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Progress Towards a Multi-ion Optical Clock Based on a Linear Chain of Yb Ions

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Abstract

We report our progress on the development of an optical clock based on the quadrupole transition of a chain of laser-cooled $^{171}Yb^{+}$ ions in a linear Paul trap. The trap is based on metallized ceramic wafers with segmented DC electrodes that allow for a linear chain of equally spaced ions due to a quartic axial potential. Numerical modeling of the trap configuration is used to investigate the ability to reduced the associated frequency shifts for a large chain of ions below the 10^{-15} level for this trap geometry.

Background

Precise timing is a critical component of many modern-day technologies. With the push to expand the operating regimes and the range of applications of these technologies, the demands on the clocks that provide this precision timing with also increase.

Microwave-based Clocks:

- Extremely successful commercially
- Miniaturizable
- Frequency stability of 10^{-15} at the very best

Optical Clocks:

- Frequency stability at 10^{-18} or better
- Large power and size requirements (large optical table)
- Require frequency comb to obtain useful clock signal

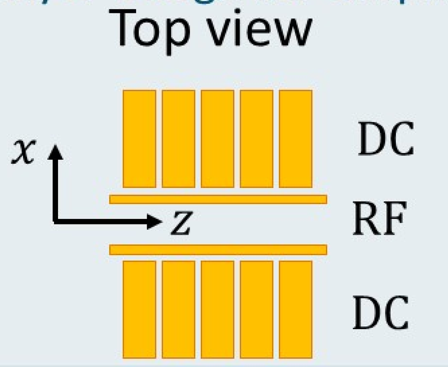
The Application Space:

- Most applications do not yet require 10^{-18} stability
- An optical clock of modest 10^{-15} stability or better that can be miniaturized
- Reduced size and power requirements
- Increased signal ⟶ multiple ions

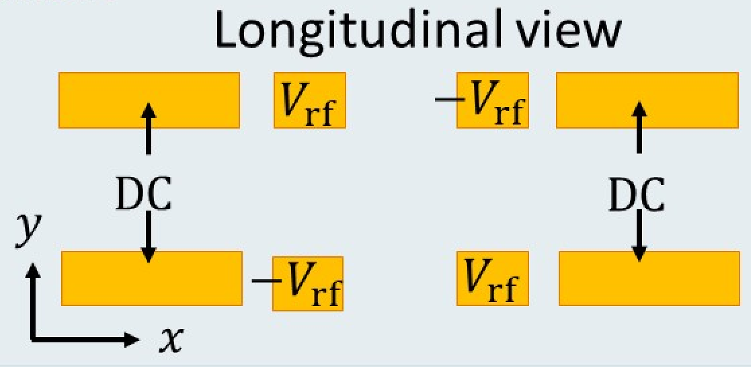
Our Approach

- Optical clock based on $^2S_{1/2} \rightarrow {}^2D_{3/2}$ quadrupole transition in $^{171}Yb^{+}$
- Increase signal using a linear chain of ~ 50 ions
- Design trap geometry to minimize frequency shifts below 10^{-15} across chain of ions; symmetric RF driving to minimize $V_{\mathrm{rf},z}$
- Segmented DC electrodes to control ion spacing
- 2-layer design for simplified alignment

Top view



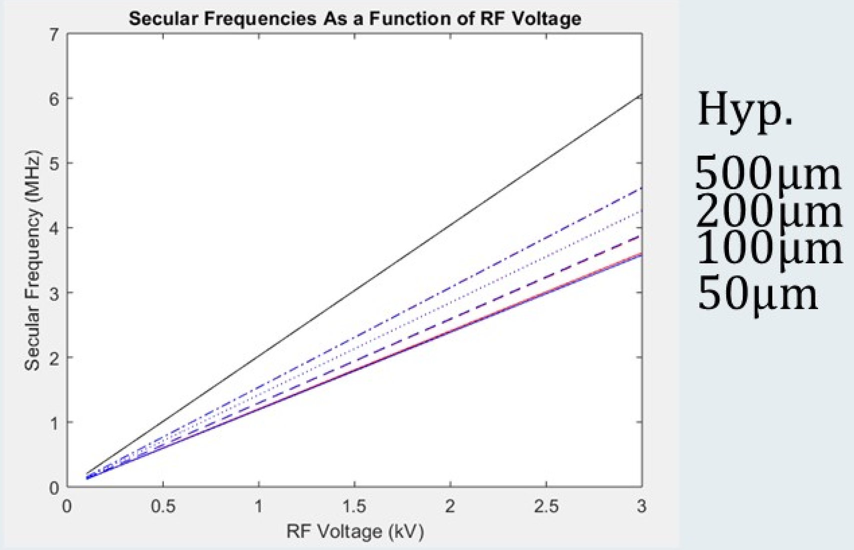
Longitudinal view



Choosing Trap Parameters

- Comparison of current trap design with ideal hyperbolic electrodes
- Finding η allows direct comparison of trap parameters to the ideal trap with analytic equations

$$\eta = \frac{\omega_r}{\omega_{\mathrm{hyp}}}$$

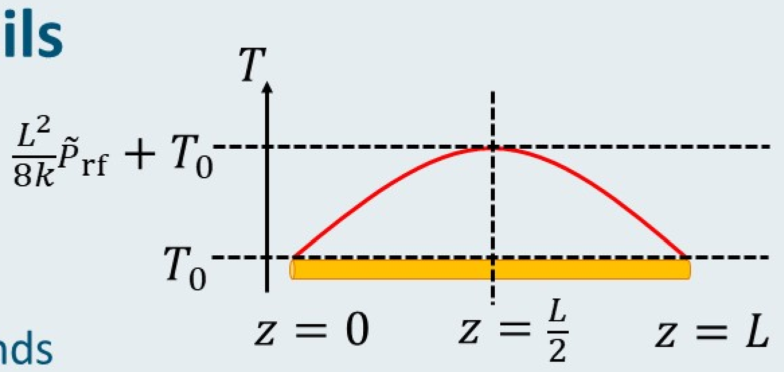


RF Rail Width	η
50µm	0.59
100µm	0.64
200µm	0.70
500µm	0.76

Joule Heating of RF Rails

Simplified model assumptions:

- Ends of rail stay the same temperature
- Alumina is able to perfectly remove excess heat at the ends

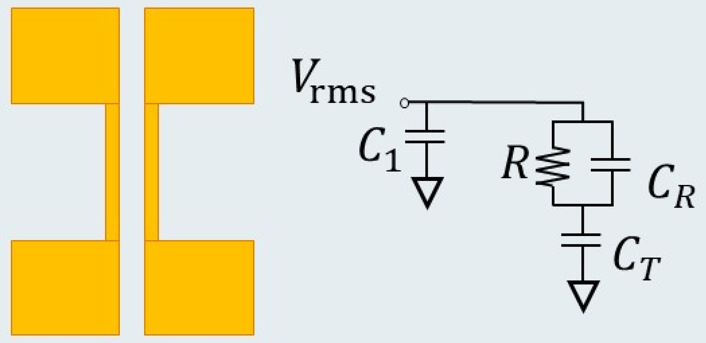


Solution (inverted parabola with peak at midpoint):

$$T(z) = -\frac{1}{2k}\tilde{P}_{\mathrm{rf}}\left(z - \frac{L}{2}\right)^2 + \frac{L^2}{8k}\tilde{P}_{\mathrm{rf}} + T_0$$

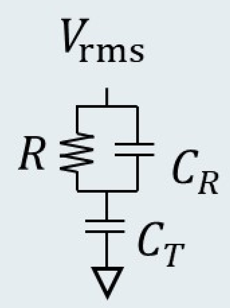
$$\Delta T = \frac{L^2}{8k}\tilde{P}_{\mathrm{rf}}$$

To find the temperature change, we need trap capacitance



C_1, capacitance of top pads
C_R, capacitance of rail-to-rail sections
C_1, capacitance of bottom pads

Top RF pads do not contribute, so the equivalent circuit is



Pad area: 10.02 mm^2, 0.1774 pF
Pad edge: 7.42 mm, 50.30 fF

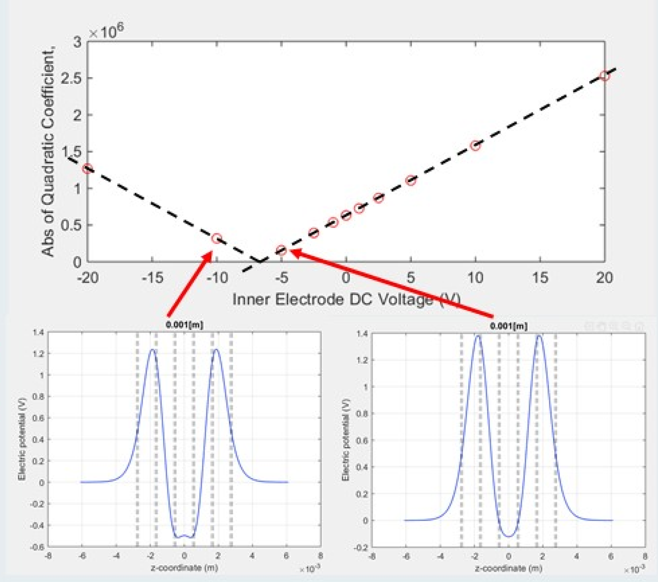
$C = 0.2277$ pF

$\omega_{\mathrm{rf}} = 2\pi \times 20$ MHz
$L = 5$ mm
$V_P = \sqrt{2}V_{\mathrm{rms}} = 2$kV

Rail Width (µm)	ΔT (K)
50	0.212
100	0.0952
200	0.0394
500	0.0104

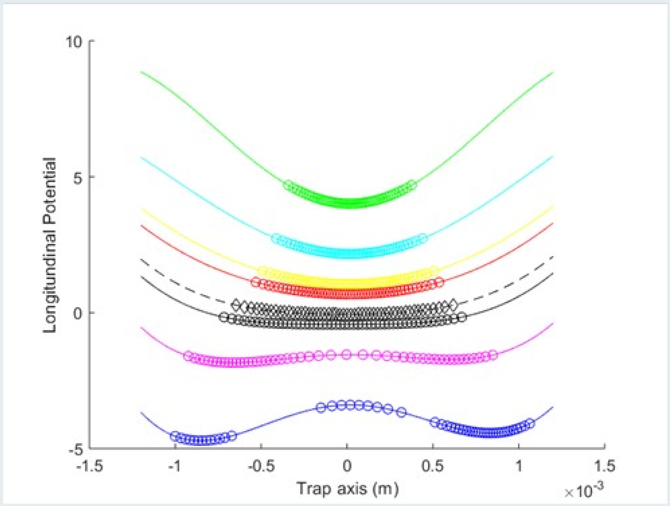
Finding a Quartic Potential

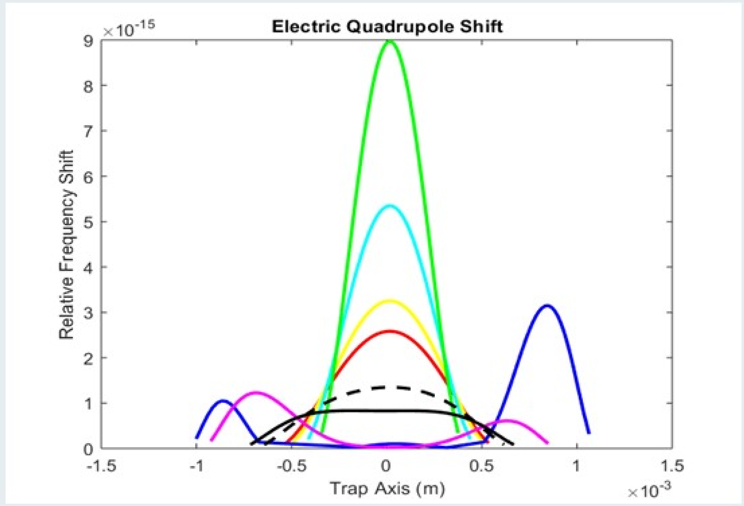
- Find axial pseudopotential for various combinations of DC voltages in COMSOL
- Fit pseudopotential to 4th order polynomial
- By sweeping one set of voltages, we find where the quadratic coefficient becomes zero



Electric Quadrupole Shift

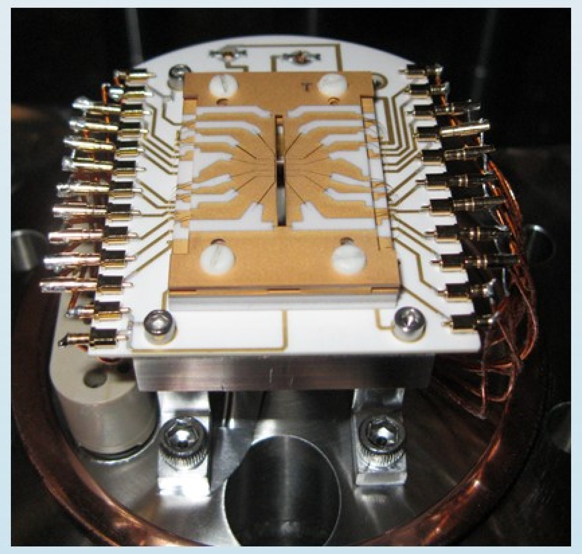
- Electric quadrupole shift depends on the gradient of the electric field not only of the pseudopotential but of the ions in the trap
- Find ion locations and calculate the relative frequency shift

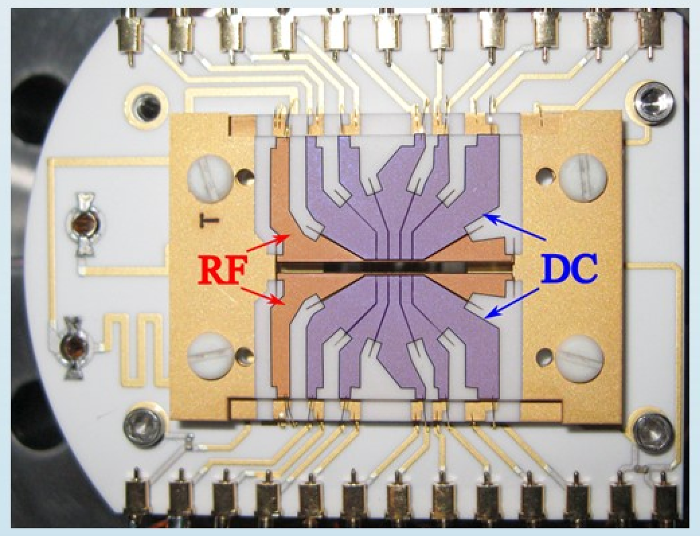




Final Trap Design

- 381 µm (15 mil) thick metallized alumina trap wafers
- 100 µm DC electrode separation
- 100 µm width RF electrodes/rails
- 635 µm (25 mil) thick-film metallized alumina PCB connected with 1x3 mil wire bonds to
- Equal path RF traces for phase matching
- Board connects via BeCu pins and pin receptacles





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