We describe experiments aimed at assessing the suitability of ions held in a Penning trap as a candidate system for quantum information processing (QIP). In an experiment employing $^{39}$Mg ions we have demonstrated a method that improves Doppler cooling in the Penning trap, resulting in ions that are more tightly localized than would otherwise be the case. Our measurements show that cooling of the magnetron motion is improved using this novel scheme. All the simply charged alkali-earth anions apart from Be$^+$ and Mg$^+$ have metastable D states that can be used for localisation for laser cooling. As a result, up until now, only these two species have been laser cooled in a Penning trap. In a separate experiment we have performed Doppler cooling of Ca$^+$ ions in a Penning trap for the first time.

We report on progress in experiments aimed at assessing individually addressable laser cooled ionic beams in a Penning trap as a candidate system for Quantum Information Processing (QIP). The Penning trap employs static electric and magnetic fields as opposed to the oscillating electric field employed in the more familiar radio frequency Paul or linear traps. As a result, the decoherence rate may prove to be significantly lower in this system. The motion of an ion in a Penning trap consists of a harmonic oscillation in the electronic potential well along the axis of the trap and an epicyclic superposition of two circular motions in the radial plane: the modified cyclotron motion and a slower ES drift around the centre of the trap, the magnetron motion. As a result of the rather complicated motion of ions in a Penning trap, laser cooling is less straightforward than it is in a radio frequency trap. One consequence is that the cooling laser beam must be offset from the centre of the trap. The magnetron motion is particularly difficult to manipulate and can lead to severe consequences for laser cooling. As a result, up until now, only these two species have been laser cooled in a Penning trap. In a separate experiment we have performed Doppler cooling of Ca$^+$ ions in a Penning trap for the first time.

**Introduction**

Axialisation

Axialisation is the process by which particles in a Penning trap are driven towards the central axis of the trap [1]. It occurs when the efficient cooling of the cyclotron motion is effectively extended to the magnetron motion by means of a coupling between the two. Axialisation has been used in conjunction with better gain cooling to increase storage times in Penning traps and to increase the density of ion clouds. Combined with laser cooling, very low temperatures should be achievable. The process can be described by the following equations:

\[
\frac{d\gamma}{dt} = \frac{\gamma}{\gamma_0} - \frac{\gamma_0}{\gamma} - \frac{\gamma_0}{\gamma_1} - \frac{\gamma_1}{\gamma} - \frac{\gamma_1}{\gamma_2} - \frac{\gamma_2}{\gamma},
\]

where $\gamma_0, \gamma_1, \gamma_2$ and $\gamma_3$ are the cooling rates for the three motions and it is the coupling rate due to the rf field. Various solutions to these equations can be found. In Figure 1 we show simulations of (a) oscillation between magnetron and cyclotron motions when the damping rates are zero (b) axialisation when $\gamma_0 < \gamma_1 < \gamma_2 < \gamma_3$ and (c) a stable orbit with finite radii $\gamma_1 < \gamma_0$. The parameters in (a) to (c) are the same and laser cooling with Doppler cooling are large and of opposite sign, the orbit expands, reducing the interaction with the laser beam, until the equality is satisfied. Notice that with laser cooling the values of the damping coefficients can be varied by changing the laser frequency and position.

**Axialisation**

The trap was used in initial experiments as a conventional Penning trap for which the inner diameter of the ring electrode is 15 mm and the separations in $+ve$ or $−ve$ are 3 mm. The magnetic field is applied along the axis of the trap between the two ends. With the excitation stilts offset it is possible to run the trap as a conventional Penning trap [2]. The laser beams enter the ring electrode through a hole in the photomultiplier tube (PMT) assembly. A T-950 Trollope laser for the purposes of Doppler cooling, the 950 nm and 854 nm transitions can be accented using double lasers. One major complication for Ca$^+$ in a Penning trap is that far field lasers near 950 nm are required to cover the two hyperfine components of the $3s^2\,^1S_0\rightarrow 3p^2\,^1P^0(854\,\text{nm})$ transition. At the same time, the 854 nm transition sits outside the products of a laser cooling scheme. This laser power can be focussed to a spot in the trap this amount of laser power can easily saturate the cooling transition (the saturation power is 10 mW). The experiment was carried out using either a Nd:YAG or a Ti:Sapphire laser. The magnetron motion is particularly difficult to manipulate and can lead to severe consequences for laser cooling. As a result, up until now, only these two species have been laser cooled in a Penning trap. In a separate experiment we have performed Doppler cooling of Ca$^+$ ions in a Penning trap for the first time.

**Doppler cooling of Ca$^+$ in a Penning Trap**

The relevant energy levels for Ca$^+$ are shown in Figure 3. In contrast to Be$^+$ and Mg$^+$, the Doppler cooling of Ca$^+$ is an axial process. The magnetic field is applied along the axis of the trap between the two ends. With the excitation stilts offset it is possible to run the trap as a conventional Penning trap [2]. The laser beams enter the ring electrode through a hole in the photomultiplier tube (PMT) assembly. A T-950 Trollope laser for the purposes of Doppler cooling, the 950 nm and 854 nm transitions can be accented using double lasers. One major complication for Ca$^+$ in a Penning trap is that far field lasers near 950 nm are required to cover the two hyperfine components of the $3s^2\,^1S_0\rightarrow 3p^2\,^1P^0(854\,\text{nm})$ transition. At the same time, the 854 nm transition sits outside the products of a laser cooling scheme. This laser power can be focussed to a spot in the trap this amount of laser power can easily saturate the cooling transition (the saturation power is 10 mW). The experiment was carried out using either a Nd:YAG or a Ti:Sapphire laser. The magnetron motion is particularly difficult to manipulate and can lead to severe consequences for laser cooling. As a result, up until now, only these two species have been laser cooled in a Penning trap. In a separate experiment we have performed Doppler cooling of Ca$^+$ ions in a Penning trap for the first time.

**Experiment**

**Results**

One blue laser is scanned from below resonance up to resonance in 1 s and the fluorescent signal is plotted. Figure 5 shows a fluorescent trace for a small cloud of ions laser cooled in this way. The minimum temperature is limited by the difficulty associated with effectively cooling the magnetron motion. In general therefore one would not expect to achieve cooling to the Doppler limit in the Penning trap. An upper bound on the sensitivity of the ions can be estimated from the width of the trace. For the traces shown in figure 6 it is found to be ~ 1 K.

**Conclusions**

We have demonstrated that axialisation can be used in conjunction with laser cooling to give very tight confinement of a single ion to the axis of a Penning trap. The laser cooling rate can be significantly enhanced by this mechanism. We have also demonstrated the trapping and laser cooling of Ca$^+$ in a Penning trap. We have therefore overcome some of the major objections to using singly ionized ions held in Penning traps as a resource for QIP. The next step in this research will be to trap and laser cool a single Ca$^+$ ion in our Penning trap and perform axialisation in this system. We are also developing a narrow linewidth 729 nm laser system which we will use to perform sideband cooling and also as a means of measuring the decoherence rate in our system.

**References**