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Ion trapping for quantum information processing

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Abstract In this paper we have reviewed the recent progresses on the ion trapping for quantum information processing and quantum computation. We have first discussed the basic principle of quantum information theory and then focused on ion trapping for quantum information processing. Many variations, especially the techniques of ion chips, have been investigated since the original ion trap quantum computation scheme was proposed. Full two-dimensional control of multiple ions on an ion chip is promising for the realization of scalable ion trap quantum computation and the implementation of quantum networks.

Keywords ion trapping, ion chip, quantum information processing, quantum computation

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1 Introduction

Quantum information processing (QIP) is a rising and vigorous field with the combination of information theory and quantum mechanics which has capabilities that exceed those of the classical information processing. It plays a fundamental role in the science of physics quite recently dating from its development in mid-20th century. The theory of quantum information has led to some profound insights into the natural world, such as quantum computation, quantum cryptography, quantum teleportation, etc. Its final intention is to build a universal quantum computer (QC) which is beyond the capability of any possible classical computer.

In this paper, we will review the development of the

quantum information processing. The first deep insight into quantum information theory came with Bell's 1964 analysis of the paradoxical thought (experiment proposed by EPR in 1935). The next connection between quantum mechanics and information theory came about when it was realized that simple properties of quantum systems, such as the unavoidable disturbance involved in measurement, could be put to practical use in quantum cryptography, of which the most firmly established is quantum key distribution. The quantum information was undergoing quiet advancement when quantum cryptography was being analysed and demonstrated. In 1985 an important step was taken by Deutsch, whose proposal is widely considered to represent the first blueprint for a quantum computer. Deutsch's system is virtually a line of 2-state system, and looks more like a register machine than a Turing machine. Deutsch's simple operations are now called quantum gates, since they play a role analogous to that of binary logic gates in classical computers. In the early 1990s several authors sought computational tasks which would be solved by a QC more efficiently than any classical computer. In 1994 Shor demonstrated two enormously important problems, including finding the prime factors of an integer, and the discrete logarithm problem. Shor's results are a strong indication that a quantum computer is more powerful than any Turing machine. Further evidence for the power of quantum computers came in 1995 when Grover showed that the problem of conducting a search through some unstructured search space could also be sped up. The widespread applicability of search-based methodologies has excited considerable interest in Grover's algorithm, which has been extended and applied to database searches and cryptography. A quantum computer can be made much less sensitive to noise by means of a new idea which comes directly from the combination of quantum mechanics and classical information theory, namely quantum error correction (QEC), it was in 1996 that two important papers, of Calderbank and Shor, and independently Steane, established

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a general framework whereby quantum information processing can be used to combat a very wide class of noise processes in a properly designed quantum system. Much progress has since been made in generalizing these ideas. An important development was the demonstration by Shor and Kitaev in 1996 that correction can be achieved even when the corrective operations were themselves imperfect. The only way to resolve the issue of feasibility in QC science is to build a QC. In 1995 Cirac and Zoller proposed the use of a linear ion trap, which was a significant improvement in feasibility, since heroic efforts in the ion-trapping community had already achieved the necessary precision and low temperature in experimental work, especially the group of Wineland who demonstrated cooling of ions to the ground state of the trapping potential in the same year. Several authors, including Gershenfeld and Chuang and Cory *et al.* in 1997, have shown that nuclear magnetic resonance (NMR) techniques can be adapted to fulfill the requirements of quantum computation, making this approach also very promising.

There are some features of quantum information processing different from classical one. First, the unit of quantum information is the quantum bit, or qubit. Classical bits can take either value 0 or 1, while qubits can be in a linear superposition of the two classical bits. That is, if we denote the classical bits by $|0\rangle$ and $|1\rangle$, a qubit can be in any state $\alpha|0\rangle + \beta|1\rangle$, where α and β are complex numbers called amplitudes subject to $|\alpha|^2 + |\beta|^2 = 1$. Any attempt at measuring qubits induces an irreversible disturbance. Unlike classical bits, where a single string of n zeros and ones suffices to describe the state of n bits, a quantum physical system of n qubits requires 2^n complex numbers to describe its state. Second, because of the quantum entanglement, many n -qubit states can be written in factored form and thus require only $2n$ numbers for their description, which is much less than the 2^n numbers generally required [1]. Computers that thrive on entangled quantum information could run exponentially faster than classical computers because n qubits require 2^n numbers for their description. Some simple operations on these qubits can affect all 2^n numbers through the use of quantum parallelism and quantum interference.

Implementation of quantum computers must satisfy the following constraints [2]: (1) the qubits must interact weakly with the environment, (2) the qubits must interact very strongly with another to make logic gates and transfer information, (3) the states of the qubits must be able to be initialized and read out efficiently. We need a set of quantum gates to perform any unitary evolution operation that can be realized on the quantum system. It has been shown that any unitary evolution can be decomposed into a sequence of

single qubit rotations and two-qubit controlled-NOT (CNOT) gates [3]. There are several proposed physical systems appropriate for the realization of a quantum computer, such as the simple harmonic oscillator, photons and nonlinear optical media, cavity quantum electrodynamics devices, trapped ions and nuclear magnetic resonance with molecules. There are also some other physical systems-quantum dots, superconducting gates, and spins in semiconductors-which are also of interest to this field. However, we will concentrate on the ion trapping scheme in this paper, since it appears to be the most promising at present.

There are two basic types of devices which can confine charged particles to well defined regions of free space: the Penning trap and the Paul trap. The Penning trap, which was primarily developed by Hans Dehmelt in 1967 at the University of Washington in Seattle, used a strong magnetic field and a static electric field to create a nearly perfect three-dimensional harmonic trapping potential. Although the Penning trap nicely solves the fundamental problems of ion confinement, so far they have not been used for quantum computation. The trap's strong magnetic field causes ions to move rapidly in a circle, whereas the physical qubits need to have as little motion as possible. The favored trap of ions for quantum computation is the Paul trap [4], in which there is no magnetic field to confine the ions, instead, a spatially varying time-dependent field is used, typically in the radio-frequency (RF) domain. This device was invented by Wolfgang Paul in the University of Bonn in Germany, who shared the 1989 Nobel Prize in physics with Dehmelt. Paul's original idea was to trap charged particles in two- or three-dimensional quadrupole fields. Furthermore, the two-dimensional quadrupole mass spectrometer or mass filter evolved to the typical linear RF Paul trap, which inspired Cirac and Zoller to put forward the first scheme of quantum computer with linearly trapped ions to implement quantum information processing in 1995 [5]. Cirac and Zoller's idea requires a linear string of ions in a single trapping potential, where the ions' internal electronic energy levels represent the qubit logic states, and the mutual Coulomb interaction facilitates the transfer of quantum information between the ions. By addressing individual ions with sharply defined laser beams, one can initialize the computer, control the qubit states during the operation of logic gates, and read out the results at the end of the computation. Since then many building blocks of quantum computing have been experimentally demonstrated [6–21], and different theoretical schemes have been proposed [22–25].

In the following sections we would briefly survey some aspects of the field of ion trapping for the quantum information processing and quantum computation. In Section 2 the basic

theory of ion trapping QIP is described. In Section 3, several typical architectures of the ion trap are described along with their progresses for ion trapping QIP. And finally, a summary and an outlook are given in Section 4.

2 Theory of quantum information processing with trapped ions

2.1 Cirac and Zoller's ion trapping QC

In Cirac and Zoller's scheme [5], ions confined in a linear Paul trap are laser-cooled and form a stable spatial array whose motion is described by normal modes. Two internal levels in each ion form a qubit. Typically, the spacing between ions ($> 1 \mu\text{m}$) is large enough that the direct coupling of internal states of two ions is negligible, thereby precluding logic gates based on internal-state interactions. It suggested that the ground and first excited states of a particular motional mode for the ions cooled to their motional ground state are used as a qubit. The motional mode can act as a data bus to transfer information between ions by first mapping the spin qubit state of a particular ion onto the selected motion qubit by the use of a laser beam focused onto that ion. Being able to perform logic gates between the motion qubit and another selected spin qubit, coupled with the ability to perform single spin qubit rotations, provides the basis for universal QC [3, 26–28]. The ion-trapping scheme satisfies the main requirements for a QC as outlined by DiVincenzo [29]: (1) a scalable system of well-defined qubits, (2) a method to reliably initialize the quantum system, (3) long coherence times, (4) the existence of universal gates, and (5) an efficient measurement scheme. The most important elements of such an ion trapping system were first realized in the laboratory by Monroe *et al.* [30]. Its situation is shown in Fig. 1. N ions were confined in a linear trap, and interact with different laser beams [see Fig. 1(a)] in standing wave configurations [31]. The confinement of the motion along x , y , and z directions was described by an anisotropic harmonic potential of frequencies $\nu_x \ll \nu_y, \nu_z$. The heart of the proposal was the implementation of a two-qubit gate between two (or more) arbitrary ions in the trap by exciting the collective quantized motion of the ions with lasers [32]. For this the collective phonon modes were assumed to be cooled initially to the ground state [33]. The qubits are represented by the long-lived internal states of the ions, with $|g\rangle_j = |0\rangle_j$ the ground state, and $|e_0\rangle_j = |1\rangle_j$ the excited state ($j = 1, \dots, N$). Single qubit rotations could be performed by tuning a laser on resonance with the internal transition ($\Delta_j = 0$) with polarization $q = 0$, $|g\rangle_j \rightarrow |e_0\rangle_j$. In

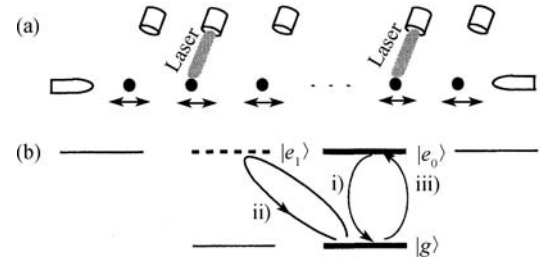


Fig. 1 (a) N ions in a linear trap interacting with N different laser beams; (b) atomic level scheme. (Schematic diagrams from Ref. [5], copyright of The American Physical Society.)

an interaction picture the corresponding Hamiltonian is

$$\hat{H}_j = \frac{\Omega}{2} [|e_0\rangle_j \langle g| e^{-i\phi} + |g\rangle_j \langle e_0| e^{i\phi}] \quad (1)$$

Here Ω is the Rabi frequency, ϕ is the laser phase. For an interaction time $t = k\pi/\Omega$ (i.e., using a $k\pi$ pulse, k is the laser wave vector), the process is described by the following unitary evolution operator:

$$\hat{U}_j^k(\phi) = \exp \left[-i \frac{k\pi}{2} (|e_0\rangle_j \langle g| e^{-i\phi} + h.c.) \right] \quad (2)$$

so a Rabi rotation can be achieved:

$$\begin{aligned} |g\rangle_j &\rightarrow |g\rangle_j \cos(k\pi/2) - |e_0\rangle_j i e^{i\phi} \sin(k\pi/2) \\ |e_0\rangle_j &\rightarrow |e_0\rangle_j \cos(k\pi/2) - |g\rangle_j i e^{-i\phi} \sin(k\pi/2) \end{aligned} \quad (3)$$

As for the problem of N ions, let $\hat{H}_0$ be the Hamiltonian for the system in the absence of any laser field. The ion chain supports N longitudinal modes, of which the center of mass (CM) mode, $\nu_1 = \nu$, is energetically separated from the rest, $\nu_k \geq \sqrt{3}\nu$ ($k > 1$). If the laser addressing the j -th ion is tuned to the lower motional sideband of the CM mode, in the interaction picture the Hamiltonian defined by the operator $\exp(-i\hat{H}_0 t)$ is ($\hbar = 1$)

$$\hat{H}_{j,q} = \frac{\eta}{\sqrt{N}} \frac{\Omega}{2} [|e_q\rangle_j \langle g| a e^{-i\phi} + |g\rangle_j \langle e_q| a^\dagger e^{-i\phi}] \quad (4)$$

Here $a^\dagger$ and a are the creation and annihilation operators of the CM phonons, respectively, η is the Lamb-Dicke parameter. The subscript $q = 0, 1$ refers to the transition excited by the laser, which depends on the laser polarization [see Fig. 1(b)].

If the laser beam is on for the time $[t = k\pi/(\Omega\eta)/\sqrt{N}]$ (i.e., using a $k\pi$ pulse), the evolution will be described by the unitary operator:

$$\hat{U}_j^{k,q}(\phi) = \exp \left[-i \frac{k\pi}{2} (|e_q\rangle_j \langle g| a e^{-i\phi} + h.c.) \right] \quad (5)$$

It is easy to prove that this transformation keeps the state $|g\rangle_j |0\rangle$ unaltered, whereas

$$\begin{aligned}
|g\rangle_j|1\rangle &\longrightarrow |g\rangle_j|1\rangle \cos(k\pi/2) - |e_q\rangle_j|0\rangle i e^{i\phi} \sin(k\pi/2) \\
|e\rangle_j|0\rangle &\longrightarrow |e_q\rangle_j|0\rangle \cos(k\pi/2) - |g\rangle_j|1\rangle i e^{i\phi} \sin(k\pi/2)
\end{aligned}
\quad (6)$$

where $|0\rangle$ ($|1\rangle$) denotes a state of the CM mode with no (one) phonon. It follows the three-step process [see Fig. 1(b)]: (1) A π laser pulse with polarization $q = 0$ and $\phi = 0$ excites the m -th ion. The evolution corresponding to this step is given by $\hat{U}_m^{1,0} \equiv \hat{U}_m^{1,0}(0)$. (2) The laser directed on the n -th ion is then turned on for a time of 2π pulse with polarization $q = 1$ and $\phi = 0$. The corresponding evolution operator $\hat{U}_n^{2,1}$ changes the sign of the state $|g\rangle_n|1\rangle$ (without affecting the others) via a rotation through the auxiliary state $|e_1\rangle_n|0\rangle$. (3) Same as (1). Therefore the unitary operation for the whole process is $\hat{U}_{m,n} \equiv \hat{U}_m^{1,0} \hat{U}_n^{2,1} \hat{U}_m^{1,0}$ which is represented diagrammatically as follows:

$$\begin{array}{ccccc}
& \hat{U}_m^{1,0} & & \hat{U}_n^{2,1} & \\
|g\rangle_m|g\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|g\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|g\rangle_n|0\rangle \\
|g\rangle_m|e_0\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|e_0\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|e_0\rangle_n|0\rangle \\
|r_0\rangle_m|g\rangle_n|0\rangle & \longrightarrow & -i|g\rangle_m|g\rangle_n|1\rangle & \longrightarrow & i|g\rangle_m|g\rangle_n|1\rangle \\
|e_0\rangle_m|e_0\rangle_n|0\rangle & \longrightarrow & -i|g\rangle_m|e_0\rangle_n|1\rangle & \longrightarrow & -i|g\rangle_m|r_0\rangle_n|1\rangle
\end{array}$$

$$\begin{array}{l}
\hat{U}_m^{1,0} \\
\longrightarrow |g\rangle_m|g\rangle_n|0\rangle \\
\longrightarrow |g\rangle_m|e_0\rangle_n|0\rangle \\
\longrightarrow |e_0\rangle_m|g\rangle_n|0\rangle \\
\longrightarrow -|e_0\rangle_m|e_0\rangle_n|0\rangle
\end{array}
\quad (7)$$

The effect of this interaction is to change the sign of the state only when both ions are initially excited. Note that the state of the CM mode is restored to the vacuum state $|0\rangle$ after the process. Eq. (7) is phase gate $|\epsilon_1\rangle|\epsilon_2\rangle \rightarrow (-1)^{\epsilon_1\epsilon_2}|\epsilon_1\rangle|\epsilon_2\rangle$ ($\epsilon_{1,2} = 0, 1$) which together with single qubit rotations becomes equivalent to a controlled-NOT gate.

2.2 Ponderomotive potential of the Paul ion traps

The RF Paul ion trap is the time average behavior of inhomogeneous oscillating electric fields [34]. Consider a charged particle moving in one dimension in an oscillating electric field of the form

$$E(z) = E_0(z) \cos \Omega_T t \quad (8)$$

where $E_0(z)$ is the spatial dependence of the electric field. Consider the case in which the electric field is non-uniform so the $\partial E_0(z)/\partial z \neq 0$. The equation of motion for an ion of

charge e and mass m is

$$m\ddot{z} = Fz(t) = eE(z) \quad (9)$$

A solution for small oscillations about some average position of the ion $\bar{z}$ is desired such that the position is $z(t) = \bar{z} + \zeta(t)$. Thus the small perturbation as a function of time is

$$\zeta(t) = -\zeta(0) \cos \Omega_T t \quad (10)$$

with amplitude $\zeta(0) = eE_0(z)/(m\Omega_T^2)$. Keeping only the first order, the electric field is

$$E_0(z) \approx E_0(\bar{z}) + \left[\frac{\partial E_0(\bar{z})}{\partial \bar{z}} \right] \zeta(t) \quad (11)$$

Here it is assumed that the amplitude of the motion is small compared to the characteristic size of the electric field inhomogeneity, and higher order terms are neglected. Averaging the force on the ion over one period, one gets

$$\begin{aligned}
\bar{F}(\bar{z}) &= e \langle E_0(z) \cos \Omega_T t + \left[\frac{\partial E_0(\bar{z})}{\partial \bar{z}} \right] \zeta' \cos \Omega_T t \rangle \\
&= e \left[\frac{\partial E_0(\bar{z})}{\partial \bar{z}} \right] \langle \zeta' \cos \Omega_T t \rangle
\end{aligned}
\quad (12)$$

A good approximation gives

$$\langle \zeta' \cos \Omega_T t \rangle = -\frac{1}{2} \zeta_0 = -\frac{eE_0(\bar{z})}{2m\Omega_T^2} \quad (13)$$

Thus the average force on the ion is

$$\bar{F}(\bar{z}) = -\frac{e^2 [\partial E_0(\bar{z})/\partial \bar{z}] E_0(\bar{z})}{2m\Omega_T^2} \quad (14)$$

This can be rewritten as a function of a pseudopotential $\psi(z) \equiv eE_0^2(z)/(4m\Omega_T^2)$ which represents the time-average potential and the average force is

$$\bar{F}(\bar{z}) = -e \frac{\partial \psi(\bar{z})}{\partial \bar{z}} \quad (15)$$

The ion motion is characterized by an oscillation frequency

$$\omega_z = \frac{e}{2m\Omega_T} \left[\frac{\partial^2 E_0(\bar{z})}{\partial \bar{z}^2} \right]^{1/2} \quad (16)$$

It can be generalized to three dimensions so that the average force on an ion near equilibrium $(\bar{x}, \bar{y}, \bar{z})$ is

$$\begin{aligned}
\bar{F}(\bar{x}, \bar{y}, \bar{z}) &= -e \nabla \psi(\bar{x}, \bar{y}, \bar{z}) \\
\nabla \psi(\bar{x}, \bar{y}, \bar{z}) &\equiv [e/(4m\Omega_T^2)] E_0^2(\bar{x}, \bar{y}, \bar{z})
\end{aligned}
\quad (17)$$

If one considers the type of quadrupole fields commonly used in ion trap experiments, the ion motion can be described

in the form of the Mathieu equations whose solutions are well-known [36].

3 Ion trapping: experiments and schemes

Since the original Cirac and Zoller's scheme, the first demonstration of a fundamental quantum logic gate that operates on prepared quantum gates were realized in the laboratory by Monroe *et al.* [30]. Experimental realization of a quantum computer requires isolated quantum systems that acts as the qubits, and the presence of controlled unitary interactions between the qubits that allow construction of the CNOT gate. Because of the most promising features of the ion trap systems for quantum information processing [35–37], many laboratories have established ion trapping experimental apparatuses, such as experiments carried out at the NIST group, the Innsbruck group, the Oxford group, the Michigan group and the MIT group. Since the ion trap scheme is scalable to build large-scale quantum computers, several variations of the standard linear RF Paul trap such as layered ion traps and surface-electrode ion chips have been proposed for the ion shuttling or two-dimensional movement. In this section we would describe and discuss several typical experimental architectures of ion trapping for QIP.

3.1 Linear RF Paul traps

Generally, qubits are implemented by using two energy levels of a single trapped ion. Quantum registers need rows of such ions that are interacting in a controlled way. This can be realized by using so-called linear Paul traps as shown in Fig. 2. Such a trap device is derived from the Paul mass filter which employed four hyperbolic electrodes and RF-voltages to transmit an ion beam in a mass-selective way. For a trap, the basic structure is an arrangement of four rods applying RF-voltages for radial confinement and two ring electrodes applying dc-voltages for axial confinement. Many variations on this structure are possible [58–65]. During the last few years, in particular the experiments of the NIST and Innsbruck groups have proved the feasibility of quantum information processing by using different approaches. While the Innsbruck experiments follow closely the original Cirac-Zoller proposal and use optical transitions with individual addressing in Ca^+ ions, the NIST experiments use Be^+ ions where the qubits are encoded in hyperfine states and coherent manipulation is achieved by using further gate proposals implemented by Raman-transitions. In the NIST experiments individual addressing is achieved by separating ions from the

string using control voltages. Although quite different experimentally, both experiments have implemented quantum information processing quite successfully and are very similar conceptually. Here we will present the Innsbruck Ca^+ experiment for discussion, which uses flat rod electrodes as shown in Fig. 3 [7–9]. After laser cooling, ions are confined along the longitudinal axis and form a string in the center of the four rods. The distance between neighboring ions slightly varies along the string because the ions all lie in a parabolic well and also repel one another. The result is that the repulsive forces from the outer ions squeeze the inner ones closer together. Such an ion string provides a register with the quantum information stored in the electronic states of the individual ions. The distance between neighboring ions can be adjusted by means of the dc voltages. Each ion can be manipulated individually with a focussed laser beam, and thus single-qubit operations are possible. Furthermore, CNOT-gate operations between any two qubits are realized to build a universal quantum computer.

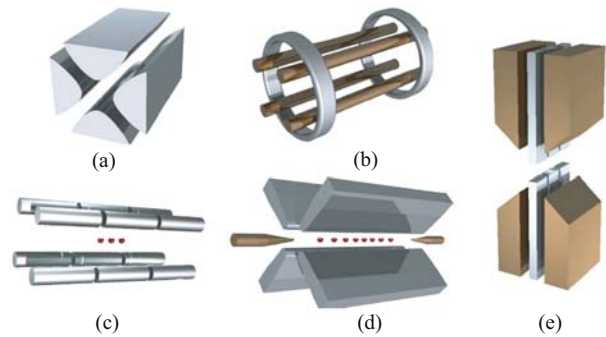


Fig. 2 Several proposed linear ion traps. (Schematic diagrams from Ref. [41], copyright of European Communities.)

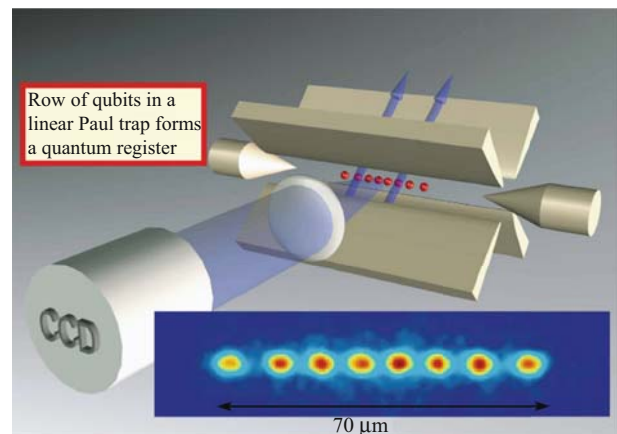


Fig. 3 Innsbruck group's setup of linear ion trap. (Schematic diagrams from Ref. [41], copyright of European Communities.)

Aside from these designs of separate electrodes, there are

also several layered-electrode geometries generate a string of trapped ions. They may be deeper and less sensitive to electric-field noise from correlated potentials on the electrodes.

3.2 Ion trapping in a layered chip

A quantum computer is a device that prepares and manipulates quantum states in a controlled way. The power of quantum computing derives from its scaling properties that when the size of these problems grows, the resources required to solve them grow in a manageable way. So a useful quantum computing technology must allow control of large quantum systems, composed of thousands or millions of qubits. All the elementary requirements for quantum computation [29], which include efficient quantum state preparation [60, 66, 67], manipulation [30, 38, 67, 68] and read-out [67, 69, 70], have been demonstrated in the original Cirac and Zoller's system. But manipulating a large number of ions in a single trap presents immense technical difficulties, and scaling arguments suggest that this scheme is limited to computations on tens of ions [36, 71–73], and current experiments have been performed with only a few qubits at most [56, 57]. The scaling up of devices to contain large numbers of qubits remains a significant challenge. The original proposal for QIP with trapped ions requires a linear string of ions in a single trapping potential, where the ions internal electronic energy levels represent the qubit logic states, and the mutual Coulomb interaction facilitates the transfer of quantum information between the ions. The technical challenges associated with manipulating a large number of ions in a single trap are considerable, hence an alternative architecture based on an array of many interconnected ion traps has been proposed as a processor for a large number of qubits 10. Such a device would contain distinct logic and memory zones for processing and storing qubits respectively, and would shuttle ions between the zones. In one possible implementation [10, 36] whose schematic diagram is shown in Fig. 4, ion qubits are held in separate trapping regions and moved around at will, so the selected ions could be brought into mutual proximity for the application of quantum gates and separated again. Ions to be used in a particular gate operation would be moved from the memory zones to processor zones. Quantum gates could be performed on a few ions in such a processor zone by means of entanglement of the motional modes of these ions with their internal qubit states as described in Refs. [5, 28, 39]. Single bit operations can be performed on ions that have been moved separately into such a trapping region. For both single- and multi-qubit operations, individual addressing of the ions through

tightly-focused laser beam would not be required [10]. So highly parallel processing is possible, and separate regions of the array may be used for readout of qubits during a computation so that the effect of scattered light from this process on memory ions will be minimized. The ions have to be sympathetically cooled after transport [10, 36, 74–76] and before additional entangling operations, for rapid ion transportation through and ion separation in such an array would lead to heating of the motional modes [77]. It implies that in a physical architecture where there are many distinct but interconnected trapping regions, the separation, transportation, and recombination of ions must be controlled by means of time-varying potentials on control electrodes linking these trapping regions.

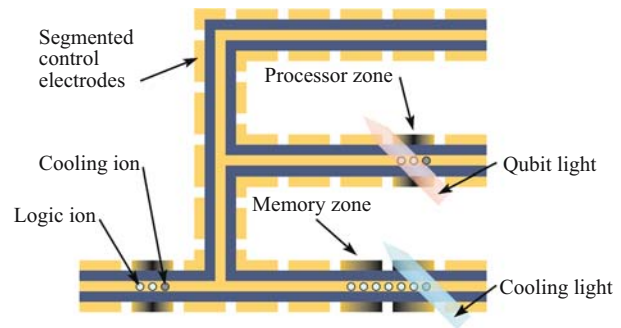


Fig. 4 Schematic diagram of proposed large-scale ion trap array for quantum information processing. Segmented control electrodes allow logic ions (lighter-colored circles) to be transferred to and from “memory” and “processor” regions. After transport, ions are sympathetically re-cooled by means of cooling ions (darker-colored circles). The laser light used for qubit operations has a frequency different from that used for sympathetic cooling to minimize decoherence of the qubit ions by the cooling light. Dark-colored electrodes are RF electrodes, and light-colored control electrodes are held at RF ground. (Schematic diagrams from Ref. [16], copyright of Rinton Press.)

A quantum charge-coupled device (QCCD) architecture (see Fig. 5) has been proposed by MIT group [10]. It consists a large number of interconnected ion traps. By changing the operating voltages of these traps, they could confine a few ions in each trap or shuttle ions from trap to trap. Trapped ions storing quantum information are held in the memory region. To perform a logic gate, the relevant ions are moved into an interaction region by applying appropriate voltages to the electrode segments. In the interaction region, the ions are held close together, enabling the Coulomb coupling necessary for entangling gates [5, 78]. Lasers are focused through the interaction region to drive gates. Then the ions are moved again to prepare for the next operation. The trapping and transport potentials needed for the QCCD are realized by using a combination of RF and quasi-static electric fields. Figure 5 shows

only the electrodes that support the quasi-static fields. The ions are confined in particular regions or transported along the local trap axis by varying the voltages on these electrodes. The other two layers of electrodes applying RF voltages lie above and below the static electrodes as shown in Fig. 6. They create a quadrupole field that confines the ions transverse to the local trap axis by means of the ponderomotive force [4]. This geometry allows stable transport of the ions around T and X junctions, so complex, multiply connected trap structures could be built.

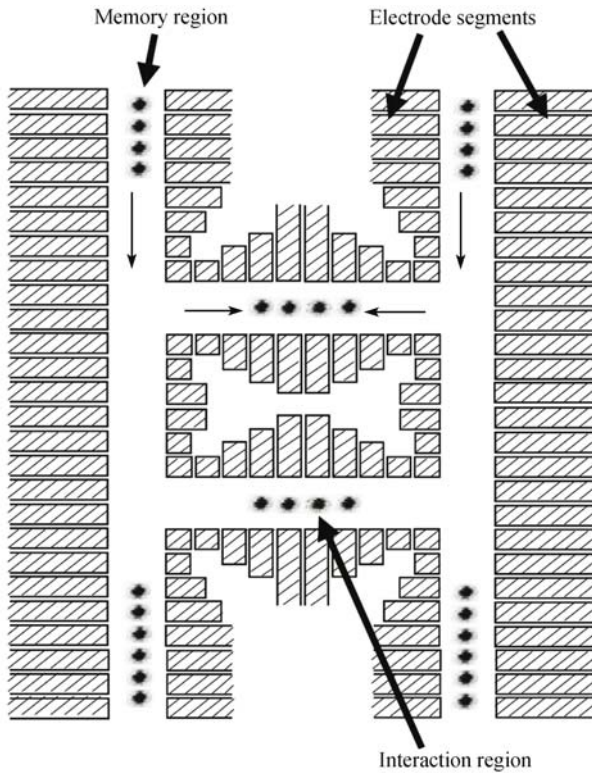


Fig. 5 Diagram of the QCCD. Ions are stored in the memory region and moved to the interaction region for logic operations. Thin arrows show transport and confinement along the local trap axis. (Schematic diagrams from Ref. [10], copyright of Nature Publishing Group.)

The Michigan group has demonstrated a T-junction ion trap array for two-dimensional ion shuttling, storage, and manipulation (see Fig. 7) [19]. The trap geometry consists of two linear RF-ion trap sections that are jointed at a 90° angle to form a T-shaped structure. The geometry is symmetric three-layered and allows confinement throughout the junction region. The middle layer carries the RF potential, and identical segmented outlayers carry control quasi-static voltages that are used to confine the ion along the axial dimensions of the trap sections. Figure 7 shows the top view and cross section of the trap used in the experiments. The trap is fabricated by

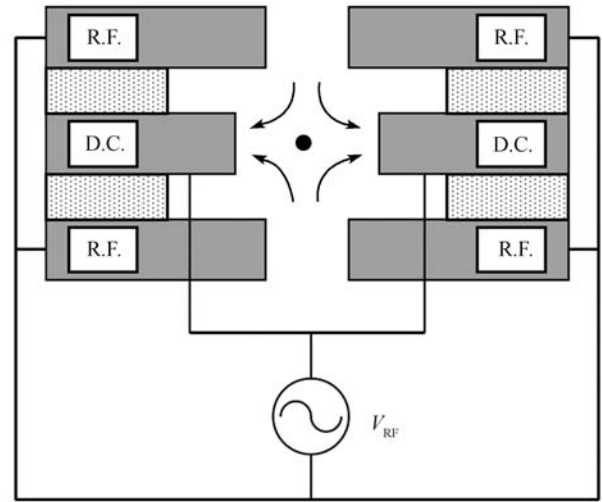


Fig. 6 Configuration of RF and DC electrodes for the QCCD. Dotted regions indicate insulating spacers. Applying high RF voltage to the two outer electrode layers while keeping the inner layer at RF ground creates the RF quadrupole field shown by the arrows. This field provides trapping potentials for confinement transverse to the local trap axis, which points perpendicular to the page and is located at the central black dot. (Schematic diagrams from Ref. [10], copyright of Nature Publishing Group.)

using thin laser machined polished alumina substrates similar to what has been used in previous one-dimensional linear trap [49, 52–54, 77, 79] and is shown in Fig. 8. Ions can be confined in any of the 11 trapping zones labelled by letters *a–k* in Fig. 7. Ovens containing cadmium oxide are heated to produce a vapor of cadmium in the trapping region with an estimated partial pressure of under 10^{-11} Torr. Cadmium ions are loaded by photoionizing the background vapor with a pulsed laser which is tuned near the atomic cadmium $^1S_0 \rightarrow ^1P_1$ transition at 228.8 nm. Storage lifetimes of several hours are typical. The trapped ions are laser cooled with a continuous-wave laser tuned near the $\text{Cd}^+ ^2S_{1/2} \rightarrow ^2P_{3/2}$ transition at 214.5 nm. The cooling laser is detuned several linewidths red of resonance with about 1 mW of power focused down to a $\sim 15 \mu\text{m}$ waist. The ion is imaged with a charge coupled device camera to a nearly diffraction limited spot with $f/2.1$ optics. An RF amplitude of $V_0 \approx 360 \text{ V}$ at $\Omega_T/2\pi = 48 \text{ MHz}$ is applied to the central layer electrode, resulting in a transverse ponderomotive secular frequency $\omega_{\text{RF}}/2\pi \sim 5.0 \text{ MHz}$ for the trapping zones *a, b, c, j, k, g, and h*. Figure 9 shows voltages applied to the electrodes carrying control voltages in order to shuttle the ions around the corner from trapping zone *d* to *i*. The two-dimensional control of multiple ions in this system could allow an efficient method for entangling arbitrarily positioned ions, with

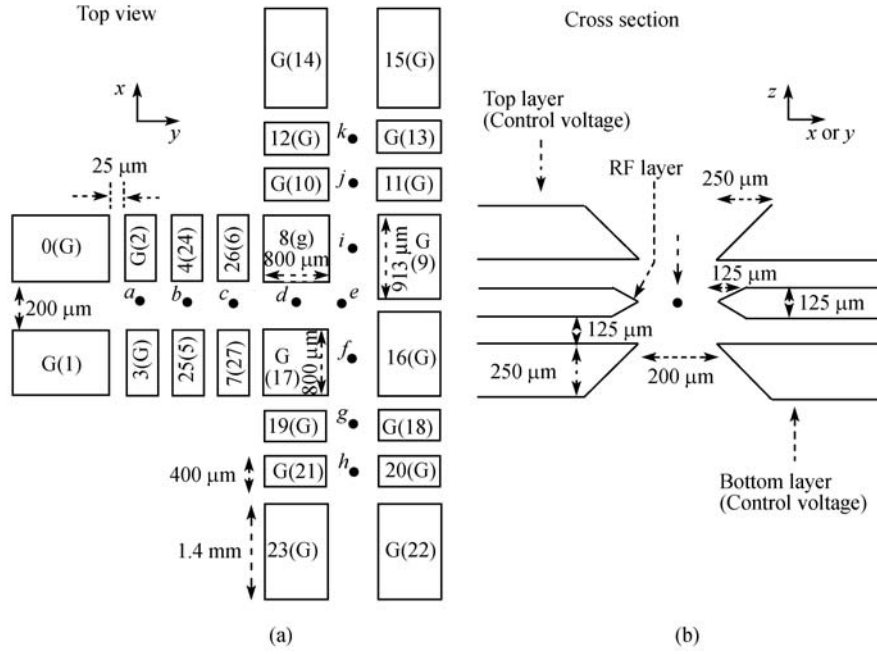


Fig. 7 Top view and cross-section of two-dimensional trapping array. Dots depict the location of trapping zones a – k . The outer control electrodes are labeled, with bottom layer electrodes in parentheses. Electrodes labeled by “G” are internally grounded. (Schematic diagrams from Ref. [19], copyright of American Institute of Physics.)

applications to large-scale trapped ion quantum computing.

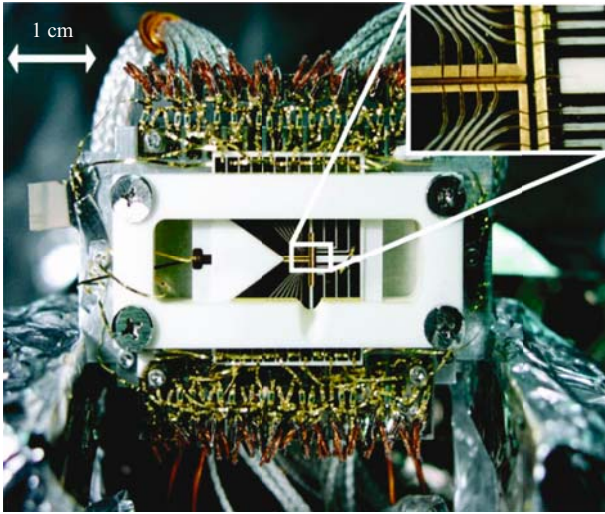


Fig. 8 T-junction trap array. The central layer contains a T-shaped channel; the electrode is formed by depositing gold around the channel with an electron beam evaporator. (Schematic diagrams from Ref. [19], copyright of American Institute of Physics.)

3.3 Surface ion chip

Recently there are many surface-electrode ion trap designs [16, 17, 21, 78] because linear ion trap schemes are

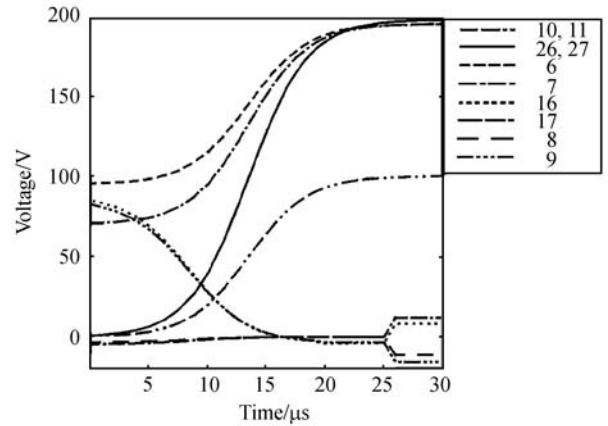


Fig. 9 Control voltage schedule over time applied to the numbered electrodes to shuttle an ion around the corner from trap zone d to trapping zone i . (Schematic diagrams from Ref. [19], copyright of American Institute of Physics.)

somewhat bulky, require considerable time and effort for construction, and are not easily extendable to more complicated layouts that will be necessary for large-scale QIP with trapped ions. Variation of the standard quadrupole geometry electrodes into a plane preserves a quadrupolar field for a wide range of parameters while also providing an avenue to more straightforward fabrication. The most obvious planar deformation is to move one control electrode and one RF electrode into the same plane of the remaining two electrodes, such that

the electrodes are of alternating potential (RF, control, RF, and control). The trap axis remains in approximately the same position, and there is also another trap axis beneath the electrodes symmetrically opposite to this one, but it will typically reside within the substrate. The outer two electrodes could be segmented and different control potentials applied for axial confinement and control. A potential benefit of the planar electrode configuration is that the location and strength of the trapping region may be altered by only varying the electrode structure in one dimension. Through overall scaling of the electrode size and spacing, the distance from the trap axis to the electrodes and substrate may be controlled and changed continuously along the length of the electrodes, in effect creating a trapping region for any desired surface-ion separation distance. Another possible benefit of the surface geometry is that it may facilitate ion separation [49, 77]. Two ions or groups of ions in the same longitudinal trapping region may be separated by raising the potential of an electrode near the center of the trapping region. Though the surface traps suffer from a much shallower trap depth, it is adequate once the ions are cooled and trapped. The NIST group has proposed a scheme as shown in Fig. 10. Such structure is made by means of patterned metal deposition onto an insulating substrate. Photolithography or electron beam lithography can be

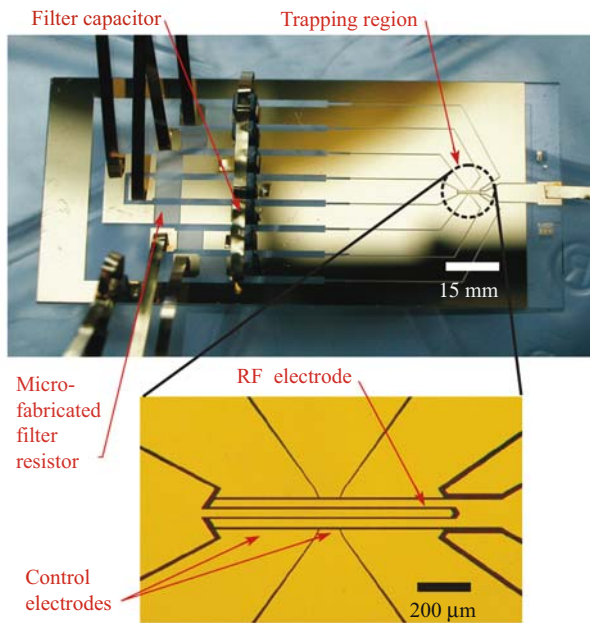


Fig. 10 Micrographs of a five-wire, one-zone linear trap fabricated of gold on fused silica. The top figure is an overview of the trap chip showing contact pads, onboard passive filter elements, leads, and trapping region. Substrate dimensions are 10 mm × 22 mm × 500 μm. The lower image is a detail of the trapping region indicated by the dotted ring in the top figure. The substrate material appears dark-colored in the lower image. (Schematic diagrams from Ref. [16], copyright of Rinton Press.)

utilized to define the electrodes. This method is similar to that used for neutral atom optics and atom guides on chips [81–87]. Calculations suggest that a trap of this construction will be capable of trapping ions approximately 50 μm from the chip surface. Secular frequencies will be in the 10 MHz range for an applied rf potential of amplitude 100 V at 100 MHz. Control electrode potentials of a few volts will lead to axial frequencies in the few megahertz range. The dissipation in the trap can be modeled as a resistor representing the leads in series with the trap capacitance and its equivalent series resistance, which is proportional to the dielectric loss.

The NIST group reported another demonstration of stable confinement of $^{24}\text{Mg}^+$ ions in a microfabricated surface-electrode ion trap [21]. The trap is constructed with standard and scalable microfabrication processes, as shown in Fig. 11, with four flat electrodes placed in a common plane applying alternating RF and control potentials [16]. The electrode structure is fabricated by means of photolithography and metal deposition using evaporation and electrodeposition. The substrate is a polished fused quartz with low RF loss. A 0.030 μm titanium adhesion layer and a 0.100 μm copper seed layer are first evaporatively deposited onto the substrate. This deposition is uniform except for small areas for resistors where the quartz is left exposed. Resistors ($\sim 1 \text{ k}\Omega$) and leads are fabricated through a liftoff process that entails patterning them with standard photolithography and evaporation of a 0.013 μm

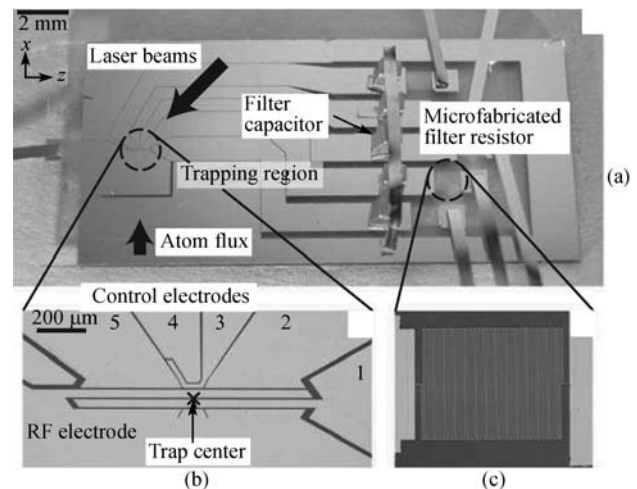


Fig. 11 Pictures of the surface-electrode trap. (a) The complete trap structure, including lead-out wires (ribbons) and filter capacitors. The directions of the laser beams (cooling and photoionization) and atom flux are indicated. (b) Expanded view of the trap region (center marked by ×). The control electrodes are numbered for reference in the text. (c) On-board meander line resistor. (Schematic diagrams from Ref. [21], copyright of The American Physical Society.)

titanium adhesion layer followed by $0.300\ \mu\text{m}$ of gold. Resistors are fabricated directly on the quartz substrate, and leads are fabricated on top of the copper seed layer. The gold electrodes near the trapping region are electroplated onto the copper seed layer after a second photolithographic patterning step. Afterward, the exposed initial seed and adhesion layers are etched away to isolate electrodes and leads. The trap electrodes are plated to a thickness of $\sim 6\ \mu\text{m}$ so that the ratio of height to interelectrode spacing is relatively high. Ions are created in the trap by photoionizing thermally evaporated neutral magnesium atoms. The trap structure is mounted in a copper tube that also serves as part of an RF transformer [88] and the entire structure is surrounded by a quartz envelope. The system is baked under vacuum prior to operation to reach a base pressure below 10^{-8} Pa with the use of an ion getter pump combined with a titanium sublimation pump. Figure 12 shows groups of ions for the $V_{\text{RF}} = 103.2\ \text{V}$ and $V_5 = 2.00\ \text{V}$ configuration. The separation of the ions is related to the CM axial oscillation frequency [36], and the horizontal bars indicate the expected ion separations according to the measurement of this frequency. When the number of ions becomes large enough, the string breaks into a zigzag configuration [89]. This relatively simple trap design and fabrication procedure provide a promising solution to large-scale quantum information processing.

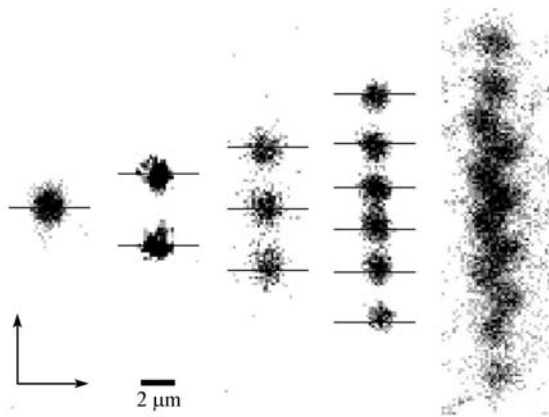


Fig. 12 Images of 1, 2, 3, 6, and 12 ions confined in the surface-electrode trap ($V_{\text{RF}} = 103.2\ \text{V}$ and $V_5 = 2.00\ \text{V}$). The length scale is determined from a separate image of the electrodes whose dimensions are known. The horizontal bars indicate the separation distance between the ions as predicted from the measured axial oscillation frequency. The ratio between transverse and axial oscillation frequencies makes it energetically favorable for the 12 ion string to break into a zigzag shape. (Schematic diagrams from Ref. [21], copyright of The American Physical Society.)

The MIT group has also presented an experiment of planar ion traps using electrodes on a printed circuit board (PCB) to trap linear chains of tens of charged particles with $0.44\ \mu\text{m}$

diameter [17]. They used a trap with 36 zones (77 electrodes) arranged in a cross to demonstrate loading of ions from a traditional four-rod linear Paul trap, linear ion movement, splitting and joining of ion chains, and movement of ions through intersections. Ions were not cooled and imaging was accomplished by classical (off-resonant) scattering of laser light. They optimized the electrode geometry to maximize the trap depth, and demonstrated loading from a conventional four rod linear Paul trap acting as a reservoir of ions. Atomic ions could be laser cooled in the four-rod trap before being transferred to the planar trap to circumvent the problem of low trap depth. The planar trap they investigated is made up of four straight arms jointed at a cross intersection (see Fig. 13). The electrodes are tin-coated copper, and the substrate is GML-1000, a microwave laminate. The trap is a five-electrode design, with outer electrodes segmented to control the axial potential. Connections to these electrodes are made on the bottom layer of the PCB using surface mount headers. Most opposing pairs of control electrodes are electrically connected, but the two pairs nearest the intersection on each arm are electrically independent for finer control. The center electrodes are also segmented at the intersection to provide additional control in that region. The middle three electrodes are all $1.27\ \text{mm}$ wide, the electrode spacing is $0.89\ \text{mm}$, and the outer control electrodes are $2.5\ \text{mm}$ long. Electrospray ionization provides ions to the trap. Figure 14 shows the ion loading scheme, the four-rod trap are interfaced directly to the planar trap by arranging the rods so that they match the strips of a planar trap. A slot cut in the side of the PCB allows one to lower the four-rod trap to a point where its trap axis coincides with that of the planar trap. Mutual repulsion of ions loaded in the far end of the four-rod trap forces them along, eventually pushing them into the planar trap. When completely full, the planar trap could hold ~ 50 ions. A planar trap with a segmented center electrode can be used to control the height of individual ions above the substrate by applying dc voltages to the electrode segments. One advantage of such a control in a quantum computer is the ability to perform single-qubit gates on different ions using a single stationary laser beam. The laser beam would have to be parallel to the ion chain but slightly raised or lowered. By changing the height of individual ions, they can be brought into the path of the beam to perform single-qubit gates. The height of an ion above the trap substrate is measured by using a CCD camera mounted on a calibrated translation stage. Figure 16 shows the average of the positions of the top and bottom of the ion motion as a function of the dc potential on the center electrode. It is clearly seen that the height of ions above substrate is an increasing function of the potential on center elec-

trode. They have also implemented a hexagonal lattice of traps which successfully trapped macroscopic ions. More recently, the MIT group has presented another surface-electrode ion trap realized [80]. They demonstrated the loading of strontium ions into a ~ 1 -mm-scale PCB surface-electrode trap. Following the design of a traditional four-rod linear Paul trap system [90], the trap is mounted in a standard UHV chamber pumped down to $\sim 10^{-9}$ Torr, loaded with $^{88}\text{Sr}^+$ by electron impact ionization of neutral atoms from a resistive oven source, and driven by an externally mounted helical resonator. A controlled buffer gas environment of up to 10^{-4} Torr of ultrapure helium may be provided through a sensitive leak valve, monitored with a Bayard-Alpert ion gauge. Their surface-electrode ion trap has five electrodes [16, 17], including one central grounded electrode, two RF potential electrodes, and two segmented DC electrodes (see Fig. 15). The electrodes are copper deposited on a low-RF-loss substrate (Rogers 4350B), and fabricated by Hughes circuits following standard methods for microwave circuits. In the loading region, slots are milled between rf and dc electrodes to prevent shortening due to strontium buildup. The inner surfaces are plated with copper to minimize trap potential distortion due to the accumulation of stray surface charges. The electrical connections are made to the trap by ultrasonically soldering Kapton-coated Cu wires to the pads using 80/20 Au/Sn solder. There is a top electrode plate mounted 6.3 mm above the trap, which has a slit for ion fluorescence detection and the trap depth can be increased by applying a voltage V_{top} to the plate above the trap that moves the trap minimum away from the RF null. So it can be a useful way to increase micromotion. The first step for loading a surface-electrode trap is the determination of the ideal compensation voltages needed to offset the inherent electrode asymmetry. They determine these potentials numerically by computing the RF and DC potentials ($\phi_{\text{RF}} \cos \Omega t$ and ϕ_{DC}), which give the secular potential $\Phi = Q^2 |\nabla \phi_{\text{RF}}|^2 / (4m\Omega^2) + Q\phi_{\text{DC}}$, where m is the ion mass and Q is the ion charge. Typically, V_{RF} is of 500–1200 V amplitude at $\Omega/(2\pi) = 7.6$ MHz, and dc electrode voltages (as defined in Fig. 15) are $V_4 = V_1 = 0$ V, $V_2 = 110$ V, and $V_3 = -50$ V. With these voltages and $V_{\text{top}} = -25.4$ V applied to the top electrode, the trap should be compensated with a trap depth of 1.0 eV as shown in Fig. 16. The trap depth can be increased to 5.4 eV by setting $V_{\text{top}} = 15$ V, at the cost of increased micromotion. As the stray field can rapidly reduce the trap depth, it required the use of the helium buffer gas to have sufficient signal and lifetimes to measure the field [91, 92]. They used a helium pressure of 10^{-5} Torr. The UHV life time in the absence of helium was less than 10 s. when the field had been compensated, ion lifetimes at

10^{-9} Torr were greater than 10 minutes. Their PCB surface-electrode ion traps allow for the rapid prototyping and testing of different architecture for studying ion motion in surface electrode traps and the loading of ions into microstructured trap arrays.

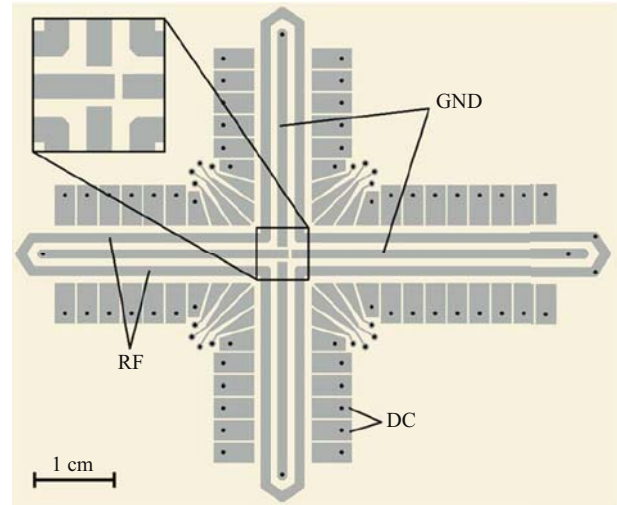


Fig. 13 Top view of the trap. Opposing electrodes in straight sections of the trap are electrically connected, but near the intersection both the outer and center electrodes are separated to provide finer control. Electrical connections are made via surface mount headers on the underside. The RF loop at each end helps prevent ions from leaking out axially. (Schematic diagrams from Ref. [17], copyright of The American Physical Society.)

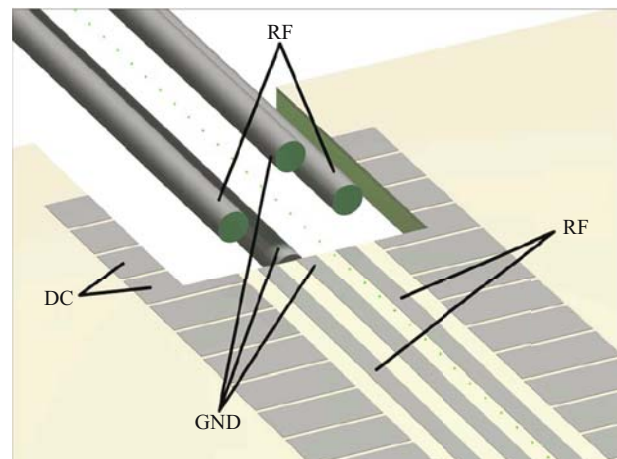


Fig. 14 Four-rod to planar interface. A slot cut in the planar trap allows for a common trap axis. The large particles form a linear Wigner crystal immediately and are pushed into the planar trap. (Schematic diagrams from Ref. [17], copyright of The American Physical Society.)

Our SIOM group also has proposed a novel and simple design of surface ion chip for scalable quantum information processing [93, 94]. One surface planar ion trap scheme proposal

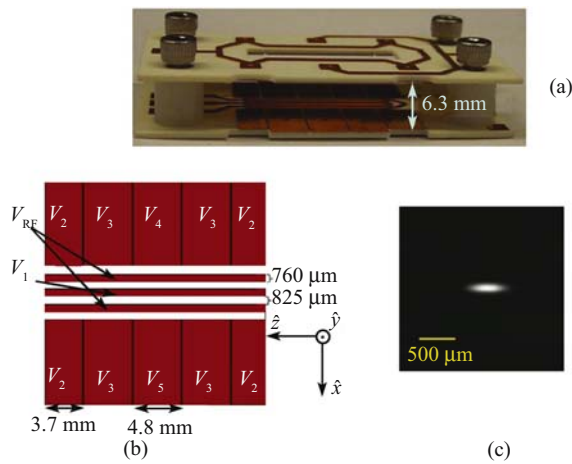


Fig. 15 (a) Photograph showing the top electrode plate mounted 6.3 mm above the trap. The top plate has a slit for ion fluorescence detection. (b) Layout of trap electrodes, each labeled with the voltage applied; all but V_{RF} are DC. The space around the long electrodes (V_{RF} and V_1) has been milled out. Coordinates referenced as shown define the origin at the trap center and on the chip surface. (c) Charge-coupled device image of trapped strontium ions. (Schematic diagrams from Ref. [80], copyright of The American Physical Society.)

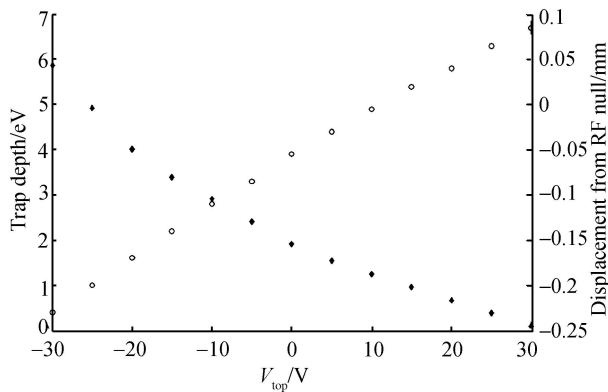


Fig. 16 Calculated values of trap depth (hollow circles) and ion displacement from the rf null (solid diamonds) as V_{top} is varied. As trap depth is increased, the displacement of the ion cloud from the RF null leads to increased micromotion. (Schematic diagrams from Ref. [79], copyright of The American Physical Society.)

is shown in Fig. 17 which consists of four parallel charged segmented rods on the two surfaces of an insulating chip made of silicon [93]. Its scale is of 1 μm magnitude. The two top rods are driven by an rf potential $V_0 \cos \Omega t$, while the other two bottom rods are driven by the opposite RF potential $-V_0 \cos \Omega t$, as shown in the endview of the electrodes in Fig. 17(b). The static voltage is applied to the end segments of the rods to provide axial confinement along the longitudinal direction. The central four segments are at static ground potential, the top four end segments are at a static positive

voltage U_0 and the bottom four segments are at a static negative voltage $-U_0$. This design could generate two traps above and below the chip, respectively [see Fig. 17(a)]. The benefit of the configuration is that the location and strength of the trapping region can be altered by only varying the scale of the trap. Since it has two trap regions, we could put forth one feasible scheme to control the trapped ions. That is, one can add two flat wires to one end side face of the chip to change the axial confinement of the trapped ions, then by controlling suitable static voltages to the end and side electrodes, the trapped ions could be transferred from the top trap to the bottom trap.

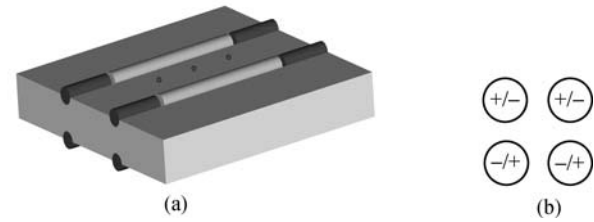


Fig. 17 (a) Schematic diagram for surface planar ion trap; (b) Endview of the electrodes.

The SIOM group also proposed another scheme of a two dimensional ion chip as shown in Fig. 18. We used a grounded metal plate at the bottom side of the substrate instead of two electrodes, similar to the idea in Ref. [95] to simplify the design. All of the parallel electrodes are driven by an rf potential $V_0 \cos \Omega t$, and the shorter end segments are biased at a static potential U_0 ($U_0 > 0$ to trap positive ions) and the longer central are at zero static potential. Its scale is of 10 μm magnitude. The simulated radial electric field contours are shown in Fig. 19. It is clearly seen that the trap axes are above the surface of the chip and at the center of two adjacent electrodes, thus a two-dimensional trap array is achieved. It's easy to expand the trap dimensions by increasing the elec-

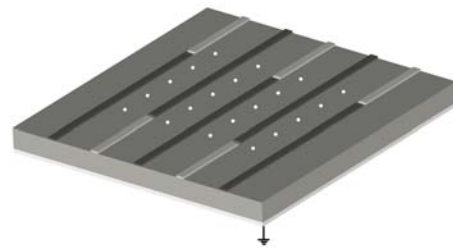


Fig. 18 A three-dimensional drawing of the two-dimensional ion trap array. Five segmented thin flat electrodes are on an insulating substrate and a grounded metal plate is on another side of the substrate. All of the electrodes are driven by an RF potential to offer radial confinement, while the end segments are applied a positive static voltage to offer axial confinement. Four lines of ions would lie along the trapping axes above on the chip as drawn.

trodes only, and the trapping depth can be changed by varying the scale of the geometry, too. The long-lived internal states of the trapped ions carry the qubits. Because those multilayered structures are relatively difficult to fabricate and the single-layer traps finally form only one trap above the plane, this simple two-dimensional design is a promising method for large-scale quantum device for quantum information processing. Furthermore, this design could be used for building ion clock with such many controlled ions.

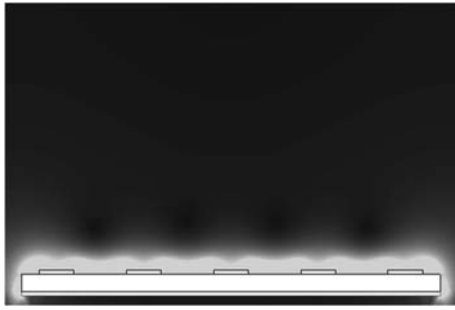


Fig. 19 Radial contours of the electric field simulated through FEAM for the array of two-dimensional ion traps. Colors from black to white indicate low to high field, respectively. For clarity, contours are not shown for electric field values above an arbitrary maximum.

4 Conclusions

In this paper, we have first reviewed the history and theory of quantum information and quantum computation, then we concentrated on discussion of the ion trapping scheme for the realization of quantum computer. From the original ion traps such as Penning trap and Paul trap, many variations have been proposed. The RF Paul trap is more appropriate for quantum information processing and quantum computation. Since the original Cirac-Zoller's proposal for ion trapping quantum computing, many subsequent experimental implementations and related ideas have been investigated because all the essential ingredients of a quantum computer were shown to be available by using experimental techniques which were already either realized or close to realization in the laboratory. For example, the NIST group, the Innsbruck group, the MIT group and the Michigan group, etc. The theory of ion trapping quantum computation to realize a logic gate such as a CNOT was investigated. Experimental advancement for ion trapping has been discussed, there are several variations of the typical linear rf Paul trap with four rods as electrodes. As for linear traps, schemes using flat electrodes constructed on the surface of a substrate by microfabrication techniques, and multilayered-electrode structures generate a string of trapped ions have been proposed. To scale the linear traps to two-

dimensional quantum registers, several proposals such as the QCCD architecture consisting of a large number of interconnected ion traps, and a T-junction ion trap array are demonstrated. There are also surface-electrode geometries to simplify the construction and building of large-scale ion trap arrays for QIP. The NIST group and MIT group have presented their surface ion traps, respectively. Our SIOM group has put forward the surface planar ion chip scheme which is relatively simple fabricated and could scale up to the two-dimensional array for QIP.

Ion traps have played a promising route towards QIP and QC. There still exist theoretical and technical challenges to scale up the ion traps to large numbers of qubits and realize true quantum computers. Further efforts will work at these and related fields. So the research of ion trapping will offer new ways of bringing the quantum world to a larger scale.

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