Abstract

We present an alternative approach for interconnecting trapped ion processor nodes by deterministic single ion transfer. In our experiments, we demonstrate the single ion extraction out of a linear Paul trap, into a free space trajectory, followed by recapture in the trapping potential. We recapture in the same trap, coined the ion fountain operation after a free-space travel of distance 110 mm and a time of flight of 7 µs. Our experimental realization yields a success probability of 95.1%, namely 715 out of 752 extracted ions are retrapped, cooled and observed. Based on such high success rate, we discuss the future perspective for an application towards scalable ion trap quantum computing and advanced quantum sensing.

1. Introduction

Trapped ions are among the leading platforms for quantum computing and quantum simulations. The basis of this success is the full control over the internal electronic states of trapped ions to encode qubits [1, 2]. The external degrees of freedom, forming collective eigenmodes due to the long range Coulomb interaction in ion crystals, are employed to drive quantum gate operations and to generate multi-particle entanglement [3, 4]. Spatial control of trapped ions and ion crystals in a segmented trap [5–8] provides the basis for a prominent shuttling based approach to multi-qubit scalability [9–11]. Alternatively, quantum information may be converted into photons for building networks of quantum processors [12–15]. The interconnectivity of ion-based quantum processors nevertheless remains a significant challenge.

The deterministic transport of a single ion carrying a qubit between two different ion traps constitutes a so far unexplored pathway for conveying quantum information [8]. Unlike the photon-mediated approach one can reach unity-efficiency, while realizing the transport at time scales much faster than common gate times, or times required for ion qubit register reordering [16–18]. So far, spatial control of the ion has been limited to the trapping region. In this work we are extending this control into the free space region, realizing an ion fountain. We will demonstrate the required methods and their optimization for the extraction of an ion from a trapping potential to a free space region, the steering of its trajectory and its recapture in the trap. We see a high application potential of our method for the development of networking between ion quantum processors. The control over a single ion in free space can, however, also enable new quantum sensing applications [19].

In this letter, we first describe the setup and experimental sequence. Then we show the optimization of parameters, starting with numerical simulations, followed by a series of calibration experiments. We employ a specialized linear ion trap setup for the experiments: ions are extracted and—instead of using a second identical linear trap downstream—we reflect the ion trajectories and capture the ions entering from free space in the linear trap where they started initially. In doing so, we realize an electrostatic cat’s eye ion reflector. We believe this ion fountain experiment fully establishes all techniques, which are required for trap-to-trap ion transport. The procedure of ion extraction, free flight, and single ion recapture, achieves a success probability of more than 95%. As an outlook, we sketch future improvements and outline various applications of the established single ion free-space transports.
2. Experimental setup

The overall setup used in this work is made up of three basic modules, (i) linear segmented ion trap module, (ii) extraction and focusing elements, and (iii) electrostatic steering elements, shown in figure 1(a), which can be stacked freely in any combination onto each other as they are held mechanically stable along the z-axis in tightly fitting titanium mounts. The assembly is mounted vertically in a ultra-high vacuum (UHV) vessel, with the z-axis in direction of gravity, to reduce the transfer of floor vibrations, and to mitigate bending or deformation due to its own weight. Not used in the setup is an Einzel lens module [20, 21].

The trap module (i) contains a segmented Paul trap in X-shape configuration [20]. Blades are fabricated from laser-cut gold-covered alumina wafers and each of the 11 DC segments is controlled individually by a $U_{\text{seg}}^{(n)}$ supplying ±40 V, see figure 1(c). We operate the RF blades at $\Omega_{\text{RF}} = 2\pi \cdot 17.85$ MHz drive frequency with a peak-to-peak $U_{\text{RF}}$ ≈ 150 V resulting in radial trapping frequencies of $\omega_{(x,y)} ≈ 2\pi \cdot 500$ kHz. Micromotion compensation electrodes are placed behind the RF and DC electrodes (not shown in figure 1). To position the ion in the trap center, thus compensating residual micromotion, a DC field is applied in both x- and y-direction. In axial (z-) direction a pair of hollow (inner hole diameter 400 $\mu$m) endcaps are placed at 1.45 mm distance from the trap center. Axial trapping is provided by application of
Figure 2. Numerically determined trajectory (blue) and velocity (red) of a single $^{40}$Ca$^+$ ion along the axial direction. The initial parameters are $v_0 = z_0 = 0$. The entire time-of-flight is 6.3 μs.

$U^{(6)} = -0.6$ V on the middle segment and $U^{(n ≠ 6)} = 0$ V, resulting in an axial trapping frequency $\omega_z \simeq 2\pi \cdot 150$ kHz. Along the z-direction, ions are transported and extracted, as depicted in figure 1(b).

Photoionization loading is achieved using a beam of neutral calcium excited with laser light at 423 nm and 375 nm at the trap center. The Ca$^+$ dipole transition $4S_1/2 – 4P_1/2$ at 397 nm serves as a Doppler cooling transition. Fluorescence at this wavelength is collected by a lens system with a magnification of 11.6(2) and imaged onto an electron multiplier gain charged coupled device (EMCCD) camera, not shown in figure 1. A laser beam at 866 nm is required to empty the metastable $3D_3/2$ level. Both beams are aimed at the ion under a direction such that all vibrational modes are laser cooled.

The trapping module is connected to an extraction and focusing module (ii), denoted with E and F, which is instrumental in controlling the free-space ion propagation. For this we may apply or switch DC voltages on E and F up to $±20$ kV, independently and within less than 100 ns time scale. The direction of the ion trajectory requires fine adjustments, despite the high mechanical alignment precision of the modules with respect to each other of $\leq 50$ μm. To adjust both the angle and the position, in both radial ($x$- and $y$-) directions, we developed an (iii) electrostatic steering assembly which is composed of eight half-spherical deflection electrodes (radius of curvature 7 mm, radial distance 12.2 mm). Downstream, a secondary electron multiplier (SEM) can optionally be used to detect single ions [20].

Triggering of RF and DC electric waveforms is performed using computer controlled switches [18, 22]. The EMCCD signal is recorded by the same computer. In the experiments presented here, we extract ions from the trap (i), and use the elements (ii) and (iii) such that the ions trajectory is reversed and the ions are recaptured in the trap (i). We name this operation ion fountain mode.

3. Operation of the ion fountain

The experimental sequence starts with the ion loading and verification, using a EMCCD picture ensuring exactly one ion is trapped. Then, the extraction DC voltage $U_E$ and the RF drive voltage $U_{RF}$, respectively, are switched on and ramped down. The endcap voltage is adjusted for extraction, while constant control voltages in the focusing and in the steering module direct the ion trajectory. Both, the timings and the amplitude of DC and RF voltages require a fine optimization. Once the ion has reentered the trapping module via the hole in the endcap, we switch off $U_E$ and ramp up the RF drive back to ideal trapping conditions.

A large set of parameters has to be optimized, including the trapping potential in $(x, y, z)$-direction, characterized by $\omega_{(x,y,z)}$ and controlled by the RF and axial trap voltages on the segments $U^{(n)}$, the extraction voltages $U^{(1,2)}_{\text{E}}$ on both the endcaps and their timings and pulse duration $\Delta_{\text{pulse}}$, the focusing voltage $U_F$ applied to module (ii) and its timing $\tau_{\text{F}}$, the ramping of the RF amplitude $U_{RF}(t)$ in phase-stable manner (for details see [22]) with respect to the endcap pulse timing set by $\Delta_{\text{pulse}}$ and steering module control voltages $U^{(1,2)}_{(x,y)}$ for both radial directions $x$ and $y$, respectively.

This large number of parameters, and their large possible ranges, in combination with the lack of gradual feedback, because of the single ion be-or-not-to-be signal (either the ion is re-trapped or lost), and the low information acquisition rate make numerical simulations essential before any successful experimental implementation.
3.1. Numerical simulations for yielding an initial set of operation parameters

We import CAD geometries (Solidworks) of the modules (i) to (iii) in the finite element method simulation tool Comsol (50 μm grid size) and perform a 1D-simulation of the particle trajectory in the axial potential using a Verlet algorithm. The particle is initially positioned at the trap center and with an initial velocity zero. The ion trajectory is run through in 2 ns time steps. An event is considered as a successful recapture, if the end of the trajectory is finally found in a region $\leq 100$ μm around the trap center and with velocity $\leq 50$ m s$^{-1}$.

We chose to limit our simulations to the most basic procedure with a single negative DC pulse $U^{(1)}_{F}$ switched, using identical timing and voltage $U_{F}$ also on the focusing module, while $U^{(2)}_{F}$ is kept at 0 V. Obviously, the multi-parameter space is excessively large and we only started its exploration. For the simulation in 1D here, the deflection electrodes are used simply to generate a reflective potential by setting all to one constant voltage $U^{(1,2)}_{R} = U_{R}$. For the initial and the final trapping potential we chose them to be identical with trap frequencies of $\omega^{\text{init}}_{z} = \omega^{\text{final}}_{z} = 2\pi \cdot 147$ kHz, using $U^{(6)}_{seg} = -0.6$ V and $U^{(n=66)}_{seg} = 0$ V, fully in a static fashion. The adjustable parameter of the simulation is the extraction pulse length $\Delta t_{\text{puls}}$. It is expected that lower extraction voltages lead to lower kinetic energy of the ion and longer travel time. We assumed that low extraction voltages $\approx 1$ V would make the process increasingly susceptible, e.g. against slight parasitic charging of the surfaces. For a fixed value of extraction potential $U^{(1)}_{E} = U_{E} = -200$ V, we run the simulation and find a suitable combination of values for $U_{R}$, and $\Delta t_{\text{puls}}$. The choice of ion energies $>30$ eV is taken in order to mitigate deflections along the ion path due to parasitic stray charge effects. We studied the regime of low ion energies previously in the same apparatus [22].

For this extraction voltage and pulse width of $\Delta t_{\text{puls}} = 6.3$ μs with $U_{R} = 7.5$ V, we plot the potential and the particle trajectory in figure 2. The particle travel range of 55 mm reaches the first pairs of semi-spherical deflector electrodes in the steering module, see figures 1(a) and (b).
Figure 4. (a) Recapture measurement for $t_{RF}$ and $\Delta t_{puls}$. For each data point, we average over 100 single ion extraction and recaptures. Optimized timings are at $\Delta t_{puls} = 6.95 \mu s$ and $t_{RF} = 6.35 \mu s$. (b) Exemplary RF signal which visualizes the necessary timings: the drive $\Omega_{RF}$ at the trap is ramped down quickly at time $t_{off}$ by destructive interference. For this we are injecting $\Omega_{RF}$ at higher power level but with opposite phase into the helical resonator. This source is triggered with a transistor–transistor logic (TTL) switch (Sw1). As soon as the resulting RF power at the trap has dropped to zero ($\approx t_{off} = 0.4 \mu s$) the higher power RF input is fully switched off (Sw2). Starting at $t_{RF}$ ($\approx t_{off} = 6.4 \mu s$) the trap drive is ramped up by switching on the higher power RF (Sw3). Once the trap drive amplitude has reached the level, we switch off Sw3 to resume back to the regular RF level driving. For a detailed analysis of the process and the layout of the RF switches, see [22]. The voltage $U_{E}^{(1)}$ is applied at $t_{off}$ and ends when the ion is back on the trap center. The duration is $\Delta t_{puls}$.

3.2. Optimization ion steering

Using a pre-optimized set of parameters from the numerical simulations with $U_{E}^{(1)} = U_{F} = -195$ V, and $U_{E}^{(2)} = 0$ V we start the experimental optimization by scanning deflection voltages $U_{E-x}, U_{E-y}, U_{E}$ on module (iii) asymmetrically for opposite pairs with $U_{E} = 7.5$ V to steer the return ion trajectory in x- and y-direction. This is necessary due to the micromotion compensation field and imperfections of the trap geometry. The discrepancy of 5 V compared to the simulations for $U_{E}^{(1)}$ is due to the voltage supply, which outputs a lower voltage. For each extraction event, retrapping is verified by waiting 1 s under Doppler
cooling of the ion and checking for single-ion laser-induced fluorescence light with a 30 ms exposure time on the EMCCD, see figure 3(a). We can clearly discriminate whether an ion has been retrapped and is Doppler cooled, or if it is lost. We investigate two-dimensional steering scans for different reflection voltages $U_R$ between 7.3 V up to 8.1 V. Note, that for the setting of $U_R = 7.5$ V the scan range of successful deflection voltages is maximized, both in x- and in y-direction in contrast to figure 3(b). We conclude that this setting realizes a cat’s eye reflector in time and space for ions [23, 24].

3.3. Optimization ion extraction time and determination of the retrapping probability

Closely related is the optimization of the extraction pulse time $\Delta t_{\text{pul}}$ and switch on time $t_{\text{RF}}$ of the RF drive, which have to be synchronized to the instant when the ion arrives in the trap. For this a single calcium ion was extracted 100 times, with the voltage pulse $U_{\text{pul}}$ and the constant RF phase $\varphi_{\text{RF}} = \Omega_{\text{RF}} \cdot t_{\text{off}}$ varied in any combination in steps of 50 ns. The retrapping probability was characterized using the laser-induced fluorescence signal, obtained after a 1 s waiting time. While the ion fluorescence acquisition time of the EMCCD is much faster, this way, we report a very conservative measure for the retrapping efficiency. We find the optimal values near $\Delta t_{\text{pul}} = 6.95$ $\mu$s and $t_{\text{RF}} = 6.35$ $\mu$s, see figure 4(a). Note, that the value of $\Delta t_{\text{pul}}$ is significantly different compared with the numerical simulation which yields 6.3 $\mu$s. This deviation may be caused by errors in the simulation, dominated by effects of the dynamical Paul potential with an oscillating RF field which has not been taken into account. In a linear Paul trap, the RF force at the trap center has no projection in z-axis, but we have shown that the time-varying electrical force has a strong z-component near the endcap. This leads to an acceleration of the ion, and consequently a change in the overall time-of-flight to return. Even more importantly, a fine-tuning of the RF phase allows for squashing or stretching out the initial velocity distribution, see reference [22]. The associated RF signal is shown in figure 4(b). As a result, the RF switch-on setting influences the acceptance range for successful retrapping. From the data we estimate a range of about 200 ns. The experimental outcome shows that even though an accurate timing is key, switching at this time scales is unproblematic with this setup.

To obtain an accurate value of the recapture success probability, we used the previously optimized values. A single ion was loaded, which was confirmed using fluorescence light during the Doppler cooling, then extracted and retrapped. The procedure was repeated 752 times and retrapping was successful in 715 cases, resulting in a probability of 0.951. Note, that we typically used the very same single ion over and over again, to avoid time consuming photoionization loading. In one of the runs, the same ion was transported 65 times out of the trapping region and back to be seen in insert of figure 5, which shows the respective number of runs for each individual ion. For the entire measurement 38 ions were used. After a certain number of runs 37 ions were lost, for the last ion the measurement was terminated after 43 runs. Figure 5 shows the probability that a new initialized ion passes a certain number of runs consecutively. The overall data acquisition time was about 30 min, dominated by loading times and the 1 s waiting time. Note, that we have chosen a conservative criterion for retrapping and some of the 37 non-successful events may be due to a recapture in a highly excited motion which could lead to ion loss within the 1 s waiting time. Also, we
observe an ion loss rate due to background gas ($p \approx 2 \times 10^{-9}$ mbar) collisions in the order of 1 per minute which would explain about 10 out of the 37 non-successful events.

4. Conclusion and outlook

We experimentally demonstrated a single ion fountain with near-unity recapture efficiency. We state, that we have not found fundamental reasons or technology roadblocks which would prevent us from improving the recapture efficiency.

In future, we will focus on the remaining challenges towards ion-transport based interconnection of distant quantum processors [8]: we will use the segmented Paul trap with dynamical control of all voltages $U^{(n)}_{\text{seg}}$ to separate one ion from a multi-qubit register, shuttle this single ion to the outermost segment [18, 19] and extract it from there, while the other charged particles remain in the linear crystal. For this, we will reduce the susceptibility of the parameters of the extraction from the RF drive by largely reducing the extraction voltage $U^{(1)}_{\text{E}}$ and controlling $U_{\text{F int}}$ in the focusing module (see figure 1(b)) fully independently of electrode E1. The potential from the focusing electrode F is fully shielded from the trapping region. This extraction method would allow to keep an ion qubit register in the trap, while extracting one single ion and transporting it into a different quantum processor node. Equally well, one may extract and transport several ions sequentially with high speed within a few µs. Using the deflection and steering unit one may implement a switchyard for branching ions into an array of different linear traps, which are offset from the z-axis, thus realizing a versatile three-dimensional cross-connectivity.

Highly complex two-dimensional trapping assemblies with multiple junction and pathways for transports have been build [25–27], but so far still most successful quantum computing have been executed in devices with rather simple geometry, comprising a reduced amount of segments, and featuring no other additional features. In this spirit, the proposed trap-to-trap-transport QC architecture would come with the advantage of a simple and repeated identical unit, with an all-to-all connectivity between nodes. The fidelity and speed of such interconnections may rival alternative approaches such as mapping trapped ion qubits on photonic qubits. Extracting one ion out of a multi-qubit register would open all options for quantum error correction against the residual errors, such as qubit loss [28] or qubit phase shift errors [10, 29].

The residual motional excitation of the recaptured ion can be reduced by optimized schemes, were the retrapping parameters are refined: we aim for using the well-established Doppler recooling method [30, 31] that allows for an estimate of the motional excitation of the incoming ion once it is trapped. The higher the motional excitation, the longer it takes to achieve full fluorescence level under Doppler cooling light. Sympathetic cooling of the incoming ion with another ion species will be required when aiming for qubit gate operations.

On the long run, the ion transport between different nodes may serve for running teleportation of qubits [32, 33] between different spatially separated traps and a teleportation of two-qubit gate operations [34–36]. Additionally, our method paves the way for quantum sensing applications, where the unique advantages of trapped ions as a probe [19, 37, 38] could be extended to sensing with ions in free space.

The deterministic transport techniques between different traps demonstrated here will be of importance for the studies of isotopes of thorium [39], or anti-hydrogen ions in the GBAR setup [40], experiments that we conduct with the vision of understanding of the fundamental symmetries of the standard model. Moreover, the single ion extraction may be combined with spin-dependent light [41, 42] or magnetic gradient [43, 44] forces to realize beam splitters [45] or interferometer devices in free space [46, 47].

Acknowledgments

We thank B Lekitsch for careful reading the manuscript. We acknowledge financial support by the Bundesministerium für Bildung und Forschung via Q. Link.X, the Volkswagen Stiftung and the Deutsche Forschungsgemeinschaft through the DIP program (Grant Schm 1049/7-1).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the author, to whom any correspondence should be addressed.

ORCID iDs

Felix Stopp https://orcid.org/0000-0003-1215-2960
References

[1] Häffner H, Roos C and Blatt R 2008 Phys. Rep. 469 155
[2] Blatt R and Roos C F 2012 Nat. Phys. 8 277
[3] Häffner H et al 2005 Nature 438 643
[4] Monroe C et al 2021 Rev. Mod. Phys. 93 025001
[5] Bowler R, Gaebler J, Lin Y, Tan T R, Hanneke D, Jost J D, Home J, Leibfried D and Wineland D J 2012 Phys. Rev. Lett. 109 080502
[6] Ruster T et al 2014 Phys. Rev. A 90 033410
[7] Kaufmann H, Ruster T, Schmiegelow C T, Linda M A, Kaushal V, Schulz J, von Lindenfels D, Schmidt-Kaler F and Poschinger U G 2017 Phys. Rev. A 95 052319
[8] Lekitsch B, Weidt S, Fowler A G, Molmer K, Devitt S J, Wunderlich C and Hersinger W K 2017 Sci. Adv. 3 e1601540
[9] Kiepinski D, Monroe C and Wineland D J 2002 Nature 417 709
[10] Hilder J et al 2022 Phys. Rev. X 12 011032
[11] Dumitrescu P T, Bohnet J, Gaebler J, Hankin A, Hayes D, Kumar A, Neyenhuis B, Vasseur R and Potter A C 2021 arXiv:2107.09676
[12] Monroe C and Kim J 2013 Science 339 1164
[13] Bock M, Eich P, Kucera S, Kreis M, Lenhard A, Becher C and Eschner J 2018 Nat. Commun. 9 1
[14] Takahashi H, Kassa E, Christoforou C and Keller M 2020 Phys. Rev. Lett. 124 013602
[15] Kaufmann H, Ruster T, Schmiegelow C T, Linda M A, Kaushal V, Schulz J, von Lindenfels D, Schmidt-Kaler F and Poschinger U G 2017 Phys. Rev. Lett. 119 150503
[16] Wan Y et al 2020 Adv. Quantum Technol. 3 2000028
[17] Ruster T, Kaufmann H, Linda M A, Kaushal V, Schmiegelow C T, Schmidt-Kaler F and Poschinger U 2017 Phys. Rev. X 7 031050
[18] Jacob G, Groot-Berning K, Wolf S, Ulm S, Couturier L, Dawkins S T, Poschinger U G, Schmidt-Kaler F and Singer K 2016 Phys. Rev. Lett. 117 043001
[19] Groot-Berning K, Kornher T, Jacob G, Stopp F, Dawkins S T, Kolesov R, Wrachtrup J, Singer K and Schmidt-Kaler F 2019 Phys. Rev. Lett. 123 106802
[20] Stopp F, Ortiz-Gutiérrez L, Lehec H and Schmidt-Kaler F 2021 New J. Phys. 23 063002
[21] Heber O et al 2005 Rev. Sci. Instrum. 76 013104
[22] Malotte A, Szabo C I and Indelicato P 2013 Europhys. Lett. 103 10009
[23] Amini J M et al 2020 New J. Phys. 12 033031
[24] Revell M 2020 arXiv:2009.02398
[25] Holz P C et al 2020 Adv. Quantum Technol. 3 2000031
[26] Stricker R et al 2020 Nature 585 207
[27] Bermudez A et al 2017 Phys. Rev. X 7 041061
[28] Wesenberg J et al 2007 Phys. Rev. A 76 053416
[29] Huber G, Deuliche T, Schützler W, Reichle R, Singer K and Schmidt-Kaler F 2008 New J. Phys. 10 013004
[30] Barrett M D et al 2004 Nature 429 737
[31] Riebe M et al 2004 Nature 429 734
[32] Neilsen M A and Chuang I 2002 Quantum Computation and Quantum Information (Cambridge: Cambridge University Press)
[33] Gottesman D and Chuang I L 1999 Nature 402 390
[34] Wan Y et al 2019 Science 364 875
[35] Ludlow A D, Boyd M M, Ye J, Peik E and Schmidt-P 2015 Rev. Mod. Phys. 87 637
[36] Brewer S M, Chen J S, Hankin A M, Clements E R, Chou C W, Wineland D J, Hume D B and Leibrandt D R 2019 Phys. Rev. Lett. 123 033201
[37] Groot-Berning K et al 2019 Phys. Rev. A 99 023420
[38] Indelicato P et al 2014 Hyperfine Interact. 228 141
[39] Monroe C, Meekhof D M, King B E and Wineland D J 1996 Science 272 1131
[40] Sørensen A and Mølmer K 1999 Phys. Rev. Lett. 82 1971
[41] Khromova A, Pilze C, Scharfenberger B, Gloger T F, Johannng M, Varon A F and Wunderlich C 2012 Phys. Rev. Lett. 108 220502
[42] Welzel J, Stopp F and Schmidt-Kaler F 2018 J. Phys. B: At. Mol. Opt. Phys. 52 025301
[43] Henkel C, Jacob G, Stopp F, Schmidt-Kaler F, Keil M, Japha Y and Folman R 2019 New J. Phys. 21 083022
[44] Zych M, Costa F, Pikovski I and Brukner C 2011 Nat. Commun. 2 1
[45] Asenbaum P, Overstreet C, Kovachy T, Brown D D, Hogan J M and Kasevich M A 2017 Phys. Rev. Lett. 118 183602