Deterministic Ultracold Ion Source targeting the Heisenberg Limit

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The major challenges to fabricate quantum processors and future nano solid state devices are material modification techniques with nanometre resolution and suppression of statistical fluctuations of dopants or qubit carriers. Based on a segmented ion trap with mK laser cooled ions we have realized a deterministic single ion source which could operate with a huge range of sympathetically cooled ion species, isotopes or ionic molecules. We have deterministically extracted a predetermined number of ions on demand and have measured a longitudinal velocity uncertainty of 6.3m/s and a spatial beam divergence of 600μrad. We show in numerical simulations that if the ions are cooled to the motional ground state (Heisenberg limit) nanometre spatial resolution can be achieved.

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The miniaturization of semiconductor devices has reached length scales of a few tens of nanometres, where statistical Poissonian fluctuations of the number of doping atoms in a single transistor significantly affect the characteristic properties, e.g. gate voltage or current amplification ¹. Further miniaturization will even cause statistical device failure. Particularly fatal are statistical dopant fluctuations for a future solid state quantum processor based on single implanted qubit carriers like colour centres in diamond or phosphorous dopants in silicon ²,₃,₄,₅. So far, the only known methods to control the number of dopants utilize statistical thermal sources followed by a post-detection of the implantation event, either by the observation of Auger electrons, photoluminescence, phonons, the generation of electron-hole pairs or changes in the conductance of field effect transistors ⁶,⁷,⁸,⁹,¹⁰. To make the detection of such an event successful the methods require either highly charged ions or high implantation energies which, as a down side, generate defects in the host material. In these systems resolutions of less than 10nm are achieved by means of masks and apertures shielding the substrate from incident ions and leading to compulsory losses of dopants. Another fabrication method, specific for Si-surfaces, uses hydrogen terminated surfaces structured with the tip of a tunneling microscope, followed by a chemical reactive surface binding of doping atoms ¹¹,¹²,¹³,¹⁴,¹⁵. With this technique sub nm resolution can be achieved but the applicability is mainly limited to specific substrates and impurities in the background gas can cause severe impairment.

Here, we present the experimental proof of a novel ultracold ion source which can be used for the deterministic implantation of a predetermined number of single ions ¹⁶. Our technique is based on a segmented linear Paul trap with laser cooled ⁴⁰Ca⁺ ions similar to setups used for scalable quantum information processing with ions ¹⁷. Additionally loaded doping ions of different elements or ionic molecules cannot be directly laser cooled but could be sympathetically cooled by ⁴⁰Ca⁺ ions. Although invisible to the laser light they are still identified ¹⁸,¹⁹ and counted by exciting collective vibrational modes. Our segmented ion trap allows for the separation of the cooling ion from the dopant ion, which is finally extracted by a tailored electric field. The implantation method is in principle independent of the dopant species and the target substrate. For 2mK laser-cooled ions accelerated to 80eV the measured longitudinal velocity distribution shows a 1σ-spread of 6.3(6)m/s ²⁰ and a spatial 1σ-spot radius of 83(±8)μm at a distance of 257nm (beam divergence: 600μrad). These properties reduce chromatic and spherical aberration of any focusing ion optics. The resolution of our system is thereby not enforced by additional masks or apertures but is an intrinsic property of our setup.

The core of the experimental setup is a Paul trap - a universal tool for trapping charged particles such as atomic and molecular ions or charged clusters using a

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FIG. 1: a) Sketch of the segmented linear Paul trap with DC-electrodes (white) and RF-electrodes (dark grey). Deflection electrodes (light grey) are used to alter the trajectories of ions which are extracted out of the trap. b) Front view showing that RF and RF-ground electrodes (generating the radial confinement) are only covering the two 410μm wide front faces of the blades.

a) b)
combination of static (DC) and alternating (RF) electric fields. A pseudo-potential of a few eV depth is generated with a properly chosen RF amplitude and frequency $\Omega$.

![Diagram](image)

FIG. 2: Typical fluorescence image of a single $^{40}$Ca$^+$ ion (a), and linear ion crystals of two (b) and four (c) ions. After the extraction we record EMT detector signal traces with a single ion detection event (e), two events (f) and four events (g), correspondingly. The EMCCD image (d) shows fluorescence from a single $^{40}$Ca$^+$ ion only; however, we can discover from its position that it is trapped in a linear crystal together with two dark ions at the left hand side. As the mixed ion crystal is extracted, we detect three events, one from the $^{40}$Ca$^+$ near 12.8$\mu$s and two events near 15.3$\mu$s. From this time-of-flight spectroscopy, we reveal the mass of CaO$^+$ ions for both dark ions. All measurements were conducted without the movable aperture plate with an effective distance of 247mm between trap centre and detector.

For our application it is necessary that the ions arrange as a linear crystal such that they can be identified and counted using laser induced fluorescence. During the extraction we apply voltages to additional DC segments tailoring the axial potential. In a conventional linear segmented Paul trap this would lead to a loss of the radial confinement because the applied extraction potential exceeds the radial pseudo-potential. We have developed a special design of our trap, in which the ions are radially guided even during the axial extraction. Our trap consists of four copper plated polyimide blades of 410$\mu$m thickness and 65mm length which are arranged in a x-shaped manner [21] (see fig. 1 for a schematic view). The RF is applied to the inner front faces of two opposing blades; the front faces of both other blades are grounded. The distance between inner front faces of opposing blades is 2mm. DC voltages are applied to eight segments of 0.7mm width which are placed on the top and bottom areas of all four blades. Under typical operating conditions we apply to the RF electrodes an amplitude of 200V at the frequency of $\Omega/2\pi = 12.155$MHz leading to a radial secular frequency $\omega_{rad}/2\pi = 430$kHz for a $^{40}$Ca$^+$ ion. The DC-electrode trap segments 2 and 8 are supplied with 35V and the remaining electrodes with 0V resulting in an axial potential with $\omega_{ax}/2\pi = 280$kHz. The location of trapped ions is above electrode 5. The trap assembly is housed in a stainless steel vacuum chamber with enhanced optical access held by a turbo-molecular pump and an ion-getter pump at a pressure of $3\times10^{-9}$mbar. Ions are illuminated by resonant laser light near 397nm and 866nm for Doppler cooling. Scattered photons are collected by a f/1.76 lens on an EMCCD camera to image individual $^{40}$Ca$^+$ ions, see fig. 2(a) - (c).

From the width of the laser excitation spectrum on the $S_{1/2} - P_{3/2}$ laser cooling transition, we deduce a temperature of about 2mK slightly above the Doppler cooling limit.

![Graph](image)

FIG. 3: Time-of-flight distribution for single ions based on 123 successful extractions out of 139 shots in total through the 1mm aperture. The bin size of the histogram is 2ns. A Gaussian fit of the data yields an average velocity of 19.47km/s with a 1$\sigma$-spread of 6.3(6)m/s.

Calcium and dopant ions are generated in a multiphoton ionization process by a pulsed frequency tripled Nd-YAG laser at 355nm with a pulse power of 7mJ. Dopant ions are sympathetically cooled and identified from the voids in the fluorescence image compared to that of a regular linear $^{40}$Ca$^+$ crystal. Fig. 2(d) shows the fluorescence of an ion crystal consisting of a single $^{40}$Ca$^+$ and two molecular CaO$^+$ ions resulting from a chemical reaction with background residual gas [18]. We identify the species of dark ions by exciting collective vibrational modes with an AC voltage applied to electrode 4 and observing a blurring of the $^{40}$Ca$^+$ fluorescence image at the resonance frequency $\omega_{ax}$ [19]. Alternatively, amplitude modulated resonant laser light is used [18] to determine the charge to mass ratio of trapped particles at a precision of better than 0.2%. Before extraction, the sympathetically cooled doping ions may be separated from the $^{40}$Ca$^+$ ions. This is achieved by converting the axial trapping potential into a double well. The doping ions are further transported away from the $^{40}$Ca$^+$ ions by time dependent DC electrode voltages [21]. As heating generated during this separation process [17] cannot be cooled away anymore an alternative separation method would deflect the unwanted $^{40}$Ca$^+$ ions after extraction e.g. by increasing the electrode voltages of an einzeln-
lens. For the extraction we increase the DC voltage of segments 4 and 5 to 500V within a few tens of nanoseconds. The switching of the extraction voltage (supplied by ise g inc., Model EHQ-8010) is performed by two high voltage switches (Behlke inc., HTS 41-06-GSM) triggered via a computer-controlled TTL-signal and synchronized with the RF-field phase. Synchronization is crucial in order to minimize shot to shot fluctuations of velocity and position. An electronic phase synchronization circuit delays the TTL signal for extraction such that a constant delay to the next zero-crossing of the trap drive with frequency Ω is ensured. We found the optimum extraction parameters by matching the time of extraction with a certain phase of the radio frequency and by adjusting the DC-voltages on the deflection electrodes, which alter the ion trajectory during extraction. All measurements described below use these settings. The detection of the extracted ions is performed via an electron multiplier tube (EMT) with 20 dynodes from ETP inc., Model AF553, which can detect positively charged ions with a specified quantum efficiency of about 80%. The detector is housed in a separate vacuum chamber at a distance of 287mm from the trap. At typical operating conditions the detector is supplied with a voltage of -2.5kV. The gain is specified with $5 \times 10^5$ and we observe an electrical signal of about 100mV. The detection events show a width of 10 to 15ns. In order to measure the beam divergence a movable aperture plate was installed in front of the detector. This plate, mounted on a nanopositioning stage from Smaract, Model SL-2040, features hole diameters ranging from 5mm down to 300µm.

Typical EMT detector signals for different numbers of ions are shown in fig. 2e) - (g). Fig. 2h) displays the detector events for one $^{40}\text{Ca}^+$ ion and two $\text{CaO}^+$ ions, which arrive at $t=15.3\mu$s. From a time-of-flight analysis through the 1mm aperture we deduce a mean ion velocity of 19.47km/s for the $^{40}\text{Ca}^+$ ions. At $3 \times 10^{-9}$mbar we detect $87(\pm 11)\%$ of all extracted single ions within a $1\sigma$-confidence interval. We found that the efficiency slightly depends on the residual gas pressure but is mainly limited by the detector efficiency (which we measure to be higher than specified). The measured longitudinal velocity distribution (see fig. 3) shows a $1\sigma$-spread of 6.3(6)m/s which is about a factor of 10 larger than the velocity distribution inside the trap at $T=2\text{mK}$. This leads to a relative velocity uncertainty $\Delta v/v$ of $3.2 \times 10^{-4}$ which may be further reduced by post-accelerating the ions after extraction. From measurements conducted with the smallest aperture (300µm) we deduce a $1\sigma$-spot radius of $83(\pm 3)\mu$m for the trajectories of the extracted ions. Here we assume a Gaussian spatial distribution and the error is due to counting statistics. Note that this value is an upper limit as our measurements are currently affected by a measured drift of the ion beam of about $15\mu$m/minute possibly caused by temperature drifts of the setup.

FIG. 4: Monte-Carlo simulation of extracted ions. Left side: (a) Spot diagram at a distance of 247mm from the trap centre for an initial ion temperature of 2mK. (b) Focal spot diagram generated by an einzel-lens with a 1$\sigma$-spot radius of 7nm. (c) Histogram of radial distribution of spots in the focal plane. Right side: (d)-(f) Similar diagrams as on the left side but for a temperature of 100µK.

For a comparison of measured data with numerical Monte-Carlo simulations we need accurate electrostatic potentials which we deduce from a complete CAD-model of the trap geometry created with AutoCAD. Electrostatic potentials and fields are calculated by using a boundary element method accelerated by the fast multipole method [22]. Symmetry properties of the trap are exploited to reduce numerical errors. The ion trajectories are obtained by applying the Verlet integration method. The initial momentum and position is determined from the thermal Boltzmann distribution in the trapping potential. As a test, we have compared measured trap frequencies $\omega_{ax}$ and $\omega_{rad}$ for various traps of different size and shape in our lab [23] with corresponding simulations and found an agreement at the level of 2 to 3%. The ion trajectory calculation takes into account the full time dependent dynamics, including the micromotion at frequency $\Omega$ yielding a $1\sigma$-velocity spread of 12m/s and a beam divergence of 130µrad. Simulated velocity uncertainty and beam divergence agree within one order of magnitude with experimental results (see tab. [1]).

In order to implant single ions into solid state materials with nanometre spatial resolution, the detector will be replaced by a simple electrostatic einzel-lens [24] with a...
diameter of 1mm and a focal length of 9mm. Simulations predict a 1σ-spot radius of 7nm for 2mK and 2nm for 100μK respectively (see fig. 1 and tab. I).

| T     | Δv     | α         | r_f    |
|-------|--------|-----------|--------|
| meas. | 2mK    | 6.3m/s 600μrad | -      |
| calc.  | 2mK    | 12m/s 130μrad  | 7nm    |
| calc.  | 100μK  | 1m/s  30μrad   | 2nm    |

TABLE I: Comparison between experimental and numerical values of the spatial components versus variance of the matter wave, which results in a spot size of 10−6 nm resolution for our setup when combined with an electrostatic einzel-lens. If the ions are further cooled to the motional ground state our setup could realize the perfect single-ion single-mode matter-wave source. By changing the trapping parameters we can freely adjust the ratio between the variance of the spatial components versus variance of the momentum components.

Thus, the spot size would be limited by the diffraction of the matter wave, which results in a spot size of 10−10m if we assume a numerical aperture of 0.001 for the ion lens and an energy of 80eV. To assure the proper alignment of a short focal length lens-system with respect to the substrate we propose to implant through a hole in the tip of an atomic force microscope 

In conclusion we have experimentally realized a deterministic ultracold source for single ions and ionic molecules. For an ion temperature of a few mK we measured a longitudinal velocity distribution of extracted ions which shows a 1σ-spread of a few meters per second which is a promising starting point for the application of ion optical elements. Ion ray tracing simulations predict nm resolution for our setup when combined with an electrostatic einzel-lens. If the ions are further cooled to the motional ground state our setup could realize the perfect matter wave source at the Heisenberg limit.

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