Vertical Ion Shuttling Protocols for Multi-Strip Surface Ion Traps

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Abstract
Using the novel surface trap design, we propose vertical ion shuttling protocols in such type of traps. Horizontal shuttling of trapped ions has already been demonstrated practically in various surface traps successfully. In this paper we verify ion transportation (shuttling) in vertical direction (above the surface), which may be important for many practical applications such as heating rate measurement in surface traps, laser cooling experiments, quantum sensors and quantum information technology. We run and compare fast and slow ion shuttling protocols in various surface traps designs. We have also discussed how to harness the power of cloud computing techniques in simulations and modelling of surface ion traps through Google Cloud Platform.

Key words:
Cloud computing; Google Cloud Platform; Ion trap modelling and Simulation; Surface ion trap; Vertical Ion Shuttling.

1. Introduction

Trapped ions are proved to be useful in quantum technology applications due to their ability to trap single to millions of atomic ions in good isolation from the outside world. Horizontal shuttling of trapped ions has already been demonstrated practically in various surface traps successfully [1][2][3][4]. The radio-frequency (RF) Paul trap was initially used in particle accelerators and mass spectrometry, recently it has been successful to implement Quantum simulations and algorithms, frequency standards [5][6][7][8], atomic clocks [9][10][11][12], quantum electrodynamics and quantum information and computing [13][14][15][16].

Earlier ion traps were of macroscopic sizes. The advanced microfabrication technology enabled us to make sophisticated microscopic and scalable planar ion traps which provide many advantages including scalability and flexibility. Recent proposals for implementation of full-scale quantum computer based on surface ion traps are already presented in references [17][18][19][20][21][22], consisting of large number of linear and 2-dimensional arrangement of trapping regions (ion traps zones) [6][7] including shuttling zones where ion(s) can be transported within various zones (such as memory zone, processing zones, storage zones etc.).

Ion shuttling has become an important feature in surface ion traps for quantum computer proposals. Plenty of work has been carried out on horizontal shuttling of ion(s) from one trapping location to another or through the junctions [3][4][25][26][27][28].

One of the limitations of surface ion trap geometries is lower trap-depth at large ion-electrode distances (ion height from trap surface) and high heating rate at small ion height [23][24][29][30][31]. Hence for fast ion loading in traps, longer ion lifetime and increased trap depth (deeper potential well) a smaller ion height is required (near trap surface) but at smaller ion heights, increase in anomalous heating of ions reduces coherence time [32][33][34].

While at lower ion heights access to laser for cooling and performing qubit operations get nearly lost or laser beam may hit the trap surface producing unwanted stray charging and heating of trap surface, thus heating rate of trapped ions rises. Therefore, a larger ion height is pre-requisite for proper Laser access which unfortunately yields a weaker trap.

Geometric factors of ion trap design and fabrication process are key factors deciding the trap depth and ion height [16][18]. It is a challenging task of realizing deeper trap (high trap depth) at larger ion-surface distances [7][14]. An ion trap geometry providing variable ion height could be beneficial in many applications. In such type of geometries, the trapped ion can be move vertically above the surface of the trap, in order to achieve desired height, hence desired trap depth as well.

Such vertical shuttling may prove useful for proper laser access of trapped ions, control of trap depth for cooling and manipulation purposes, fast loading of ions at higher trap depths and heating rate studies for surface ion trap geometries. More detailed discussion about such geometries is already presented in [1].

This research investigates trap modelling and simulations of various shuttling protocols for fast and slow vertical shuttling of ion in a multi-strip surface ion trap geometry providing adjustable ion height, as proposed in [1], and illustrated in Fig.1.

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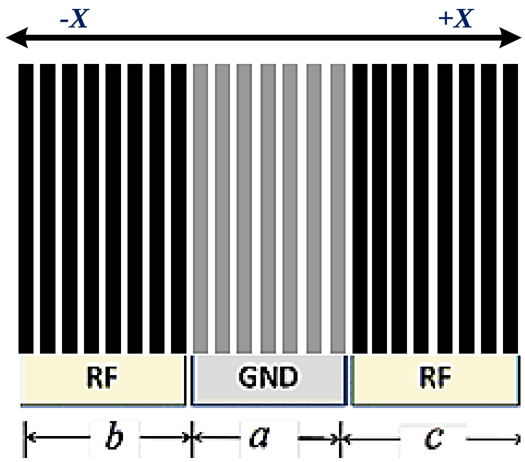

Fig.1. Trap design for vertical shuttling of ion, RF-electrodes of width "b" and "c" are set by many micro-strips combined together "electrically" (by applying RF-voltage) and central electrode "a" (by grounding)

Realizing the high computing power required for ion shuttling simulations, we have used cloud computing techniques provided by Google Inc. for the trap modelling and simulations purpose.

Cloud computing is among the latest trends in technology which provides many advantages including flexibility, cost effectiveness and time saving over traditional approach of maintaining in house, high speed computers. Scientific community can take advantage of cloud computing platforms for scientific computing [35][36]. This paper also provides guidelines for implementation of trap modelling and simulation techniques over Google cloud computing.

2. Trap Modeling and Simulations

2.1 Trap Design

As discussed in [1], the ion trap is a sequence of extended micro-strips of fixed width. RF-voltage is applied on selected micro-strips in a way that it creates effective RF-electrode(s) of (adjustable) widths of "b" and "c" as well as central ground electrode "a", as shown in Fig.1. Further details and modelling of electrodes is demonstrated in [37: Ch.7].

2.2 Trap Modeling

Electrostatic potential produced by RF-electrodes was modelled through analytic method with gapless approximation, M. G. House has discussed in [17].

$Eq.1$: The secular motion of the ion in terms of a pseudo-potential energy.

$$\psi(u,v,w,t) = \frac{Z^2 e^2}{4m\Omega^2}\left|\nabla\varphi_{rf}\right|^2 \qquad \dots(1)$$

$Eq.2$: Classical Equations of motion for ion trajectories.

$$\sum_{j}^{3} m\ddot{\mathcal{X}}_j + \nabla_j\psi(u,v,w,t) = 0 \qquad \dots(2)$$

Trajectory of shuttled ion can be calculated by solving above classical differential equations of motion numerically [25].

Numerical solution of the above equations is used to calculate the kinetic energy gained by the ion during vertical transportation. In order to obtain the ion dynamics, we used a package named "NDSolve" provided in Mathematica to numerically solve these differential equations.

Despite some limitations as discussed in [38] this analytical method gives us a reasonable and quick solutions for ion dynamics in our simple trap geometries.

2.3 Computational Techniques and Tools used for Simulations

Wolfram Mathematica was used for modelling and simulations. Initially, Mathematica was installed on an Intel Core-i5 Laptop with 6 GBs of RAM and ion traps were modelled, as the program got complicated while simulating the ion trajectories with NDSolve function [37: p.152] (as discussed in above section), our system was unable to perform efficiently due to huge amount of required RAM.

We got frequent system crashes, because the simulations required intense computing and huge memory resources. The Mathematica function NDSolve was responsible for the behaviour, as it must calculate trapping field at every point above the surface of ion trap throughout the shuttling time. The data produced in each shuttling time was ranging from 5 GB to more than 25 GBs depending on the shuttling time, "accuracy goal", "precision goal" and other parameters of NDSolve function. Backup storage of the data generated by the program, was also a challenging task which required large amount of disc space.

To resolve these issues, Google Cloud Platform was chosen. It provided us the necessary computational tools for our computing needs. Initially an instance of Google Compute Engine (GCE) was created. The instance is actually a virtual machine (VM) hosted on Google's infrastructure. The instance with two vCPUs (virtual CPUs) with 4 GBs of RAM was created. Later on it extended up to eight vCPUs and 52 GBs of RAM (maximum allowed limit in free trial Mode [39]) for longer shuttling time. 100 GB of disk space was also added on the virtual system (Google Cloud Documentation [40].

Linux operating system (UBUNTU Server 18.04 LTS) was installed with the help of GCP Console and Xfce desktop environment (lightweight desktop environment for UNIX-like operating systems) was installed (using SSH terminal). Then Mathematica was installed using VNCViewer application [41].

Later on 10 GB of swap space was also added to meet our memory requirements. Whole setup process was completed with tools provided by Google. VNCViewer was used for remote desktop access. Google Drive (cloud memory) was used for data backup and files transfer between Virtual Machine (VM) and Local computer, it provided virtually unlimited space [42] and high-speed data transfer rate (it was free for us with our institutional student account).

The step-by-step setup process is described below:

(i) Create or sign in your Google account and signup for "Google Cloud Platform" to setup Google Cloud Platform account and add credit/debit card information. It will give you a free credit \$300 for one year to try their services.

(ii) Create a new project and create an instance (a virtual machine "VM"). Select number of vCPUs and amount of RAM. It is recommended to start with fewer vCPUs and little ram as needed, later on you can increase it as your program gets complicated. Next, select operating system to be installed on VM. We chose UBUNTU 18.04 LTS because it is open source and has free license, you can also choose windows server for some charges.

(iii) Now, start your VM instance and connect with it using SSH (Secure Shell key) terminal option.

(iv) Install Desktop environment for frontend Graphical User Interface (GUI) if it is not already there. We prefer Xfce [43] as it is lightweight and takes few resources on VM.

(v) Install and Configure VNCServer, configure network and firewall in GCE properties for remote connection through VNCViewer. Now you should be able to connect with front-end of VM instance using VNCViewer using external IP address of VM.

(vi) Install Mathematica on the VM instance. You can either directly download from internet to your VM or upload to your VM from local computer.

Once this procedure is done, we can implement our computer program as usual.

2.4 Trap Parameters and Constraints

With the aim of modelled trap to look like a real-life trap, constraints were imposed during the whole modelling and simulation process. Hence certain parameters were carefully chosen keeping in view that current practical limitations of

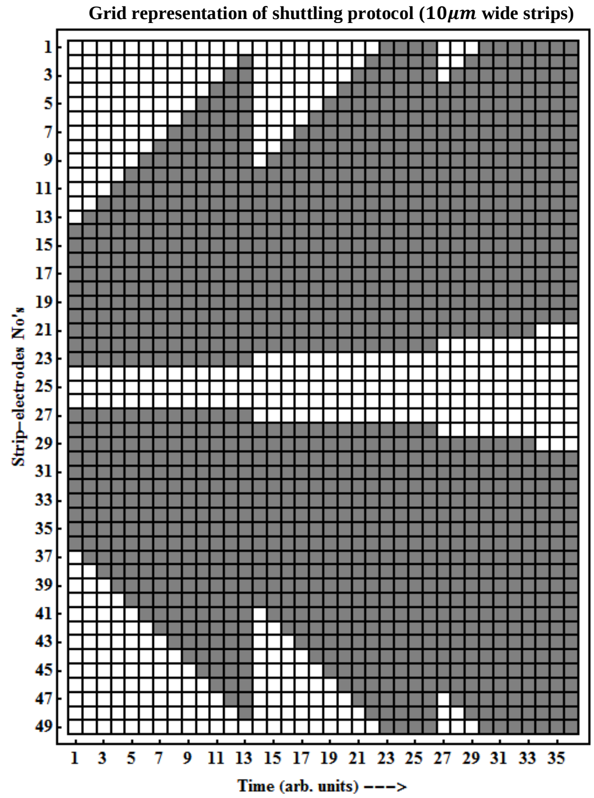

Fig.2. Each row of the "Grid" represents time function of strip-electrode. Each box represents state "ON"(Black) or "OFF"(White) of the electrode during that time.

fabrication process are not violated. In order to verify simple shuttling protocol, simulations were restricted to ion height ranging from $40\mu m$ to $200\mu m$. Ion height was varied by varying the RF strip-electrodes width ranging from $10\mu m$ to $30\mu m$. The trap RF-voltage Rf-voltage (Vp_{rf}) was set to $200V$. Whereas trapping RF-frequency (Ω) was set to $2\pi \times 15MHz$. For simulation purpose, $Yb+$ ion is considered here. The Vrf can be set as high as $500V$ as discussed in [32]. Although higher RF-voltage increases the trap depth but it may cause heating of electrodes and surface flashover as discussed in [44][45], so being on the safe side we restricted to $200V$. Gapless approximation ($0\mu m$) is used in simulations as discussed in [28][29][30].

In longitudinal direction, infinite length of the RF-strips is set. These assumption doesn't have any considerable effect on trapping parameters as discussed in [32]. Nevertheless, complex RF-power supply and control circuit requirement is required to control the varying strip-electrodes widths.

2.5 Shuttling Procedure

As discussed earlier, trap has many straight parallel strip-electrodes of equal widths, an RF-electrode of any width (size) can be set by turning ON (by applying RF-voltage to) a group of adjacent strip-electrodes simultaneously.

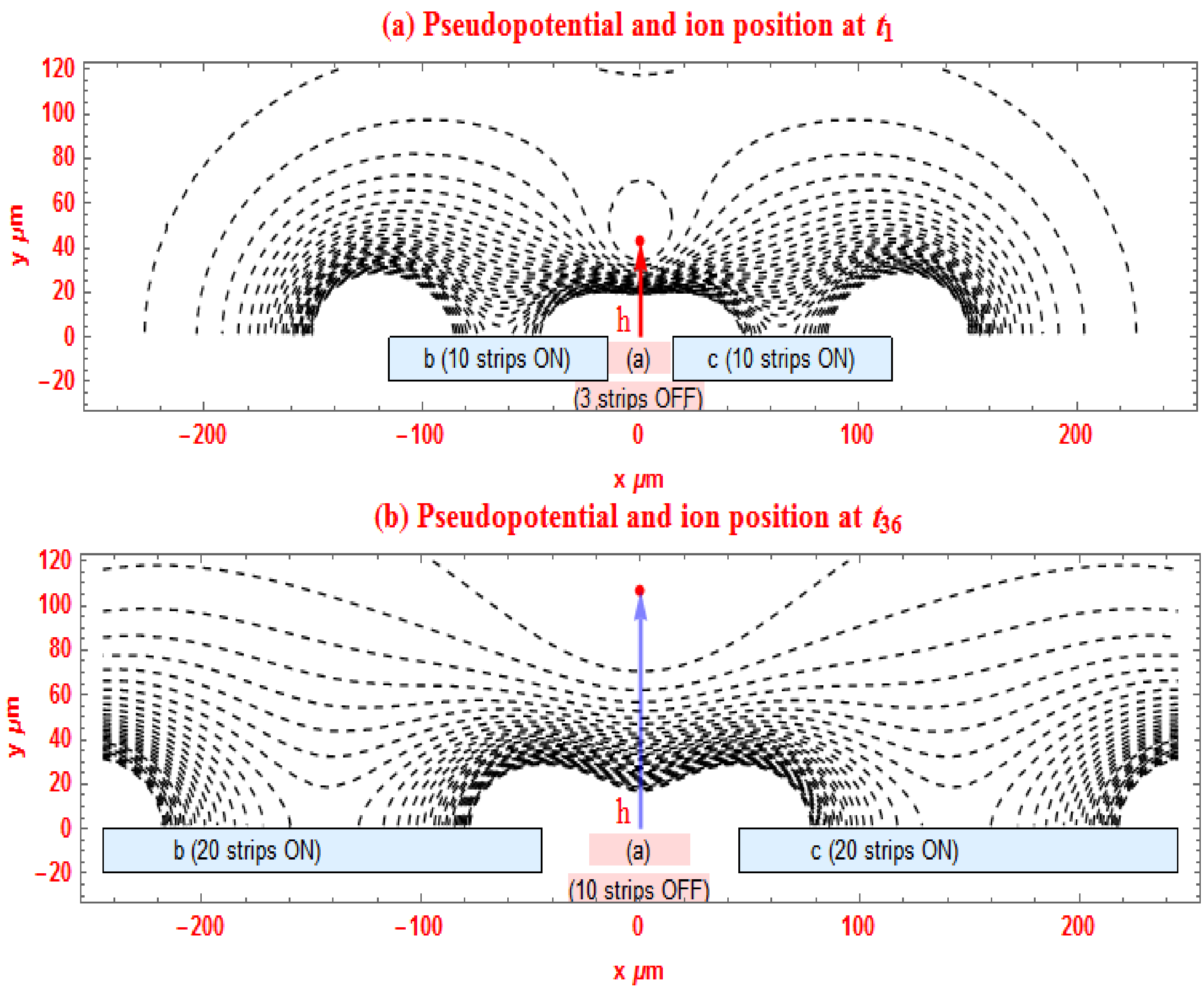

Fig.3 (a) & (b): Vertical shuttling of ion is demonstrated by turning on selected strip-electrodes (10 strips in (a) and 20 strips in (b)). The red dot shows the RF-Null point or trap centre.

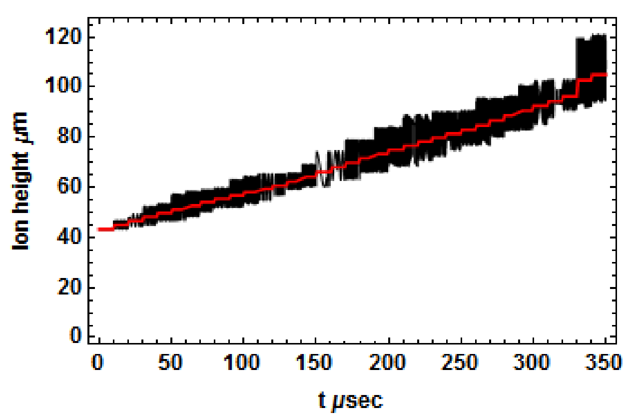

Fig.3 (c) Shows vertical trajectory of ion (Red) and secular motion of ion (Black). Trap with strip width of 10μm (Fast).

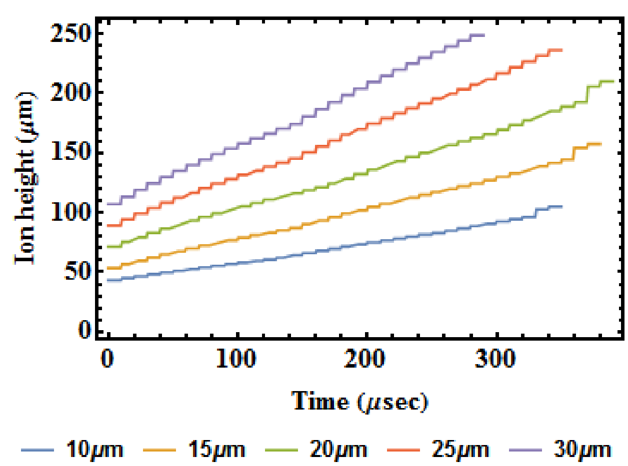

Fig.3 (d) Shows vertical motion with different widths of strip-electrodes.

In this way, we can create RF–electrodes or can control the width of the RF-electrodes; "*b*" and "*c*". By turning OFF electrodes in between the created RF-electrodes, we can make the ground electrode of width "*a*" as well. Hence by changing the width of the RF and ground electrodes by using the above procedure, we vary the trap configuration, hence moving the RF-null position (ion height) above the trap surface.

The principle of vertical shuttling of an ion is demonstrated in Fig.3, by turning ON the pre-selected strip-electrodes at certain times defined by shuttling protocol [50][51][52]. For demonstration purpose simple shuttling protocol is presented in Fig.2 and Fig.3. In Fig.2, three strip-electrodes each of 10 μm (30μm in total) in the centre (strip number 24 to 26 in Fig.2) are turned OFF to make the ground electrode of size "*a*" in the middle. While 10 strips making total width of 100μm (strip number 14 to 23 in Fig.2) are turned ON to make an RF-electrode of width "*b*", similarly strips 27 to 36 make the other RF-electrode of equal width "*c*". Pseudo-potential over the trap surface created in such trap is illustrated in Fig.3(a) and Fig.3(b), red dot represents RF null position where the ion can be trapped.

We can also see changing ion height (highlighted with red dot and arrow) due to changing configuration of strip-electrodes. Fig.3(c) shows the ion trajectory (red line) and fluctuations caused during shuttling (black).

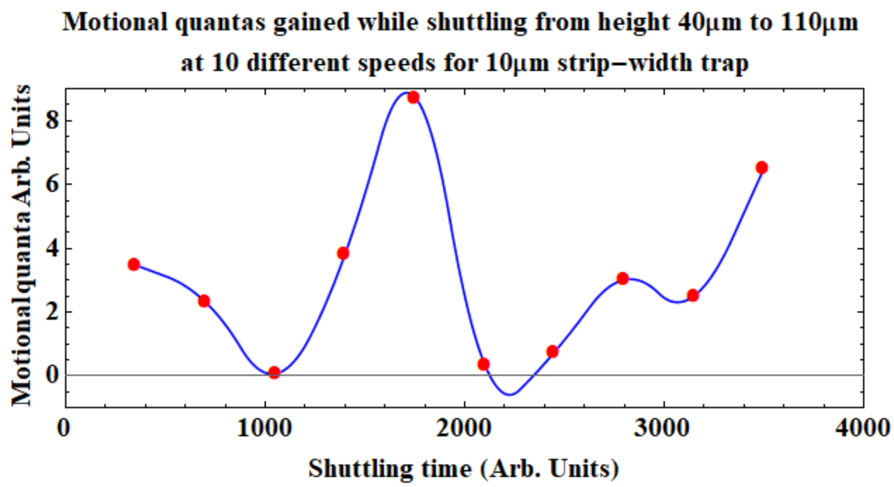

Fig.4. (Above) Motional quanta gained while shuttling from height 40μm to 110μm at 10 different speeds for 10μm strip-width trap.

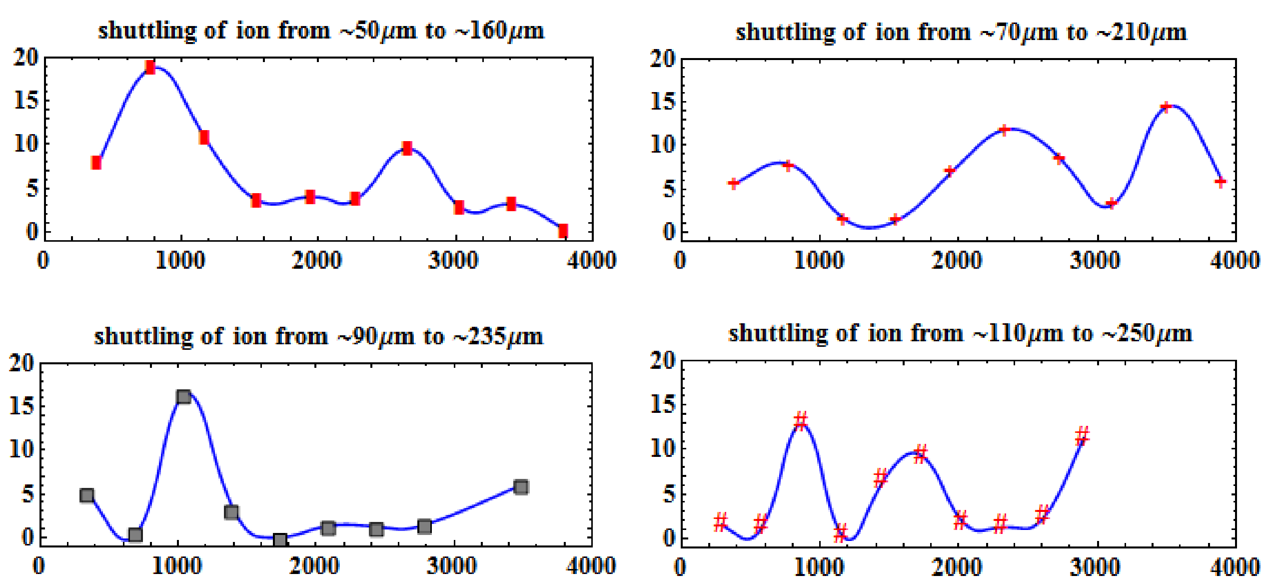

Fig.4. (Below) Motional quanta gained while shuttling from height 40μm to 110μm at 10 different speeds for 15, 20, 25 and 30μm strip-width trap respectively.

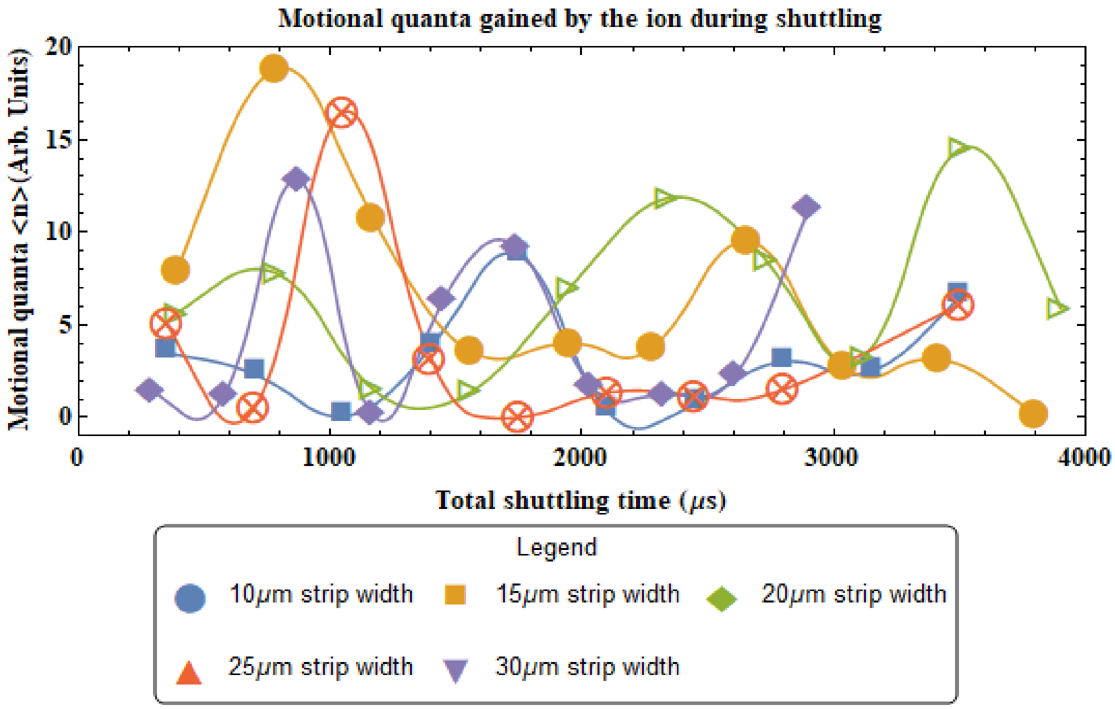

Fig.5. A comparison of motional quanta gained by the ion in different trap configurations shows regular peaks in quanta gain. It shows that moving the ion slower or faster has lesser impact on ion's energy gain than order or arrangement of “kicks” w.r.t. time steps.

2.6 Vertical Shuttling Protocols

The variable trap parameters such as ion height, trap depth, secular frequency and optimum electrode ratio as in [32], were calculated for all the possible combinations of 55 strip-electrodes using equations discussed in [16][28]. Data was filtered with conditions of minimum trap depth of $0.1eV$, minimum secular frequency of $1MHz$ and optimum electrode ratio within 1 to 8 [32].

The process was repeated for different trap geometries with strip-electrode widths of $10\mu m$, $15\mu m$, $20\mu m$, $25\mu m$, $30\mu m$ respectively. Shuttling protocols were set in such geometries by arranging above data according to increasing ion height and decreasing trap depth with respect to time and further filtering out some sudden “kinks” in the ion trajectory.

Shuttling protocol for trap with $10\mu m$ strip width is shown in Fig.2, while Fig.3(d) shows trajectory of ion (trap centre) for all the shuttling protocols. These ion shuttling protocols in each trap configuration were simulated with two time-intervals; at fast ($10\mu s$) and slow ($100\mu s$) speeds.

Gain in kinetic energy and motional quanta during vertical motion of the ion were calculated using equations discussed in [16][30][53][54].

3. Results and Discussion

Calculated motional quanta gain by the ion with various strip widths is summarized in Fig.4, shuttling protocol is applied for 10 different shuttling speeds which shows that faster and properly configured “set of kicks” (shuttling protocol in other words) may be more efficient as compared to slow shuttling of ion as evident in Fig.4 and Fig.5.

Most of the energy gained by the ion is within first few potential “kicks”. Initially, ion starts from rest, and receives sudden kicks periodically defined by time interval or “step size” (in this case; at fixed time intervals, for e.g. in Fig.3(c), ion gets kick at every $10\mu s$ step).

At every kick the ion either gains (or potentially may loses energy) depending on the direction of ion’s secular motion relative to upward potential “kick”.

Many such shuttling protocols are suggested for horizontal shuttling of ions [16][17] (by DC voltage variations) in which minimum amount of energy is transferred during the process. Similar approach can be investigated for vertical shuttling in this trap design (RF voltage variation).

4. Recommendation

In our trap simulations it has been noted that motional quanta gained by the ion is in orders of 106, for real practical applications, however, this must be reduced significantly. This can be done utilizing various techniques already demonstrated. One way to do this by using appropriate configuration of "kicks" received by the ion during shuttling process, as discussed by Walther et al. in [26], or alternatively following the shuttling protocols as discussed in [17].

Further studies are recommended in this regard. Further to this variation in height can also be achieved by applying reduced RF-voltage or DC-voltage to the central electrode as demonstrated by Boldin $et\ al.$ in [31] and Pearson et al. in [49], but ion energy gain needs to be calculated for real applications.

Further to this horizontal shuttling can be implemented as well along the vertical shuttling [46][47][48]. This could be considered as $2D$ shuttling protocol. These studies could also be helpful for future trap geometries and quantum technology experiments.

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