Novel ion traps using planar resistive electrodes: implications for miniaturized mass analyzers

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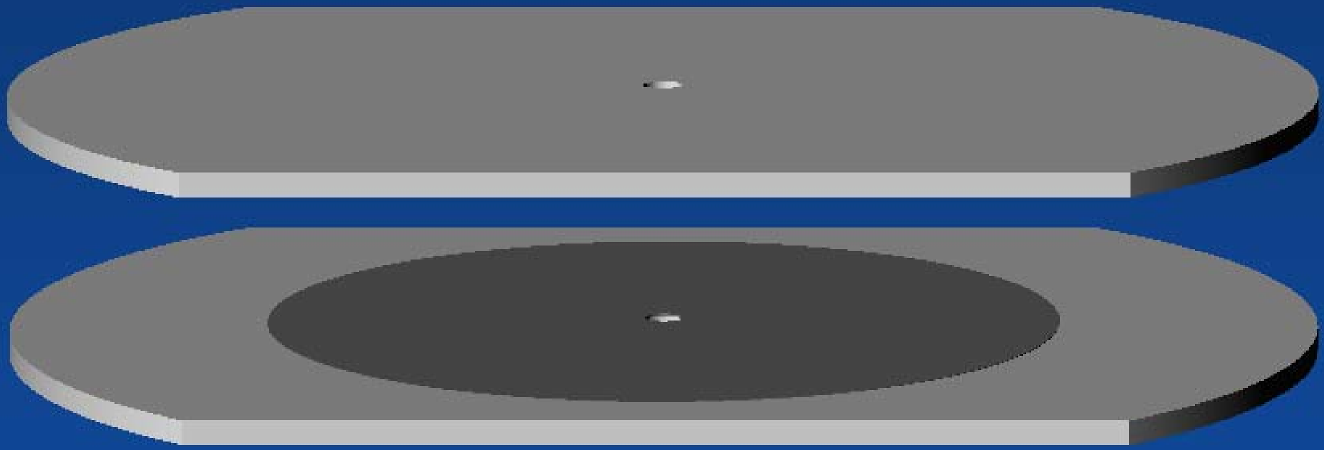
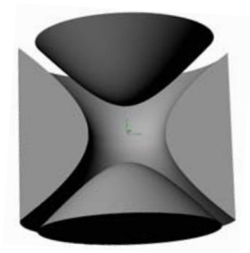
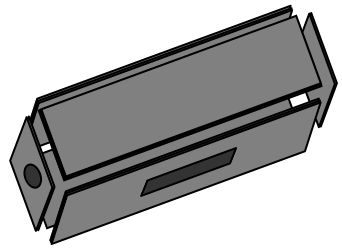


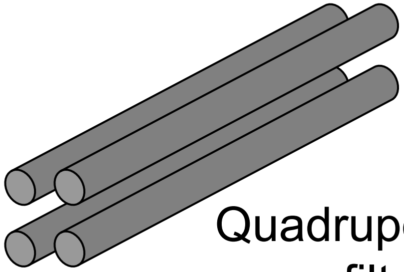
Ion traps used as mass analyzers



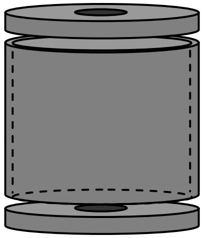
Quadrupole ion trap
or Paul trap



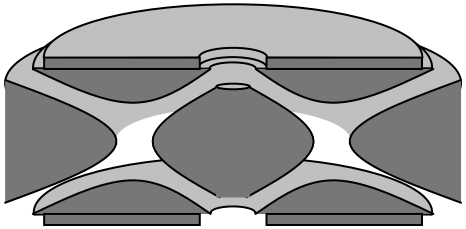
Rectilinear ion trap



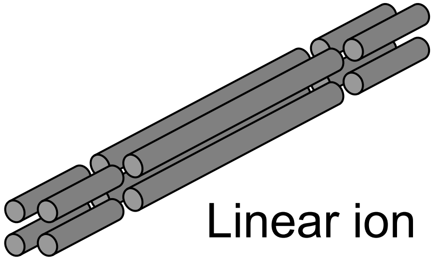
Quadrupole
mass filter



Cylindrical ion trap



Toroidal ion trap



Linear ion
trap

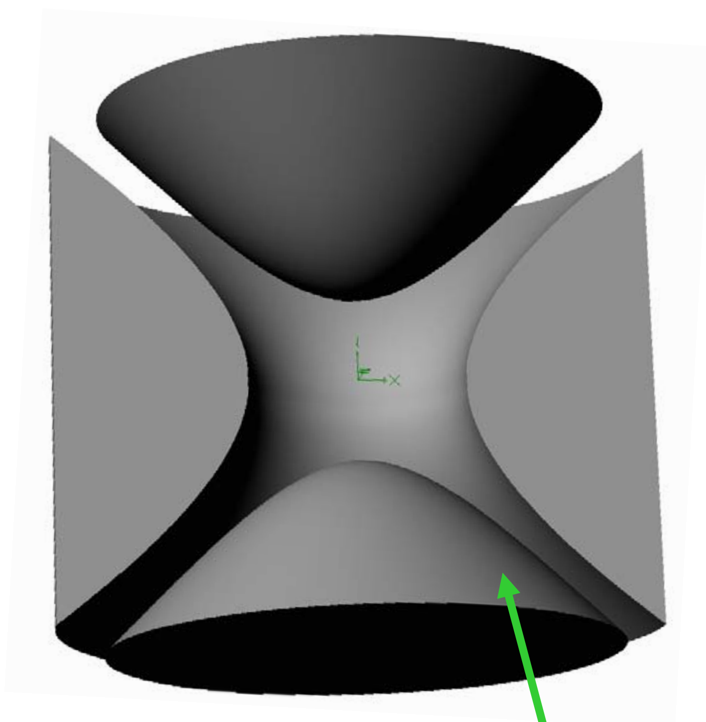
High sensitivity, throughput, and resolution,

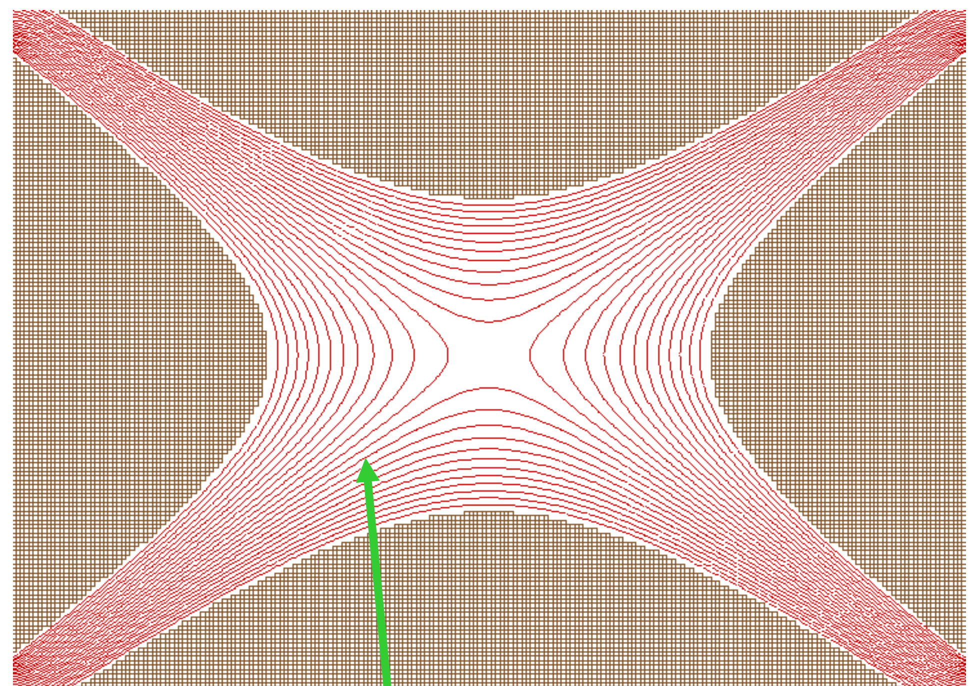
Tandem capabilities, ion-molecule reactions, inherently small

Many trap geometries, each with unique capabilities

Time-varying quadrupolar fields in 2 or 3 dimensions allow trapping and mass analysis

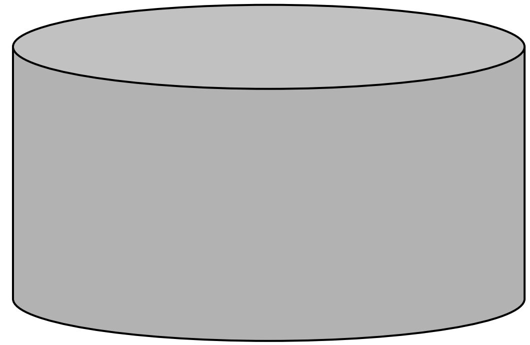
Metal electrodes provide equipotential boundary conditions



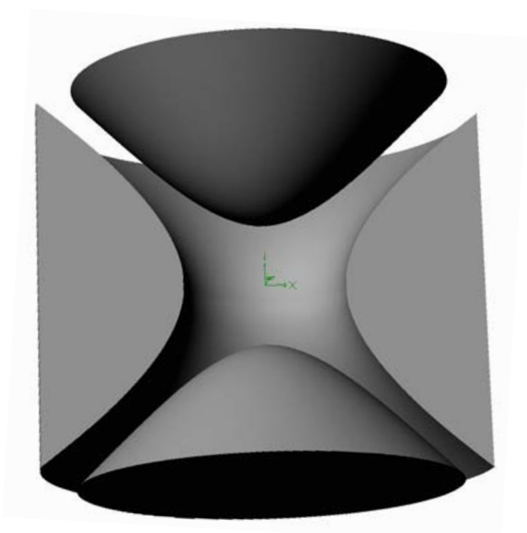


Hyperbolic surfaces produce quadrupolar fields

Non-equipotential boundary conditions

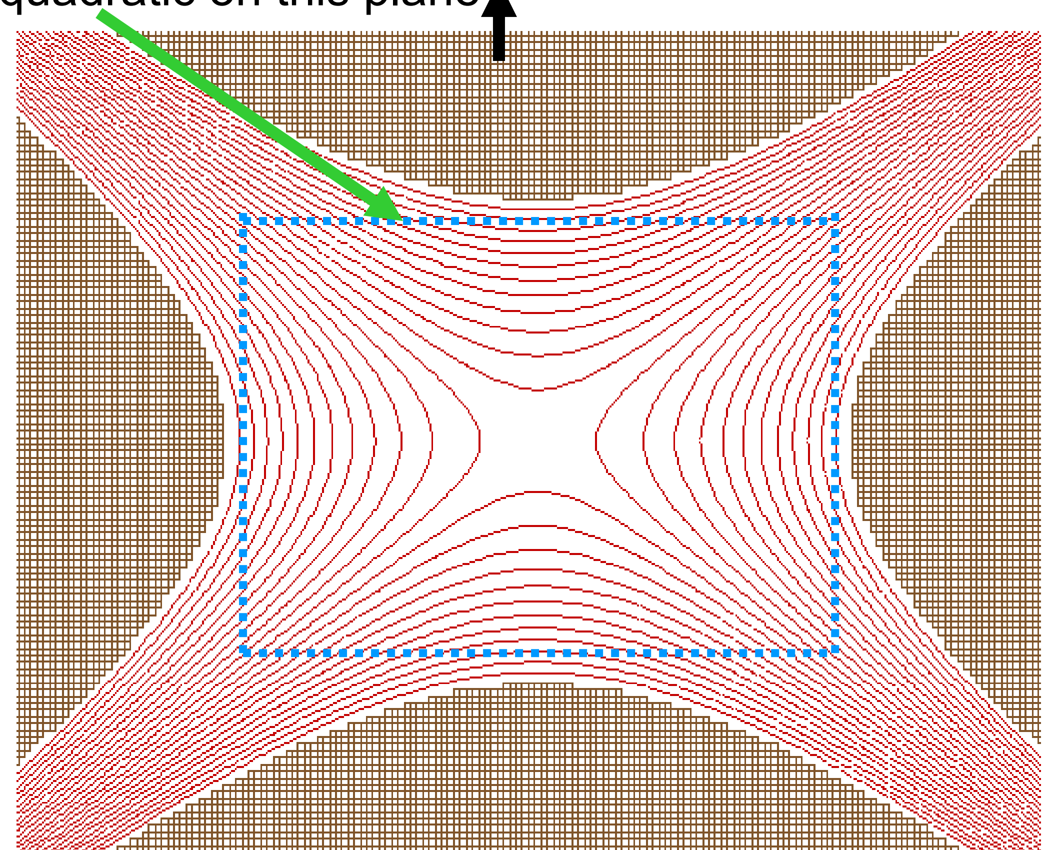


New boundary conditions: cylindrical surfaces with quadratic potential functions—fields inside are the same!



Equipotential boundary conditions: three hyperboloidal electrodes

Potential is quadratic on this plane



Resistive Electrodes

● Can make non-equipotential boundary conditions

● Other applications: resistive glass IMS drift tubes, reflectrons

Resistive disk

Resistive glass tube

All we need is a way to produce the desired function on the resistive material, either through a combination of electrode geometry and appropriate electrical connection points

For disk, we use metal rings under the resistive material

Planar resistive electrode ion traps

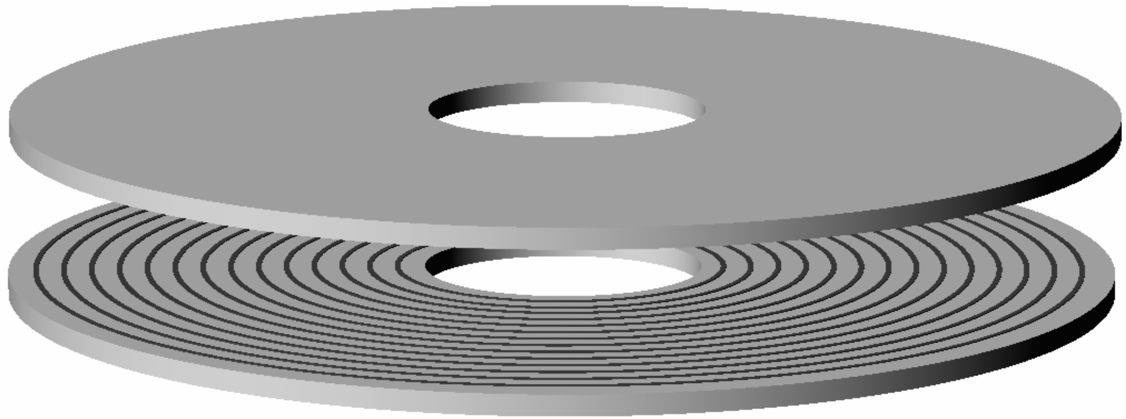
Two plates together make a trap

Field between plates defined by potential function on plates

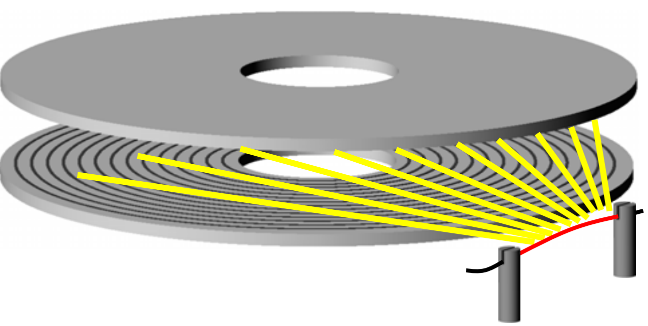
Field is optimized or changed by changing potential rather than geometry

The Halo Ion Trap—toroidal trapping geometry

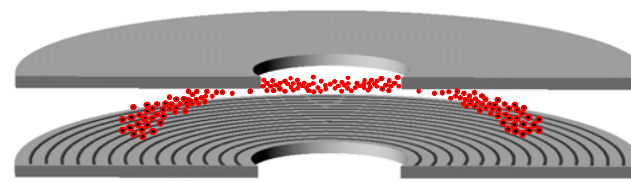
On the facing surfaces of two ceramic plates, 15 gold rings are deposited, then overlaid with germanium, quadratic potential function created using the rings



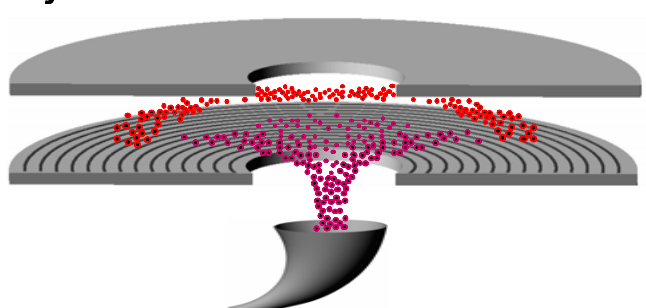
Electron ionization



Ion storage

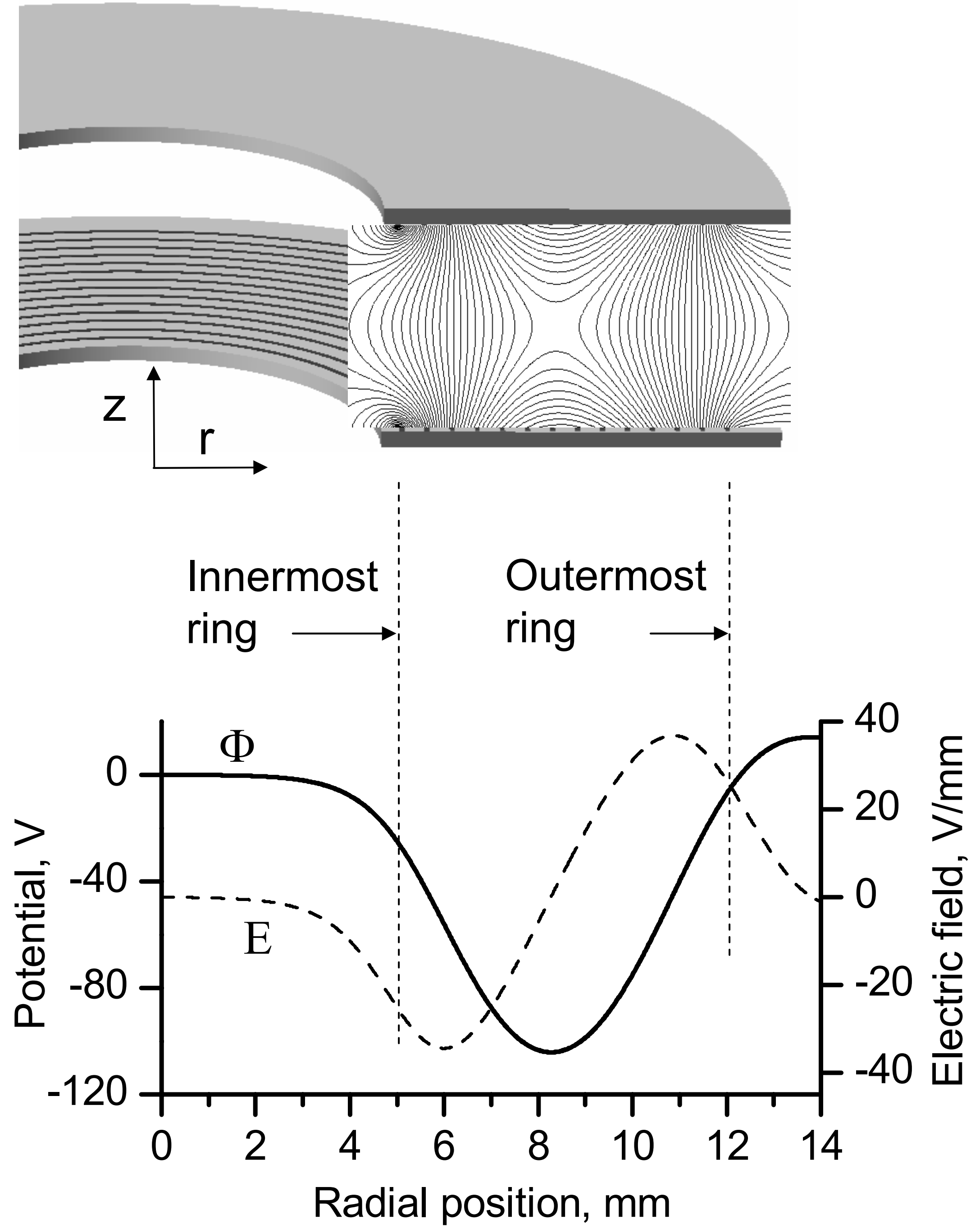


Ejection and detection of ions



Electric fields in the halo trap

as approximated by SIMION



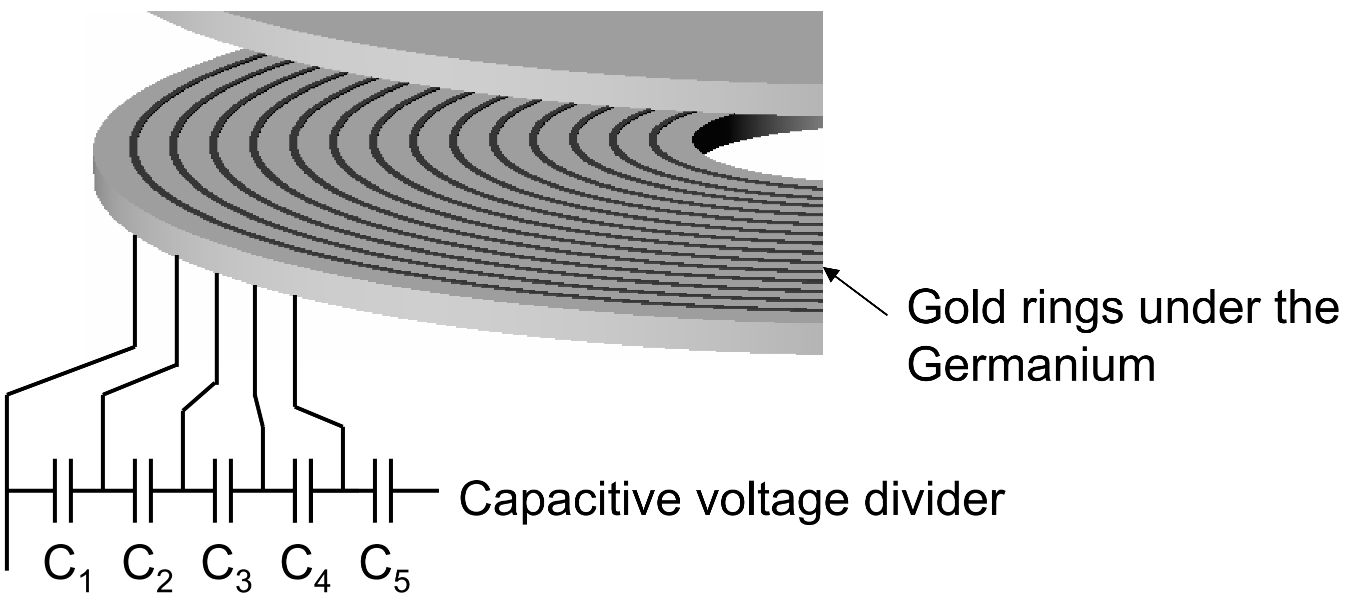
Note:

Every ring is independent, so there are many variable parameters

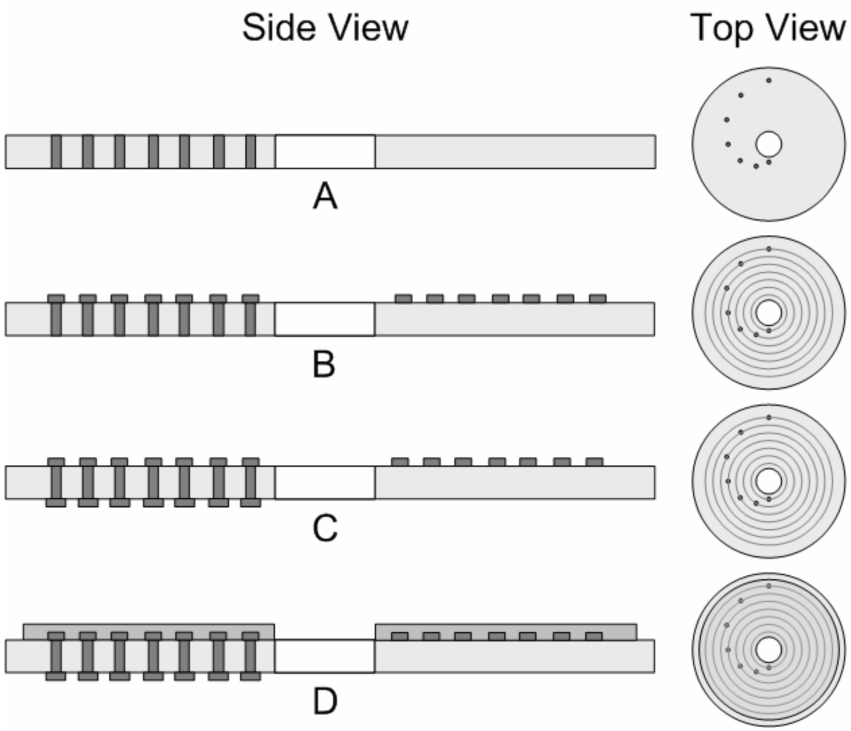
Quadrupole theory is not well defined in toroidal geometry

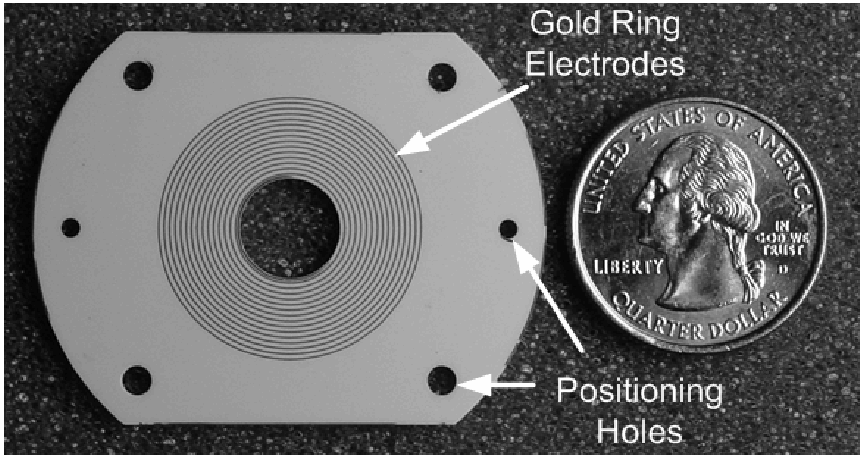
How the potential function is made

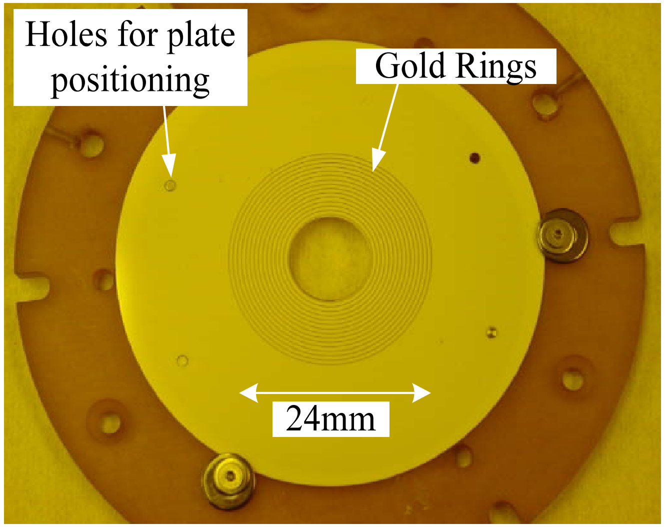
- Potential function on resistive material dictated by underlying rings
- Function on rings from capacitive voltage divider
- Very low current across resistive material
- Very thin (50 nm) Germanium used

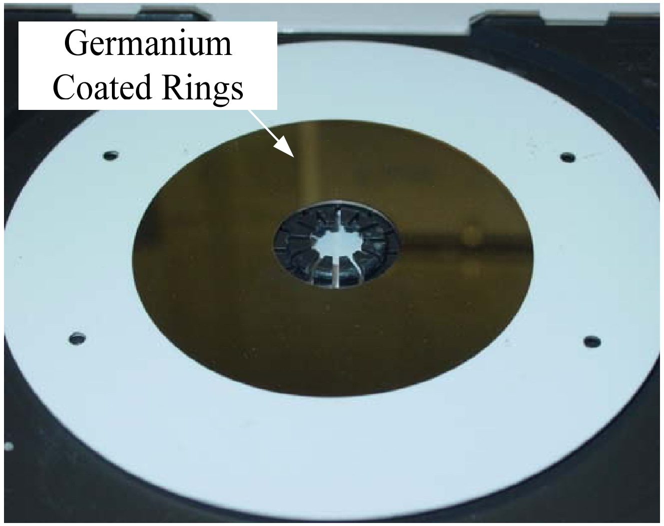


The prototype halo trap



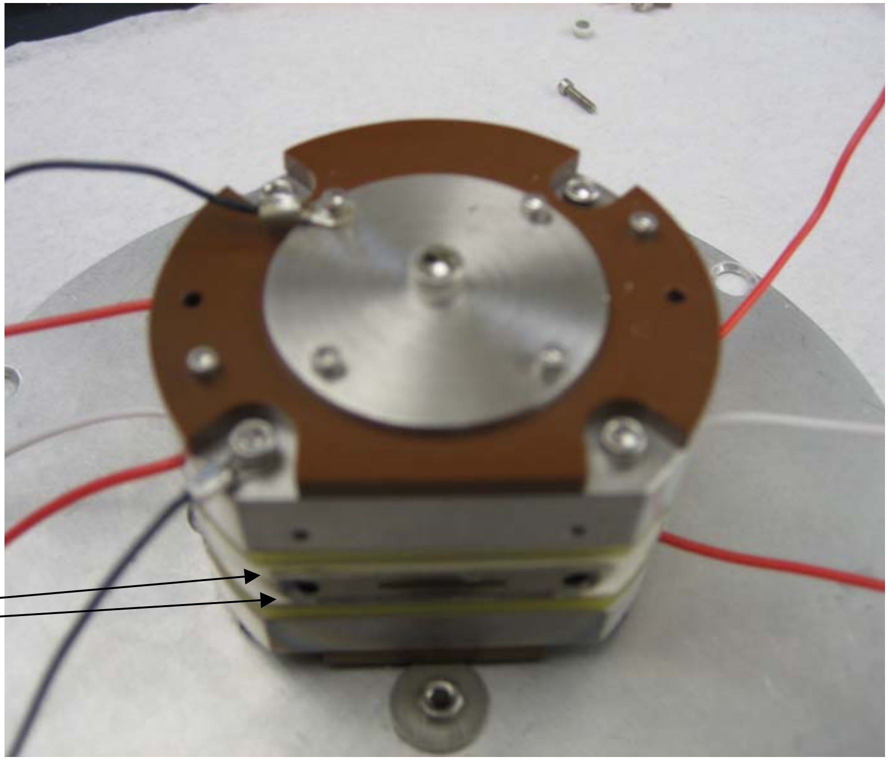






Experimental evaluation of Halo Ion Trap

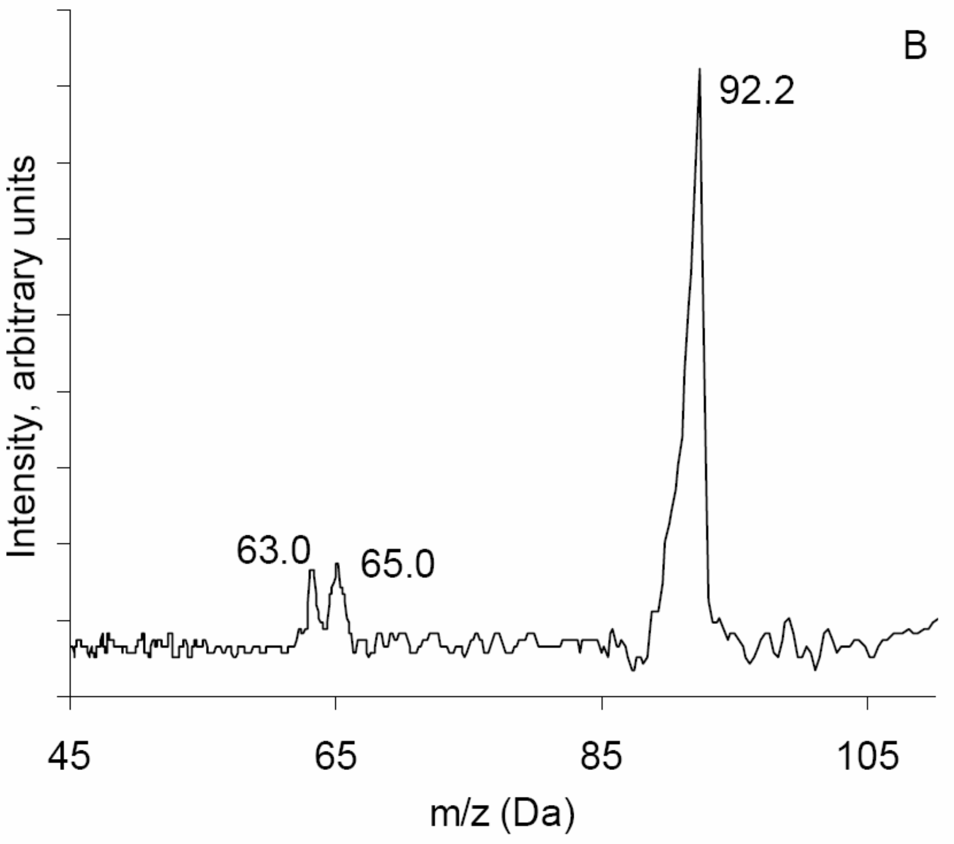
- 25 pF capacitive voltage divider establishes potentials on each plate
- 1.9 MHz driving RF, constant amplitude 650 V p-p
- Resonance ejection using frequency scan (50 to 600 kHz)
- Channeltron electron multiplier
- 1 mtorr He buffer gas
- *In situ* electron ionization



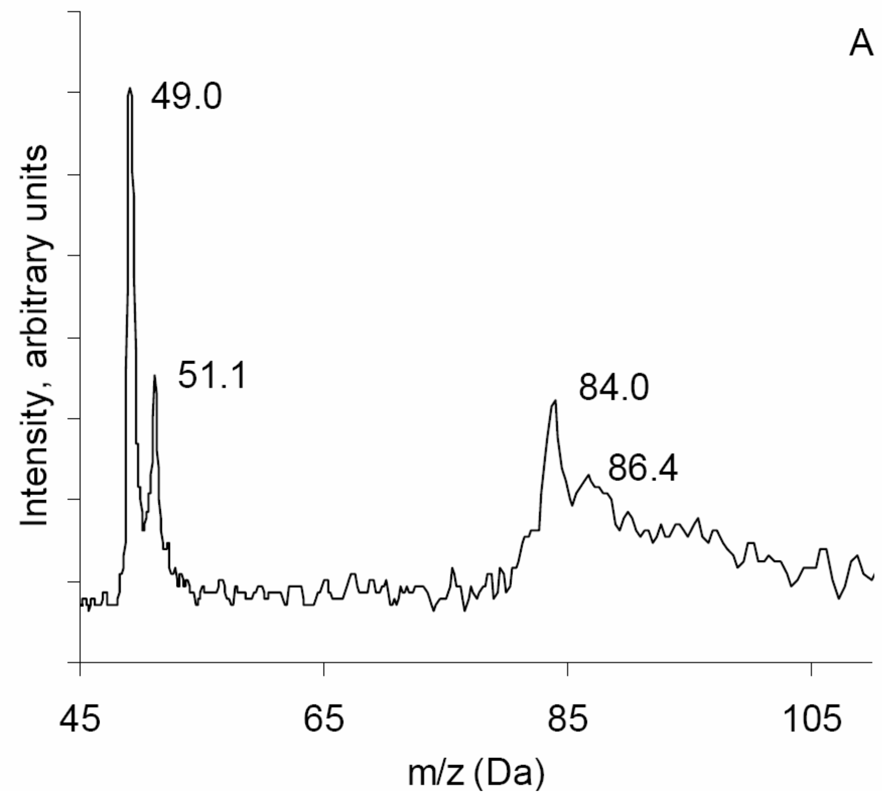
plates

Preliminary spectra

toluene



dichloromethane

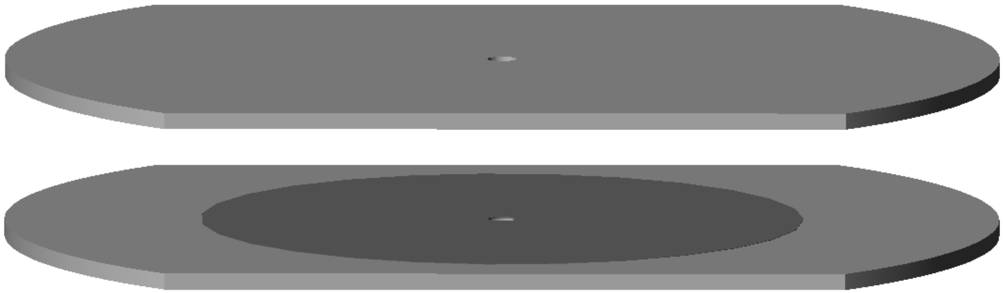


Potential advantages of Halo trap design

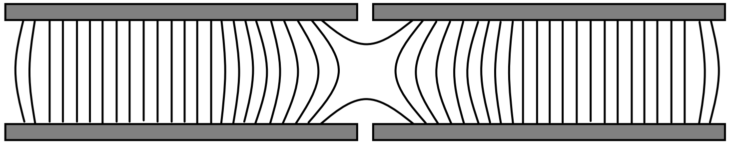
1. Fields can be optimized electrically rather than physically—no shims or spacers needed
2. Possible real-time field optimization—during a scan, switch between best trapping field and best analyzing field shapes
3. Alignment is simplified—only two parts to align
4. Fabrication can be done with sub-micron precision
5. Other trap geometries are possible using this approach

Main issue: edge effects

Other trap geometries using similar plates



Standard Paul trap

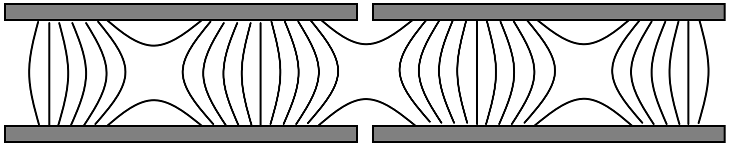


Ideal trapping geometry

Octopole can be added in

Status: built, no data yet

Double trap (Halo plus Paul)



Two traps in one

Status: started working
last week

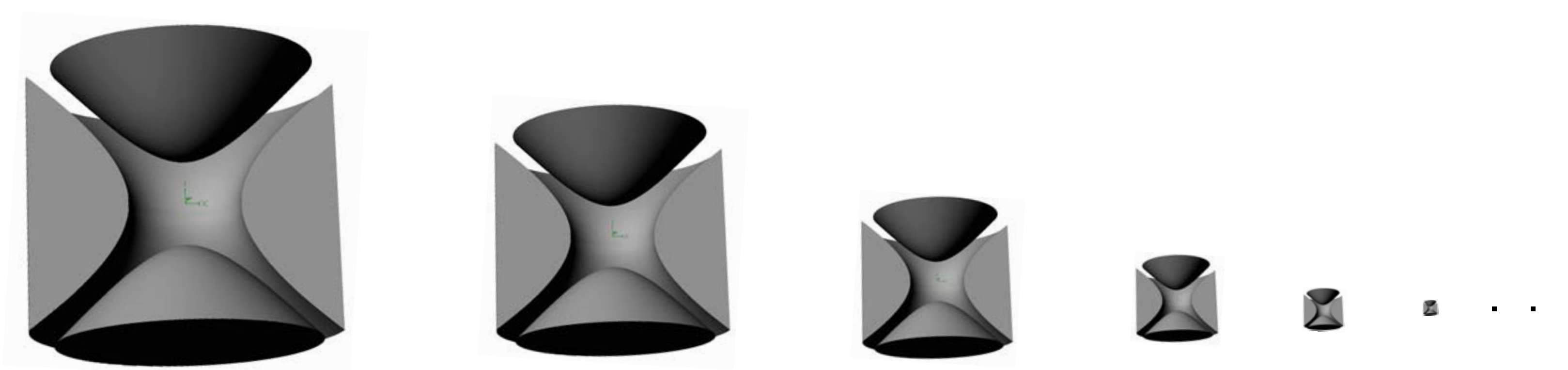
Making smaller mass spectrometers

Smaller mass analyzer is not the same as smaller overall instrument

However, 3 general results of a smaller mass analyzer

1. smaller mean free path = higher operating pressure, smaller pump
2. reduced power = smaller batteries
3. lower cost

Drawback: fewer trapped ions, arrays used to recover sensitivity



Making smaller mass spectrometers

$$\frac{m}{z} \propto \frac{Vt^2}{d^2}$$

Time-of-flight

$$\frac{m}{z} \propto \frac{r^2B^2}{V}$$

Magnetic

$$\frac{m}{z} \propto \frac{V}{r_0^2\Omega^2}$$

Quadrupole

Efforts to miniaturize each of these, but more efforts on quadrupoles
(both filters and traps)

The standard approach: smaller and smaller fabrication methods

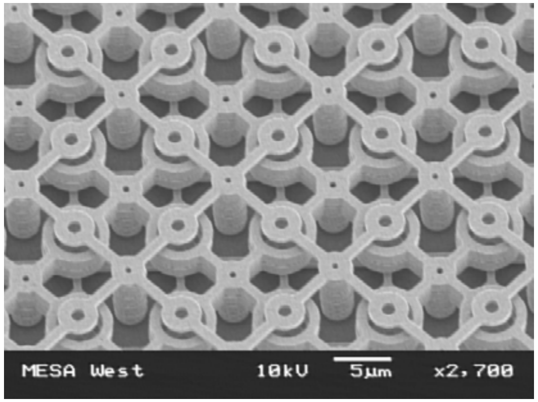
simplified geometry (cylindrical)

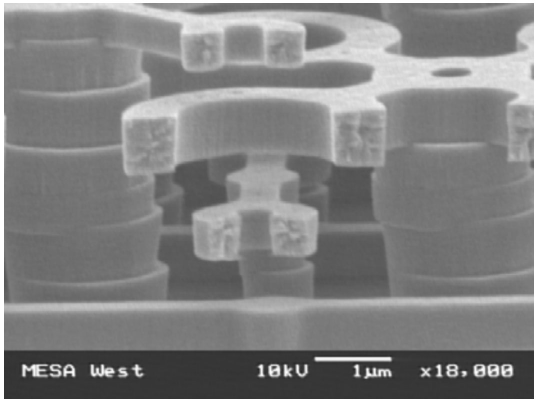
microfabrication techniques

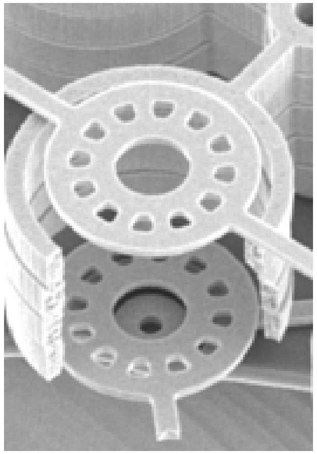
machinist with microscope and lots of patience

Microfabricated cylindrical ion trap arrays at Sandia National Labs

1-10 micron radius, 1-2 GHz, arrays of up to 10^6 traps







Issues: hard to get ions in—hole too small, short stopping distance

hard to get electrons or photons in for *in situ* ionization—same access issue

capacitance was large—no power advantage

issues with layer alignment, tapering

only one ion per trap could remain stable

noise—detector too close to RF

collisions disrupt phase of ion motion more than larger traps

device was fragile

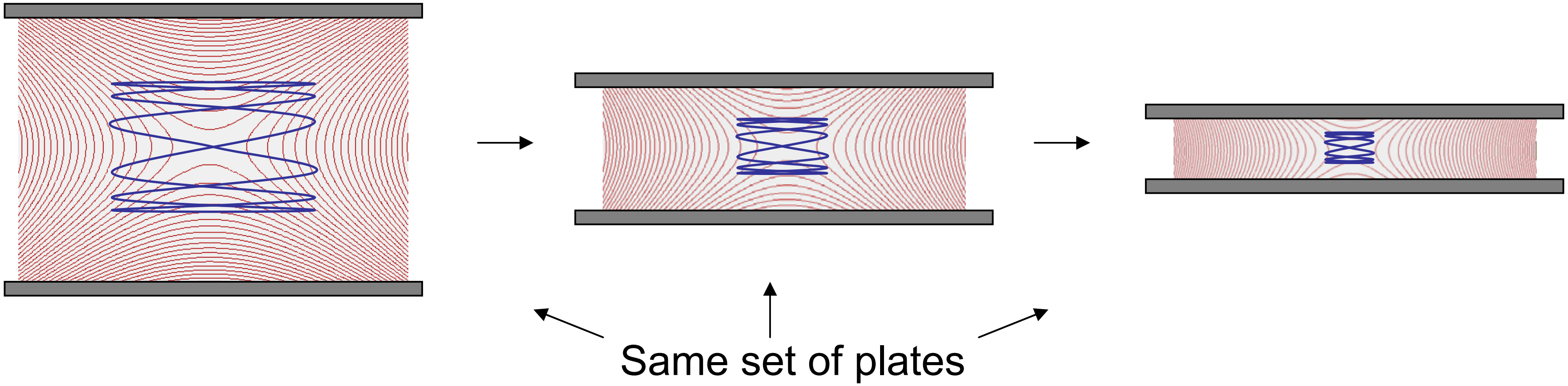
Rethinking…

Perhaps making traps smaller is not the most effective approach to achieve the goals of miniaturization

However, this is a necessary limitation of metal electrodes

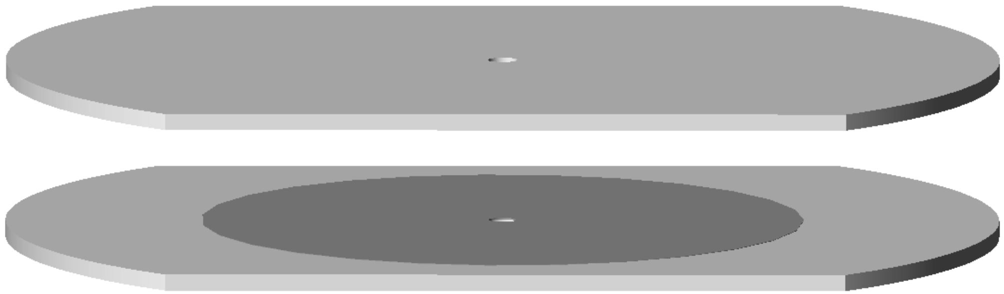
What about resistive electrodes?

Smaller ion mean free path by moving resistive plates closer together and raising trap frequency



- Because the potential on the plates is quadratic, the field is quadrupolar regardless of the distance between plates—this is not shimming!
- The two plates have identical potential distributions, so capacitance does not increase as they are moved together
- This is the same using higher voltage on standard trap—but without higher V
- Edge effects are reduced using this process

Expected advantages of resistive electrode traps for miniaturization:

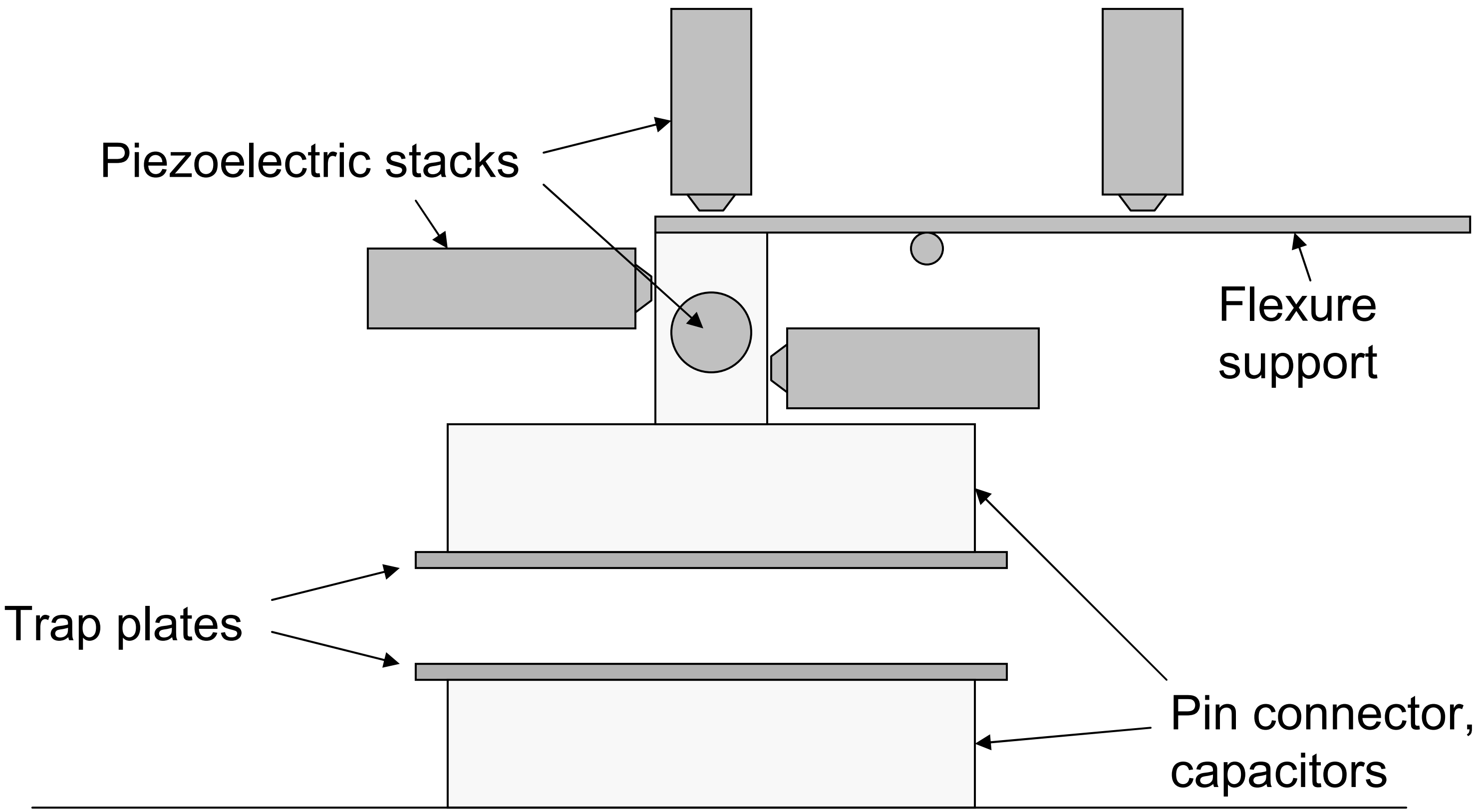


- surface planarity, roughness controlled to within tens of nanometers
- amenable to microfabrication methods
- alignment simplified: only two pieces
- larger access area for ionization
- sturdy—no tiny parts
- ceramic disks can be any thickness—greater strength

Piezoelectric alignment of plates

Only 5 degrees of freedom

Five piezoelectric actuators allow 10 nm positioning in all directions, angles

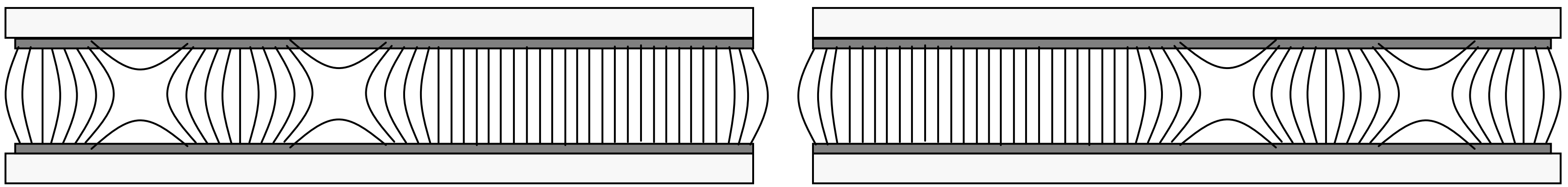


A new world of possibilities

Trapping center does not have to stay in the same spot during a scan

Multiple trapping regions perform different, simultaneous functions

Ions ejected from toroidal trapping region are escorted into center of plates



Acknowledgements

Austin Group

Ying Peng

Shawn Perdue

Shawn Pitcher

Ivan Miller

Seth Call

Todd Wickard

Terik Daly

Aaron Hawkins Group
(Elec Eng)

Brett Hansen

Collaborators

Miao Wang

Milton Lee

Ed Lee

Samuel Tolley

Steve Lammert

Doug Later

Alan Rockwood

Funding from NASA Planetary Instrument Definition and Development Program