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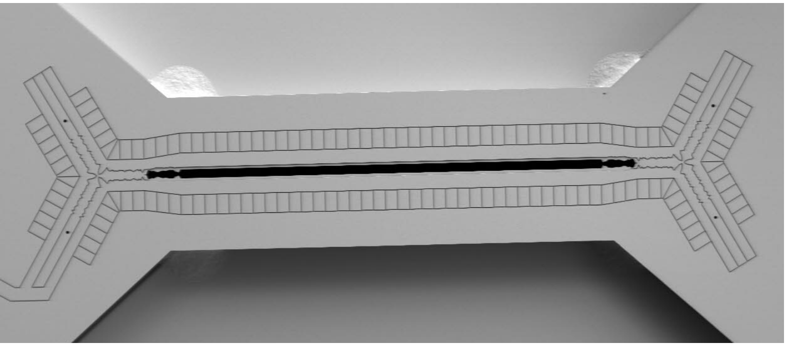
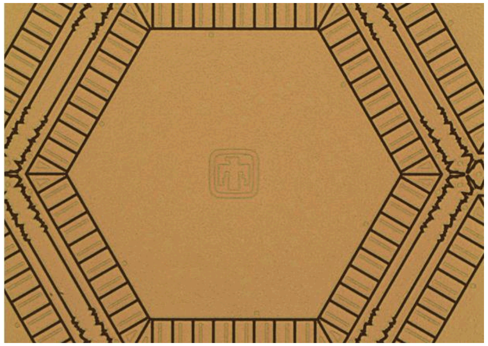
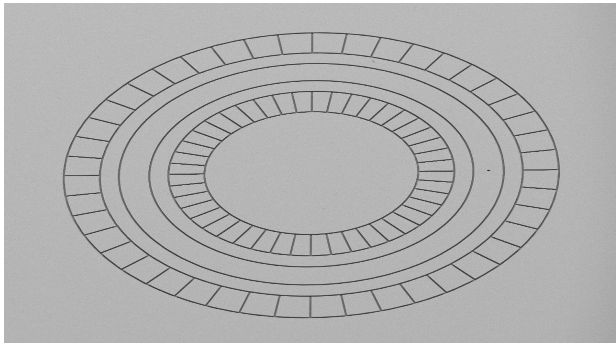

High optical access micro-fabricated ion trap with improved axial control

Jonathan D. Sterk, Chris Tigges, Jay van der Wall, Matthew Blain, Peter Maunz

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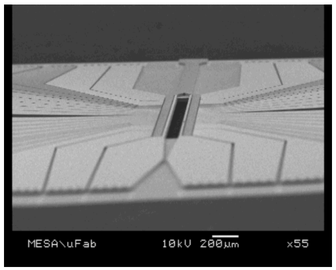
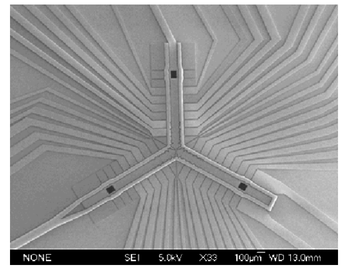
Previous Work



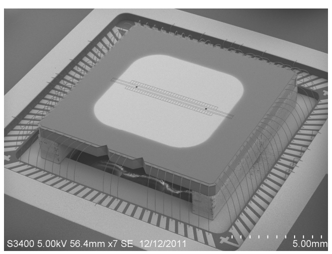
Thunderbird Trap

- Workhorse trap
- Loading Slot



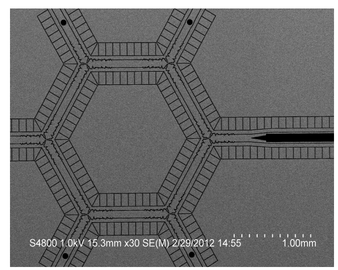
Y Junction

- Optimization of junction
- Reliable shuttling



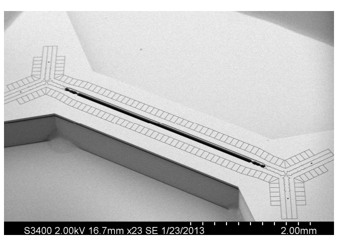
CQED Trap

- Four level metallization
- Custom die shapes



Hexagon Circulator

- Multi-junction device
- Transition from slot to junction



HOA1 Trap

- Custom shape for high optical access
- Trench capacitors

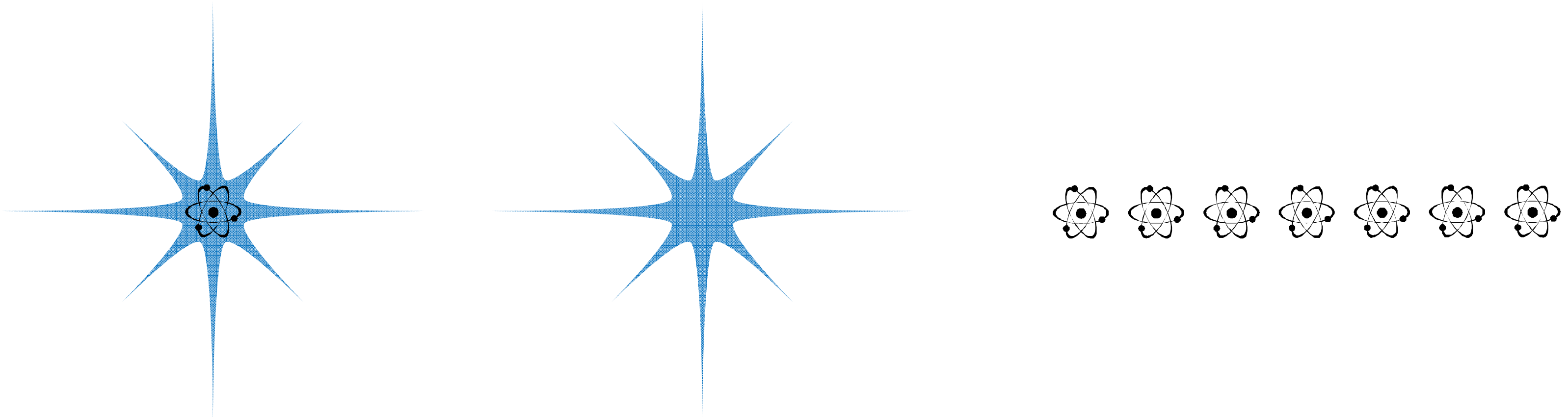
HOA2

- Resolve issues of HOA1
- Provide more control of ion chains
- Operational regimes

Device operation

Experimental motivation/integration into MUSIQC architecture

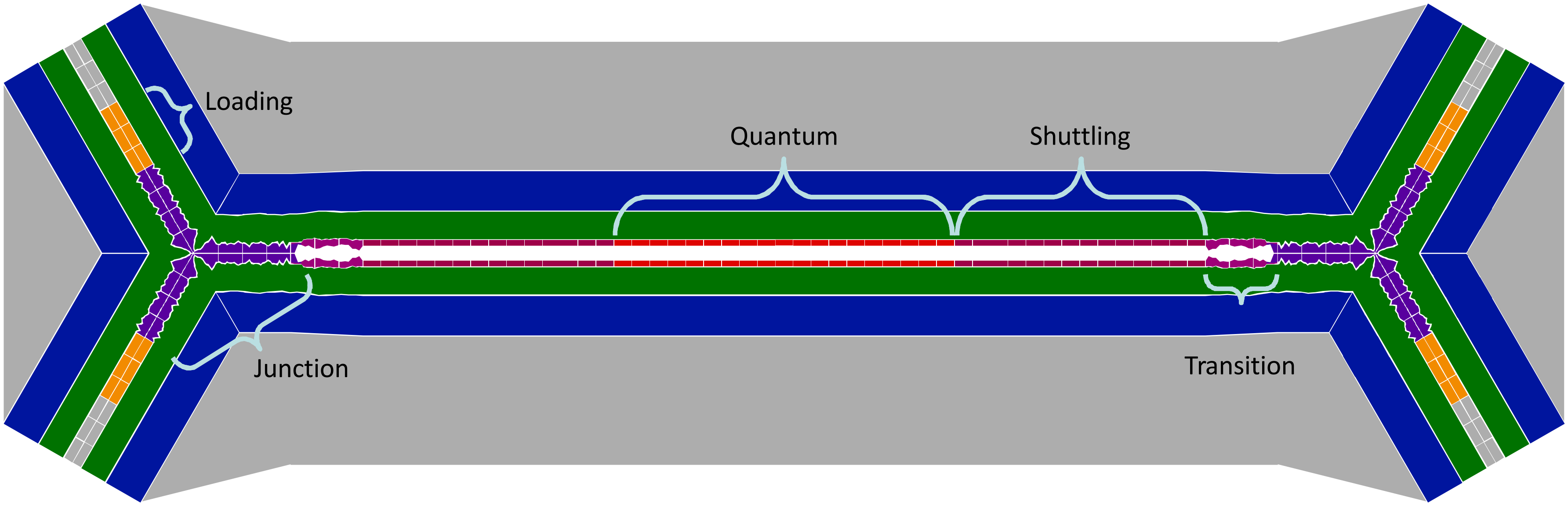
- Three operational sections:
    1. Photon generation for remote interface
    2. State detection
    3. Coherent operations
- Ability to shuttle between sections, split ions
- Inside field of view of large NA optic



Requirements for HOA2

Requirement	*Design*
Integration with trench capacitors	Isthmus design from HOA1
Horizontal optical access	Isthmus design from HOA1
Vertical optical access	Slotted linear section from HOA1
High radial frequencies	Drop inner DC to M3; Adjust electrode widths
Junction Operation	Ensure Q section has highest radial frequencies. Junction optimization
Principal axes rotation	Independent control on inner and outer DC
Voltage efficacy for separation and recombination	Inner DC electrodes segmented (control electrodes are closer to the ion). Geometry optimization

Device Structure

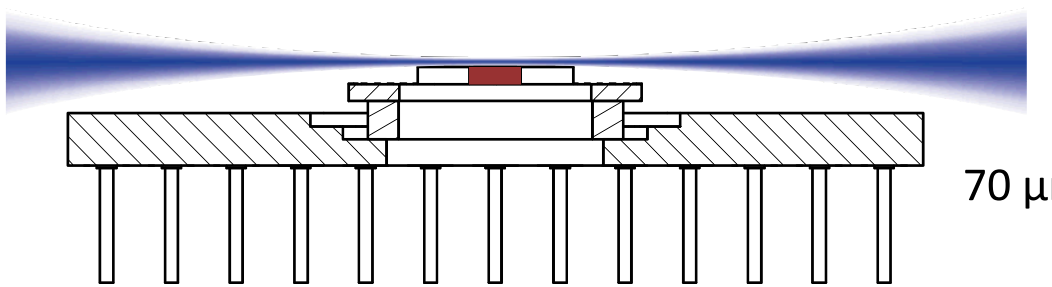


Electrode Count:

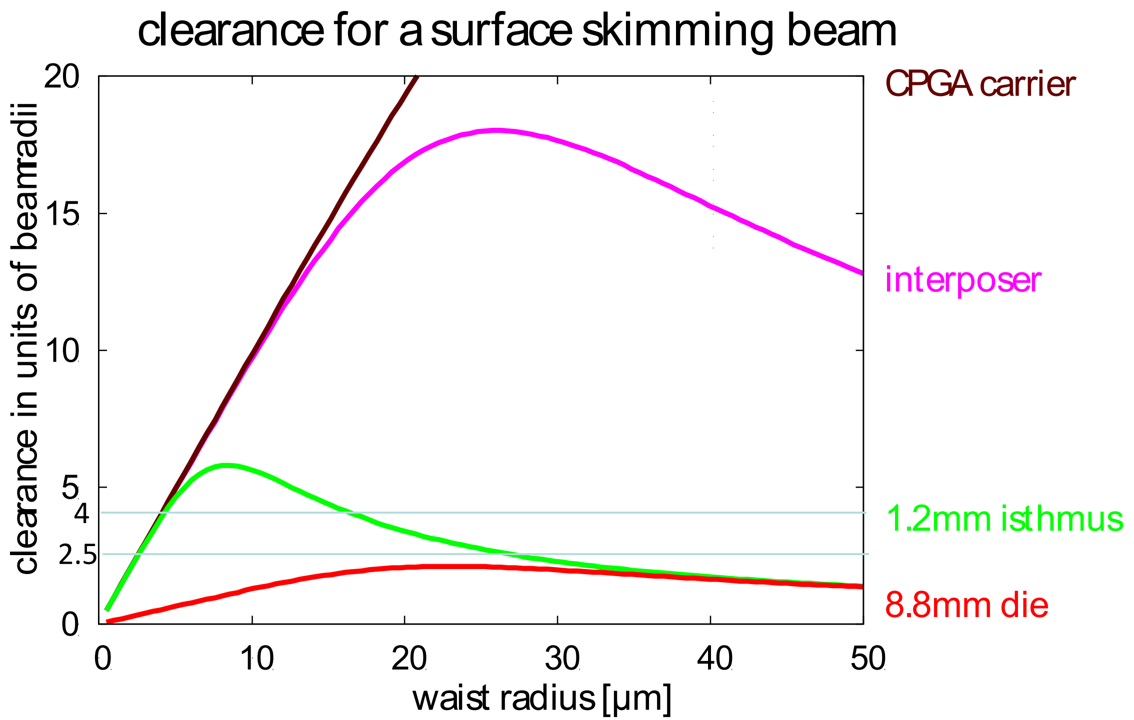
- Use left-right symmetry for Shuttling, Transition, Junction, and loading sections
- Co-wiring of shuttling section into groups of 4

Region	# Electrodes	# Independent Voltages
Quantum	19 pairs	38
Shuttling	28 pairs	8
Outer DC	10 electrodes	6
Junction	24 pairs	24
Transition	6 pairs	6
Loading	12 pairs	12
Total:		94

High Optical Access trap *beam clearance*



70 µm ion height



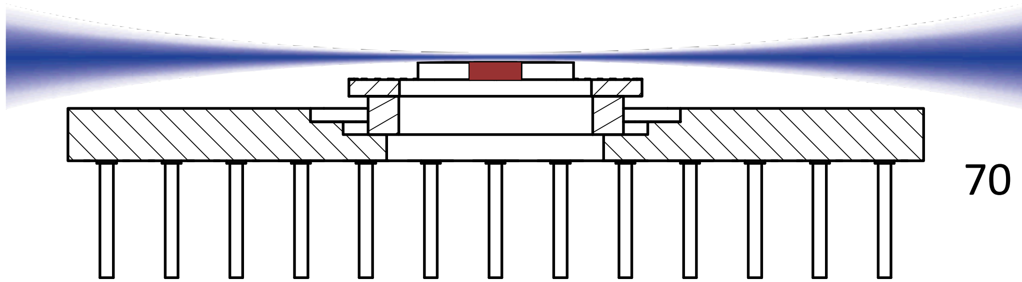
4: $<2\times10^{-14}$

3: $<2\times10^{-8}$

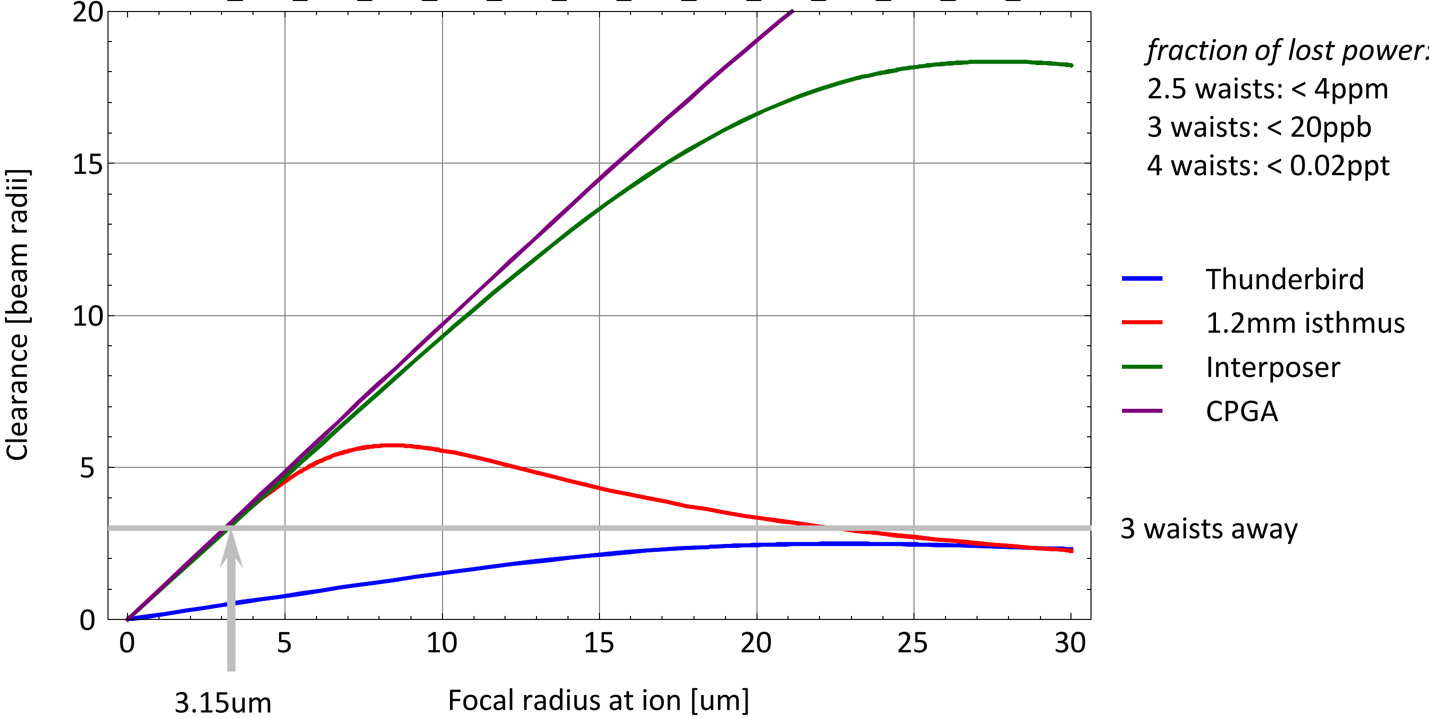
2.5: $<3\times10^{-6}$

4 µm waist is possible

HOA2
Horizontal beam clearance

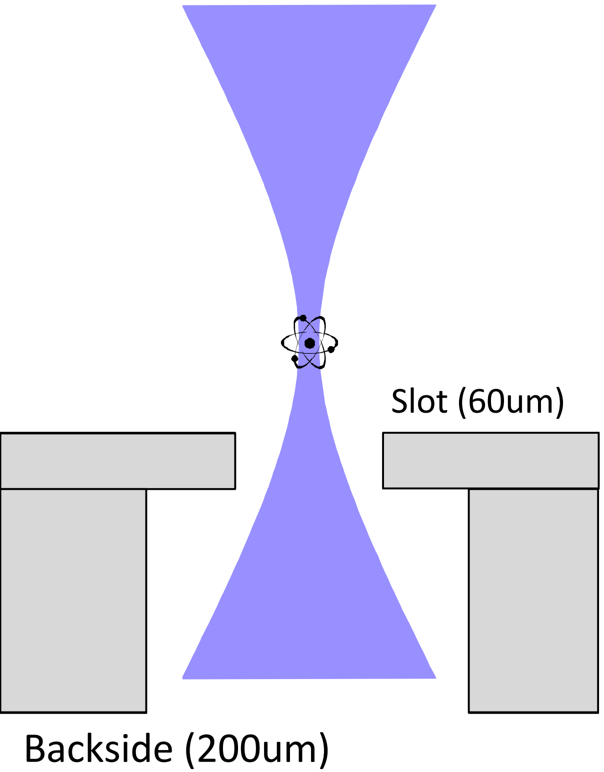


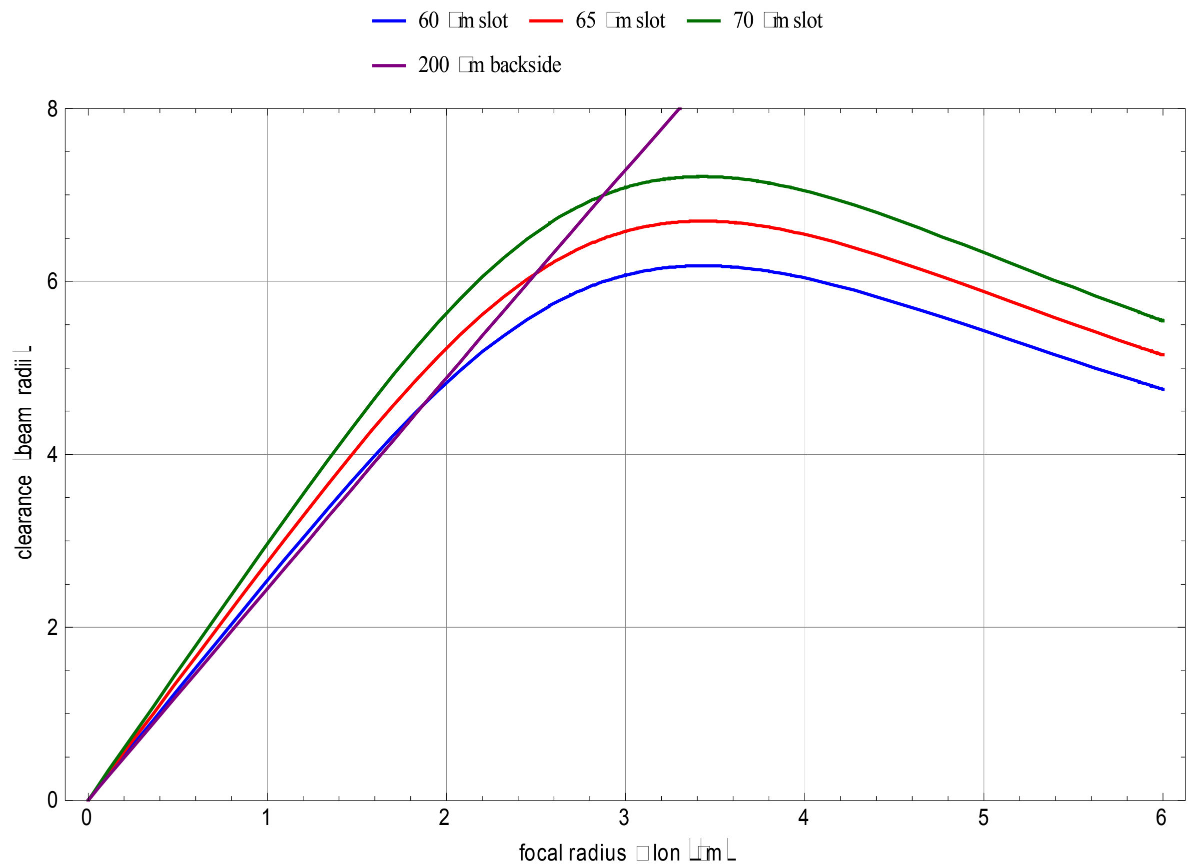
70 µm ion height



4um waist at ion is possible

Vertical Optical access and slot width





HOA2: 60um slot

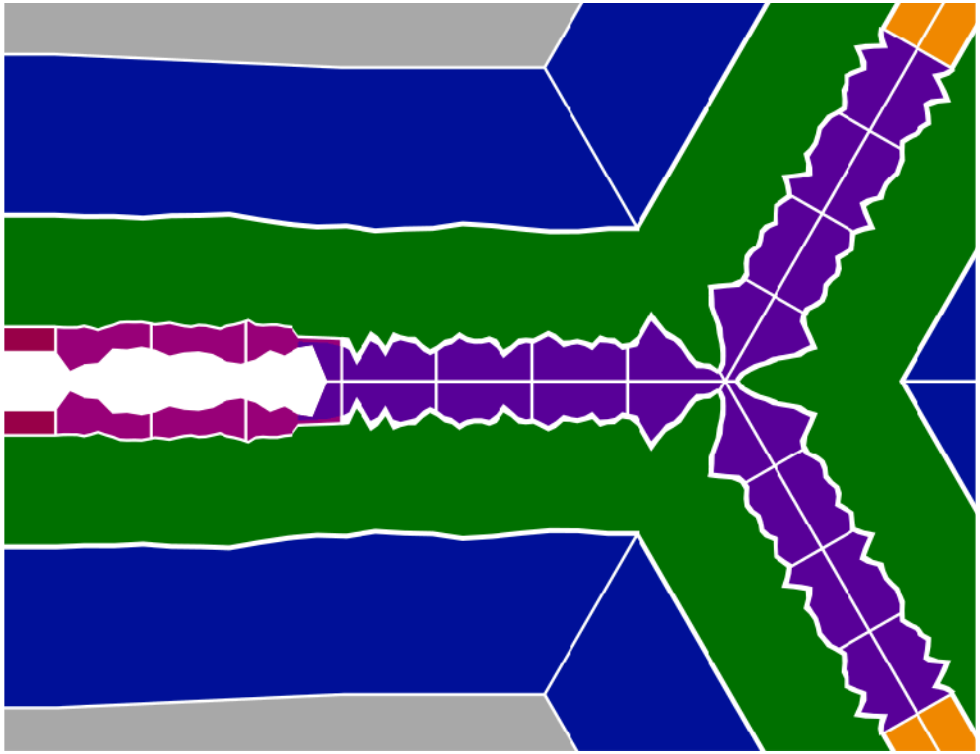
- Minimal effect on (vertical) optical access
- Greater voltage efficacy for DC control

Junction and Transition optimization

Goal

Minimize weighted sum of the following costs

1. Potential maximum
2. RMS value of potential
3. Axial curvature of potential
4. Variance of ion height
5. Radial frequency variance
6. Weighted average of slope
7. Punishment for frequencies exceeding 'asymptotic' values.



Control Points

Transition

41 control points in inner RF

21 control points on Inner DC

Junction

52 control points on inner RF per leg

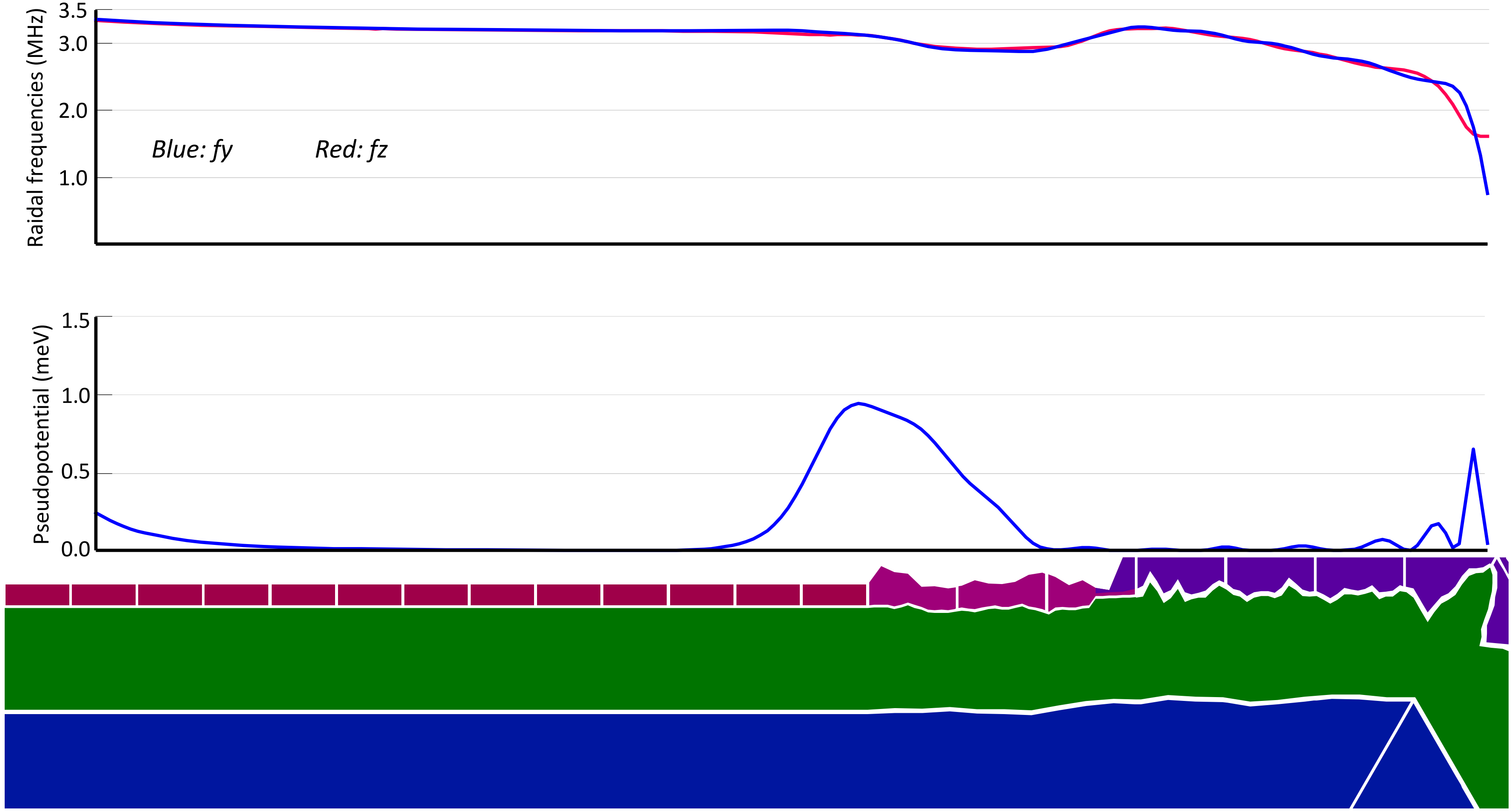
Costs computed for:

RF Frequency: 30MHz

RF Voltage: 200V

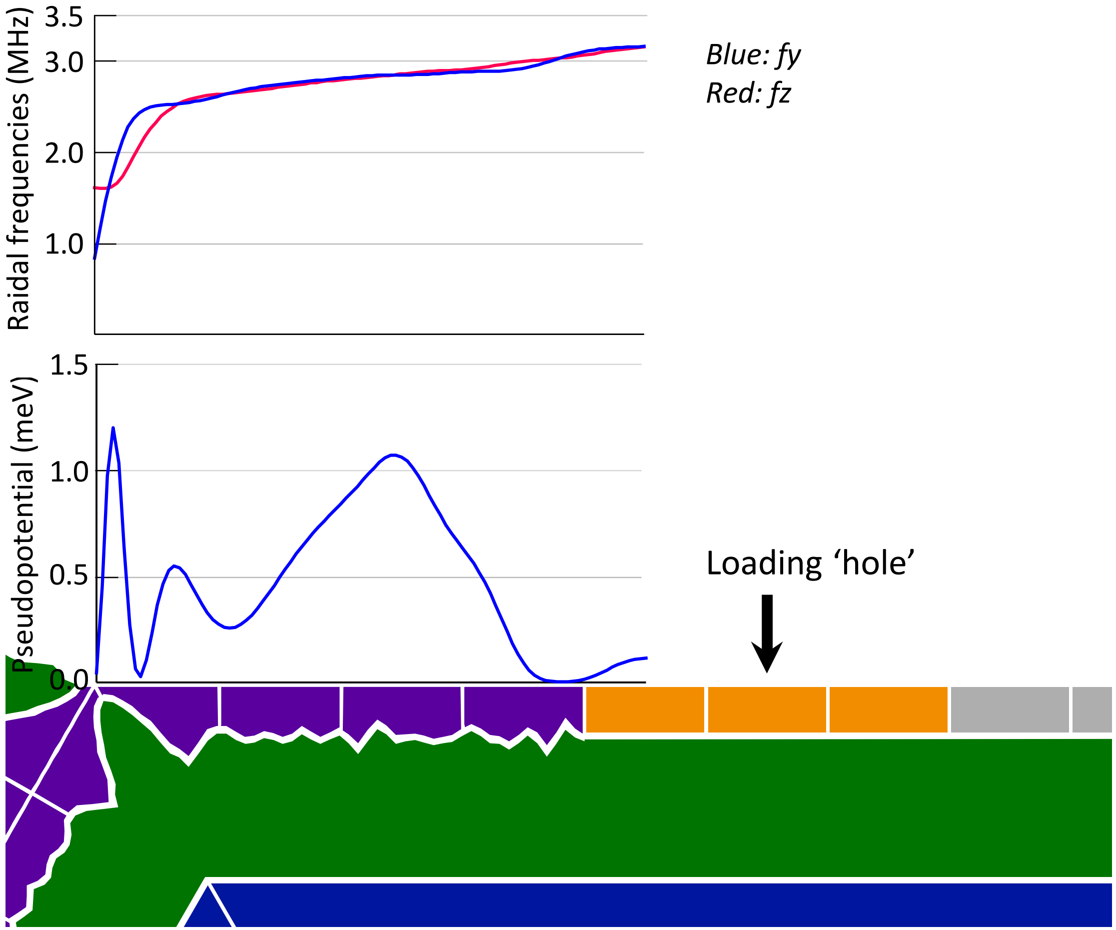
Ion: ytterbium

Slot Leg



Raidal frequencies (MHz)
3.5
3.0
2.0
1.0
Blue: fy
Red: fz
Pseudopotential (meV)
1.5
1.0
0.5
0.0

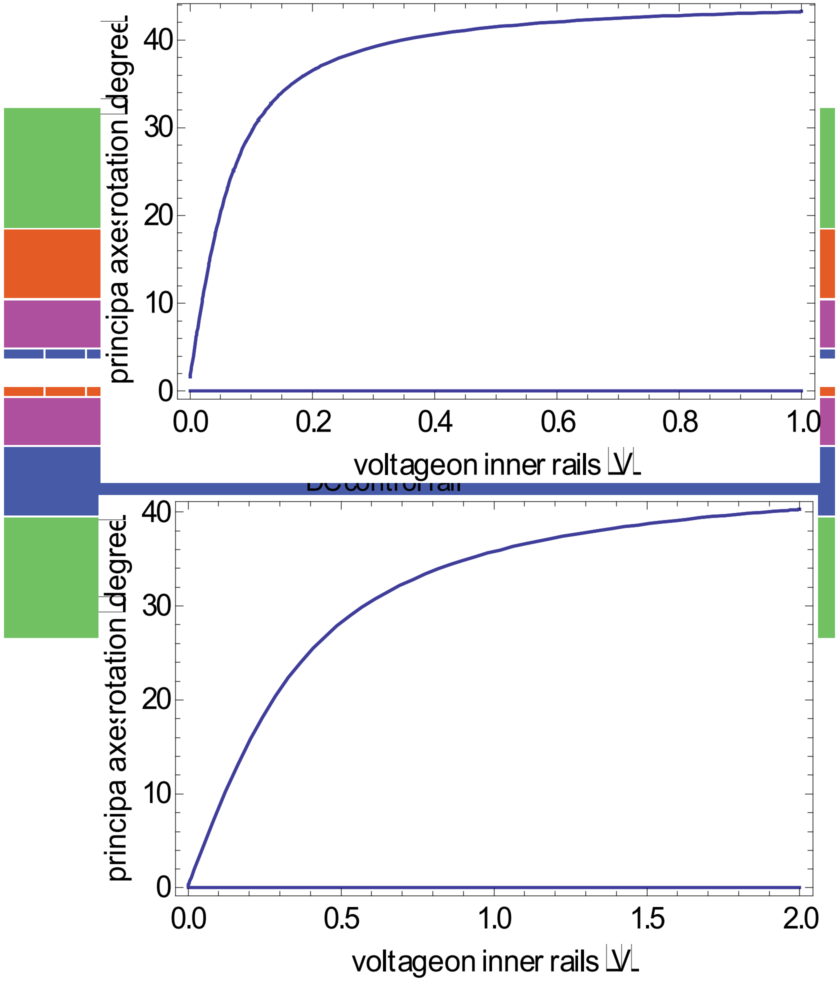
Load Leg

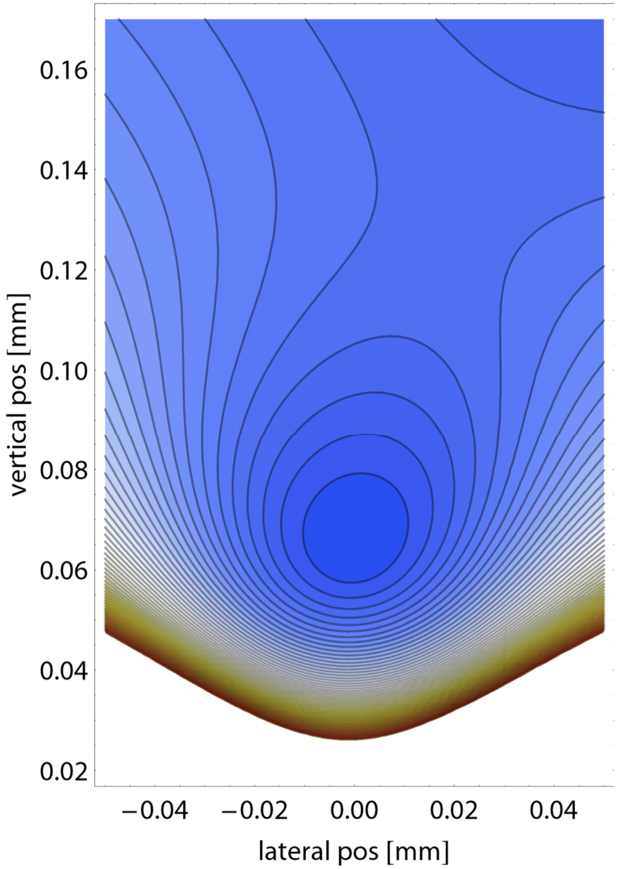


Raidal frequencies (MHz)
3.5
3.0
2.0
1.0
Blue: fy
Red: fz
Pseudopotential (meV)
1.5
1.0
0.5
0.0
Loading 'hole'

Rotation of principal axes

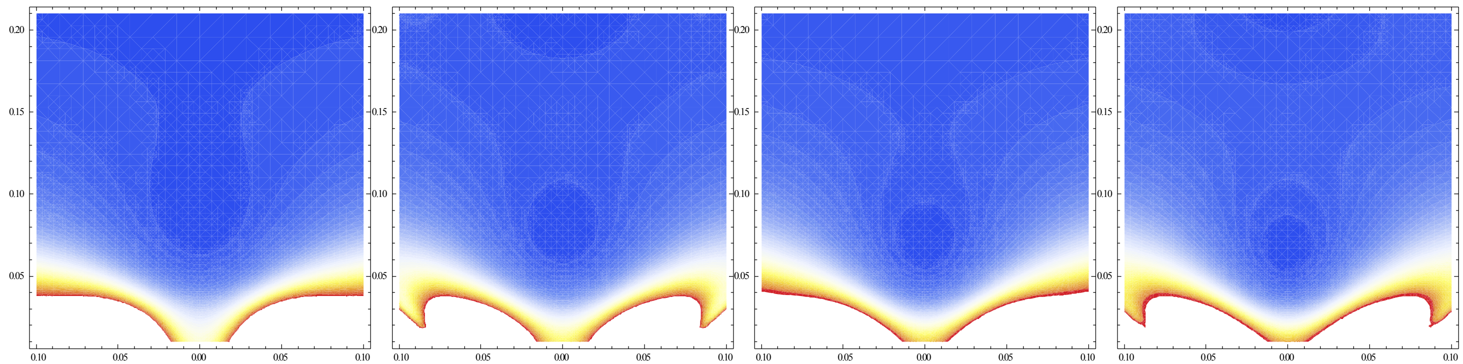
- Convert inner ground electrodes to split inner DC electrodes





Yb: All control voltages <4V; Axial 920kHz, radial 2.6MHz, 3.1MHz 250V rf @ 45MHz

Optimization of slotted linear section
Influence of oxide thickness



Oxide thickness	0µm (M4)	8µm (M3)	12.5µm (M3)	16µm (M3)
Ion height	82µm	74µm	69µm	65µm
Trap frequency*	2.1MHz	2.4MHz	2.7MHz	2.9MHz
Trap depth*	94meV	123meV	147meV	164meV
Trap freq* @q=0.2	2.56MHz	2.78MHz	2.92MHz	3.02MHz
Characteristic distance†	165µm	152µm	144µm	140µm
3rd order anharm	34µm	33µm	32µm	32µm
4th order anharm	44µm	44µm	44µm	44µm

Trap frequency and depth for rf potential only and for $^{171}Yb^{+}$, 250V, 45MHz

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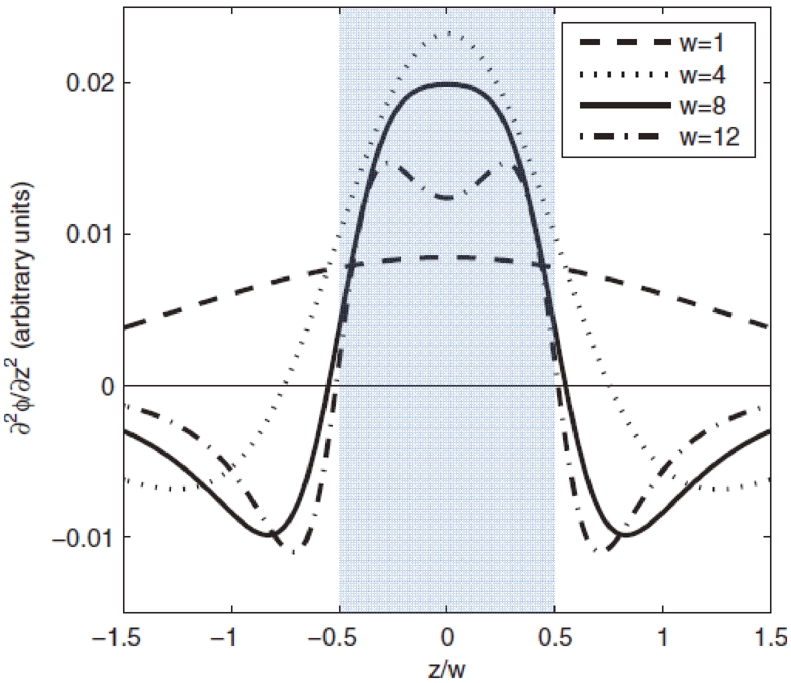
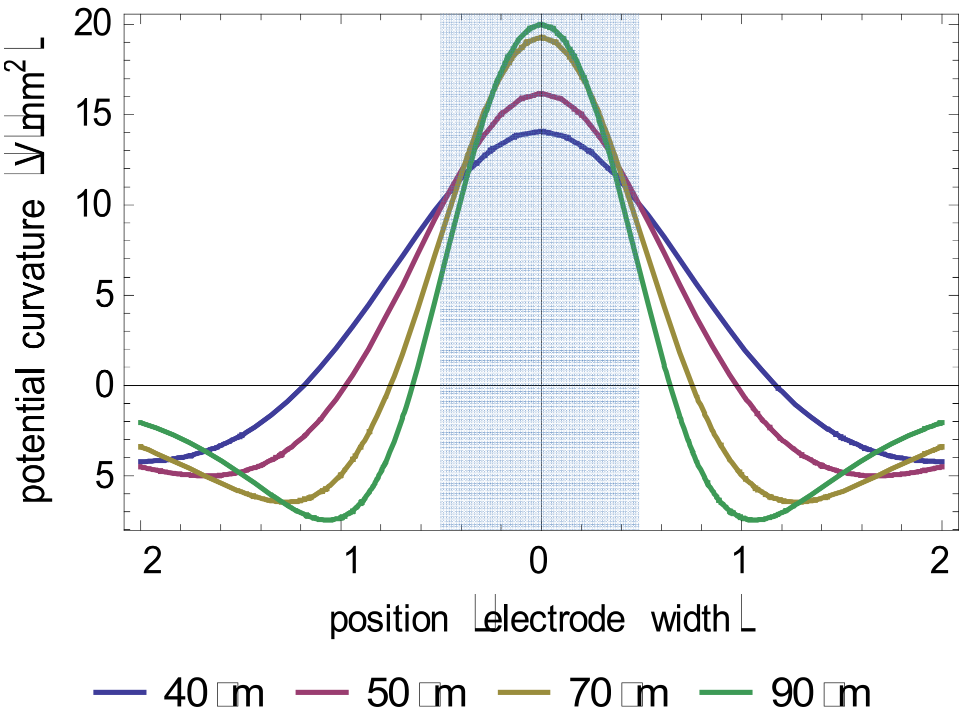
Electrode Pitch

Shaded: width of electrode



M. G. House *Phys. Rev. A* **78**, 033402 (2008)



- Electrode too wide: poor control over field between electrodes
- Electrode too narrow: too many control voltages
- House recommends w=4

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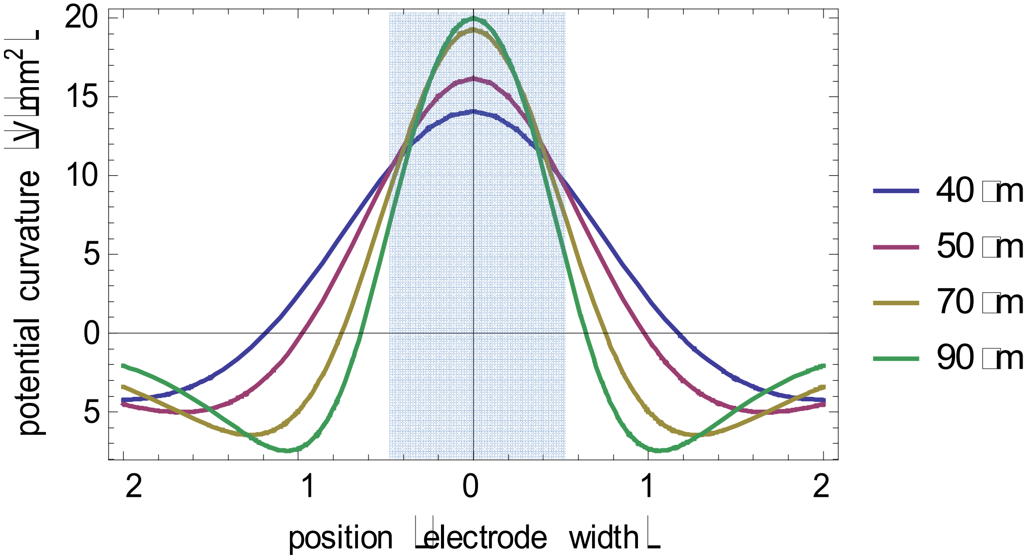
Potential Curvature

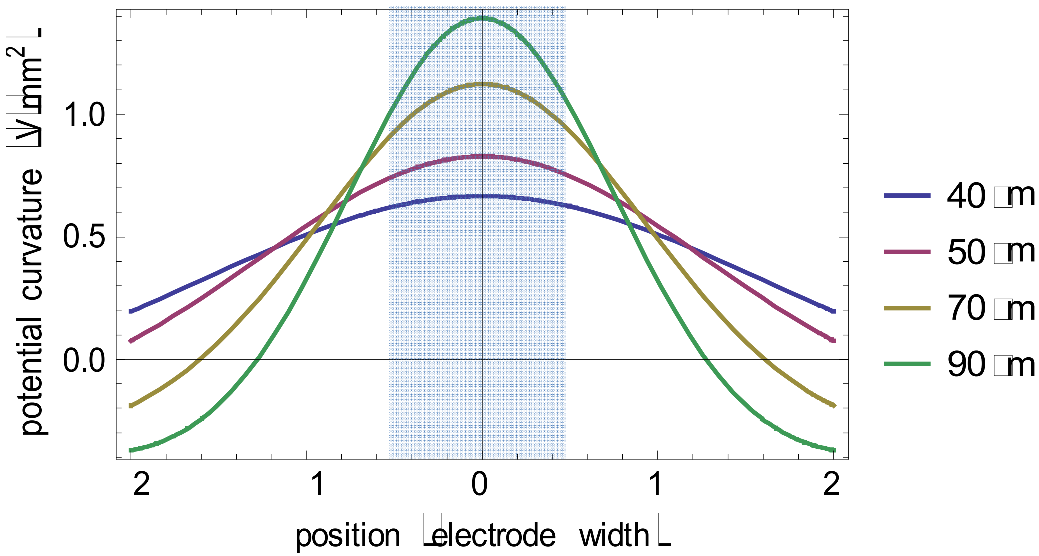
inner control electrodes

- 70 µm is promising



outer control electrodes

- Even 90 µm is too narrow



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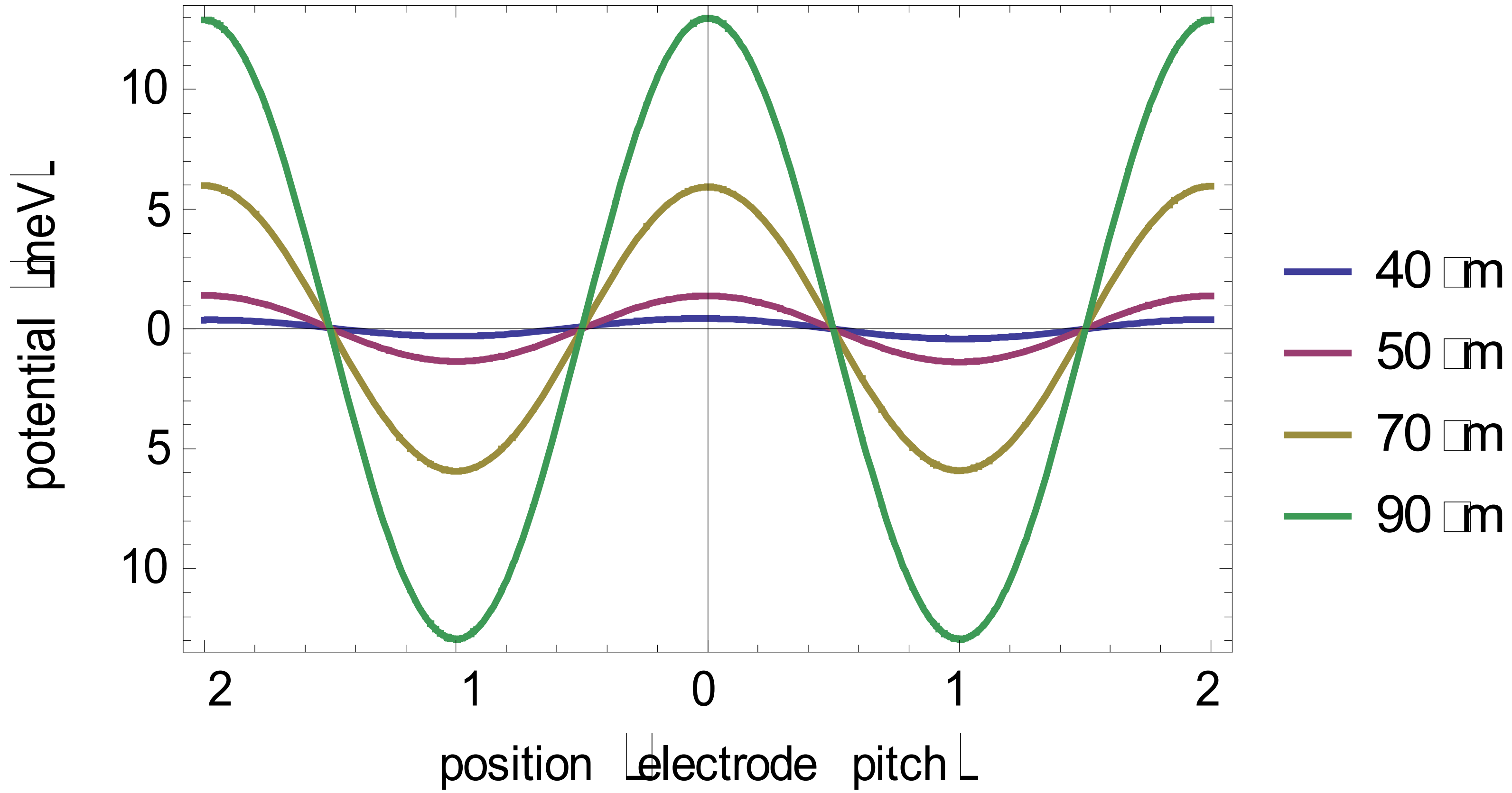
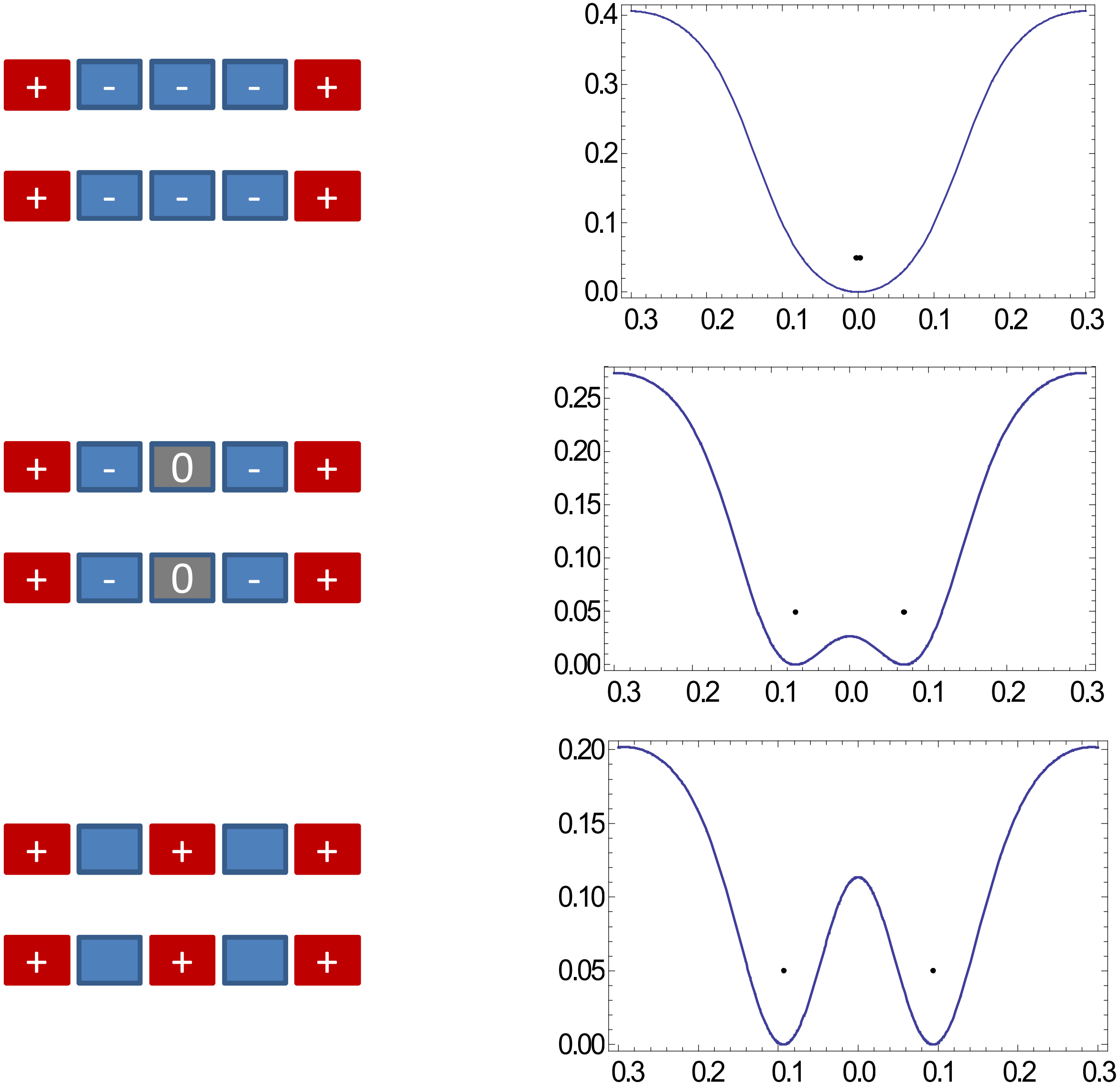
Alternating voltages

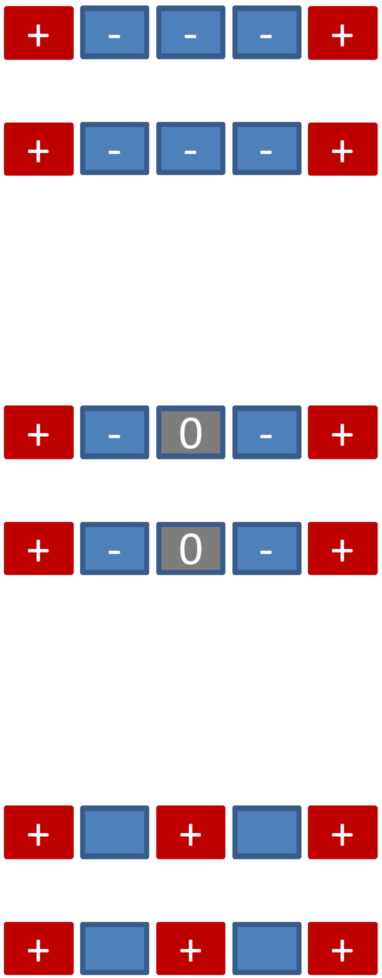
- potential generated by alternating voltages (0V, 1V, 0V, …)

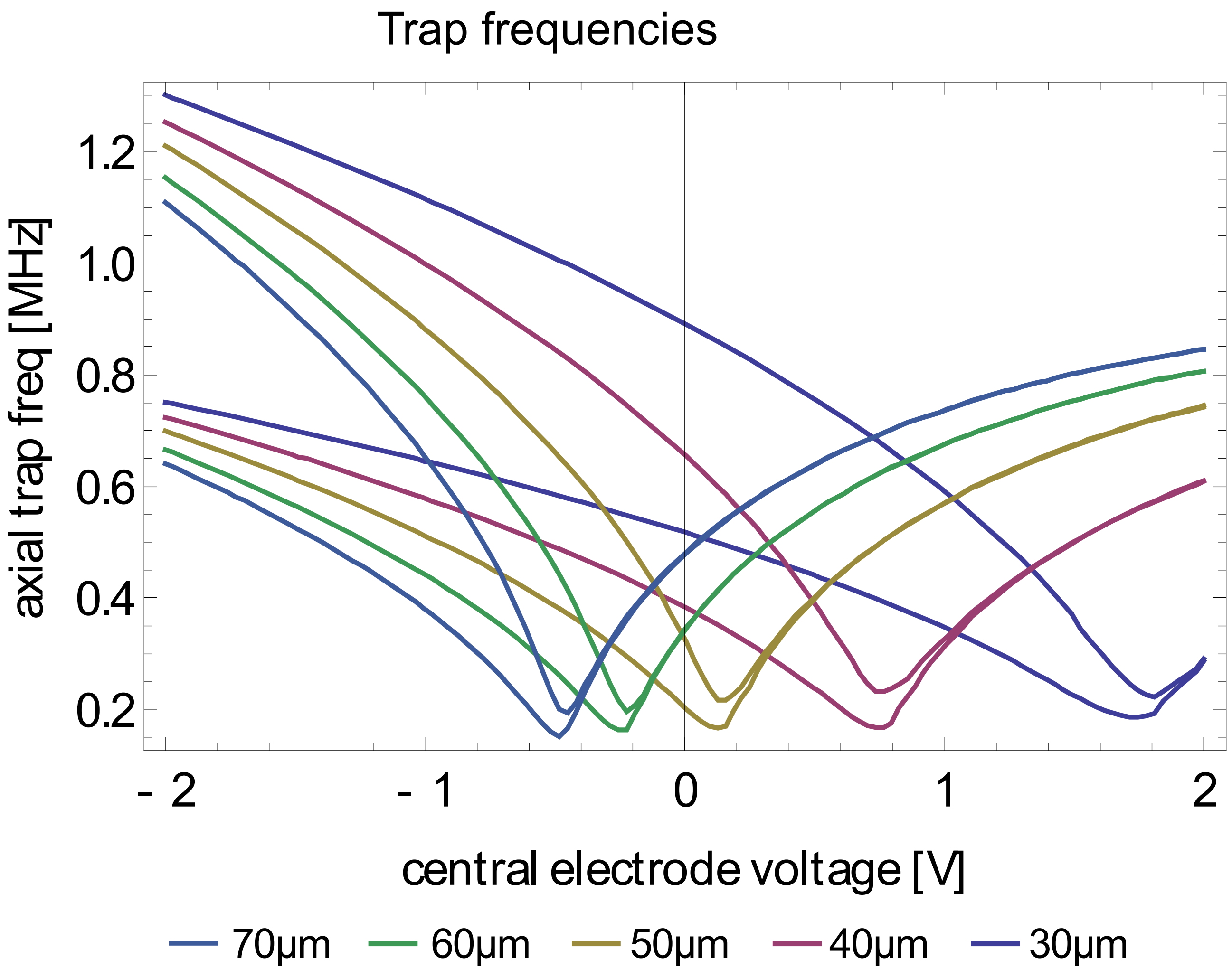


Splitting two ions



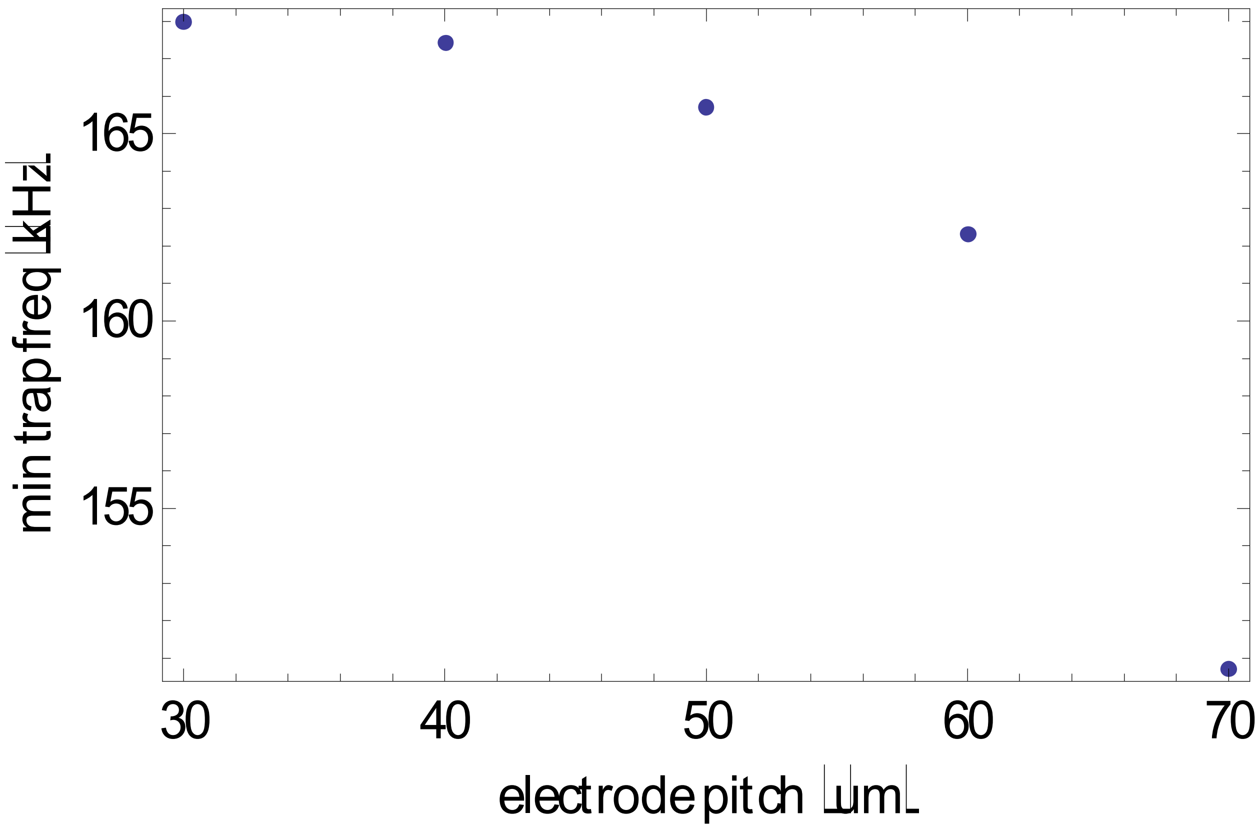
Splitting two ions





Effect of electrode pitch on minimal trap frequency

- Same voltages for all control electrode pitches



Splitter electrodes, narrower than 60µm only offer small increase in Minimal frequency

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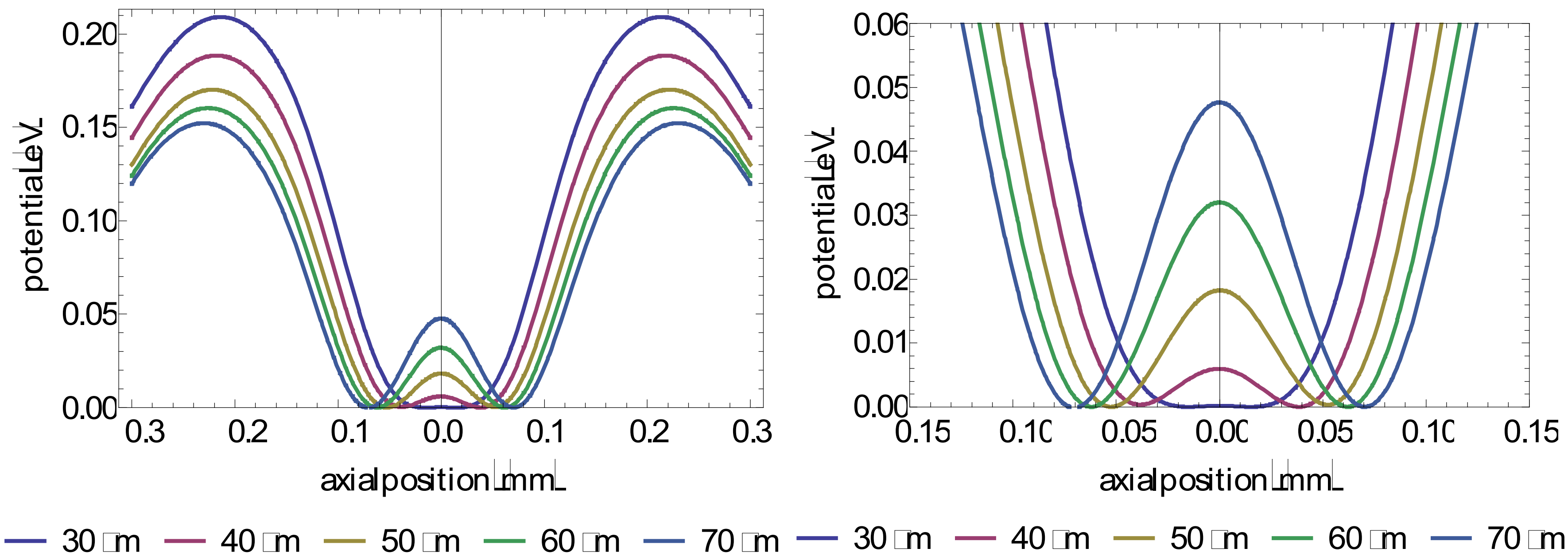
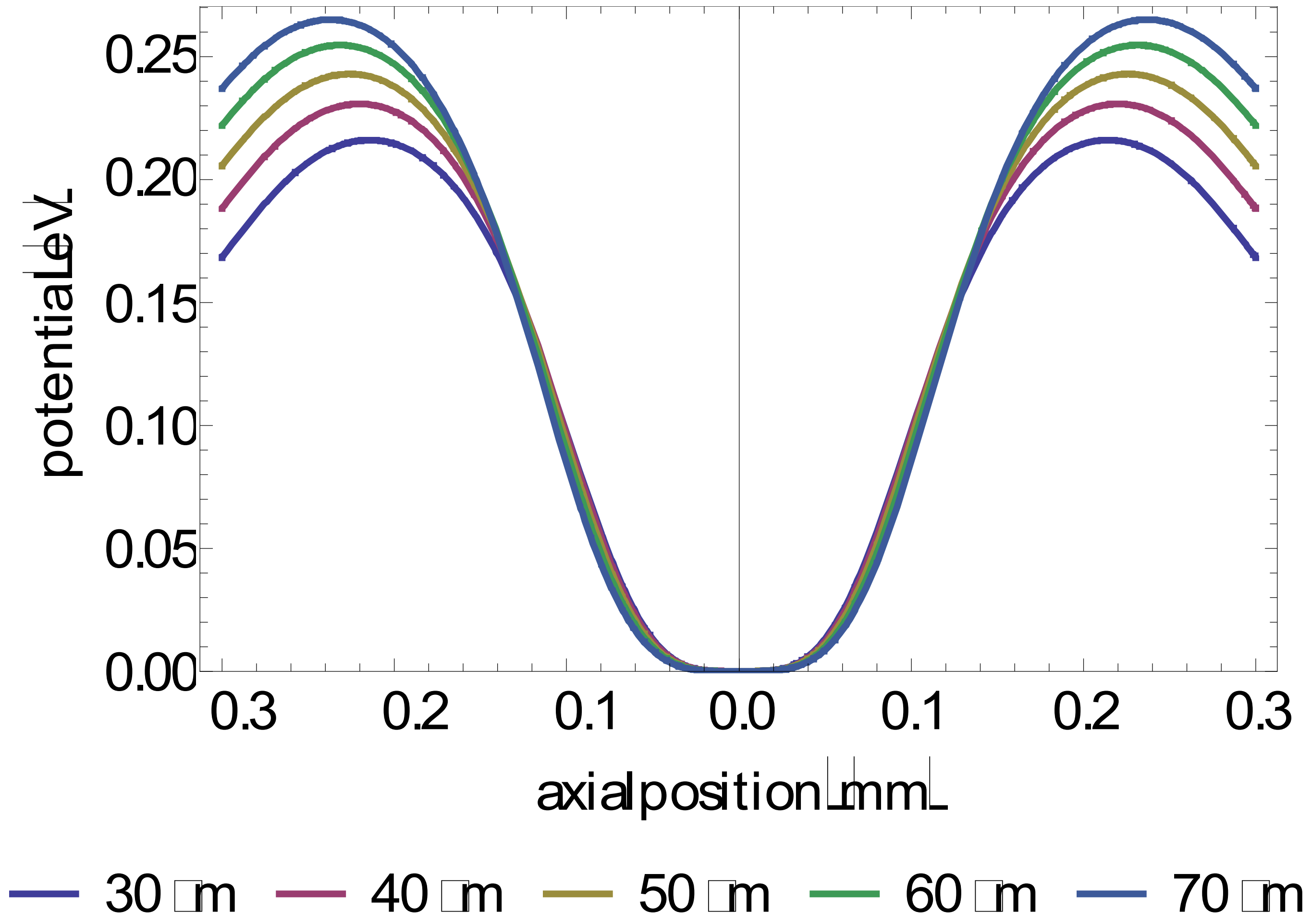
Splitted potential



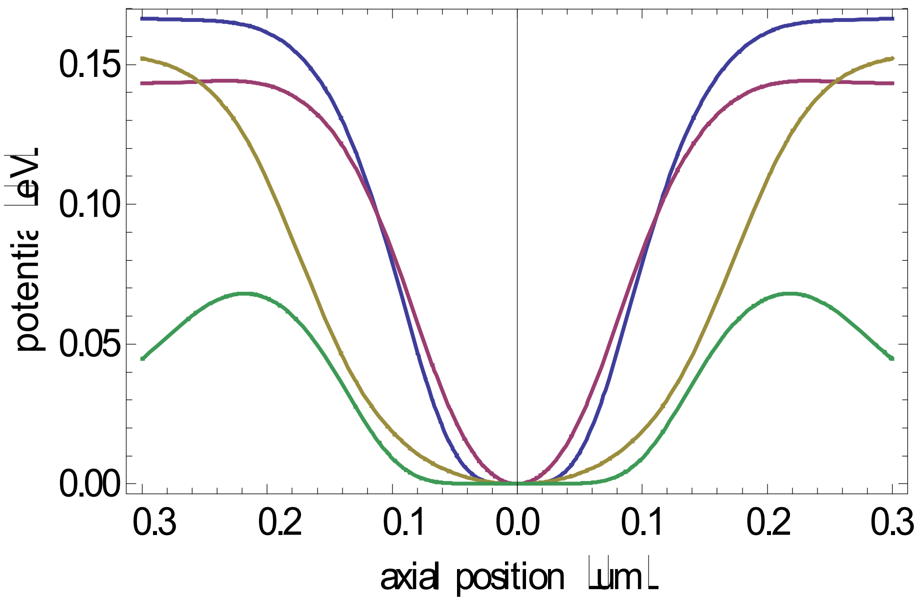
Splitter electrodes, narrower than 60μm have limited barrier

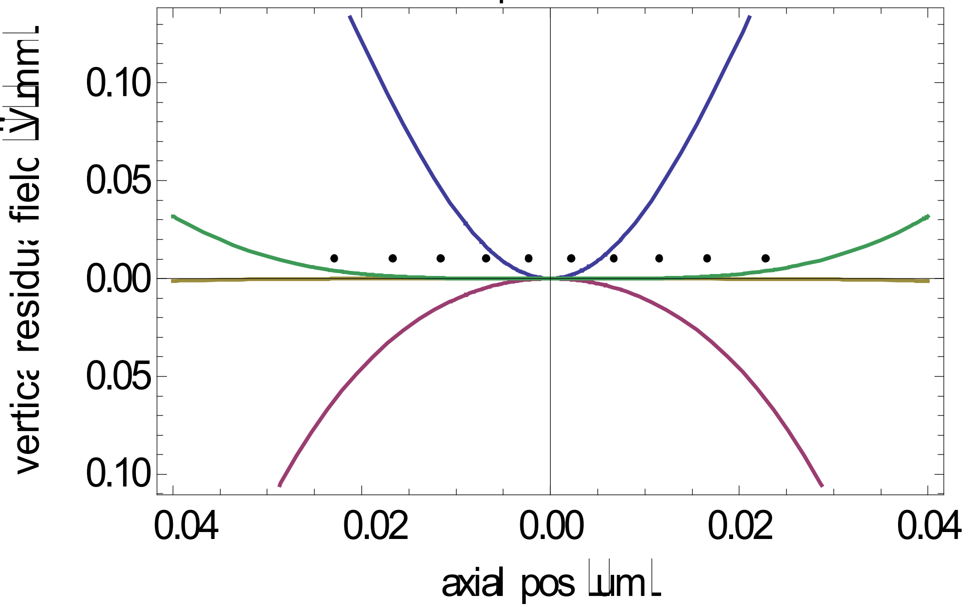
Potential @ Quadrupole Point



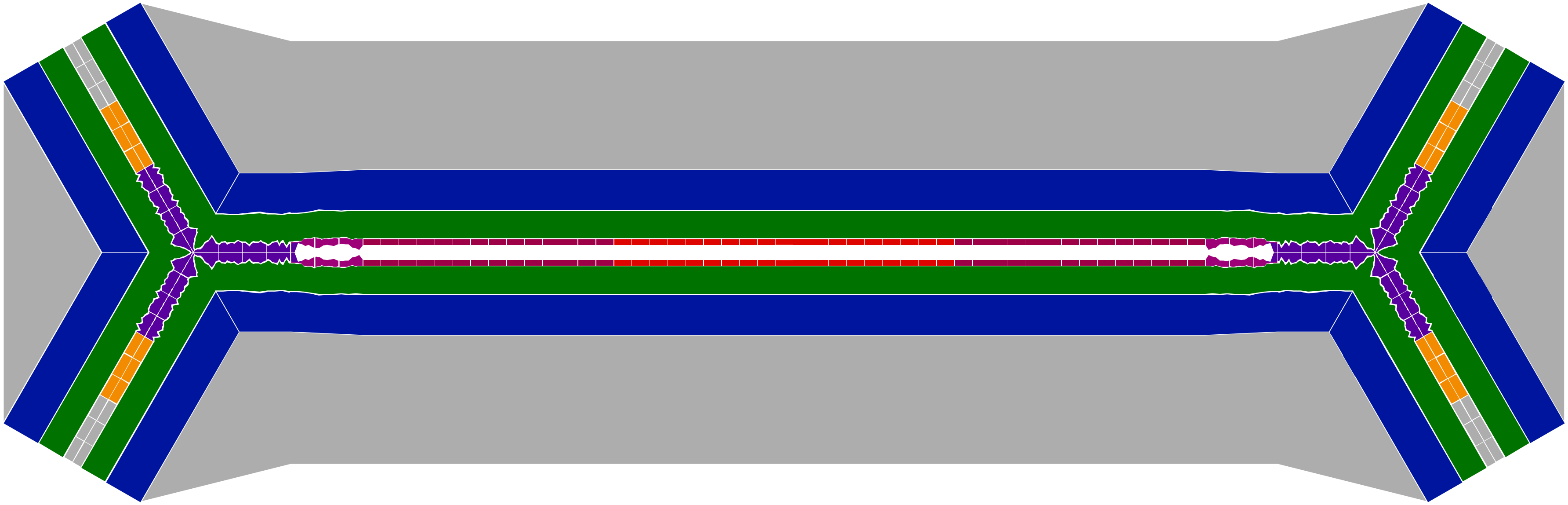
Compensation for long chain of ions

- Compensation for vertical electrical fields on rf node
- Compensation in one point is trivial using outer control electrodes
- Segmented outer electrodes are NOT a solution
- Compensation for ion chains is possible by adequate selection of segment voltages
- Potentials for splitting two ions can be compensated (symmetry)





Conclusion



- Trap optimized for Quantum Information Processing
- Excellent optical access (both in plane and perpendicular)
- High radial trap frequencies (short characteristic length)
- Full control over principal axes
- Excellent axial control voltage efficacy

Will be available to the MUSIQC performer team in September 2014

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Acknowledgements

Funding

UNM

CQuIC

Collaborators

MUSIQC

UNIVERSITY OF MARYLAND

GEORGIA TECH

UBC

MagiQ

Georgia Tech Research Institute
Problem. Solved.

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