Surface Ion Trap Designs for Vertical Ion Shuttling

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Abstract

Trapped ion transportation operations in the horizontal direction have been already demonstrated successfully by several researchers. In this paper, we propose a novel trap design for fast and adiabatic vertical shuttling of trapped ions. The novel planar surface electrode ion trap consists of a set of independently controlled small strip-electrodes of fixed widths. New trap geometry was modelled to support vertical shuttling protocols. Ion trajectory in the vertical direction from the surface of the trap was simulated for from $\sim 40\mu m$ height to $\sim 100\mu m$. Trap-depth and secular frequencies were investigated during shuttling of ion with slow and fast shuttling protocols.

Key words:
Ion trapping, Quantum Computation, Quantum information and technology, Surface ion trap, Trap modelling and Simulation, Vertical Ion shuttling.

1. Introduction

Trapped ion transportation operations in the horizontal direction have been already demonstrated successfully by several researchers [1][2][3][4]. Since a few decades, trapped ions have proven a powerful tool to implement quantum algorithms and quantum simulations [5]. Recently, surface electrode ion traps are used for the implementation of linear ion traps (with a large number of trapping regions along a line) as well as $2D$ arrays of ion traps [6][7], coulomb crystals in $1D$ and large $2D$ coulomb crystals [8][9], two-dimensional trap geometries have also been proven to implement in quantum simulations [7][10][11].

Advanced micro-fabrication technology enables us to make scalable ion traps [7][12][13]. Higher trapping depths at larger ion-electrode distances may be achieved by optimizing the geometry of trap [6][13][14]. Further research is required to develop such optimized traps for low heating rates and de-coherence for the greater goal of scalable quantum computer [15]. Furthermore, adiabatic ion shuttling operations within multi-region scalable ion traps are vital for a full fledge quantum computer [16][17].

Fast ion loading and enhanced lifetime in surface ion trap depend on trap depth, which depends on trap-parameters and these are highly dependent on geometric factors and fabrication processes [16][18]. Achieving higher trap depth at a larger ion-electrode distance is a challenging task for surface ion traps [7][14]. The trap depth decreases as the ion-electrode distance increases. Further to this, coherence time for quantum computation operations decreases as ion-electrode distance decreases due to anomalous heating of trapped ions. In order to trap ions in a deeper potential well (high trap depth), the ions need to be trapped near to trap surface where trap depth is high. Laser beam access to trapped ions is prerequisite for cooling and performing Qubit operations. At lower ion heights laser access is almost lost or laser beam interacts with trap surface which produces undesirable effects including charging of trap electrodes and heating of trap electrodes which ultimately increases the heating rate of trapped ions. Relatively large ion height is required for proper Laser access but as a result, we get a weaker trap.

Here we propose an alternate trap design providing adjustable ion height may potentially prove useful to improve laser access and control trap depth as well as for useful for heating rate study of the traps. Adjustable ion height may be helpful in a process where ions initially trapped at lower ion-electrode distances where trap depth is high; but heating rate is also too high to perform any qubit operation for quantum computation or quantum information, and then bring the ions at higher ion-electrode distance for qubit operations where heating rate is significantly low as the heating rate scales down with $\sim {}^{1}\!/_{d^4}$ [19][20]. Laser access for cooling and qubit operation is also significantly improves when the ion-electrode distance is high.

More flexible ion-trap designs with adjustable height above the surface of the trap will lead to significantly improve the applications of quantum simulation, quantum information and computation, metrology, quantum sensing and interactions of an ion with atoms and laser. Current surface ion traps with fixed ion–electrode distance (ion height) are limited in performance.

Before fabrication and implementation of surface electrode ion-traps for qubit operations, designing and simulating these geometries are prerequisites for the feasibility of the ion trap.

In this proposed surface trap design several aspects of trap designing are addressed for trapped ions so that new possible ion shuttling protocols could be investigated for such traps, especially for vertical shuttling. By analyzing the vertical shuttling of trapped ions we could investigate ion heating caused problem caused by variations in trap-depth, secular frequency as well as anomalous heating of ions that depends on ion-electrode distance. Vertical shuttling could

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also be important for proper laser access of trapped ions for cooling and manipulation purposes.

In order to change the height or vertical shuttling Sedlacek et. al. in [21] used a surface-electrode ion trap with many regions in which ions can be held at five different heights from electrodes, the ion is moved in horizontal and vertical directions simultaneously along the changing width of RF-electrodes. Boldin et. al. in [22] applied reduced RF-voltage to the central electrode to achieve variation in height. Pearson et.al [23] applied dc potential on the centre electrode for the same purpose. Da An et.al in [24] controlled vertical ion height via only dc-electrodes. Authors of [25] used circular electrode geometry.

Our trap design has many novel features discussed in Section-3. This research will also impact on scaling of ion quantum technology by improving the ion trapping techniques and many exciting applications are to be expected.

2. Trap Modelling and Simulations

Our surface ion trap was modelled in Mathematica with gapless approximation using equations of the analytic method as discussed by M. G. House [17]. Electrodes were modelled using the $Eq. (1)$ as given below:

$$\varphi(u,v,w)$$

$$= \frac{V}{2\pi}\left\{\arctan\left[\frac{(u_2-u)(w_2-w)}{v\sqrt{v^2+(u_2-u)^2+(w_2-w)^2}}\right]\right.$$

$$- \arctan\left[\frac{(u_1-u)(w_2-w)}{v\sqrt{v^2+(u_1-u)^2+(w_2-w)^2}}\right]$$

$$- \arctan\left[\frac{(u_2-u)(w_1-w)}{v\sqrt{v^2+(u_2-u)^2+(w_1-w)^2}}\right]$$

$$\left. + \arctan\left[\frac{(u_1-u)(w_1-w)}{v\sqrt{v^2+(u_1-u)^2+(w_1-w)^2}}\right]\right\} \ldots\ldots Eq. (1)$$

Where V is the peak voltage, φ is the trapping field above the trap surface in three direction, u, v and w are space coordinates. Our trap is a series of long micro-strips of equal widths. Electrically combined micro-strips then collectively make RF-electrodes of an effective adjustable width of "b" and "c" as well as central ground electrode "a", as illustrated in Fig.1.

Height "h" of the ion depends on the width of electrodes "a", "b" and "c" and can be found by following $Eq. (2)$ [26]:

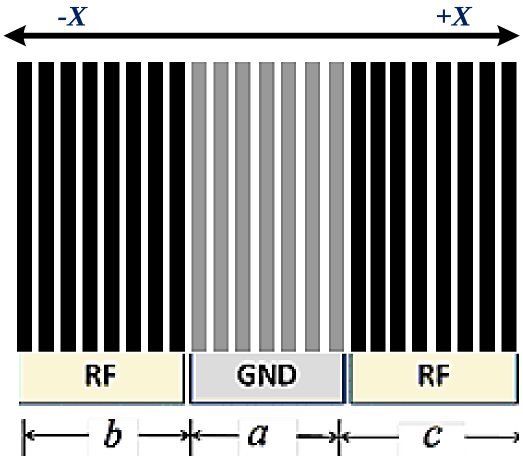


Fig. 1. Illustration of Multi strip trap design for vertical shuttling. Many micro-strips collectively make RF-electrodes of width "b" and "c" and central ground electrode "a".

$$h = \frac{\sqrt{abc(a+b+c)}}{b+c} \quad \ldots\ldots Eq. (2)$$

Ion height, trap depth and secular frequency for all the combinations of "a", "b" and "c" were calculated. Only those combinations were selected for trap operations where trap depth did not decrease due to geometric parameters. This could be achieved by keeping the optimum electrode ratio $\zeta = \frac{b}{a}$ within 2 and 8, as suggested in [16]. Keeping in view the practical aspects of fabrication processes and trap parameter constraints, the ion height of $40\mu m$ to $100\mu m$ can be safely achieved with strip-electrodes of 10μm width. This has been enhanced further to $200\mu m$ with larger strip-widths of up to $30\mu m$.

In order to avoid complex electronic circuit requirement and keeping the design features near to real fabrication limitations, the number of strip-electrodes is limited to 26 pairs (overall 52 strip-electrodes) in the trap design discussed here for simulation purpose.

Fig.2 illustrates the electrode made using $Eq. (1)$; where u_1, u_2, w_1 and w_2 are the coordinates of the vertices of electrode, whereas v_1 and v_2 are coordinates above the electrode.

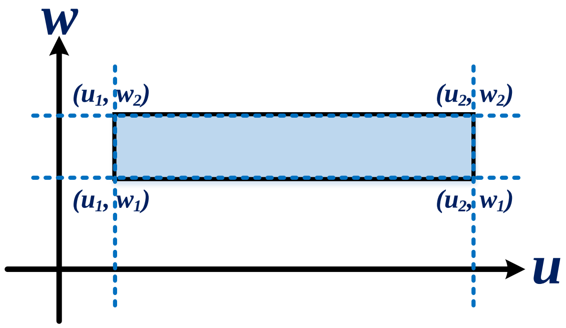
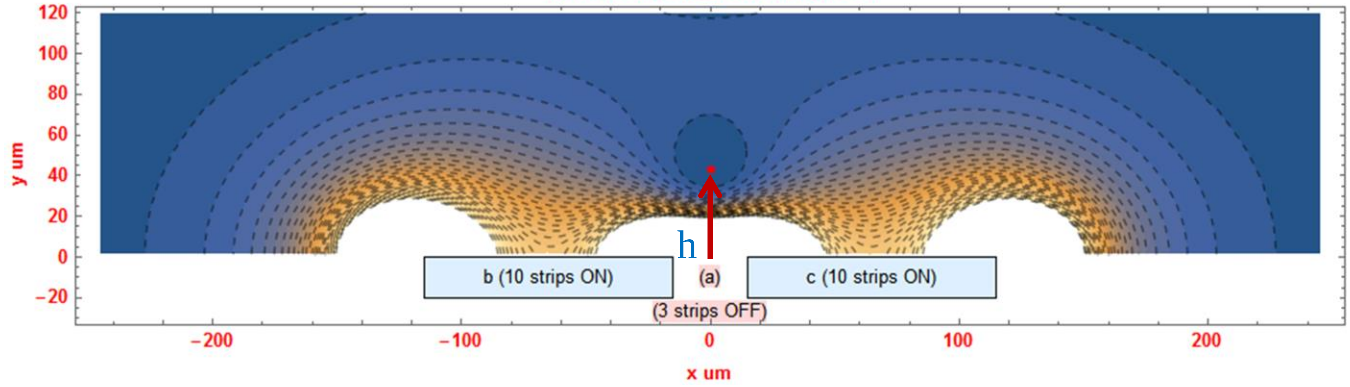


Fig. 2. An example electrode made using Eq. (1).


(a) Pseudopotential and ion position

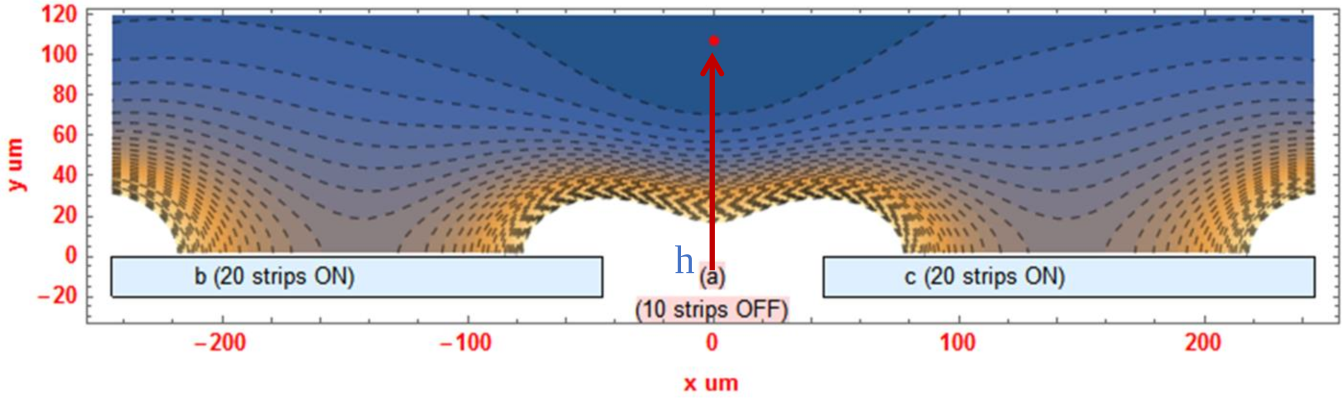

(b) Pseudopotential and ion position

Fig. 3. Demonstrates the principle of vertical shuttling of ion by turning on selected RF-strips. The red dot shows the calculated trap centre.

2.1 Electrode Configuration

As mentioned above, RF electrodes are made of many individual strip-electrodes, by turning them ON or OFF at certain time, we can create an RF –electrode and also can change the size of overall effective RF-electrodes "b" and "c" and the central separation ground electrode(s) of size "a". By varying the sizes of RF and Ground electrodes we can change the position of a trapped ion(s) above the surface.

Fig.3 demonstrates the principle of vertical shuttling of an ion by turning ON the selected RF-strips-electrodes. In Fig.3(a), three strip-electrodes are grounded (turned OFF) to make the central ground electrode of size "a", while "b" and "c" RF-strip-electrodes are turned ON by applying an RF-voltage. Pseudo-potential produced by above arrangement of strip-electrodes is shown in the Fig.3(b); where we can see the changing position of RF null or ion height (highlighted with red dot) with different strip-electrode configurations.

2.2 Demonstration of Ion Shuttling

The trap was modelled and simulated with RF-strip width of $10\mu m$, ion was shuttled in the total time of $350\mu s$, and data was calculated and saved, this process was repeated for different shuttling times up to $3500\mu s$. Similarly, the whole process was repeated for other RF-strip widths of $15\mu m$, $20\mu m$, $25\mu m$, $30\mu m$. Ion heights from $\sim 40\mu m$ to $\sim 200\mu m$ were simulated having sufficient trap depth and secular frequencies. For the demonstration purpose, the trap with $10\mu m$ strip-width is presented here.

In order to resemble the modelled trap with real-life traps, throughout the modelling and simulation process, peak RF-voltage V_{rf} was fixed at $200V$, the trapping RF frequency (Ω) was $2\pi\ 15MHz$ [16]. Separation between strip-electrodes was considered as a gapless approximation $(0\mu m)$ as discussed in [26][27][28]. The length of the RF-strip in the longitudinal direction is set to infinite for simulation purpose. This assumption doesn't have any significant impact on trap parameters as discussed in [16]. Vertical shuttling range was constrained within $\sim 40\mu m$ to $\sim 100\mu m$, the trap depth not less than 0.1 eV and secular frequency not less than 1 MHz.

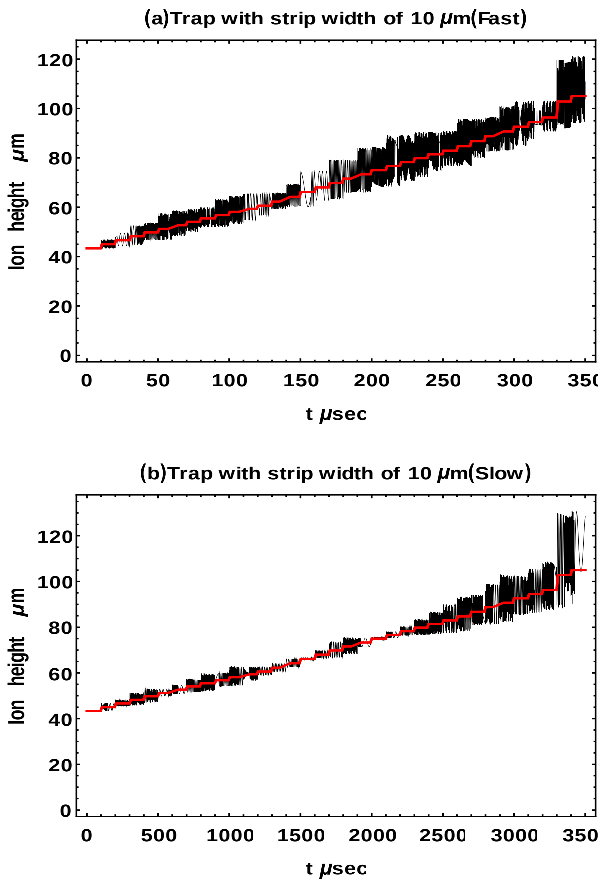


Fig. 4. Simulated motion of ion (black line) in vertical direction in 350μs (fast) and 3500μs (slow). Red Line shows the calculated trap centre.

These parameters are set to satisfy the RF- Paul trap $a-q$ parameters within reasonable range [29], peak RF voltage V_{rf} can be set up to $500V$ as discussed in [16], higher RF-voltage will increase trap depth, but it may result in heating of electrodes and surface flashover as discussed in [30][31], however being on safe side we chose $200V$.

3. Novel Features of the Trap Design

Our trap design provides more versatile control on the ion position. The strip electrodes give us the control over its height, by implementing shuttling protocol, as demonstrated in this paper. By applying RF-voltage with reduced amplitude to central DC electrode, additional control over the height of ion can be achieved as demonstrated by Boldin et al. [22]. Further studies are recommended to integrate Boldin method. Horizontal shuttling can also be achieved in such trap design by modifying the trap design such that central DC electrodes are segmented [15]. This modification can make this design of its kind which provides shuttling in two dimensions simultaneously. Further study is required to implement such type of traps in real life [33].

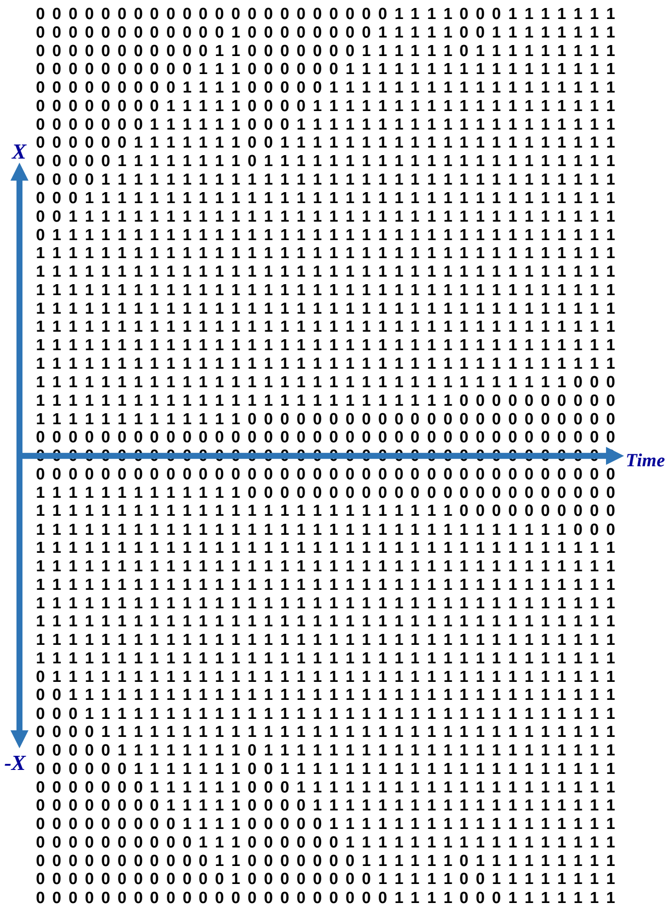


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Fig. 5. For demonstration purpose shuttling protocol for 10μm strip-width trap is presented. Each column represents state of 29 electrodes at time t_1, t_2, t_3, and so on. The ion moves from ~40μm to ~100μm in 36 steps, each of 10 μs.

It may be possible to trap the ions at different heights or even in $2D$ arrays using the same chip by turning ON and OFF appropriate strip-electrodes. Further study in this aspect is recommended.

4. Results and Discussion

The trap was simulated with setting parameters defined in Section-2, with strip-electrode width of $10\mu m$. Trap depth and secular frequency with respect to ion height were calculated for a quick working estimates of the trap design. Fig.4 shows simulated motion of ion (black line) in vertical direction in total $350\mu s$ by changing strip configuration in $10\mu s$ steps (fast) and $3500\mu s$ by changing strip configuration in $100\mu s$ steps (slow). Changing trap configuration with respect to time steps is illustrated in Fig.5 where each "0" and "1" represents a strip state OFF and ON showing configuration certain time steps. The resulting shuttling of ion is shown in Fig.4, where red line shows the trajectory of $Null$ point or trap center. During the shuttling

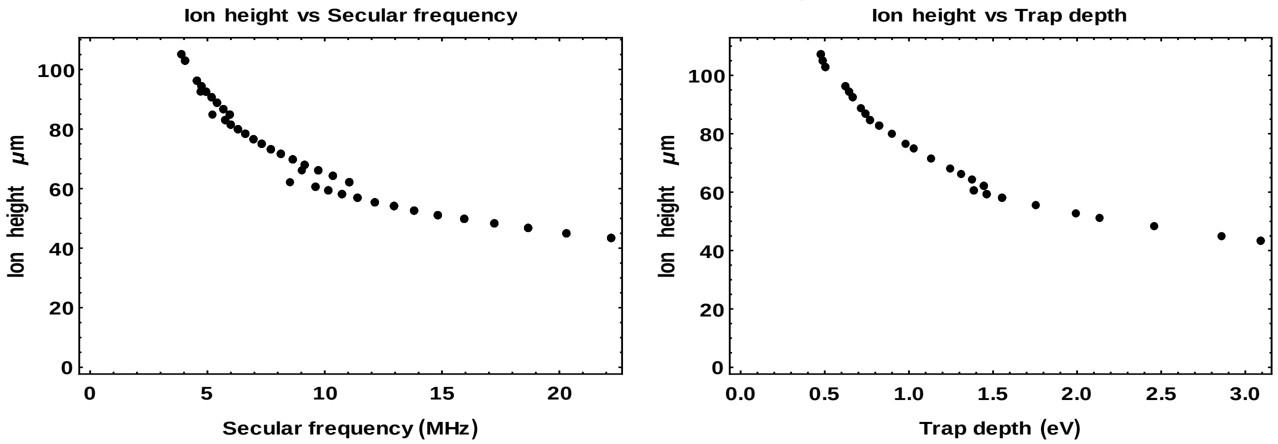

Fig.6(a):

Fig.6(b):

Fig.6 (a). Shows variation in secular frequency of ion from 5MHz to approximately 20MHz. Secular frequency decreases with increase in ion height. Fig.6 (b). Shows variation in trap depth from 0.5eV to 3.0eV. Trap depth decreases with the increase in ion height.

process, number of "kicks" can be observed on the red line as the result of (sudden) changes in strip-electrode configuration, which shifts the trap position (ion height) upward (or downward).

At each kick produces high amplitude harmonic oscillations of ion around mean position as shown by black lines (oscillations). These "kicks" may be configured in such a way that they cancel or decrease the vertical harmonic motion of ion. Such method of cancelling the acquired motional excitation has been demonstrated by [32] for horizontal case, further studies are recommended.

During slow vertical shuttling; amplitude of oscillations of ion are relatively low as compared to fast shuttling.

Expected decrease in trap depth and Secular frequency was observed from $3.0\,eV$ to $0.5\,eV$ and $\sim 20\,MHz$ to $\sim 5\,MHz$ respectively with the increase in ion height from $\sim 40\,\mu m$ to $\sim 100\,\mu m$. Fig.6 (a) and Fig.6 (b) show the simulated results of secular frequency and trap depth respectively. This shows that the trap parameters are quite stable during the shuttling process.

5. Recommendations

These results are calculated for the trap made with strip-electrodes with $10\mu m$ width. We recommend enhancing the study to wider strips and a good comparison should be made between the traps. Further to this full dynamics of the shuttling protocols should be analyzed for different size traps and compared accordingly.

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