Wiring up trapped ions to study aspects of quantum information

N Daniilidis[1], **T Lee**[1,2], **R Clark**[1,3], **S Narayanan**[1] **and H Häffner**[1,4,5]

[1] Institut für Quantenoptik and Quanteninformation, Innsbruck, Austria
[2] Department of Physics, California Institute of Technology, Pasadena, CA, USA
[3] Center for Ultracold Atoms, Massachusetts Institute of Technology, Cambridge, MA, USA
[4] Department of Physics, University of California, Berkeley, CA 94720, USA
[5] Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

E-mail: hhaeffner@berkeley.edu

Abstract
There has been much interest in developing methods for transferring quantum information.
We discuss a way to transfer quantum information between two trapped ions through a wire.
The motion of a trapped ion induces oscillating charges in the trap electrodes. By sending this
current to the electrodes of a nearby second trap, the motions of ions in the two traps are
coupled. We investigate the electrostatics of a setup where two separately trapped ions are
coupled through an electrically floating wire. We also discuss experimental issues, including
possible sources of decoherence.

1. Introduction

Trapped ions are an ideal system to store and process quantum information. Held by electrodynamical forces inside a vacuum chamber, the ions hardly interact with the environment. Thus, extremely long coherence times of up to 10 min for the electronic state [1, 2], and more than 300 ms for the motional state [3, 4] have been demonstrated with trapped ions. Furthermore, the internal and external degrees of freedom can be controlled very accurately with laser radiation [5]. With these techniques, researchers have implemented quantum gates [6, 7], multiparticle entanglement [8–10] and even basic quantum algorithms [11–13]. For a review of ion–trap quantum computation see [14]. Currently, the goal is to expand to larger quantum registers in order to be able to use quantum computing to solve nontrivial problems. One strategy is to work with small and easy-to-control ion strings and then physically transport ions between different zones [15]. Other schemes transfer quantum information via optical cavities [16, 17] and long-distance entanglement [18, 19].

In this contribution, we concentrate on a different coupling mechanism: ions in two separate traps can be coupled by allowing the charges they induce in the electrodes to affect each other's motion [20, 21]. This inter-trap coupling may be used for scalable quantum computing, cooling ion species that cannot be laser cooled, and for coupling an ion–trap quantum

computer to a solid-state quantum computer, e.g. a system of Josephson junctions [22, 23]. Related schemes have been proposed for coupling Rydberg atoms [24] and oscillating electrons [25].

2. Coupling mechanism

In the following, we discuss experiments towards inter-trap coupling using ^{40}Ca$^+$ ions in a planar RF trap. Experiments in a similar direction with electrons trapped in Penning traps are discussed in [26]. The basic idea is that quantum information stored in the electronic degree of freedom of a single ion cooled to the motional ground state can be mapped onto the motional degree of freedom by driving the motional sidebands of the electronic transition [5]. Thus, the information is stored in superpositions of the form $\alpha|0\rangle + \beta|1\rangle$, where $|n\rangle$ is the quantum number of the harmonic oscillator describing ion motion. This oscillating motion yields a considerable dipole moment, of order 1.8×10^{-27} C m for a calcium ion at a secular frequency of 1 MHz, which can be coupled to the motion of an ion in a different trap. For instance, starting with one ion in $(|0\rangle + |1\rangle)/\sqrt{2}$ and the other ion in $|0\rangle$, we expect that after some time t_{ex}, the ions have exchanged states to within acquired phases. The main idea of these experiments is to enhance the coupling using a wire and thus provide a valuable means of interconnecting trapped ions.
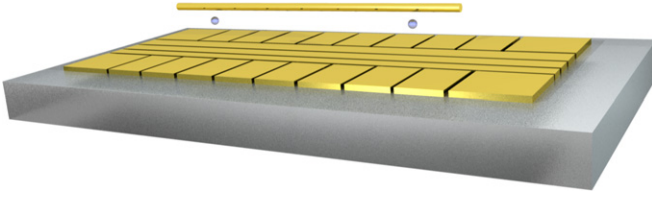
Figure 1. Schematic representation of the experimental setup used for the trapped-ion coupling experiments. A planar trap with several dc electrode segments provides multiple trapping regions on the same trap chip. An electrically floating electrode is in proximity to ions in different trapping regions and couples their motional states.

(This figure is in colour only in the electronic version)
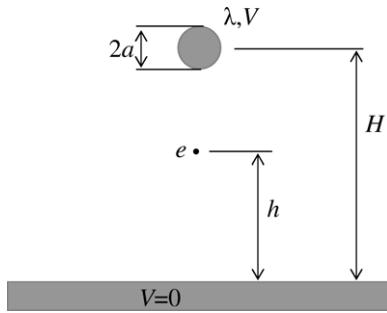
Figure 2. Schematic of a wire of radius a, length L, and total charge λL at height H and the ion at height h above the grounded plane. The wire is coming out of the page.

Figure 1 sketches the experimental setup. A planar RF trap confines two ions in two different potential wells above the trap surface. An electrically floating wire mounted above the trap carries currents induced by ion motion, enhancing the Coulombic coupling between ions. In what follows, we study the dynamics of the coupled ion system using the system Hamiltonian and also using the equivalent circuit approach, described in [20, 21].

2.1. Ion–wire interaction

We first derive the electrostatic coupling term, under some simplifying assumptions. Our analysis follows a procedure similar to that described in [27]. We consider a wire of radius a and length L, situated some height H above a (infinite) ground plane and oriented parallel to the plane (see figure 2). Two point charges, henceforth ions 1 and 2, are at heights h_1, h_2 ($h_1, h_2 < H$) above the ground plane, located on the plane passing through the centre of the wire and vertical to the ground plane. The horizontal distance, d, between the ions satisfies $h_1, h_2, H \ll d < L$. The point charges are treated here as infinitesimally small conductors with variable, externally set, charge. Consider the situation where the wire is at potential V and carries a total charge $\lambda \cdot L$, while the 'point charge' conductors carry zero charge. Then, in the limit $L, d \gg H, a$, the potentials V of the wire and $\Phi_{1,2}$ at the ion positions are

$$
\begin{aligned}
V &= \frac{\lambda}{2\pi\epsilon_0} \ln\left(\frac{2H - a}{a}\right), \\
\Phi_i &= \frac{\lambda}{2\pi\epsilon_0} \ln\left(\frac{H + h_i}{H - h_i}\right), \qquad i = 1, 2.
\end{aligned}
\tag{1}
$$

A convenient dual situation is the one in which both point charges carry the same charge, e, while the wire carries zero net charge and is at potential V'. Application of Green's reciprocity theorem to the above situations results in the relation:

$$
V' = \frac{e}{2\pi\epsilon_0 L}\left[\ln\left(\frac{H + h_1}{H - h_1}\right) + \ln\left(\frac{H + h_2}{H - h_2}\right)\right]. \tag{2}
$$

We are interested in the ion–ion interaction that is mediated by the wire, and we neglect their direct electrostatic interaction. The potential energy of each ion in the wire potential is

$$
U_i = \frac{eV'}{\alpha} \ln\left(\frac{H + h_i}{H - h_i}\right), \qquad i = 1, 2, \tag{3}
$$

where $\alpha = \ln[(2H - a)/a]$. For the remainder of this section, it is convenient to switch to coordinates in which the instantaneous height of each ion is denoted by the deviation, y_i, about the equilibrium height, $h_i = h_{0,i} + y_i$. In these coordinates, the coupling constant that enters the Hamiltonian of the system is

$$
\gamma \equiv \frac{1}{2}\frac{\partial^2(U_1 + U_2)}{\partial y_1 \partial y_2} = \frac{2e^2 H^2}{\pi\epsilon_0\alpha L}\cdot\frac{1}{\left(H^2 - h_{0,1}^2\right)\left(H^2 - h_{0,2}^2\right)}. \tag{4}
$$

Here the factor $1/2$ is introduced to avoid double counting of the electrostatic energy, as described in [28]. As stated above, each ion is confined in an independent harmonic trap. Thus the Hamiltonian for the coupled ion system in the presence of the floating wire is[6]

$$
H = \frac{p_1^2}{2m} + \frac{1}{2}m\omega_1^2 y_1^2 + \frac{p_2^2}{2m} + \frac{1}{2}m\omega_2^2 y_2^2 + \gamma y_1 y_2. \tag{5}
$$

The time evolution of the above Hamiltonian has been studied for the resonant case ($\omega_1 = \omega_2$) exactly and also in the rotating wave approximation [29]. It was found that the rotating wave approximation is in almost complete agreement with the exact solution in the limit of small coupling constants ($\gamma/m\omega^2 < 0.1$). More recently, a solution in the rotating wave approximation showed that full exchange of motional states occurs only in the resonant case and for specific initial states [30]. One interesting case is with one ion initially in a superposition of Fock states of the form $(|0\rangle + |n\rangle)/\sqrt{2}$ and the second ion in the ground state. In this case, the inverse time for state exchange of the two ions is

$$
\frac{1}{t_{\text{ex}}} = \frac{\gamma}{\pi\omega m} = \frac{2e^2 H^2}{\pi^2\epsilon_0\alpha m\omega L}\cdot\frac{1}{\left(H^2 - h_{0,1}^2\right)\left(H^2 - h_{0,2}^2\right)}, \tag{6}
$$

where the geometry constant α was defined below equation (3). After time t_{ex}, the first ion is in the ground state and the second ion is in $(|0\rangle + e^{-in\Theta}|n\rangle)/\sqrt{2}$, where $\Theta = \pi(m\omega^2/\gamma + 1/2)$. In experiments aiming to transfer quantum information, the presence of the acquired phase Θ poses requirements similar to those for preserving the coherence of the motional state of a single ion.

Another important case concerns coupling of coherent states in the resonant system. It is easy to verify that if the first

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[6] It is interesting to note that the Hamiltonian for the case of N individually trapped ions is $H = \sum_{i=1}^{N} H_{\text{h.o.},i} + \sum_i \sum_{j>i} \gamma_{i,j} y_i y_j$, where $H_{\text{h.o.},i}$ is the harmonic oscillator Hamiltonian for the ith ion.

ion starts out in a coherent state $|\mu\rangle$, with complex amplitude μ, and the second ion in the ground state, then after time t_{ex} the first ion is in the ground state and the second ion is in a coherent state $|\mu\, e^{-i\Theta}\rangle$, where Θ, defined above, describes the change of the coherent state complex amplitude. This effect will be present in the classical regime. It is due to the fact that each oscillator continues to oscillate while the state exchange is in process and thus acquires some phase. The presence of such a phase can most easily be observed by allowing the coupled ions to evolve for time $2t_{\text{ex}}$, so that the first ion has returned to a state $|\mu\, e^{-i2\Theta}\rangle$.

An important aspect of the above result is the extraction of the dependence of the coupling rate on experimental parameters. The coupling rate increases with decreasing size of the experimental setup: in the practically interesting case where the ions are much closer to the wire than the trap ($h_{0,1}, h_{0,2} \approx H$) the length of the wire as well as the ion–wire distances enter mainly as $1/[L(H - h_{0,1})(H - h_{0,2})]$. Dependence on the wire radius is only logarithmic, included in the geometric constant α. Physically, the increased coupling with smaller system sizes corresponds to the fact that for ions closer to the wire the induced charges are larger, and also that for shorter wires the induced charges are distributed over shorter distances. The scaling of t_{ex} with system size yields a decrease of t_{ex} by roughly an order of magnitude for a decrease of the trap size, i.e. H, $h_{0,i}$, and wire length, L, by a factor of 2. Besides these geometrical considerations, we find an inverse law dependence of the coupling rate on the ion secular frequencies, $t_{\text{ex}} \propto \omega$. This can be understood physically by the increase in effective coupling as the dipole moment corresponding to each ion ($\propto 1/\sqrt{\omega}$) increases with lower secular frequency.

Typical parameters that are feasible in current setups are $H = 200\,\mu\text{m}$, $h_{0,i} = 150\,\mu\text{m}$, $L = 10\,\text{mm}$, $a = 12.5\,\mu\text{m}$, $\omega = 2\pi \cdot 1\,\text{MHz}$. With these values and for two $^{40}\text{Ca}^+$ ions, one obtains $t_{\text{ex}} \approx 190\,\text{ms}$. We point out that the direct electrostatic interaction between the ions is smaller than the wire-mediated term by a factor of order $(H - h_{0,1})(H - h_{0,2})/L^2$, which for these parameters is $\sim 3 \times 10^{-5}$. Thus, the direct electrostatic interaction between the ions is negligible, as assumed in the derivation of equation (6).
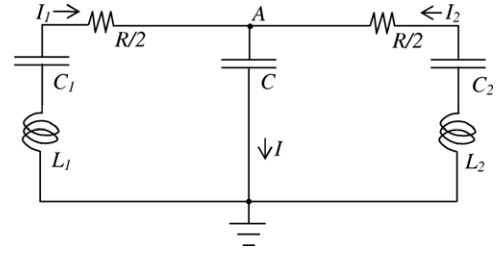
2.2. Equivalent circuit model

We now derive the circuit model for the system of two trapped ions and a coupling wire, following [20, 21]. The analysis starts from the equations of motion for the ions

$$\frac{e}{m}E_i = \ddot{y}_i + \omega_i^2 y_i, \qquad i = 1, 2. \tag{7}$$

Here, the electric field E_i at the position of ion i is due to the potential of the floating wire used for coupling. The field E_i is proportional to the potential V_i of the wire. In addition, following the analysis described in [27], we find that in the presence of a single ion at height h, the charge induced in the wire is

$$q_{\text{ind}} = -\frac{e}{\alpha}\ln\left(\frac{H + h}{H - h}\right), \tag{8}$$

Figure 3. Equivalent circuit of two ions, each with inductance L_i and capacitance C_i, coupled by a wire with capacitance C to ground. The wire has ohmic resistance R. The current I_i, $i = 1, 2$ in each branch of the circuit corresponds to the velocity of the corresponding ion.

A key consequence of this result is that the induced current is proportional to the ion velocity. Thus, equation (7) can be recast in the form

$$V_i = L_i \frac{dI}{dt} + \frac{1}{C_i}\int I\, dt, \qquad i = 1, 2. \tag{9}$$

We see that on application of an external potential V_i to the floating wire, the I–V response in the presence of an oscillating trapped ion is equivalent to the response of a series LC circuit. The equivalent inductance and capacitance of the ion are

$$L_i = \frac{1}{\beta_i^2}\frac{mH^2}{e^2}, \qquad C_i = \frac{1}{\omega_i^2 L_i}, \qquad i = 1, 2, \tag{10}$$

with the geometry parameter, β_i, given by

$$\beta_i = \frac{2H^2}{\alpha\left(H^2 - h_i^2\right)}, \qquad i = 1, 2. \tag{11}$$

We note here that typically the inductance of a single trapped ion is counter-intuitively large, while the capacitance is rather small. The values corresponding to the setup parameters mentioned earlier are $L_{1,2} \approx 6 \times 10^4\,\text{H}$ and $C_{1,2} \approx 4 \times 10^{-19}\,\text{F}$. The equivalent circuit of two trapped ions coupled through a wire, with capacitance C to ground and ohmic resistance R, is shown in figure 3. For the wire dimensions mentioned above, the wire resistance is estimated to be approximately $0.6\,\Omega$, resulting in a high quality factor $Q \approx 6 \times 10^{11}$ for the ions.

It is interesting to point out that the classical solution of this circuit results in equation (6) for the rate of state exchange between the two ions. In addition, the exchange rate can be expressed in terms of circuit parameters as

$$\frac{1}{t_{\text{ex}}} = 2\nu\frac{C_i}{C}, \tag{12}$$

where ν is the secular frequency of the ions. By expressing the exchange rate in this form, we see that it is maximized by minimizing the capacitance of the wire to ground. This is evident from the equivalent circuit: a signal originating from the motion of one ion will be shorted to ground due to the capacitance of the wire. This is also the reason for keeping the coupling conductor electrically floating. Any conducting path from the coupling wire to ground will reduce the portion of the signal that couples the two ions.

Here the circuit model has only been considered in the classical regime, but a quantum treatment is possible following

standard techniques [31]. Such an approach can be particularly useful in applications where a trapped ion is coupled via a conductor to solid state systems, e.g. Josephson junctions. The circuit model also provides insight into the effect of various decoherence sources, which we discuss next.

3. Sources of decoherence

The goal of these experiments is to coherently couple trapped ions with a conductor. While it is not intuitively clear whether the transport of quantum information through a macroscopic wire is possible, a theoretical analysis shows that there are no known fundamental obstacles [32].

One source of decoherence is the dissipation of the induced current inside the wire. Using equation (8), the current induced by a single ion with a low motional quantum number will be of order $I = e\dot{z}\beta/H \sim e\sqrt{\hbar\omega/m}\beta/H$. For the parameters mentioned before, this current amounts to approximately 0.1 fA, so we expect that it takes approximately 2×10^5 s to dissipate one motional quantum on a wire resistance of 0.6 Ω. More important in this context, however, is the inverse process by which the ion picks up motional quanta from Johnson noise in the wire. The Johnson noise heating power P is given by

$$P_{\text{noise}} = kT\Delta\nu, \qquad (13)$$

where kT is the thermal energy and $\Delta\nu$ is the frequency bandwidth in which the ion accepts the power. The time τ in which one motional quantum of energy $E_q = h\nu$ is generated is given by

$$\tau^{-1} = \frac{P_{\text{noise}}}{E_q} = \frac{kT\Delta\nu}{h\nu} = \frac{kT}{hQ}, \qquad (14)$$

Inserting the expression $Q = R^{-1}\sqrt{L_i/C_i}$ into equation (14), we arrive at

$$\tau^{-1} = \frac{kTR}{h}\sqrt{\frac{C_i}{L_i}}, \qquad (15)$$

for the inverse time in which one motional quantum is acquired. For the values used above, the expected heating time from Johnson noise is $\tau \approx 0.1$ s/quantum at room temperature, which is comparable to the exchange time, t_{ex}. However, this can be significantly improved by cooling to liquid helium temperatures. Assuming a resistivity ratio $\rho_{300K}/\rho_{4K} \approx 50$ for the wire, the time constant for Johnson noise heating is $\tau \sim 380$ s/quantum. Thus, Johnson noise is not expected to prevent the coherent transfer of quantum information at cryogenic temperatures.

However, ion-trap experiments usually report heating rates higher than what would be expected from Johnson noise [5, 33]. The source of this noise is believed to be fluctuating patches of charges on the electrodes. Experiments hint that coating the electrode surface with contaminants has a strong influence on the observed heating [5, 33, 34]. Furthermore, recent experiments have shown that the fluctuations are thermally activated and can be suppressed many orders of magnitude by cooling the trap electrodes [35–37]. Indeed, heating rates as small as a few phonons per second have been

observed for ions trapped as close as 75 μm to the nearest electrode of a planar trap [36, 37].

Finally, we consider the effects of a leakage current from the coupling wire to ground. In the equivalent circuit, figure 3, this is modelled as a large resistor in parallel to the capacitor C between node A and ground. This time constant needs to be larger than the motional coupling timescale, t_{ex}, which can easily be satisfied for realistic values of the leakage equivalent resistance. A simple analysis shows that the current decay constant due to the resistor is $4R_gC$. From the estimated resistance of the insulating support of the wire (see the following section), we find a discharge time constant of more than 100 s.[7]

4. Experimental status

From section 2, it is clear that the trap should be small, allowing the ions to be close to the coupling electrode. In addition, as discussed in section 3, operation at cryogenic temperatures is advantageous for the reduction of decoherence processes. Both these demands are being experimentally pursued.

The experimental setup consists of a planar surface trap housed in a vacuum vessel. ^{40}Ca$^+$ ions are trapped at a height of about 200 μm above a sapphire substrate coated by gold electrodes (see figure 1). The fabrication of these traps will be described elsewhere. Typical trap frequencies are on the order of 1 MHz in the radial direction and 400 kHz in the axial direction.

A gold wire with diameter $2a = 25$ μm and length $L = 10$ mm can be positioned above the trap using nano-positioning stages employing a slip-stick mechanism. Two nanopositioning stages allow displacement of the wire perpendicular to the trap axis on the plane of the trap, as well as perpendicular to the trap plane. Two additional stages perform rotation of the wire about axes both parallel and perpendicular to the plane of the trap, allowing one to adjust the orientation of the wire so that it is parallel to the trap axis and to the plane of the trap. The translation stages have a minimum step size of 50 nm and the rotation stages a minimum rotation of 1 mdeg. Fine tuning of the wire orientation and position can be achieved using the imaging optics normally used for ion detection.

Macor pieces support the wire and electrically isolate it from a larger metallic arm that connects the nano-positioning stages to the wire. The wire is attached to the Macor pieces using UHV compatible epoxy (for example EPO-TEK® 353ND). The estimated resistivity of the insulated support is more than 10^{15} Ω. In constructing the coupling wire assembly, one has to bear in mind the conflicting constrains imposed: on the one hand, it is essential to minimize the wire capacitance to ground. Therefore the wire length has to be kept as small as possible, and there should be insulating pieces to separate the wire from the electrically grounded metallic arm. On the other

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[7] It is important to point out that modelling the insulating wire support by a large resistor is a rough approximation. Typically the *I–V* response will be nonlinear, with nontrivial frequency scaling. Factors that contribute to an observed current in an insulator can be as different as internal polarization changes in the dielectric and surface currents due to adsorbed contaminants.

hand, the amount of insulating material near the ions should be minimized, as insulators lead to unwanted stray-field effects. Modelling and optimizing the compromise between these opposing constraints are difficult. In practice, one follows an empirical, trial-and-error approach for the design of the coupling wire assembly.

The main goal of the current setup is to explore the interaction of single ions with the electrically floating wire. Of interest are the influence of the wire on the trap potential, heating of the motion due to the wire, the minimum achievable ion–wire distance and the reproducibility of day-to-day trap parameters with the electrically floating wire present. For these investigations a room temperature setup is sufficient.

In view of the smaller dimensions required for future experiments of coherent ion–wire–ion interactions, an additional cryogenic setup is being constructed, of which the construction details will be discussed elsewhere. The cooling power is provided by an ARS Cryosystems closed-cycle cryostat operating in the range of 4–300 K. A large contribution to the heat load of cryostats with optical access arises from room temperature black-body radiation. For this reason, two radiation shields are included between the room-temperature vacuum housing and the trap–wire assembly. One radiation shield is at 40 K and the second one is at 4 K. The latter encases the trap chip, coupling wire and nano-positioning stages. Both radiation shields provide up to eight 25 mm diameter viewports for optical access parallel to the trap plane, and one 25 mm diameter viewport above the trap plane, which will be used for ion detection. The atomic calcium oven is mounted on the room temperature stage and pinholes on the radiation shields allow the atomic beam to reach the trap region. Calcium ions are produced via two-step photoionization [38]. While at room temperature, the vacuum chamber can be pumped down using a turbomolecular pump. When cold no external pumps are necessary as cryopumping by the 4 K stage will provide the necessary vacuum more efficiently than any external pump.

5. Summary

The possibility of coupling trapped-ion motional states through a floating conductor opens promising directions in quantum information processing and coupling quantum-optic systems to solid-state systems. Analysis of the coupling mechanism shows that the miniaturization of the ion trap and coupling electrode yields significant gain in the coupling rate. Moreover, it is possible to reduce the decoherence rates to levels much below the coupling rate by working at liquid helium temperatures. Current experiments are making progress in both directions.

Acknowledgments

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