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Surface-electrode ion trap development

T. Abbasov[+1)], S. Zibrov[*], I. Sherstov[+]

[+]Skolkovo Institute of Science and Technology, 121205 Moscow, Russia

[*]P. N. Lebedev Physical Institute Russian Academy of Sciences, 117924 Moscow, Russia

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Since the first experiments with trapped ions were conducted in the late 50s of the 20th century [1–3], systems with stored ions became very popular in frequency standards and quantum simulation applications [4–8]. Precise frequencies are being used for accurate definition of physical units and timekeeping. Enough to mention, the resolution of global navigation satellite systems (GNSS) like GPS, GLONASS, and GALILEO rely on the stability of the onboard atomic clocks [9–10].

The further development of optical frequency standards for practical applications as (sat and inertial navigation, gravimetry etc.) requires a significant miniaturization of all key components of existing standards by factor of 10 [9]. The most promising architecture for a compact Paul trap typically used for frequency standard applications is a chip-based surface trap with electrodes located in one plane. Such architecture also has the advantage of optical access to the stored ion because ions are trapped above the surface of the trap. It allows guiding radiation from different laser systems into the ion, detecting it, and collecting light with a higher probability [11]. Also such architecture can be used with integrated photonic circuits which can help to minimize the sizes of the whole system and make it more convenient to use.

We chose a surface-electrode trap design in which all electrodes were aligned in the same plane. The model of our trap is based on the approach described in [11–13] and is shown in Fig. 1. A stripe of a ground (GND) electrode is located between two stripe-shaped radio frequency (RF) electrodes. The direct current (DC) voltages are applied to the segmented electrodes on both sides of the RF electrodes which confine the ions in the axial direction and compensate the secular motions. All electrodes are located on top of the dielectric substrate.

To have an additional optical access for the laser light to the stored ions and/or enable additional optical

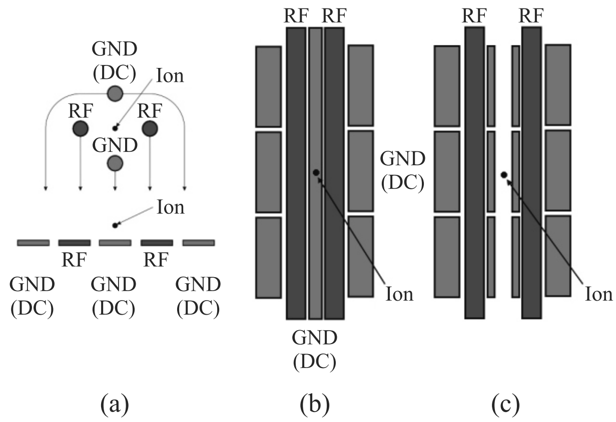

Fig. 1. (Color online) Planar ion trap design serve as equivalent to the rod electrodes. The surface electrodes from a side view (a), top view (b) and surface trap with the hole in the central electrode (c)

elements such as the photonic integrated circuits into the design of ion traps, it is possible to introduce a hole in the central electrode [11] under the stored ion, as shown in Fig. 1c.

As for the main tap parameters which we want to calculate, we chose the depth of the trap (d), the secular frequency (ω_{sec}), and the height of the ion above the surface of the electrodes (h). According to the linear Paul trap theory, which is described in [13], the depth of the trap can be defined as the highest value of a pseudopotential which the ion needs to overcome on its way to infinity. The pseudopotential can be written as:

$$\Psi(x,y,z) = \frac{Q}{4M\Omega^2} \times (|\nabla\Phi(x,y,z)|)^2, \qquad (1)$$

where Q is a charge of the ion, M is a mass of the ion, Ω is a frequency of the RF field. From the simulations of Ψ, it is clear that in the $xy-plane$ maximum of the Ψ is located on the y-$axis$ (perpendicular to the trap xz-$plane$). So d can be calculated as:

$$d = \Psi(h_{\max}) - \Psi(h), \qquad (2)$$

1)e-mail: timur.abbasov@skoltech.ru

where $h_{\max}$ is the coordinate (altitude) where the highest value of a pseudopotential on a *y-axis* above the ion is achieved. To estimate the secular frequency, we use the following equation from the linear Paul trap theory [13]:

$$\omega_{\rm sec}(x, y) = \frac{q_0 \Omega}{2\sqrt{2}}, \tag{3}$$

where $q_0 = q \cdot \varepsilon$ is a stability parameter (q-parameter) of a non-hyperbolic trap, ε is an efficiency parameter (typically $0.2-0.3$ for the surface trap as shown in [13]) and q is a *q-parameter* for a hyperbolic trap:

$$q = \frac{2QV_{rf}}{mR_0^2\Omega^2}, \tag{4}$$

where V_{rf} – is an amplitude of the RF voltage. To be in the experimental conditions convenient for the laser focusing, we have to consider $h > 150\,\mu$m.

The following parameters were being changed during the optimization process: the width of the central electrode $wc \in [200; 600]\,\mu$m and $wc \in [70; 100]\,\mu$m for the trap with the hole in the central electrode, the width of RF electrodes $wr \in [100; 400]\,\mu$m and $wr \in [70; 100]\,\mu m$ for the trap with the hole in the central electrode, and the width of the central hole $hc \in [20; 50]\,\mu$m for the trap with the hole in the central electrode. The following parameters were being calculated in our simulations: d – the trap depth, h – the height of the stored ion above trap surface, and $\omega_{\rm sec}$ – the secular frequency of the stored ion. The frequency of the RF field (Ω) in our simulations was chosen to be $2\pi * 10$ MHz and an amplitude of the RF voltage (V_{rf}) was chosen to be 100 V as a suitable value for electrodes situated at a distance of 5–10 μm to prevent electrical breakdown in the vacuum between them.

The simulation results indicate that by decreasing the geometrical parameters of the trap we have an increase in the trap depth and the secular frequency, while the height of the stored ion is decreased. There are no significant changes in these parameters with the variation of the width of the RF electrodes, particularly in comparison to changes resulting from the varying of other geometrical parameters.

Based on the calculated data, one can select appropriate parameters and fabricate the ion trap with customized characteristics to suit a specific range of applications.

Using the results of our calculations, we have identified several designs for our future surface ion trap. The parameters of these designs chosen to meet the specific requirements and based on the outcomes of this study.

Our study demonstrates the development process of the chip-based surface ion traps with the electrodes located in a plane.

In this research, we have presented the development process for the class of the segmented planar ion traps that is used for various applications. Our focus was primarily on the determination of the trap depth, the secular frequency, and the ion height above the surface. Our results can be used to design the traps with the designed characteristics and for the specific purposes. Furthermore, the scalability of the trap design allows the storage of extended chains of ions, making it a promising candidate for the quantum computation.

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