Two-ion Coulomb crystals of Ca^+ in a Penning trap.

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Abstract: Results demonstrating laser cooling and observation of individual calcium ions in a Penning trap are presented. We show that we are able to trap, cool, image and manipulate the shape of very small ensembles of ions sufficiently well to produce two-ion 'Coulomb crystals' aligned along the magnetic field of a Penning trap. Images are presented which show the individual ions to be resolved in a two-ion crystal. A distinct change in the configuration of such a crystal is observed as the experimental parameters are changed. These structures could eventually be used as building blocks in a Penning trap based quantum computer.

OCIS codes: (270.5585) Quantum information and processing; (020.3320) Laser cooling

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1. Introduction

1.1. Quantum information processing with trapped ions

Laser cooled trapped ions represent one of the most promising candidate systems for quantum information processing (QIP). Inspired by the theoretical work of Cirac and Zoller [1], small 'crystallized' ensembles of ions held in radio-frequency (RF) traps have been used to demonstrate quantum gates, simple algorithms [2–9] and to generate multiparticle entanglement [10, 11]. The original scheme of Cirac and Zoller envisaged a quantum computer com-

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prised of a long string of ions in a linear RF trap. Each ion would represent a qubit and entanglement would be engineered through the ions' collective quantised motion in the trap. It is now clear that this approach is not scalable to large numbers of qubits, so alternative strategies for scalability of trapped ion QIP have been suggested and are being investigated. In particular Wineland *et al.* and later Kielpinski *et al.* suggest a quantum computer made up of ions held in two dimensional arrays of miniature traps [12, 13]. Ions are brought together into a single miniature trap for gate operations and then separated and shuttled into other trapping zones for storage. Miniature traps and large RF voltages are required in order to provide tight confinement, leading to high motional frequencies which, in turn, give relatively fast gate operation times. However, the presence of time-varying patch potentials on the surface of the electrodes gives rise to decoherence effects in the trapped ions. In current traps this is at a tolerable level, however, this source of decoherence scales strongly with trap size [14, 15] and is likely to present challenges in the next generation of even smaller traps.

Unlike a radio-frequency trap, which uses a high voltage oscillating potential to realise ion confinement, the Penning trap uses entirely static electric and magnetic fields for this purpose. Although the oscillating drive potential in RF traps is not a major cause of decoherence at the scale of current traps (∼0.1-1 mm) its effects in the case of future generations of smaller traps are as yet unknown. In particular the RF potential may enter the problem indirectly through its influence on the less well understood problem of patch potentials [14].

The motion of an ion in an RF trap can be approximated as a superposition of three harmonic oscillations along three orthogonal axes. Laser cooling of ions in such a trap leads to tight confinement in all three dimensions. In a Penning trap the motion along the axis of the imposed magnetic field is simple harmonic motion, but the motion in the other two dimensions (the radial plane) is more complicated. As a result laser cooling is less straightforward in this system leading to relatively poor confinement in the radial plane [16]. In addition, the energy levels of atomic ions display large Zeeman splittings (tens of GHz for Ca^+ at B = 1 T) when held in the high magnetic field of a Penning trap. Thus a more complicated laser system is required when compared to cooling the same ion species in an RF trap. For these reasons ions held in Penning traps have not so far been employed in QIP experiments. However, better control over the radial motion (and tighter confinement) can be achieved through a process known as axialization [17, 18]. Also, modern laser diode and optical fibre technology allow a multiple-laser setup to be implemented relatively straightforwardly. The confinement in a Penning trap is largely provided by the magnetic field together with only moderate static voltages. Therefore, tight trapping and high motional frequencies can in principle be achieved with larger trapping structures – eliminating some other possible disadvantages of very small RF traps such as excessive laser beam scatter and trap damage due to RF power dissipation or electrical breakdown [19] as well as the patch potential effect.

1.2. Ions in a Penning trap

A conventional Penning trap consists of a set of electrodes, to which static electric potentials are applied, held in a region of a large homogeneous magnetic field in a vacuum. Typically three electrodes are used: a ring shaped electrode and two endcaps. For trapping positively charged ions the endcaps are held at a positive potential with respect to the ring. This leads to harmonic trapping along the axis between the endcaps. However the ions are attracted to the ring electrode by the inhomogeneous electric field. The magnetic field applied along the axis of the trap forces the ions into cyclotron orbits in the radial plane. The presence of the electric field means that the cyclotron motion is modified and occurs at a reduced frequency ω_c' compared to the true cyclotron frequency $\omega_c = eB/m$. Furthermore the ions perform a slow drift motion about the centre of the trap at the magnetron frequency $\omega_m = \omega_c - \omega_c'$ [20].

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Laser cooling of ions in the Penning trap is complicated by the unstable motion in the radial plane. If energy is removed from the axial and cyclotron degrees of freedom these motions shrink as expected. On the other hand, if energy is removed from the magnetron mode this motion expands as the ions move down the sides of the radial potential hill. In order for laser cooling to improve three dimensional confinement, a strategy is required which simultaneously removes energy from the axial and cyclotron motion but pumps energy into the magnetron motion. Very soon after the first demonstrations of laser cooling in other systems such a strategy was devised for ions in a Penning trap [16]. It consists of positioning a focused, red-detuned laser beam slightly offset from the centre of the trap. If the beam is offset to the correct side of the trap, scattering occurs when the laser opposes the cyclotron motion but is in the same direction as the magnetron motion. This results in the amplitude of both motions being reduced. This strategy is effective but the radial confinement, although improved, is limited by the size of the laser beam focus, and the resulting motion is never as small as it can be for ions in an RF trap.

A second strategy (axialization) is available provided the trap is equipped with a ring electrode that is split into four segments. If a weak oscillating radial quadrupole potential is applied to the ring at the true cyclotron frequency $\omega_c = \omega_c' + \omega_m$ the effect is to couple together the two otherwise independent radial modes. In the absence of damping, the result is that energy is periodically transferred between these two motions. For our trap, simulations show that the frequency of this transfer of energy is approximately 10 Hz per mV of axialization drive voltage. If a source of damping is present the overall orbit size gradually shrinks [18]. This is essentially the same as a process called ‘sideband cooling’ (which is used in, for example, ion trap mass spectrometry) [21] with the exception that in axialization the damping is provided by laser cooling whereas in conventional sideband cooling it is provided by buffer gas collisions.

1.3. QIP in a Penning trap

A scheme for scalable Penning trap QIP has been suggested based on multiple miniature Penning traps made from planar electrode structures [22]. In this proposal ions would be moved between trapping zones, in directions perpendicular to the magnetic field, by using the electrodes to impose near-linear electric fields. The ions move from one trap to another via cycloid loops and if they start out at rest in one trapping zone they are automatically brought to rest as they arrive in the target trapping zone. Quantum gate operations could be accomplished by bringing ions together in a privileged trap which has multiple trapping zones along the axial direction. A two-ion crystal along the axis of a Penning trap behaves in the same way as a similar structure in a linear radio-frequency trap and the techniques developed in RF traps can be employed in this system. In theory, the combination of single qubit rotations and a universal two-qubit quantum logic gate is sufficient to build any quantum logic network [23]. Thus with the ability to control single ions and two-ion axial crystals, the Penning trap QIP scheme discussed in Ref. [22] should be possible. We note that the potential advantage of the Penning trap in terms of the ability to provide tight trapping with relatively distant electrodes only applies to the qubit storage aspect of the scheme outlined in [22]. The size scale of the individual planar electrodes in that scheme is not critical. Their role is simply to provide either the standard trapping field, or a nearly linear electric field in the radial plane to facilitate controlled movement of the ions. They do not need to be small enough to act as a wedge in the process of ion-pair separation – this operation would be accomplished in a multiple trap aligned along the magnetic field axis.

A number of other ideas for Penning trap QIP have also been put forward, including the use of trapped electrons with radio-frequency and microwave techniques [24]. More recently, inspired by images of large radial crystals in a Penning trap obtained using a rotating electric

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field technique [25], the use of planar crystals of ions in a Penning trap has been proposed for QIP and as a quantum simulator [26, 27].

2. Single ions and quantum jumps

The trap used in this work has been described in detail elsewhere [28]. It is a conventional Penning trap whose electrodes have conical cross sections. The ring electrode is split into four segments to allow the application of an axializing potential. Light is sent into the trap through a gap between two ring segments and emerges through another diametrically opposed gap. In a direction at 90° to the laser beams the gap between the ring segments is enlarged to allow fluorescence to escape the trap. The fluorescence is collected by a plano-convex singlet lens held 19 mm away from the centre of the trap, inside the vacuum chamber. Ions are loaded into the trap by electron bombardment of a weak atomic beam of calcium. Electrons are generated using a thoriated tungsten filament placed behind one of the endcap electrodes. The endcap electrodes have small central holes to allow the electrons to pass through the centre of the trap. The background gas pressure in the trap vessel is $\sim 2\times 10^{-10}$ mbar. A representation of the trap geometry is shown in Fig. 1.

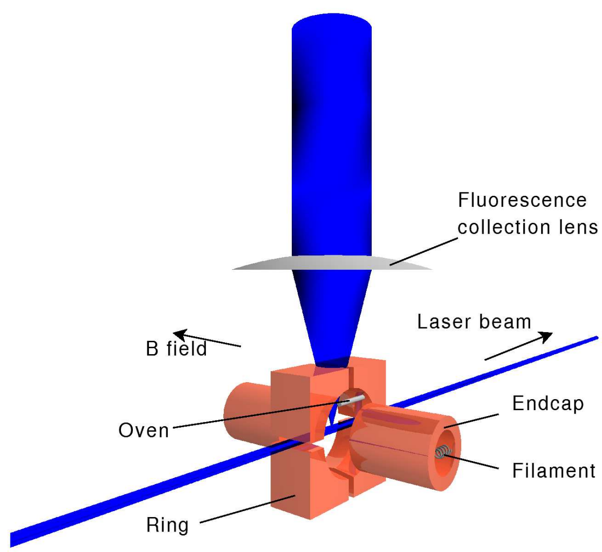

Fig. 1. Schematic layout of the Penning trap used in this work.

A partial energy level diagram for $^{40}Ca^{+}$ is shown in Fig. 2. Two lasers near 397 nm are required to avoid optical pumping – one for each of the $^2S_{1/2}$ state Zeeman sub-levels. These wavelengths are provided by a pair of extended cavity diode lasers (ECDL).[1] Four home-made

[1] Toptica DL100

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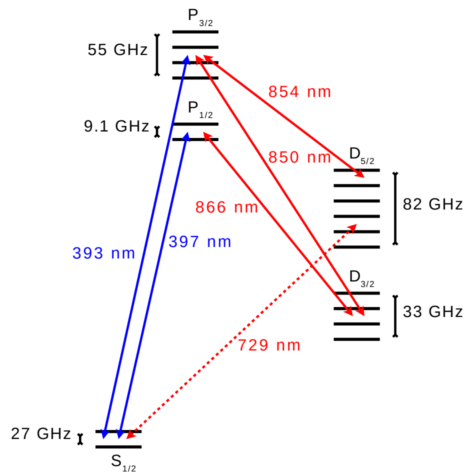

Fig. 2. Partial energy level diagram of $^{40}Ca^+$ in a 0.98 tesla magnetic field.

ECDL's operating near 866 nm are used to repump ions from the $^2D_{3/2}$ metastable state to close the cooling cycle. Doppler cooling of Ca^+ ions in a Penning trap had previously been achieved using a simpler repumping strategy that used two infra-red lasers near 866 nm with sidebands generated by direct modulation of the diode injection current [29]. However, the amount of power that can be generated in the sidebands at the high frequencies required is relatively low and so we have now opted for a more direct approach using four separate lasers.

The two blue laser beams are combined on a beam splitter and coupled into a polarisation maintaining optical fibre.[2] Similarly the four infra red beams are coupled into a second optical fibre.[3] The outputs of the two fibres are then combined using a dichroic mirror and sent to the trap via a focusing lens.

Quantum jumps into the $^2D_{5/2}$ state can occur via excitation to the $^2P_{3/2}$ state. Normally this would not be populated but transitions to this state can be mediated by amplified spontaneous emission (ASE) present in either the 397 nm lasers (ASE at 393 nm) or in the 866 nm lasers (ASE at 850 nm). To avoid these quantum jumps, and to optimise the laser cooling, another laser at 854 nm may be used to repump ions in the $^2D_{5/2}$ levels back into the cooling cycle. In principle this laser should be broadband and cover all six of the required transitions from $^2D_{5/2}$ to $^2P_{3/2}$. However, the ASE only results in jumps into the $^2D_{5/2}$ level at a rate of a few events per second. In order to achieve a high fluorescence signal, the repumper laser only needs to bring the ion back into the cooling cycle at a rate comparable to this and so a single ECDL tuned centrally to the band of transitions suffices for this purpose. For future experiments where these unwanted quantum jumps must be avoided the laser outputs will be dispersed using gratings or prisms before being coupled into the optical fibres to prevent ASE from reaching the trapping region [30].

The fluorescence collection lens attached to the trap forms part of a multi-lens imaging system, with the other lenses outside of the vacuum chamber. The photomultiplier tube (PMT) used for detection is adversely affected by magnetic fields and so it must be held $\sim$50 cm from the trap centre. The light is focused onto the PMT using another two lenses, with an overall magnification of roughly unity. A 200 μm aperture is placed in the image plane to cut down the

[2] Nufern PM-S350-HP

[3] Oz Optics SMJ-A3A-3AF-850-5/125

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collection of stray light. A pair of filters is placed after the aperture to reduce other unwanted background light, e.g. room light, and light from the electron beam filament.

In order to obtain images of the trapped ions the light can alternatively be sent to an image intensified CCD camera.[4] This is done by flipping a mirror into the optical path between the middle and final lens of the optical system. The light is then diverted at 90° to another lens system which forms an image which is then re-focused onto the camera using a commercial camera lens.[5] The overall magnification is appoximately 4.

The trap is usually operated with a magnetic field of 0.98 ± 0.01 tesla, produced by a conventional electromagnet. Initially the wavelengths of the various lasers are set at their correct values using a home-made wavemeter and the beams are aligned centrally in the aperture formed by the gap in the ring segments. A large cloud of ions is loaded by running the atomic beam and electron filament simultaneously until some fluorescence signal is observed. Initially the fluorescence level may be low but fine adjustment of the six laser frequencies and the two beam positions (397 nm and 866 nm) allows this signal to be optimised. The optimum beam positions and laser detunings depend on the size of the cloud so we proceed to load a smaller cloud of ions (by lowering the current in the filament) and re-optimise the fluorescence level. For a very small cloud of ions the character of the noise on the fluorescence signal changes visibly due to the presence of quantum jumps. When this is the case we proceed to try to load a single ion by lowering the filament current still further and adopting a slightly different loading strategy.

The atomic beam oven is turned on for 60 seconds. After the first 30 seconds the electron filament is turned on for the remaining 30 seconds. Both are then switched off. At this stage there is usually no fluorescence detected, however an ion (or ions) may have been loaded into the trap. If the ion is in a large magnetron orbit, which is likely, then it spends very little of its time in the focused laser cooling beam. It can therefore take a significant time for the ion to cool. As the ion is slowly cooled it moves closer to the centre of the trap and the cooling rate and fluorescence level then increase dramatically. It is not uncommon to wait up to 5 minutes for the fluorescence from a single ion to become visible above the background level of scattered light. However, when this does happen the fluorescence increases to its maximum value very suddenly. Figure 3 shows the fluorescence rate during such a loading procedure. The trace begins just after the filament is switched off. After a waiting time of 35 seconds an ion cools to the centre of the trap and the fluorescence level rises to $\sim$5000 counts per second. This count rate is somewhat lower than expected given the solid angle for fluorescence detection (0.16 steradians), the transmission coefficients of the filters, optics and window and the quantum efficiency of the detector (we calculate an overall detection efficiency of 1.2×10^{-3} which we would expect to lead to a count rate of $\sim10^4$ s^{-1}). The lower than expected signal level per ion is probably due to the more complicated laser cooling scheme for Ca^+ in a Penning trap, which requires optimisation of the frequencies of six lasers, taking care to avoid the generation of unwanted 'trapped states'.

The fluorescence during a sequence where two ions are loaded into the trap is shown in Fig. 3. A second ion joins the first at $t\approx70$ s. The number of cold ions in the trap can be checked by observing quantum jumps in the signal level when the repumper laser at 854nm is blocked. Figure 4 shows histograms of fluorescence rates corresponding to different numbers of ions in the trap. The example in Fig. 4(d) shows that the number of ions (two in this case) can be simply determined by eye in real time.

An interesting feature to note in Fig. 3 is the temporary loss of signal at $t\approx70$ s. We interpret this as being due to the second (hot) ion coming into the centre of the trap and temporarily heating the cold ion that is already there. The two ions then re-cool resulting in the subsequent

[4]Andor DH534-18S-03
[5]Minolta MD 50mm F1.7

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