

TUTORIAL

Applications of laser cooled ions in a Penning trap

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Online at stacks.iop.org/JPhysB/42/154003**Abstract**

This paper aims to describe in basic terms how the different types of ion traps work, giving some examples of their use. It then discusses some recent ‘exotic’ designs of ion traps and shows how they are optimized for particular experiments. Recent work at Imperial College London is used to illustrate some of the ideas introduced in this paper.

(Some figures in this article are in colour only in the electronic version)

1. Penning traps and RF traps

Penning traps and RF (Paul) traps have been in use in atomic physics experiments now for over 40 years. Perhaps the defining moment that opened up the possibilities for the wealth of experimental techniques in atomic physics and quantum optics that we now see was the first photograph of a single ion, published in 1980 [1], which followed soon after the proposal [2] and subsequent realizations of laser cooling in trapped ions [3, 4]. Later in this paper, we will discuss various applications of trapped ions but first we introduce the different types of ion traps and the principles of laser cooling.

1.1. The Penning trap

The Penning trap works using very simple applications of electricity and magnetism. First, three electrodes are used to set up a quadrupole electrostatic potential, i.e. a potential which varies quadratically with distance from a point. Gauss’s law in electrostatics states that there can be no minimum in the electrostatic potential in free space; a quadratic variation of potential must mean that there is a saddle point at the origin. Specifically, the variation of potential with position is given by

$$V(r, z) = A(2z^2 - r^2).$$

A quadratic potential gives rise to simple harmonic oscillations, and therefore trapping, if the potential energy increases with distance. For positive A , this potential therefore

traps positively charged ions along the z -direction. But how is this potential generated in the first place? This is done by manufacturing electrodes that match the shape of the surfaces with a constant value of V . These surfaces are hyperboloids of revolution about the z -axis and have the shapes shown in figure 1.

When voltages are applied to these surfaces, they generate exactly the potential distribution given above. There are two endcaps separated along the z -axis by $2z_0$ and one ring which lies in the radial (r) plane and has radius r_0 . If we apply a potential U_0 to the endcaps with respect to the ring, we find that positively charged ions (of mass and charge m and q) are subject to simple harmonic motion (SHM) along z with an (angular) frequency ω_z , where

$$\omega_z^2 = 4qU_0/m(r_0^2 + 2z_0^2).$$

However, this arrangement only gives trapping along the z -direction and does not confine the motion in the radial plane because the curvature of the potential is negative in the r -direction (i.e. like an upturned bowl). For a stable trap, it is necessary to provide confinement along all three dimensions. In the Penning trap, this is achieved by applying a large magnetic field along the z -direction. This has no effect on the motion along z but it stops ions moving out to larger values of r because of the Lorentz force, which arises whenever a charged particle moves in a magnetic field. The force is in a direction perpendicular to both the magnetic field and the direction of motion. The result of this additional force is that the radial motion becomes stable and it then consists of a superposition

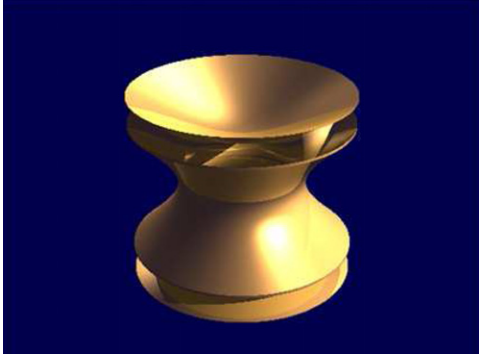


Figure 1. Electrode structure of a Penning trap. The z -axis is vertical and the applied magnetic field is also in this direction. The trapping zone is located at the centre of the structure.

of two circular orbits at different frequencies (see figure 3(a)). These are the modified cyclotron frequency

$$\omega'_c = \omega_c/2 + \omega_1$$

and the magnetron frequency

$$\omega_m = \omega_c/2 - \omega_1,$$

where

$$\omega_1 = \sqrt{\omega_c^2/4 - \omega_z^2/2}$$

and $\omega_c = qB/m$ where B is the magnetic field strength. So long as ω_1 is real, the motion is therefore now confined in all three dimensions and ions can in principle be trapped indefinitely. However, there is one feature which gives rise to several problems. The total energy associated with the magnetron motion is negative, in other words, as the radius of the magnetron orbit of the ion increases, the total energy decreases. This is due to the fact that since for this motion the frequency is low, the kinetic energy is small compared to the (negative) potential energy at a given radius. Any perturbations, such as collisions with background gas, would normally reduce the energy of the ions (until thermal equilibrium was reached), but in this case they are likely to increase the magnetron radius leading eventually to loss of ions from the trap. This is one reason why experiments with ions in Penning traps must always be carried out under ultra-high vacuum (UHV) conditions. Typical values of parameters for Penning traps are magnetic fields in the range 1–10 T, dimensions of the order of a few millimetres to a few centimetres, and oscillation frequencies in the range 10 s of kHz to a few MHz [5].

The force experienced by a charged particle moving in a magnetic field is rather like the Coriolis force which arises when a particle is moving in a rotating frame of reference. The Coriolis force is perpendicular to the direction of motion and to the rotation axis. This fact suggests a different way to look at the Penning trap motion. The transformation of any motion into a rotating frame introduces a Coriolis force. Therefore, if there is a magnetic field present, can a rate of rotation can be found such that the Coriolis force cancels out the force due to the magnetic field?

This can indeed be done, and the correct rotating frame to pick is the one that rotates at one half of the cyclotron

frequency ω_c [6]. However, there is one further consequence, which is that the rotation also gives rise to a centripetal force as well as the Coriolis force. This has the effect of changing the radial potential in which the ion moves, but since the electrostatic potential is quadratic, it simply changes the magnitude of the curvature of the potential in this frame. In fact it also changes its sign, resulting in a potential which now has a positive curvature and which therefore gives stable SHM (leading to circular orbits in two dimensions). In this frame, the motion is therefore stable in all three dimensions, and the radial oscillation frequency is ω_1 , which we defined earlier. If we now transform back into the laboratory frame we obtain the cyclotron and magnetron frequencies introduced above [6]. The two different points of view of the Penning trap motion therefore agree with each other and are complementary descriptions of the same phenomenon.

1.2. The RF (Paul) trap

The RF trap, also often referred to as the Paul trap, after Wolfgang Paul who developed this device, has many features in common with the Penning trap. It uses the same set of three electrodes and it also has potentials applied between the endcaps and the ring. However, in this case the potential is an oscillating (ac) one rather than a dc one. This is done in order that the motion can become stable in all three dimensions, so this is a different way to get around the stability problem arising from the application of Gauss's law discussed above. As a result, there is no need for a magnetic field in this case.

The principle is that for half of the cycle of the applied potential (oscillating at angular frequency Ω), the motion is, as in the Penning trap, stable along z and unstable along r . For the other half of the cycle it is the other way round: stable along r and unstable along z . It turns out that if the oscillation frequency lies between certain values, the motion along both z and r can be stable overall. This is because the ions move in an inhomogeneous field, and if they move such that the positive restoring force experienced during half the cycle is stronger than the negative restoring force in the other half of the cycle, the overall effect is a (smaller) restoring force giving rise to SHM [5]. The ion motion is described by a Mathieu equation [7], and the solution to this equation shows that the motion is stable for particular ranges of values of stability parameters defined by

$$a_z = -2a_r = -16eU_0/m\Omega^2(r_0^2 + 2z_0^2)$$

$$q_z = 2q_r = 8eV_0/m\Omega^2(r_0^2 + 2z_0^2),$$

where V_0 is the amplitude of the oscillating voltage applied to the trap [5]. The resulting motion of ions around the centre of the trap consists of a fast oscillation at Ω superimposed on a slower oscillation at frequencies $\omega_i = \beta_i\Omega/2$ where $\beta_i^2 \approx a_i + \frac{1}{2}q_i^2$ (here i represents either z or r for axial and radial motions respectively). Typically q is of the order of 0.3 and $|a|$ is less than 0.1.

This motion is often described in terms of an effective potential or 'pseudopotential' in which the ions move. This potential does have a minimum in all three dimensions at the centre of the trap because it is not bound by the restrictions of

Gauss's law which only applies to real potentials. A further consequence of this is that the motion can be cooled using a buffer gas, since the unstable nature of the magnetron motion in the Penning trap does not apply here. Buffer gas cooling therefore results in thermal equilibrium being set up between the thermal motion of the buffer gas and the ions in the trap.

The RF trap is in many ways more flexible than the Penning trap, in particular because there is no requirement for a magnetic field, so it is easier to get good access to the ion, for instance, with laser beams and imaging optics. Also, since traps can be made very small, it is possible to reach very high oscillation frequencies, which gives advantages for laser cooling (see section 2.1). However, one feature that needs to be addressed in experiments is the so-called 'micromotion' at frequency Ω , which arises from the applied ac potential. It is only at the exact centre of the trap that the amplitude of this motion is zero. Therefore as soon as there is more than one ion in the trap, there will be some residual micromotion, and this has an effect on the way that the ion interacts with light because the motion can generate sidebands on the spectral lines. Moreover, if there is any misalignment of the trap such that the minimum of the pseudopotential does not correspond exactly to the origin of the applied quadrupole field, the result is that there is micromotion present even for a single ion at rest at the centre of the trap. In many cases, it is therefore necessary to provide additional compensation electrodes to apply a field to move the ion back to the correct position.

RF traps are often operated with drive frequencies in the range of several megahertz and with an amplitude of several hundred volts in a trap with dimensions of the order of 1 mm. This gives oscillation frequencies around 1 MHz. However, the parameters are highly dependent on the size of the trap and the strength of the confinement that is required. Generally, tighter confinement requires stronger fields and higher frequencies, so such traps are made small in order to keep the voltages required at a reasonable level.

1.3. Novel designs of traps

One way to get around the problem of micromotion when more than one ion is present is to build a trap with a different geometry. This is the linear RF trap, in which the applied ac potential gives a two-dimensional rather than a three-dimensional quadrupole. The field is set up by using four rods as electrodes and applying the ac potential between opposite pairs of rods. This gives rise to a pseudopotential which has a minimum along a line rather than at a point. Of course there is then no restoring force along the third dimension, so this is supplied using a pair of electrodes, one at each end of the trap, to which a dc potential is applied. The significance of having a pseudopotential with a line minimum is that the micromotion is therefore zero along this line. The equilibrium state for a small number of cold ions in this trap is a one-dimensional string along the central axis of the trap, and so in this state there is no micromotion for any of the ions. In contrast, if a small number of ions are present in a standard RF Paul trap, only one ion can experience no micromotion.

A further extension of this idea is to take a long linear RF trap and bring the two ends together to make a ring. In

this case, there is therefore no confinement along the axial direction and ions can in principle move around the ring while trapped radially. A trap like this can hold a very large number of ions in a linear string or a related 'crystallized' state [8, 9].

Three-dimensional RF ion traps have evolved enormously from the original design with three electrodes shaped like the equipotential surfaces for a quadrupole potential (see figure 1). Studies showed that the shapes of the trap electrodes could be changed significantly while still having a potential close to the centre of the trap that remained close to the quadrupole shape [10]. As oscillation frequencies were made higher to give tighter confinement, traps became smaller, and it became necessary to use electrode shapes that were simpler and easier to machine. Various electrode configurations were developed that allowed miniature traps to be made with excellent optical access and simple electrodes, such as a single wire ring electrode with no endcaps or two endcap structures with an open gap between them (e.g. [8, 11]).

A different approach involves the development of planar traps where electrodes are deposited on a surface. The manufacture of electrode structures in this way allows smaller structures to be developed, and in the case of linear RF traps the sizes of the traps have been reduced to much less than 1 mm using microfabrication techniques. Such techniques have been used to build traps having tens of electrodes arranged so that ions can be shuttled between different trapping sites [12]. Some planar trap designs use a single plane of electrodes (e.g. a Penning trap developed for electrons [13]); others use both sides of a chip structure [12]; others use two sets of planar electrodes (see section 3.1). One problem with the microfabricated traps that arises as dimensions reduce is that there seems to be an interaction between the trap electrode surfaces and the ion that results in heating of the motional state of the ion, which is highly undesirable. This remains a problem that needs to be solved in order to be able to further reduce the size of traps without having heating effects that destroy the coherence of quantum states [14]. Interestingly, operating miniature traps at cryogenic temperatures has been shown to greatly alleviate these problems [15].

Another technique that gives a design for a trap that can be manufactured straightforwardly is the use of wires to create the necessary potential distribution. Three parallel wires with a positive voltage on the centre wire and a negative voltage on the outer wires create two lines, one above and one below the centre wire, where the electrostatic potential has a two-dimensional saddle point. If this is combined with a second set of three wires perpendicular to the first, a three-dimensional saddle point is created between the two sets of wires [16]. A structure like this can be used to make an RF trap or, with the addition of a magnetic field perpendicular to both sets of wires, a Penning trap [17]. This is illustrated in figure 2.

One advantage offered by many of these simplified trap designs is that they can be extended in a straightforward manner to make arrays of traps rather than a single trap. This is of great interest for quantum information applications. The performance of the traps can be studied by using one of a number of simulation packages that evaluate the three-dimensional distribution of potential for a given configuration

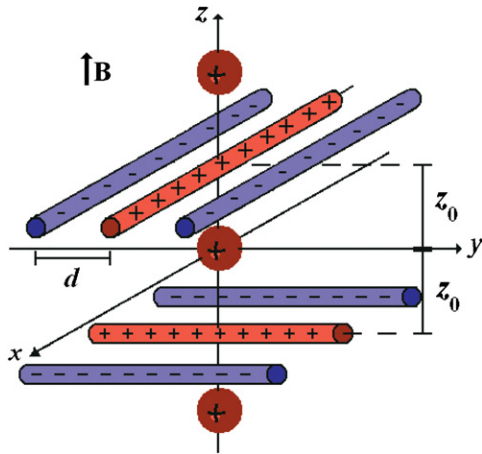


Figure 2. Two sets of wires with positive (red) and negative (blue) potentials applied, creating a three-dimensional saddle point between them where ions can be trapped. There are two additional trapping points created above and below the structure (from [16]).

of electrodes. Then one can determine how close this potential is to a quadrupole around a trapping site, and investigate how the potential can be optimized by varying the shapes of the electrodes. Also, the motion of ions can be directly simulated, in order to check what parameters are necessary for ions to be trapped and transported in real electrode structures. In this way, one can be confident that when constructed the traps will have known properties.

Other adapted geometries of traps are used for other applications. For instance, Penning traps that are designed to be used in a superconducting magnet are often made with electrodes constructed out of open cylinders. Apart from simplicity of construction, this matches the geometry of a superconducting magnet and allows good access along the axis of the trap for light or for loading and ejection of ions [18, 19]. It also gives the possibility of having a string of traps along an axis, designed so that ions can move between the traps, along the magnetic field lines.

Even with the conventional type of electrode structure, it is possible to use different operating parameters to adapt the trapping properties. The so-called ‘combined trap’ uses both a magnetic field and an RF potential at the same time, which has the effect of increasing the range of masses which can be trapped simultaneously and making the trap more stable [20]. This arrangement can even be used to trap particles of opposite charges at the same time: parameters can be chosen such that electrons can be trapped by the RF potential and ions by the magnetic field. This configuration may have application in experiments designed for the creation of antihydrogen from trapped particles [21]. A further example of non-conventional fields being generated in a trap is the use of a rotating RF potential rather than an oscillating one [22]. This is a modification to the RF trap but actually has an analytical solution to the equations of motion, whereas the Mathieu equation for a conventional RF trap only has a series solution [7].

Finally, there is actually no need to build a trap having a quadrupole potential, although this is the obvious starting

point. One recent development has been the use of traps similar to linear RF traps but with 22 rod electrodes rather than four (e.g. [23]). This has the advantage that RF micromotion only occurs at the edge of the trapping volume, though of course the motion inside the trap is no longer harmonic. These traps are finding application in the area of molecular physics.

1.4. Models of ion traps

Many ion trap research groups have built ‘model’ RF traps which illustrate the trapping principles using charged dust particles [24]. For this, it is necessary to have an applied frequency of the order of 100 Hz and an ac voltage of several hundred volts. This can be generated fairly straightforwardly using the mains supply together with a high voltage transformer. Aspects of the dynamics of trapped ions can be demonstrated with these model traps, and in fact some of the earliest work with ion trap-like devices was performed with this type of arrangement [25]. This experiment demonstrated trapping and ‘crystallization’ of particles in the trap when the motion was damped by the buffer gas.

It would be useful to be able to build a similar type of model trap to illustrate the motion of ions in a Penning trap. However, a simple calculation shows that for dust particles a magnetic field of the order of 1 MT would be required. Since this is not available in the laboratory, a different method has to be found, and the solution is to exploit the equivalence between rotation and the effect of a magnetic field introduced earlier.

Since a transformation into a rotating frame can be used to cancel out the effect of a magnetic field, there has to be an equivalent transformation that mimics the effect of a magnetic field using rotations. However, this is not as straightforward as it sounds because negative and positive rotations both produce a positive centripetal force, whereas the force from a magnetic field is in the opposite direction.

Now the radial motion of an ion in the rotating reference frame is just two-dimensional SHM, and can be represented using any simple realization of 2D SHM, for example, the motion of a ball bearing in a (stationary) parabolic dish. A ball bearing can ‘orbit’ the centre of the dish in a positive sense (cyclotron motion) or in a negative sense (magnetron motion). Elliptical motion represents the most general case, corresponding to a superposition of positive and negative rotations in the trap’s rotating frame and cyclotron and magnetron motions in the laboratory frame [6].

This is not very useful and does not illustrate what the motion is like in the laboratory frame of the trap. However, the application of an appropriate rotation should give the correct transformation to allow the trap motion to be observed. It can be shown that it is not rotation of the dish that is required (this would in any case not affect the motion, in the absence of friction!) but rather rotation of the point of view of the observer. In other words, it is the observer that needs to move into a frame that rotates relative to the dish in order to see the true Penning trap motion. The way to realize this is to observe with a camera that is fixed to a rotating mount; the rate of rotation has to be somewhat faster than the oscillation frequency in the dish [24]. With this set-up, it is possible to

demonstrate all the different types of motions in the Penning trap, including the effect of axialization to be discussed in section 2.2.

2. Laser cooling in ion traps

2.1. Principles of laser cooling

Laser cooling, as mentioned above, was first proposed for trapped ions in 1975 [2] at around the same time as it was proposed for neutral atoms [26]. It uses the radiation pressure of light to exert a damping force on ions, and the Doppler effect to turn this force on and off depending on whether the ion is moving towards the laser or away from the laser. The technique is elegant, effective and relatively straightforward to implement for both RF traps and Penning traps. Laser cooling has been described in many papers, for example [27], and we will not treat it in detail here. However, we list the most important features of laser cooling in the context of this paper:

- The force on the ion arises from an excitation by the laser followed by a spontaneous decay back to the ground state.
- Laser cooling requires an ion with a simple level structure. This limits the number of species of ions that can be directly laser cooled to around ten.
- The atomic transitions must be strongly allowed and accessible by narrowband CW lasers.
- If the ion can also decay to other states apart from the ground state, lasers must be supplied to empty these states and return the ion to the cooling cycle.
- The laser must be detuned to the red side of the transition so that the transition rate and force are greater when the ion is moving towards the laser and weaker when it is moving away from the laser.
- Under ideal conditions the minimum temperature reached with this ‘Doppler cooling’ is given by $kT = \hbar\gamma/2$ where γ is the natural linewidth of the transition. A typical value for T is 1 mK.
- In order to cool from room temperature to the Doppler limit, typically 10 000 excitations are necessary, so the ion must return to the ground state rapidly for laser cooling to be effective.

Laser cooling is used routinely for cooling single ions and clouds of ions of a limited number of singly ionized species. Most of this work has been performed in RF traps. If several ions are present, cold ions condense into a ‘crystal’ structure where they take up fixed positions relative to each other. The typical separation of ions in such a crystal is of the order of 10 μm . Since the outer ions experience micromotion, there is a practical limit to the number of ions that can be crystallized in this way. Linear traps also allow crystals to be formed, and in this case the effect of micromotion can be less because of the linear geometry which guarantees that more ions are close to a zero-micromotion point.

Doppler cooling as described above is only able to bring the temperature down to around 1 mK at best. However, when an ion is tightly bound in the trap, one can reach a situation where the spectrum of an atomic transition becomes a carrier

with discrete sidebands rather than the continuous Doppler-broadened profile which is obtained with a weakly bound cloud of ions. It is often desirable to reach the situation where only the first-order sidebands are present, as the quantum state of the particle can then be manipulated precisely. This is termed the ‘Lamb–Dicke’ regime, and the criterion for reaching this regime is that the amplitude of the motion of the ion is much less than the wavelength of the light. It is reached by exciting the ion on the first red sideband of a weak transition, a process called ‘sideband cooling’ which can be seen as an example of optical pumping. It results in the ion occupying the quantum mechanical ground state of the potential most of the time, with an effective temperature well below the Doppler limit. Most experiments in the areas of high-resolution spectroscopy and quantum information with trapped ions require the ions to be in this regime. Other techniques are also available for reducing the temperature further, but these are outside the scope of this paper (see, for example, [28]).

2.2. Laser cooling in the Penning trap

In Penning traps, the situation is complicated by the presence of the magnetic field which splits the atomic levels by large amounts compared to the laser linewidth. Although an elegant optical pumping technique can be used to overcome this for Mg^+ and Be^+ , where decay to the ground state is the only possibility (e.g. [3]), this is not available for other ions and, for example, in Ca^+ it is necessary to use a minimum of six laser frequencies to obtain effective laser cooling [29].

Another problem with laser cooling in the Penning trap is the magnetron motion. In the same way as for buffer gas cooling, laser cooling would normally only be effective for the cyclotron and axial motions, and would actually heat the magnetron motion. It was discovered very early on that the way to avoid this was to offset the laser beam from the centre of the trap [27]. This procedure does work well but it remains true that the magnetron motion is not cooled as effectively as the cyclotron motion. With large ion clouds this limits the final density of ions when laser cooled. This can be overcome using the ‘rotating wall’ technique [30] where a rotating dipole or quadrupole field is applied to the trap and is used to increase the rotation speed of the cloud, which is related to the magnetron motion for a single ion. It can be shown that the rotation speed is closely linked to the density of ions, so in this way the density of the laser-cooled cloud can be increased.

For single ions the non-ideal cooling of the magnetron motion leads to the ion not being as well localized as might be expected from the Doppler limit temperature. One way of tackling this is to use an additional oscillating field with a small amplitude to couple together the two modes of motion in the radial plane. This ‘axialization’ technique transfers energy between the magnetron and cyclotron modes, and the strong cyclotron cooling is then dominant so that the end result is that the magnetron motion is also cooled via the coupling set up by the additional field [31, 32]. This is simply a case of two coupled oscillators where one oscillator is strongly damped.

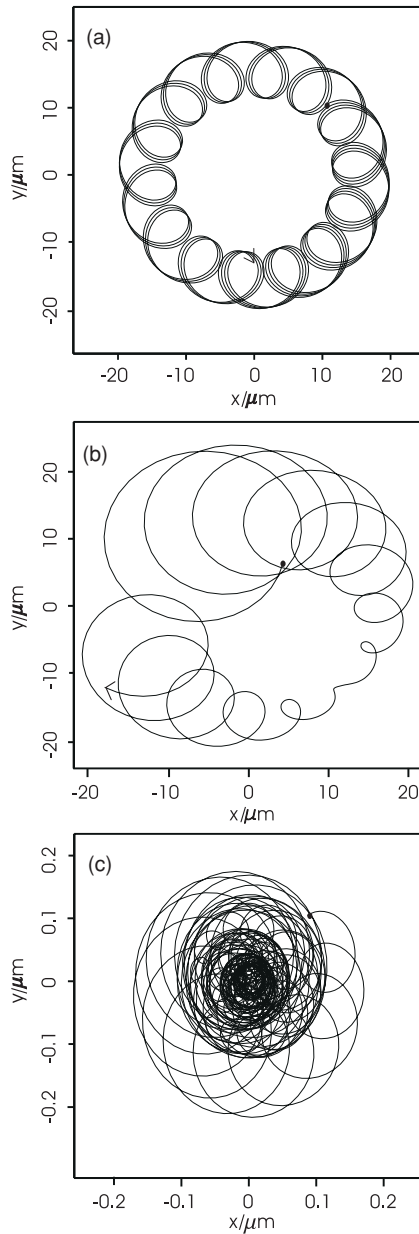


Figure 3. Simulation of ion motion in the radial plane of the Penning trap: (a) stable motion in the trap in the absence of external fields, consisting of fast cyclotron and slow magnetron motions; (b) effect of the axialization drive, which causes energy to be exchanged between the cyclotron and magnetron motions; (c) effect of adding weak laser cooling so that both motions are cooled.

Figure 3 shows a simulation of axialization with laser cooling. We discuss an experimental realization of this technique in section 3.1. A similar technique is also used in combination with buffer-gas cooling in mass spectrometry experiments with trapped ions [33].

It is possible to understand the effect of the axializing field by extending the idea of coupled oscillators. The frequency of the applied field in axialization is the cyclotron frequency ω_c , and it is applied with a quadrupole symmetry. In order to do this, the ring electrode is split into four segments and the potential is applied between the two pairs of opposite quadrants. This oscillating radial quadrupole field can be

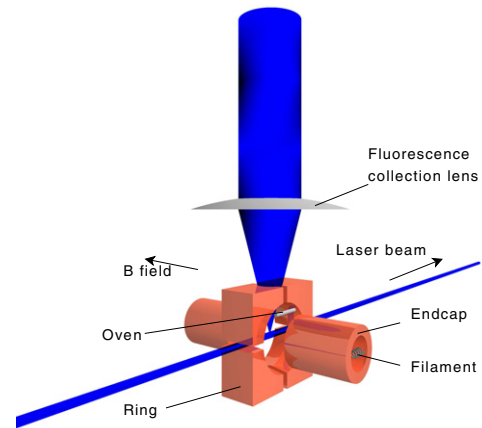


Figure 4. Diagram of the split ring Penning trap used for trapping calcium ions (from [34]).

shown to be exactly equivalent to two counter-rotating static (i.e. non-oscillating) quadrupoles with the rotation frequency of $\pm\omega_c/2$. Therefore in the Penning trap rotating frame this gives a stationary quadrupole potential together with another quadrupole rotating at $-\omega_c$ (this field can be neglected as it is not resonant with any other oscillation frequency in this frame). The stationary quadrupole distorts the parabolic dish-shaped potential in the rotating frame so that it no longer has equal curvature along perpendicular axes. In fact the normal modes in this frame are no longer degenerate as they were before but rather they are perpendicular linear oscillations at slightly different frequencies.

Consider initially pure cyclotron motion, corresponding to a positive sense of rotation in the rotating frame. This can be decomposed into equal amplitudes of each of the normal modes. These have slightly different frequencies so the effect is that the motion in this frame evolves from rotation in a positive sense to linear motion at 45° to the principal axes to rotation in a negative sense, corresponding to the magnetron motion (and so on). So the coupling between magnetron and cyclotron motions can therefore be seen simply as the evolution of the two non-degenerate normal modes of the system. The result is an interchange between cyclotron and magnetron motions (see figure 3(b)), and because energy is drawn out of the cyclotron motion by the laser cooling, this eventually results in cooling of both motions (see figure 3(c)).

Now let us return to the ‘model’ Penning trap. Axialization can be demonstrated with the model by distorting the dish potential, representing the potential seen in the rotating frame of the Penning trap. The distortion takes the form of a slight squeezing together of opposite sides of the dish. It can then be shown that the only stable motions are linear oscillation in the direction of the squeeze and perpendicular to it. But if the ball bearing is set in motion in a circle, the path evolves first into a linear motion and then into a circular motion in the opposite direction and back again, as expected. When this is viewed with the rotating camera, giving the view of the motion as it should be in the Penning trap laboratory frame, one can observe the magnetron motion evolving into cyclotron motion and back again, as illustrated in figure 3(b).

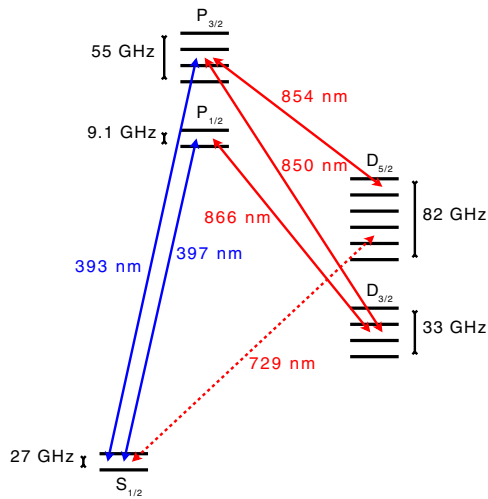


Figure 5. Simplified energy level diagram of $^{40}\text{Ca}^+$ in a magnetic field close to 1 T showing the Zeeman splittings (not to scale) (from [34]).

Unfortunately it is not possible to demonstrate the effect of laser cooling using the model: although the motions gradually decay away, this is because of friction and does not represent accurately the effect of the interaction with the laser.

3. Experiments with laser-cooled calcium ions in a Penning trap

3.1. Images of one and two ions

At Imperial College London, we work with calcium ions in a Penning trap. A diagram of the trap is shown in figure 4. The electrodes are made of OFHC copper and are machined with

conical cross sections that give a close approximation to a pure quadrupole potential at the trap centre [35]. A minimum of six laser beams are required for laser cooling in this system (see figure 5): two at 397 nm for the resonance transition from the $^2\text{S}_{1/2}$ state to the $^2\text{P}_{1/2}$ state and four at 866 nm to drive ions out of the $^2\text{D}_{3/2}$ state into which they can decay from $^2\text{P}_{1/2}$. We also generally use another laser at 854 nm for emptying the $^2\text{D}_{5/2}$ state. Ions are loaded into the trap by heating a small oven made of a tantalum tube containing filings of Ca metal, and the atoms are then ionized at the centre of the trap with electrons from a heated filament located behind one of the endcaps. Once ions are loaded in the trap, we are able to observe their fluorescence at 397 nm using a photomultiplier. We detect about 3000 counts per second per ion.

When ions decay from the $^2\text{P}_{1/2}$ state, they can generally only decay to the $^2\text{S}_{1/2}$ ground state or the $^2\text{D}_{3/2}$ state. However, in the presence of the magnetic field of the Penning trap, the decay to $^2\text{D}_{5/2}$ becomes allowed through J -mixing of states of equal M_J but different J [36]. As a result of this, we see periods where the fluorescence from a single ion stops due to quantum jumps into this state. These jumps are nearly eliminated if the 854 nm laser is present but otherwise they result in the fluorescence turning on and off randomly. When two or three ions are present in the trap, they all undergo quantum jumps independently so the fluorescence has a definite number of levels, which can be clearly seen in figure 6.

Instead of simply counting the fluorescence photons from ions, it is also possible to image them using an intensified CCD camera. In this way, we can see the images shown in figure 7 for one and two ions. These images are obtained with the axialization potential applied. Without this the cooling is weaker and the orbit is larger. The size of the image of a single

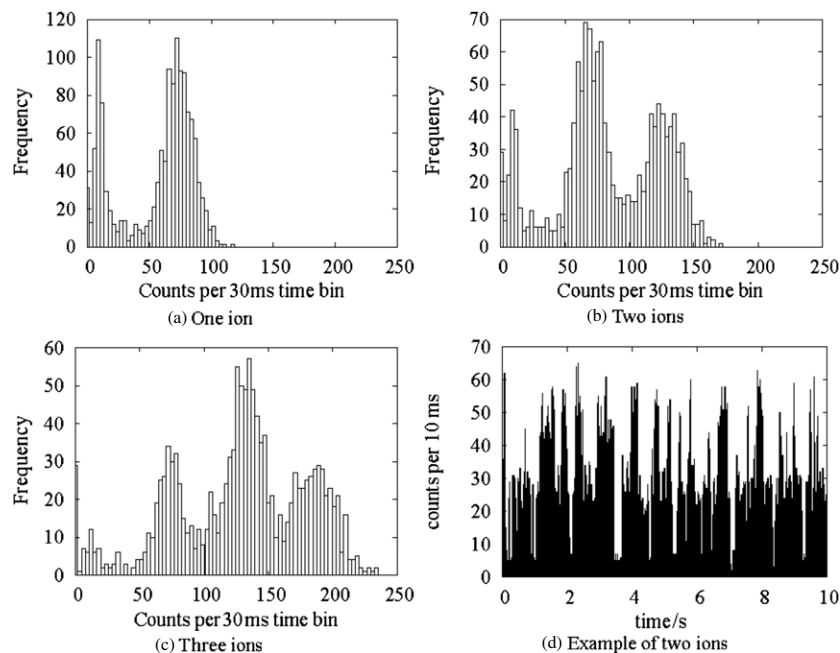


Figure 6. Histograms of the fluorescence signal for 1, 2 and 3 ions together with a plot of the observed fluorescence counts for 2 ions. Different levels corresponding to different numbers of fluorescing ions can clearly be seen. The bin time is 30 ms in all cases (from [34]).

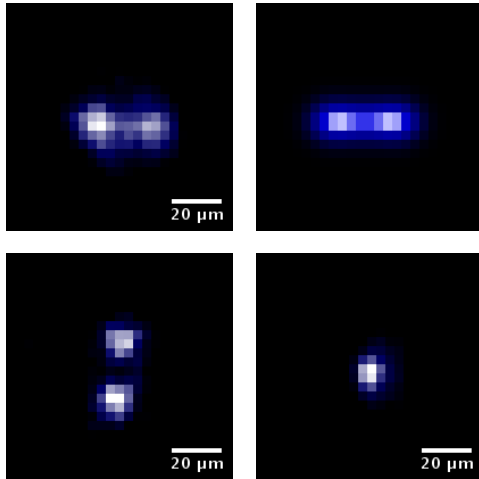


Figure 7. Images of axialized Ca^+ ions in a Penning trap. The magnetic field axis is vertical. (a) two ions in the radial plane; (b) theoretical fit of (a); (c) two ions in an axial crystal; (d) single ion (from [34]).

ion in figure 7 is limited by the imaging optics, not by the size of the orbit which is likely to be significantly smaller than $10 \mu\text{m}$. Two ions in a Penning trap can arrange themselves either along the axis of the trap or in the radial plane. If they lie in the radial plane, they will rotate around the centre of the trap so an image of the fluorescing ions viewed perpendicular to the axis will be a line with two bright spots corresponding to the two edges of the orbit. Both ions contribute to both spots as they orbit the trap centre. The orientation taken by two ions depends on both the trapping parameters and the laser cooling. For strong axial confinement (high voltage applied to the trap), the equilibrium configuration is in the radial plane and the minimum separation of the ions can be calculated from first principles to be equal to $(e^2/16\pi\epsilon_0 m\omega_1^2)^{1/3}$ [6]. For lower axial confinement and strong cooling, the equilibrium configuration is an axial ‘crystal’ where the ions are both located on the trap axis. In this case the image is two spots, one for each ion, and the separation is $(e^2/16\pi\epsilon_0 m\omega_z^2)^{1/3}$. In order to achieve this configuration, we found it necessary to apply the axialization as otherwise the ions remain in the radial plane [34].

3.2. Ion shuttling

Much effort worldwide has gone into studies of quantum information processing (QIP) with trapped ions. This appears to be one of the best systems in which QIP can be demonstrated and much progress has been made (see, for example, [12, 37, 38] and references therein). Most of this work has been performed using linear RF traps with strings of up to 8 ions along the axis of the trap. The communication of information between the ions makes use of the vibrational motion of the ion string. However, it has become clear that in order to demonstrate QIP with large numbers of qubits, it will not be possible to use a single trap because the motional spectrum becomes ever more complex with larger numbers of ions and it becomes more difficult to maintain the string of

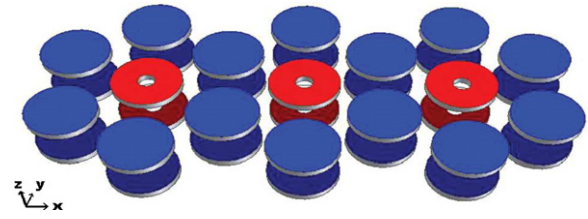


Figure 8. Electrode structure of the printed circuit board trap showing three separate trapping zones. The magnetic field direction is perpendicular to the plane of the electrodes (from [17]).

ions and to address individual ions. Attention has therefore shifted to systems where ions can be moved about between separate micro-traps, so that two ions can be brought into contact in order to perform a quantum gate before they are separated again [39]. In this system, ions are shuttled into and out of a quantum memory and some type of junction is required in order to allow different ions to be selected. The technology required for this, including the provision of many traps on a microfabricated chip, is very complex, especially the requirement for moving ions around a corner in a junction. The protocols for shuttling ions are also very complex because of the need to keep the ion in a potential well all the time it is moving. A separate approach is to use arrays of Penning traps. Shuttling of ions along the magnetic field direction is straightforward and is in common use in the mass spectrometry community [33]. However, shuttling of ions in a direction perpendicular to the magnetic field between separate Penning traps is problematical. We decided to investigate a possible method for this using well-timed pulsed electric fields and exploiting the cycloid motion of an ion in the presence of a magnetic field.

The trap for this work is of a novel design based on the use of a vacuum-compatible printed circuit board. Details of the design, which used a hexagonal array of electrodes to create trapping zones, are given in [40]. Figure 8 shows the layout for three adjacent traps where electrodes coloured red represent endcaps and those coloured blue act as the ring electrodes. Since all electrodes are deposited onto the two circuit boards, which are facing each other, ions may move freely between different trapping zones under the influence of appropriate fields. The separation of the two circuit boards is 5 mm and the distance between trap centres is approximately 10 mm.

Although the individual traps have hexagonal symmetry and the electrodes are planar, it can be shown with simulations that the potential generated inside the traps follows the desired quadrupole closely. Ions are therefore expected to be trapped effectively within each of the trapping zones, and this is what we find.

In order to move ions from one trap to the adjacent one, the normal trapping field is replaced by an essentially linear electric field parallel to the circuit boards, by applying different voltages to the five rows of electrodes shown in figure 8. The effect of this is to move ions from one trap in a cycloid loop in a direction perpendicular to both the magnetic field and the electric field. The linear field has to be present for approximately one period of the cyclotron frequency, which in this case is only about $2.5 \mu\text{s}$ and is independent of the

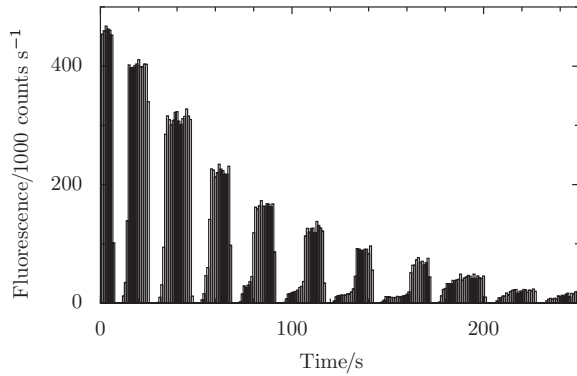


Figure 9. Fluorescence signal after shuttling ions from one trap to the other (where no fluorescence is observed) and then back again. Ten cycles of shuttling are shown (from [40]).

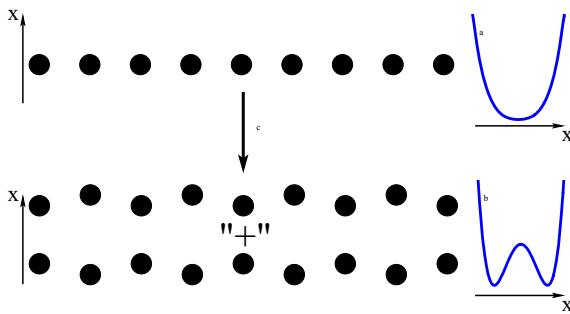


Figure 10. Multiple ions in a trap in a linear configuration and in a degenerate zig-zag configuration (from [41]).

distance between the trap centres. After this time the ions are automatically brought to rest again and if the strength of the field is correctly chosen, they end up at the centre of the next trap. It can also be shown that the ion remains in an axial potential minimum all the time, so it will not be attracted towards either of the boards.

In experiments we found this process to be very effective [40]. Small clouds of ions can be shuttled from one trap to another and back again with an efficiency of better than 80%, as can be seen in figure 9. We expect to be able to optimize this technique so that it works well with single ions by adjusting the parameters for the shuttling, in particular the voltages and times. Future plans include miniaturizing the trap structure and integrating it with a linear array of traps along the axial direction to allow for moving ions at will into a privileged trap in which qubit operations can be performed.

4. Phase transitions in ion chains

Phase transitions in physical systems have been of interest for many years, especially in the quantum regime. However, one problem with investigations of quantum phase transitions is that it is difficult to find a system which can be well controlled and that is theoretically tractable. One possibility is to study transitions between different states of a string of ions confined in an ion trap [41]. Figure 10 shows schematically a string of ions confined in an equilibrium state along the axis of

a trap. This might be a linear RF trap or a Penning trap (viewed in the rotating frame). The number of ions is not critical. If the trapping parameters are changed so that the confinement along the x -direction becomes weaker, the ions will eventually rearrange themselves in a zig-zag configuration because this has a lower energy than the linear string (see figure 10). However, there are two degenerate zig-zag configurations, with one a mirror image of the other. This means that the whole system is effectively in a double-well potential with an energy barrier between the two states.

There are two points to make about this system. The first is that the transition from linear string to zig-zag can be carried out in a well-controlled and reproducible manner by varying the trapping parameters, which makes it an ideal system for investigation. The second point is that by careful choice of the parameters, the system can be prepared in a superposition of two states in which the system possesses exactly one localized quantum state in each of the potential wells. This means that the phase transition becomes a quantum mechanical process. The well-established techniques of experimental QIP can be used to prepare the ions in a well-defined initial state and to detect the state of the system after a set interaction time, in order to determine whether a phase transition has taken place and whether there is tunnelling between the two potential wells. Calculations show that it is feasible to observe these effects with realistic values for the operational parameters of the trap with various numbers of ions in the trap.

It is important to note that in order to reach this regime it is necessary to have the two potential wells separated by a distance comparable to the width of the ground-state wavefunction of the system. This cannot be achieved by using a single ion and imposing an external double-well potential using miniature electrodes, as they cannot be manufactured to be small enough to generate the correct potential shape. In this system, however, the double well is created by the available states of the ion string. The system of a string of ions is therefore a very powerful system in which to investigate the dynamics of quantum phase transitions and quantum tunnelling [41]. This is just one example of novel applications of trapped ions in new areas of physics.

5. Conclusions

In the last 40 years, ion traps have been at the forefront of many important developments in physics. In particular, laser cooling in both Penning traps and RF traps has enabled new experiments to be performed in the areas of quantum information processing, quantum optics and spectroscopy that were previously impossible. In future, novel traps with new geometries and carefully chosen operating conditions promise more advances that will enhance our understanding of fundamental processes in physics.

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