Trapped-ion probing of light-induced charging effects on dielectrics

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Abstract. We use a string of confined ⁴⁰Ca⁺ ions to measure perturbations to a trapping potential which are caused by the light-induced charging of an antireflection-coated window and of insulating patches on the ion-trap electrodes. The electric fields induced at the ions’ position are characterized as a function of distance to the dielectric and as a function of the incident optical power and wavelength. The measurement of the ion-string position is sensitive to as few as 40 elementary charges per √Hz on the dielectric at distances of the order of millimetres, and perturbations are observed for illuminations with light of wavelengths as large as 729 nm. This has important implications for the future of miniaturized ion-trap experiments, notably with regard to the choice of electrode material and the optics that must be integrated in the vicinity of the ion. The method presented here can be readily applied to the investigation of charging effects beyond the context of ion-trap experiments.

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1. Introduction

As segmented ion traps are scaled to ever smaller dimensions, and hold ever more ions [1], questions necessarily arise about the size and location of the experimental apparatus accompanying the trap [2, 3]. To collect as much light as possible, there are clear advantages in having optics very close to the ion. This requires either a vacuum window in close proximity to the trap or optics within the vacuum, such as lenses [4], fibres [3] or cavity mirrors [5]–[7]. While experiments currently operate with ion-dielectric separations of a few millimetres to centimetres, proposals exist for reducing this to a few hundreds of microns to facilitate, for example, strong ion–cavity coupling [5], or coupling ions to nanomechanical resonators [8].

Insulating materials can accumulate charge, which is hard to dissipate and drifts slowly over time. Such materials in or near ion traps can thus frustrate efforts to obtain a well-controlled trapping potential. Slowly drifting charges in the vicinity of trapped ions can give rise to problems of excess micromotion [9] and difficulties in reliably addressing ions with focused laser beams. A common approach is, therefore, to avoid insulating materials in the vicinity of the ion as much as possible. It is clear, however, that the pragmatic solution of simply keeping insulators far removed becomes increasingly untenable as questions of trap miniaturization move to the fore.

In addition to miniaturization of optical components around the trap, there are significant advantages to miniaturizing the trap itself. Smaller traps allow for higher ion motional frequencies, facilitating faster gate speeds and simplifying fast ion transport. However, as ion–electrode separations are reduced, ions become increasingly sensitive to fluctuating charges on the electrodes’ surfaces [10]. Thermally induced fluctuations are believed to play an important role in the anomalous heating observed in ion traps [10, 11]. While such effects can be mitigated by cooling traps to cryogenic temperatures [12], this provides, at best, only an engineering solution to a little-understood physics problem. Possibly related phenomena are held responsible for decoherence in super-conducting qubit experiments [13, 14]. Here the coherence is destroyed by electric field modulation due to thermally activated dipoles, the so-called ‘two-level fluctuators’. Ideally, the source and nature of these fluctuations should be understood.

Furthermore, issues regarding surface charging are of interest in the context of neutral atom experiments. When neutral atoms are brought close enough to dielectric or metallic surfaces they become sensitive to the associated local electric fields [15]–[17]. Understanding the charging effects in materials used for such experiments is of great import for correctly
interpreting the results. In particular, strong light fields may impinge on the materials being investigated, such as in evanescent-field experiments [18, 19], and may potentially charge the surfaces.

In this work, a systematic and quantitative investigation of the charging effects on an insulator is undertaken, using trapped ions as a highly sensitive probe for the electric field. Specifically, the charging effects due to optical illumination of a dielectrically coated glass plate placed a few millimetres away from an ion chain are characterized as a function of the ion–glass separation. The open geometry of the planar ion trap used is advantageous as it grants easy access to the ions for the material under investigation. Additionally, the charging of insulating patches on the copper trap electrodes is observed and investigated. These patches may be a complete insulating layer, and are presumably formed from an oxide. Charging of the glass plate and of the electrodes is characterized as a function of the incident laser wavelength, in the range 375–729 nm.

Ions held in a radio frequency (RF) trap are known to be sensitive field probes: a single ion has previously been used to map out the electromagnetic field of an optical resonator [20], and fluctuating electric fields have been measured by motional heating of trapped ions [12, 21]. It has recently been proposed that an ion in a ‘stylus trap’ could be used to sensitively measure electric and magnetic fields [22]. In the work presented here, up to four $^{40}$Ca$^+$ ions are trapped in a standard surface ion trap, and a glass plate with a dielectric anti-reflective coating can be moved relative to the ions using a mechanical vacuum feedthrough. By observing the change in position of a three-ion string, the presence of $\sim 40$ elementary charges can be detected at a distance of 1.2 mm within 1 s.

2. Apparatus and method

All charge-sensing experiments described here are performed with a string of ions in a five-wire planar trap [23, 24]. The trap, depicted in figure 1, was made from copper electrodes on a vacuum-compatible printed circuit board (PCB) material (Rogers 4350), and mechanical cut-outs reduce the amount of exposed dielectric surface (courtesy of the group of IL Chuang, MIT). A string of $^{40}$Ca$^+$ ions is trapped $\sim 800 \mu$m above the surface (the exact height of the RF null is dependent on the position of the glass plate, shown in figure 2). In the experiments described, the ion string typically has motional frequencies of $2\pi \times (90, 230, 790)$ kHz in the axial and two radial directions, respectively. The ions are laser-cooled on the $S_{1/2}-P_{1/2}$ transition using 397 nm light [25] so that they form a stable ion crystal, where each ion can be individually resolved. The cooling beam runs parallel to the surface of the trap, at a slight angle to the trap axis (figure 1(b)).

As depicted in figure 2 the fluorescence light is imaged on an EM-CDD camera. A glass plate with an antireflective coating can be brought close ($\sim 1$ mm) to the ions using a mechanical vacuum feedthrough, or withdrawn completely to be $\sim 10$ cm distant, out of the optical path. Using a small mirror in the path of the fluorescence light, different charging laser beams can be shone through the glass plate and onto the trap. The beams are focused to a diameter of less than 100 $\mu$m and the beam pointing is calibrated by observing the position of the laser beam on the trap with the CCD camera. Once this position is known, narrow-band dielectric filters are added in front of the camera for transmission at 397 nm, to allow

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4 Anti-reflective coating from Laseroptik Garbsen.
Figure 1. Ions are trapped using a Cu-on-PCB planar ion trap [23] (a). The geometry is shown schematically in plane view (b) and cross section (c). An RF voltage of $\sim 340$ V amplitude is applied to the RF electrodes to provide radial confinement, and dc voltages of up to 50 V are applied to the remaining electrodes for axial confinement. The red dashed line (b)/dot (c) gives the position of the RF null along which the ions are confined, $\sim 800 \mu$m above the surface. The ions are cooled by lasers, indicated by the blue line in (b), parallel to the trap surface, and at $4^\circ$ to the trap axis.

detection of light scattered by the ion despite the presence of stray light from the trap surface. A series of CCD images is taken, each comprising ten accumulations of 100 ms exposure, and 1.9 $\mu$m resolution to measure the positions of the ions. By fitting the individual ion positions and averaging over all ions, the precision of the string’s centre of mass position is increased beyond the resolution of the camera picture. The axial motional frequency of the ions gives information on the curvature of the confining potential. This, in turn, allows changes in the ions’ position to be used to calculate the axial forces acting on the ion string and thereby infer the axial electric field at the ions’ position. For the study of charging by 397 nm light, discrimination between ion fluorescence and stray light is not possible with the use of optical filters. Instead, a pulsed scheme with shorter charging durations and interleaved detection phases is applied.

3. Results

Two different effects are observed, depending on the presence or absence of a glass plate. Throughout the following section, the graphics on the left-hand side refer to the situation without a glass plate, whereas the graphics on the right describe the results obtained in the presence of a glass plate. Figure 3 shows the centre of mass position of the ion string as a function of time during and after laser illumination of the centre electrode. Here, a laser beam ($\lambda = 375$ nm) is incident to the right of the ion string at $\Delta x = 200 \mu$m. In the first case (a), an attractive force acts on the ions as the substrate is illuminated (grey-shaded area), making them move at $\sim 1 \mu$m s$^{-1}$ towards the laser beam. This movement saturates on a timescale of $\sim 1$ min. Switching off the
laser beam causes the ion string to relax close to its original position on a somewhat longer timescale. In the second case (b), with the glass plate placed close to the ions, the attractive force during laser illumination is superimposed by a repulsive one, which saturates depending on the applied laser intensity on a timescale of minutes. The displacement caused by this additional force subsequently remains unchanged for days. Additionally, when a glass plate is present, room light from fluorescent tubes affects the position of the ion string. Light from tungsten filament lamps has no observable effect.

The observed results point to two different charging effects: negative charging of the copper electrode surface (Figure 4a) and positive charging of the glass substrate (Figure 4b). While the exact nature of the copper charging is not known, it is assumed that the surface is partially or completely covered by a thin insulating layer, probably an oxide [26]. One might expect that charges directly above the copper surface produce negligible fields, because image charges form directly beneath them and shield their effect. However, the resulting field is that of a dipole, which drops off more quickly than a monopole, but is still easily detected by the sensitive ion probe.

Analyzing the data more quantitatively leads to the following model for the charging processes: under illumination with laser light, local charges are produced with a wavelength-dependent production rate, $P$. It has been experimentally verified that this production rate scales linearly with incident laser power for both the charging processes. The presence of existing charges creates a barrier inhibiting the creation of new charges. This may, to first order, be
Figure 3. Typical example of the axial positions of the ion string as the illuminating laser is turned on (grey-shaded area) and off. (a) No glass plate is present, so the charging leading to the ions’ displacement towards the laser beam occurs at the trap surface only. The data were taken with 8.5 µW of $\lambda = 375$ nm light, focused on the trap at $\Delta x = 200$ µm away from the ion. In (b) the ions’ movement towards the laser beam is superimposed by a repulsive effect that arises at the glass plate. The data were taken with 2.5 µW of $\lambda = 375$ nm light, focused on the trap at $\Delta x = 300$ µm away from the ion, with the glass plate a distance of $h_{\text{glass}} \approx 2$ mm from the ion. The solid lines are the exponential fits to the data.

Figure 4. Two distinct charging effects are observed. The first (a) is consistent with electrons being held on a thin oxide layer above the copper. The electrons and their image charges create a dipole that attracts the ion string. The second effect (b) is consistent with electrons being ejected from the front and back surfaces of the glass plate, leaving two regions of positive charge that repel the ion string.

accounted for by considering a production rate $P = P_0(1 - \delta \cdot n_q)$, where $n_q$ denotes the number of charges present and $\delta$ describes the barrier effect. In addition, the produced charges may be neutralized at a rate $\gamma$. The total process is then described by the differential equation

$$\dot{n}_q = P_0(1 - \delta \cdot n_q) - \gamma \cdot n_q,$$

(1)
Figure 5. Initial ion velocity as a function of the laser beam position ($\lambda = 375$ nm) due to the charging of (a) the trap surface for different laser powers and (b) the glass surface for two ion–glass distances. The lines are fits to the data, according to the proposed model.

where the values for $P_0$, $\delta$ and $\gamma$ depend on the process and the (local) material properties. The deduced time dependence of the number of charges present during and after laser illumination then becomes

$$n_q = \begin{cases} n_{eq} \cdot [1 - \exp(\gamma_{on} t)], \\ n_0 \cdot \exp(-\gamma_{off} t), \end{cases}$$

where the inverse settling times are $\gamma_{on} = \gamma + P_0 \delta$ and $\gamma_{off} = \gamma$; $n_{eq} = P_0/\gamma_{on}$ is the steady state solution under illumination, and a constant, $n_0$, reflects the amount of charge present at the moment the laser is switched off. These two solutions represent the core for fitting both the charging effects where, for the charging of the glass plate, the absence of relaxation is accounted for by setting $\gamma = 0$.

Charging of the copper electrode may be explained by the excitation of electrons onto insulating patches directly above the bulk material. Together with the induced image charge this creates a small electric dipole. Such an excitation represents a metastable state that may easily relax back to a neutral state ($\gamma \neq 0$). This hypothesis is corroborated by the investigation of the axial electric field. The initial velocity of the ion string during laser illumination is proportional to the electric field per created charge multiplied by the charge production rate. By changing the position of laser illumination with respect to the ions’ positions, the lateral field per created charge is mapped out.

Figure 5(a) shows the initial velocities for different powers of laser illumination for $\lambda = 375$ nm. The behaviour for other wavelengths is similar. The fitted curves correspond to the velocity expected from the axial component of a dipole field as described by

$$\dot{x}_{ion} = \dot{D}_{rel} \cdot \frac{h_{trap} \cdot \Delta x}{(\Delta x^2 + h_{trap}^2)^{3/2}}.$$ (3)

Here $\dot{D}_{rel} = \frac{3q_{Ca}}{4\pi\varepsilon_{Ca}} \cdot \dot{n}_q \cdot \epsilon_{dip}$ is the fit parameter for the net production rate of surface charges (hence dipoles), with $q_{Ca}$ and $m_{Ca}$ being the charge and mass of a calcium ion, $\omega$ the axial
trap frequency, \( q_e \) the electron charge and \( r_{\text{dp}} \) the distance between the charge and the image charge, which is twice the thickness of the insulating layer. The symbols \( h_{\text{trap}} \) and \( \Delta x \) denote the ion–electrode distance and the axial distance between ion and laser beams, respectively. The measured data exclude any significant contribution from monopole or quadrupole (and higher order) terms.

As the thickness of the insulation patches, and hence the extension of the dipole \( r_{\text{dip}} \), is unknown, the quantum efficiency of the dipole production process, \( \eta_{\text{dip}} \), can only be expressed including this unknown value. For the wavelengths \( \lambda = (375, 422, 729) \) nm, we deduce \( \eta_{\text{dip}} = (14, 62, 0.2) \times 10^{-9}/(r_{\text{dip}}/\mu\text{m}) \), respectively. The data do not provide sufficient information to propose a model that describes the wavelength dependence of the dipole-production rates, e.g. the significant reduction of the rate at 375 nm compared to that at 422 nm.

It is interesting to note that the time dependence of the ion-string position for electrode charging is not well fitted with equation (2) alone. This is attributed to the fact that there is a multitude of metastable states to which the electrons may be excited, given the likely inhomogeneous nature of the electrodes’ surface. Each state may have its own excitation probability and decay constant, leading to an inhomogeneous broadening. Heuristically, we take this into account by expressing the total number of charges as the result of two separate charging processes with independent production rates and relaxation constants. The individual constants do not have a direct physical meaning and may depend on the specific investigated time span. However, as an indication, the derived relaxation constants for the charge production (laser on) are \( 1/\gamma_{\text{on},1} = 2 \) s and \( 1/\gamma_{\text{on},2} = 16 \) s and for the decay (laser off) \( 1/\gamma_{\text{off},1} = 5 \) s and \( 1/\gamma_{\text{off},2} = 120 \) s. The limitation to two production processes does not affect the evaluation of the above quantum efficiencies since they depend only on the total initial charge production rates.

When the dielectric glass plate is brought close to the surface trap, it might be expected that electrons are extracted from the trap electrodes by light or by the trap voltage and settle on the glass. While we cannot exclude that this negative charging effect occurs to a small degree, the only detectable effect is a net positive charging at the position where the laser penetrates the glass. The induced repulsive effect on the ion string can be separated from the surface effects, because the surface effects relax on a small timescale while the glass charging remains. We attribute the positive charging to the ejection of electrons from the antireflective coating of the substrate. Since these holes are produced in a dielectric surrounding, no electrons can be reabsorbed; therefore the charge creation is irreversible. In figure 3(b) the line represents a fit according to the model and is fitted to the ion’s movement which sums both the attractive and repulsive effects. The ion velocities induced by the glass charging are shown in figure 5(b) for two different ion–glass distances \( h_{\text{glass}} \) at a laser power of \( \sim 2.5 \) \( \mu \) W. The charging saturates on a timescale of \( 1/\gamma_{\text{on}} = 38 \) s. The fitted curves indicate the expected axial field for a point charge located at the glass surface closest to the ion trap. The charging effect at the back of the glass plate has been neglected as the thickness of the glass (5 mm) is large compared to the ion–glass distance. In addition to this monopole-like contribution

\[
\dot{x}_{\text{ion}} = \dot{Q}_{\text{rel}} \cdot \frac{\Delta x}{(\Delta x^2 + h_{\text{glass}}^2)^{3/2}},
\]

the small shielding due to an image charge with opposite sign and appropriate distance (at \( h_{\text{glass}} + h_{\text{trap}} \) below the trap surface) has also been taken into account. No significant contribution to the field from dipoles on the glass surface is observed. In equation (4), \( \dot{Q}_{\text{rel}} = \frac{q_C}{4\pi \varepsilon_0 \varepsilon_{\text{rel}}} \cdot n_\parallel q_e \).
is the relative charge production rate, \( h_{\text{glass}} \) is the ion–glass distance and \( n_q \) is the number of positive charges created on the glass plate. With the known trap frequency \( \omega \sim 90 \text{ kHz} \), the charge-production efficiency is calculated to be \( \eta_{375} = 1.2 \times 10^{-10} \) electrons per photon at \( \lambda = 375 \text{ nm} \) and \( \eta_{397} = 0.4 \times 10^{-10} \) at \( \lambda = 397 \text{ nm} \). For \( \lambda = 422 \) and 729 nm, no movement of the ion string, and therefore charging of the glass, could be detected at the given level of sensitivity.

4. Estimation of the charge sensitivity

Using ions as electric field probes, two different quantities are of direct interest: the electric field itself and the connected force acting on the ion string. The two quantities are linked by the charge of the probe and hence the number of ions used for the measurement. In systems where the field under study is not, or not strongly, affected by the probe, a higher field sensitivity can be obtained by increasing the number of ions. The force on the ions, however, scales linearly with the number of ions, and so does the backaction on the field source. If this backaction must be kept small, a high force sensitivity is desirable, which can be achieved by reducing the number of ions.

With the imaging method described here, an upper limit for the position uncertainty of a three-ion crystal is computed from the residuals to be \( \delta x = 0.12 \text{ \(\mu\)m} \) for 1 s acquisition time. The uncertainty in position scales with the inverse square root of the averaging time and of the number of ions \( n_{\text{ion}} \). The time and ion-number dependence can thus be combined with the uncertainty to yield a sensitivity of \( 0.12 \text{ \(\mu\)m} \cdot \sqrt{3/n_{\text{ion}}} \text{Hz} = 0.21 \text{ \(\mu\)m}/\sqrt{n_{\text{ion}}} \text{Hz} \). Given the trap frequency of 90 kHz, this corresponds to an electric field sensitivity of 30 mV (m \(\cdot\sqrt{n_{\text{ion}}}\text{Hz})^{-1}, and a force sensitivity of 4.5 zN \cdot \sqrt{n_{\text{ion}}}/\text{Hz} (1 \text{ zN} = 10^{-21} \text{ N}). With the laser displacement, \( \Delta x \), at the most sensitive position (peaks of the curves in figure 5) and with a glass–ion distance of 1.2 mm, this is equivalent to detecting the presence of 40 elementary charges with three ions within 1 s. For similar charge sensitivities, near-field probes such as scanning atomic force microscopes are usually required [27]. However, using the ion trap as a measuring device has the advantage that the sensor leaves the surface completely unobstructed and does not interfere with the measured effect.

Very recently, measurements as sensitive as 0.4 zN (\(\sqrt{\text{Hz}}\))^{-1} have been reported with an ion cluster in a Penning trap, using RF excitation of a driven harmonic system near resonance [28]. For comparison, this is equivalent to a single-ion field sensitivity of 0.3 mV (m \(\cdot\sqrt{\text{Hz}}\))^{-1} and a single-ion force sensitivity of 0.05 zN (\(\sqrt{\text{Hz}}\))^{-1}. This system measures a pulsed RF force and infers the magnitude from Doppler velocimetry. This technique is applicable to the ‘high frequency’ range over which the trap frequency can be tuned. By contrast, while being a factor of 100 less sensitive, the simple technique described here measures slowly varying forces in real time.

Provided the precision of the ion-position measurement is limited by the imaging technique, rather than the ion’s thermal spread, the measurement sensitivity scales with the inverse square of the trap frequency. Beyond this limit, it scales with the inverse of the trap frequency. It would thus be relatively simple to improve the sensitivity of the ion probe method by an order of magnitude by reducing the ions’ motional frequency. The sensitivity could be further increased using homodyne detection (e.g. observing micromotion sidebands for transverse excursion) or using quantum detection schemes [22].
5. Summary and outlook

While there has previously been a number of speculative assumptions regarding the perturbing effects of insulators in the vicinity of trapped ions, the true nature of the perturbations was untested. Here, two distinct mechanisms for charging dielectrics are revealed, using the trapped ions themselves as sensitive and non-invasive field probes. Laser or room light incident on an optically coated glass surface was observed to locally create positive charges, while laser light impinging on the copper trap electrodes caused the accumulation of negative charges on the electrode surface, presumed to be located on insulating patches. The low activation energy for the latter process of less than 1.6 eV suggests the direct light-induced occupation of these patches. Within the resolution of the measurement, no spatial variation was observed in the patch distribution. These findings are of interest for a wide variety of experiments that involve probing of particles (neutral or charged) in close proximity to surfaces. For ions, this effect is sufficiently strong that the operation of ion traps may be compromised even when the distance to the charged material is of the order of a centimetre. This is of particular importance in the field of miniaturized ion traps, where the integration of optical high-finesse microcavities with ion traps necessitates the placement of optically coated glass surfaces in close proximity to the ions. This work may also contribute to the discussion about patch-charge fluctuations that are thought to be responsible for the heating of ions in proximity to conductive surfaces. With a tightly focused laser beam it may be possible to directly resolve single patches of sizes of the order of a micrometre. Finally, this method provides a general tool to study local charging of any surface that can be brought close to an ion trap.

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