Sideband cooling and coherent dynamics in a microchip multi-segmented ion trap

Stephan A Schulz¹, Ulrich Poschinger, Frank Ziesel and Ferdinand Schmidt-Kaler

Universität Ulm, Institut für Quanteninformationsverarbeitung, Albert-Einstein-Allee 11, D-89069 Ulm, Germany
E-mail: stephan.schulz@uni-ulm.de

New Journal of Physics 10 (2008) 045007 (15pp)
Received 18 December 2007
Published 30 April 2008
Online at http://www.njp.org/
doi:10.1088/1367-2630/10/4/045007

Abstract. Miniaturized ion trap arrays with many trap segments present a promising architecture for scalable quantum information processing. The miniaturization of segmented linear Paul traps allows partitioning the microtrap into different storage and processing zones. The individual position control of many ions—each of them carrying qubit information in its long-lived electronic levels—by the external trap control voltages is important for the implementation of next generation large-scale quantum algorithms. We present a novel scalable microchip multi-segmented ion trap with two different adjacent zones, one for the storage and another dedicated to the processing of quantum information using single ions and linear ion crystals. A pair of radio-frequency-driven electrodes and 62 independently controlled dc electrodes allows shuttling of single ions or linear ion crystals with numerically designed axial potentials at axial and radial trap frequencies of a few megahertz. We characterize and optimize the microtrap using sideband spectroscopy on the narrow S₁/₂ ↔ D₅/₂ qubit transition of the ⁴⁰Ca⁺ ion, and demonstrate coherent single-qubit Rabi rotations and optical cooling methods. We determine the heating rate using sideband cooling measurements to the vibrational ground state, which is necessary for subsequent two-qubit quantum logic operations. The applicability for scalable quantum information processing is proved.

¹ Author to whom any correspondence should be addressed.
1. Introduction

A long-term goal of our research is the large-scale quantum computer with multiple ions and linear ion crystals for encoding complex entangled states, with optimized laser pulses for processing quantum information (QIPC) and with well-suited time-dependent trap control voltages to shuttle quantum information between a central processing unit and the quantum memories or qubit readout sections \[1, 2\]. On the way towards this goal, we present in this paper the most complex microstructured ion-trapping device with a large number of control segments such that, in future, qubits of the order of \(10^2\) might be processed. Currently, we do not exploit at all the complexity of our segmented trapping device and the corresponding options for large-scale quantum processing. The purpose of this paper, however, is to describe the trap device, characterize its basic performance and prove the necessary building blocks for quantum gates with ions.

The work presented here should be seen in context with pioneering work to fabricate specialized ion microtraps for QIPC (instead of using millimeter-sized conventional designs \[3\]–\[6\]) by using microscale planar \[7, 8\], linear three-dimensional (3D) \[9\]–\[11\] or even more complex geometries \[12\]. Gold-plated substrates allow electrode structures with gaps of a few micrometers, but semiconductor structuring may allow, in future, even finer and more complex traps \[13\]. Shuttling protocols for single ions \[14\]–\[17\] have been tested and even used for implementing quantum algorithms \[18, 19\]. On the other hand, the application of well-controlled laser pulses has led to the entanglement of up to eight ions \[20\] and the realization of complex quantum algorithms, e.g. teleportation \[21\].

The present paper is organized as follows: first, we outline the steps for the fabrication of the multi-segmented linear ion trapping device and the integration in the overall experimental...
Figure 1. (a) The Ulm microchip trap installed in the vacuum housing and connected to the filter board. In the front are the two calcium ovens. (b) Scheme of the trap: 31 electrode pairs of the different zones for storage, transfer and processing are characterized by the slit widths $g$ and $h$ and the electrode dimensions $w$ and $d$.

set-up. Cold crystals of trapped $^{40}\text{Ca}^+$ ions show the elementary operation of this device. For refined studies of trapped ions and the properties of the trap, we employ quantum jump spectroscopy on the narrow $S_{1/2} \leftrightarrow D_{5/2}$ quadrupole transition, where all components of the ion motion are resolved easily. Investigating the micromotional sideband allows shifting of the ion to the center of the radio-frequency (RF) trapping field. Since we are observing a very small variation of the necessary compensation voltage only, we conclude that charging effects are indeed effectively impeded by the advanced trap construction. If the ion is excited by a narrow band laser source, we observe Rabi flopping as we vary the pulse duration. Finally, we study the secular sidebands and sideband cool a single ion from the Doppler temperature down to the vibrational ground state. Cooling time and trap heating time are revealed. Finally, in section 5, we sketch future applications.

2. Microchip ion trap

The Ulm microchip trap is a two-layer electrode design modeled as logical continuation of conventional linear Paul traps (figure 1(a)). The storage zone is connected to the processing zone by a multi-segment transfer region in order to achieve a smooth passage avoiding vibrational excitation (figure 1(b)). The electrode layers are as symmetric as possible for well-balanced electric potentials on the trap axis such that micromotion should be minimized. Thus, the non-segmented RF segments are cut with notches precisely opposite to the separation cuts in the dc electrodes to improve the axial electric field symmetry. The microtrap is assembled in a UHV-compatible ceramic chip carrier with the advantage of exceptional alignment precision of the electrode layers. Furthermore, easy electric connectivity, exchange usability and in the near future the integration in UHV-compatible electronic boards with fast digital–analog converters and digital RF-synthesizers prioritize this proof of concept.
Figure 2. Fabrication process of the microtrap: processing of the Al₂O₃ wafer includes laser machining (a), cleaning and coating (b)/(c) and laser cutting (d). Assembly includes mounting (e) with adhesive (grey) and bonding (f).

2.1. Design and fabrication

The Ulm microtrap is based on a geometric three-layer stack design fabricated using gold-coated and laser-structured Al₂O₃ wafers. The development process of the wafers starts with micro-machining of the blank wafers (figure 2(a)) using a femtosecond pulsed laser source. In the storage zone the central slit width is \( h = 500 \mu m \), while the transfer region narrows the slit to \( g = 250 \mu m \) according to the width of the processing zone (figure 1(b)). The central slit in the storage/transfer zone and the processing zone is bounded by the dc electrode fingers with a width of \( d = 250 \mu m \) and \( w = 100 \mu m \) separated with a spacing of \( 30 \mu m \). The constant length of the dc electrode fingers is 200 \( \mu m \). The length of the RF notches with 60 \( \mu m \) is optimized for mechanical stability and provides axial field symmetry with a 30 \( \mu m \) spacing. Additional holes with a diameter of 240 \( \mu m \) in the outer region allow alignment and mounting.

The wafer metallization is done after a careful ultrasonic cleaning procedure (acetone, isopropyl and piranha) and oxygen plasma cleaning. The laser-cut blank Al₂O₃ wafer is coated in an electron beam evaporator during a continuous rotation with 50 nm titanium and 500 nm gold (figures 2(b) and (c)). A declination angle of 45° is required during the coating process for an overall continuous coating. The surface roughness is better than 10 nm, which was verified by atomic force microscopy. The conductor paths are manufactured by laser structuring of the wafer metallization (figure 2(d)). Finally, the wafer is laser diced. The bottom, center and top layers of the microtrap are aligned and mounted with UHV-compatible UV epoxy adhesive (figure 2(e)). The stack of three layers is mounted in a center-holed UHV-compatible leadless ceramic 84-pin chip carrier with outer dimensions of 30 mm and an inner cavity size of 12 mm. Electrical connections to the ceramic chip carrier rely on ball bonding with a 15 \( \mu m \) diameter gold wire (figure 2(e)). Our design avoids dielectric blank Al₂O₃ areas; unavoidable isolation lines between the electrode segments are shifted away >200 \( \mu m \) from the ions position by the

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2 Reinhardt Microtech AG, Wangs, Switzerland.
3 Micreon GmbH, Hannover, Germany.
4 Kyocera, type LCC8447001.
extended electrode finger design. From an electron microscopy analysis, we checked that the dc electrode finger segments are gold-plated completely from all sides (figure 3).

The microtrap chip carrier is mounted on a low-pass filter printed circuit board (PCB), which serves as an electrical connector device for the 80-pin ribbon cables. The PCB is based on the UHV-compatible polyimide laminate Isola P97, which is 200 µm gold-electroplated. The UHV-compatible Kapton ribbon cables are connected with ceramic D-type connectors in vacuum. Low-pass filters (ceramic SMD type) with a cutoff close to 10 MHz are soldered close to the chip carrier (figure 1(a)).

Decreasing the electrode geometries of the processing zone as compared with the storage zone of the microtrap has some advantages with respect to quantum information experiments: a smaller electrode design provides stronger confinement of the ions at the same voltage levels. Stronger confinement leads to higher axial vibration frequencies, which set the time scale for multi-qubit gate operations. For the details of the trapping fields in the axial and radial directions, we use numerical simulations.

2.2. Field simulations

The trap region of the microtrap is partitioned into a 9-segment loading and storage section, a 3-segment transfer region and a 19-segment processing zone. Each electrode pair of a segment is voltage-controlled separately, providing full control for each trap site individually and effective micromotion compensation. Numerical simulations give insight on how to form potentials suitable to trap single ions or linear crystals (figure 4). The loading zone is optimized such that a thermal beam of calcium passes through; therefore the cross-section of the storage zone is asymmetric with a ratio 4 : 1. The more symmetric cross-section of the processing zone with a ratio 2 : 1 leads to a strong confinement of the ions and higher radial and axial frequencies [22].

The 2D dynamical confinement in the radial cross-section at the storage region (figure 4(a)) is described numerically by the quadrupole potential strength of the dynamical trap potential \( \phi \). The lowest-order approximation \( \phi = c_2/2 (y^2 - z^2) \cdot U(t) \) shows the geometric factor \( c_2 \) of the

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Figure 3. Electron microscope picture of the loading region (a) and narrower processing region (b). The gold-coated finger structure and laser cuts defining electrodes are visible.
Figure 4. Numerical field simulation of the microtrap: (a) the pseudopotential cross-section of the loading region shows equi-pseudopotential lines at 0.125, 0.25, 0.375, 0.5, 0.625 and 0.75 eV for a $^{40}$Ca$^+$ ion trapped at $\Omega = (2\pi) 24.841$ MHz with $U = 140$ V. The trap depth is 0.755 eV. (b) The axial potential is plotted along the trap axis in the loading (I) and processing (II) regions. The individual electric potential of a single electrode pair at $-5$ V (other electrodes at 0 V) is shown for three adjacent electrode pairs.

quadrupole potential strength ($yz$-cross-section). The storage region is characterized by $c_2 = 0.52 \times 10^7 \text{m}^{-2}$; the processing region shows a stronger confinement with $c_2 = 1.99 \times 10^7 \text{m}^{-2}$. Under typical operating conditions, see section 3.1, and with the trap drive frequency denoted by $\Omega/2\pi$, the dimensionless stability parameter $q = 2eU/(m\Omega^2) c_2$ results in $q = 0.14$ for the storage region and $q = 0.55$ for the processing region. The calculated simplified frequency of the secular motion $\omega = \Omega \cdot q / 2\sqrt{2}$ in the storage region is $\omega = (2\pi) 1.26$ MHz and is reproduced experimentally with high accuracy. The measurements presented here are implemented in the storage region, so the processing region allows a tighter confinement of the ion in future experiments.

The axial potential along the trap axis is calculated in a numerical 3D electric potential simulation (figure 4(b)). Requirements for fast ion transport are deep axial potentials with moderate control voltages and a large spatial overlap of the axial potentials from adjacent electrode pairs [22]. The peak widths at half-height of the axial potentials are 500 $\mu$m at the storage region (250 $\mu$m segment width) and 264 $\mu$m at the loading region (100 $\mu$m segment width). For the wider segments of 250 $\mu$m in the storage zone, the trap allows a tight confinement with an axial frequency of 1.20 MHz with $-5$ V applied only, which is experimentally verified within 5% accuracy via sideband spectroscopy.

3. Experimental set-up

3.1. Trap operation

For the RF supply of the trap, an RF synthesizer is used, followed by an amplifier to feed $+26$ dBm ($\sim$400 mW) power into a helical resonator matching the 50 $\Omega$ amplifier output impedance with the trap. The injected RF power is monitored by a capacitive divider. Under typical operating conditions, we reach amplitudes of 280 V$_{pp}$ at a frequency of 24.841 MHz. The
dc electrodes are supplied with voltages in the range of ±10 V. Here, the ion is trapped in the middle of the storage region with one electrode pair; the trap electrodes and the adjacent pairs are biased for micromotion compensation. The trap is installed in a stainless steel DN200CF vacuum chamber with a regular octagon DN63CF viewport symmetry. With a pump system comprising a 75 litre ion pump and a titanium sublimation pump, we operate the experiment at a pressure of 10^{-10} mbar. Pairs of magnetic field coils in a three-axis Helmholtz configuration are used for compensating the stray magnetic fields and generating a quantization axis with a magnetic field of 0.3 mT directed at −45° to the trap axis x.

3.2. Laser configuration

Single {superscript}40Ca{superscript}+ ions stored in the trap are generated by photoionization of a neutral calcium atomic beam from a resistively heated oven. The two-step process is driven by laser light near 423 and 375 nm [23]. Figure 5(a) shows the level scheme of {superscript}40Ca{superscript}+: the dipole transitions 4{superscript}2S_{1/2} → 4{superscript}2P_{1/2} at 397 nm allow Doppler cooling of the ions; the 3{superscript}2D_{3/2} → 4{superscript}2P_{1/2} near 866 nm and the transition 3{superscript}2D_{5/2} → 4{superscript}2P_{3/2} near 854 nm allow depletion of the metastable D-levels. The quadrupole transition near 729 nm from the 4{superscript}2S_{1/2} ground state to the metastable 3{superscript}2D_{5/2} level is employed for sideband spectroscopy, sideband cooling and coherent quantum dynamics.

All transitions of the {superscript}40Ca{superscript}+ ion are driven by grating stabilized diode lasers. The lasers at 397, 866 and 854 nm are locked to external Zerodur Fabry–Perot cavities (finesse F = 250) for frequency stabilization using the Pound–Drever–Hall (PDH) technique. The laser at 729 nm (laser diode followed by a tapered amplifier) is PDH-locked to a cavity with finesse F \geq 50 000, reaching a sub-kilohertz linewidth; the cavity is fabricated from ultra low expansion glass (ULE). Lasers at 866, 854 and 729 nm can be switched off using acousto-optical modulators in double-pass configuration, also being employed for tuning the laser frequency near 729 nm. Laser beams at 397, 866 and 854 nm are within the xy-plane (see figure 4) and intersect the trap at +45° with respect to the trap axis x. A separate \sigma + beam deviates from the laser near 397 nm for optical pumping. Also this beam lies in the xy-plane but intersects the trap axis under −45°, parallel to the magnetic field direction. The beam near 729 nm, in the xy-plane, is focused to a waist size of 15 \mu m and intersects the trap under 45° perpendicular to the magnetic field axis. The Lamb–Dicke factor of excitation depends on the projection of the \vec{k}_{729}
vector on the trap axis as well as the trap frequency \( \omega_{\text{ax}} = (2\pi)1.1 \text{ MHz} \) and mass \( m \) of the ion like \( \eta_{729} = |\vec{k}_{729}| \cos \theta \sqrt{\hbar/2m\omega_{\text{ax}}} \) and we calculate \( \eta_{729} = 0.065 \). The polarization at 729 nm is chosen such that only \( \Delta m = 2 \) transitions are allowed, e.g. from \( S_{1/2}, m = +1/2 \) to \( D_{5/2}, m = +5/2 \) and \( m = -3/2 \).

3.3. Doppler cooling, fluorescence detection and cold ion crystals

The ion fluorescence is imaged by a custom lens system\(^6\) (focal length 66.8 mm and numeric aperture 0.27) on an EMCCD camera\(^7\) (efficiency of 50\%) and a photomultiplier tube (PMT) of quantum efficiency \( \sim 27\% \) for detecting ions and reading the quantum state. The magnification of the imaging branch is roughly 20. The fluorescent light is collected from a solid angle of \( \sim 2.5\% \). It is distributed at a ratio of 80 : 20 between PMT and camera by a beam splitter and filtered by a band pass filter to suppress background photons. For trapping and cooling, 1 mW of 866 nm light is focused to a spot size of 30 \( \mu \)m. The power of the laser near 397 nm is focused to a spot size of 20 \( \mu \)m and can be switched between zero, a reduced power level of 30 \( \mu \)W (Doppler cooling) and full power of about 300 \( \mu \)W (detection). With the laser slightly red-detuned and proper micromotion compensation, a single ion count rate of 16 kHz at a background of 4 kHz can be achieved with the PMT. If an ion is shelved in the long-lived \( D_{5/2} \) level, no light is scattered. With a detection time of 5 ms, we are able to discriminate the qubit states with an error probability of \( 3 \times 10^{-3} \) \([5]\). Figure 5(b) shows linear ion crystals trapped and observed in the microtrap.

4. Quantum jump spectroscopy

Quantum jump spectroscopy has been used to determine the frequency of clock transitions with an accuracy of about 7 parts in \( 10^{-17} \) \([24]–[27]\). A narrow dipole forbidden transition is driven and, subsequently, the excitation to the metastable level is tested by exposure to resonant radiation on a dipole allowed transition.

4.1. Sideband spectroscopy on the \( S_{1/2} \) to \( D_{5/2} \) transition

In the experiments presented here, we perform spectroscopy on the \( S_{1/2} \) to \( D_{5/2} \) transition (figure 6). With a lifetime of 1.2 s, the spectroscopic resolution is limited by the laser pulse duration, the Rabi frequency during the excitation and the frequency stability of the laser source. The harmonic motion of the ion in the trap can be investigated spectroscopically at the level of single vibrational quanta. The electronic and vibrational states are manipulated coherently with the following sequence:

1. Doppler cooling: the laser near 397 nm is red-detuned from the \( S_{1/2} \) to \( P_{1/2} \) transition to \( \lesssim 1/2 \) of the maximum fluorescence rate. This corresponds to a setting of about \( \Gamma/2 \), where \( \Gamma = (2\pi)22.3 \text{ MHz} \) is the natural linewidth of the dipole transition. The beam is attenuated in order to avoid saturation. The laser frequency near 866 nm is tuned for maximum fluorescence. Additionally, resonant laser light depopulates the metastable \( D_{5/2} \) level. Typically, we apply Doppler cooling for 5 ms. While the theoretical cooling limit

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\(^6\) Sill Optics, Wendelstein, Germany.

\(^7\) iXon DV860-BI, Andor Technology, Belfast, UK.
Results in a mean phonon number of $\bar{n} \hbar \omega_{\text{trap}} = \Gamma/2$, with $\bar{n} \sim 12$, typically we observe a slightly higher $\bar{n}$ between 12 and 25.

2. Optical pumping: with a typically 5 $\mu$s short pulse of $\sigma^+$ polarized light near 397 nm, we pump the ion into the $S_{1/2}, m = +1/2$.

3. Sideband cooling (optionally): we tune the laser light near 729 nm such that the red secular sideband of the $S_{1/2}, m = +1/2$ to $D_{5/2}, m = +5/2$ is excited. The $D_{5/2}$ state is quenched by resonant laser light near 854 nm to the $P_{3/2}$ level, which quickly decays to $S_{1/2}$, closing the cooling cycle. Short pulses of optical pumping as in step (2) are inserted and also conclude the sideband cooling.

4. Spectroscopy pulse: all laser sources, except the laser light near 729 nm, are switched off. We excite the $S_{1/2}, m = +1/2$ to $D_{5/2}$ transition with pulses of well-defined frequency, duration and intensity.

5. State detection: the lasers at 397 and 866 nm are switched back on. The power of the 397 nm laser is at maximum such that a maximum count rate is obtained. The PMT counts photons of the ions fluorescence. If the ion had been excited on the quadrupole transition to the $D_{5/2}$ level, no fluorescence photons will be observed. The entire sequence is repeated typically 50–500 times depending on the requirements, and the average excitation to the $D_{5/2}$ level is recorded. For $N$ measurements and an excitation probability $p$, the projection noise error is given by $\sqrt{p(1-p)/N}$. Then, e.g., the laser frequency near 729 nm is varied, see figure 6. Here, the ion is excited without sideband cooling (step 3) such that the radial and axial red and blue motional sidebands show equal strength. These resonances are denoted by rRSB to rBSB. Additional resonances show up at a laser detuning for a second sideband excitation $\pm 2\omega_{ax}$ and at difference frequencies of the sidebands $\omega_{rad} - \omega_{ax}$.

Figure 6. Quantum jump spectroscopy with a single ion: the laser frequency near 729 nm is scanned over the carrier transition and the vibrational sidebands. For the data shown here, we have used a laser linewidth of $\sim 200$ kHz. The fit to the data (shifted and downsized for clarity) determines the axial and radial trap frequencies, $\omega_{ax} = (2\pi)1.2$ MHz and $\omega_{rad} = (2\pi)2$ MHz.
4.2. Micromotion compensation

If an ion is displaced from the node of the RF electric field either by asymmetries or by patch charges, it will oscillate at the trap drive frequency $\Omega_0/2\pi$. Consequently, Doppler cooling and fluorescence detection will be affected. However, micromotion is compensated by applying a balanced voltage difference to the particular segments of an electrode pair such that the ion is moved into the RF trap center. Various methods of measuring the micromotion have been studied [28]; yet another method uses sideband spectroscopy: we excite the sideband at $\omega_{\text{carrier}} + \Omega_0$ and compare the sideband excitation with that on the carrier [5]. The Rabi frequency $\Omega_1$ on the micromotion sideband and that on the carrier $\Omega_0$ holds $\Omega_1/\Omega_0 = J_1(\beta)/J_0(\beta) \approx \beta/2$ for $\beta \ll 1$, with $\beta$ denoting the index of modulation and $J_n$ indicating the Bessel functions of the $n$th order. As the excitation to the $D_{5/2}$ state is proportional to $\Omega^2$ for low saturation, we can measure the ion micromotion directly, see figure 7. We find the minimum excitation close to $-1.77$ V. At this minimum, thus for optimum compensation voltage, we reduce the ratio of excitation strength to zero with an error of $\pm 0.03$. This measured value corresponds to the ratio of squared Bessel functions $J_1^2(\beta)/J_0^2(\beta)$ with a modulation index of $0.0 \pm 0.17$, which is due to a residual micromotion oscillation amplitude $x_{\text{min}} = \beta_{\text{min}}(\lambda/2) = (0.0 \pm 0.17)(729 \text{ nm}/2)$ of $(0 \pm 130)$ nm. The optimal compensation voltage changes by less than 0.5% from day to day.

In conclusion, the micromotion can be nulled by a properly set compensation voltage and, due to the shielding effect of the gold-coated finger-shaped electrodes, stray electric fields from isolating parts of the microtrap do not show up with large and fluctuating contributions.

4.3. Coherent single ion dynamics

The coherent ion–light interaction leads to Rabi oscillations between the $S_{1/2}$ ground state and the excited metastable $D_{5/2}$ state when the duration of the interaction is varied. If the single ion internal states are used to store qubit information, a $\pi$-pulse will flip the qubit between the two logic states.

Figure 7. Excitation on the micromotional sideband for compensation: the amplitude of the excitation line is plotted as the compensation voltage is varied. For comparison, the excitation amplitude of the carrier with a laser power reduced by a factor of 10 is indicated by the red square data point.
Here, we present Rabi oscillations on the carrier transition for a single ion which has been Doppler-cooled, see figure 8. The data show a 95% efficiency for the $\pi$-pulse at 2.5 $\mu$s, corresponding to a Rabi frequency of $\Omega_0 = (2\pi)200$ kHz. The decay of contrast is due to the fact that we observe an incoherent superposition of Rabi oscillations with a different frequency for each thermally occupied Fock state: $\Omega_{n,n} \propto \eta^{2}_{729}n$. If we model the data with $P_{D}(t) = \sum p_{n}(\bar{n}) \sin^{2}(\Omega_{n,n}(t))$, we find agreement for a thermal distribution $p_{n}$ with $\bar{n} \sim 12$ (figure 8).

### 4.4. Sideband cooling

For Doppler cooling, the temperature limit is given by the natural linewidth of the dipole transition. For quantum logic operations, however, a mean phonon number below this limit is often required. Therefore we apply sideband cooling on the narrow $S_{1/2}$ to $D_{5/2}$ transition [29]. Laser radiation near 729 nm on the red sideband of the transition excites from $S_{1/2}, m = +1/2$ to $D_{5/2}, m = +5/2$. The effective width of this cooling transition can be increased by applying resonant laser light near 854 nm. This mixes the $D_{5/2}$ state with the $P_{3/2}$ state, which rapidly decays to the $S_{1/2}, m = +1/2$. The cooling rate is modified accordingly, and the effective width of the $D_{5/2}$ level sets an upper limit for the rate of cooling cycles.

For the introduction of laser cooling of trapped particles, we apply the semiclassical theory [30], determine all laser cooling parameters experimentally and compare the cooling result with the theoretical expectation.

The theoretical limit of sideband cooling is given by the ratio of laser cooling $\Gamma_{\text{cool}}$ and the heating rates $\Gamma_{\text{heat}} = \Gamma_{\text{laser-heat}} + \Gamma_{\text{trap}}$, yielding $\bar{n} = \Gamma_{\text{heat}}/(\Gamma_{\text{cool}} - \Gamma_{\text{heat}})$ as the steady-state average phonon number. Heating by laser processes is due to either an off-resonant excitation on the carrier transition with subsequent decay on the blue sideband or an off-resonant blue sideband excitation followed by a decay on the carrier [30]. A calculation of the detailed balance
Figure 9. (a) Depletion of the D$_{5/2}$ state by a 3 µs pulse near 854 nm. The observed dip corresponds to the resonance line and allows for tuning the laser to resonance. We model the data by a 37 MHz power-broadened Lorentzian. (b) After a π-pulse on the carrier transition at 729 nm, the depletion pulse length to the P$_{3/2}$ state is scanned. The exponential decay fit determines $\gamma_{\text{eff}}$, plotted here with four different laser powers at 854 nm. (c) The dependence of $\gamma_{\text{eff}}$ is plotted as a function of the 854 nm laser power; a linear fit yields 31.6(5) kHz $\mu$W$^{-1}$.

of phonon states leads to

$$\bar{n} = \left( \frac{\eta^2_{\text{spont}}}{\eta^2_{729}} + \frac{1}{4} \right) \frac{\gamma_{\text{eff}}^2}{4\omega_{ax}}$$  \hspace{1cm} (1)

if trap heating is excluded. Here, the parameter $\eta_{\text{spont}} = |\vec{k}_{395}|\sqrt{\hbar/2m\omega_{ax}}$ is 0.17, for the axial trap frequency $\omega_{ax} = (2\pi)1.1$ MHz, as it takes into account the recoil if the ion decays spontaneously from the P$_{3/2}$ level to the S$_{1/2}$ ground state. Due to the laser recoil on the S$_{1/2}$ to D$_{5/2}$ excitation, we get $\eta_{729} = 0.065$. In equation (1) only the cooling rate, but not the cooling limit, depends on the intensity of the laser near 729 nm. $\gamma_{\text{eff}}$ denotes the effective linewidth from quenching the D$_{5/2}$ state to the P$_{3/2}$ and is adjusted by the laser power at 854 nm.

The average phonon number $\bar{n}$ increases with the intensity of the laser near 854 nm; thus one has a tradeoff between cooling rate and minimum temperature. However, even for $\gamma_{\text{eff}} \simeq 90$ kHz, equation (1) predicts an almost perfect ground state of vibration with only $\bar{n} \leq 0.01$. The situation is more complicated if we take trap heating into account: the steady-state photon number results from the balance

$$\bar{n} = \frac{\Gamma_{\text{trap}}}{\Gamma_{\text{laser-cool}} - \Gamma_{\text{trap}}} \simeq \frac{\Gamma_{\text{trap}}}{\Gamma_{\text{laser-cool}}} \sim \frac{\Gamma_{\text{trap}}}{\Gamma_{\text{laser-cool}} - \Gamma_{\text{trap}}}$$ \hspace{1cm} (2)

if the laser-induced heating is small compared to the trap heating rate. We find that the thermal mean phonon number becomes

$$\bar{n} = \frac{\Gamma_{\text{trap}}}{(\eta_{729}\Omega_0/\gamma_{\text{eff}}^2)\gamma_{\text{eff}} - \Gamma_{\text{trap}}}.$$ \hspace{1cm} (3)

for the case where the net cooling rate $W = (\eta_{729}\Omega_0)^2/\gamma_{\text{eff}} - \Gamma_{\text{trap}}$ is positive. In contrast to equation (1), the cooling limit now depends on the intensity of the laser near 729 nm driving the red sideband of the quadrupole transition. We consider here the case where the sideband excitation is incoherent, with $\eta_{729}\Omega_0 \lesssim \gamma_{\text{eff}}$. 

New Journal of Physics 10 (2008) 045007 (http://www.njp.org/)
Figure 10. (a) Sideband cooling of the axial vibration of a single ion. The imbalance of blue and red sideband intensities $P_{\text{blue}}$ and $P_{\text{red}}$ leads to an estimation of a mean phonon number $\bar{n}$ of 1.2(3). The spectrum has been measured with a 200 $\mu$s delay after the sideband cooling. (b) The trap heating is determined from a linear fit to the data, see figure 11.

In order to compare the above cooling theory with the experiment, we need to determine $\gamma_{\text{eff}}$, $\Omega_0$ and $\Gamma_{\text{trap}}$ in independent experimental measurement sequences and compare the theoretical prediction in equation (3) with the experimental outcome on $\bar{n}$.

$\gamma_{\text{eff}}$ is determined by controlled depletion of the metastable state: after Doppler cooling and optical pumping, we apply a 1 $\mu$s laser pulse on the carrier transition such that the ion is transferred into the D$_{5/2}$ state. A pulse of laser light resonant with the D$_{5/2}$ to P$_{3/2}$ transition is then applied and finally the remaining D$_{5/2}$ population is determined. From the exponential decay, see figure 9(b), we determine the effective cooling width that is, as expected, a linear function of the laser power at 854 nm, with $\gamma_{\text{eff}}$ (kHz) $= 31.6(5)P_{854}$ ($\mu$W).

The Rabi frequency on the quadrupole transition is revealed from measurements such as in figure 8. With the maximum available laser power of 60 mW, we reach $\Omega_0 \simeq (2\pi)200$ kHz. Correspondingly, the maximum possible sideband excitation with this laser power is $\eta_{729}\Omega_0 = (2\pi)13$ kHz.

4.5. Heating rate measurement

The mean phonon number of $\bar{n}$ is determined from spectra such as in figure 10 showing the red and blue sidebands after sideband cooling. We deduce from the ratio of the sideband intensities $A = P_{\text{red}}/P_{\text{blue}}$ by means of the asymmetry of the excitation (figure 10) the mean phonon number $\bar{n} = A/(1 - A)$, here $\bar{n} = 0.56(5)$. To obtain the trap heating rate, we insert a variable waiting time interval between steps 3 and 4 in the experimental sequence, see section 4.1 of the present paper [4]. The data plotted in figure 11 yield a trap heating of 2.1(3) per millisecond. As this heating rate is attributed to the contamination of trap electrodes due to the loading process from the thermal beam of neutral calcium, we expect a lower mean phonon number $\bar{n}$ in the processing region, which is spatially separated from the loading zone.

Note that quantum gate operations and the transport of ions in the trap are about 10–100 times faster than the measured trap heating. In the future, we will investigate the influence of the gold coating (different surface qualities and thickness) on the trap heating.
Figure 11. Heating rate measurement of the axial vibrational mode of a single ion as measured from the temperature increase after a delay time. The values of $d\bar{n}/dt = 2.1(3)$ per millisecond and the minimum phonon number of $0.56(5)$ are determined from a linear fit to the data.

5. Conclusion and outlook

We have outlined the design, the fabrication and the first characterization of a novel multi-segmented microchip ion trap, and we have shown that this trap is suited for scalable quantum logic. In some detail, the sideband cooling on the quadrupole transition has been investigated. In the future, we will explore Raman transitions between Zeeman ground (qubit) states $S_{1/2}$, $m = +1/2$ and $m = -1/2$ for the cooling, for coherent qubit rotations and for two-qubit gate operations. Additionally, we will study the transport of quantum information between the processor and the memory section benefiting from the large number of trap segments. Further development will include the integration of micro-optical elements.

Acknowledgments

We thank Frank Korte (Micreon GmbH) for his expertise in laser cutting, H Roscher for the cooperation in the cleanroom facility, K Singer and R Reichle for their contributions in an earlier stage of the experiment, K Singer for his important help with the experimental control software and J Eschner for discussions. We acknowledge financial support by the German Science Foundation (DFG) within SFB/TRR-21 and by the European Commission within MICROTRAP (contract no 517675) and EMALI (contract no MRTN-CT-2006-035369).

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