Loading of large ion Coulomb crystals into a linear Paul trap incorporating an optical cavity for cavity QED studies

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April 29, 2008

Abstract We report on the loading of large ion Coulomb crystals into a linear Paul trap incorporating a high-finesse optical cavity ($F \sim 3200$). We show that, even though the 3-mm diameter dielectric cavity mirrors are placed between the trap electrodes and separated by only 12 mm, it is possible to produce $in situ$ ion Coulomb crystals containing more than $10^5$ calcium ions of various isotopes and with lengths of up to several millimeters along the cavity axis. We show that the number of ions inside the cavity mode is in principle high enough to achieve strong collective coupling between the ion Coulomb crystal and the cavity field. The results thus represent an important step towards ion trap based Cavity Quantum ElectroDynamics (CQED) experiments using cold ion Coulomb crystals.

PACS 32.80.Fb; 37.10.Ty; 42.50.Pq;

1 Introduction

In recent years there has been much focus on light-matter interactions at the level of single photons, primarily motivated by applications within quantum information science, where an efficient light-matter interface is indispensable for many applications[1,2]. Of particular interest has been the so-called strong coupling regime of Cavity Quantum ElectroDynamics (CQED)[3], in which the rate of coherent evolution within the system exceeds that of any dissipative processes, making this regime ideal for the quantum engineering of light-matter interfaces. A strong collective coupling between a medium of $N$ atoms and the light field can be achieved if the single atom-photon coupling strength $g_0$ is large enough to satisfy the inequality $g_0 \sqrt{N} > \gamma, \kappa$, where $\gamma$ and $\kappa$ are the decay rates of the atomic dipole and the cavity field, respectively. For optical frequencies, experiments with neutral atoms have been extremely successful and have reached the strong coupling regime for single atoms[4]. Such experiments benefit from the use of cavities of extremely small mode volumes to increase the single atom-photon coupling strength, given by: $g_0 = \frac{D}{\hbar} \sqrt{\frac{\hbar \omega}{2\epsilon_0 V}}$, where $D$ is the transition dipole moment, $\omega$ is the frequency of the transition and $V$ is the mode volume of the cavity. However, since the cavity decay rate is inversely proportional to the cavity length, such experiments require very high finesse cavities, which are technically challenging to operate. One further complication of such experiments is the difficulty in efficiently trapping and confining the neutral atoms inside the cavity. While short-time solutions to this problem have recently been found[5,6], ions, by contrast, can be stored for hours in ion traps and offer relatively easy access to a regime in which the spatial extent of their wave packet is well-localized on the scale of the optical wavelength of their atomic transition (Lamb-Dicke regime). Though experiments with single ions in cavities have confirmed this[7,8], the strong coupling regime has not yet been reached, mainly due to the difficulty in lowering the mode volume, i.e. minimizing the mirror separation, without severely modifying the trapping potential, which makes trapping extremely challenging. The requirement of a small mode volume can be relaxed for ensembles of atoms or ions due to the $\sqrt{N}$ factor entering in the collective coupling strength of the ensemble. This means that a technically less demanding longer cavity with a lower finesse can be used in such experiments.

In addition to the issue of tight confinement and long storage time, ion Coulomb crystals have a number of advantages over cold atomic samples. As the ions are confined in a crystal lattice, the decoherence rate due to collisions is very low. Furthermore, the lattice structure in conjunction with the standing wave field of the optical resonator might be interesting for the engineering of the atom-photon interaction. Whereas spatial structuring would require the use of optical lattices for neu-
tral atoms it is inherent in an ion Coulomb crystal and as described in a recent paper[9], the structure of ion Coulomb crystals can be made very regular and periodic. Finally, the low optical density of the ion Coulomb crystal ($\sim 10^8 \text{cm}^{-3}$) makes optical pumping and state preparation unproblematic.

In this paper we focus on the production and characterization of large cold ensembles of ions, specifically ion Coulomb crystals, of up to hundreds of thousands of ions in a linear Paul trap incorporating a high finesse optical cavity designed for CQED experiments. We show that it is possible to insert cavity mirrors in between the trap electrodes without significantly perturbing the trapping fields, that the ion Coulomb crystals can be produced in a clean and efficient way that preserves the finesse of the cavity, and that the number of ions in the cavity mode can be high enough to potentially satisfy the strong coupling criterion, $g_0N > \gamma, \kappa$. These results thus represent an important step towards ensemble-based CQED with ion Coulomb crystals and open up for the use of such media as a tool for quantum information processing[10,11,12].

The paper is organized as follows: In section 2, we describe our linear Paul trap along with the integrated cavity. In section 3, we describe the loading scheme used for the production of the Coulomb crystals of calcium ions and present results on loading of the trap with various naturally abundant calcium isotopes. In section 4, we address the issue of optimization of the loading in terms of maximizing the total number of ions within the cavity mode volume. In section 5, we conclude.

2 Experimental setup

Fig. 1 shows a sketch of the setup used in the experiments. The trap is a linear Paul trap[13] which consists of four sectioned cylindrical electrode rods placed in a quadrupole configuration. The length of the center-electrode is $z_0 = 5.0 \text{ mm}$, and the length of the end-electrodes is $z_E = 5.9 \text{ mm}$. The electrode diameter is $d = 5.2 \text{ mm}$ and the distance from the trap center to the electrodes is $r_0 = 2.35 \text{ mm}$. Confinement in the radial plane ($xy$-plane in Fig. 1) is obtained by applying time varying voltages $\frac{1}{2}U_{rf} \cos(\Omega_{rf} t)$ and $\frac{1}{2}U_{rf} \cos(\Omega_{rf} t + \pi)$ to the two sets of diagonally opposite electrode rods. The sectioning of each of the electrode rods allows for application of a static voltage, $U_{end}$, to the end-electrodes, which provides confinement along the $z$-axis. The potential along the $z$-axis is well described by

$$\Phi_z(z) = \frac{1}{2} M \omega_z^2 z^2, \quad \omega_z^2 = \frac{2 \eta Q U_{end}}{M z_0^2}$$

where $M$ and $Q$ are the mass and charge of the ion and $\eta = 0.342$ is a constant related to the trap geometry. For $2Q U_{rf}/M z_0^2 \Omega_{rf}^2 \ll 1$ one can introduce an effective or pseudo-potential in the radial plane described by[14]

$$\Phi_r(r) = \frac{1}{2} M \omega_r^2 r^2, \quad \omega_r^2 = \frac{Q^2 U_{rf}^2}{2 M^2 r_0^4 \Omega_{rf}} - \frac{\eta Q U_{end}}{M z_0^2}.$$ (2)

In such a three-dimensional potential, one finds that the density of ions in an ion Coulomb crystal is controlled only by the rf-voltage and given by[15]

$$\rho = \frac{\epsilon_0 U_{rf}^2}{M r_0^4 \Omega_{rf}^2}.$$ (3)

The trap is operated at a frequency $\Omega_{rf} = 2 \pi \times 4.0 \text{ MHz}$ and the end-voltage, $U_{end}$, is typically 1 to 10 V. The rf voltage, $U_{rf}$, is typically between 100 and 400 V, which leads to ion densities between $6.8 \times 10^7$ and $1.1 \times 10^9 \text{ cm}^{-3}$.

The unique feature of this trap is the incorporation of a high finesse optical cavity, with mirrors situated in between the electrodes. The cavity is designed for operating on the $4d^2 3D_{3/2} \leftrightarrow 4p^2 3P_{1/2}$ transition of $^{40}\text{Ca}^+$ at 866 nm (see insert Fig. 1). The mirrors, both with a radius of curvature of 10 mm, are placed in a near-confocal geometry supporting a standing wave mode of light at 866 nm with a waist of $\sim 37 \mu\text{m}$ at the trap center. The transmission of the two mirrors is 1500 ppm and 5 ppm at 866 nm, respectively. The cavity finesse at 866 nm is determined by measuring the free spectral range (FSR) and the width of the resonance peak. The FSR is measured to be $\Delta \nu_{FSR} = (12.7 \pm 0.6) \text{ GHz}$, corresponding to a cavity length of 11.8 mm. This value was obtained by tuning the laser frequency over one FSR of
the cavity while recording the number of (known) FSR of a longer reference cavity. The width of the resonance peak is found to be $\delta \nu = (4.0 \pm 0.2)$ MHz by comparing the width with sidebands at 5 MHz. The resulting finesse is then $\mathcal{F} = \Delta \nu_{\text{FSR}} / \delta \nu = 3200 \pm 300$. This is also consistent with the incoupling mirror transmission of 1500 ppm and intra-cavity losses of 350 ppm, which we derived from the cavity reflection signal. The intra-cavity loss is due to mirror contamination introduced mainly during degassing of the ion pump connected to the vacuum chamber and will be avoided in the future by inserting a valve between the ion pump and the trap chamber. This should allow for intra-cavity loss of only a few tens of ppm. Based on the measurements quoted above, we deduce a cavity decay rate of $\kappa = 2\pi \times (2.0 \pm 0.1)$ MHz. From the spontaneous decay rate, $\Gamma$, of the excited 4p $^2P_{1/2}$ state of $^{40}\text{Ca}^+$, the decay rate for the atomic dipole is $\gamma = \Gamma / 2 = 2\pi \times 11$ MHz. From the dimensions of the cavity, the ion-photon coupling strength of a single $^{40}\text{Ca}^+$ ion at the cavity waist and field anti-node is expected to be $g_0 = 2\pi \times 0.53$ MHz. In principle it thus requires $\approx 500$ ions within the cavity mode volume to enter a regime governed by a strong collective coupling (where $g_0 \sqrt{N} > \gamma, \kappa$ is satisfied).

3 Loading of the trap

In order to efficiently load large crystals into the trap we employ the technique of resonance-enhanced photoionization[16]. As compared to conventional electron bombardment, this method has several advantages which are all essential to the experiment. First of all, the problem of charging surrounding isolating materials, e.g. mirror substrates, is greatly reduced as only a single electron is produced per ion[16,17]. Secondly, the ionization efficiency can be made much higher, leading to loading rates which are significantly higher than what can be achieved with electron bombardment[18]. This makes loading at a lower atomic flux practical[19] and thus reduces the risk of contaminating both the trap electrodes and closely spaced delicate objects, such as the mirrors integrated into the ion trap. While deposition of material on the electrodes is suspected to give rise to heating of the ions [20,21], contamination of the mirrors will be devastating to the quality of the resonator. Finally, the technique can be extremely isotope selective[22] allowing for loading of different isotopes in well-controlled ratios.

The level scheme used in this work for photoionization is presented in Fig. 2. A single UV-light source at 272 nm ionizes atomic calcium in a two-photon process through resonant excitation of the 4s5p $^1P_1$ state followed by absorption of a second 272 nm photon from either the 4s5p $^1P_1$ state or the 4s3d $^1D_2$ state (populated through spontaneous emission) into the continuum (see Fig. 2) [16,22]. The light at 272 nm originates from a laser system based on a commercial Ytterbium-doped DFB fiber laser that has been frequency doubled twice to produce light at the fourth harmonic. The DFB fiber laser system was described in detail in a recent paper[23]. In brief, light from a CW DFB fiber laser operating at 1088 nm is first frequency doubled in a bow-tie cavity containing a LiNbO$_3$ crystal to produce light at 544 nm. This light is subsequently frequency doubled in a bow-tie cavity containing a $\beta$-BaB$_2$O$_4$ crystal to finally produce light at 272 nm. Frequency tuning can be achieved by controlling the length of the fiber laser cavity either with a piezoelectric transducer (PZT), or by changing the temperature.

For loading of the trap, a thermal beam of atomic calcium with a cross section of $\approx 1.0 \times 1.5 \text{ mm}^2$ is intersected by the 272 nm laser beam in the center of the trap at right angles in order to minimize Doppler broadening. The atomic beam is produced from an effusive oven followed by a series of skimmers, inserted to avoid deposition of calcium on the trap electrodes and cavity mirrors. The UV-beam has a power of about 20 mW and a waist of $\approx 160 \mu\text{m}$ at the trap center. The ions produced are then Doppler laser cooled on the 4s $^{2}S_{1/2} - 4p$ $^2P_{1/2}$ transition along the trap axis (z axis in Fig. 1) by two counter propagating beams at 397 nm (beam diameter $\approx 1 \text{ mm}$), while in the radial plane (xy-plane in Fig. 1) the ions are sympathetically cooled through the Coulomb interaction. An 866 nm beam, resonant with the 4d $^{4}D_{5/2} - 4p$ $^2P_{1/2}$ transition, is applied to prevent the ions from being shelved into the metastable $D_{3/2}$ state (see insert of Fig. 1). Typically, 8-10 mW of 397 nm light detuned by $\approx 20 - 40$ MHz below resonance is used during loading. Both power and detuning are then decreased upon completion of the loading in order to optimize the cooling. Detection of the ions is performed by imaging spontaneously emitted light at 397 nm onto an image intensified CCD camera located above the trap in Fig. 1. The number of ions loaded can then be deduced from the recorded images by the method described in Ref. [24].

Fig. 3 shows the number of loaded ions versus time when the frequency of the 272 nm light source is tuned close to the resonance of the 4s$^2$ $^1S_0 - 4s5p$ $^1P_1$ transi-
The ionization laser frequency is tuned close to the 4s \( ^1S_0 \rightarrow 4s5p \ ^1P_1 \) transition of 46Ca. The UV-power used for ionization was 20 mW and the oven temperature 400°C. The loading rate deduced from the linear fit is \( \sim 3200 \text{ ions/s} \).

**Fig. 4** Image of a 3 mm long 40Ca\(^+\) Coulomb crystal with 88000 ions. The rf and end-voltages are 300 V and 1.7 V, respectively. The visible features outside the crystal region are from the trap and due to light scattered from the 397 nm beams as they pass through the mirrors. Due to the low magnification needed to image the whole crystal, no detailed crystal structure is visible.

As mentioned previously, compared to electron bombardment, the method of resonant photoionization minimizes charging effects as well as trap contamination and formation of patch potentials. From the images shown in Fig. 5 and 6, there appears to be no visible perturbation on the shape caused by such effects. In Fig. 5 the upper and lower boundaries of the inner component have been measured to be parallel at least to within 2 mrad, indicating that the introduction of cavity mirrors inside a linear Paul trap does not significantly perturb the trapping of such crystals. Furthermore, as the high-finesse cavity constitutes an excellent detector of trap contamination, the observation that the finesse has not degraded during the loading process confirms the cleanliness of the loading technique.
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Fig. 5  a) Image of a two-component crystal consisting of ∼2000 $^{40}\text{Ca}^+$ (inner component) and ∼13000 $^{44}\text{Ca}^+$ (outer component) that are being laser cooled simultaneously (16 s exposure time). b) $^{44}\text{Ca}^+$ laser cooled, $^{40}\text{Ca}^+$ sympathetically cooled (1 s exposure time). c) $^{40}\text{Ca}^+$ laser cooled, $^{44}\text{Ca}^+$ sympathetically cooled (1 s exposure time). For technical reasons the cooling light resonant with the sympathetically cooled component was not turned off completely and in both b) and c) this component is still weakly visible.

4 Optimizing the total number of ions inside the cavity mode

As mentioned in the introduction, one of the main challenges for the realization of CQED with ion Coulomb crystals is to load a large number of ions into the cavity mode to enhance the collective atom-light coupling. For our trap, with the optical cavity axis coinciding with the trap axis, the highest number of ions in the cavity mode is achieved when the product of the crystal length and the density, $\rho$, is maximized. The length is controlled by both the end- and rf-voltage, whereas the density is determined solely by the rf-voltage (c.f. eq. 3). Ideally, we would therefore wish to work at a very low $U_{\text{end}}$ and a very high $U_{rf}$. In practice, we find that the crystals become unstable at lengths above a few mm, although the exact length is very dependent on the rf-voltage and on the total number of ions in the crystal as well as the level of cooling power. In qualitative terms, we interpret this as a result of rf-heating in the crystal[27,28]. This heating drives the radial motion of the ions, while the laser cooling beams act only directly along the trap axis (see Fig. 1). Since the coupling between axial and radial motion is weaker for longer than for shorter prolate crystals, compensation of rf-heating by axial laser cooling is less efficient in longer prolate crystals. Increasing the cooling power may help to confine longer crystals containing more ions, however, there is ultimately a tradeoff between the maximal attainable length, the total number of crystalized ions, and the ion density. Fig. 7 shows the maximal attainable number of ions in the cavity mode, $N$, as a function of rf-voltage, $U_{rf}$, (density, $\rho$). Each point was found by lowering the end-voltage and letting the crystal expand axially until it became unstable and was lost. The number of ions in the cavity mode is found to be maximal for rf-voltages around 350 V ($\rho \approx 8.3 \times 10^8 \text{ cm}^{-3}$). Here, more than 2000 ions are in the cavity mode, which would correspond to a collective coupling strength of $g_0\sqrt{N} \approx 2\pi \times 24\text{MHz}$. The dashed line in the figure indicates the level above which the number of ions becomes large enough to satisfy the strong collective coupling criterion.

$^1$ $N$ is defined through the definition of the collective coupling strength $g_0\sqrt{N} = g_0\sqrt{\rho} |\Psi|^2 dr$, where the standing wave TEM$_{00}$ mode function is given by $\Psi = \frac{1}{l} e^{-\left(x^2+y^2\right)/w(z)^2} \sin^2(kz)$ and where the integral is evaluated over the crystal length, $l$. With this definition $N = \rho \frac{w(z)}{2} l$. 
Fig. 7 Number of ions, $N$, in the cavity mode volume versus rf-voltage, $U_{rf}$. The interval from 150 V to 400 V corresponds to ion densities between $6.8 \times 10^8$ to $1.1 \times 10^9$ cm$^{-3}$. The dashed line indicate the level above which the criterium for strong collective coupling is potentially satisfied.

5 Conclusion

We have achieved efficient in situ loading of large ion Coulomb crystals in a linear Paul trap with an integrated optical resonator. This work demonstrates that such a high finesse optical cavity can be incorporated into a linear Paul trap without impeding the trapping of large ion Coulomb crystals, that these crystals can have lengths comparable to that of the cavity (more than one third of the cavity length) and that the finesse of the cavity is preserved by the method of resonant photoionization.

We have investigated the optimal trapping parameters for maximizing the number of ions in the cavity mode and found that more than 2000 ions could be confined in the cavity mode volume. This number indicates that the system should be able to enter the strong collective coupling regime and opens up for the possibility of CQED experiments with ion Coulomb crystals.

Acknowledgements

The Authors would like to thank Joan Marler and Magnus Albert for useful discussions and for proofreading the manuscript.

This work has been financially supported by The Carlsberg Foundation.

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