Multi-functional surface ion trap for effective cooling and large-scale trapping of ions

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Abstract. Scaling up the number of trapped ions and effective cooling ions in surface ion traps is a central challenge in the research of trapped-ion systems. In this paper, we propose a novel surface ion trap design that enables innate principle-axes rotation of trapped ions. In the manipulation zone of our chip, a symmetric seven-wire geometry enables the rotation of principal axes of two parallel linear ion strings. This can be used to ensure the efficient laser cooling of the trapped ions. Furthermore, to avoid electrode surface adsorbates or other pollution from occurring during the loading process, we design a standard five-wire geometry for the loading zone and a Y-junction to connect loading zone and manipulation zone. A multi-objective optimisation procedure suitable for arbitrary junctions is described in detail, and the corresponding optimisation results for all ingredients of our chip are presented. With this multi-functional ion trap design and innate principle axes rotation, the proposed design can be useful in the construction of large-scale ion chip quantum processors with low heating rates and is also the high efficiency ion beam splitter and multi-ion-mixer. the trap has potential applications in precision measurements and quantum metrology.

Keywords: ion trap, surface ion trap, quantum information and quantum simulation
1. Introduction

The ion trap system is one of the most attractive candidates for quantum computing [1], offering a long coherence time and a strong ability to scale up quantum bits [2]. The surface ion trap is one of the major schemes for scaling-up quantum bits and integrating ion traps [3]. Recent developments in micro/nanofabrication technologies make the manufacturing of such traps simpler and more feasible [4,5], completely eliminating several difficulties in the assembly of macroscopic devices such as blade and four-rod traps [6,7]. The performance of confined ions depends entirely on the configuration of the electrode structure in the surface ion trap. Nowadays, the standard five-wire (FW) geometry trap is the dominant structure for trapping ions [8–11]. In functional zones, the standard FW trap is widely used in scaling-up the confinement of ions [12–14]. The main reason is that its geometry and fabrication process are relatively simple. However, the standard FW trap has inherent problems in cooling ions.

The geometry of the chip is two-dimensional, which limits Doppler-cooling laser beams whose wavevectors are parallel to the chip to cool the ions’ motion in 2D. To effective ions’ cooling, it is necessary to allow laser-cooling in 3D with a beam parallel to the surface. Fortunately, this can be achieved by rotating the principal axes of the trap. This rotation is achieved by an elaborate configuration of the radio frequency (RF) electrodes [12–15,21]. Currently, there are three main methods of rotating the principle axes of the trapped ions: the four-wire geometry [22,23], the asymmetric design [21,24,26], and the six-wire geometry [15,16]. These methods have each achieved good results. However, in the four-wire trap, the effects of stray charge can result in the heating of ions that are trapped above the electrode gap [1]. Furthermore, it is difficult to apply a control potential to segments of electrodes without affecting the application of the RF potential [4]. The asymmetric design leads to a more capacitive coupling strength and higher losses in the RF drive [4]. The six-wire trap is design based on standard FW trap by dividing the ground of the RF electrodes into two electrodes, and cannot trap ions tightly or deeply [22]. Furthermore, the negative effects of these methods are enhanced in large-scale trapped ion systems. For example, the asymmetric geometry trap suffers high RF loss, which is proportional to the scale and the asymmetric degree of the RF electrodes [18]. To rotate the principle axes, special designs with additional electrodes are required [28]. These designs need an extremely complex and difficult preparation process, such as multi-layer structures and buried wire technology.

To avoid the problems mentioned above, we propose a novel surface RF ion trap that has innate rotating principle axes without excess electrodes or asymmetric geometry and enables 2D large-scale parallel trapping ion strings at the same time. The chip consists of a SW geometry trap for the manipulation zone, a standard FW geometry trap for the loading zone, and a mirror symmetry Y-junction for the transition zone. The SW trap simultaneously realises double traps confining a pair of parallel linear ion strings at a distance of 200 µm and the rotation of their principal axes at 35 degrees in opposite directions. This enables 2D large-scale and 3D cooling ions to be present in the manipulation zone at the same time, representing a simple but practical technique. To prevent electrode surface adsorbates or other pollution from affecting the loading process, we design an standard FW trap as the loading zone. This produces a single trap in which the null point of the pseudopotential is located 100 µm above the surface of the chip. A Y-junction with mirror symmetry is designed to shuttle ions from the loading zone to the manipulation zone after pre-cooling. The junction is optimised through a combination of the ant colony algorithm and a multi-objective function.

2. Design of linear electrode zones

In the design, fabrication, and testing of the ion traps, we reported some prominent research results [29,30]. To further improve the confinement performance, cooling, and shuttling of ions in surface ion traps, the overall layout of a multi-functional ion trap chip is designed as shown in Figure 1. There are three parts in the chip: two linear electrode zones and a mirror symmetric Y-junction. The single trap indicates the loading zone where ions are trapped at a height of h = 100µm above the surface, and ions pass through the Y-junction in the transition zone into the double trap (in which d = 200µm) in the manipulation zone. The advantage of this trap is that it can efficiently solve the problem of cooling the ions in 3D without redundant (DC or RF) electrodes and a large-scale 2D system.
The potential curvature tensor is proportional to the square of mass relatively lower-voltage RF source. We consider ions trapping depth and high trapping frequency with the optimal parameter for obtaining an effective ponderomotive pseudopotential curvature is used optimising the trapping height, depth, frequency, and satisfied.

Causes them to become unstable. One simple way of chip that significantly influences the trapped ions and possible when the conditions of the trapped ions are generated on the substrate of the dielectric material when RF voltages are applied to the surface ion trap to constrain ions in the strong-binding regime, but a higher voltage in the RF source generally produces a greater loss. In general, the loss of RF on a dielectric substrate is mostly in the form of thermal energy, which results in a high-temperature chip that significantly influences the trapped ions and causes them to become unstable. One simple way of remedying this is to reduce the RF voltage as much as possible when the conditions of the trapped ions are satisfied.

Our design method is different from that of previous designs. Instead of directly optimising the trapping height, depth, frequency, and q parameter of the Mathieu differential equation, the ponderomotive pseudopotential curvature is used as the optimal parameter for obtaining an effective trapping depth and high trapping frequency with a relatively lower-voltage RF source. We consider ions of mass m and charge q that are confined by the ponderomotive potential created by an RF electric field with amplitude $\vec{E}(\vec{r}) = -\nabla \Phi(\vec{r})$ at angular frequency $\Omega_{RF}$. In the adiabatic approximation, which assumes that the motion of the ions is slow on the time scale $\Omega_{RF}$, the ponderomotive pseudopotential is

$$\Phi(\vec{r}) = \frac{q^2 \| \vec{E}(\vec{r}) \|^2}{4m \Omega_{RF}^2}.$$  

(1)

At arbitrary positions $\vec{r}$ above the chip, the pseudopotential curvature tensor is proportional to the square of the electric potential curvature tensor

$$\Phi^{(2)}(\vec{r}) = \partial_\alpha \partial_\beta \Phi(\vec{r}).$$  

(2)

According to the Laplace equation, the trace of this tensor is zero, $Tr\Phi^{(2)}(\vec{r}) = 0$, and the principal curvature of the pseudopotential cannot be chosen independently. In the linear Paul trap, the pseudopotential curvature tensor matrix can be described as

$$\Phi^{(2)}(\vec{r}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$  

(3)

The method of reverse solution using the above matrix as the boundary conditions can be used to design the geometric structure and size of the electrodes in terms of the spatial arrangement of a linear equidistant ion chain. In this process, the pseudopotential curvature tensor is applied globally to the entire ion string. Note that the tensor is not used locally at each ion position. In addition, according to a previous result, we can quantify the strength of a trap, independently of the distance to the electrode plane y and the potential $U_{RF} \cos(\Omega_{RF}t)$ applied to the RF electrodes, using the following expression

$$\kappa = |det\Phi^{(2)}(\vec{r})|^\frac{1}{2}(\frac{\Omega_{RF}^2}{U_{RF}}).$$  

(4)

The dimensionless curvature $\kappa$ depends solely on the geometry of the surface electrodes. Although a large value of $\kappa$ can be achieved by increasing $\Omega_{RF}$ or reducing $U_{RF}$ to some extent, subject to the Mathieu stability requirements, it is preferable to optimise the electrode shapes such that $\kappa$ is maximised for the given constraints. Furthermore, the larger the $\kappa$ value, the higher the trapping frequency when the same RF voltage is applied. A higher secular frequency is preferred because it allows tighter confinement, faster ion transportation, effective cooling, and less sensitivity to external noise. Higher secular frequencies are also preferable for multi-qubit entangling gate operations using motional modes.

### 2.2. The manipulation zone design

Based on the analysis above, we designed and optimised the symmetric SW geometry trap. The geometry and size of the RF electrodes are solved in reverse using two parallel linear ion strings. The arrangement and position of the ions are specified, and then the electric potential is solved by the boundary element method (BEM) to obtain the electrodes’ size for the expected $\kappa$ value. The potential generated by the electrodes is analytically calculated in the gapless plane approximation using the SurfacePattern software package. Here, our target trapping...
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Figure 2. Parameters of seven-wire trap and distribution of pseudopotential. (a) Diagram of the trap layout and dimensions (DC control electrodes (blue) with 150 µm width, RF electrodes (red), and the ground (green)). The structure consists of an RFCentre electrode with 120 µm width, a pair of RFSide electrodes of width b = 167 µm, and two ground electrodes of width c = 83 µm width. (b) Radial contour plot of total pseudopotential generated by (a). There is a double trap in the x direction. The pseudopotential is becoming smaller from red to blue. (c) 1D plot of the pseudopotential along the line through the null and saddle points. The trap depth is about 0.129 eV, and the trapping point and escape position are approximately 98 µm and 201 µm above the surface of the trap, respectively.

height (RF null) is 100 µm above the surface of the ion trap, and the two ion strings are juxtaposed at a distance of 200 µm. Finally, the RF electrodes in the SW trap include one RFCentre and two RFSide, which have widths of 120 µm and 167 µm, respectively. Both ground electrodes have the same width of 83 µm, as shown in Figure 2(a). As we can see from the distribution of pseudopotential in Figure 2(b), the principal axes can be rotated by 35 degrees using symmetric electrodes. This allows effective ions’ cooling by a laser-cooling beam along all dimensions of ions’ motion. Most importantly, symmetrical RF electrodes simplify the configuration of the DC control voltages relative to the asymmetric trap in experiments. We can apply a DC voltage on RFCentre to achieve double traps of electrostatic potential overlapping pseudopotential double traps.

The height of the trapped ion is found to be about 98 µm using a BEM simulation with a 100-V-amplitude RF driving source at a frequency of 25 MHz. Figure 2(c) shows that the escape position (saddle point) is approximate 201 µm, and the trap depth is 0.129 eV. The secular frequency in the radial x and y directions are approximately 2.731 MHz and 2.487 MHz, respectively. The trap depth and frequency obtained by size optimisation are considerable. In the surface ion trap, the voltage applied to the trap RF cannot reach a high level, and thus can only constrain trapped ions in the weak-binding regime. This is not conducive to the preparation of quantum states in later experiments. Therefore, our targets achieve deeper trap depths and higher trap frequencies by optimising the electrode size, which can be made as high as possible with a low RF voltage. As double traps are mirror symmetric along the RF direction, the parameters of the double traps are the same, although the rotation direction of the trap principle axes is different.

The distance between the two null points is 200 µm, as shown in Figure 2(b). Two parallel linear ion strings can be trapped along the direction of the RF electrodes. The Coulomb interaction between two ion strings at 200 µm distance is small, and is negligible compared with the pseudopotential generated by the RF electrodes. Furthermore, the force can be effectively compensated by DC electrodes, even if the Coulomb force interaction is taken into account. A DC bias voltage can be applied on the intermediate RF electrode RFCentre in conjunction with the DC electrodes arranged on both sides of the RF electrodes. To achieve the steady confinement of ions through the coincidence between the two corresponding null points of pseudopotential and electrostatic potential, the RFCentre electrode requires a DC voltage to be applied. The DC and RFCentre electrodes under a DC voltage can realise the double-trap distribution of electrostatic potential in the radial direction.

2.3. The loading zone design

According to recent reports [8–14], it is more convenient to use an standard FW trap for the pre-cooling and loading of ions. In addition, the requirements of experimental conditions are relatively low when we load and simple manipulate ions, involving laser beams, voltage configuration on the DC electrodes, and so on. A separate loading zone also prevents contamination of the entire chip, which can extend the ions’ lifetime and improve their manipulation. When ions are transported from loading to manipulation zones, the parameters of the ions (e.g. trapped height, depth, frequency) should be as similar as possible to ensure that the motional modes of the ions are not excited.

The layout of RF electrodes in the standard FW trap is solved in reverse using a 1D linear ion string
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100 µm above the surface of the chip. The calculation process is the same as for double traps. The resulting trap is composed of two RF electrodes of 130 µm width and a ground electrode of 108 µm width, as shown in Figure 3(a), and has \( \kappa = 0.186 \), which is sufficiently large. The performance of the trap is simulated using BEM for trapped \( ^{40}\text{Ca}^+ \) ions under an applied 100 V RF voltage at an angular frequency of 25 MHz. The distribution of pseudopotential for this design is shown in Figure 3(b). The trapped height and escape position are approximately 102 µm and 190 µm above the chip surface, respectively. The depth of the trap potential is approximately 0.122 eV, which is sufficient to trap ions. A deeper trapping depth is desirable for the loading zone, because it improves the probability of loading ions, allowing the working time of the ion oven to be effectively shortened in experiments and maintaining the surface cleanliness of the chip. However, it is necessary to ensure that the traps in different zones have the same depth. The secular motion frequencies in the radial \( x \) and \( y \) directions can be as high as 2.845 MHz and 2.8220 MHz, respectively. Here, we achieve a higher frequency by using a relatively low voltage for the RF source. The \( q \) parameter along \( x \) is 0.229.

For the layout of RF electrodes obtained by optimising \( \kappa \), we can obtain a deeper trap depth with a slightly lower voltage. The RF loss is reduced by using a low-voltage RF source, and this greatly reduces the temperature on the chip and minimises the heating rate of the ions. In our chip, the designed five-wire trap is used for loading and pre-cooling ions. In addition, the amount and arrangement of the ions can be regulated by adjusting the voltage on the DC electrodes on both sides of the RF electrodes. The arrangement of the ions can be controlled by forming a long 1D linear ion chain, a series of ions with a high-order mode, or a multi-potential well along the RF direction, allowing them to be stored in this zone before being moved to the double traps.

3. Multi-objective optimisation of Y-junction

To shuttle ions between loading and manipulation zones (as described in sections B and C above), the Y-junction acts as a bridge between the two zones. This allows for the orderly merger of two parallel linear ion strings from the double-trap to the single trap through the sequential control of voltages on the DC electrodes, and vice versa. As the fidelity of the entanglement gates is highest when the ions are near their motional ground state, it is important that shuttling ions between zones be accomplished with a high success rate and minimal kinetic energy.

![Figure 3](image-url)
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which is the first derivative of the pseudopotential [42]. The axial motional modes of ions will be excited by the unwanted pseudopotential gradients, which must be minimised. Then, the second objective is to find an RF electrode structure that maintains a low pseudopotential gradient.

The shuttling process of ions is approximately adiabatic, so we need to depict a slowly varying physical quantity: the trapping height along the shuttling path. The fluctuation of the trapping height should be as small as possible; under large fluctuations, the ions will escape from weak confinement. This greatly affects the stability and repeatability of the ions in the shuttling process. If the trap height of the pseudopotential fluctuates significantly along the shuttling path, the potential minimum value generated by the time-dependent voltages on the DC electrodes may not overlap with the pseudopotential null generated by the RF electrodes, resulting in aggravated micro-motion and heating rate of the ions. Furthermore, trapping height fluctuations lead to misalignment between ions and the laser beam. The third objective should be to ensure a consistent trapping height throughout the shuttling process.

In a linear surface ion trap, the secular frequency of the ions is usually a fixed value in the radial direction. The confinement of ions in the transition zone is normally weaker than in the linear zones. During the transporting process, the transformation of high and low secular frequencies signifies changes in the energy of the ions, with the amount of energy directly proportional to the number of shuttling ions. To keep the secular frequency of the ions fairly constant, it is necessary to limit the confinement of ions above the Y-junction electrodes to be as strong as in the standard FW and SW traps. Thus, unifying the shape of the pseudopotential tube is the final optimisation target.

3.2. Multi-objective optimisation of electrode structures

The terms of the multi-objective function are described in Table 1, where $E_i(i = x, y, z)$ is the component of the electric field in the corresponding direction and $F_j (J = 1, 2, 3, 4)$ denotes the different target functions. The meaning of these expressions is explained on the table. The potential barrier $\psi_{\text{max}}$ is obtained by finding the maximum value of the pseudopotential excursion along the pseudopotential null $y|\psi_{\text{min}}$; $l_{\text{min}}$ and $l_{\text{max}}$ are the start and end points of the ion-shuttling path, respectively, and $l$ denotes the whole path. $N_i$ and $\Delta$ denote the number of segments on the path and the radius of the pseudopotential tube, which is the displacement from the pseudopotential null position to the pseudopotential position $\psi_{\text{const}} = 10\text{meV}$ in the loading zone. To effectively optimise the multiple objective functions, we make the following adjustments using weighted multi-objective functions and the normalisation operation:

$$F_{\text{multi-objective}} = \sum_{i=1}^{4} \omega_i (\sigma_i \cdot F_i), \quad \sigma_i = \frac{1}{F_{\text{min}}}.$$  

Figure 4. Diagram of the initial electrodes. (a) The layout of standard FW and SW traps (grey) and initial geometry of the Y-junction (yellow). (b) Variable selection in x direction for about half of the initial layout under the symmetrical geometry. $P_i (i = 1 - 38)$ are independent variables.

3.3. Analysis and optimisation results

Initially, we simply connected the RF electrodes of the standard FW trap and the SW trap; the initial structure of the trap is shown in Figure 4(a). The grey electrodes were obtained from the previous design, and their layouts have been maintained. The initial geometry of the Y-junction (yellow part) should be optimised using the multi-objective function discussed in the previous subsection. From the initial geometry, we optimise the junction shape to retain fidelity during the shuttling of ions. This is accomplished by adjusting the 38 control points along the inside edge of the RF electrodes as shown in Figure 4(b). Thus, we have 38 degrees of freedom, from P1 to P38. Each point can only be adjusted in the $x$ direction within the yellow area. The locations of these points are modified using an ant colony optimisation (ACO) [43] algorithm for multi-objective functions. In the process of optimisation, the value of the multi-objective functions in Eq. (5) decreases from 219 to 5.39 only after one iteration. This shows that our
functions exhibit rapid convergence. The Figure 5(a)-(d) show the results before and after optimisation. In the initial structure, the trapped height fluctuates approximately 65 µm above the surface of the trap and the maximum pseudopotential barrier is approximately 1 meV, which is about 0.7% of the trapped depth. In the optimised structure, the height fluctuation has been reduced by a factor of five to just 0.221 meV, less than a quarter of the non-optimised value. The pseudopotential barrier on the shuttling path is three orders of magnitude smaller than the trapped depth. The maximum derivative of the pseudopotential along the trapped path is 2.15 × 10^{-5} eV/µm, as shown in Figure 5(c), which is approximately three times smaller than the pre-optimised value. This drastically reduces the heating of ions from the unwanted electric field of the junction electrodes. The comparison of optimisation with and without function $F_1$ is shown in Figure 5(d). The grey represents the area above the junction electrodes and the rest is the space above the linear electrodes. The improvement from unifying the shape of the pseudopotential tube is obvious from comparing the results using all multi-function equations and those without applying $F_4$. The values of the standard and maximum deviation of the tube radius are extremely different with and without $F_1$, giving $\Delta \sigma = 10.963$ and $\Delta \sigma_{\text{max}} = 26.897$, respectively. The secular motion frequency of the trapped ions is simulated for $^{40}\text{Ca}^+$ with an applied RF amplitude of $V_{\text{RF}} = 100$ V at an angular frequency of $\Omega_{\text{RF}} = 25$ MHz are shown in Figure 6. According to the simulation results, the pseudopotential distribution on the confinement surface (which is based on the shuttling path stretching along the $y$ direction perpendicular to the surface of the chip) is significantly promoted after optimisation. The results are presented in the form of contour lines, and it is clear that the pseudopotential generated by the original structure suffers a discontinuity along the shuttling path, as shown in Figure 6(a). In contrast, the pseudopotential distribution produced by the RF electrodes with multi-objective function optimisation is continuous and smooth (see Figure 6(b)). Comparing the two single-value contour lines (the black line displays the pseudopotential $\psi = 10$ meV in the figure) confirms that the optimised electrodes are significantly more effective. A large potential barrier is generated by the non-optimised Y-junction, preventing the steady confinement of trapping and shuttling ions in the shuttling path. However, a pseudopotential transport tube is achieved through optimisation with the multi-objective function, enabling ion shuttling with a low heating rate.

The implications of the study are that the method of optimisation described in this paper can be used as a general method for designing any simple or complex traps. The surface ion trap system is a promising candidate for scalable quantum information processing and quantum simulation, and our aim is to promote the realisation of an ion system using a multi-function trap design.

### 4. Conclusion

We have studied the design of a multi-functional surface ion trap by optimising the geometrical
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Figure 5. Results of the hybrid multi-objective optimisation for the Y-junction (red and blue lines denote non-optimised and optimised results). (a) Fluctuation of trapped height. (b) Pseudopotential barrier of the naive and processing Y-junction. (c) Derivative of the pseudopotential barrier in (b). (d) Scale (y direction) of the RF pseudopotential tube at 10 meV from the nodal line.

Figure 6. Pseudopotential distribution over the Y-junction. (a) and (b) are contour maps of the pseudopotential distribution generated by pre-optimisation and the optimised Y-junction. The black solid line denotes a pseudopotential with a single value of 10 meV.

structure of the RF electrodes in a seven-wire trap, five-wire trap, and a junction for different functional zones. A novel configuration of the seven-wire trap enables the generation of double traps with innately rotating principle axes for effective cooling of ions. Our proposed method can be used in large-scale systems because a pair of ion trains is trapped at a distance of 200 µm. Of course, the distance of double traps can be adjusted using controlling the balance of the RF voltages applied to RF_{Centre} and RF_{Side} electrodes. An standard FW trap for loading ions effectively isolates the pollution in the manipulation zone from the loading process, and a mirror symmetric Y-junction optimised by a multi-objective function is used to transport ions between different zones without significant heating of the ions. Furthermore, the trap can be considered as a mixer of ions, which allows arbitrary mixed ion strings to be ordered in a zone from the two-species ions loaded on the side of double traps. This is expected to be useful in collaborative cooling technology. The trap also can be applied in the beam splitter for electrons in electronic imaging technology. We can also use the trap to fast split ion
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The trap not only solves some technical problems in cooling experiments but also provides an effective way for the expansion of quantum bits. In a linear surface ion trap, ions no longer exist as a single linear chain in the radial x direction \[^{29,30}\] but as multiple ion strings spread over the trapped surface forming a quantum network. In future studies, it is possible to increase the number of RF electrodes, such as in interdigital electrodes \[^{47}\], to produce many parallel ion strings covering the trap surface. There will be some interaction between the different ion trains with a radial frequency in the axial direction. By controlling the distance between the ion strings, it is possible to store and exchange information, as well as apply quantum logic control between adjacent ion strings. The results of this study provide additional theoretical concepts and breakthrough experiments for quantum computation, precision measurements, and quantum metrology.

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