High-Harmonicity Planar Penning Traps for Single-Electron Qubits

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Synopsis Planar Penning traps provide a promising platform for the confinement and control of single electrons, with potential applications in quantum information processing and precision measurements. For such applications, the anharmonicity of the trapping potential must be minimized to suppress unwanted frequency shifts and nonlinear coupling between motional modes. Achieving a highly harmonic confinement while maintaining a compact planar geometry is therefore a key challenge in the design of single-electron traps.

We investigate sub-millimetre planar Penning traps for highly harmonic confinement, essential for single-electron qubits in quantum information processing. Extending the treatment of larger planar traps [1], we show that finite electrode gaps become significant at the sub-millimetre scale and must be included in realistic designs. We optimize electrode geometries and voltages for harmonic confinement while minimizing the axial frequency shift Δf_z in three configurations: mirror-image, covered, and three-gap traps (see Fig. 1). These configurations can serve as building blocks for 2D trap arrays, with the three-gap trap attractive for future scalable implementations. For this configuration, we evaluate gap-potential models [2] by benchmarking their predictions against finite-element simulations. The optimized parameters and comparisons are summarized in Table 1 [3].

Table 1. Optimized three-gap trap parameters for different gap-potential models and finite-element simulation at $V_0 = -0.3591$ V, $f_z = 4$ GHz, and $\rho_1 = 10$ μm. Δf_z is in Hz.

Param.	Linear	Cubic	Corner	Sim.
ρ_3, (μm)	83.662	82.179	81.983	63.934
z_0 (μm)	13.714	13.592	13.575	12.490
V_1 (V)	9.573	9.397	9.373	7.180
V_2 (V)	9.807	9.629	9.606	7.374
V_3 (V)	26.841	27.069	27.102	38.252
a_2	0.0	0.0	0.0	$\sim 10^{-10}$
a_3	0.0	0.0	0.0	0.0
a_4	0.0	0.0	0.0	$\sim 10^{-9}$
a_5	0.0	0.0	0.0	0.0
a_6	-0.0043	-0.0044	-0.0044	-0.0079
Δf_z@4 K	0.731	0.750	0.752	1.3

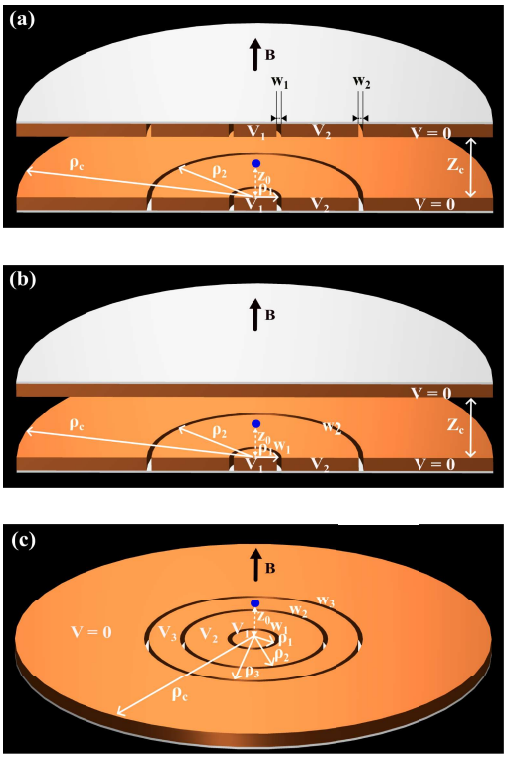

Figure 1. Schematic of the electrode structures of (a) a mirror-image trap, (b) a covered trap, and (c) a three-gap planar Penning trap. A stored electron is indicated at the centre of the trap, at a distance z_0 above the plane of the electrodes.

References

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