Effective potentials in SLIM employing planar arrays of RF electrodes with DC inserts

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Overview

• Structures for Lossless Ion Manipulations (SLIM) involve the fabrication of two parallel surfaces, having arrays of RF/DC electrodes
• We explore the next generation of SLIM employing optimized layouts of electrodes
• Additional electrodes, not included in RF circuit, can be used to generate tailored spatial and temporal electric fields

Introduction

Structures for Lossless Ion Manipulations (SLIM) are capable of efficient ion transport, trapping, turning and switching between alternative paths, potentially enabling the construction of devices for executing complex and extended sequences of ion manipulations. In this study we consider patterns of electrodes having variable gap to width ratios and incorporating additional electrodes, not included in RF circuit, to generate tailored spatial and temporal electric fields. Effective and DC potential profiles are analyzed for the trial configurations.

Methods

Ion motion in SLIM is confined by the RF effective potential in the direction y, orthogonal to the planar RF electrodes, and limited by the guard DC potentials in the transversal x direction. Potential in the standard configuration c1 uses RF electrodes separated by equally sized gaps; in c2 the width of RF electrodes is increased, mimicking dielectric surfaces. The DC gradient is applied to RF electrodes via RC circuit, to promote ion transport along the z-axis.

Additional electrodes can be inserted between RF electrodes carrying patterns of DC potentials to enable the ion manipulations.

Results

Effective and DC potential z-profiles

The effective potential $V_{\text{eff}}$ and DC potential $V_{\text{DC}}$ profiles are calculated for different configurations, $c_i$, of DC electrodes. The gradient $V_{\text{RF}}$, obtained numerically:

$$V_{\text{RF}}(x, y, z) = z \times E_{\text{RF}}$$

where $E_{\text{RF}}$ is the RF electric field. The pattern $c_2$, wide RF electrodes and narrow gaps, produces the effective potential barrier close to the standard $c_1$; z-oscillations are more pronounced at close positions, $h < 1$ mm.

With DC inserts added, the effective potential barrier is reduced. DC z-oscillations are suppressed at $h > 1$ mm.

The pattern with narrow DC electrodes shows the effective potential barrier close to standard, with just minor z-oscillations.

Wide DC electrodes produce the smallest effective potential barrier and higher z-oscillations, the DC potential penetration is larger.

In summary, the DC inserts can be configured such that the RF effective barrier is maintained at a desired level, with acceptable uniformity along the ion path, i.e., in a direction. The ion packets are positioned optimally at a distance $h$, sufficient to reduce z-oscillations of both the effective and the DC potential, considered next.

Effective field calculations

The ion density is concentrated around the potential well minimum; the $y$ position is defined by a balance between the effective potential gradient $E_{\text{eff}}(y)$ and DC field $E_{\text{DC}}(y)$.

The effective field $E_{\text{eff}}$ calculated as the $y$-gradient of the effective potential, obtained numerically for RF electrode geometries $c_1$-5. Maximum $y$ range is 2.2 mm, corresponding to 6.8 mm-inter-board spacing.

The DC field $E_{\text{DC}}$ is determined largely by the DC offset applied to the RF electrodes. $\approx 10$ V/cm for practical SLIM implementations. This corresponds to the well minimum position at $y = 1$ mm, off-board distance $h = 1.2$ mm, where the smooth effective and DC potential profiles have been observed.

Effective potential 2D formula

The red dotted line is obtained using 2D relationship for the effective potential:

$$V_{\text{eff}}(h) = \begin{cases} \frac{1}{2} h^2 \frac{d_{\text{RF}}}{\delta} & \text{for } h < \delta \\ \frac{1}{2} \delta^2 \frac{d_{\text{RF}}}{\delta} & \text{for } h \geq \delta \end{cases}$$

In the 2D formula, $\delta$ is the distance between RF electrodes, $d_{\text{RF}}$ is the distance between RF electrodes, $\delta = 1.6$ mm has been used for configurations $c_1-5$.

Accordingly, the effective field is

$$E_{\text{eff}}(h) = \frac{1}{2} \frac{d_{\text{RF}}}{\delta} \frac{h^2}{\delta}$$

$\approx 10$ V/cm for practical SLIM implementations. This corresponds to the well minimum position at $y = 1$ mm, off-board distance $h = 1.2$ mm, where the smooth effective and DC potential profiles have been observed.

The 2D red dashed line is obtained using 2D relationship for the effective potential:

$$V_{\text{eff}}(h) = \begin{cases} \frac{1}{2} h^2 \frac{d_{\text{RF}}}{\delta} & \text{for } h < \delta \\ \frac{1}{2} \delta^2 \frac{d_{\text{RF}}}{\delta} & \text{for } h \geq \delta \end{cases}$$

The 2D approach provides evaluation of the low and high m/z range, as a function of RF parameters and normal component of the DC field $E_{\text{DC}}$.

In summary, the DC curves can be configured such that the RF effective barrier is maintained at a desired level, with acceptable uniformity along the ion path, i.e., in a direction. The ion packets are positioned optimally at a distance $h$, sufficient to reduce z-oscillations of both the effective and the DC potential, considered next.

Conclusions

• The new generation SLIM designs employ optimized layouts of electrodes patterned on flat surfaces of the planar boards
• RF electrode width can be extended, minimizing inter-electrode gaps
• Additional electrodes can be inserted between RF strips to drive manipulations; e.g., controlled patterns of DC potentials can be applied to the inserts, enabling ion manipulations, such as ion transport, ion mobility separation and ion trapping
• RF and DC electrode arrays are de-coupled, streamlining SLIM circuitry and improving the overall efficiency
• Insulator surface area potentially subject to charging is minimized, providing robust operation

• A scaling law is developed for analytical evaluation of the effective potential, ion density distribution and m/z range as a function of dimensions, RF and DC voltages

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References