \end{aligned} \quad (4)$$