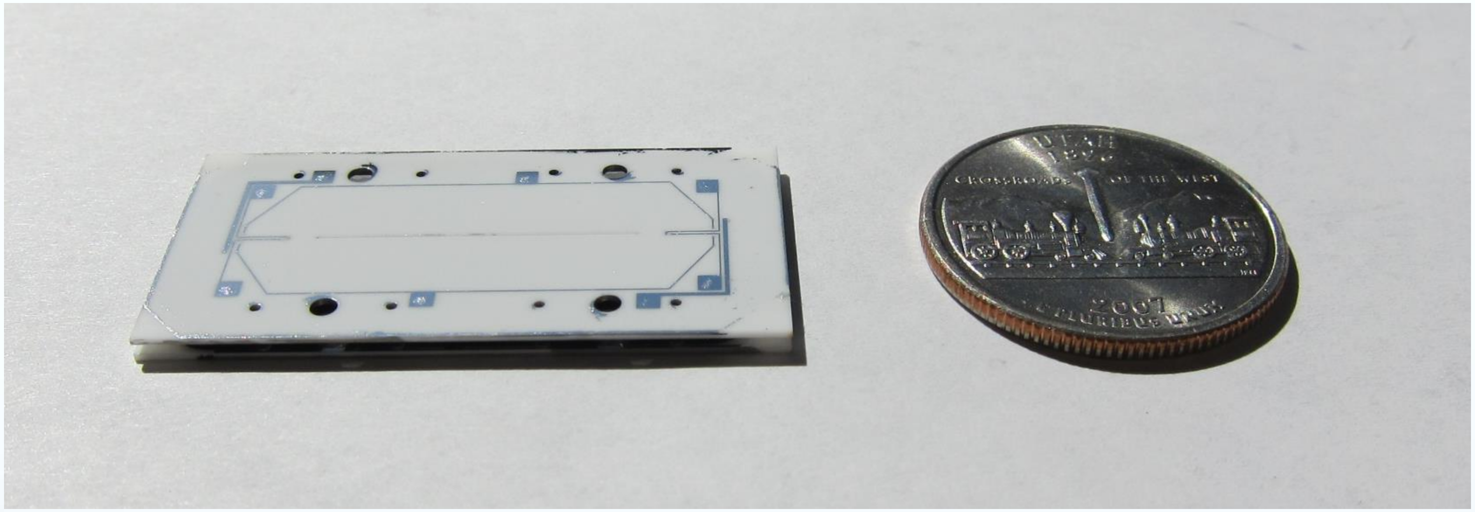
Sub-mm Linear Ion Trap Mass Spectrometer Made Using Lithographically Patterned Ceramic Plates



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Brigham Young University, Provo, UT

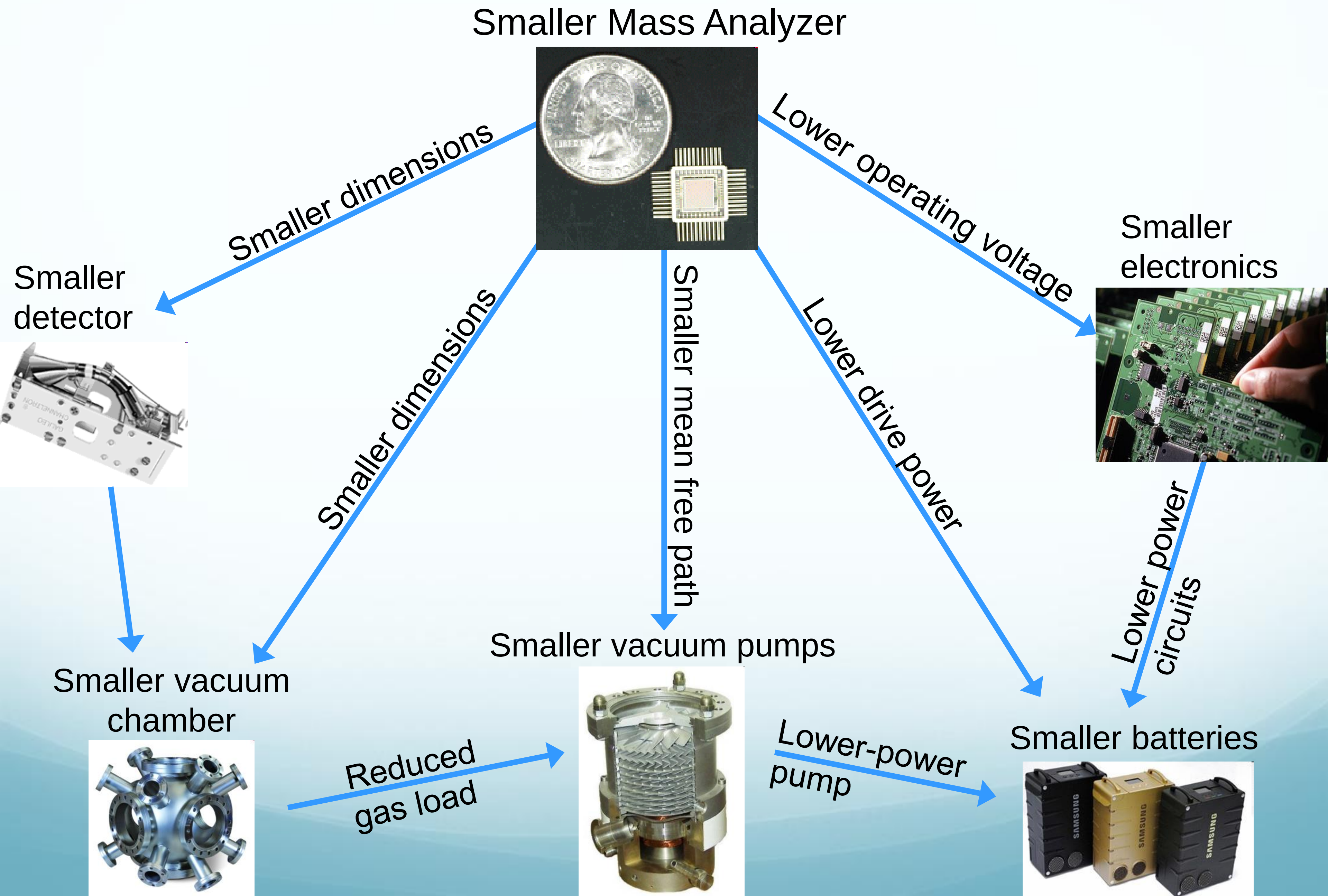
Coauthors: Qinghao Wu, Yuan Tian, Derek Andrews, Aaron Hawkins, and Daniel E. Austin

Towards the Portable Mass Spectrometer

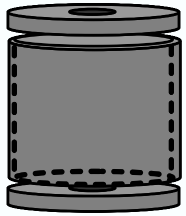
High
performance
Fragile
Cannot be moved
No hurry
High cost

Good performance
Rugged
Goes anywhere
Fast Results
Low cost

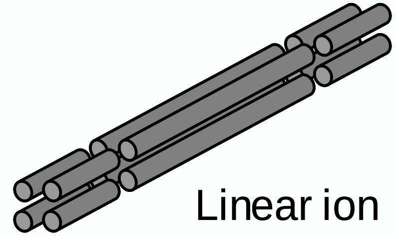
Mass Analyzer Miniaturization Leads to Smaller Overall Instrument



Radiofrequency Quadrupole Ion Traps

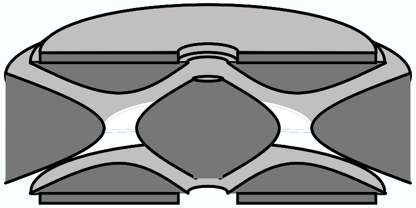


Cylindrical ion trap

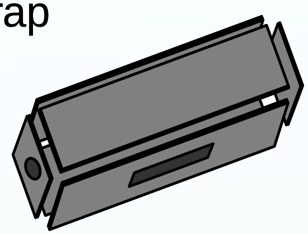


Linear ion trap

Quadrupole ion trap or Paul trap



Toroidal ion trap



Rectilinear ion trap

- High sensitivity, throughput, and resolution
- Higher pressure than other mass analyzers
- Tandem capabilities, ion-molecule reactions
- Many trap geometries, each with unique capabilities

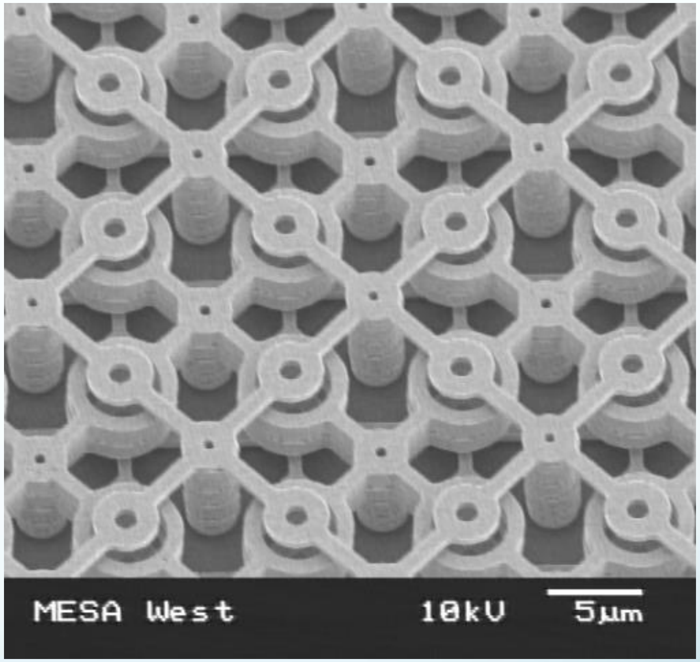
Obstacles to Miniaturization of Mass Analyzers (esp. ion traps)

Making accurate fields:

- Machining / fabrication accuracy
- Electrode alignment
- Surface roughness

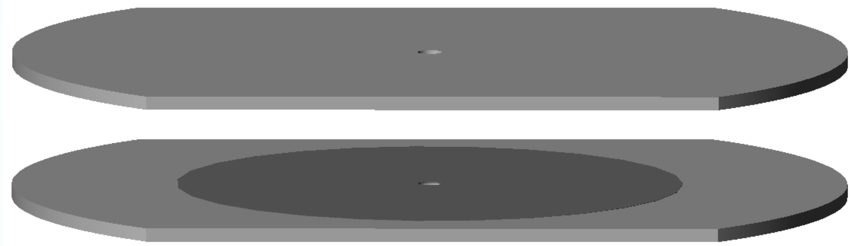
Practical issues:

- Reduced access for ions or ionizing radiation
- Reduced ion count (space charge)
- Keeping arrayed traps parallel
- Insufficient stopping distance to trap ions

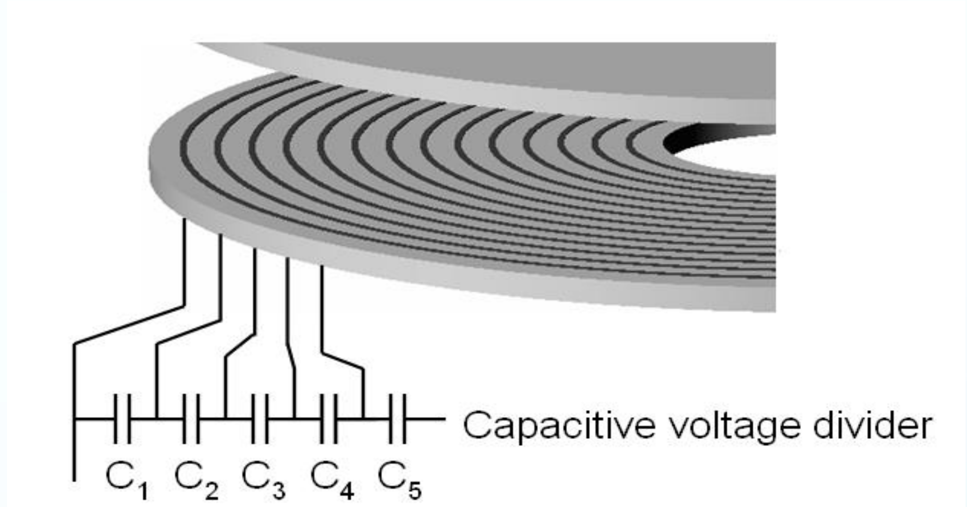


From Austin et al, *JASMS* 2006

Two-Plate Ion Traps

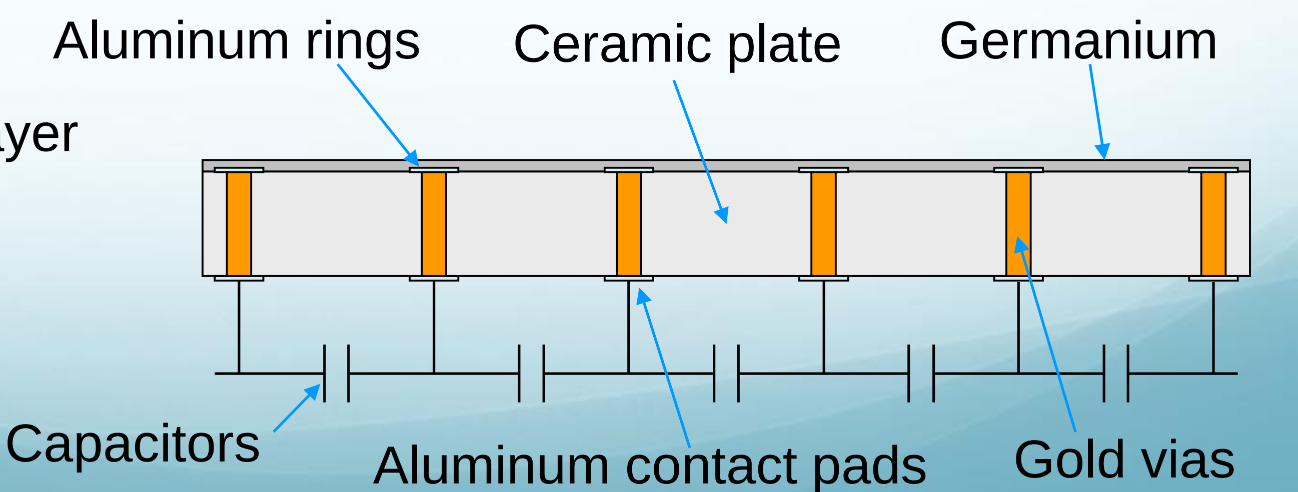


Each plate contains series of lithographically-defined metal “wires”, overlaid with resistive germanium



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

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

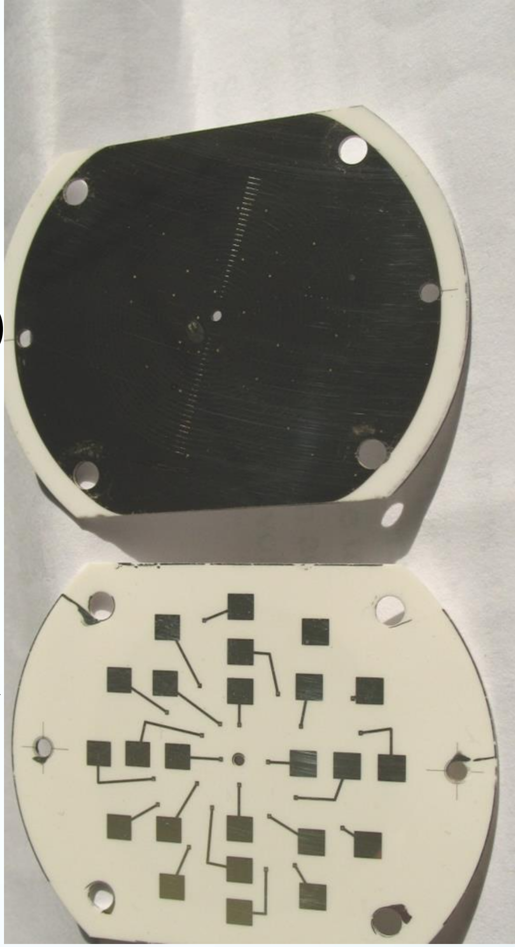


Trap Plate Fabrication

Laser-drilled vias backfilled with gold

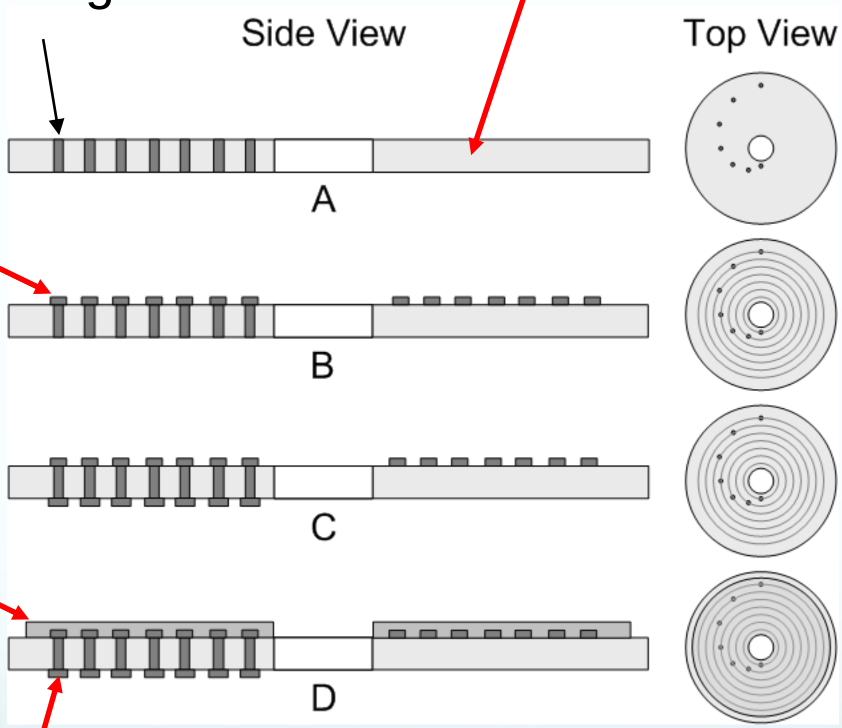
Alumina substrate

Trapping side (top)



Ring electrodes (Au or Al)

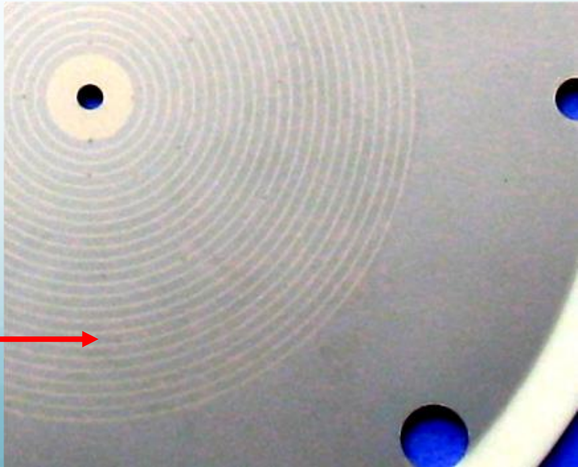
Germanium layer (resistive)



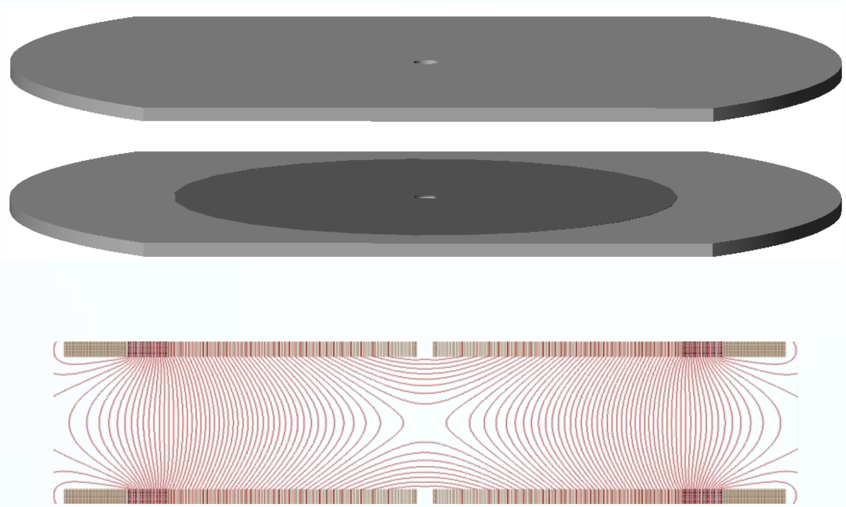
Back side

Backside contact pads (Al)

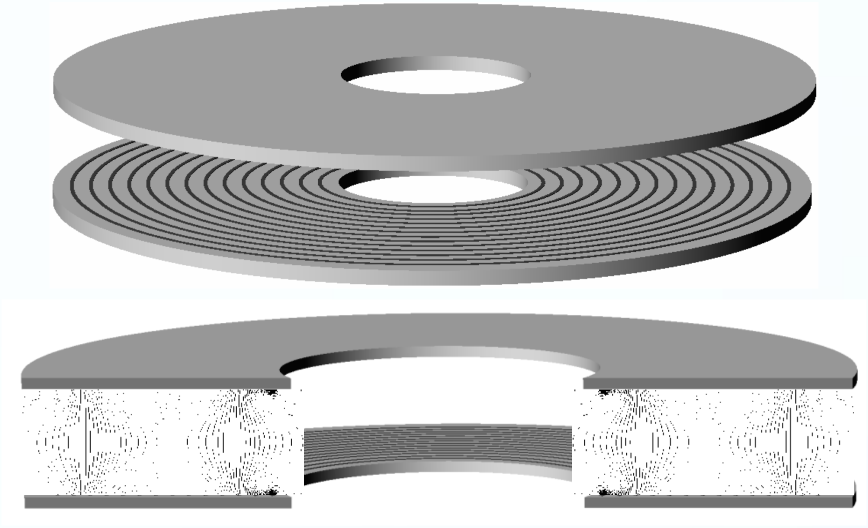
Rings visible through germanium



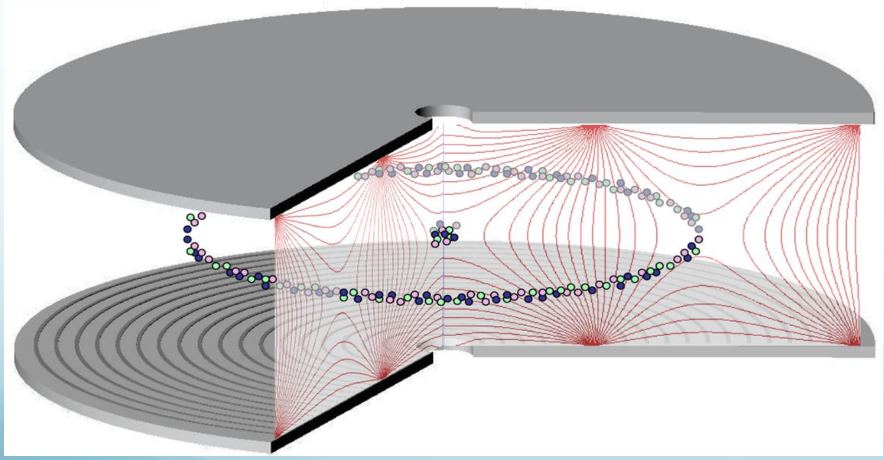
Different Trapping Geometries of Two-plate Ion Traps



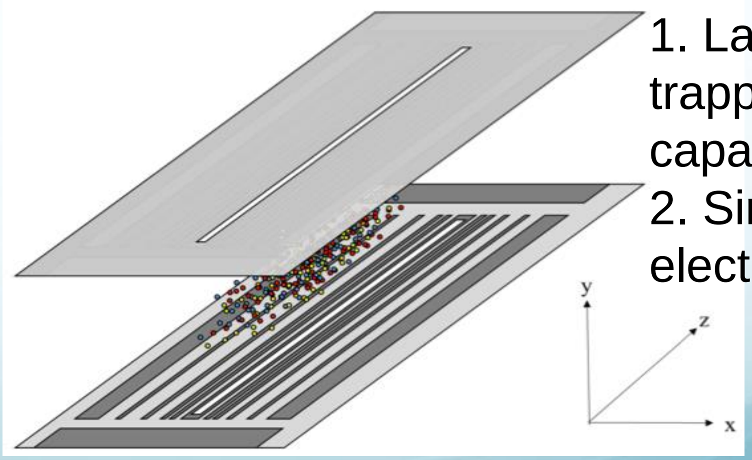
Quadrupole ion trap, the “Planar Paul Trap”



Toroidal ion trap, the “Halo Trap”



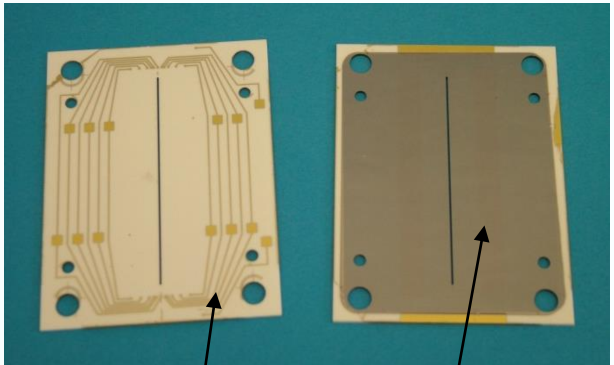
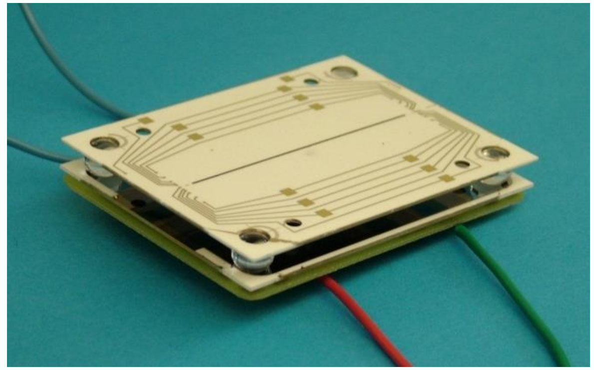
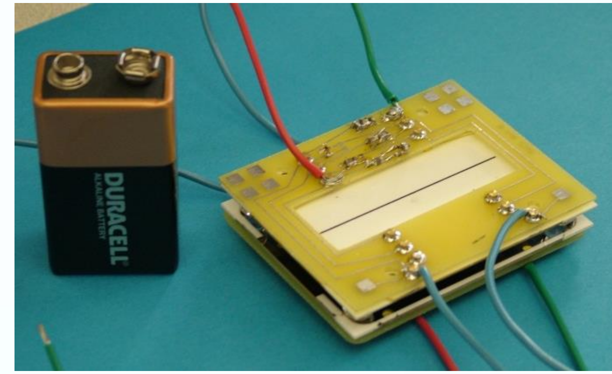
Quadrupole + toroidal, the “Coaxial Trap”



1. Larger trapping capacity
2. Simpler electric field

A linear-type ion trap

Two-plate Linear Ion Trap

Back side Trapping side

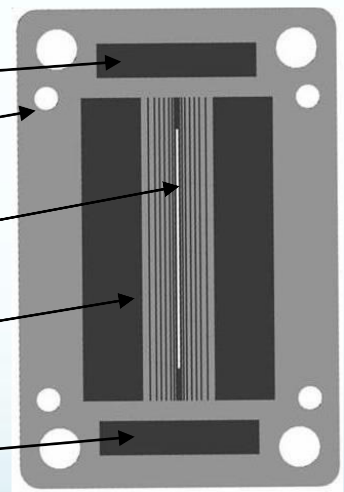
DC trapping potential

Mounting holes

Ejection slit

Patterned electrodes

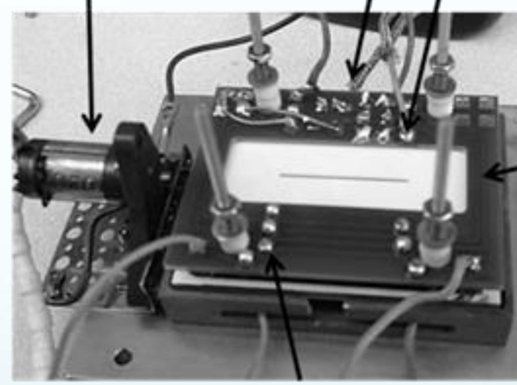
DC trapping potential



Electron gun

Power supply connections

PCB with capacitive voltage divider



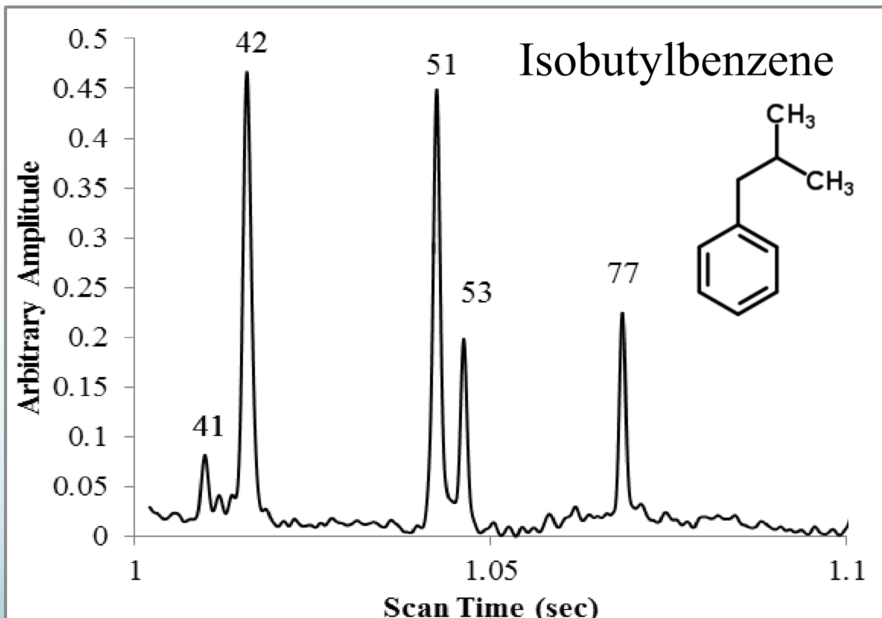
Pogo pin connectors to ceramic substrate

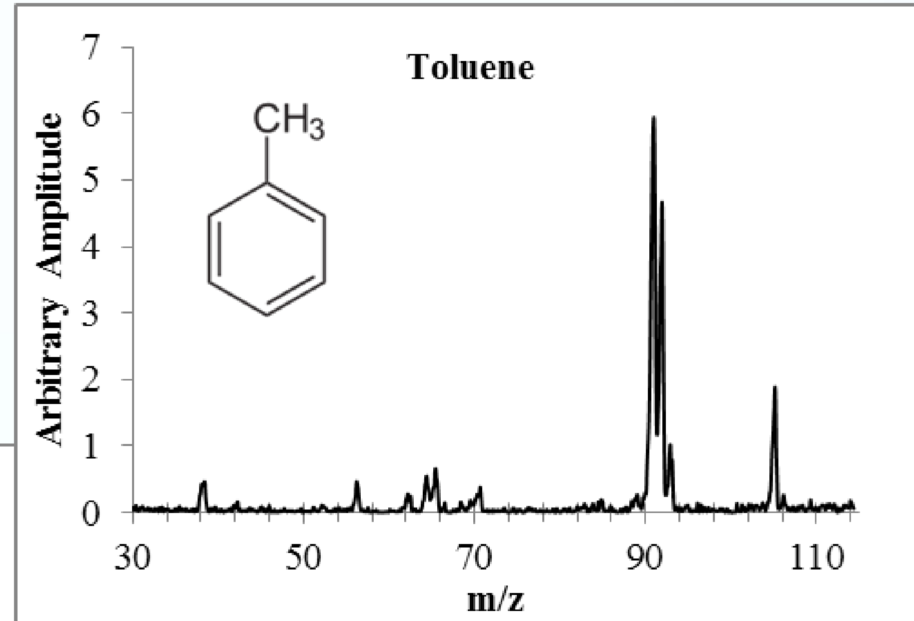
Original design: r_0 = 2.19 mm

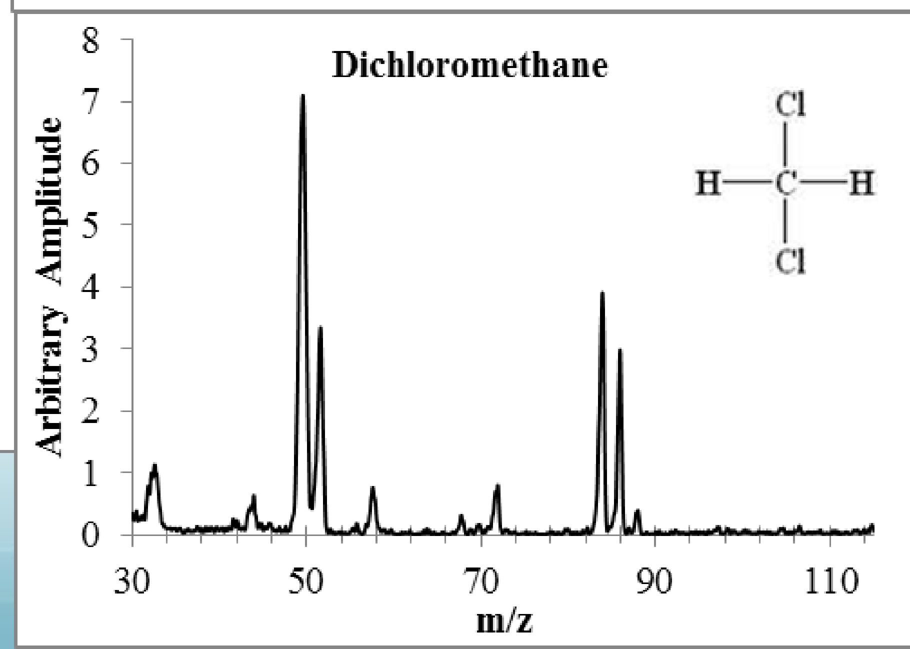
Mass spectra with r_0 < 1 mm were also demonstrated

Planar LIT Results r_0 = 2.19 mm

RF frequency: 2.3 MHz
RF amplitude: 720 $V_{0\text{-}p}$
Resonant AC frequency:
1.1 MHz to100 kHz
AC amplitude: 3.5 $V_{0\text{-}p}$

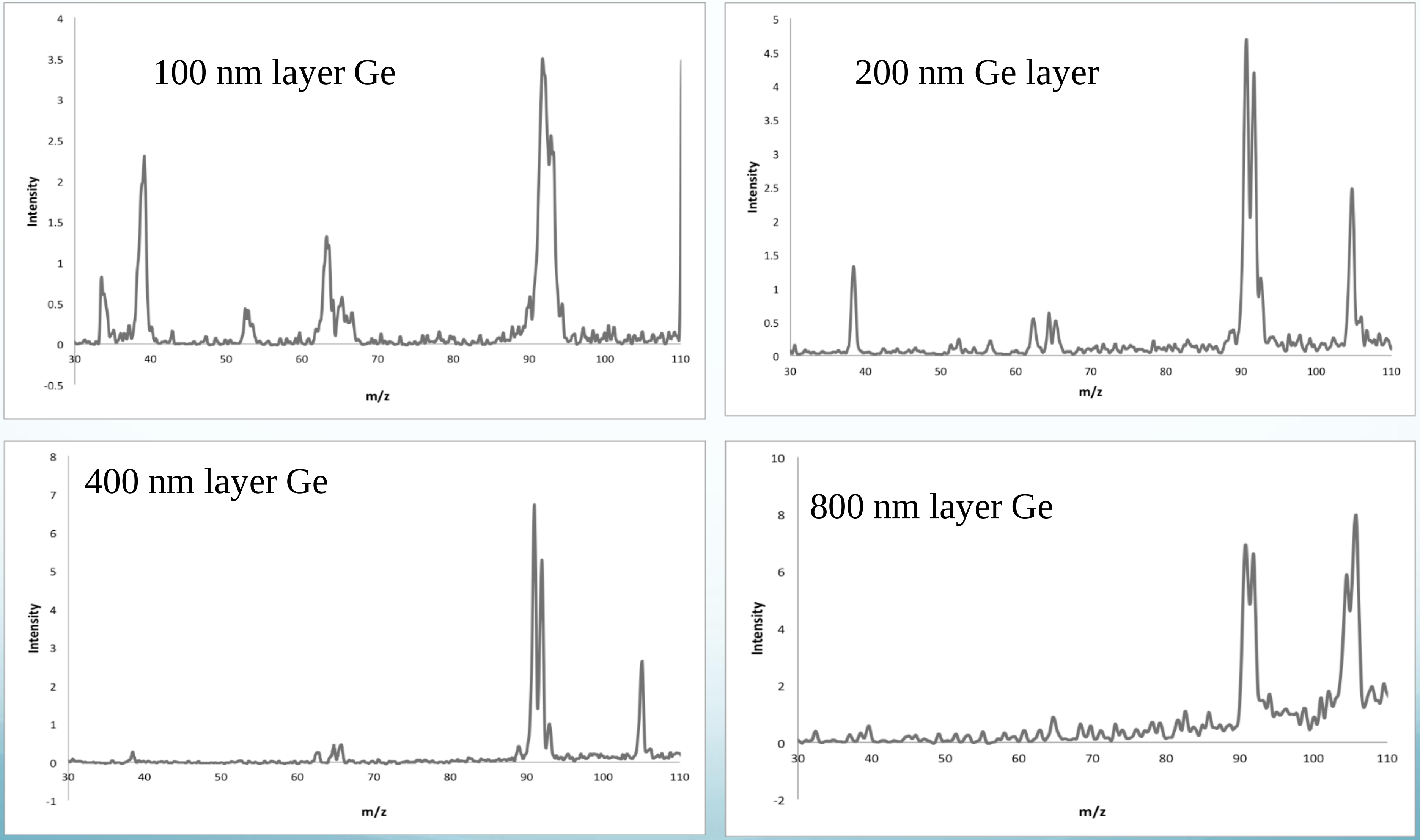






Experiment to Optimize the Thickness of the Germanium Layer

Ge layer: prevents charge build-up on insulating ceramic;
establishes continuous, well-defined potential



Results inconclusive—may be other differences such as plate alignment

Simple Miniaturization Experiment: Moving the Plates Closer Together

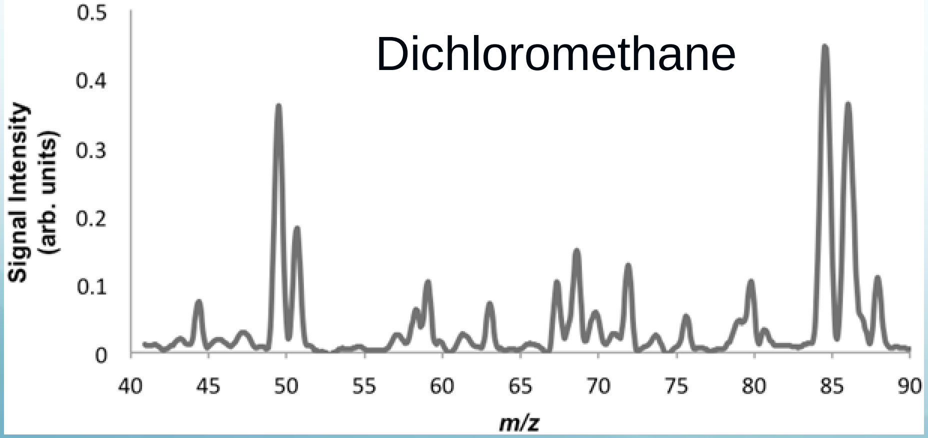
Without remaking the plates, spacing was decreased from 4.38 mm to 1.90 mm

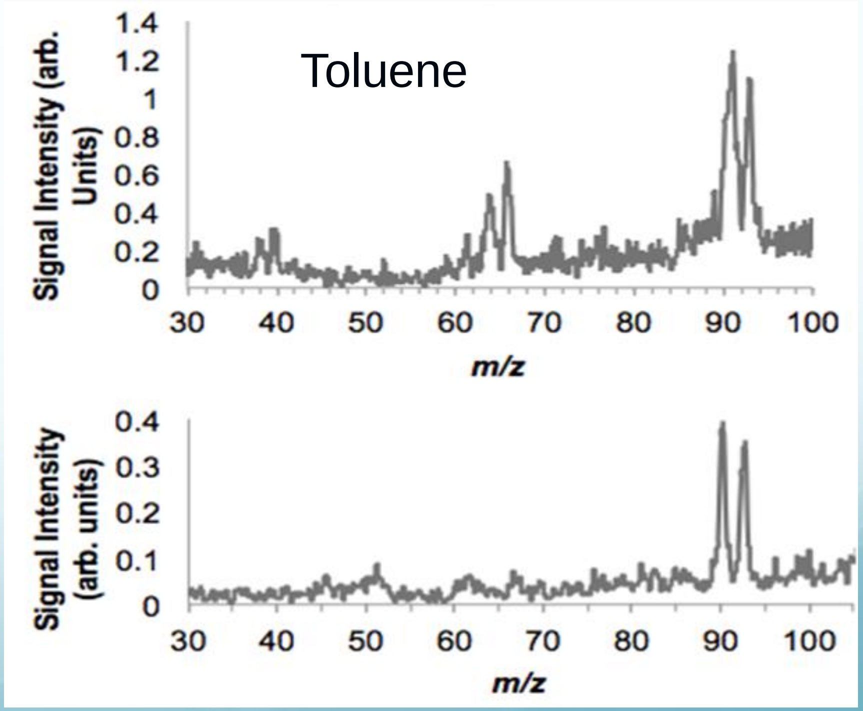
Fields were redesigned using different capacitor values on PCBs

Plate alignment becomes significant factor in performance

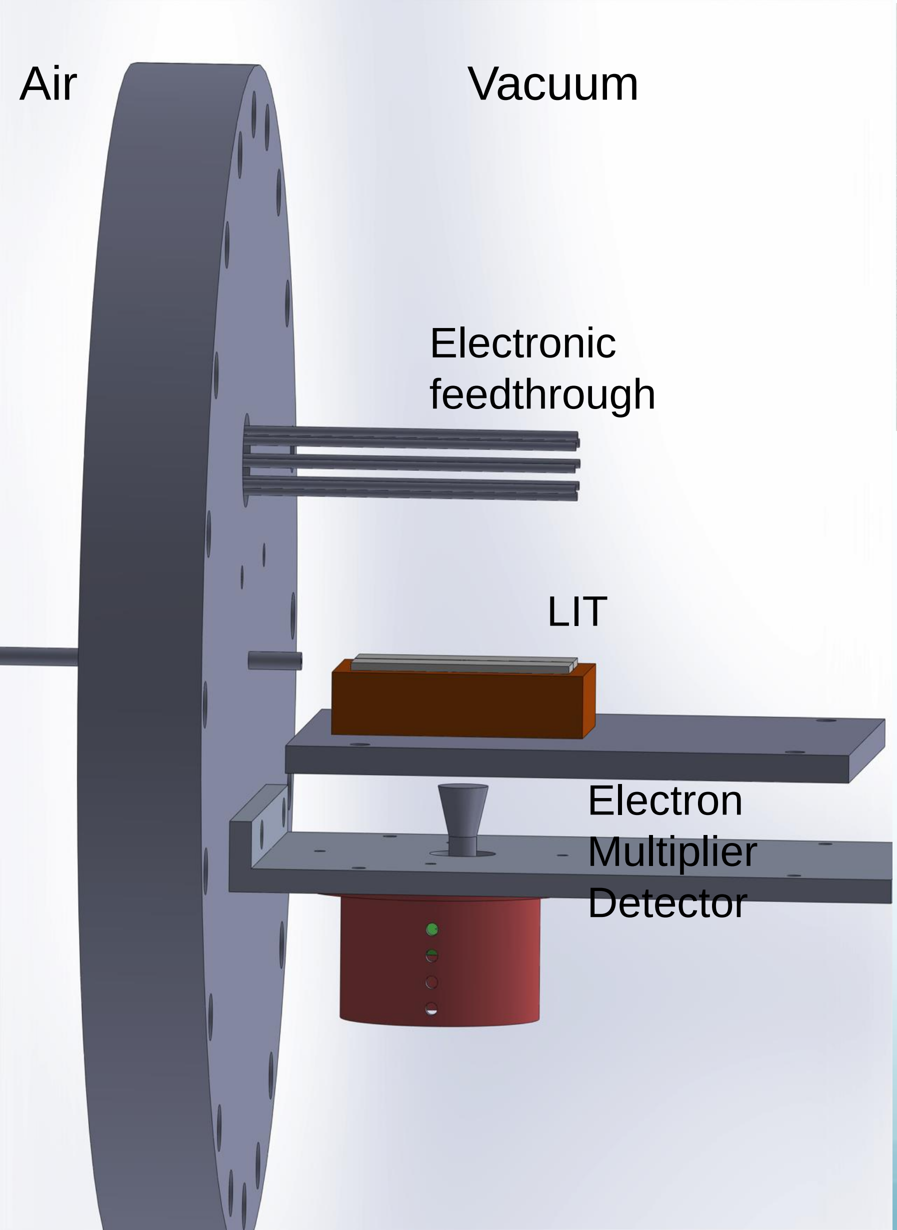
Reduced S/N as expected

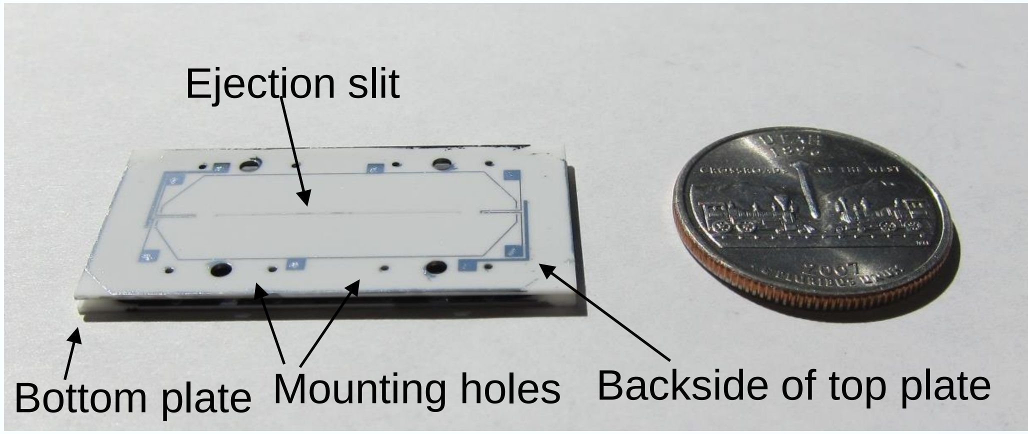
Planar LIT Results
r_0 = 0.95 mm

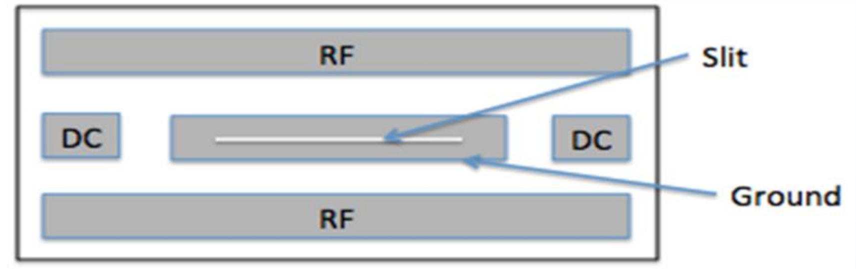




Sub-mm LIT







r_0 = 362 μm

Plate spacing 724 μm

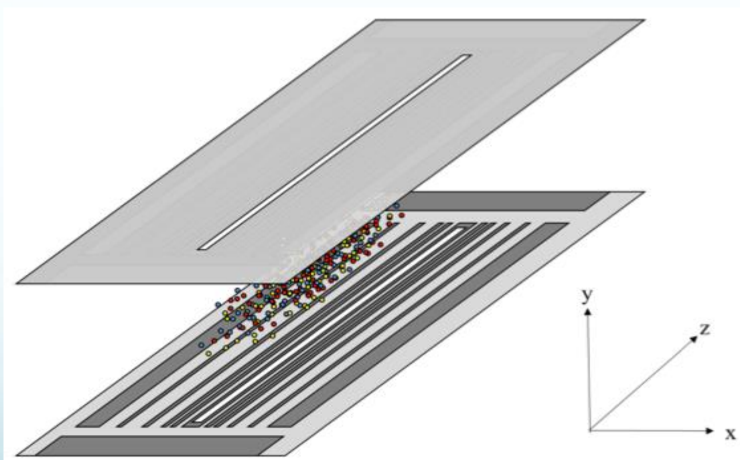
Plates 2 x 4 cm alumina

No capacitive voltage divider

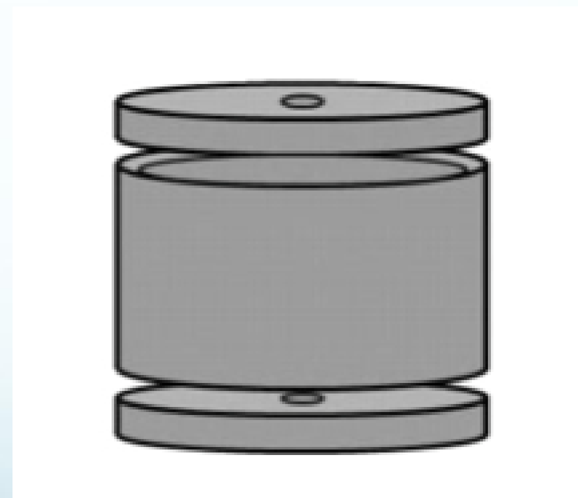
Plate alignment is potential issue

Sub-mm LIT
Ion Trapping Capacity

r_0 = 362 μm	Sub-mm LIT	Cylindrical Ion Trap
$V_{0\text{-}p}$	50 V	190 V
Ω	4 MHz	3.8 MHz
Capacity	85000	29000

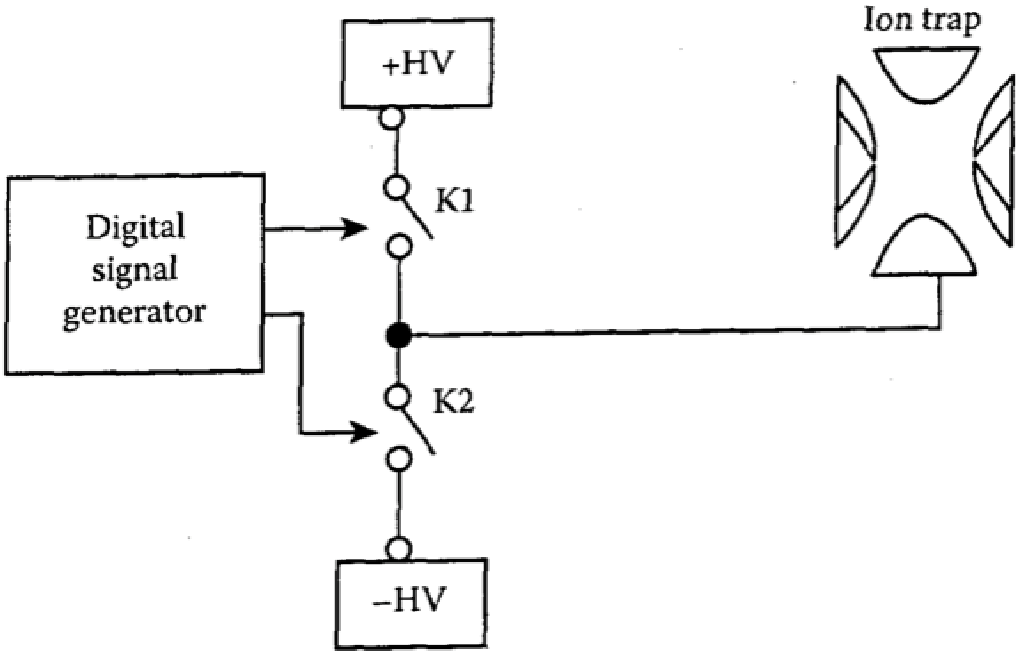


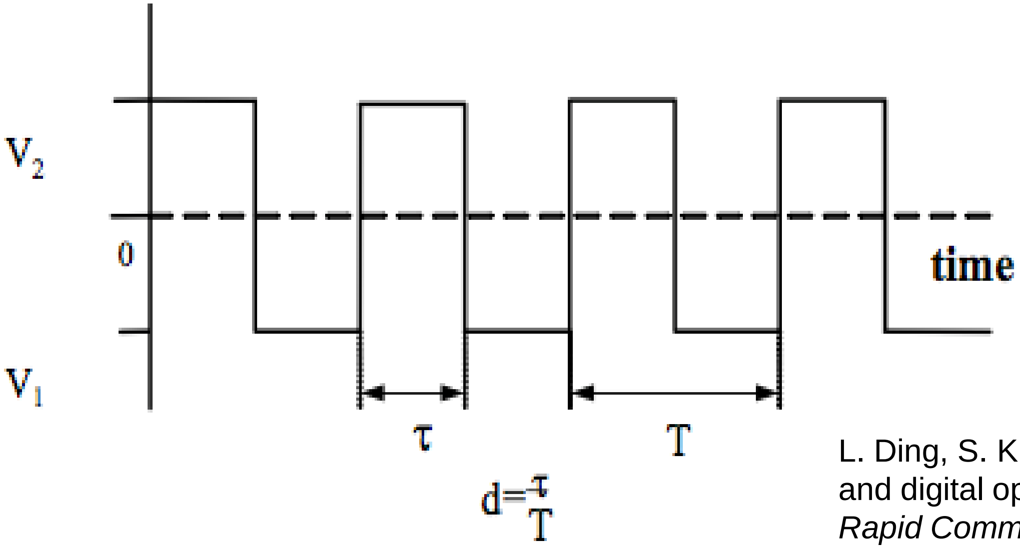
Linear ion trap



Cylindrical ion trap

New Method with New LIT
— Digital Operation





$$a_z = -\frac{8eU}{m\Omega^2 r_0^2}$$

$$q_z = \frac{4eV}{m\Omega^2 r_0^2}$$

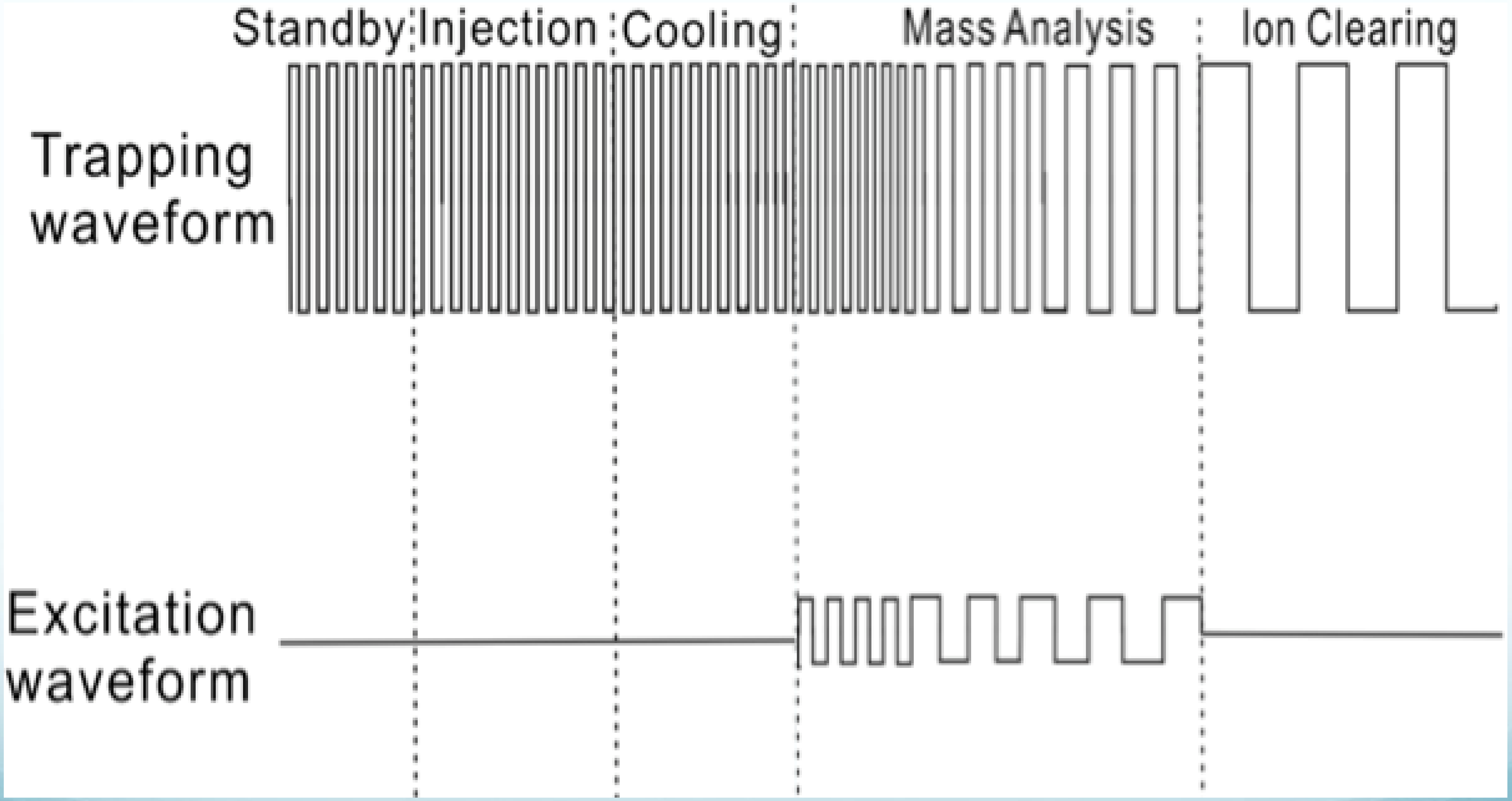
$$\Omega = 2\pi/T$$

$$U = d\,V_1 + (1 - d)\,V_2$$

$$V = 2(V_1 - V_2)(1 - d)d$$

L. Ding, S. Kumashiro. Ion motion in the rectangular wave quadrupole field and digital operation mode of a quadrupole ion trap mass spectrometer. *Rapid Commun. Mass Spectrom*. **2006**, *20*, 3.

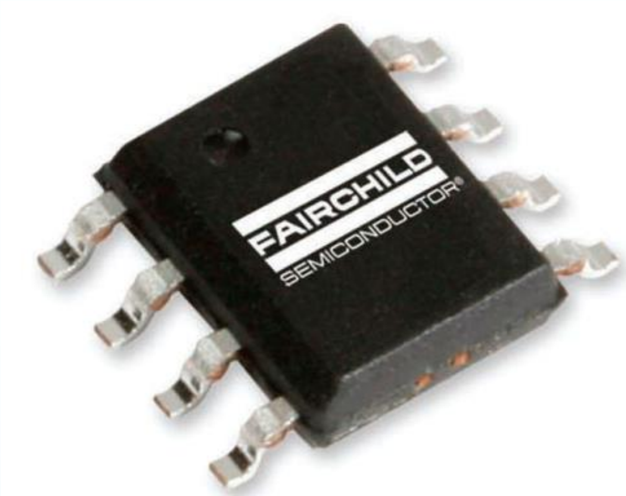
Digital Waveform Operation



Why Digital Operation?

Advantages

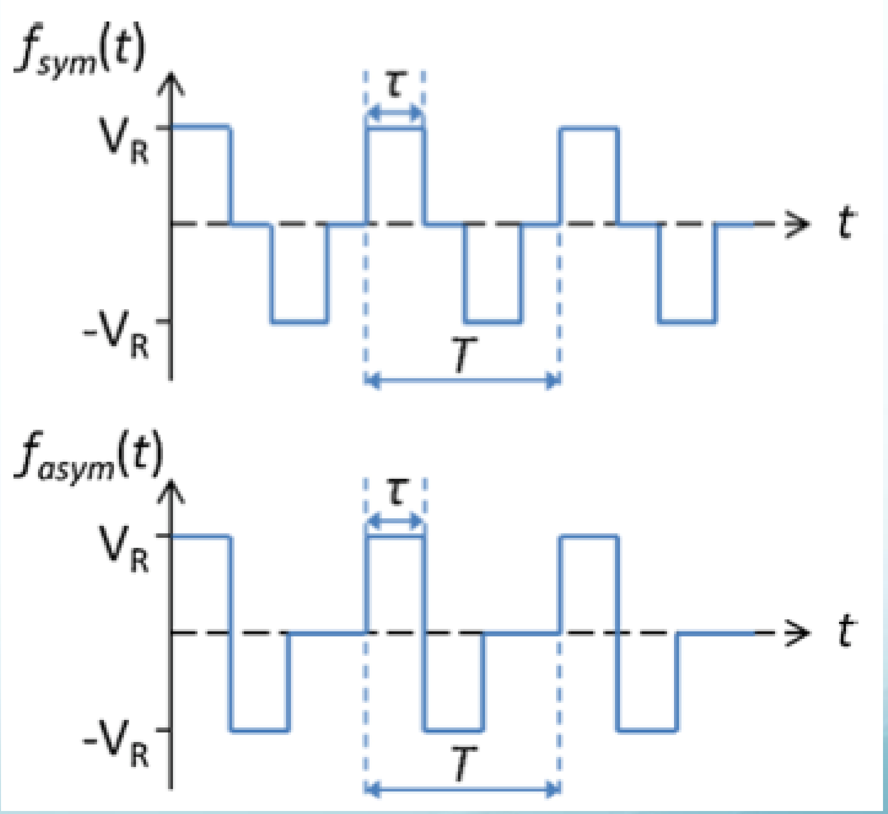
1. Less voltage requirement



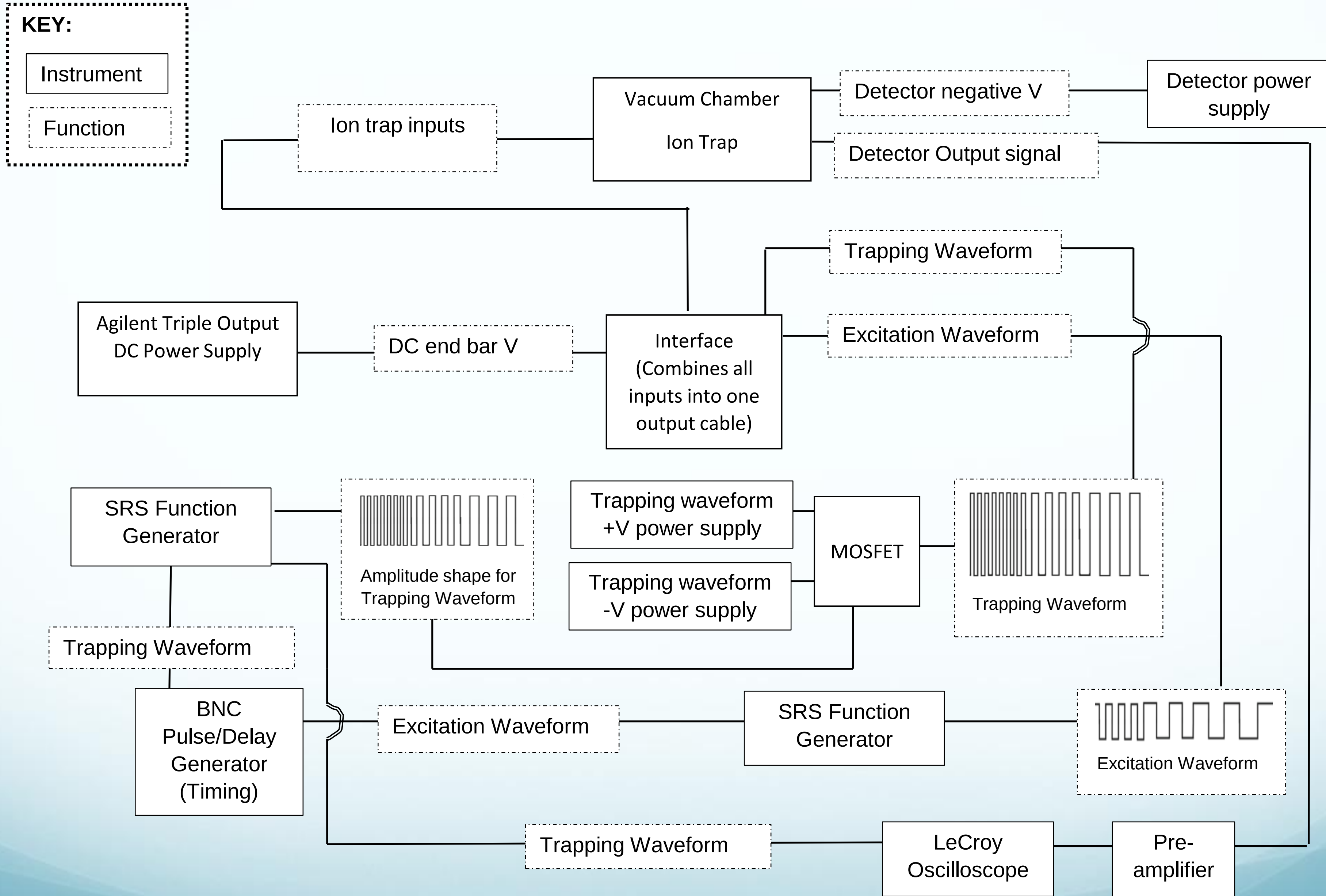
MOSFET: Metal-Oxide-Semiconductor Field-Effect Transistor

Voltage: +/- 30 $V_{0\text{-}p}$

2. Variable digital waveforms



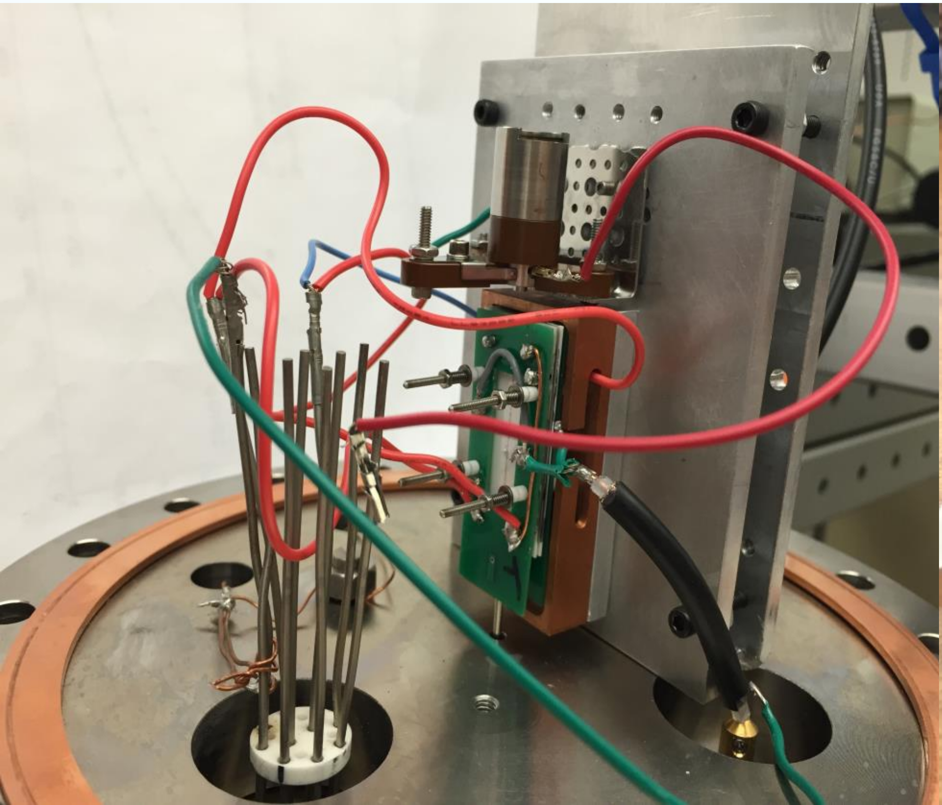
S. Bandelow et al. / International Journal of Mass Spectrometry 353 (2013) 49–53

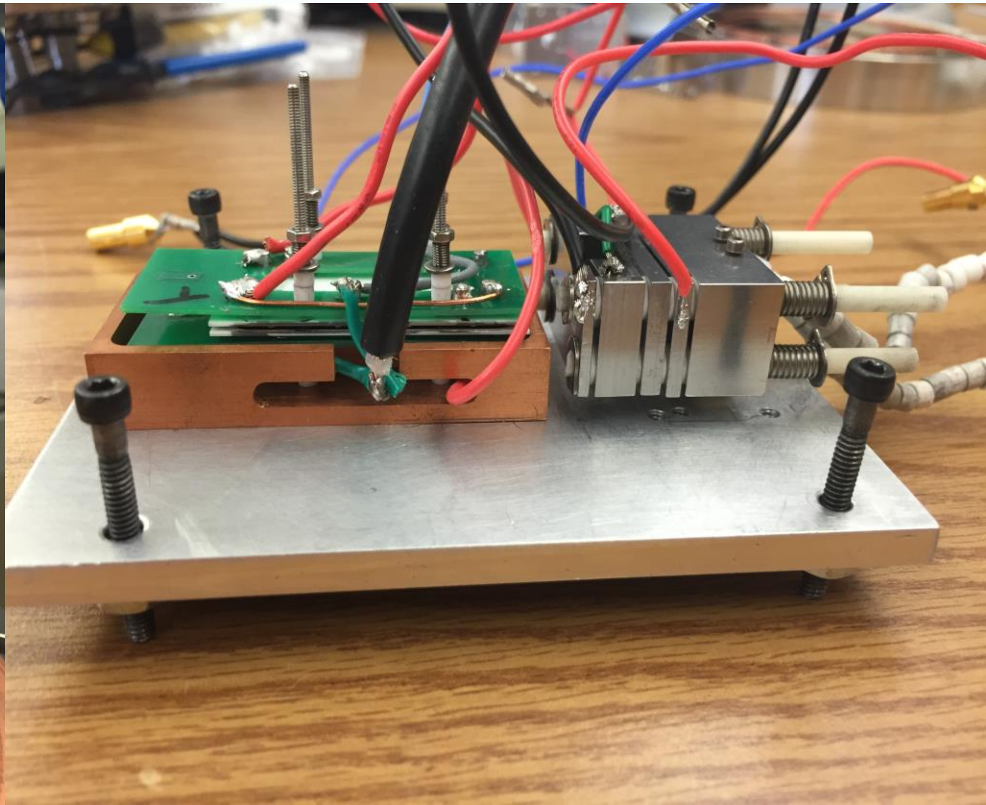


KEY:
Instrument
Function
Ion trap inputs
Vacuum Chamber
Ion Trap
Detector negative V
Detector power supply
Detector Output signal
Trapping Waveform
Agilent Triple Output DC Power Supply
DC end bar V
Interface (Combines all inputs into one output cable)
Excitation Waveform
SRS Function Generator
Amplitude shape for Trapping Waveform
Trapping waveform +V power supply
Trapping waveform -V power supply
MOSFET
Trapping Waveform
Trapping Waveform
BNC Pulse/Delay Generator (Timing)
Excitation Waveform
SRS Function Generator
Excitation Waveform
Trapping Waveform
LeCroy Oscilloscope
Pre-amplifier

Electron-gun Improvement

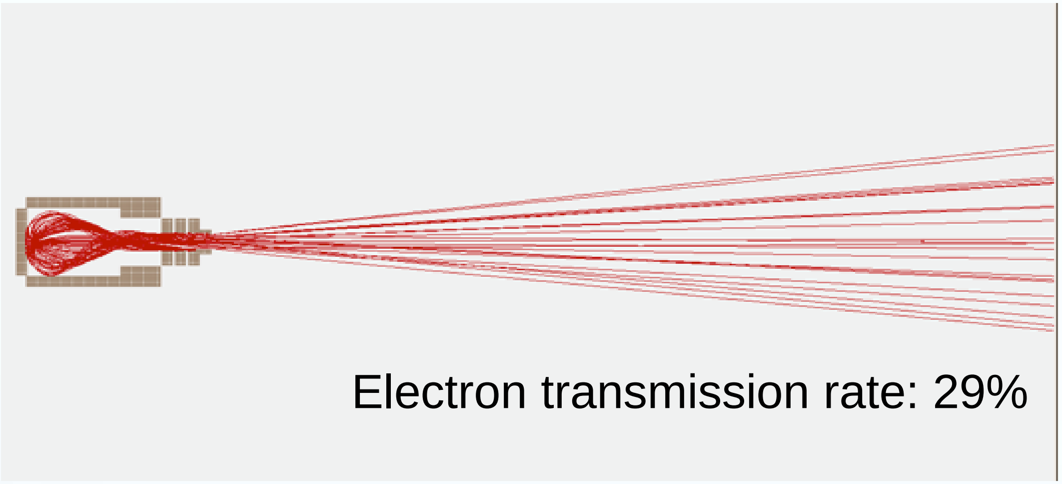
Old e-gun vs. New designed e-gun

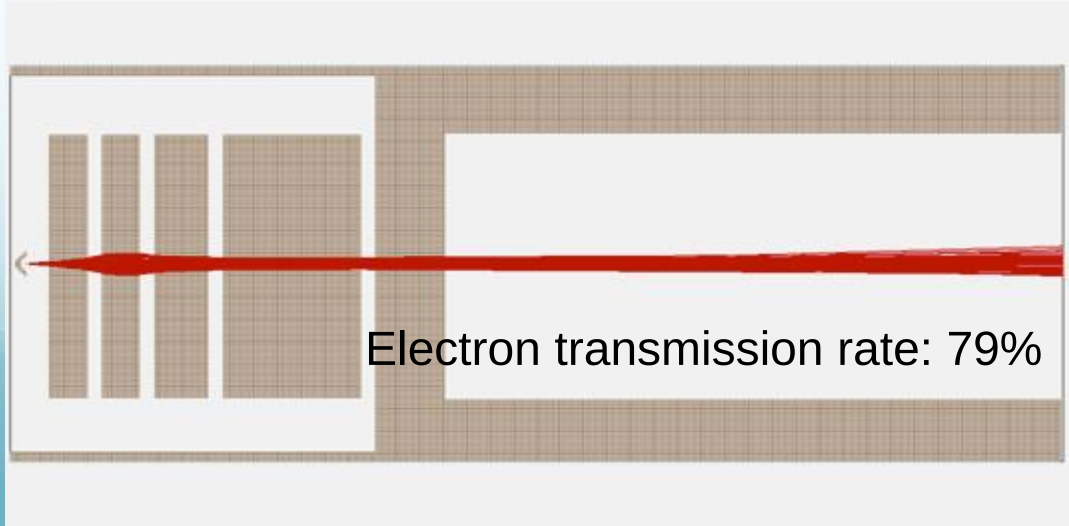


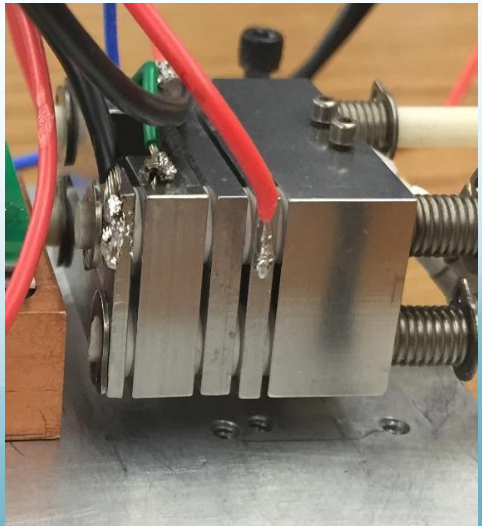


Electron-gun Improvement

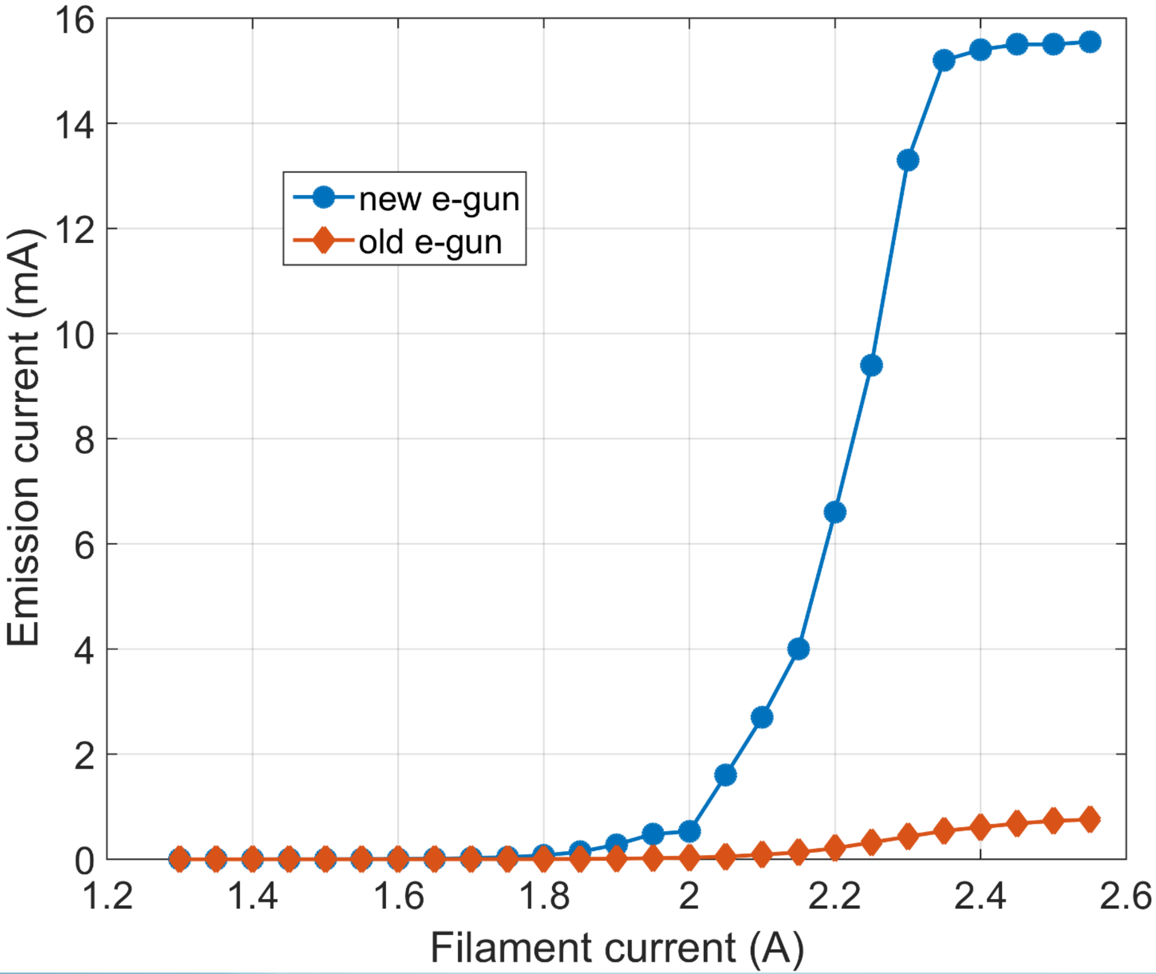
As the ion trapping capability in the small plate is lower than that in the large trap, a new e-gun with higher electron transmission efficiency is needed to increase the ionization.







Electron-gun Improvement



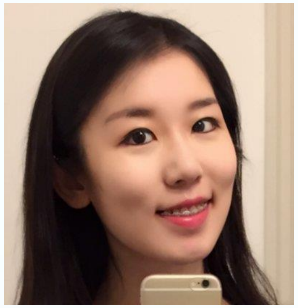
Filament Voltage: -61 V

Detector: Faraday Cup

Pressure: High Vacuum

Converging onto a Truly Portable Mass Spectrometer

Acknowledgments



Ailin Li

Dr. Daniel Austin

Dr. Qinghao Wu

Yuan Tian

Dr. Aaron Hawkins

Derek Andrews

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Dr. Steve Lammert (Perkin Elmer Corp.)

Funding from NASA, NSF and DoD

Thank you!

Gas breakdown? Or not?

High vacuum

↓

Very low density

↓

High mean free path

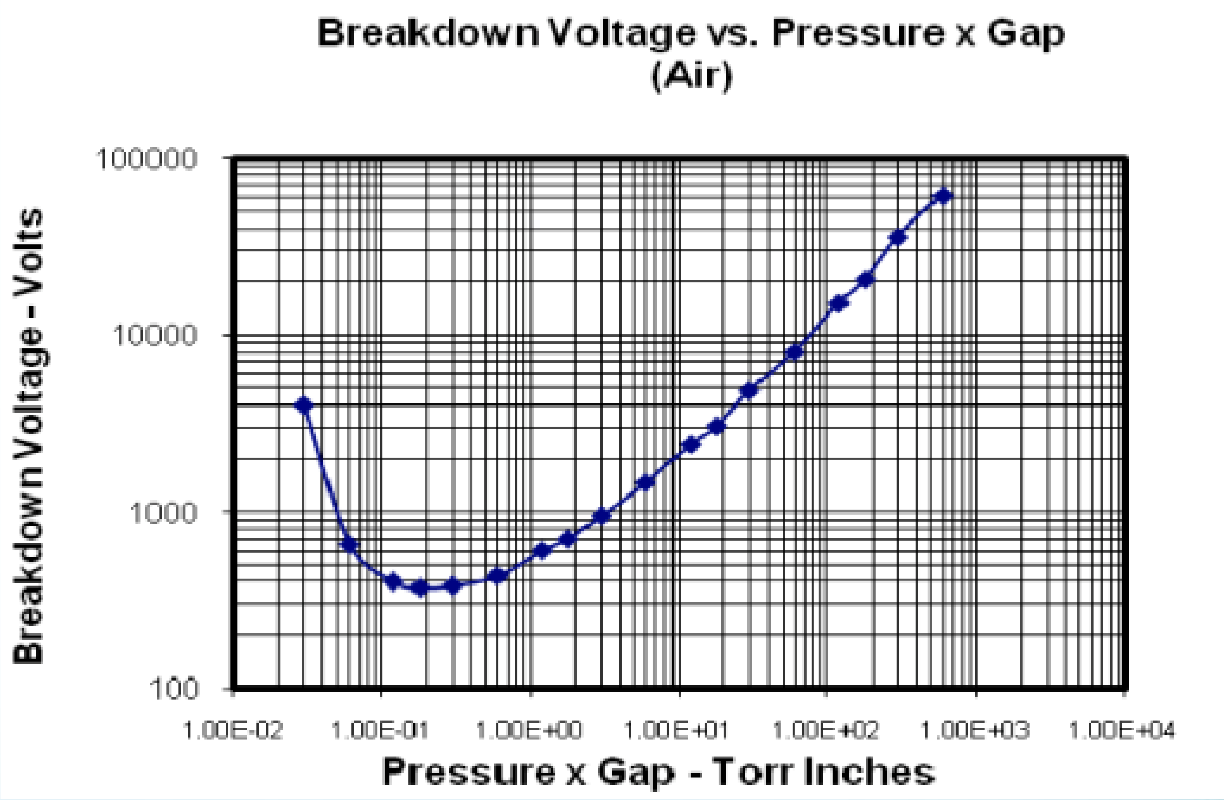
↓

Less collision ionization

↓

High breakdown voltage

Paschen's Law: V= f (*dp*)



Next generation design LIT:
Pressure * Gap ≈ 2.8E-7

Germanium? Or Silicon?

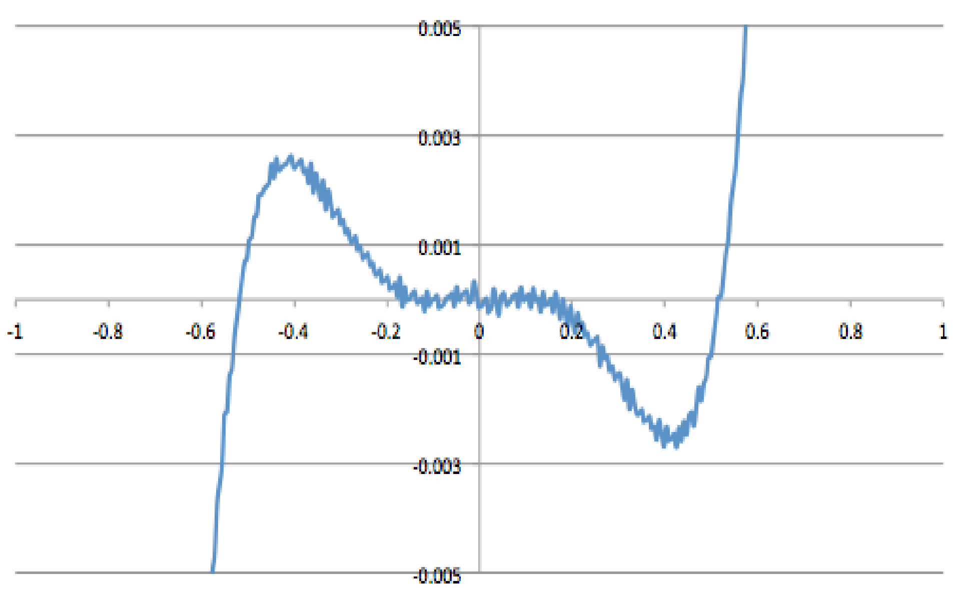
T= 300 K	Ge	Si
Electron mobility	3900 $cm^2V^{-1}s^{-1}$	1600 $cm^2V^{-1}s^{-1}$
Hole mobility	1900 $cm^2V^{-1}s^{-1}$	430 $cm^2V^{-1}s^{-1}$
Band gap	0.66 eV	1.12 eV
Melting point	1211 K	1687 K
Heat of vaporation	334 kJ/mol	383 kJ/ mol

Ge: More conductive → Better material

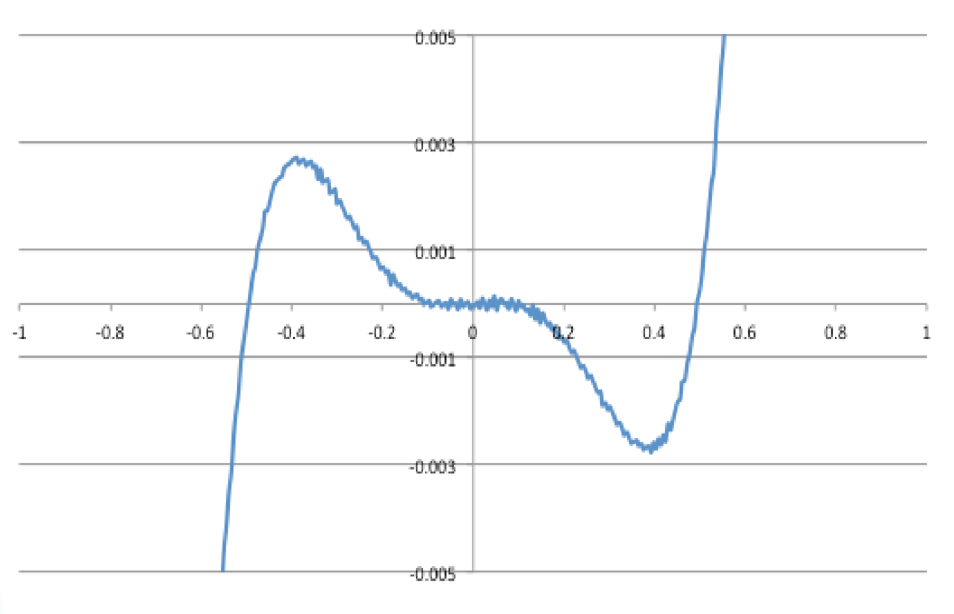
Easier to evaporate → Easier in plate fabrication

Electric Field Simulated by SIMION

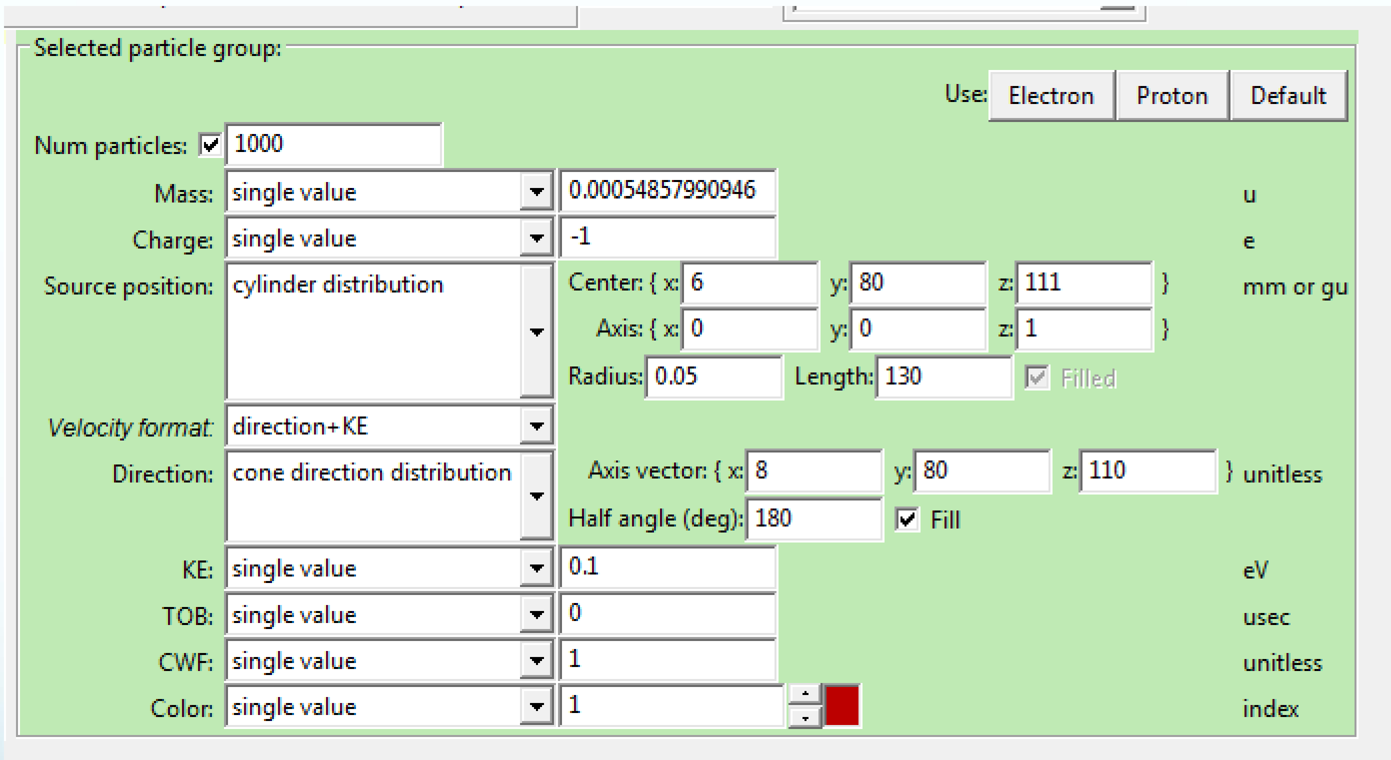
Next generation LIT
r_0=360 μm



RIT
x_0= 5 mm, y_0= 4 mm



- ➢ 150 configurations were simulated to find a similar electric field with the published optimal electric field of RIT.


Selected particle group:
Use: Electron Proton Default
Num particles: 1000
Mass: single value 0.00054857990946 u
Charge: single value -1 e
Source position: cylinder distribution
Center: { x: 6 y: 80 z: 111 } mm or gu
Axis: { x: 0 y: 0 z: 1 }
Radius: 0.05 Length: 130 Filled
Velocity format: direction+KE
Direction: cone direction distribution
Axis vector: { x: 8 y: 80 z: 110 } unitless
Half angle (deg): 180 Fill
KE: single value 0.1 eV
TOB: single value 0 usec
CWF: single value 1 unitless
Color: single value 1 index