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A double Paul trap system for the electronic coupling of ions

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Abstract. We report on the progress towards the implementation of a double trap system for the coupling of ion clouds stored in different traps through the charges they induce in a common electrode. The two traps have cylindrical symmetry and can be used either as Penning or Paul traps. The laser system for Doppler cooling of $^{40}Ca^{+}$ clouds is described. The cooling can be performed differentially in the two traps, aiming at the study of the coupling between two clouds of ions at different temperatures. This setup is the starting point for the realization of energy transfer between two Doppler-cooled ions stored in different traps. We report on the status of the experiment and evaluate the performance required for an efficient coupling.

1 Introduction

The electronic coupling of two ions stored in different traps through a common electrode is a technological challenge that has not been accomplished so far. Such a technology would allow extending the applicability of precision Penning-trap mass spectrometry [1], the development of devices for the detection of weak radio frequency (RF) signals [2–4] or contributing to build a scalable platform for quantum computing [5]. This approach appears as an alternative to other spectroscopic techniques or experiments in quantum optics where two ions are stored in nearby traps and allowed to interact through Coulomb interaction [6–8].

There are several technological challenges that have to be solved prior to the establishment of this technique. In particular, it requires very low levels of noise on the common electrode and very high stability of the oscillation frequency and phase of the trapped ions. At least two groups have been working on the coupling of two ions in different traps during the last years. The group of Prof. Häffner in Berkeley has been working on the feasibility of transferring quantum information between two trapped ions electronically connected through a wire. Their approach is based on the use of planar Paul traps with characteristic sizes on the micrometer scale [5]. Our group

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in Granada has been developing a system to connect two ions stored in different Penning traps with the aim of sympathetically cooling and measuring the mass of super-heavy elements [1,9]. Recently, other group has started the implementation of a similar scheme [10], proposing a double Penning-trap experiment where a cloud of laser-cooled beryllium ions can be used to sympathetically cool protons and anti-protons in an adjacent trap for an ultra-high precision comparison of their properties.

There is another yet experimentally unexplored field where the development of this technology might have a major impact, namely the field of hybrid coupled systems. It has been proposed that a similar scheme could be applied to couple a single ion to other types of oscillators like RF electrical circuits, micro and nano-mechanical resonators and superconducting LC circuits, to name but a few [2,11,12]. These implementations will benefit from the technology being developed for the connection of two ions in different traps, paving the way to many novel applications in the field of quantum technologies.

In this work, we report on the first tests of a double Paul trap system built at the University of Granada and propose a proof-of-concept experiment that could be performed to test the feasibility of common endcap coupling. The system is based on a design devised to work as a Penning trap inside a 7-T superconducting magnet [1, 13–16]. Prior to its implementation inside the magnet, an intermediate step to test the electronics that feed the RF signal to the traps and the electrical connection between ions will facilitate the future development of the project. This also opens the way to new experimental studies where the connection of two clouds of ions laser-cooled to different temperatures can be used to investigate energy exchanges at the microscale in a controlled manner.

2 The coupling through a common endcap

The coupling of two ions in different traps via induced currents was first proposed in Ref. [2]. A singly charged particle of mass m is bound in an ion trap by electromagnetic fields and is laser-cooled. It induces an image charge on an adjacent electrode given by $q_{\rm ind} = ez/d$, where e is the elementary charge, z is the displacement of the charged particle from its equilibrium position and d is the effective distance between the electrodes, i.e., $d = 2z_0/\alpha$, where $2z_0$ is approximately the axial distance between the two endcap electrodes and α is a geometric factor that accounts for the deviation of the electrode configuration from the ideal hyperbolic geometry ($\alpha \leq 1$). Due to the motion of the ion in the trap, there will be a current flowing in the electrode, given by the time derivative of $q_{\rm ind}$, i.e., $i_{\rm ind} = e\dot{z}/d$. If we consider that a cloud with N ions is trapped, the current induced in an adjacent electrode will be:

$$I_{\rm ind} = \frac{Ne\dot{Z}}{d}, \tag{1}$$

where Z is the axial position of the center-of-mass (COM) of the cloud, and $\dot{Z}$ its time derivative. The induced current couples the motion of the ion cloud with that of a second cloud stored in the other trap. It has been shown that the dynamics of the coupled system can be easily understood considering an electrical analogue (see Fig. 1) [2,12]. The two ion clouds are equivalent to two series RLC circuits connected by shunt capacitors $C_{\rm trap,1,2}$. Doppler laser-cooling of the ions [17] leads to an effective damping rate $\gamma_{1,2}$ that reduces their average energy, and it is considered as energy dissipation in the electrical simile through the resistances $R_{1,2}$. In our notation, $\gamma_{1,2}$ also includes the effect of coupling of the CM mode to the internal degrees of freedom of the cloud [18].

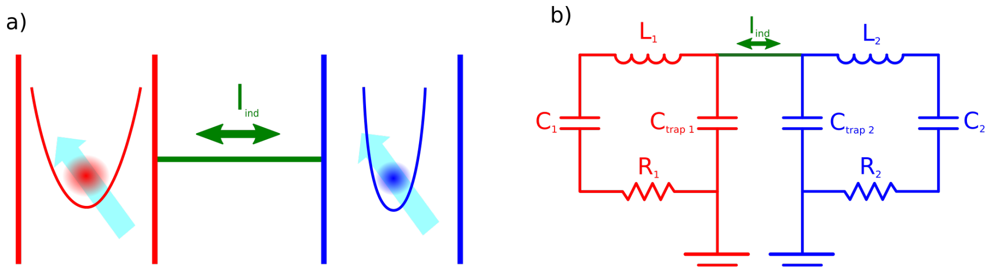

Fig. 1. Connecting ions in different traps. a) Sketch of the experiment, where two ions or clouds of ions stored in different traps are allowed to interact through the currents $I_{\rm ind}$ they induce in a common electrode. The traps are illustrated as parabolic potential wells created by parallel plate capacitors, though the electrodes will in general have a different geometry. Laser cooling beams, depicted by the light-blue arrows, can be used to set different temperatures for each ion cloud. b) The electrical response of the laser-cooled trapped ion is equivalent to an RLC circuit in parallel with the capacitance of the electrodes of the trap $C_{\rm trap}$.

We are interested in the resonant coupling, and therefore we assume that the two ion clouds, hence the two RLC circuits, have the same effective resonant frequency ω_0. Note that one can consider different properties of the traps and the ions stored in each trap, and hence we also distinguish between m_i, N_i and d_i with $i = 1, 2$ referring to trap 1 and 2, respectively. The only constraint is that ω_0 is the same in both traps. The relation between the parameters of the equivalent circuit and the real system is given by [2,18]:

$$L_i = \frac{m_i d_i^2}{N_i e^2} \tag{2}$$

$$R_i = \frac{m_i d_i^2 \gamma_i}{N_i e^2} = \gamma_i L_i \tag{3}$$

$$C_i = \frac{N_i e^2}{m_i d_i^2 \omega_0^2} = \frac{1}{L_i \omega_0^2} \tag{4}$$

where L_i, R_i and C_i with $i = 1, 2$ are equivalent inductance, resistance and capacitance of each cloud, respectively. As an illustration, $C_i \simeq 3.8 \times 10^{-17}$ F and $L_i \simeq 6.6 \times 10^4$ H for a cloud with 100 $^{40}Ca^+$ ions in the present geometry when $\omega_0 = 2\pi \times 100$ kHz. An important parameter is the quality factor $Q_f = \omega_0/\Delta\omega$ of the equivalent circuit, where $\Delta\omega$ is the width of the resonance. This can be expressed in terms of the properties of the RLC series circuit as:

$$Q_{f,i} = \frac{1}{R_i}\sqrt{\frac{L_i}{C_i}} = \frac{m_i d_i^2}{R_i N_i e^2}\omega_0 \tag{5}$$

which is inversely proportional to the number of ions in the cloud. We note here that an efficient coupling requires that ω_0 is the same for both clouds, but they can have a different width of their resonance, i.e., a different Q_f. For the illustration mentioned above, $Q_f \simeq 7 \times 10^{11}$. We can quantify the interaction via the coupling rate g, which tells how fast the two systems exchange energy. If $g \ll \omega_0$, it can be expressed as [12]:

$$g = \frac{\omega_0}{2}\sqrt{\frac{C_1 C_2}{(C_1 + C)(C_2 + C)}} \tag{6}$$

with $C = C_{\text{trap},1} + C_{\text{trap},2}$ the total capacitance of the connecting electrodes. At resonance, the two oscillators exchange their motional energies after a time $\tau_{\text{ex}} = \pi/2g$. In terms of the equivalent circuit, and assuming $C \gg C_{1,2}$, we find that the time needed for such an exchange is:

$$\tau_{\text{ex}} = \pi\omega_0 C\sqrt{L_1 L_2} \tag{7}$$

It is instructive to write Eqs. (6) and (7) in terms of the physically meaningful quantities of the clouds:

$$g = \frac{e^2}{2\omega_0 C d_1 d_2}\sqrt{\frac{N_1 N_2}{m_1 m_2}} \tag{8}$$

$$\tau_{\text{ex}} = \frac{\pi\omega_0 C d_1 d_2}{e^2}\sqrt{\frac{m_1 m_2}{N_1 N_2}} \tag{9}$$

Finally, we shall mention that an efficient coupling requires that the two oscillators have the same frequency down to an uncertainty smaller than the inverse exchange time, hence $\Delta\omega_0 = |\omega_{0,1} - \omega_{0,2}| < \pi/\tau_{\text{ex}}$ [19], posing challenges in the implementation of the technique.

The coupling between the two systems can be used for several purposes [1,2,5]. In the simplest scenario, one ion in one trap that is continuously laser-cooled (sensor ion) can be used to sympathetically cool another one in a second trap that cannot be laser-cooled nor optically interrogated (problem ion), see Fig. 1. Interestingly, the connection between the two traps can be switched on and off by setting an off-resonant condition via the trapping potentials, and therefore more complex schemes can be envisioned. For example, once the two ions achieve a steady state, the interaction can be switched off and one mode of the problem ion can be excited. By further allowing the interaction, the motional state of the problem ion can be transferred to the sensor ion while laser-cooling is off. By monitoring the fluorescence after laser cooling is switched on again, one can probe the oscillation frequency of the problem ion. Instead of two individual ions, coupling between two ion clouds or one ion and an ion cloud can also be considered, depending on the intended application. In the next sections, we discuss technical issues leading to a proof-of-concept experiment to implement the cooling of a single ion by a laser-cooled cloud.

3 Experimental setup

3.1 The double Paul trap system.

In our experiment, $^{40}\text{Ca}^+$ ions are confined in a double-trap system with rotational symmetry around the z-axis [16] that is operated as double Paul trap. The trapping in a Paul trap is achieved by applying an RF electric potential to a set of electrodes that creates a quadrupolar potential of the form $V(r,z,t) = \frac{1}{2}(K_{2,r}r^2 + K_{2,z}z^2)V_{\text{RF}}\cos(\Omega_{\text{RF}}t)$, where we have assumed cylindrical geometry. Averaged over time, the effect of the quadrupolar potential can be described by a parabolic pseudopotential. The dynamics of ions stored in such a trap is described by the Mathieu equation [17]. In the absence of DC fields, this is governed by the parameter $q_u = 2eK_{2,u}V_{\text{RF}}/m\Omega_{\text{RF}}^2$ with $u = r, z$, $K_{2,u}$ being a factor describing the geometry of the potential, and V_{RF} and Ω_{RF} being the amplitude and the frequency of the RF signal, respectively. When $q_u \ll 1$, the motion is well described by the secular approximation, under which the particle oscillates harmonically at the secular frequency $\omega_u = q_u\Omega_{\text{RF}}/2\sqrt{2}$, superimposed with a small jiggling at frequencies $\Omega_{\text{RF}} \pm \omega_u$. The higher frequency components are usually neglected due to their small amplitude, and therefore the only relevant frequency for the coupling is the secular one. Note that even if there is a significant contribution of micromotion in the dynamics of one cloud, its influence on the second one is completely negligible compared to the voltage signal externally applied to the electrodes which is responsible for the trapping. Anyway, it can be filtered in order to avoid any disturbances.

The trap electrodes are made of gold sputtered on fused-silica and located on top of a fused-silica substrate. Each trap consists of four opposed disks made of fused-silica wafers, with two electrodes per wafer. The whole system is housed in a 6-way CF 63 vacuum cross where pressures of 4×10^{-10} mbar are currently achieved and still subject to improvement. The quadrupole potential is created by applying an RF signal to a pair of opposite ring electrodes with inner diameter of 3 mm and spaced 1 mm. The traps are driven by a resonant RF amplifier, capable of providing up to $V_{\mathrm{RF}} = 250$ V at its resonant frequency of $\Omega_{\mathrm{RF}}/2\pi = 4.025$ MHz.

Figure 2(a) shows a 3D cut-view of the double microtrap system, as well as the laser beams going through both radial and axial directions for each trap. The calcium oven, omitted here for clarity, creates an axial flux of Ca atoms that enter the trapping regions, where the photoionization is accomplished. Figure 2(b) depicts the entire electrode configuration for the traps. The atomic Ca beam enters the double-trap system through a 400 μm hole that corresponds to the inner diameter of the innermost electrode at the lower trap (see Figure 2(c)).

SIMION simulations of the electrode arrangement return an electrostatic potential of the form $V(r,z,t) = \frac{1}{2}(K_{2,z}z^2 + K_{2,r}r^2)V_{\mathrm{RF}}\cos(\Omega_{\mathrm{RF}}t)$, with $K_{2,z} = 1.152$ mm^{-2} and $K_{2,r} = -0.499$ mm^{-2}. The trap geometry sets the characteristic distance relevant in Eq. (1) equal to $d = d_z/\alpha$, with $d_z \simeq 1$ mm and $\alpha = 0.62645$ [16]. SIMION also permits one to simulate trajectories of individual ions at different initial energies. For $\Omega_{\mathrm{RF}}/2\pi = 4.025$ MHz, simulations predict that trapping of $^{40}\mathrm{Ca}^+$ ions with radial kinetic energies up to 0.35 eV is feasible. Further, the analysis of single trapped ion trajectories allows the estimation of the secular frequency via the analysis of the power spectral density (PSD), as it is usually done in experiments with levitated nanoparticles [20,21]. Figure 3 depicts the PSD for three different RF signals, all with the same driving frequency $\Omega_{\mathrm{RF}} = 4.025$ MHz but different amplitudes. Each curve features three peaks, corresponding to the secular frequency ω_z and the two components due to micromotion at frequencies $\Omega_{\mathrm{RF}} \pm \omega_z$. When V_{RF} is small, the secular approximation holds, the micromotion is negligible and the two frequencies associated to it are almost identical. This is the case $V_{\mathrm{RF}} = 10$ V in Fig. 3, which corresponds to the values of Mathieu parameters $q_r \simeq 0.038$ and $q_z \simeq 0.087$. In this regime, the axial secular frequency obtained from the simulation ($\omega_z \simeq 118$ kHz) agrees well with the value obtained from the prediction based on the Mathieu equation ($\omega_z = q_z\Omega_{\mathrm{RF}}/2\sqrt{2} \simeq 123$ kHz). As V_{RF} is raised, the corresponding values of the q parameter increase, and the secular approximation is violated. For $V_{\mathrm{RF}} = 30$ V and $V_{\mathrm{RF}} = 100$ V we obtain $(q_r, q_z) \simeq (0.11, 0.26)$ and $(q_r, q_z) \simeq (0.38, 0.87)$, respectively. In these cases, the predictions based on the secular approximation depart from the results obtained from the simulation, observing that the micromotion is not negligible anymore and its components are not degenerated.

The trajectories of the ions in the trap are complicated when other ions are also trapped due to space-charge effects and anharmonicities of the electric field. In particular, ions with higher energies will explore the regions where the electric field is large and nonlinear, leading to micromotion and frequency shifts. This is clearly seen in Fig. 4, where a comparison is made between the typical oscillation of the COM mode of an ion cloud with 200 ions and two typical trajectories of two ions in the cloud. In this figure, we see that the more energetic ions experience significant micromotion, and that this is reduced for less energetic ions and the COM mode. Since the relevant dynamics for the coupling is that of the COM mode, together with the aforementioned comparison with the trapping field, we can safely neglect the influence of micromotion in the coupling. It is also apparent that ions in the cloud do not oscillate in phase, due to the high temperature. In order to facilitate a proof-of-concept experiment where coupling is demonstrated, a coherent oscillation of the cloud can be induced with a resonant pulsed external driving [1].

3.2 Generation of the ions and laser setup for cooling and imaging.

We generate $^{40}Ca^{+}$ through the evaporation of neutral Ca atoms using a resistive oven source and subsequently ionizing them via resonance-enhanced two-photon ionization. The 422 and 375 nm photoionization lasers enter the traps along the radial direction, ensuring that the ionization occurs near the trapping regions. Both atomic and laser beams are crossed in order to minimize the Doppler broadening of the 422 nm $4s^1S_0 \rightarrow 4p^1P_1$ transition experienced by the moving atoms. The Doppler cooling lasers (397 and 866 nm) enter the traps along the axial direction. The 397 nm laser addresses the $4s^2P_{1/2} \rightarrow 4s^2S_{1/2}$ transition needed for cooling. The 866 nm laser drives the $3d^2D_{3/2} \rightarrow 4s^2P_{1/2}$ transition, which prevents the shelving from the excited P state to the metastable D state. An additional 397 nm laser can be overimposed with the photoionization beams to perform the Doppler cooling of the ions in the radial direction. The 422 nm and Doppler cooling lasers are locked to a wavelength meter with an absolute accuracy of 10 MHz. Ions are detected by means of the 397 nm scattered fluorescence photons. The fluorescence is collected by a custom-made optical system and focuses onto an Electron-Multiplying CCD (EMCCD) camera. The overall optical system yields a magnification factor of 6, which leads to an effective pixel size of 2.7 μm.

Figure 5 shows the first image of an ion cloud stored in the upper trap of the device operated at $\Omega_{\rm RF}/2\pi = 4.025$ MHz. The cloud has the shape of an oblate spheroid with semiaxes $a_r \simeq 320$ μm and $a_z \simeq 230$ μm, the latter being the revolution axis. From this image, we can provide an estimation of the ion number of the cloud through its fluorescence counts, collected for an integration time of 1 s. We estimate the collection efficiency of the optical system to be 0.02 %, as well as a QE of 40 % for the UV photons imaged onto the EMCCD camera. We therefore estimate that the cloud has around 140 ions, in fair agreement with those numbers inferred from typical density values of ion clouds stored in Paul traps [22].

4 Performance analysis and proposed experiments

In this section, we try to evaluate the feasibility of an experiment where a significant coupling can be achieved. The first thing to evaluate is whether the current induced in the coupling electrode is larger than the Johnson noise in the electrodes. For this comparison, we consider that the current induced by the motion, Eq. (1) can be expressed as $I_{\rm ind} = NeA_z\omega_0/d$, where A_z is the amplitude of the oscillation of the COM mode in the axial direction. This current has to be compared with that due to Johnson noise in the bandwidth $\Delta\omega/2\pi$ where the ion cloud can be excited. This current can be expressed as:

$$I_{\rm th} = \sqrt{\frac{4k_BT\Delta\omega}{2\pi{\rm Re}(Z)}} \tag{10}$$

where k_B is the Boltzmann constant, T the temperature of the electrodes and Z the impedance of the equivalent circuit. In resonance and in the absence of laser cooling,

Z is equal to the resistances in the circuit, i.e., the resistance of the wire connecting the electrodes R_w. The ratio of I_{ind} to I_{th} gives the signal-to-noise ratio (SNR). We consider the signal induced by cloud 1 on the electrodes, and this is to be compared with the buildup of phonons in cloud 2 due to Johnson noise:

$$\text{SNR} = \frac{I_{\text{ind},1}}{I_{\text{th},2}} = \frac{N_1 e A_z \omega_0}{d}\sqrt{\frac{2\pi R_w}{4k_B T \Delta\omega_2}} \tag{11}$$

Inserting the relation given by Eq. (5) into Eq. (11) we obtain:

$$\text{SNR} = N_1 A_z \omega_0 \sqrt{\frac{\pi m}{2k_B T N_2}} \tag{12}$$

suggesting that the optimal configuration for proof-of-concept experiment we aim at is that of a large cloud in one trap interacting with a single ion stored in the second trap.

We plan to operate the traps with a typical axial frequency of $\omega_z/2\pi \simeq 100$ kHz. Consider a single $^{40}\text{Ca}^+$ ion interacting with a cloud with 200 $^{40}\text{Ca}^+$ ions. Under these conditions and estimating $C = 2$ pF for the capacitance of the electrodes, the coupling rate is $g \simeq 0.85$ Hz and the exchange time $\tau_{\text{ex}} \simeq 1.8$ s. This would force the precision of the axial frequency of the ion and the cloud to be equal within about 1 Hz in the case of an experiment where the motional estates are to be exchanged. Such stability can in principle be achieved in a Penning trap at cryogenic temperature, as it is the final goal. The main limitation for such exchange in the case of ion clouds is the broadening due to anharmonicities of the trap over the size of the cloud, which in the current setup we estimate to be larger than 100 Hz. Anharmonicities are negligible in the case of two individual laser-cooled ions in a Penning trap.

Currently the work is focused on the detection of the motion of an ion cloud by the effect it causes in an ion or cloud of ions in an adjacent trap. This experiment will be similar to previous works where we evaluated the sensitivity of one ion to a small, resonant driving directly applied to one endcap of the trap [3,4]. The scheme of this experiment, previously presented for single ions in Refs. [1,14], is illustrated in Fig. 6. With the present setup, the effects of the anharmonicities can be overcome by forcing a coherent oscillation of the ion cloud to be sensed by means of an electric field pulse in the trapping region. If the 200 $^{40}\text{Ca}^+$ ions cloud is forced to oscillate with an amplitude $A_z = 100$ μm, we obtain a SNR $\simeq 63$ for the induced signal over the Johnson noise on one ion at room temperature, which is large enough to ensure a significant effect of the cloud on the ion. The current induced by this coherently-oscillating cloud on the common electrode can be tuned by means of the intensity of the driving field, and therefore the strength of the coupling can be evaluated. The two systems will be allowed to interact during a time equal to the characteristic exchange time τ_{ex} in the absence of laser cooling. The oscillation frequency can be modified through the trapping voltage in order to set a non-resonant condition, thus avoiding any interaction out of the prescribed exchange time.

Sweeping the driving frequency and amplitude, as well as the length of the excitation pulse, will allow the evaluation of the expected performance of the experiment and to find the optimal parameters for an efficient coupling of the two systems. We notice that even the incoherent oscillation of the COM mode of the cloud at room temperature, which from Fig. 4 we estimate to be $A_z > 10$ μm, may be enough to heat up the single ion stored in the adjacent trap, since we expect that the incoherent current induced by the cloud will overcome the thermal noise on the electrodes, with a SNR > 4.5.

This novel experiment will be part of our ongoing effort to test the electronics developed for the coupling of two single ions [16]. The implementation of this intermediate step will teach how to deal with the challenge of coupling two single ions in a

Penning trap. Moreover, interesting physics could still be learned from the connection of two ion clouds, with applications in the understanding of energy exchanges at the microscale, where Brownian fluctuations strongly influence the dynamics [23,24]. In fact, since the temperature of each ion cloud can be controlled independently via the two radial cooling lasers, our platform will be an ideal playground for heat-transport studies at the microscale.

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Author contribution statement
All Authors contributed to the construction and commissioning of the experiment. F.D. and J.J.D.P. performed the measurement. R.A.R performed the numerical simulations. R.A.R. and F.D. developed the theoretical models and prepared the manuscript. M.J.G., J.J.D.P., and D.R. contributed with ideas, revisions and comments. D.R. conceived the experiment.

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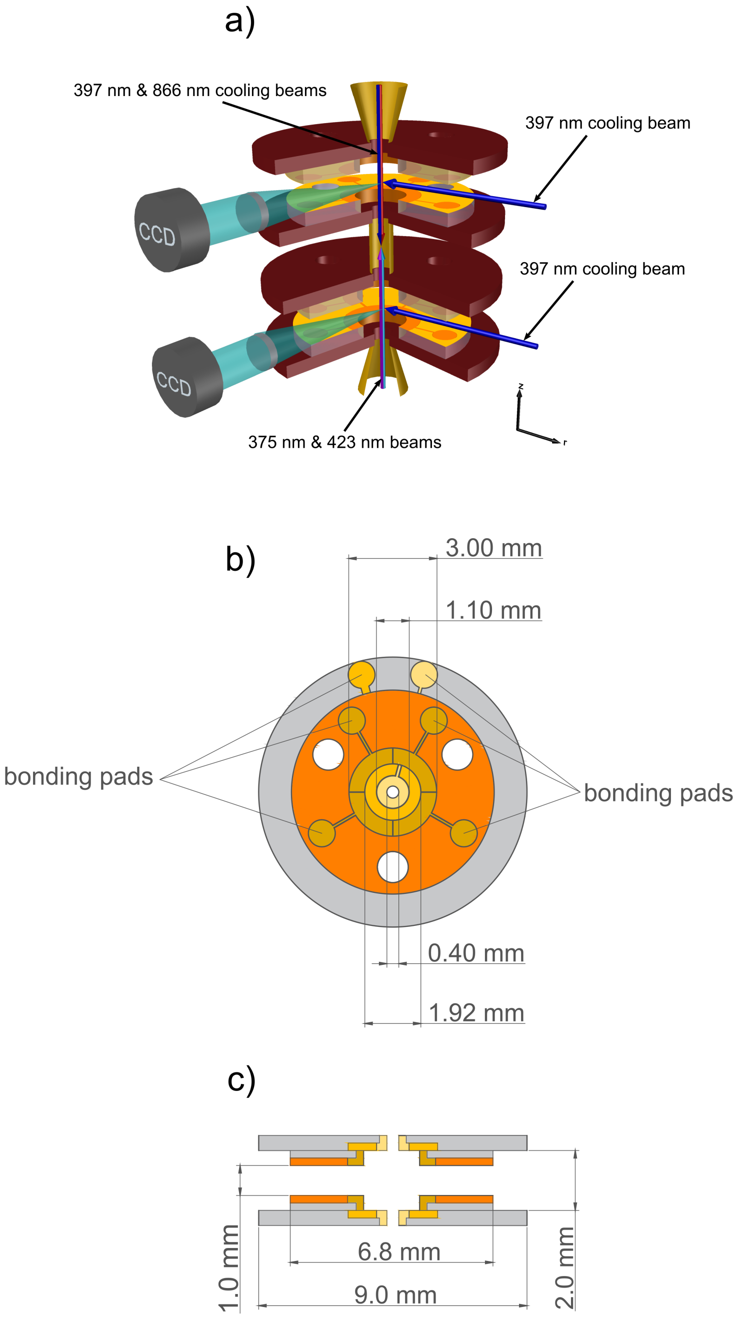

Fig. 2. The double-trap system. a) Schematic 3D CAD drawing of the experimental apparatus. In each trap, the ions are trapped due to the RF quadrupole potential formed between two segmented electrodes (orange). Both traps are identical, and two of their inner electrodes are connected through a wire. The ions are laser-cooled in both axial and radial directions, and the resulting fluorescence is collected by an optical system (assembled outside the vacuum chamber) and then imaged onto a EMCCD camera. b) Top view of the two fused-silica disks where the trap electrodes are placed (not to scale). Each trap is formed by a pair of these disks, fixed by means of the mounting holes. The segmented electrodes relevant for trapping are shown in dark yellow. c) Front view of the fused silica disks with all relevant dimensions (not to scale). The electrodes are located on top of the disks, with a thickness of 50 μm. The thickness of electrodes has been exaggerated in the figure for illustrative purposes.

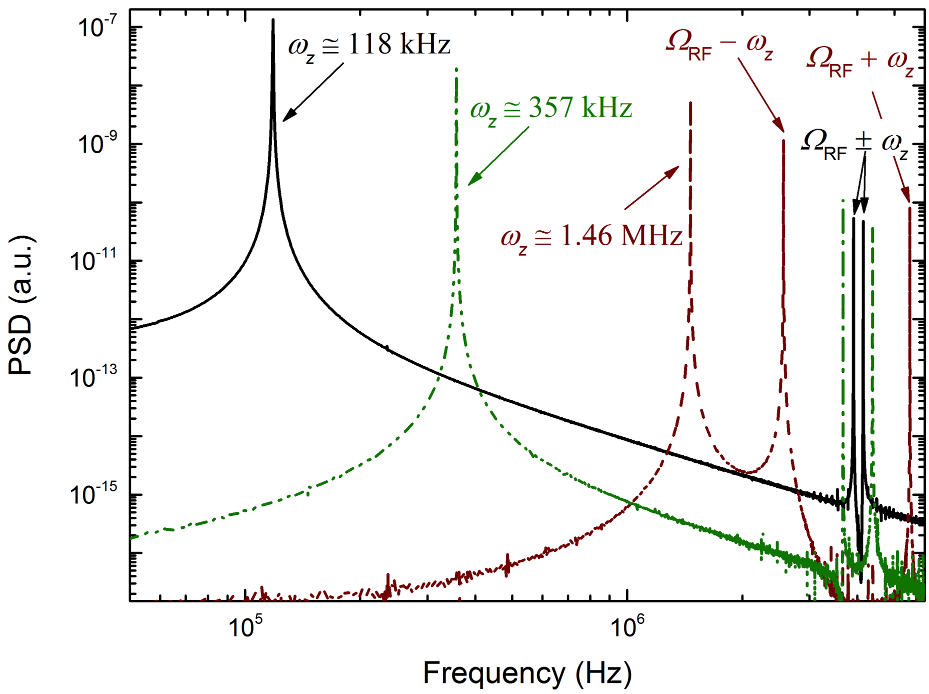

Fig. 3. Simulations of the spectrum of one trapped ion. Power spectral density (PSD) of the projection along the z axis of trajectories of a trapped $^{40}Ca^{+}$ ion for three different RF signals at the same $\Omega_{RF}/2\pi = 4.025$ MHz, differing in the value of $V_{RF} = 10\ V$ (black solid line), $V_{RF} = 30\ V$ (green dash-dot-dot line) and $V_{RF} = 100\ V$ (brown dashed line). The frequencies of the peaks for the secular and micromotion components are indicated. The predictions from the secular approximation are $\omega_z = 123$ kHz, $\omega_z = 371$ kHz and $\omega_z = 1.2$ MHz, respectively. PSD spectra in the radial directions are similar to the ones shown in this figure, with the only difference that a smaller q, and hence secular frequency, dictates the dynamics of the trapped ions.

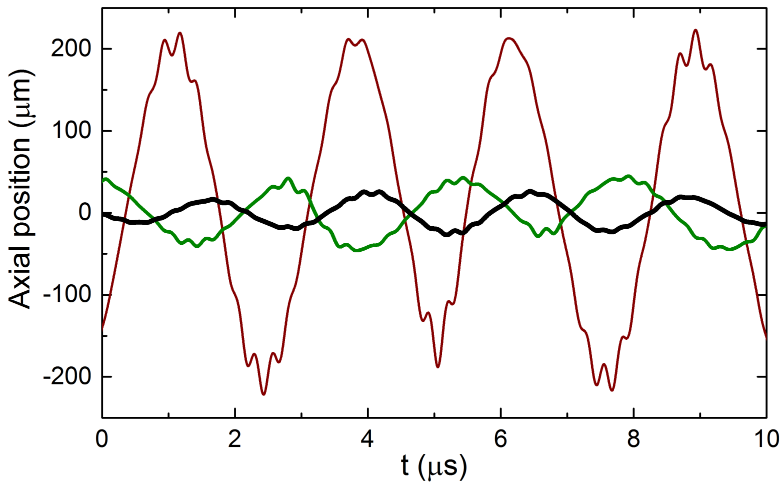

Fig. 4. Simulations of trajectory of an ion cloud with 200 ions at 300 K. Trajectory of two ions (thin-brown and green lines) and the COM motion of the cloud (thick-black line) along the axial direction. Trapping conditions: $V_{\rm RF} = 30$ V and $\Omega_{\rm RF}/2\pi = 4.025$ MHz. As it can be clearly seen, even at this high temperature the micromotion is a small contribution to the dynamics of the cloud. At such high temperatures, some energetic ions oscillate with amplitudes comparable to the whole size of the cloud, and oscillation of the cloud is only weakly correlated.

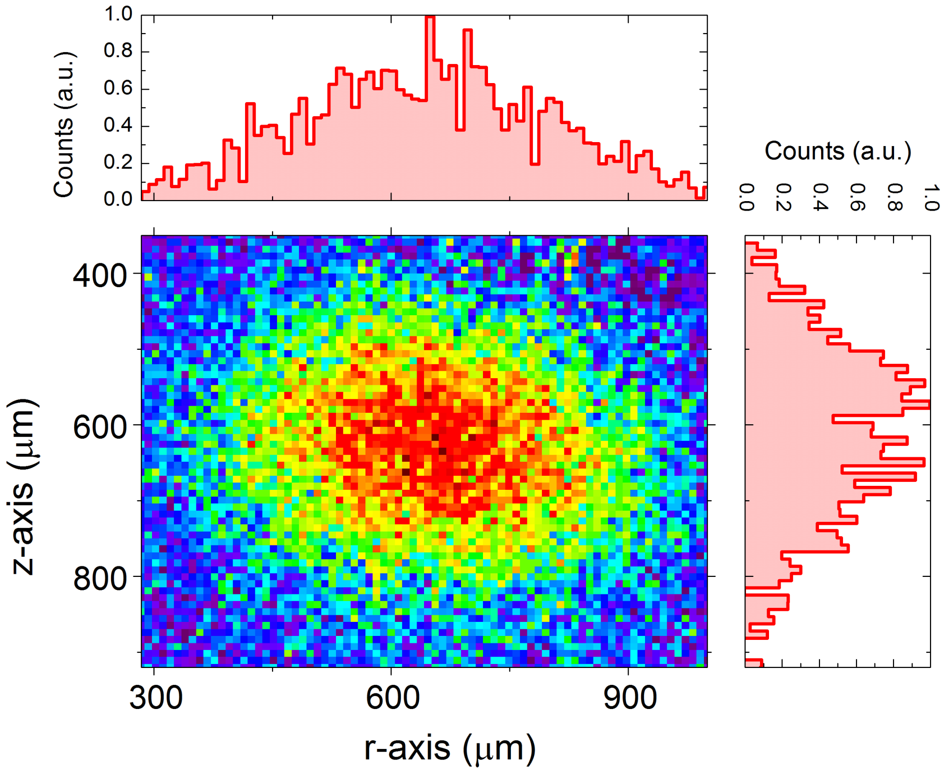

Fig. 5. Fluorescence image of an ion cloud. This image shows the fluorescence of one cloud of $^{40}Ca^{+}$ ions for an acquisition time of 1 s, together with the projections along the radial and axial axes. The cloud has spheroidal shape, with semiaxes $a_r \simeq 320$ μm and $a_z \simeq 230$ μm, giving an aspect ratio of ~ 1.4.The number of trapped ions is found to be around 140.

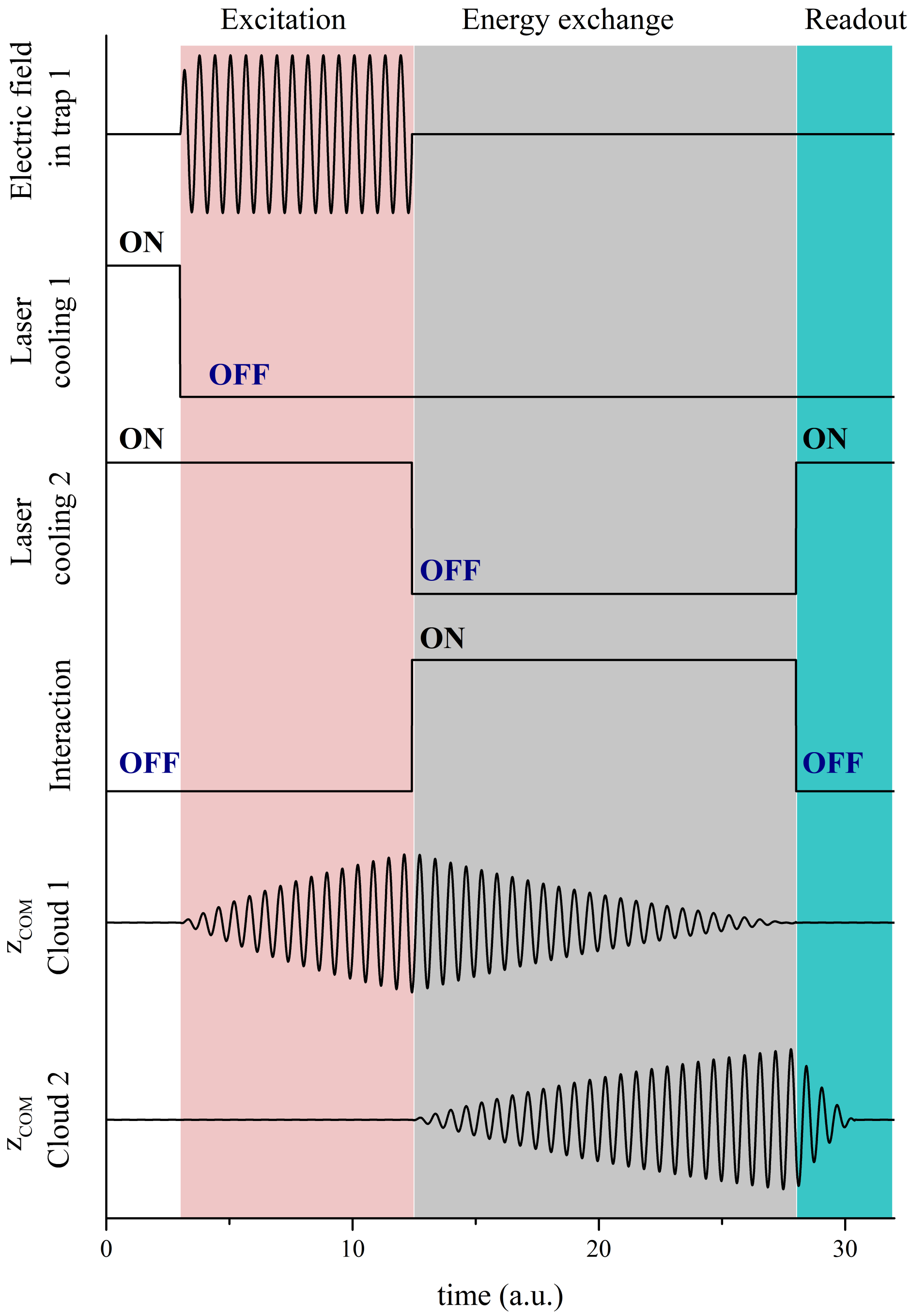

Fig. 6. Simplified operation scheme. Initially the two clouds are cooled to the Doppler limit in an off-resonant condition. At a given time, the laser cooling on cloud 1 is switched off, and an electric field pulse is applied in trap 1 in order to set a coherent oscillation of this cloud. After this excitation pulse, laser cooling is also switched off in the second trap and the traps are set in a resonant condition, so that energy exchange between the two clouds is allowed. Under the given conditions, energy will flow from cloud 1 to cloud 2. After a time equal to the exchange time $\tau_{\rm ex}$, an off-resonant condition is again established and laser cooling on trap 2 is switched on. Readout is accomplished by monitoring the time evolution of the fluorescence emitted by this second cloud. The different characteristic times and dynamics will depend on the particular set of parameters (secular oscillation, number of ions, intensity of the drive) chosen for a given experiment.