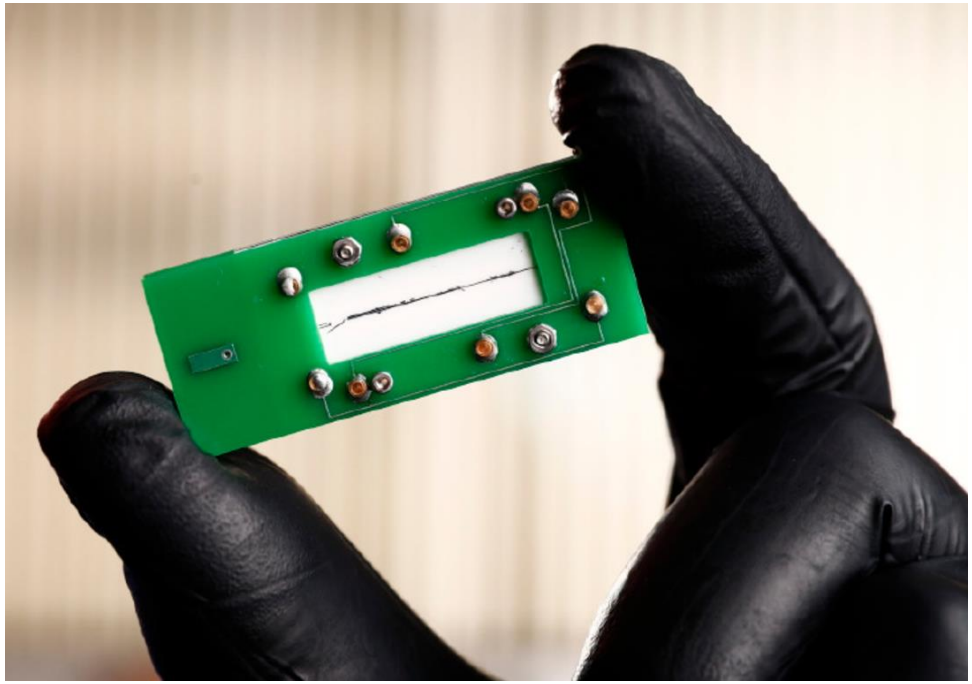
Surprises in Small Packages:
What We Have Learned Making Miniaturized Linear Ion Traps



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Towards the Portable Mass Spectrometer

High cost
High performance
Cannot be moved
Fragile
No hurry

Low cost
Good performance
Goes anywhere
Rugged
Fast Results

(Not an actual device… yet)

How do smaller ion traps lead to portability?

Ratio of mean free path to trap dimensions
Operating pressure is higher for smaller traps – smaller pump

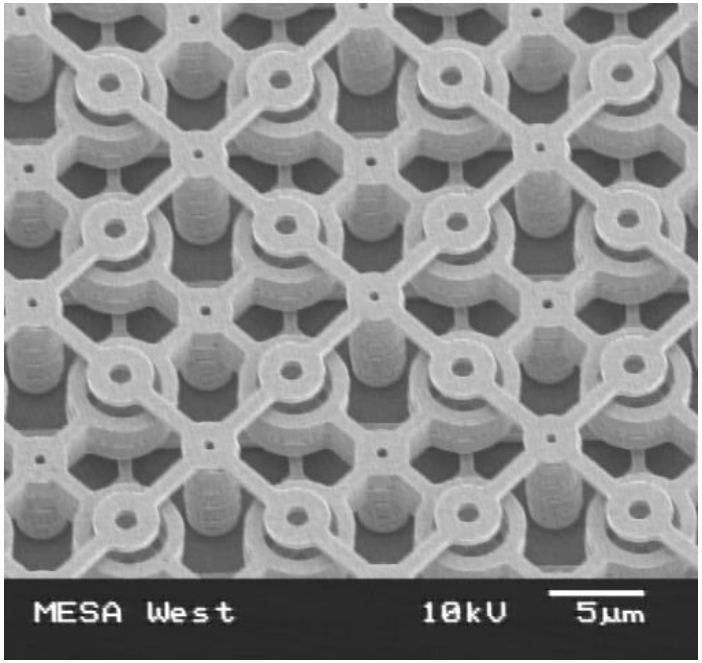
Electric field scales as voltage/distance
Lower voltages and electrical power

Potential issues:

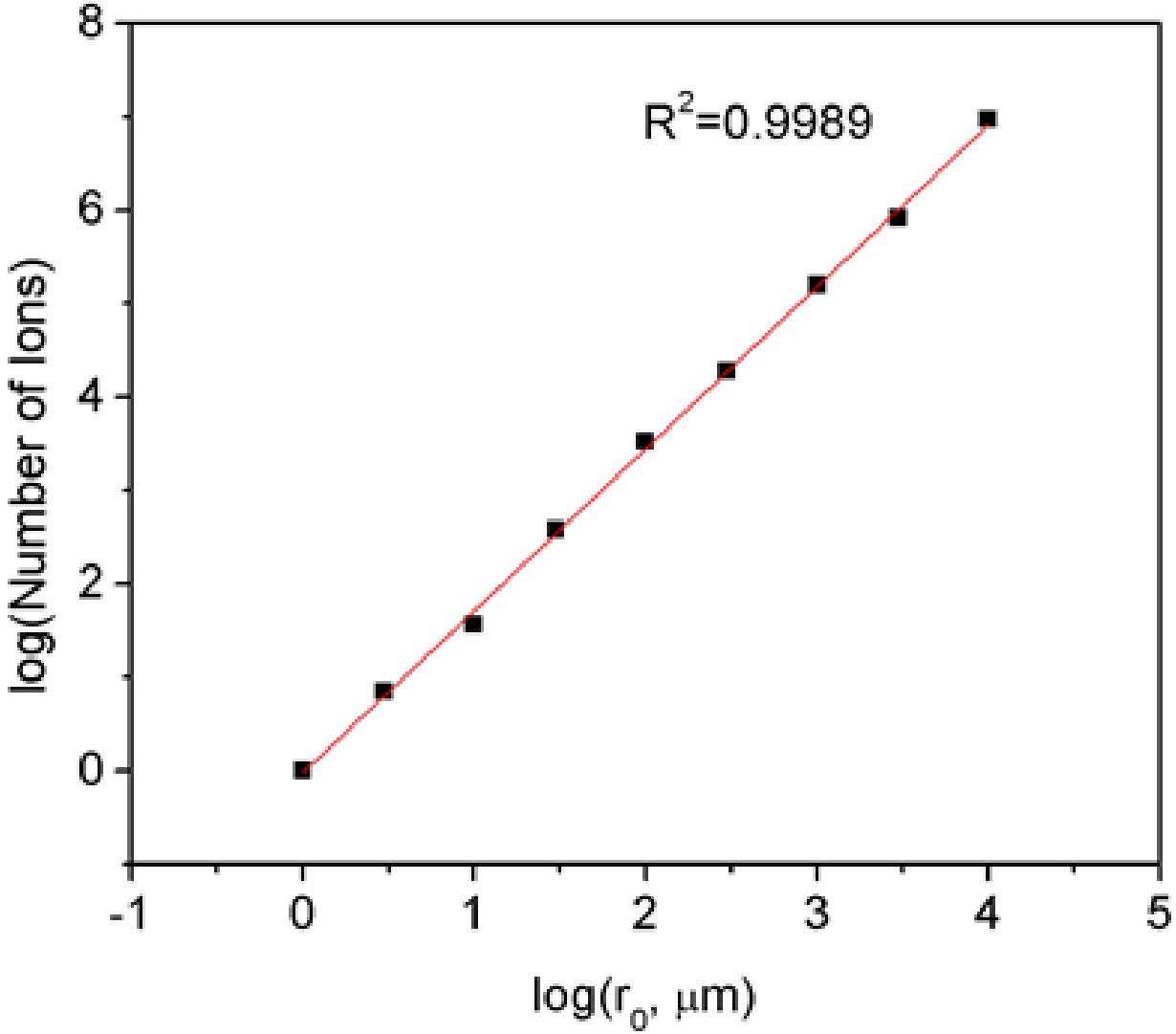
fewer ions trapped

Harder to fabricate smaller traps

Relative alignment tolerances must be maintained



Maximum number of analyzable* ions as a function of CIT trap size, r_0, from 1 μm to 1 cm (SIMION 8.0)



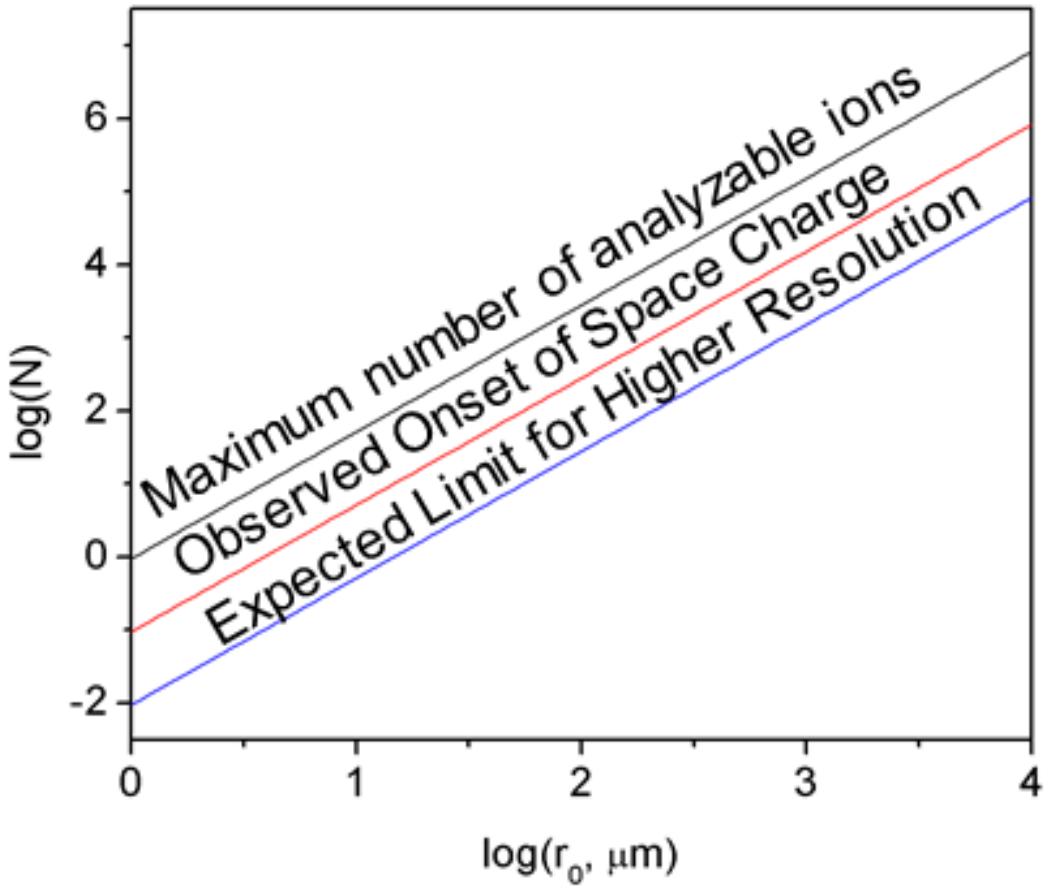
*Max # of ions before resolving power falls by factor of 2 (R~50)

RF voltage scales as $r_0^{0.5}$

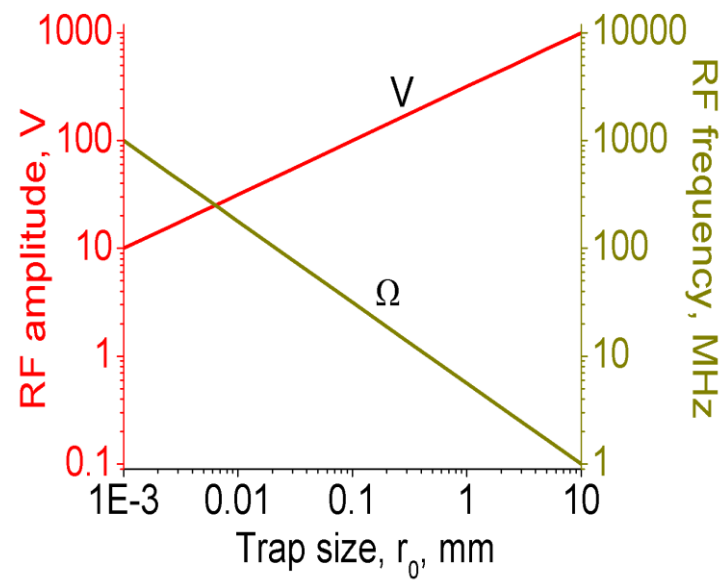
Results show functional form: $N = Ar_0^k$, where $A = 1.3$, $k = 1.70$

For voltage scaling of $r_0^{0.33}$ and $r_0^{0.67}$
$k = 1.55$ and 1.75 respectively

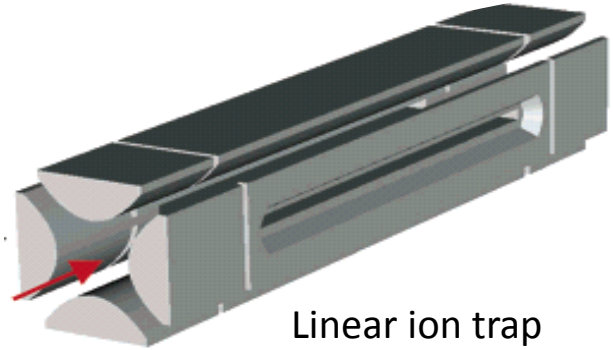
A comparison of maximum number of analyzable ions, observed onset of space charge in simulations, and expected limit for higher resolution (100x lower than maximum) in different trap sizes.



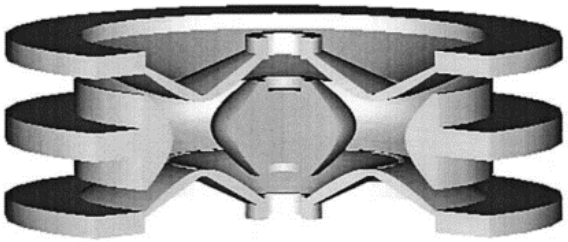
RF voltage scales as $r_0^{0.5}$



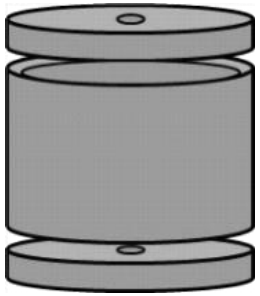
Quadrupole ion trap



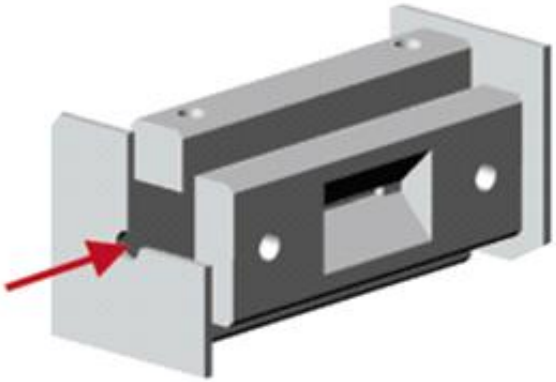
Linear ion trap



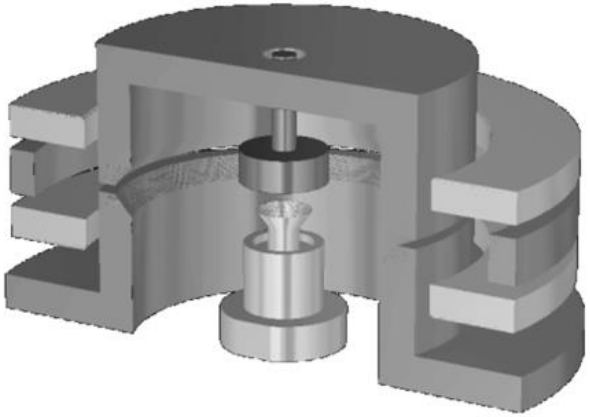
Toroidal ion trap



Cylindrical ion trap



Rectilinear ion trap

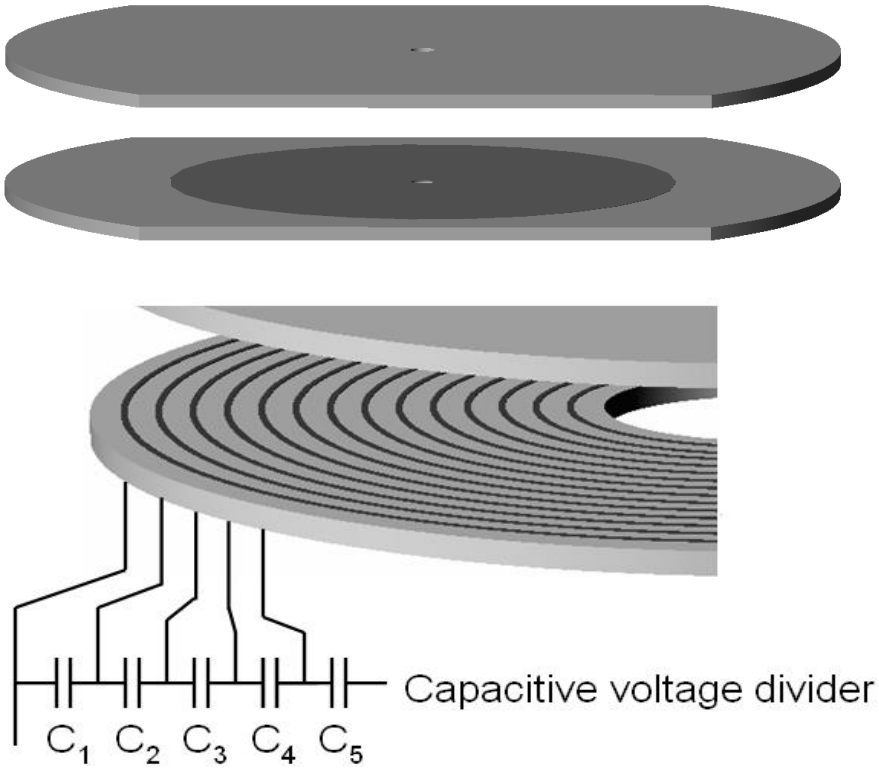


Toroidal ion trap with cylindrical electrodes

Traps with extended trapping dimension have larger capacities 10-1000 times)

Arrays of traps also recover trapping capacity

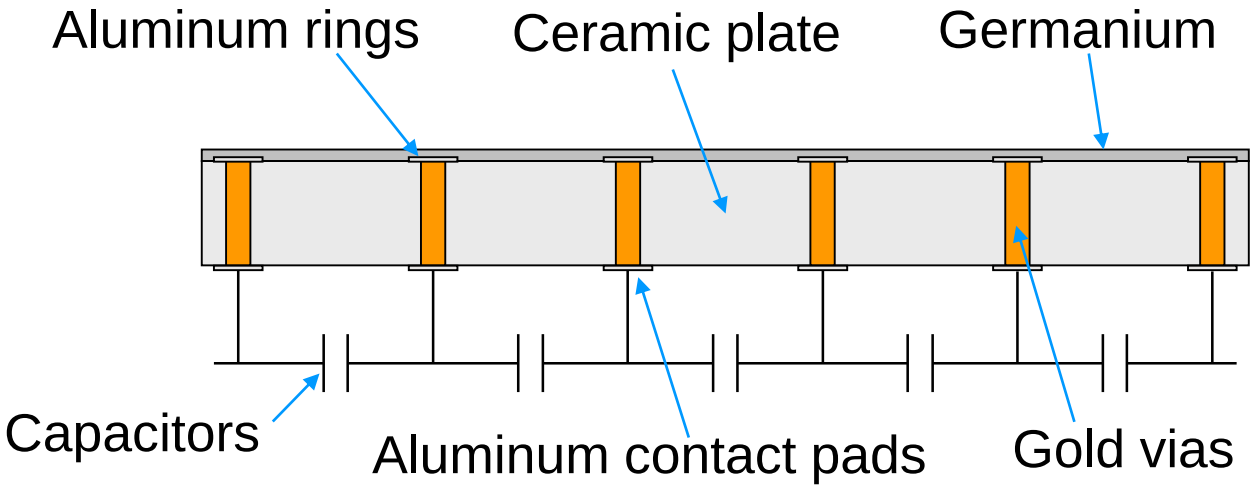
Two-Plate Ion Traps



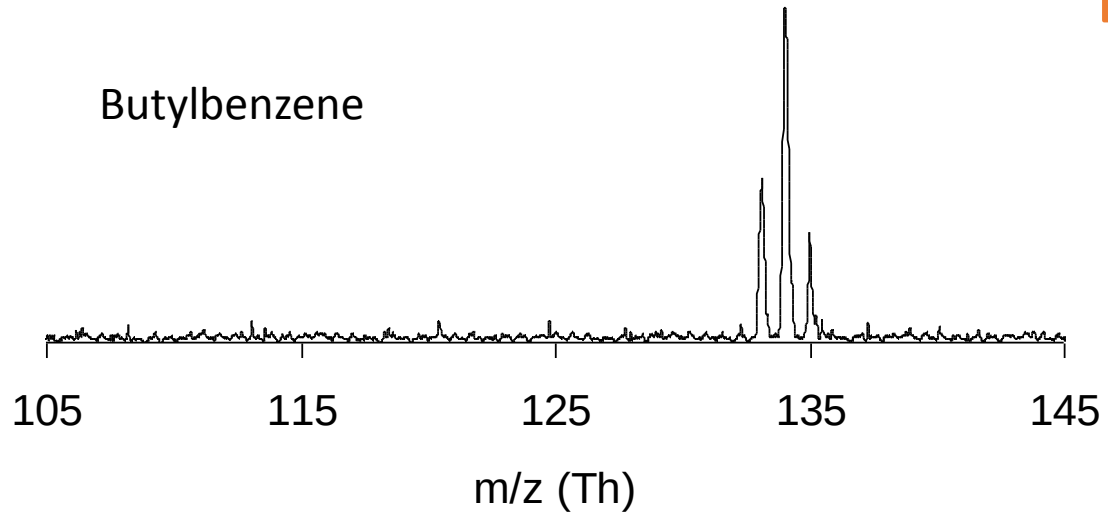
Each plate contains series of lithographically-defined metal “wires”, overlaid with resistive germanium

Different RF amplitudes applied to each “wire” produce trapping fields

50-100 nm germanium layer prevents charge build-up and provides continuous surface potential



Early Results from Planar Quadrupole Ion Trap

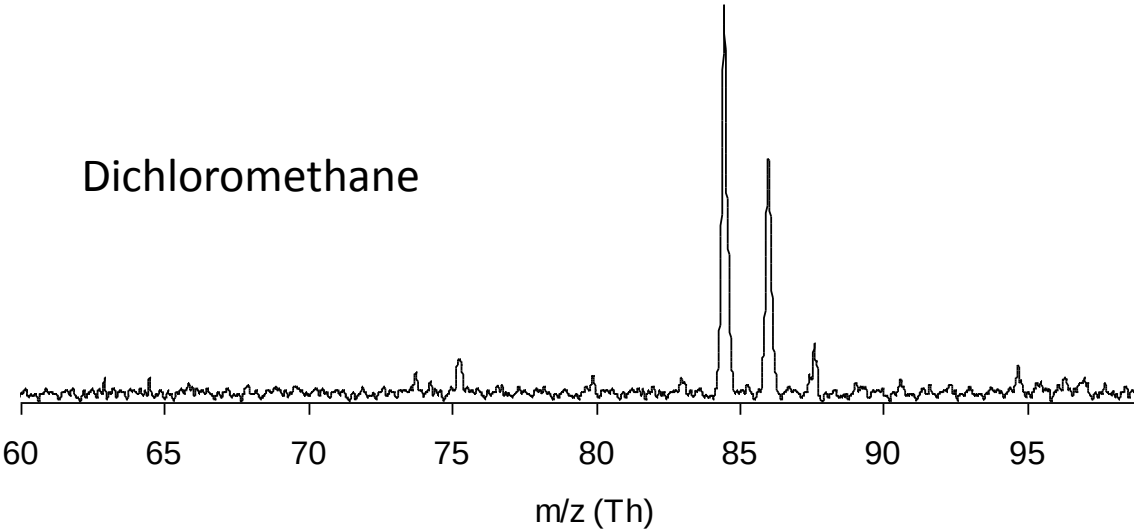


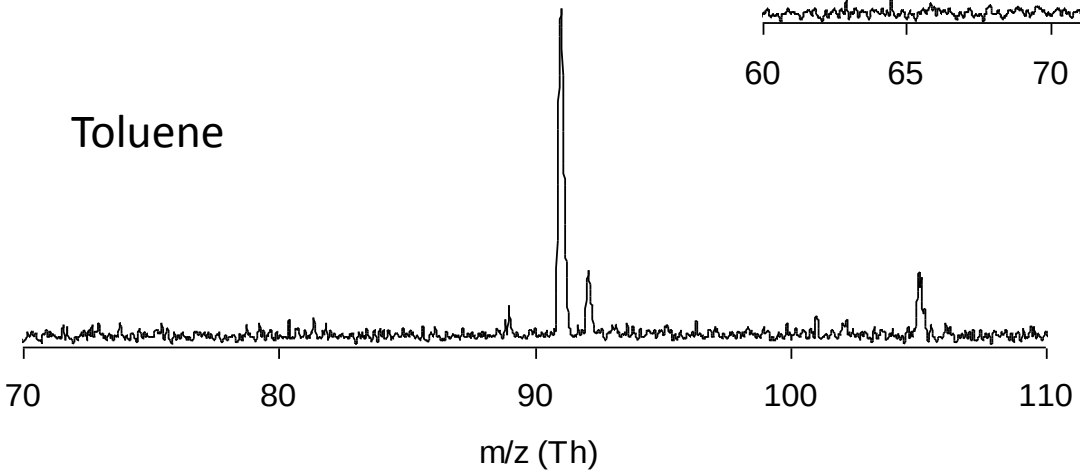
z_0 = 2 mm

RF 100-700 $V_{0\text{-}p}$

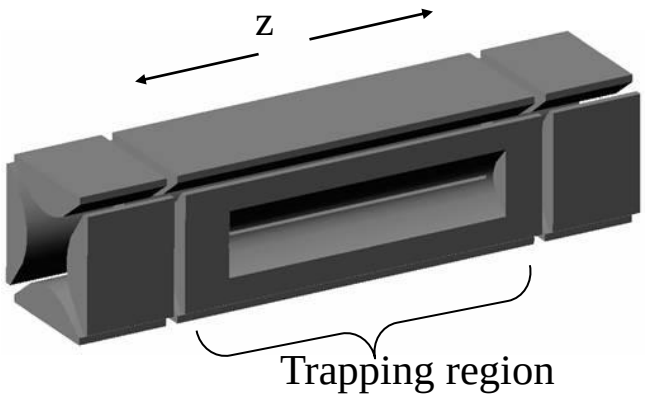
Drive frequency 1.2 MHz

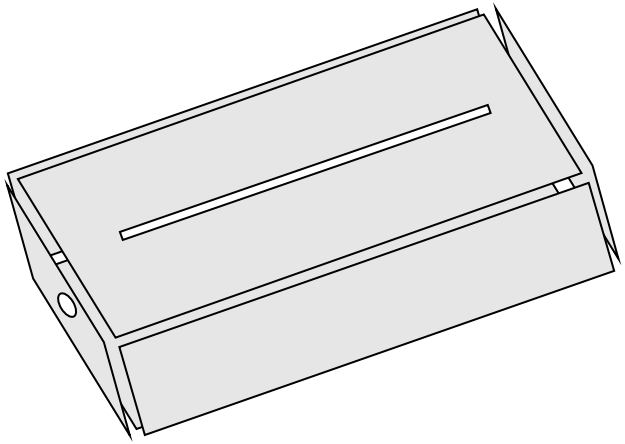
Dipole resonant ejection at β=0.46

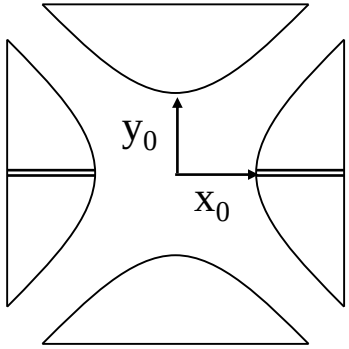




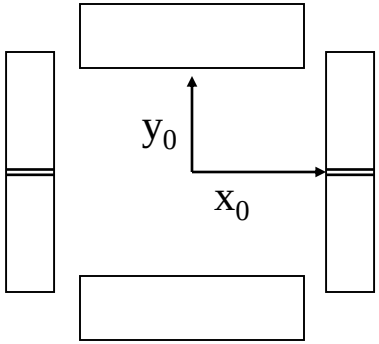
Linear Ion Traps







Linear Ion Trap

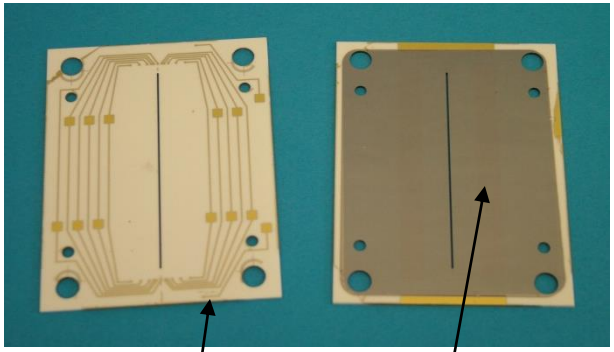


Rectilinear Ion Trap

Extended storage volume = less space charge, more ions analyzed, better sensitivity, better dynamic range

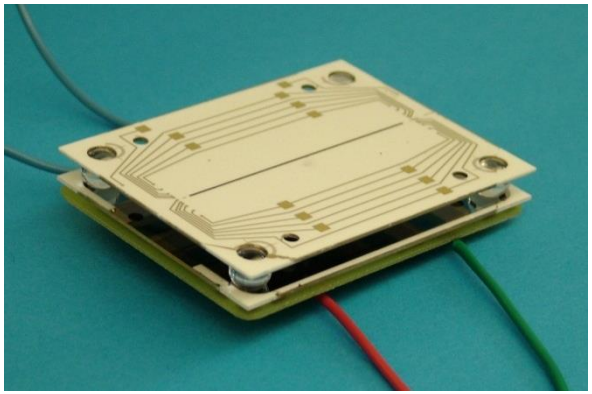
Improved efficiency of trapping externally-generated ions

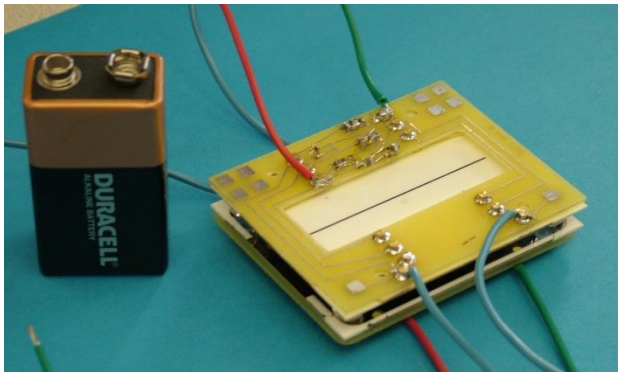
Two-plate linear ion trap

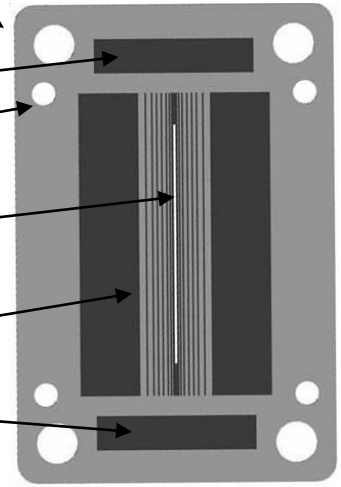


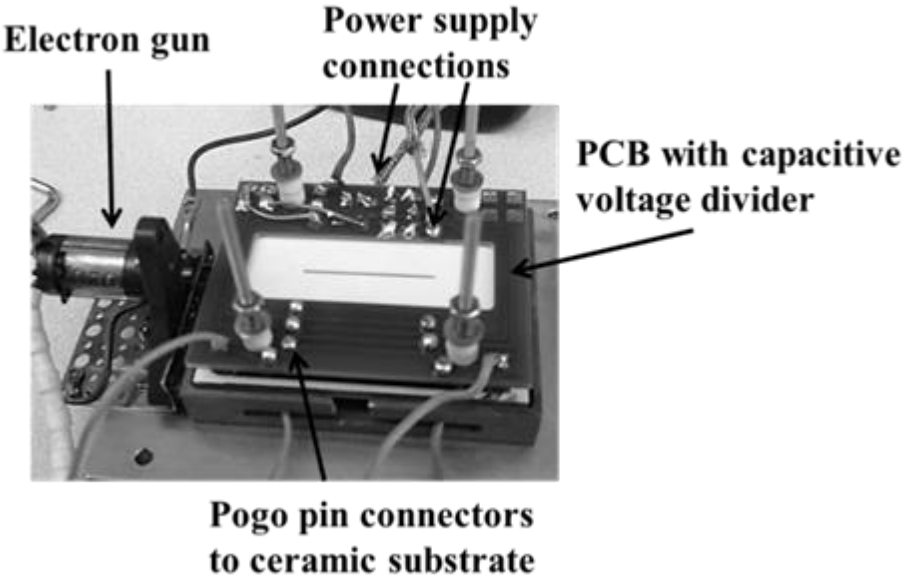
Back side

Trapping side









Original design: r_0 = 2.2 mm

Planar LIT results
y_0 = 2.19 mm

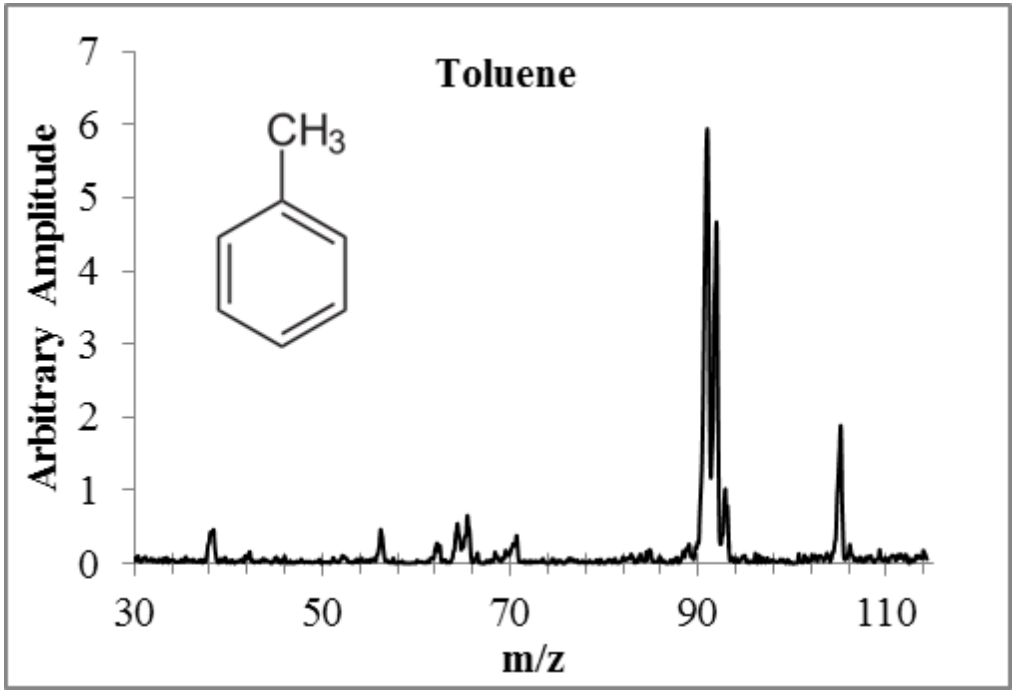
RF frequency: 2.2 MHz

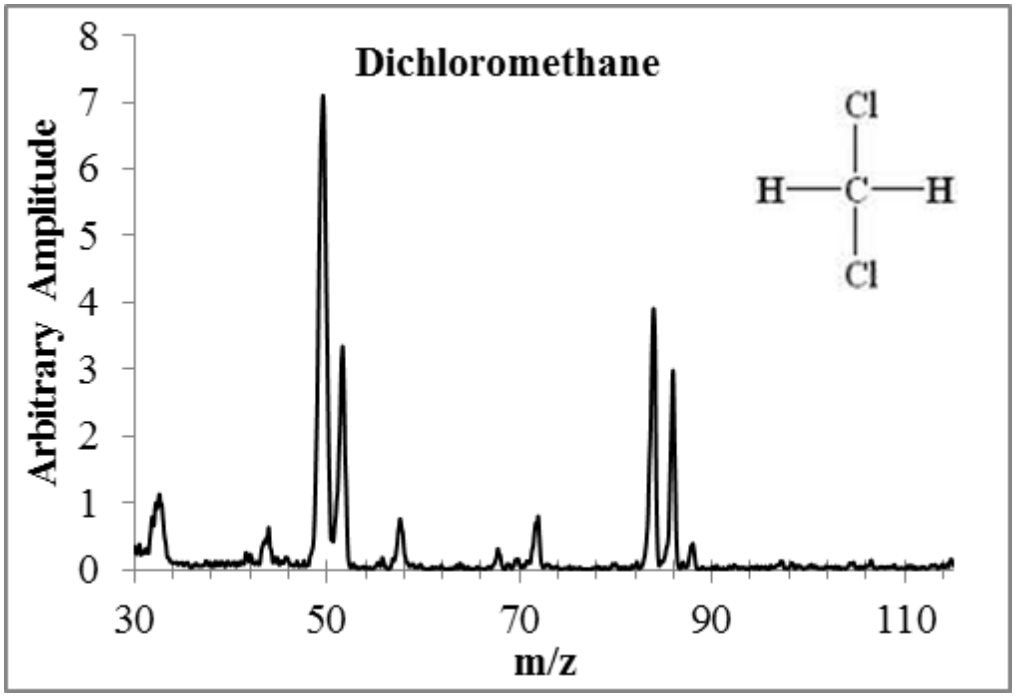
RF amplitude (trapping) 300 V

Resonant AC 560 kHz

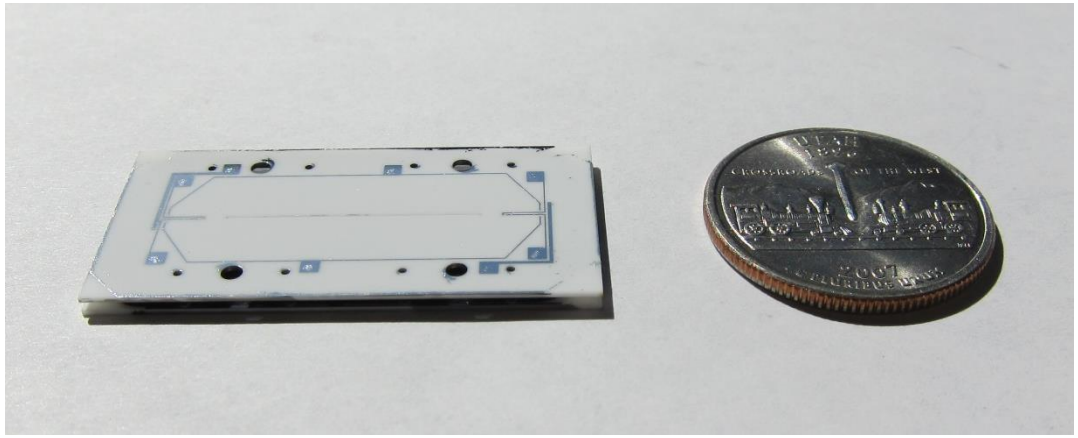
AC amplitude: 1.1 V

Also obtained spectra with y_0 = 0.95 mm





LIT with smaller plates



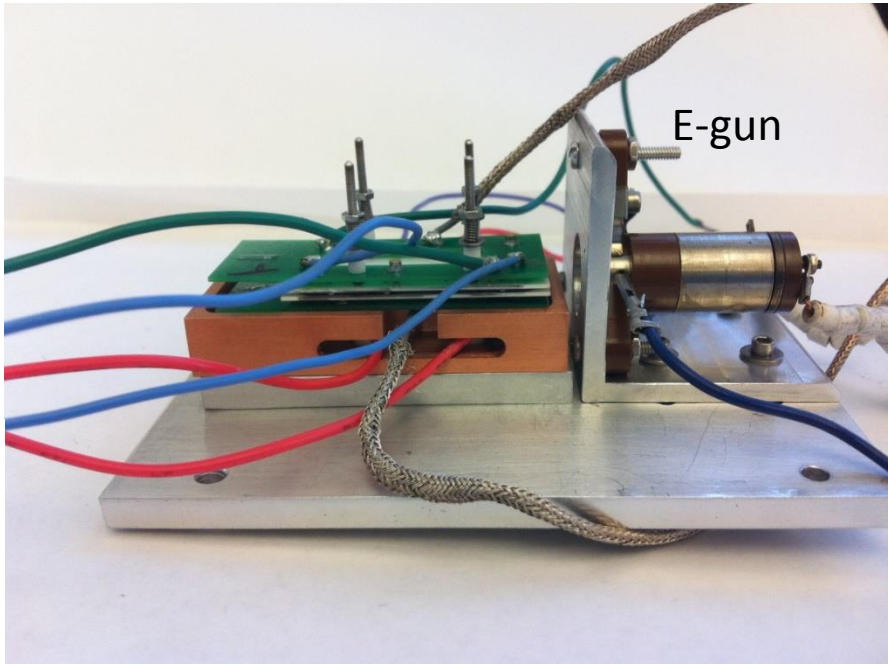
y_0 = 360 microns

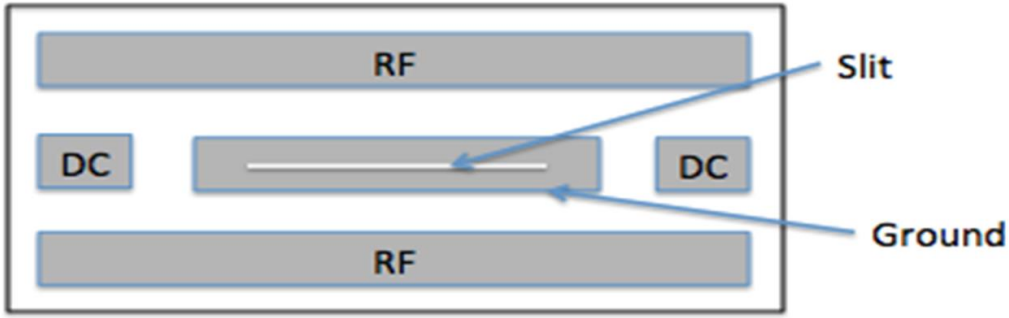
Plate spacing 720 microns

Plates 2 x 4 cm alumina

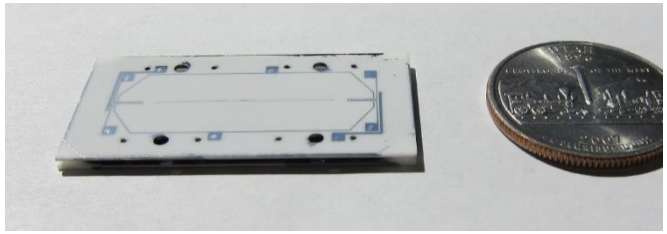
No capacitive voltage divider

Plate alignment is critical





No signal with small PLIT (y_0 = 360 micron)



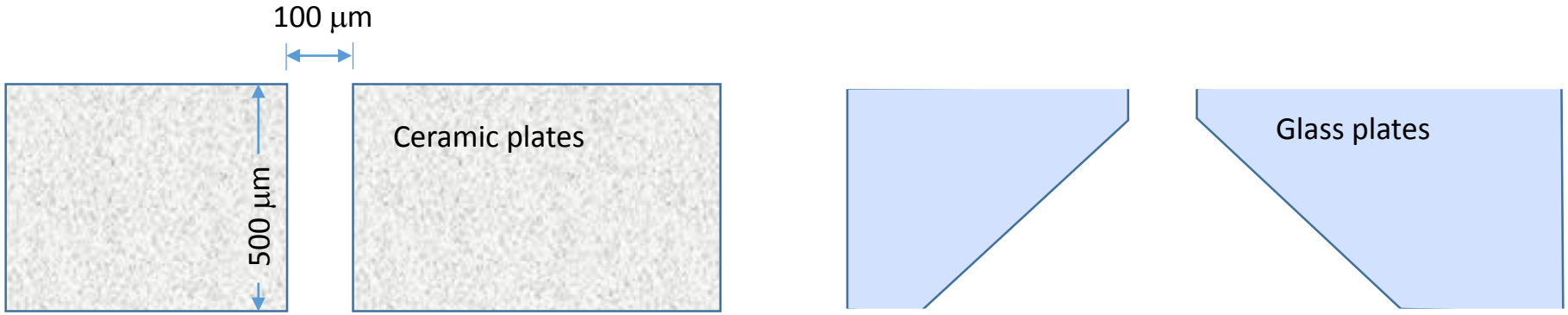
Ions are not getting through the ejection slit

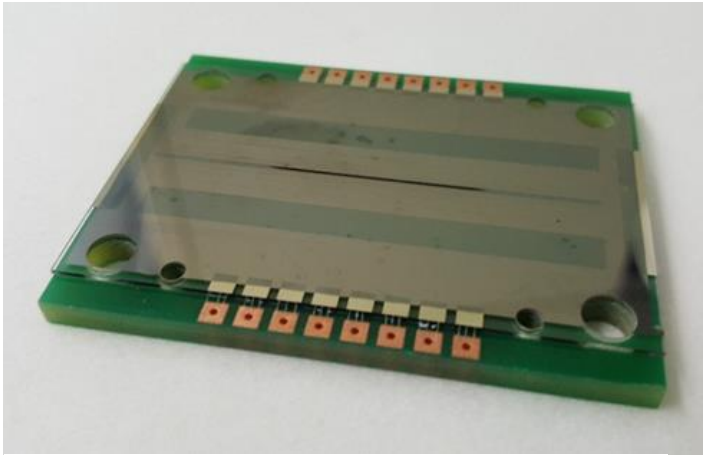
Ionization signal is present and ions are being trapped
Aspect ratio of slit is very high
Ions are emerging from trap at an angle, hit slit wall
Charging of ceramic surface repels other ions
need to maintain ceramic thickness for strength

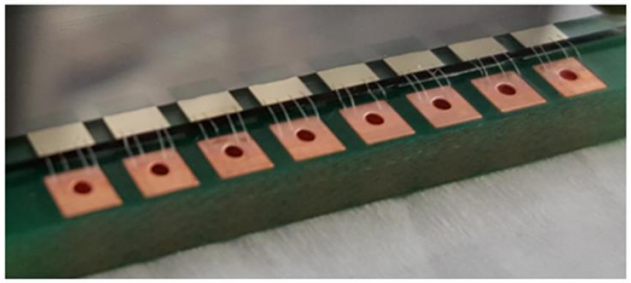
Solution: taper the slit so it opens to the outside
Easier to do with glass substrate

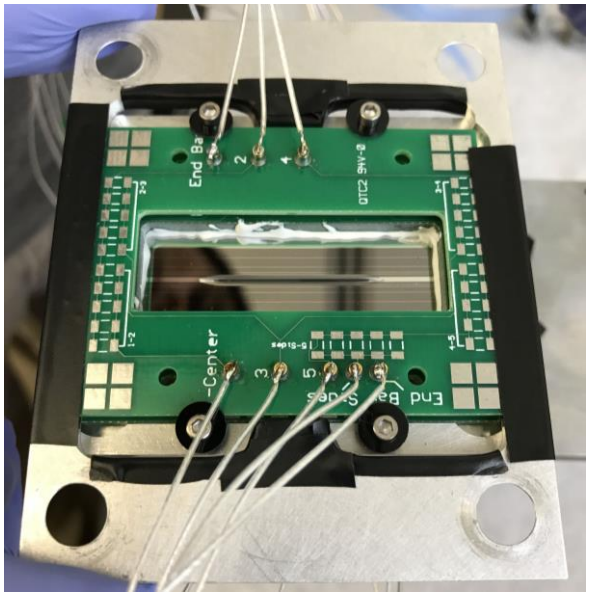
Second problem: poor connection with vias, difficult to make vias smaller

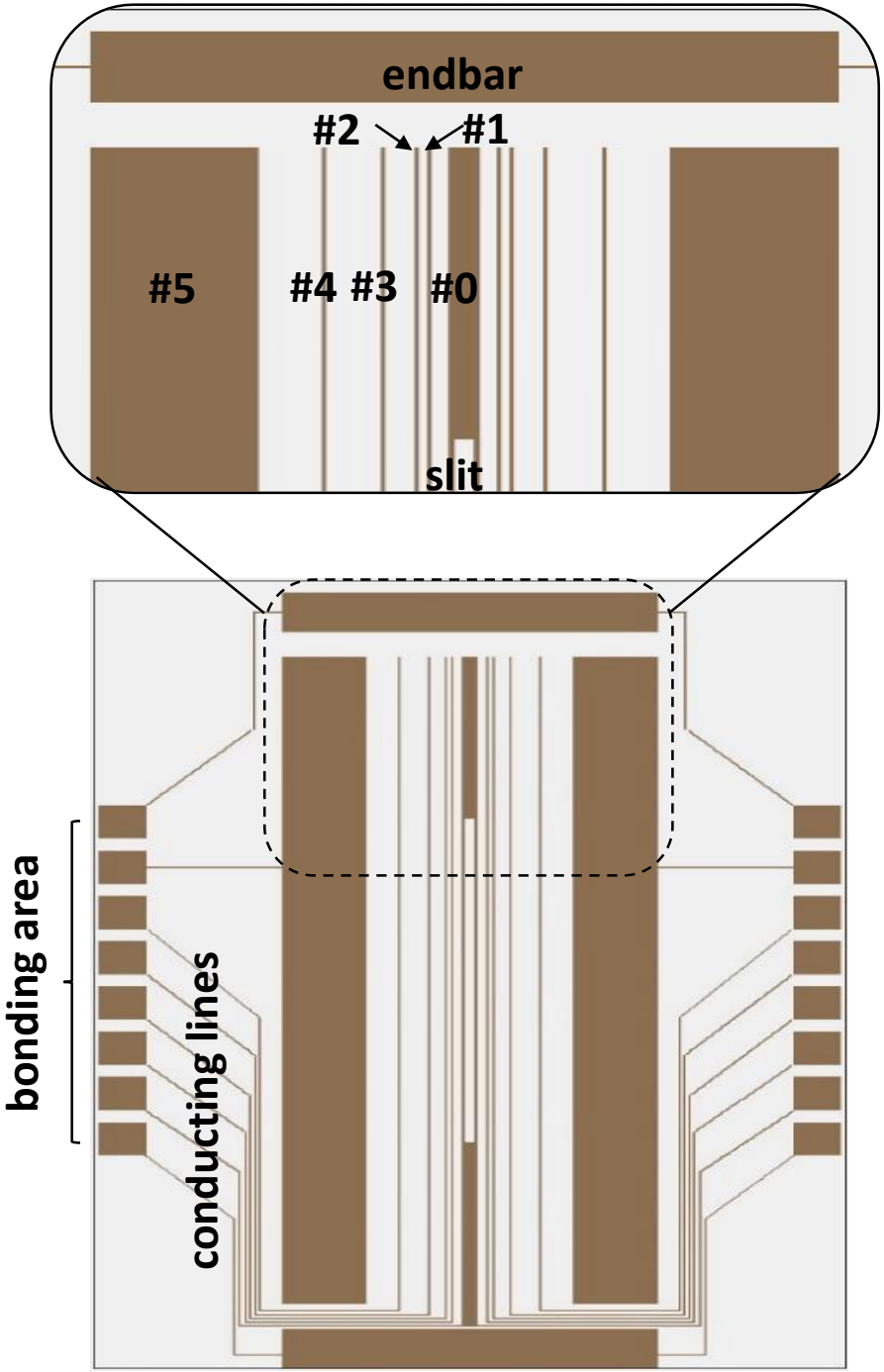
Solution: single-side patterning; wirebond all connections to PCB

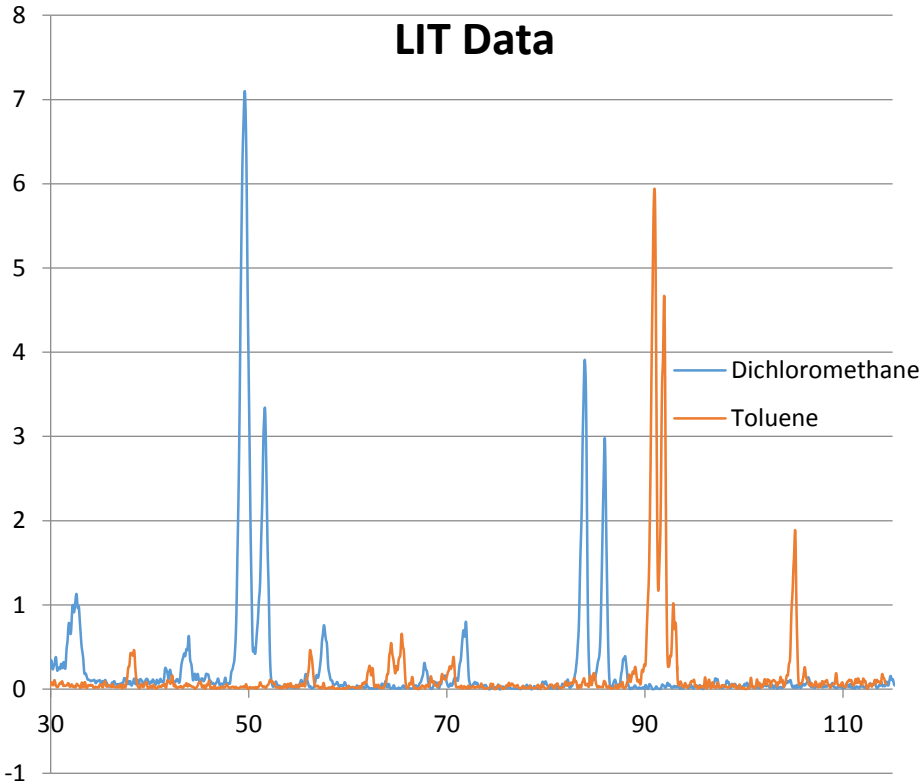







End Ba
2
4
UTCL
-Center
3
5
End Ba
S-Gues


endbar
#2
#1
#5
#4 #3
#0
slit
bonding area
conducting lines


LIT Data
8
7
6
5
4
3
2
1
0
-1
30
50
70
90
110
Dichloromethane
Toluene

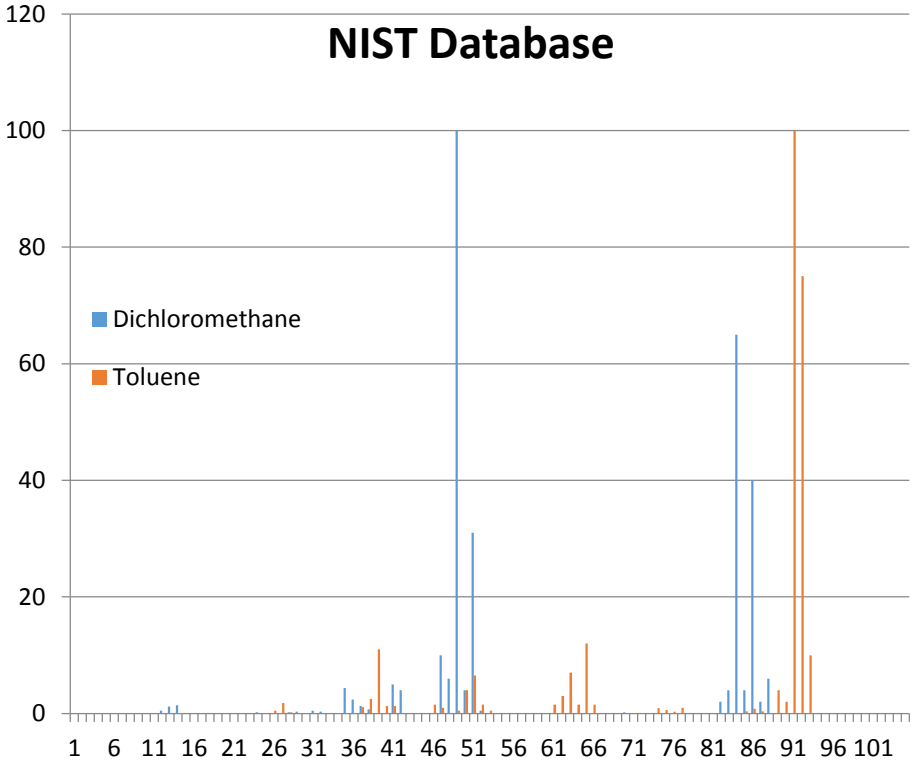
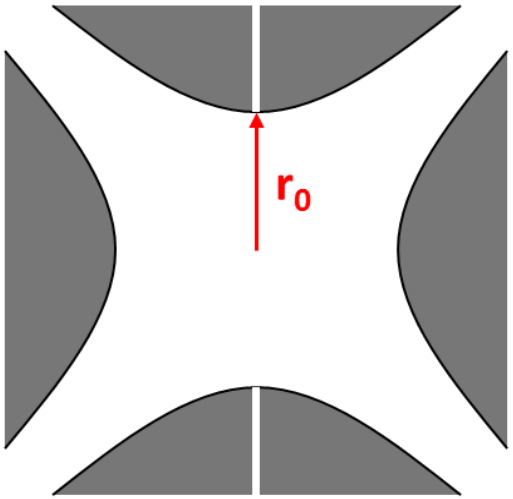
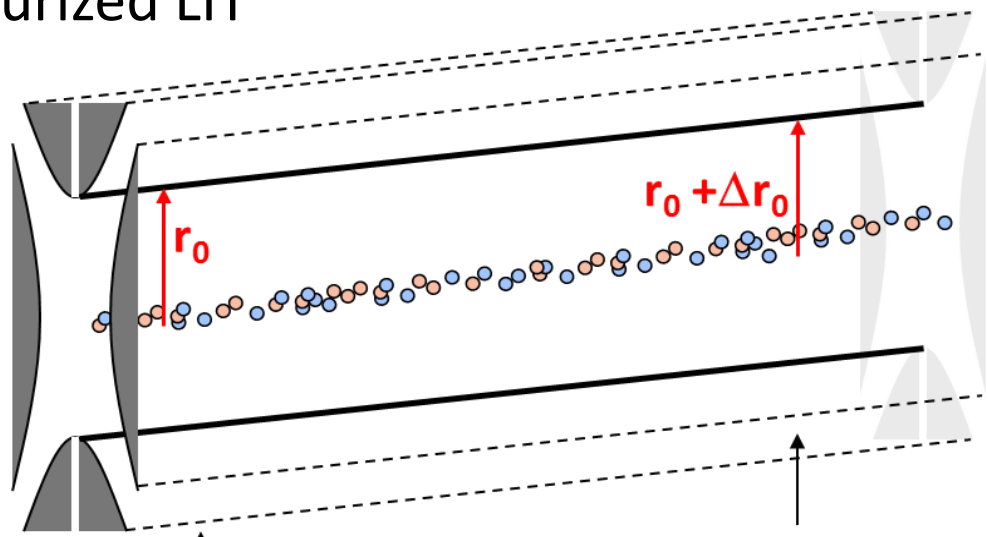

NIST Database
120
100
80
60
40
20
0
1 6 11 16 21 26 31 36 41 46 51 56 61 66 71 76 81 86 91 96 101
Dichloromethane
Toluene

Plate alignment in a miniaturized LIT





Mass selected here, m

$$\frac{m}{z} = \frac{4V}{q_r r_0^2 \Omega^2}$$

Mass selected here, $m + \Delta m$

$$\frac{m+\Delta m}{z} = \frac{4V}{q_r \left(r_0 + \Delta r_0\right)^2 \Omega^2}$$

Required Δr_0 to maintain resolution of 1000 ($m/\Delta m$)

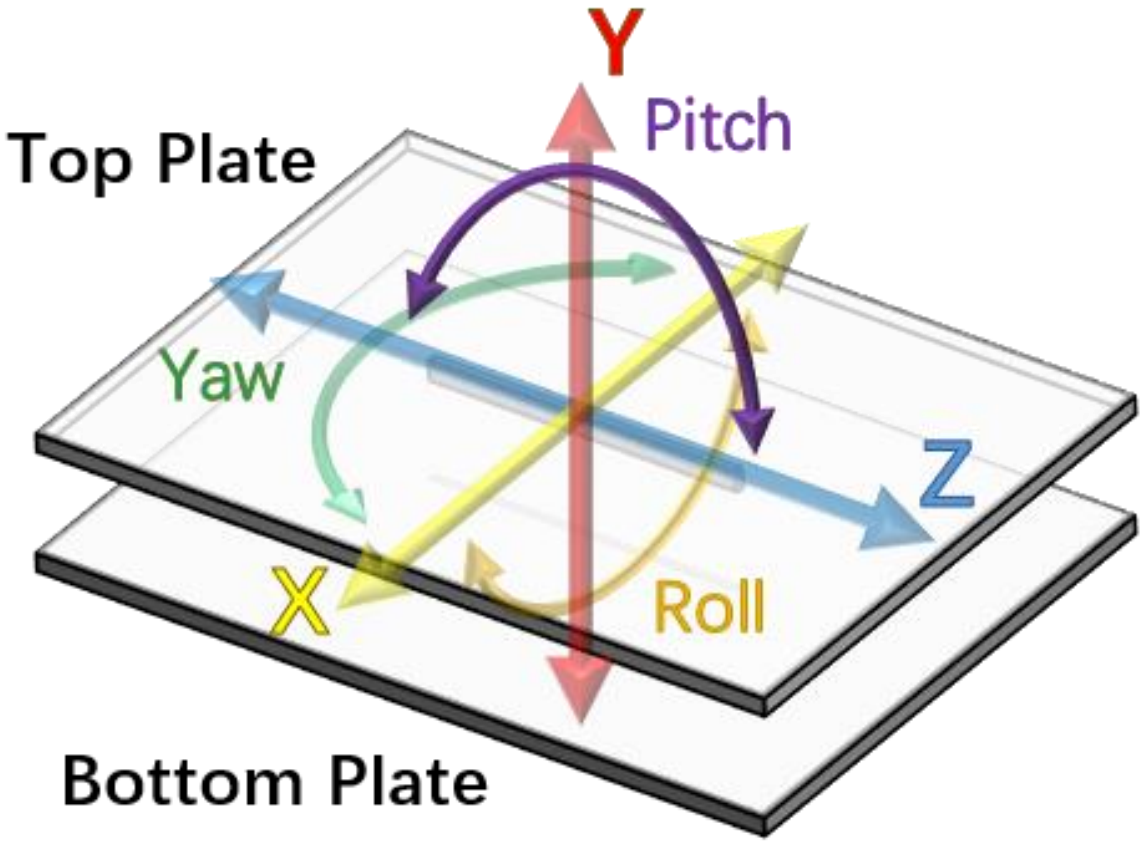
- r_0 = 1 cm, Δr = 5 microns
- r_0 = 1 mm, Δr = 500 nm
- r_0 = 0.1 mm, Δr = 50 nm

(Rough estimates)

Arrayed analyzers have an analogous problem

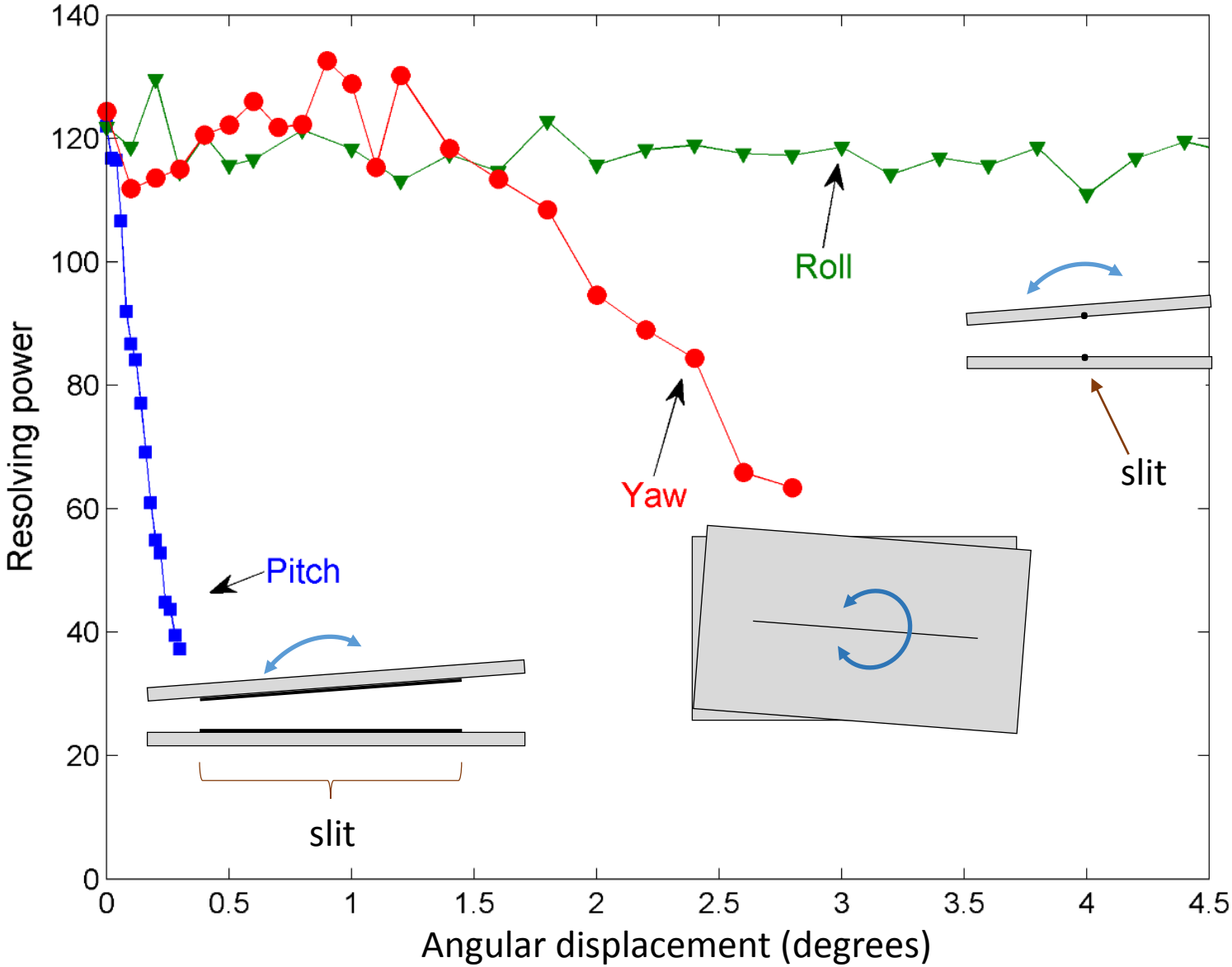
This is the heart of the resolution vs. sensitivity tradeoff in miniaturized ion traps

Six degrees of freedom of plate alignment (or misalignment)



These were evaluated both in simulations and experiments

Resolving power of fast scan as function of plate misalignment (boundary ejection, m/z 150, z_0 = 2 mm, 2 MHz RF, using SIMION)



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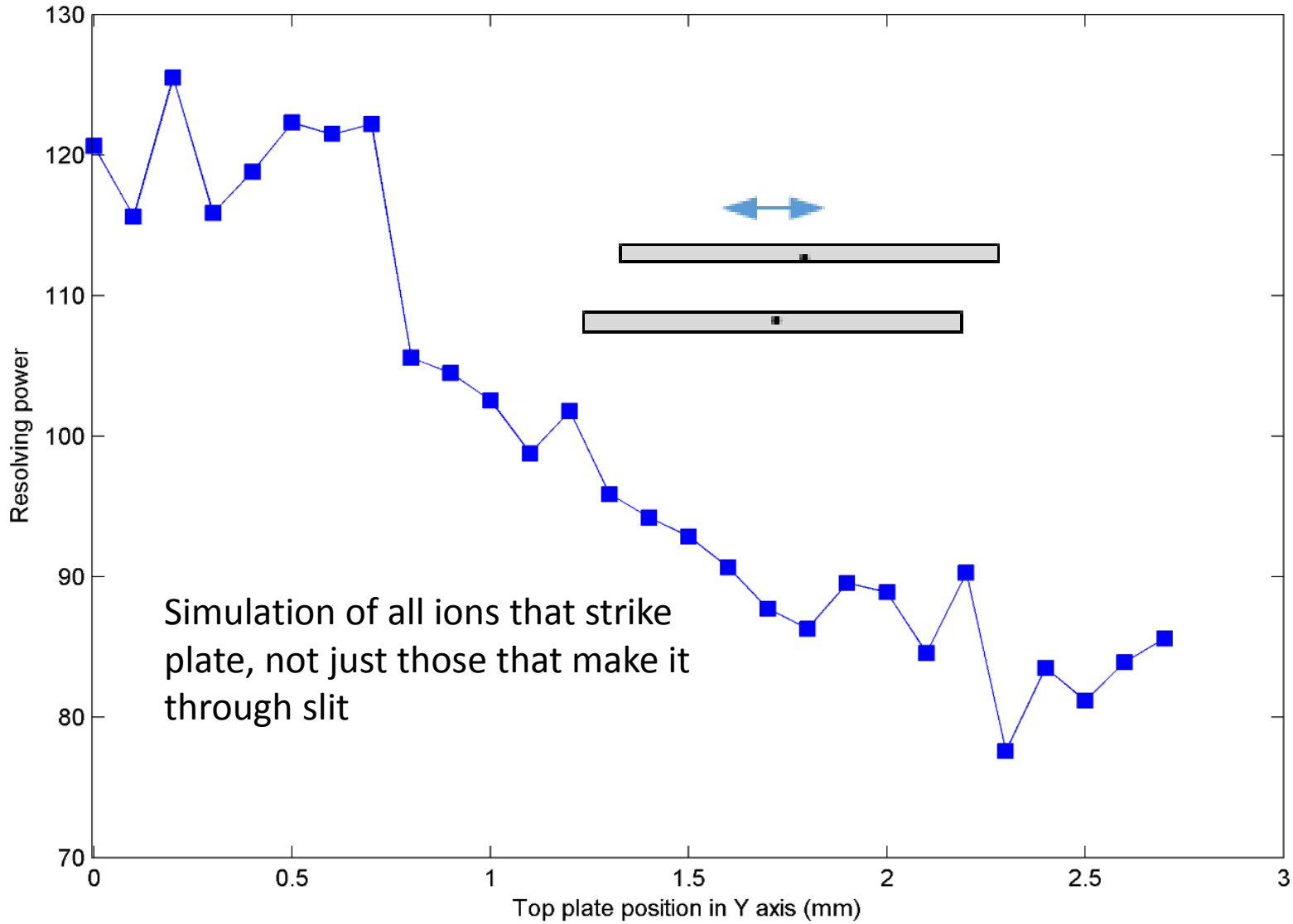

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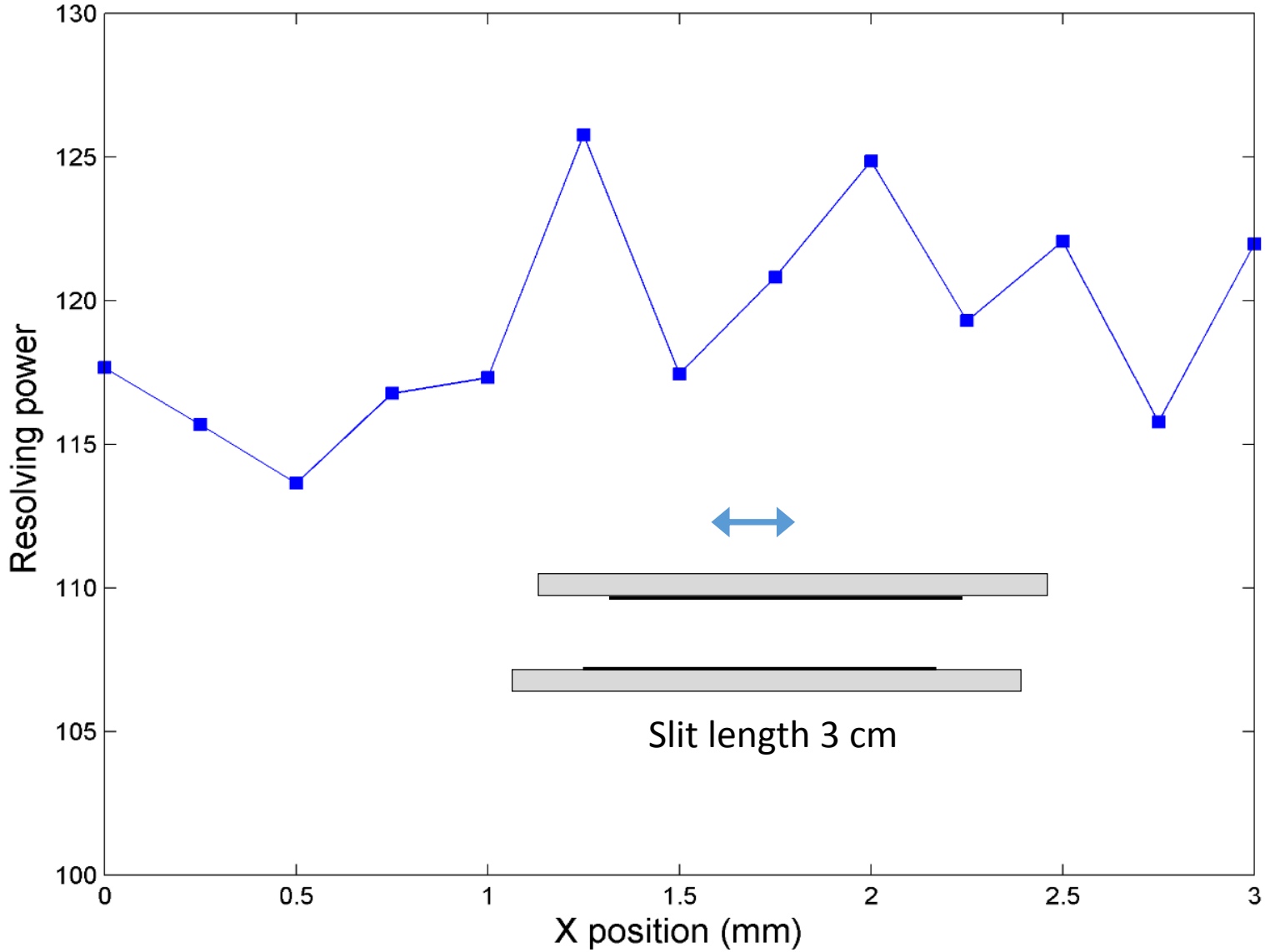

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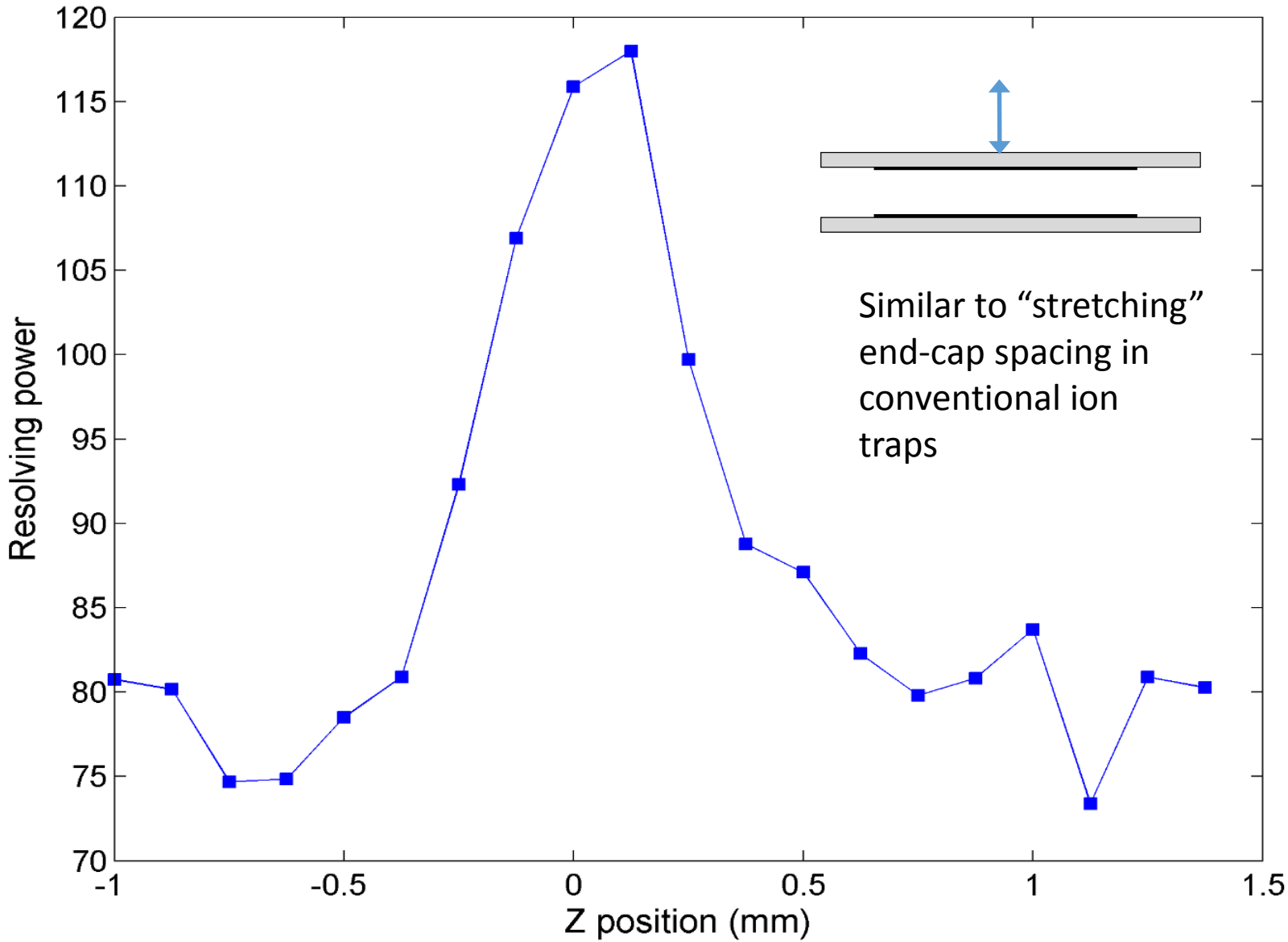
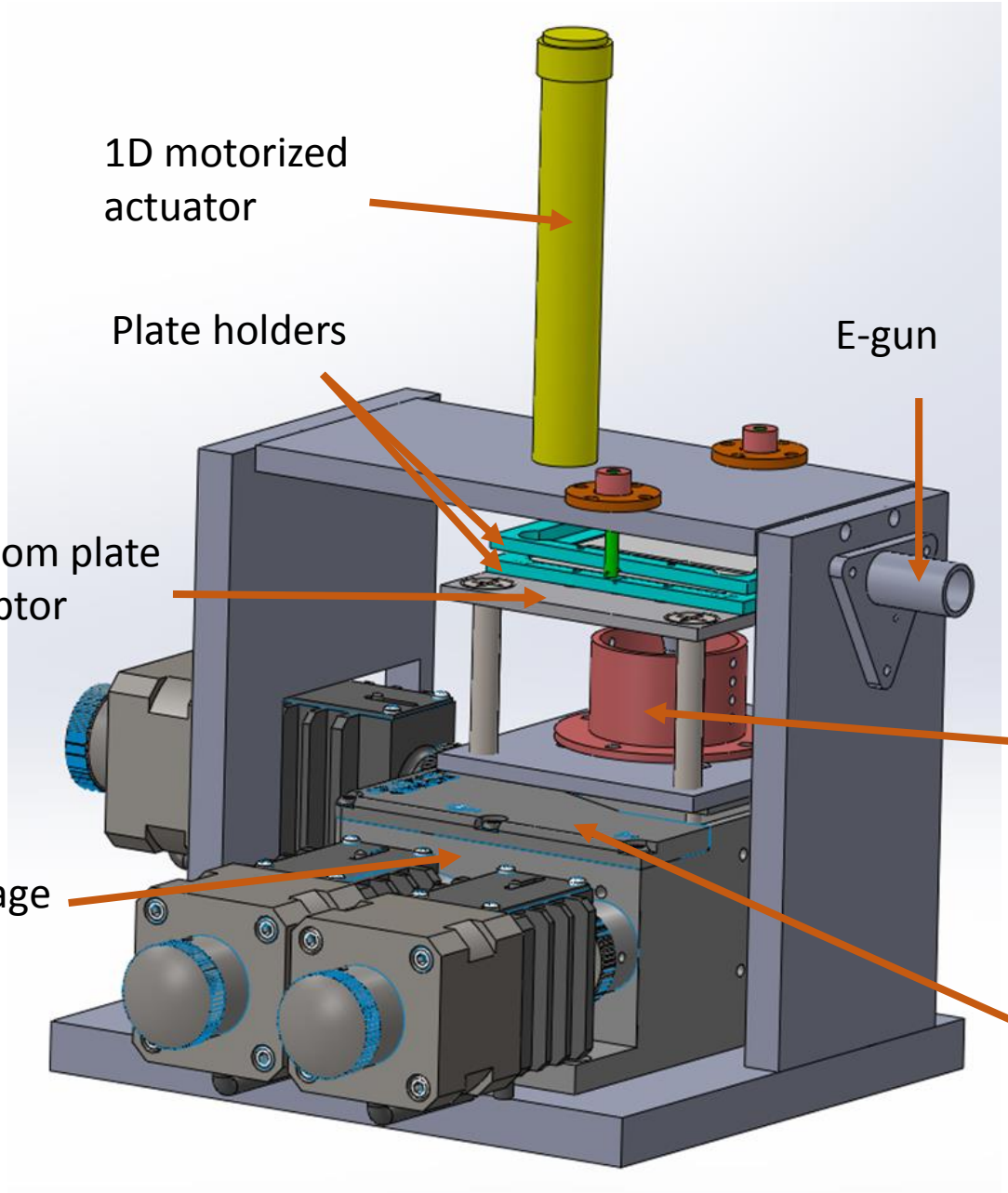
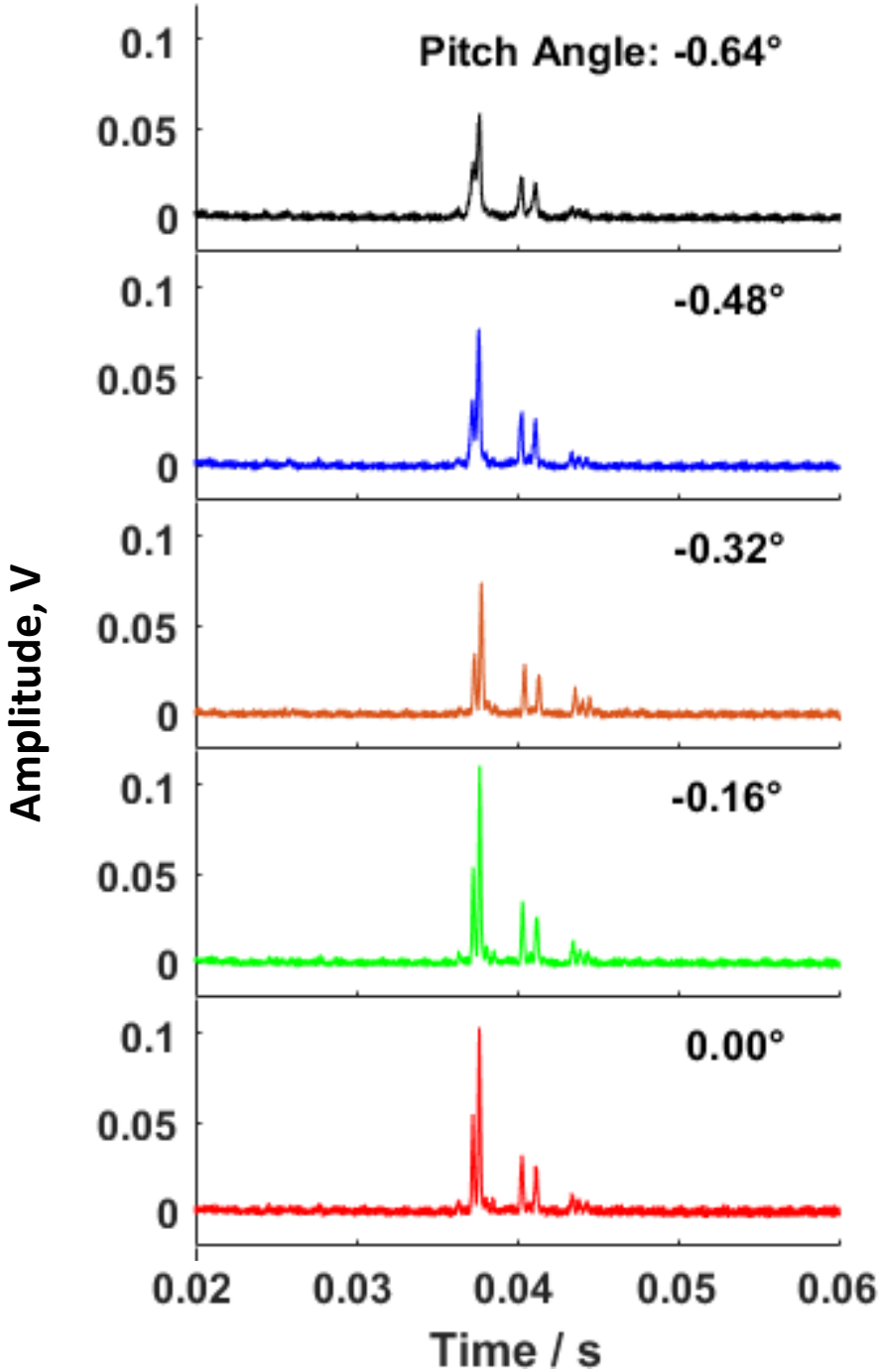
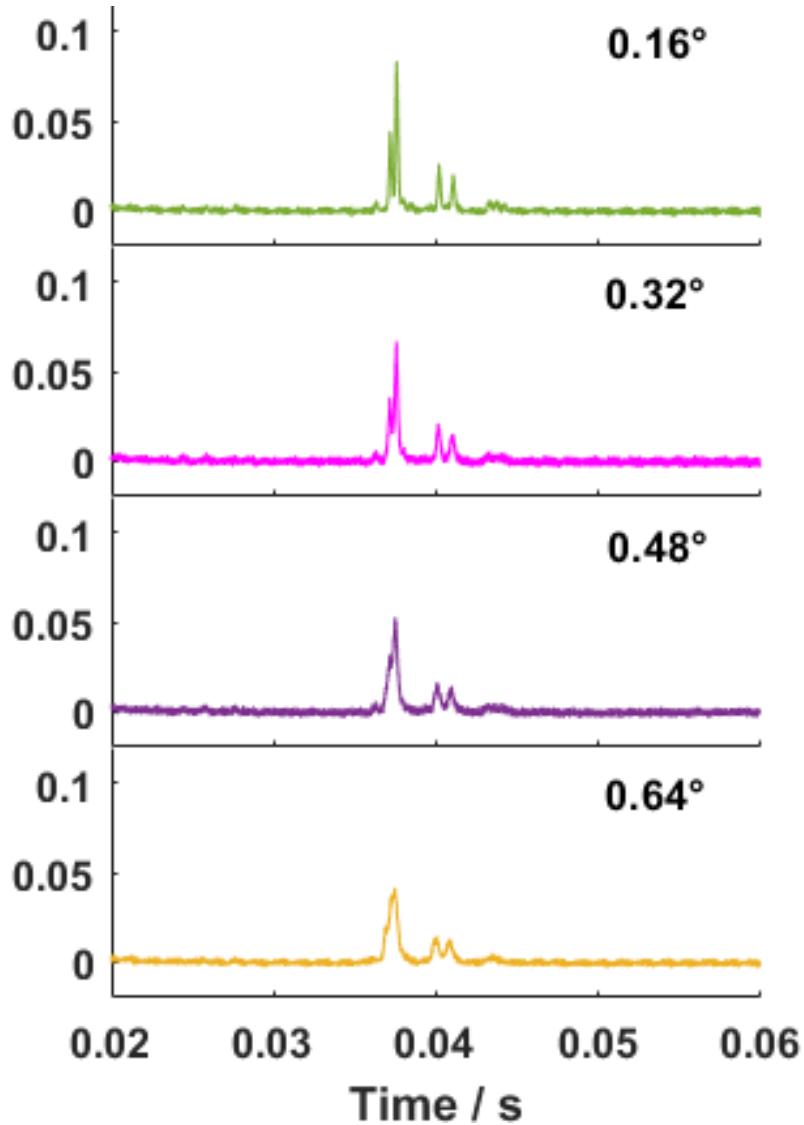


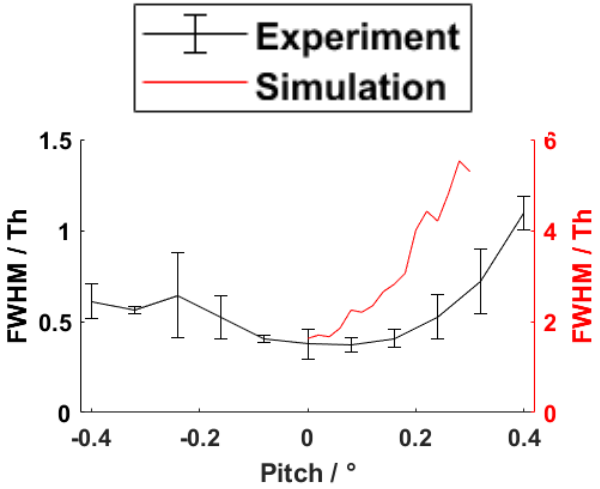
Set up to vary 5 of the 6 degrees of freedom during operation

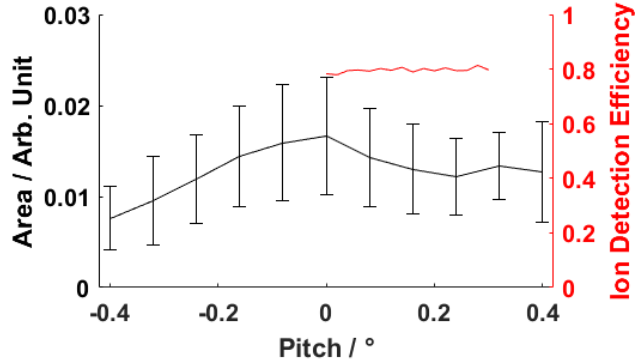


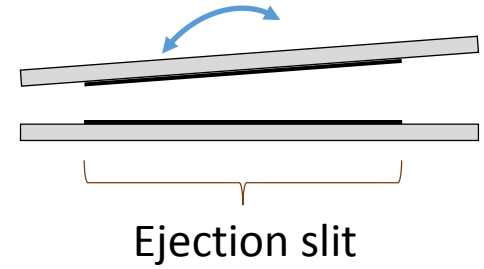
Mixture of toluene and D-8 toluene

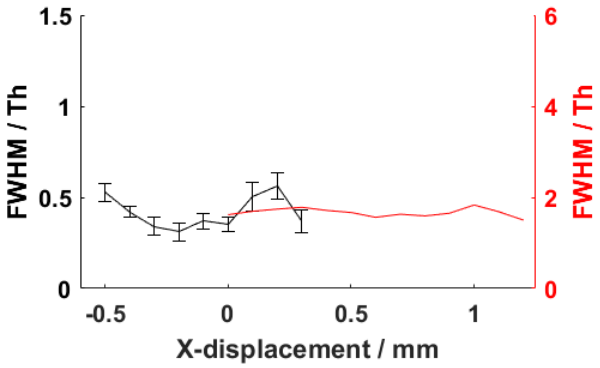


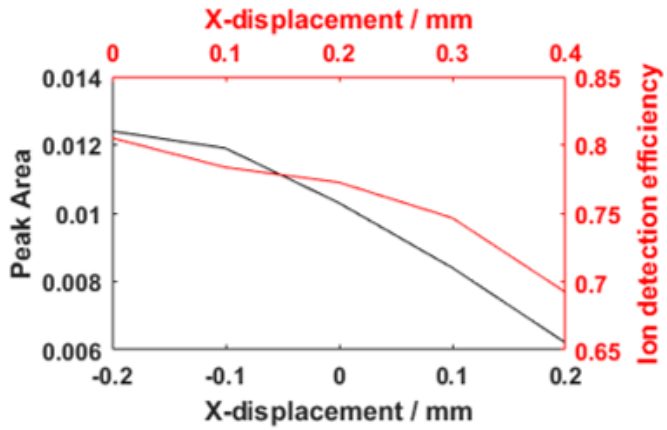


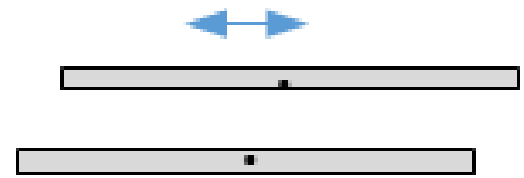

Experiment
Simulation
FWHM / Th
FWHM / Th
Pitch / °

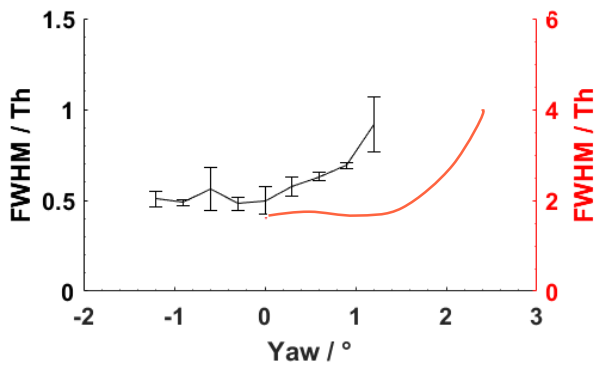

Area / Arb. Unit
Ion Detection Efficiency
Pitch / °

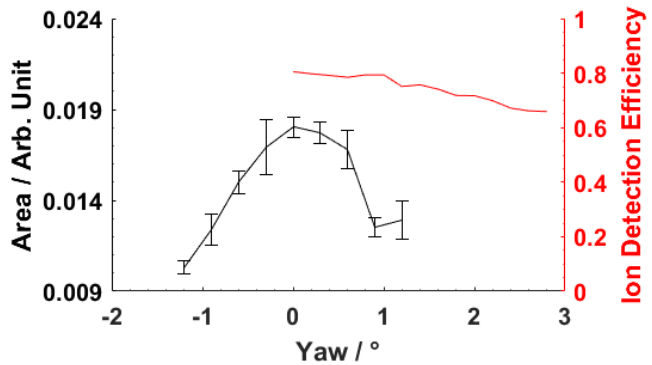

Ejection slit

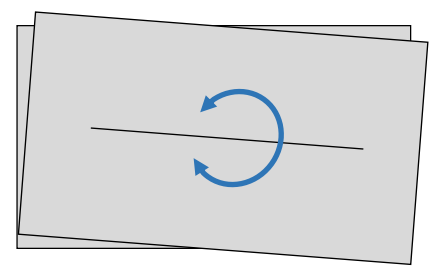

FWHM / Th
FWHM / Th
X-displacement / mm


X-displacement / mm
Peak Area
Ion detection efficiency
X-displacement / mm

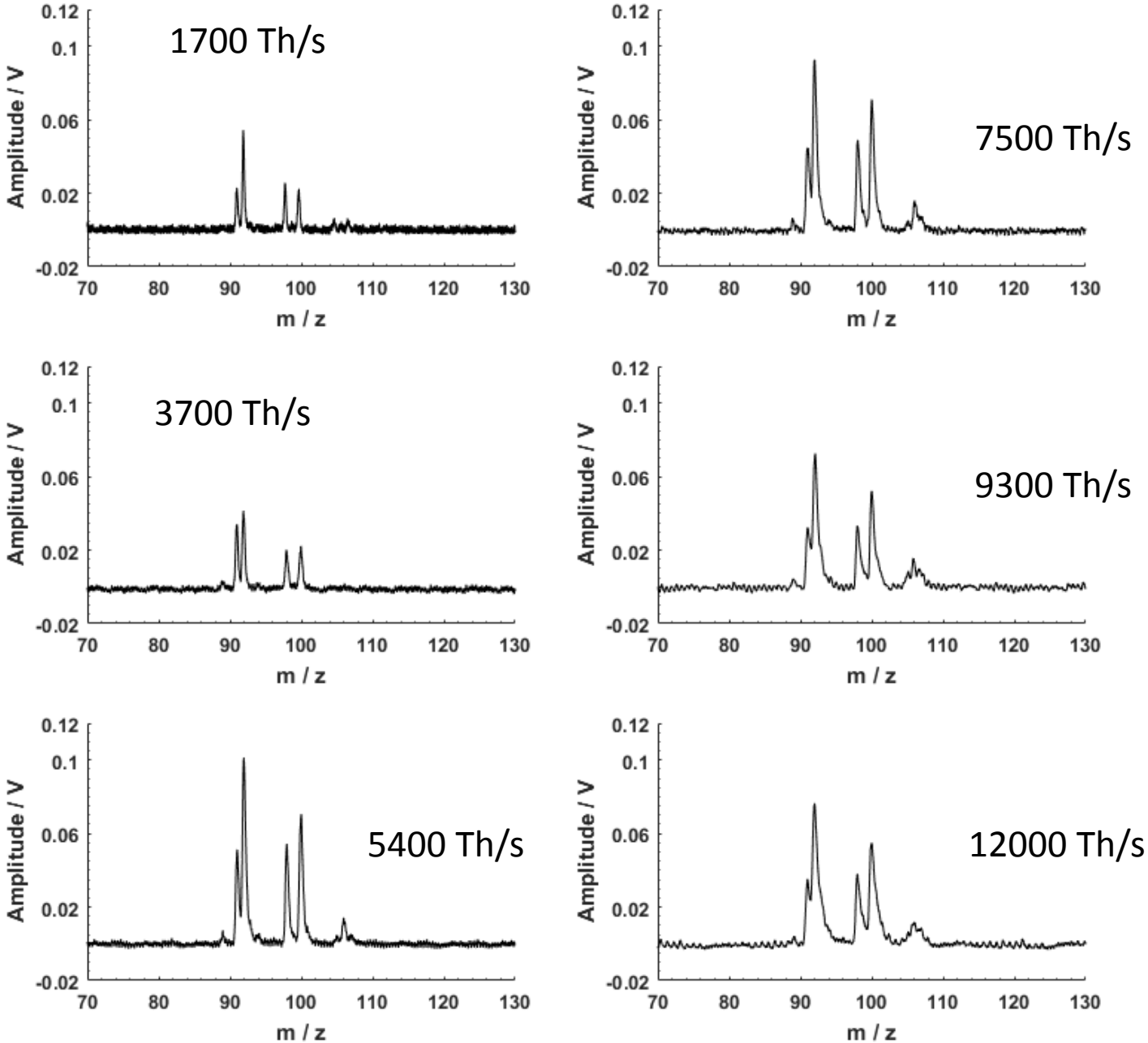



FWHM / Th
FWHM / Th
Yaw / °


Area / Arb. Unit
Ion Detection Efficiency
Yaw / °



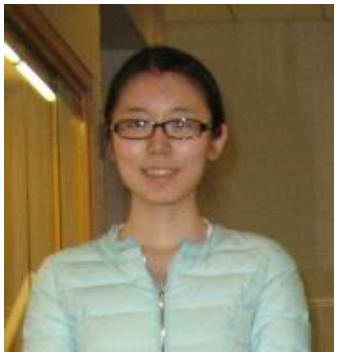
Effects of scan rate on signal



Next steps:

- Plate alignment effects and requirements now well established
- No intention of using multi-axis positioner in portable instrument
- Cartridge assembly of aligned plates can be made in lab
- Next two generations of smaller PLIT are currently being built
- Integration of PLIT with micro GC

Acknowledgments



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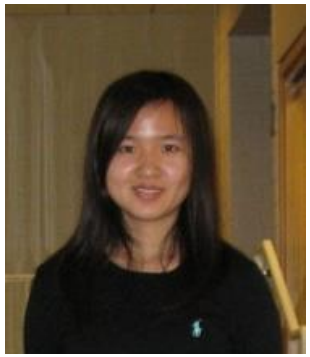

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