Validation of surface-electrode ion trap for high-coherence quantum information processing

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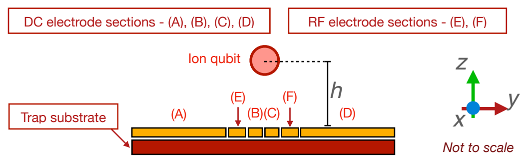
ABSTRACT

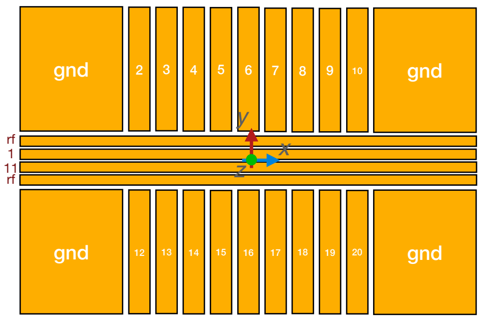
Trapped-ion quantum information processing devices rely on optimized ion confinement to enable high-coherence operations. [1] Surface-electrode ion traps are commonly used to confine ion qubits in space, using a combination of radio frequency (RF) and static (DC) electric potentials. [2] A key aspect of optimal ion control is in determining appropriate electrode potentials for stable ion confinement. Here, we present techniques based on Allcock et. al [3] to characterize surface-electrode Paul traps and generate corresponding optimal basis potential sets, paving the way for in-situ experiments. We also compare the efficacy of different numerical methods in performing these characterization tasks.

BACKGROUND

Cross-sectional view of surface-electrode trap



Plan view of surface-electrode trap



Not to scale

$$\Phi(\mathbf{r},t) = \frac{1}{2}\sum_i u_i r_i^2 + \frac{1}{2}\sum_i v_i r_i \cos(\omega_{rf} t)$$ **Ideal Paul trap potential [4]**

$$\nabla^2 \Phi = 0$$ **Laplacian of potential constrains coefficients of curvatures**

$$\sum_i u_i = \sum_i v_i = 0$$ This implies that at any instant in time, if there is positive curvature along one direction, there will be negative curvature in a different direction. Thus, the potential cannot confine in all directions simultaneously.

$$\Phi_{ps}(\mathbf{r}) = \frac{e}{4m\omega_{rf}^2}\mathbf{E}_{rf}^2(\mathbf{r},0)$$ Use a combination of oscillating and static electric fields to confine the ion instead.

$$\Phi_{dc}(\mathbf{r}) = \sum_i \phi_i(\mathbf{r}) U_i$$ Φ_{ps} *pseudopotential* is the oscillating rf potential. Φ_{dc} is derived from the static dc potential.

ANALYSIS METHODOLOGY

2D Analysis

We used Python and the *NIST Electrode* simulation package [4] to analyze the trap in 2D. The method is derived from Allcock et. al. [3].

$$\frac{d^2 r_i}{d\tau^2} + \left(a_i - 2q_i \cos(2\tau)\right) r_i = 0$$

$$\tau = \frac{\omega_{rf} t}{2},\ a_i = \frac{4eu_i}{m\omega_{rf}^2},\ q_i = \frac{2ev_i}{m\omega_{rf}}$$

- Numerically solve the Mathieu equation above [3] using *Electrode* to find the minima location of the total potential $\Phi_{ps} + \Phi_{dc}$.

$$V_x = a_{2x}x^2 + a_{1x}x + a_{0x}$$

- Apply a unit voltage to each of the 20 dc electrodes one by one, and ground all others.
- **Numerically calculate the potential** induced by each electrode at the potential minima.
- Perform least-squares fit to obtain 2nd order Taylor coefficients of potential due to each electrode along $\pm 10\mu m$ around minima, along each principal axis.

$$V_{target} = t_{2x}x^2 + t_{1x}x + a_{2y}y^2 + t_{1y}y + t_{2z}z^2 + t_{1z}z$$

- **Determine target potential** to generate.
- **Group chosen electrodes that have the same potential** by summing their coefficients.
- Number of groups = degrees of freedom.

$$A = \begin{pmatrix} a_{group1,2x} & \cdots & a_{groupN,2x} \\ \vdots & \ddots & \vdots \\ a_{group1,1z} & \cdots & a_{groupN,1z} \end{pmatrix}$$

$$b_{target} = \begin{pmatrix} t_{2x} \\ t_{1x} \\ \vdots \\ t_{2z} \\ t_{1z} \end{pmatrix} \qquad x_{basis} = \begin{pmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{pmatrix}$$

- **Find basis voltages to apply to each group by solving $Ax_{basis} = b_{target}$ with a linear solver.**

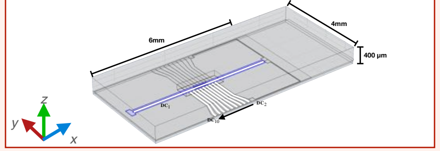
3D Analysis

We used COMSOL to perform electrostatic simulations of the trap in 3D. COMSOL analysis was essential to:

- Benchmark 2D characterization accuracy.
- Account for the exposed substrate dielectric on electric potential calculations (no exposed dielectric was assumed for 2D simulation).

1. Apply $1V$ to single electrode, $0V$ to the rest.
2. Compute the potential along the trap center.
3. Iterate through the 10, right plane electrodes.

Isometric view of the simulated surface electrode trap



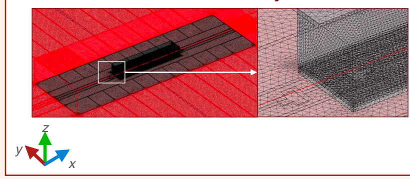
Assumptions:

- Predominant Trap Material: Oxide
  - $(\sigma = 0, \varepsilon = 3.8)$
  - Zero Charge applied to Oxide: $\mathbf{n} \cdot \mathbf{D} = 0$
- Symmetry with respect to x axis.
- Conservation of Charge Applied to GND Planes [5]:
  - $\mathbf{E} = -\nabla V$
  - $\nabla \cdot (\varepsilon_o \varepsilon_r \mathbf{E}) = \rho_V$

Simulation Specifications:

- Free Tetrahedral Mesh: min. Element size $12\mu m$

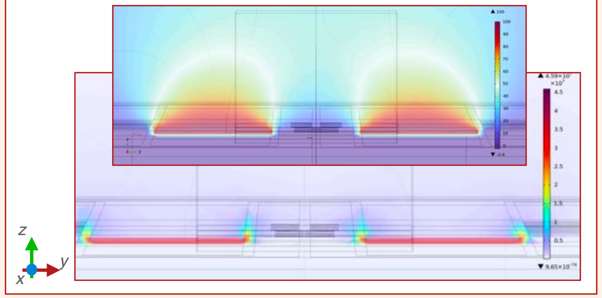
Mesh Granularity



- Stationary study: ignore transients & RF pseudo-potential
- Computation time: $\tilde{t} = 36$ min
- Trap Geometry Size: 13GB
- Simulation Memory Requirement: 70GB

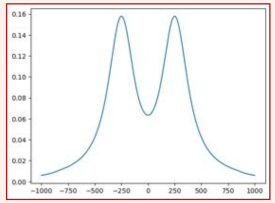
SIMULATION VALIDATING STRATEGY

Electric potential (up) and electric field norm (down) at trap center given 100V



Objective: Validate the 3D computation & our intuition of device electrostatics.

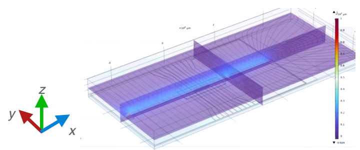
Procedure: Apply 100V to electrode 1, compare electric field norm with electric potential at the trap center.

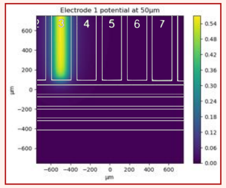


- Assess potential distribution in space using methods of different numerical accuracy.
- Compare Taylor approximation in 2D with finite-element analysis method for 3D.
- **Left:** Potential along x-axis for axial voltage set generated in 2D analysis.

STUDY RESULTS

Electric potential across the center





We simulated effects of DC voltages applied to individual (left) and grouped (right) electrodes to determine:
(a) **Congruence in NIST and Electrostatics simulation results.**
(b) **Evaluate computational efficiency of both methodologies.**

FUTURE WORK

Primary conclusions of our work

- Maintainability of open source, surface electrode trap voltage calculations (NIST electrode)
- Collaboration with Duke Quantum Center to develop multi-application voltage solutions.
- Community-wide need for automated calculations

Our ongoing work

- Determining ion micromotion achieved using these voltage sets, and devising shim mechanisms to cancel it.
- Verifying electrode voltage sets in-situ for ion confinement.
- Creating code to control Artiq digital to analog converter to enable electrode control.

References

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