Long-term drifts of stray electric fields in a Paul trap

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We investigate the evolution of stray electric fields in a linear Paul trap over a period of several months. We demonstrate a way to clearly distinguish between the two main sources of these fields, namely insulated charged up patches and patch charges originating from contact potentials. To achieve high sensitivity in these measurements, we operate the trap in a way that strongly suppresses the generation of additional patch charges. For this, we shield the ion trap from ambient light and only allow the use of near-infrared lasers. Furthermore, we minimize additional contaminations of the trap electrodes by minimizing the flux of atoms into the trap chamber. We find that photo-induced electric fields decay on time scales of days. In contrast, stray fields due to contamination-induced contact potentials on trap electrodes mainly exhibit slow dynamics on the order of months, probably dominated by diffusion and slow chemical processes. Long-term operation of our shielded trap led us to a regime of very low residual electric field drifts of better than 0.03 V/m per day.

INTRODUCTION

Paul traps have become essential tools in widely different fields of research ranging from quantum information[1–3] and quantum simulation[4] to precision metrology[5] and cold collisions between ions and neutrals[6–11]. The further development of all these lines of research hinges on improving the performance of the trap architectures and on a better understanding of the current experimental issues.

Ideally, a single ion in a Paul trap is only subjected to the electric fields generated by the voltages applied to the trap electrodes. However, even small uncontrolled patch charges in the vicinity of the trap center create stray electric fields which significantly perturb this ideal configuration. This leads to unwanted experimental complications, such as positional shifts of the trapped ions while the experiments are carried out. The resulting changes of the patch charges lead to changes of the electric fields at the trap center and thus to positional shifts of the trapped ions. These shifts increase the ion micromotion which generally perturbs the experimental conditions and requires frequent adjustments of trap electrode voltages.

In addition to these light-induced effects, the trap loading procedure can also be detrimental for the performance of the trap. Ion traps are often loaded from atomic beams which are directed towards the trap center. If the atomic beam hits the Paul trap electrodes, atoms are deposited on the electrode surface which can lead, among other effects, to contact potentials. Such contamination of the electrode surfaces has been seen to cause severe deteriorations of the trap[16–18], in some cases even to the point where the trap becomes unusable due to very high heating rates[19]. These so-called anomalous heating processes are believed to be caused by fluctuating charges, i.e. patch-potential noise[13–15]. Indeed, by reducing the contaminations on the electrodes, the trap performance can be greatly improved[16, 20, 21].

Patch charges have thus been found to be the common source of both static electric fields which cause micromotion issues and of fluctuating charges leading to anomalous heating. Clear experimental evidence of direct connections between these two effects has been reported in different setups[17–19]. Here, we study long-term patch charge dynamics in a Paul trap in an environment where we systematically suppress both continuous surface contamination and continuous photo-induced patch charge build-up. We observe smooth drifts of electric stray fields on various time scales from days to months. These different time scales indicate different physical and chemical processes that take place. For example, patch charges that are created by the photoelectric effect typically decay within a few days. Patch charges that are induced by surface contamination show slower dynamics on the order of months. Furthermore, our measurements indicate that patch charge dynamics depend on the materials of the components of the Paul trap and its geometry. After longer time periods without surface contamination and photo-induced charging, the stray electric fields settle smoothly towards a stable value with very small residual drifts as low as 0.03 V/m per day. This is encouraging for the design of future experiments where electric field stability is crucial.

In our setup, we achieve the suppression of surface contamination and photo-induced patch charges as follows. We create and probe ions (Rb+) in a linear Paul trap by using only near-infrared light sources (λ = 780 nm and 1064 nm) and small clouds of ≈ 10⁵ ultracold Rb atoms, which have previously been optically transported into the chamber[22]. Thus, the net flux of atoms into the chamber is negligible. We measure the electric stray fields of the patch charges by applying compensating electric fields until the micromotion of the ion is minimized[23].
FIG. 1. Paul trap with mounts. The trap consists of four rf electrodes (blue), two endcap electrodes (yellow) and two pairs of compensation electrodes (green). The mounts for the trap and the barium oven are made of MACOR. The aperture plate was installed to reduce the amount of barium deposited on the trap electrodes.

EXPERIMENTAL SETUP AND METHODS

The design of our linear Paul trap is shown in Fig. 1. The effective distance from the trap center to each of the four radiofrequency (rf) electrodes is 2.6 mm while the distance to the endcap electrodes measures 7 mm. To create radial confinement, a voltage driven at a frequency of $4.17 \text{ MHz}$ with an amplitude of 500 V is applied to two of the rf electrodes while the other two are held at ground potential. Axial confinement is generated by applying static voltages of about 8 V to the two endcap electrodes while the other two are held at ground potential. Axial confinement is generated by applying static voltages of about 8 V to the two endcap electrodes. Under these experimental conditions, an $^{87}\text{Rb}^+$ ion is confined at radial trapping frequencies of about 350 kHz and an axial trapping frequency of about 50 kHz. The total depth of the trap is on the order of 4 eV and allows for ion storage times of many days, even without any type of cooling. The Paul trap is part of a hybrid atom-ion trap setup that brings the trapped ion into contact with an ultracold cloud of $^{87}\text{Rb}$ atoms[24]. Ensembles of $^{87}\text{Rb}$ atoms are prepared in a separate vacuum chamber and transported into the Paul trap using a long-distance optical transport line. They are then loaded into a crossed dipole trap where further evaporative cooling down to typical temperatures of 700 nK is performed. The atom numbers typically range between $10^5$ and $10^6$ atoms. Both the optical transport and the crossed dipole trap are implemented using several W of laser power at a wavelength of 1064 nm. To perform absorption imaging of the atoms, resonant laser light at 780 nm is used. After this destructive imaging process, a new atom cloud is prepared within 30 s for the next measurement. To load an ion, a Rb atom cloud with a density of several $10^{13} \text{ cm}^{-3}$ is prepared and positioned at the center of the Paul trap. Three-body recombination processes in the atom cloud produce Rb$_2$ molecules which are subsequently ionized by a REMPI process using photons from the dipole trap laser[22]. Subsequently, the molecular Rb$_2^+$ ions quickly dissociate via collisions with neutral atoms and finally yield Rb$^+$ ions.

To detect the number of trapped Rb$^+$ ions and measure their micromotion, we employ a sensitive probing scheme using ultracold atomic clouds[23]. For this, we immerse the ions into clouds consisting of about $10^6$ atoms at densities around $10^{12} \text{ cm}^{-3}$. After a few seconds of interaction time, we detect the final atom number and atom temperature which depend on the number of ions and their micromotion. This enables us to reliably work with a single ion and, by minimizing its excess micromotion with the help of electric compensation fields, to measure the stray electric fields acting on the ion[12, 23]. Due to the production time required for the atom clouds, an electric field measurement requires about an hour of measurement time, resulting in a limited temporal resolution. The measurement precision is high and typically ranges around 0.1 V/m for the results presented here.

RESULTS

As a first step we investigate the susceptibility of our trap setup with respect to laser light at various wavelengths which are available in our lab (Fig. 2). As expected, for wavelengths below 500 nm we find a sharp increase in light-induced patch charge build-up resulting in corresponding electric fields. For 780 nm or the even longer wavelength of 1064 nm, we did not detect any measurable light-induced charging effects. In our setup, the mounts for the trap electrodes and for the barium oven are made of machinable glass-ceramic (MACOR), which is very susceptible for accumulating patch charges. Although the laser beams never directly impinge on these insulating surfaces, some stray reflected light still illuminates them diffusely. They can thus be charged via the photoelectric effect. In general, when we create photoelectric charges, we measure the strongest shifts of the electric field components in the vertical (y-axis) and axial (z-axis) directions. This asym-
metry in the direction of the electric fields is explained by the asymmetry of the Paul trap setup caused by the mounts of the barium oven. This will be discussed in detail below.

Next, we start a long-term experiment where we monitor the evolution of the stray electric fields in all three spatial directions over a time span of about four months. During this period (except for two short occasions) the whole experimental setup is almost entirely shielded from ambient light by means of light-tight protective covers to avoid any patch charge build-up (Fig. 3). Before the start of these long-term measurements, the ion trap was operated with Ba\(^+\) ions so that both the barium oven and the necessary lasers were frequently used. Consequently, there is a substantial stray electric field due to a large number of patch charges to begin with. All three electric field components (in x, y, z direction) show a more or less monotonic decay and converge towards long-term limits which are set to \(\Delta \varepsilon = 0\) in the plot. The solid lines in Fig. 3 are double-exponential fits of the form

\[
\varepsilon(t) = \Delta \varepsilon_1 \exp(-t/\tau_1) + \Delta \varepsilon_2 \exp(-t/\tau_2),
\]

where \(\Delta \varepsilon_{1,2}\) are the electric field shifts and \(\tau_{1,2}\) are the time constants of the exponential decay curves. For the two radial directions (x- and y-directions) we find relatively rapid initial decays with time constants \(\tau_1 = 0.3 - 3\) days and subsequent slow decays with \(\tau_2 \approx 90\) days. In axial direction the time constants are 0.6 and 18 days. For all three directions the slow decays are dominant as they account for roughly 80-95\% of the electric field shifts (see table 1). On two occasions (\(t \approx 70\) days and \(t \approx 100\) days), the light-tight protective covers around the experimental setup had to be removed for several hours so that the Paul trap was subjected to ambient white light from the fluorescent ceiling lights. As a consequence, the electric field in vertical (y) direction shows a sharp increase and then decays back towards its long-term behavior within several days. We investigate this effect in detail below. After about 100 days, the daily drift of the vertical field was below 0.03 V/m yielding extremely stable experimental conditions. In addition, this slow drift allows for a precise prediction of the expected electric fields at a given time so that the field compensation can be adjusted without requiring additional measurements.

After the time period shown in Fig. 3 we make use of the low stray electric field drift to selectively test the dynamics of photo-induced patch charges. For this measurement we shine through the chamber about 2.5 mW of laser power at a wavelength of 413 nm (3 eV) for 4 minutes. The strongest effect is again observed in the vertical electric field component which increases by about 6 V/m. The axial field component increases by 1.5 V/m, the horizontal component by 0.6 V/m. The laser was then switched off and the decay of the vertical field component was monitored over 5 days (Fig. 4). The data is fit by a double-exponential curve with an initial decay on a timescale \(\tau_1 = 1.2\) days and a slow decay with \(\tau_2 = 11\) days. This slow decay accounts for about 80\% of the field shift. The observed initial increase and subsequent decay of the electric field are in rough agreement with the behavior seen in Fig. 3 after the Paul trap had been subjected to ambient light. The axial field shift seen when performing the measurement of Fig. 4 is not fully matched by observable axial field shifts in Fig. 3. However, this may be explained by the somewhat lower field resolution that we achieve in axial direction and the generally low temporal resolution of our measurements.

As briefly mentioned before, the stray electric fields should mainly stem from patch charge build-up through diffuse light on the oven mount. Light of sufficiently short wavelength can cause the emission of electrons via the photoelectric effect. As a result, positive charges accumulate on the surface of the MACOR mount and increase the electric field at the lo-
heat dissipated by the oven. The conductivity of MACOR increases by more than ten orders of magnitude when heated from room temperature to several hundred °C. It can thus be expected that any patch charges in the vicinity of the oven will be efficiently removed at such high temperatures. However, the electric field $\Delta E$ drops much further than the initial value of $-2 \text{V/m}$ in Fig. 4, namely down to $-6.5 \text{V/m}$. This additional negative electric field cannot be explained by patch charges produced by the photoelectric effect – it is most likely caused by contact potentials. Despite the collimation of the atomic beam through the aperture plate (see Fig. 1), a fraction of the atoms emerging from the barium oven reaches the rf electrodes close to the trap center. Such a coating of the electrodes might immediately change the distribution of the contact potentials in close vicinity to the ion. These potentials can be on the order of a few V, as determined by the difference in work function of the metals involved. In our setup there is a clear asymmetry on how the Ba oven coats the trap electrodes with Ba atoms. The two lower rf electrodes will each be coated only on one side, whereas the two upper electrodes will probably be coated over the full tip. It is then to be expected that contact potentials of the upper electrodes dominate over the potentials of the lower ones. As the work function of Ba is lower than that of stainless steel, a positive patch charge should build up which leads to an electric field component pointing towards the negative y-axis. This is indeed what we observe. Furthermore, there is also an asymmetry in z-direction, as the atomic beam from the oven passes at an angle of about 45° through the blades (see Fig. 1). This may give rise to an electric stray field component in z-direction. Fig. 5 shows that after the oven is turned off, the vertical electric field component gradually increases with a time constant on the order of one day. This behavior agrees with the observations at the beginning of the long-term measurements shown in Fig. 3 and suggests that the operation of the oven also induces the 90 day long-term drifts that we observe. These slow drifts may be explained by slow chemical reactions in the ultrahigh vacuum environment and by diffusion and migration processes on the electrode surface. It is known that barium reacts and forms compounds with $\text{O}_2$, $\text{N}_2$, $\text{CO}_2$ and $\text{H}_2\text{O}$. It also acts as a getter material, inclosing non-reactive gases. Thus, the mobility on a surface is sizeable. (Interestingly, the work function of barium is known to remain quite constant ($\approx 2.5 \text{eV}$) even when contaminated with other substances.) Diffusion or migration of barium on the electrode surface can also lead to drifts of patch charges in the broadest sense. This process could coat certain compound layers and set other ones free – giving rise to slowly changing patch fields. Our observations agree with previous studies. The time constant identified in Fig. 3 ($\tau_0 = 90 \text{days}$) agrees well with the timescale reported in ref. [19], where barium contaminations on Paul trap electrodes made of Be-Cu were investigated. Furthermore, it was found in [16] that coating a Paul trap with tungsten electrodes that had been coated with Ba significantly changed patch charge fields. At room temperature the vapor pressure of barium is very low. Even at 200°C it only reaches $10^{-12} \text{mbar}$. This suggests that barium coatings have a long lifetime at ambient temperatures.

**FIG. 5.** Vertical electric field shift induced by heating the barium oven for 10 minutes. During the oven heating time the field dropped by about $7.5 \text{V/m}$. After the oven was turned off, the field shows a drift towards higher voltages.
TABLE I. Overview of the observed drift time constants and the corresponding electric field shifts. Oven-induced and light-induced effects give rise to drifts with opposite signs.

| direction        | cause                               | $\tau_1$ [days] | $\Delta\varepsilon_1$ [V/m] | $\tau_2$ [days] | $\Delta\varepsilon_2$ [V/m] |
|------------------|-------------------------------------|-----------------|-----------------------------|-----------------|-----------------------------|
| vertical (Fig.3) | blue light + oven operation         | 0.3±0.4         | -0.4±0.2                   | 90±10           | -7.4±0.4                   |
| horizontal (Fig.3)| blue light + oven operation         | 2.7±0.8         | -2.1±0.3                   | 94±21           | -7.3±0.7                   |
| axial (Fig.3)    | blue light + oven operation         | 0.6±0.8         | 0.4±0.2                    | 18±3            | 1.9±0.1                    |
| vertical (Fig.4) | blue light                          | 1.2±0.1         | 1.2±0.1                    | 11±0.3          | 4.9±0.1                    |
| vertical (Fig.5) | oven operation                      | 0.6±0.4         | -0.7±0.9                   | -               | -                           |

CONCLUSION

In conclusion, we have investigated the long-term behavior of electric stray field drifts in a linear Paul trap. We find drifts on different time scales ranging from about half a day to three months. We identify these time scales as due to certain physical or chemical processes. Light-induced patch fields decay on relatively short time scales on the order of a few days due to discharge via an electric resistance. Patch fields produced from coating electrodes or mounts with Ba showed long term drifts on time scales of up to 90 days. These long timescales might be explained by slow migration or reaction processes taking place on the electrode surface. The fact that we can clearly distinguish the behavior of patch charges that are based on contact potentials and the photoelectric effect is an important finding. It might be another piece in the puzzle in understanding effects like anomalous heating. The results presented here are a first investigation with our setup in the direction of surface dynamics of patch charges. In the future the experiments can easily be refined to obtain more detailed information and to test hypotheses. For example, by locally applying laser fields on trap mounts and electrodes (either to heat them up or to produce photo-induced patch charges in a controlled way), we should be able to spatially probe surface properties. Another result of our work is that by systematically avoiding the creation of electric patch potentials we were able to get into a regime of very small and predictable electric stray field drifts as low as 0.03 V/m per day. Such stability of the trap conditions may prove invaluable for the future development of precision ion trap experiments.

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