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Operation of a planar Penning trap

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Abstract. We demonstrate experimentally the confinement of electrons in a novel planar Penning trap. Measurement of the eigenfrequencies of the trapped electron cloud exhibits similar behaviour as in conventional 3-dimensional penning traps. The trap may be of future use in quantum computing schemes using single cold electrons.

PACS. 39.10.+j Atomic and molecular beam sources and techniques – 03.67.Lx Quantum computation – 52.27.Jt Nonneutral plasmas

1 Introduction

Penning traps confine charged particles by static electric and magnetic fields in a small volume in space. Conventional 3-dimensional Penning traps use a voltage applied between a ring electrode and two equally charged endcaps for confinement in the axial direction while radial confinement is assured by a static magnetic field directed along the trap axis. The properties of these traps have been extensively discussed in the literature [1–3].

Recently we proposed an alternative trap geometry consisting of a series of conducting rings placed on a surface [4] (Fig. 1). The simplest case would be a central disc surrounded by a ring. When voltages of different signs are applied between these two electrodes the electric potential along the central axis shows a minimum in the axial direction which can be used to trap charged particles axially. The potential shape may be modified by voltages applied to additional ring electrodes. Figure 2 shows calculated axial potentials for different trap parameters. Radial confinement is provided by a magnetic field along the z-axis. The potential minimum appears at a distance above the trap surface which is approximately equal to the diameter of the central electrode. The concept of planar traps may be of particular advantage when applied to novel proposals in quantum computation [5–8]. The same idea has been recently implemented in a Paul configuration [12,13].

Here we report about first measurements to demonstrate that the planar trap can be operated as expected.

Fig. 1. Conceptual view of a planar trap with two electrodes. For negatively charged particles, the disk electrode must have a potential smaller than the ring electrode.

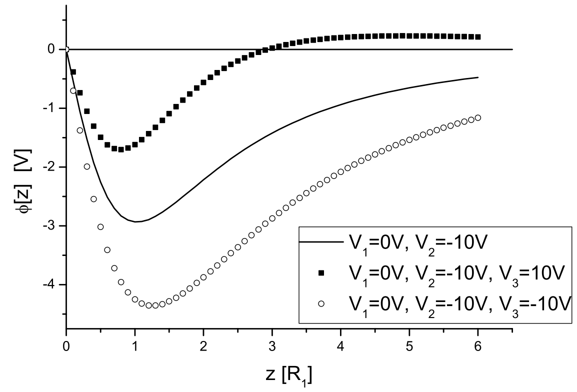

Fig. 2. Calculated axial potential for different trap configurations. The continuous curve is for two electrodes, and the discontinuous ones correspond to the case of adding a third electrode. The voltages at the electrodes, numbered from inside to outside, have been chosen for trapping negatively charged particles.

2 Experimental set-up

Our planar trap is made of silver electrodes produced by standard thin film technology on a ceramic substrate. The inner disk radius is 3 mm. Spaced by a 0.3 mm gap we have provided 4 concentric rings of 3 mm width. Figure 3 shows a picture of the actual trap. In our first experiments only 2 ring electrodes are used while the remaining ones are held at ground potential. Electrical contacts are provided from the back side. The inner disk has a central hole of 0.5 mm diameter for injection of electrons from a filament

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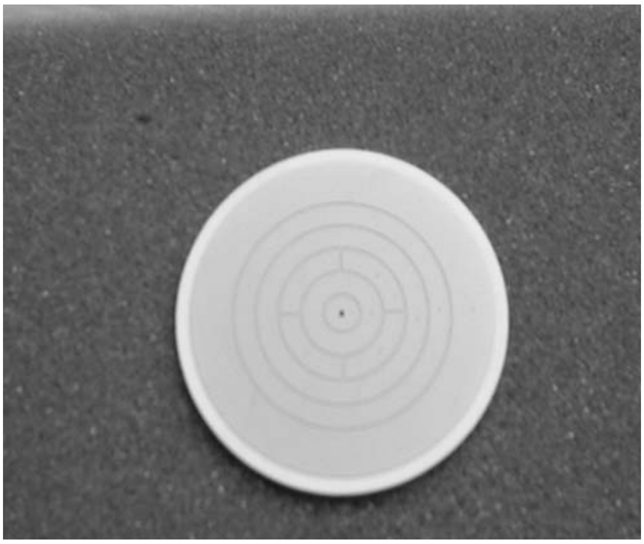

Fig. 3. Front view of the planar trap in use, with 5 electrodes surrounded by a wide ground electrode. Except for the measurements presented in Figures 10 and 11, only the three inner ones have been used, and one of them is divided into four segments for quadrupolar excitation purposes. The central hole in the disk serves for injection of particles from behind the trap. The total radius of the device is ≈20 mm. The trap's electrodes' connections are at the rear side of the trap.

placed a few mm behind the trap. The injected electrons ionise the background molecules in the vacuum of typically 10^{-8} mbar. Secondary electrons created near the potential minimum are trapped. They are detected destructively by ejection from the trap at a given time interval after the injection pulse and counted in a multi-channelplate detector. The trap is placed in the room temperature bore of a superconducting magnet. Maximum field strength is 1.9 T. By moving the trap into the fringe field of the magnet the field strength can be reduced.

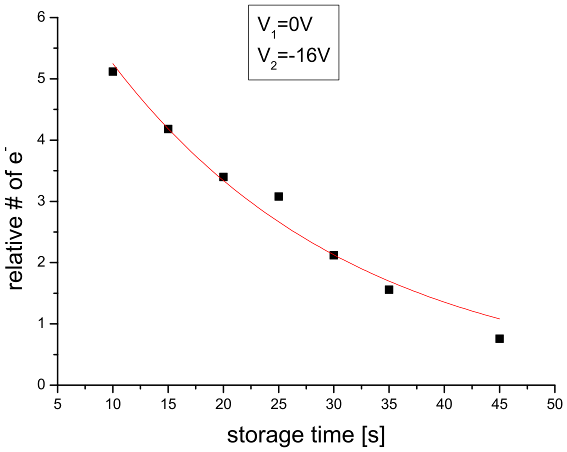

Fig. 4. Detected relative electron numbers at different storage times in a magnetic trapping field of 1.9 T. The time constant from an exponential fit is 22 ± 2 s.

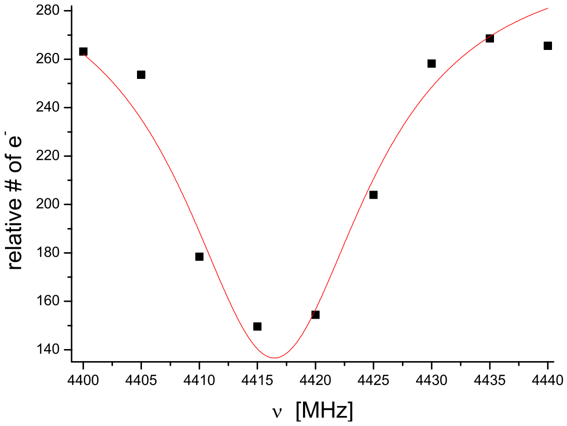

Fig. 5. Excitation of the perturbed cyclotron oscillation of electrons in a planar Penning trap. Least squares fitted Lorentzian to the experimental data points ($B \approx 0.16$ T).

3 Measurements

To demonstrate the trapping properties of the planar trap we measured the storage time of electrons by variation of the time delay between injection and ejection. The mean storage time of 22 s obtained at a B-field of 1.9 T (Fig. 4) is typical for electrons at our background pressure. A tilt of the trap axis with respect to the magnetic field may also contribute to particle loss due to axial-radial motional coupling. In a similar run under seemingly identical conditions we found a much shorter storage time and discovered later an obvious misalignemnet. When we apply a radio frequency field to one of the additional ring electrodes we can excite the ion motion in the trap at the proper frequency. As in three-dimensional ion traps the motion consists of 3 oscillations: an axial oscillation at frequency ω_z, given by the shape of the electric potential and independent of the magnetic field, the "perturbed cyclotron oscillation" at frequency $\omega_+ = \omega_c/2 + \sqrt{(\omega_c^2/4 - \omega_z^2/2)}$, and the "magnetron oscillation" $\omega_- = \omega_c/2 - \sqrt{(\omega_c^2/4 - \omega_z^2/2)}$. $\omega_c = (e/m)B$ is the free electron's cyclotron frequency. For low trapping voltages ω_+ is close to ω_c, slightly shifted to a lower value by the presence of the electric trapping field, while the magnetron oscillation is a slow drift of the cyclotron orbits around the trap center. It is independent of the trapped particle's mass in first order. In the ideal case of a homogeneous magnetic field and a harmonic axial trapping potential as in perfect three-dimensional traps with hyperbolic electrodes the resonance shape of an excited oscillation would be a Lorentzian. This is approximately the case in the planar Penning trap for the radial perturbed cyclotron and magnetron oscillations. Figures 5 and 6 show examples. Upon excitation some electrons leave the trap and at resonant excitation the detected electron number shows a minimum. As expected the data points can be well fitted by a Lorentzian. The width of the cyclotron resonance is determined by the inhomogeneity of the magnetic fringe field at the position of the trap. Operation in the homogeneous part ($B \approx 1.9$ T) could not be performed since the required oscillator at 53 GHz was not available. The shape of the axial resonance depends

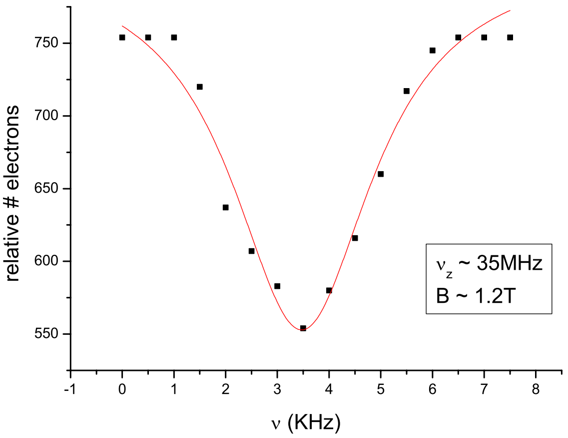

Fig. 6. Excitation of the magnetron oscillation. Experimental data fitted with a Lorentzian curve.

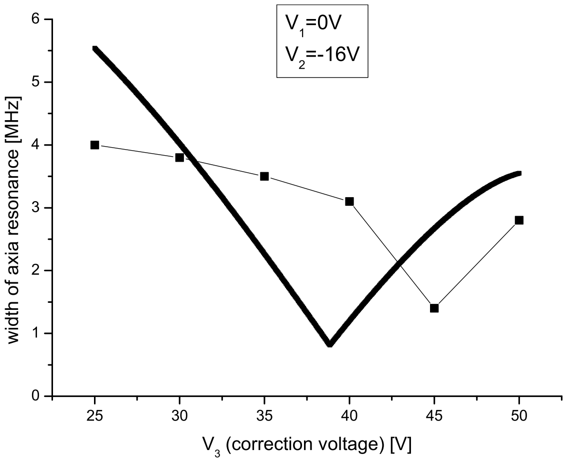

Fig. 7. Calculated (solid line) and measured width of the axial resonance for various correction voltages applied to electrode #3.

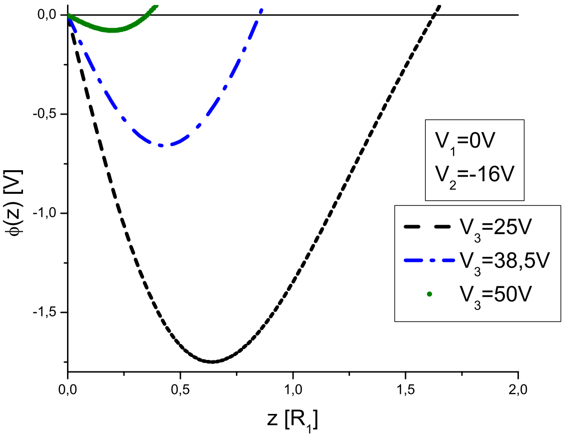

Fig. 8. Potential shapes corresponding to three points in Figure 7. The voltages for maximum harmonicity are $V_1 = 0$ V, $V_2 = -16$ V, $V_3 = 38.5$ V and it can be seen that for either bigger or smaller V_3, the potential shape gets more asymmetric. (The sign of voltages was changed with respect to the situation of Fig. 7 in order to present a more intuitive potential shape.)

strongly on the potential shape. As seen from Figure 2 it can be varied by voltages applied to the outer ring electrodes. It can be described by a series expansion:

$$\phi(z) = \sum_{i=0}^{\infty} C_i (z - z_0)^i \qquad (1)$$

where z_0 is the position of the potential minimum. In the case of a 3-dim. Penning trap only even orders in the expansion would contribute if mirror symmetry around the mid plane is preserved. Due to lack of this symmetry in the planar trap also odd terms will be present. An estimate of those coefficients can be made from the width $\Delta\omega_z(E) = \kappa(E)\omega_z$, with:

$$\kappa(E) = \sum_{i=1}^{\infty} [A(E)]^i \left|\frac{C_{i+2}}{2C_2}\right|, \qquad (2)$$

$$A(E) = \sqrt{\frac{E}{m\omega_z^2}} \qquad (3)$$

is the amplitude of the axial motion if we consider the deviation from the harmonic oscillator as small. Figure 7 shows $\Delta\omega_z$ for a range of correction voltages near the minimum deviation from harmonicity. The theoretical curve was estimated by calculating numerically the position of equilibrium for every V_3 and evaluating the derivatives of the potential at that point, which are the C_i. The experimental width follows qualitatively the expectation. The deviation can be attributed to the fact that neither the finite space between the electrodes nor the effect of the apparatus walls surrounding the trap at ground potential have been considered. At more positive correction voltages the approximation made in (3) is no longer valid. A more comprehensive study of the harmonicity for a bigger range of parameters would need a non-perturbative approach, solving explicitly the equations of motion and Fourier transform them. For the purpose of demonstration of the planar trap operation, however, the present approach is sufficient. Figure 8 gives an intuitive picture of why the curve in Figure 7 has a minimum. Since in our experiment we fill the trap almost completely, the reader should imagine the potential filled with electrons till the $\phi(z) = 0$ V level, so that it becomes obvious that only the curve for $V_3 = 38.5$ V has z-reflection symmetry.

The density of trapped electrons is estimated to about 10^4–10^5 in a trapping volume of about 10 mm^3 (between 100 and 1000 electrons are trapped) from the observed frequency shift of the axial resonance when the electron number is varied, using simple space charge models [2]. Such a cloud shows as particular feature the splitting of the axial resonance in two components, the individual ion resonance and the center-of-mass resonance [9]. They appear at slightly different frequencies since the individual electrons experience the space charge from the neighbouring particles and thus their resonance is shifted to lower values while the center-of-mass oscillation is independent of space charge. This effect is particularly pronounced in the parametric excitation of the axial oscillation at $2\omega_z$ [9].

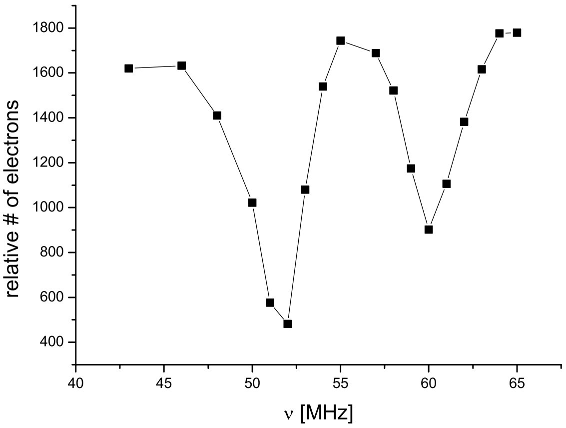

Fig. 9. Parametric excitation of the axial electron oscillation in an electron cloud at $2\omega_z$ showing a double structure from individual (left) and center-of-mass (right) oscillation.

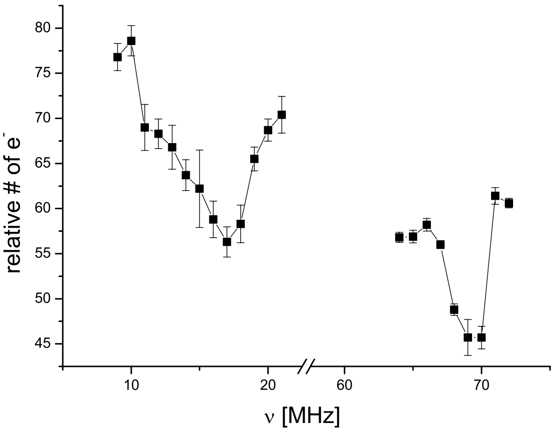

Fig. 11. Axial resonances $2\omega_z$ detected for the situation of a double-well axial potential.

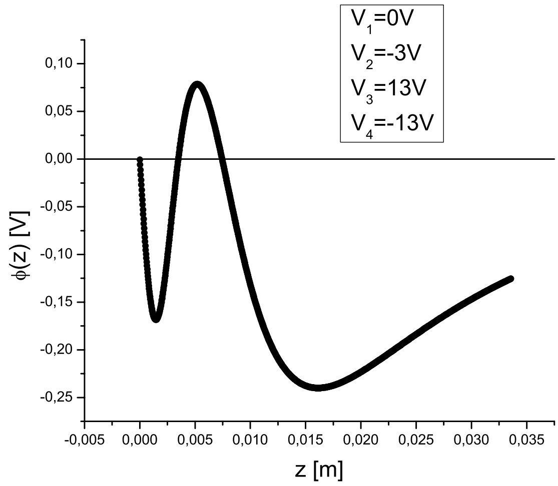

Fig. 10. Double-well situation.

Figure 9 shows that the same happens in the planar trap. An additional feature of the planar trap is that we can create a double-well potential when using 4 electrodes. Figure 10 shows the expected shape of the potential for a given set of parameters. Storing electrons in such a potential results in two different axial oscillation frequencies as experimentally observed (Fig. 11).

4 Conclusion and outlook

We have experimentally realized confinement of electron clouds in a planar Penning trap. The trap behaves as expected. Axial, perturbed cyclotron and magnetron oscillations have been detected. As a particular feature we demonstrated operation in a double well potential. We consider our experiments as a first step towards the realization of novel quantum computation schemes using the spin directions and the lowest quantum states of the cyclotron oscillation of single trapped electrons as proposed in [10]. As further steps we have to realize non-destructive detection via induced image charges at the electron's oscillation frequencies. For clouds of electrons as is the present case ordinary tuned circuits having quality factors of about 100 attached to the electrodes operated at room temperature would be sufficient. For single electron detection superconducting circuits and operation below liquid He temperatures have to be employed [11]. This will also be required for encoding qubits in the lowest quantised energy levels of the cyclotron oscillator as demonstrated by Peil and Gabrielse [11]. We further plan to scale down the size of the trap in order to find out at what level surface effects would limit successful operation.

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