Optimum surface trap geometries for fast ion separation and the development of junctions within ion trap arrays

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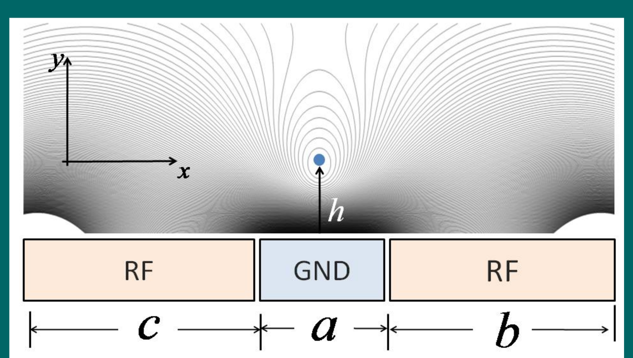
Introduction

For many quantum information implementations with trapped ions, effective shuttling operations are important. The maximum speed of separation and recombination of trapped ions for adiabatic shuttling operations depends on the secular frequencies the trapped ion experiences in the process. Higher secular frequencies during the transportation processes can be achieved by optimising trap geometries.

Potential barriers within the junction region make adiabatic transport of ions through a junction challenging. We relate the constraints involved in maintaining high secular frequencies whilst keeping the barrier height small to the low-order multipole expansion of the rf potential to particular junction designs and present results on the design of optimal junctions within surface ion traps.

Optimum size of RF and ground electrodes

Surface traps only offer a fraction of the trap depth compared to symmetric traps of similar ion-electrode distances. It is therefore important to optimise the size of the rf and ground electrodes for a given ion-electrode distance to maximise trap depth.



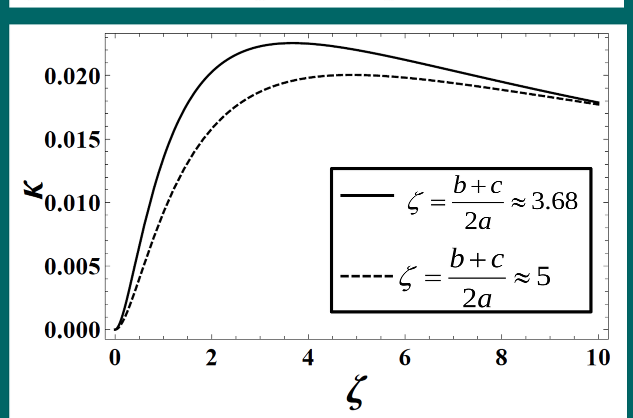
Using the equations given by M.G House [1], with reference to the diagram, if b=c , then the trap centre location and ion height is;

$$x_0 = \frac{ac}{(b+c)} \qquad y_0 = h = \sqrt{abc(a+b+c)}/(b+c)$$

for a given ion height , the trap depth can be calculated by;

$$\psi_E = \frac{\Gamma}{h^2}\kappa \quad \text{where} \quad \Gamma = \frac{e^2V_{rf}^2}{\pi^2 m\Omega^2} \quad \text{and}$$

$$\kappa = \left(\frac{2\sqrt{abc(a+b+c)}}{(2a+b+c)(a+b+c+2\sqrt{a(a+b+c)})}\right)^2$$

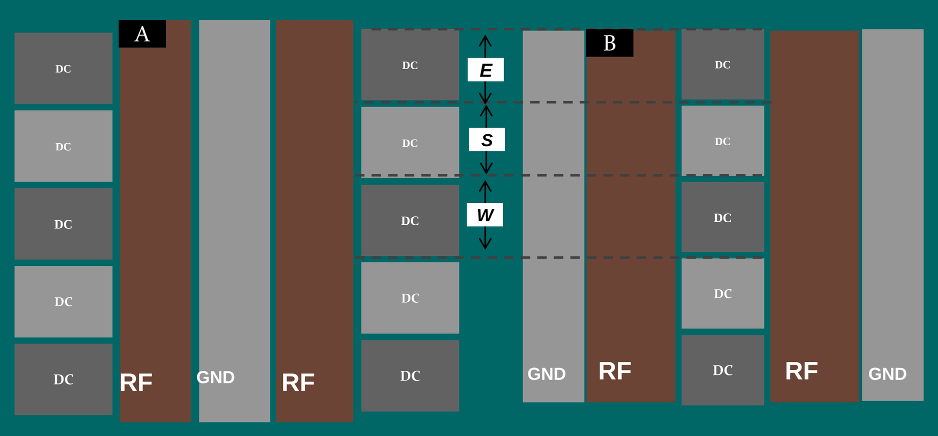


The trap depth is inversely proportional to square of "h" and directly proportional to geometric factor "κ" which can be maximised when the ratio between rf electrode width "b" and separation "a" is 3.68 when (b=c) and (~5 when c=b/2) .

[1] M.G.House, Phys. Rev A **78**,033402 (2008)

Segmented electrode geometries

The arrangement of the segmented dc electrodes are illustrated in the diagrams below.



(A) With outer segmented static electrodes and rf electrodes separated by a ground .

(B) rf electrodes are separated by segmented static electrodes. Ions will be trapped and separated or recombined above the middle electrode(s).

Following the discussion by Home *et al.* [2] the dc potential providing confinement near the centre of the trap can be analyzed by using Taylor expansion;

$$V_{(0,0,z)} \approx \alpha e z^2 + \beta e z^4$$

- α and β terms depend upon electrode sizes and the applied voltages on electrodes
- Only a trap design in which α goes *negative* can produce double well

[2] J.P Home and A.M.Steane, Quantum Info & Comp: vol.6, No.5 (2003)

Ion separation process and secular frequencies

The separation of ions can be created by introducing a wedge potential between two ions. DC electrodes can be used which pulls the single potential well into a double well for effective separation such that the ions remain trapped and acquire less energy during separation.

During the separation process it is important to consider the secular frequency variation. This is outlined below. Both α and β terms depend upon the applied voltages on the electrodes and their dimensions.

(a) Initially ions are trapped in a single potential well and $\alpha > 0$

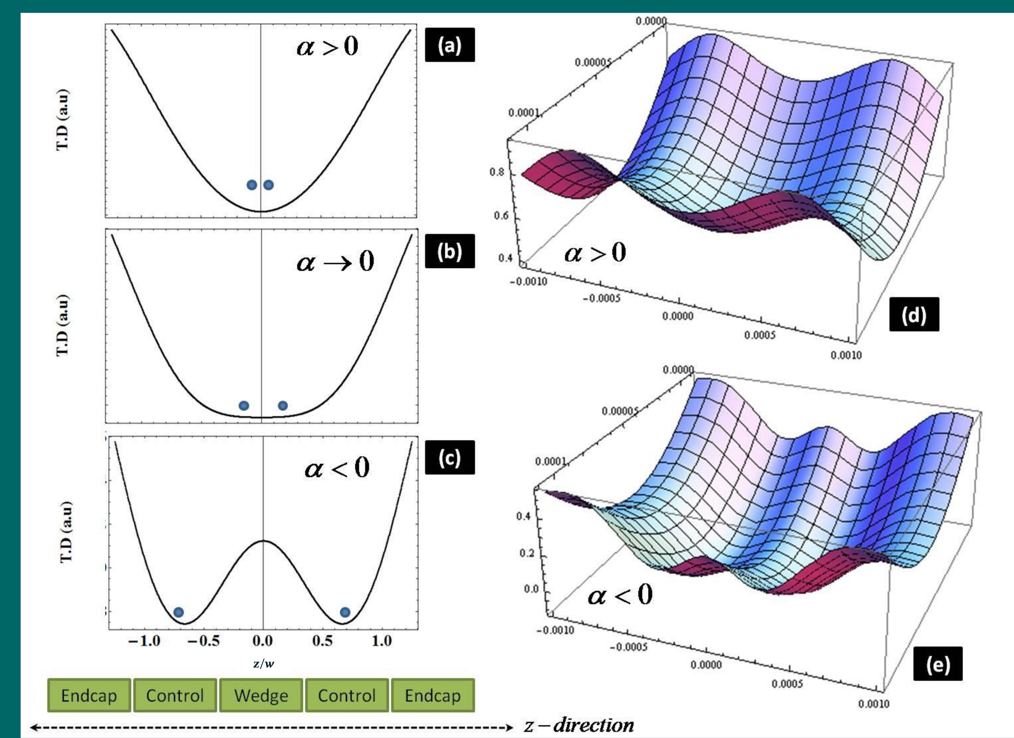
$$\omega_z \approx \sqrt{\frac{2e\alpha}{m}}$$

(b) Voltage is applied on wedge electrode so that $\alpha \to 0$

$$\omega_z \approx \sqrt{\frac{3e}{m}}\left(\frac{e}{2\pi\varepsilon_0}\right)^{2/5}\beta^{3/10}$$

(c) Voltage is increased on wedge electrode and double well is created and $\alpha < 0$

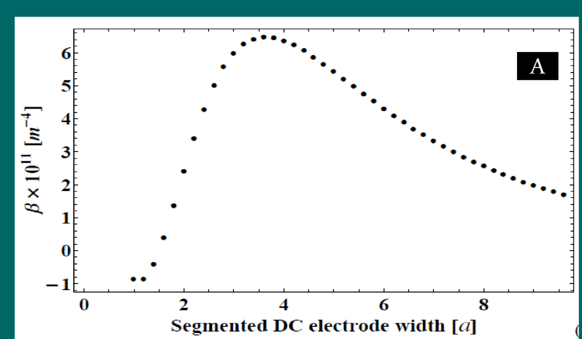
$$\omega_z \approx \sqrt{\frac{4e|\alpha|}{m}}$$

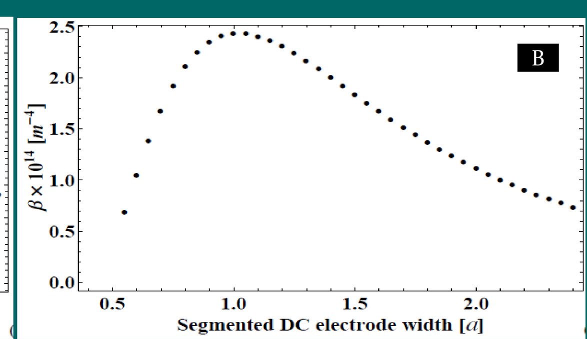


The secular frequency is a minimum when $\alpha \to 0$. This sets an upper limit on the speed of the separation. During process (b) ω_z is only due to the contribution of octupole term β.

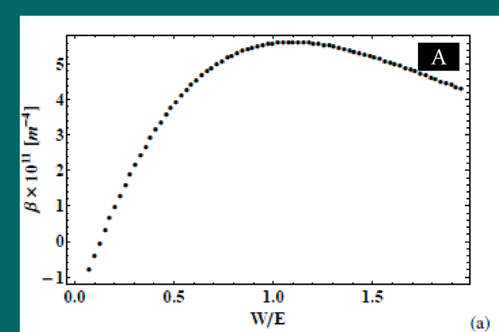
Optimising segmented electrodes to maximise β

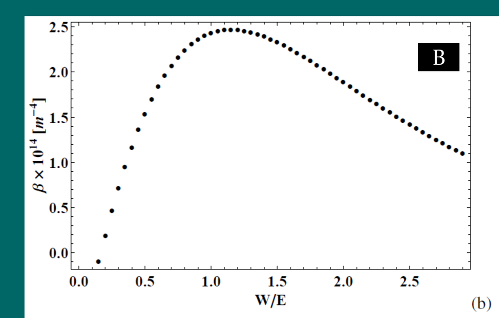
To provide optimum trap geometry which provides maximum values for β and allows for negative values for α for certain applied voltages. We varied the width of DC electrodes to maximize β. A gapless electrostatic potential analytic model for rectangular electrodes was used to calculate the electrostatic potential.





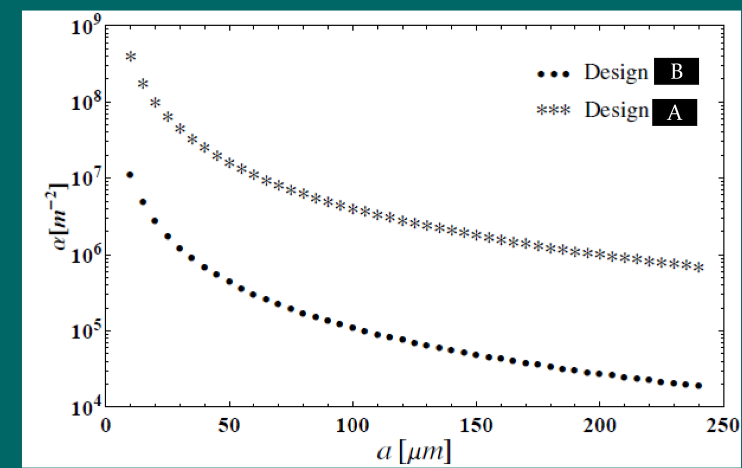
β is plotted against electrode widths (W=S=E) in the units of a. For design (A) β is maximum when the width of the segmented DC electrodes is ~ 4 a. For design (B) β is maximum at ~ a.

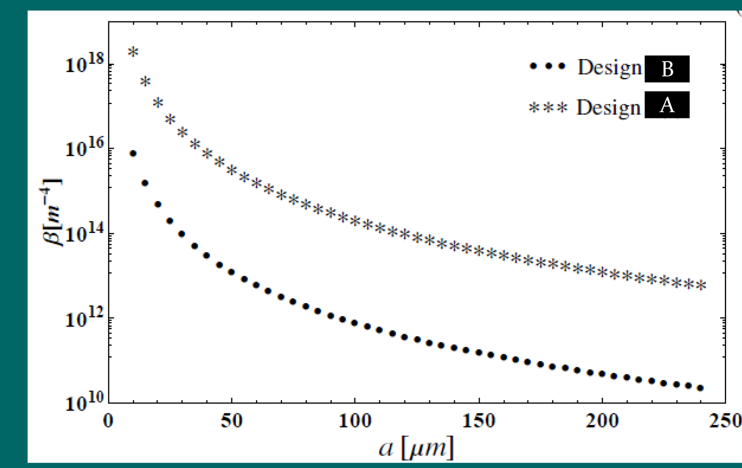




β is plotted against the ratio of wedge electrode to endcap electrode width (W/E) for the outer segmented electrode design (A) and for the central segmented electrode design (B). In both cases W=E ≈1.1.

Comparison between the designs





From these plots, it is clear that smaller traps give larger α parameters and decreasing the ion-static electrode distance can substantially improve the ability of a trap array to provide fast ion transportation. The same trend is seen for β.

* More details are available at; Altaf H. Nizamani and Winfried K. Hensinger, *Optimum electrode configurations for fast ion separation in microfabricated surface ion traps*, arXiv:1007.3542v1 [quant-ph]

Optimising junction design

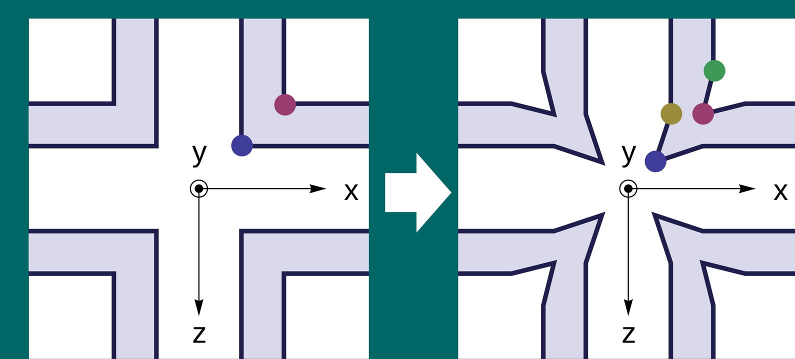
When considering the precise electrode geometry to simulate, a gapless plane approximation is used which assumes infinitely small separation between the electrodes. The electric field is obtained by the "Biot-Savart-like" line integral [3];

$$E(\vec{x}) = \frac{U}{2\pi}\oint_{\substack{\text{contours of}\\ \text{electrodes}}} \frac{d\vec{s}\times(\vec{x}-\vec{s})}{|\vec{x}-\vec{s}|^3}$$

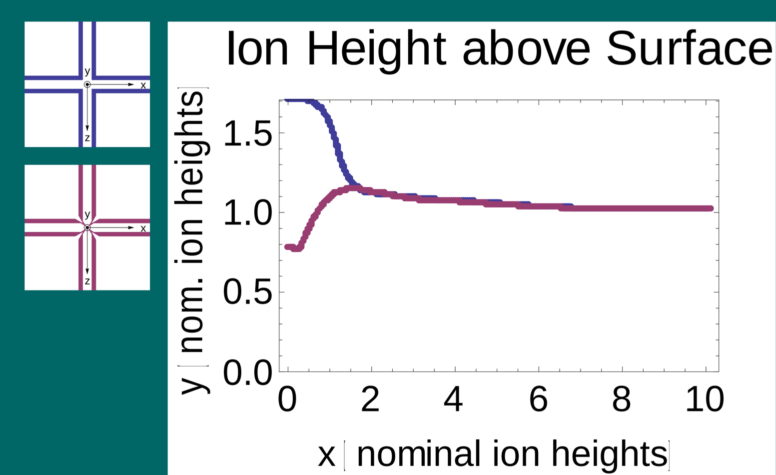
This has a complicated but analytic solution, thus the field of a polygonal electrode can be calculated efficiently. The optimisation process starts with a simple rail geometry which forms a junction via four separate linear sections as seen below.

The corners are defined at (x,z) = (1,-1), (2,-2).

Four control points are added at (1,a), (yellow)
(2,b), (green)
(c,c), (blue)
(d,d). (Purple)



Mathematica's implementation of the principal axis minimization algorithm was used [4]. The aim is to manipulate the geometry to provide low rf barrier and high secular frequency (at junction's centre). But these are conflicting goals [5].



Instead of a 'hump' in the ions trajectory, this has been replaced by a 'dip'.

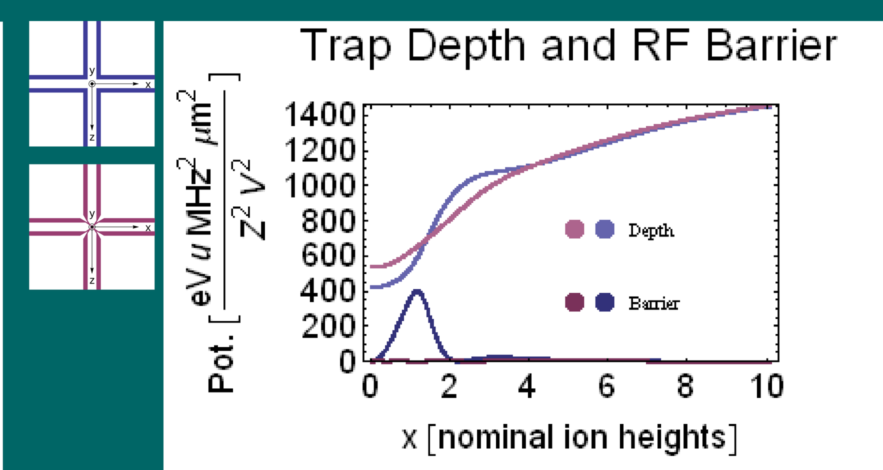


Figure showing the trap depth is smoothed out in the junction region and the rf barrier has been significantly reduced.

[3] Oliveira and Miranda, Eur. J. Phys. **22**, 31 (2001)
[4] Brent, Algorithms for Minimization without Derivatives, Prentice Hall (1973)
[5] Wesenberg, Phys. Rev. A **79**, 013416 (2009)