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

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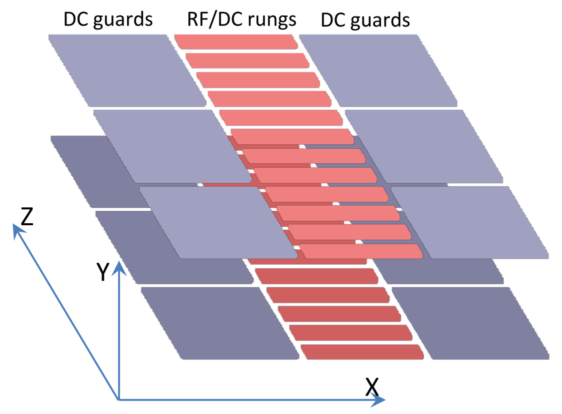
Overview

- 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 employ optimized layouts of electrodes
- Additional electrodes, not included in RF circuit, can be used to generate tailored spatial and temporal electric fields
- We report a scaling law that enables evaluation of the effective potential and m/z range

Introduction

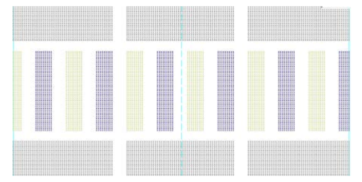
Structures for Lossless Ion Manipulations (SLIM) are capable of efficient ion transport, trapping, turning and switching between alternative paths, potentially enabling the construction of devices for executing complex and extended sequences of ion manipulations. In this study we consider patterns of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



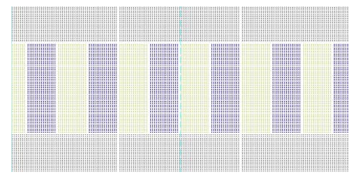
SLIM formed by two parallel surfaces, each having a sequence or RF electrodes, bordered by DC "guard" electrodes. The coordinate system used for modeling has been described previously [1].

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. The “standard” configuration **c1** uses RF electrodes separated by equally sized gaps; in **c2** the width of RF electrodes is increased, minimizing dielectric surfaces. The DC gradient is applied to RF electrodes viaan RC circuit, to promote ion transport along the z-axis.

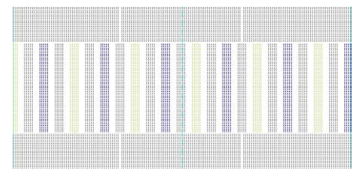


c1: standard
d_RF = 0.9mm; gap = 0.7 mm



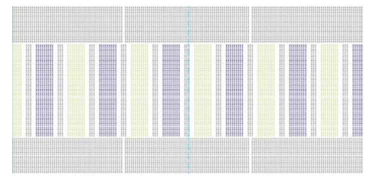
c2 : wide RF electrodes, narrow gaps
d_RF = 1.3mm; gap = 0.3 mm

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

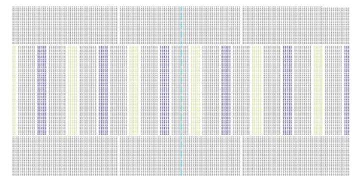


c3: equal size DC inserts
d_RF = 0.5 mm; d_DC = 0.5 mm
gap = 0.3 mm

Configurations c4 and c5 have reduced gap size of 0.2 mm and varying electrode widths:



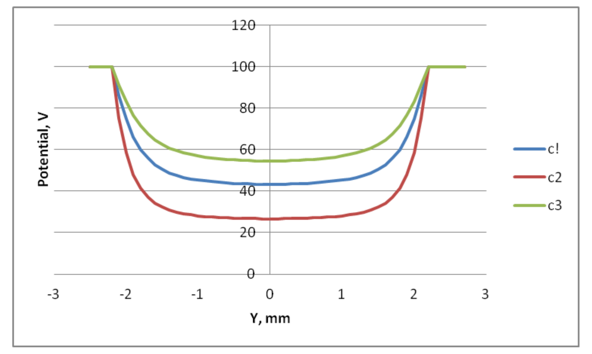
c4: narrow DC inserts
d_RF = 0.9 mm; d_DC = 0.3 mm



c5: wide DC inserts
d_RF = 0.3 mm; d_RF = 0.9 mm

Potential calculations were applied to analyze distributions of the effective potential and DC electric potential.

DC electric potential profile between the boards. The inter-board spacing is 4.4 mm; 100 V is applied to the DC inserts. Penetration to the mid-plane is 43%, 27% and 55%, respectively for c3, c4 an c5.



Results

Effective and DC potential z-profiles

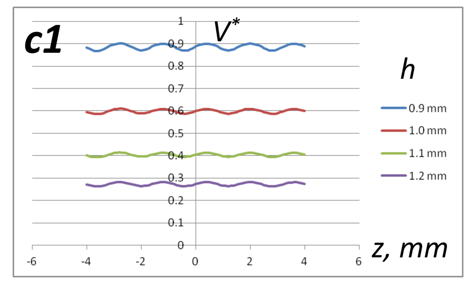
The effective potential V^* and DC potential V_{DC} z-profiles are calculated for different off-board distances $h = y - y_0$, where y_0 is lower board y-position; RF frequency and voltage are f=1MHz, V_{RF} = 100 V_{0p}, m/z = 1000.

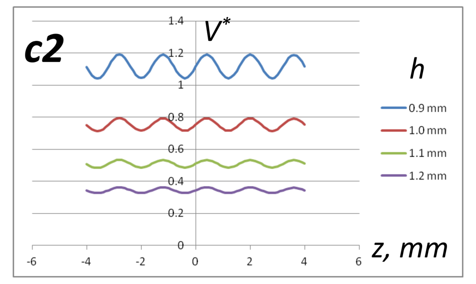
Effective potential z-profiles

The effective potential $V^*(x, y, z)$ is calculated based on the classical equation [2], using the gradient of RF potential distribution, $E_{RF}(x, y, z)$, obtained numerically:

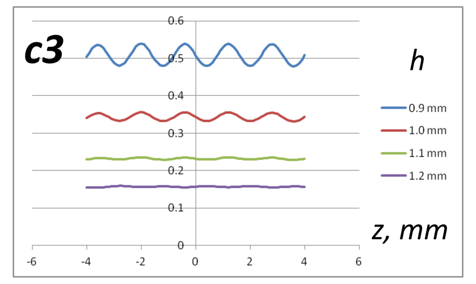
$$V^*(x, y, z) = zeE_{RF}^2 (x, y, z)/4 m\omega^2$$

where m and ze are ion mass and charge; ω is RF frequency in angular units: $\omega = 2\pi f$



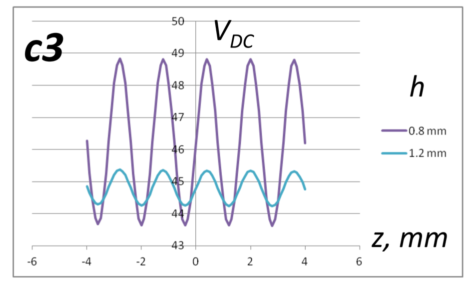


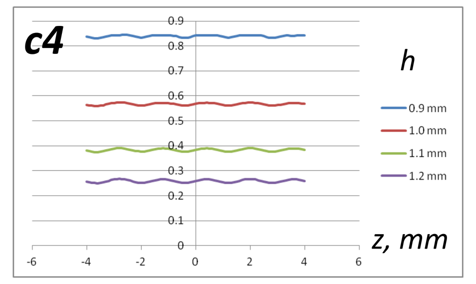
The pattern c2, wide RF electrodes and narrow gaps, produces the effective potential barrier close to the standard c1; z-oscillations are more pronounced at close positions, h < 1 mm.



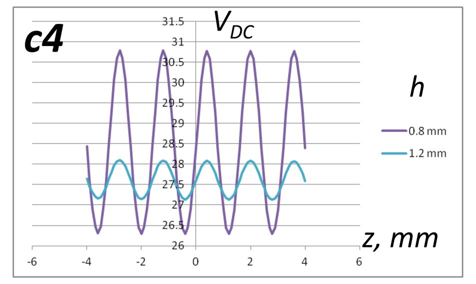
With DC inserts added, the effective potential barrier is reduced. DC z-oscillations are suppressed at h > 1 mm.

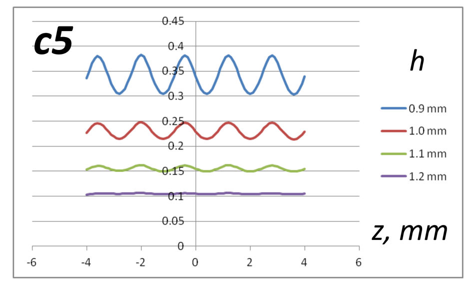
DC potential z-profiles



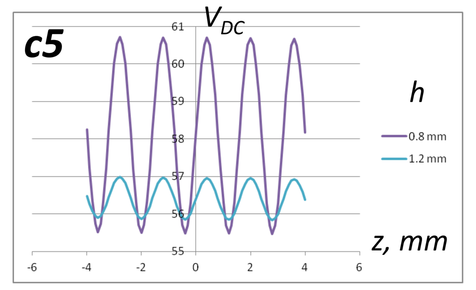


The pattern with narrow DC inserts shows the effective potential barrier close to standard, with just minor z-oscillations.





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

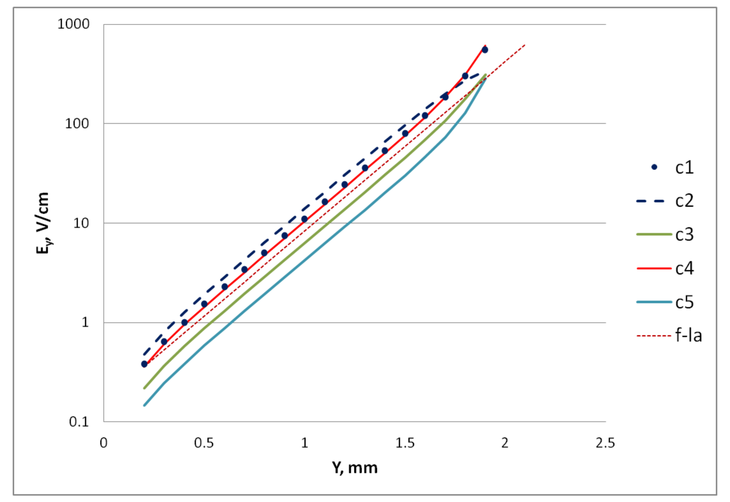


In summary, the DC inserts can be configured such that the RF effective barrier is maintained at a desired level, with acceptable uniformity along the ion path, i.e., in z direction. The ion packets are positioned optimally at a distance h, sufficient to reduce z-variations of both the effective and 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 $E_y(y)$ and DC field $E_{DC}(y)$.

The effective field E_y, calculated as the y-gradient of the effective potential, obtained numerically for RF electrode geometries c1-5. Maximum y range is 2.2 mm, corresponding to 4.4 mm inter-board spacing.



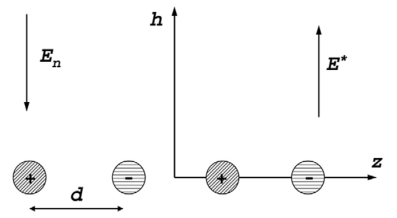
The DC field $E_{DC}(y)$ is determined largely by the DC offset applied to guard electrodes, ~10 V/cm for practical SLIM implementations. This corresponds to the well minimum positioned at y =~1 mm, off-board distance h = 1.2 mm, where the smooth effective and DC potential z-profiles have been observed.

Effective potential 2D formula

The red dotted line is obtained using 2D relationship for the effective potential [3]:

$$V^*(h) = zeV_{RF}^2 \exp(-2h/\delta) / 4m\omega^2\delta^2$$

where $\delta = d/\pi$; d is distance between RF electrodes. d = 1.6 mm has been used for configurations c1-5 above.



2D RF grid model

Accordingly, the effective field is $E_y(h) = zeV_{RF}^2 \exp(-2h/\delta) /2 m\omega^2\delta^3$

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_h [4]

$$(m/z)_{low} = 8eE_n / m_u\omega^2\delta \alpha^2 \qquad (m/z)_{high} = eV_{RF}^2 \exp(-2h_0/\delta) / 2 m_u\omega^2\delta^3E_n$$

where α ~1 is adiabaticity constant

The 2D formula is consistent with numerical calculations, providing a way to predict characteristics for re-scaled designs.

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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