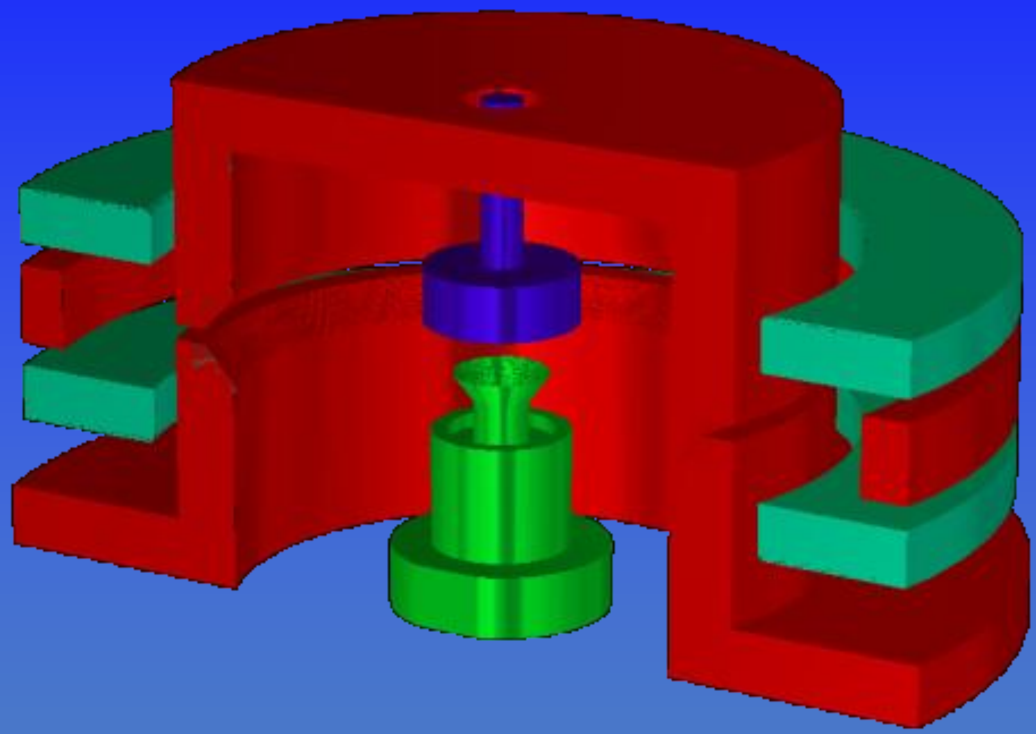
Cylindrical Toroidal Ion Trap Mass Spectrometer



Daniel Austin and Nick Taylor

Brigham Young University, Provo, Utah

Why miniaturize ion traps…

- Geometrically compact
  - Higher tolerance to pressure
    - Amenable to GC-MS, LC-MS
      - Tandem MS capabilities

…and how this leads to smaller MS?

Smaller traps lead to:

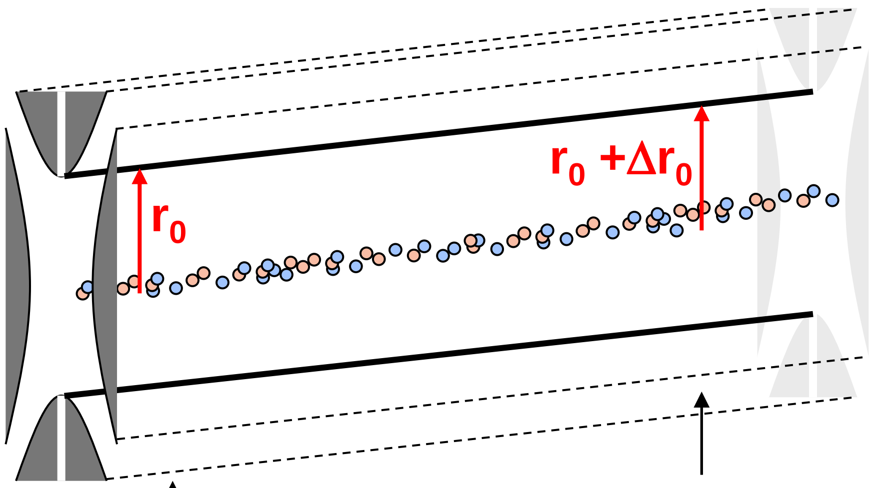
- Smaller vacuum systems
- Smaller power supplies
- Smaller vacuum chamber
- Faster analysis

Issues in miniaturization of ion traps

Sensitivity: reduced number of trapped/analyzed ions

- Arrays of traps
- Extended trapping dimensions (linear or rectilinear ion traps)

Resolution: harder to maintain relative accuracy of electric fields



Mass selected here, *m*

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

Mass selected here, *m* + Δ*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/Δm)

r_0 = 1 cm, Δr = 5 microns

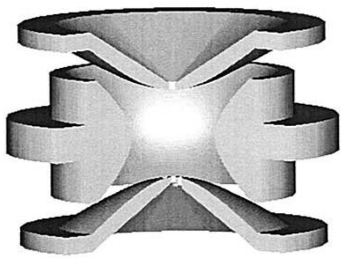
r_0 = 1 mm, Δr = 500 nm

r_0 = 0.1 mm, Δr = 50 nm

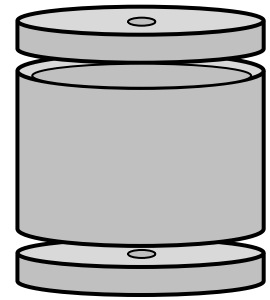
The same is true with arrayed analyzers

Simplified electrode shapes for miniaturized ion traps

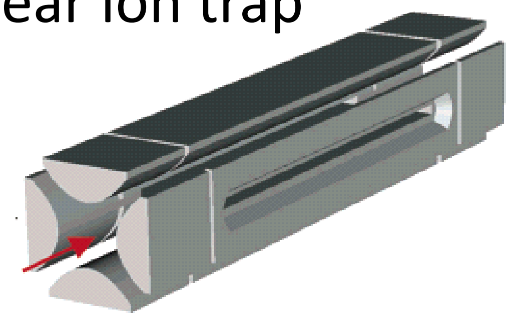
Quadrupole ion trap



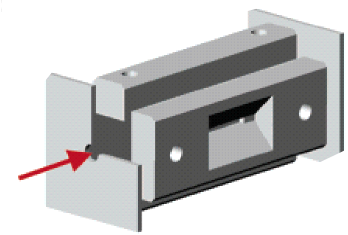
Cylindrical ion trap



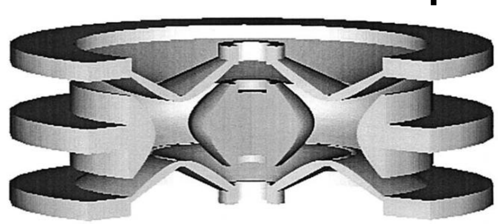
Linear ion trap



Rectilinear ion trap

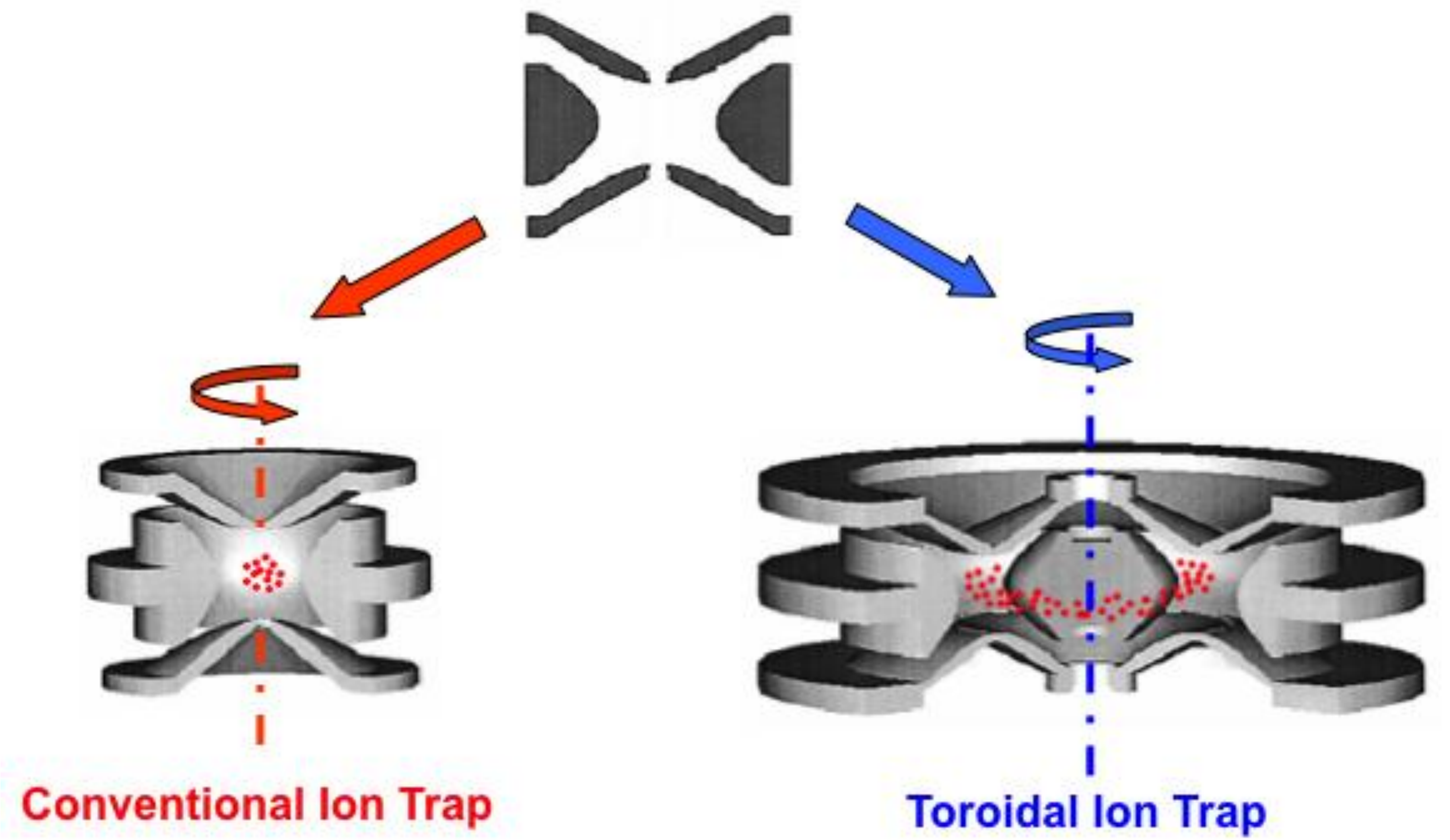


Toroidal ion trap



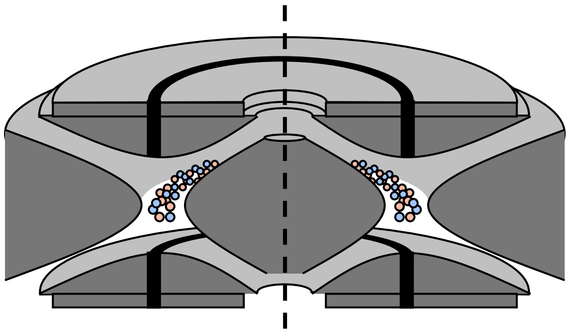
???

The Toroidal Ion Trap

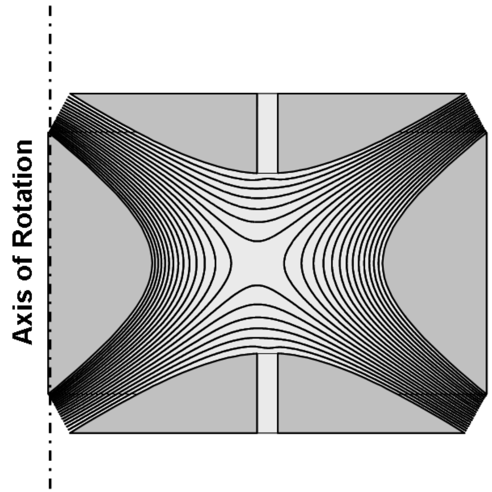


Lammert et al, *IJMS*, 2001.

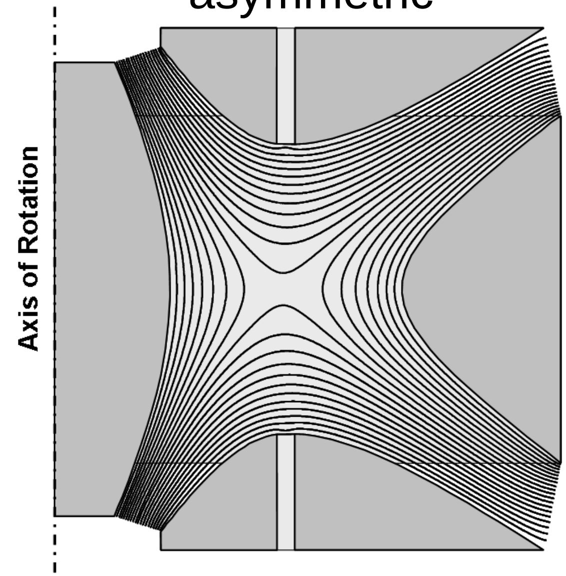
Toroidal ion trap requires electrode asymmetry to offset curvature

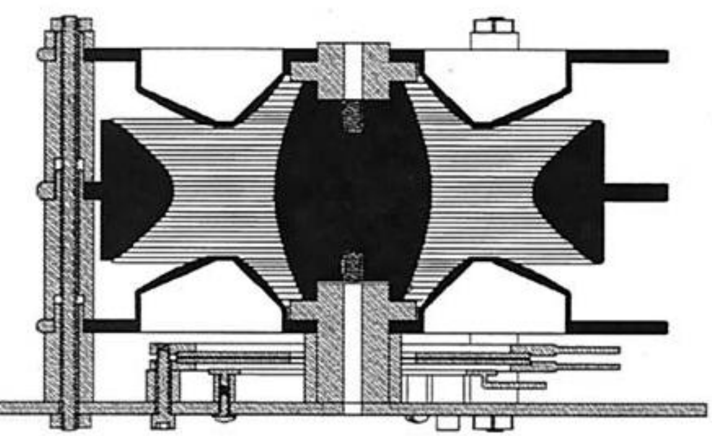


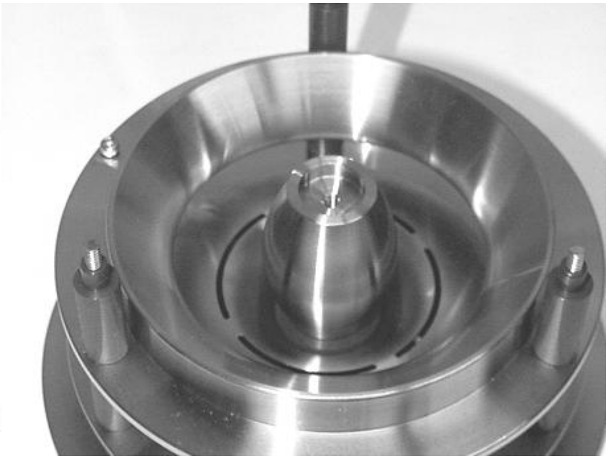
symmetric

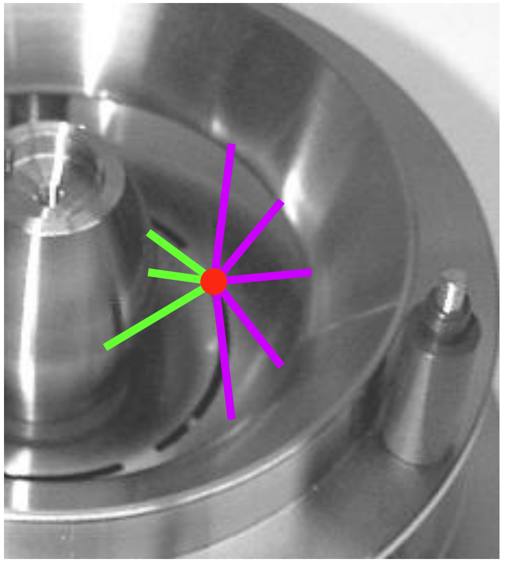


asymmetric



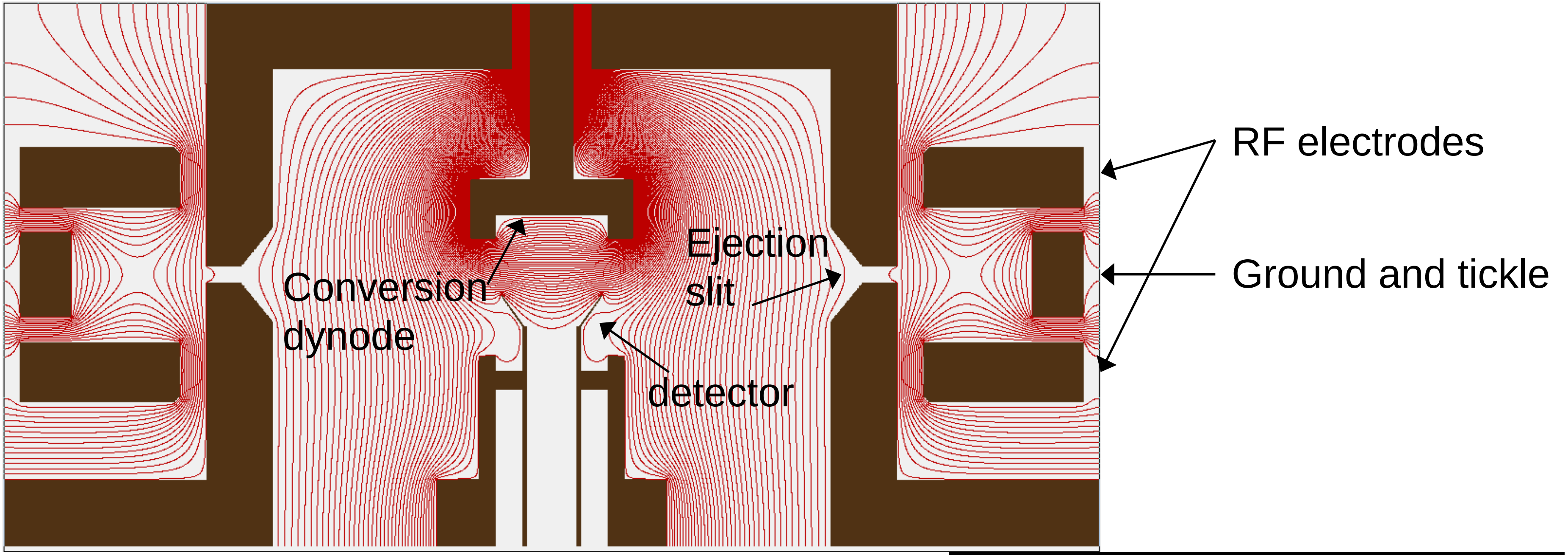






Lammert et al, *IJMS*, 2001.

Cylindrical Toroidal Ion Trap

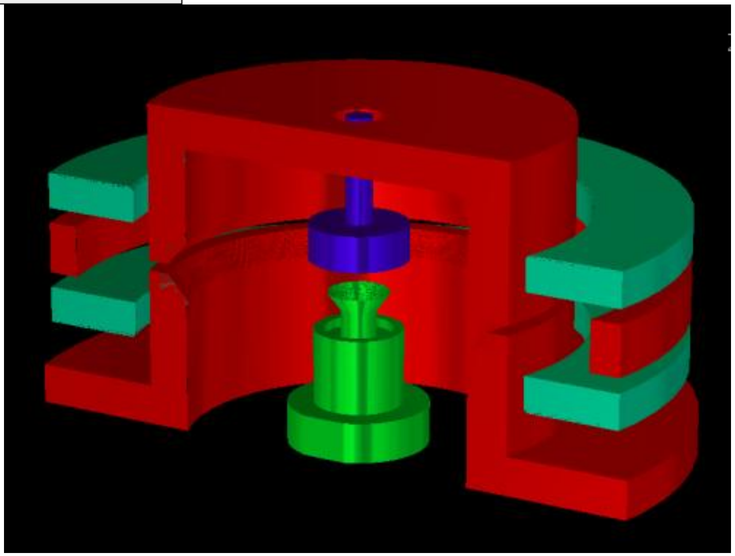


Electrodes are cylindrical surfaces—easier to machine or fabricate

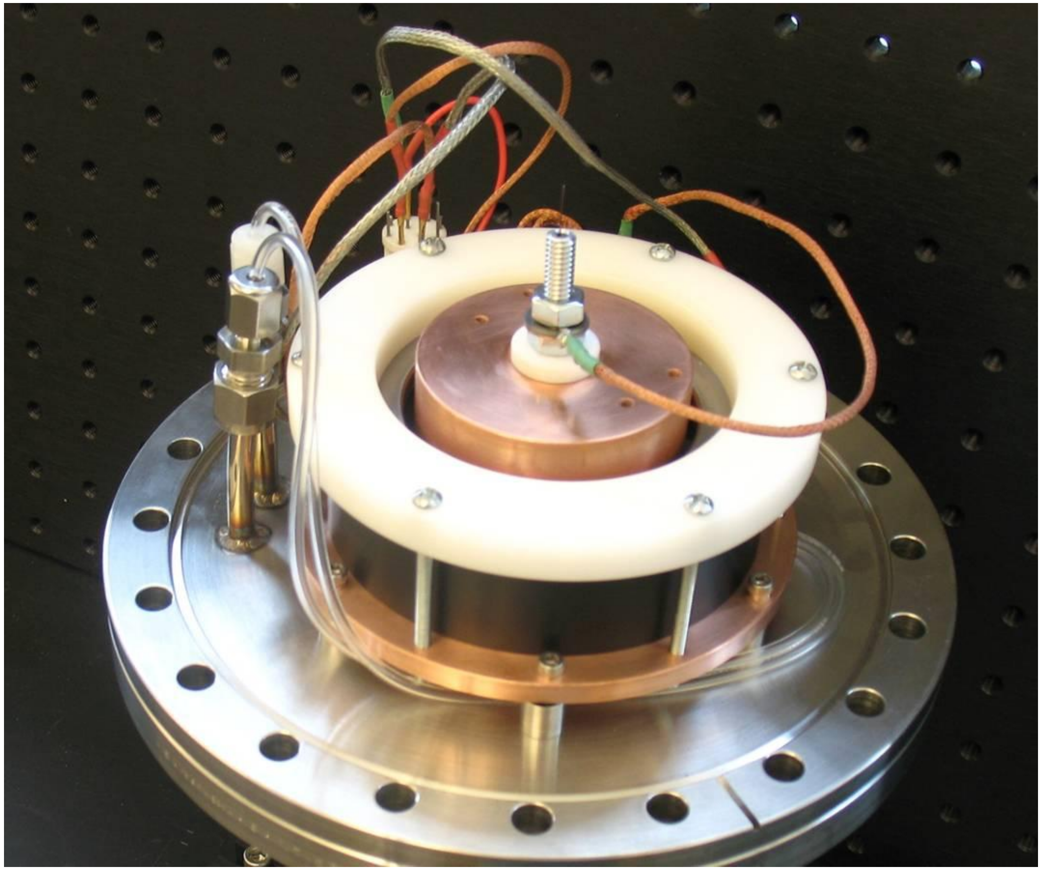
Asymmetric overlap of electrodes corrects for toroidal curvature

Ejected ions focused onto a single point for simplified detection (small EM or Faraday wire)

All ions ejected inward



Prototype Cylindrical Toroidal Ion Trap



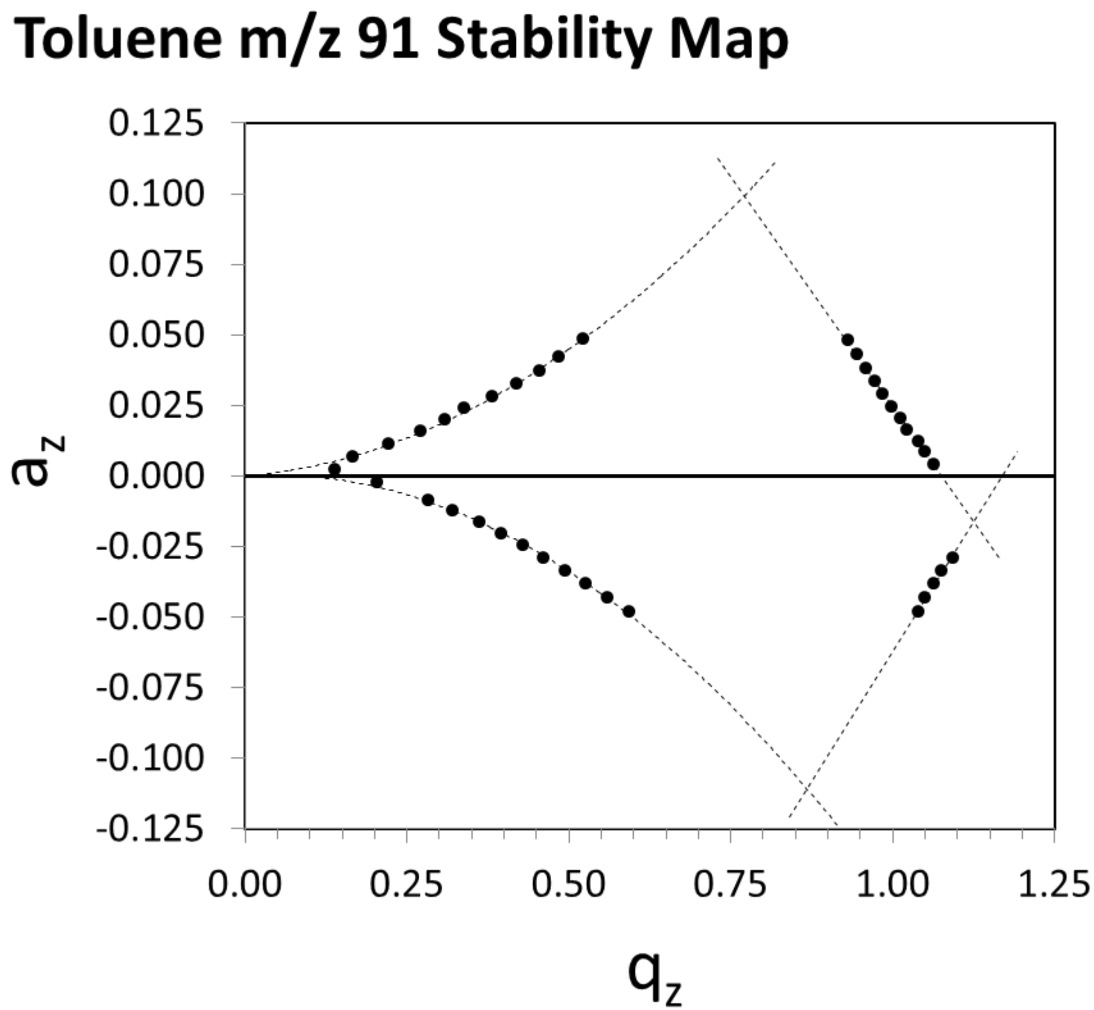
Major radius: 30 mm

Minor radius: 6 mm

RF frequency: 1.2-2 MHz

RF amplitude: <700 V 0-p

Experimental Stability Map of Cylindrical Toroidal Ion Trap



This very closely resembles the stability map reported for a RIT with x_o = 5.0 mm, y_o = 3.8 mm

Slight asymmetry of stability region attributed to two factors:

1) Asymmetric electrode spacing

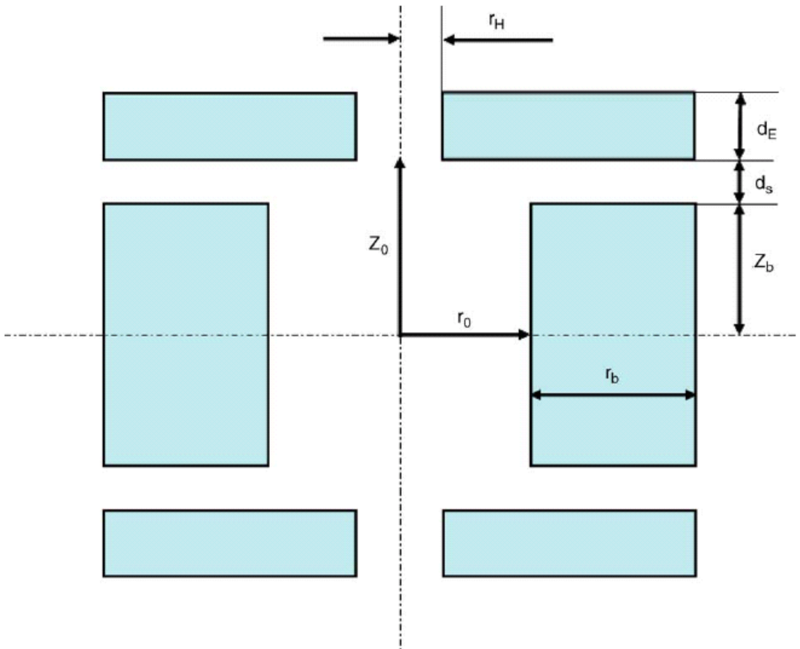
x_o = 6.00 mm

y_o = 5.88 mm

2) Curvature of the trapping volume

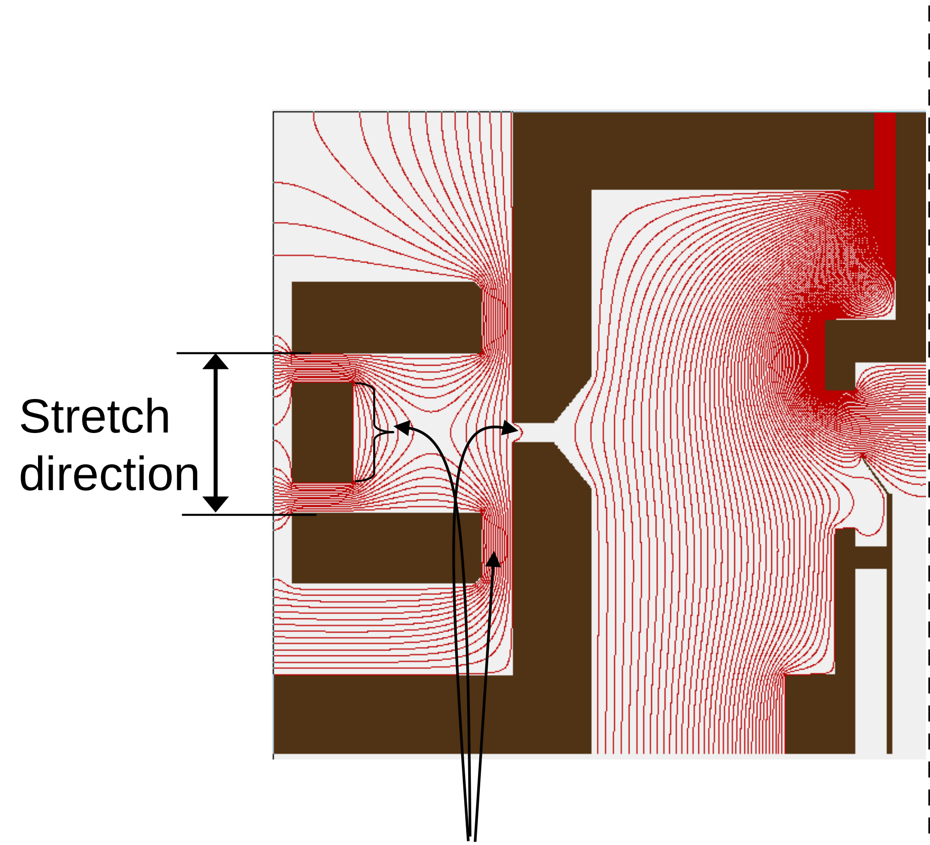
Stretching electrode spacing to adjust higher-order multipoles

Analogous to CIT



CIT	z_0 (mm)	z_b (mm)	d_s (mm)	r_H (mm)
CIT-0	5.0	3.4	1.6	0.5
CIT-1	5.0	3.4	1.6	1.5
CIT-2	5.3	3.7	1.6	1.5
CIT-3	5.5	3.4	2.1	1.5
CIT-4	5.0	4.3	0.7	1.5

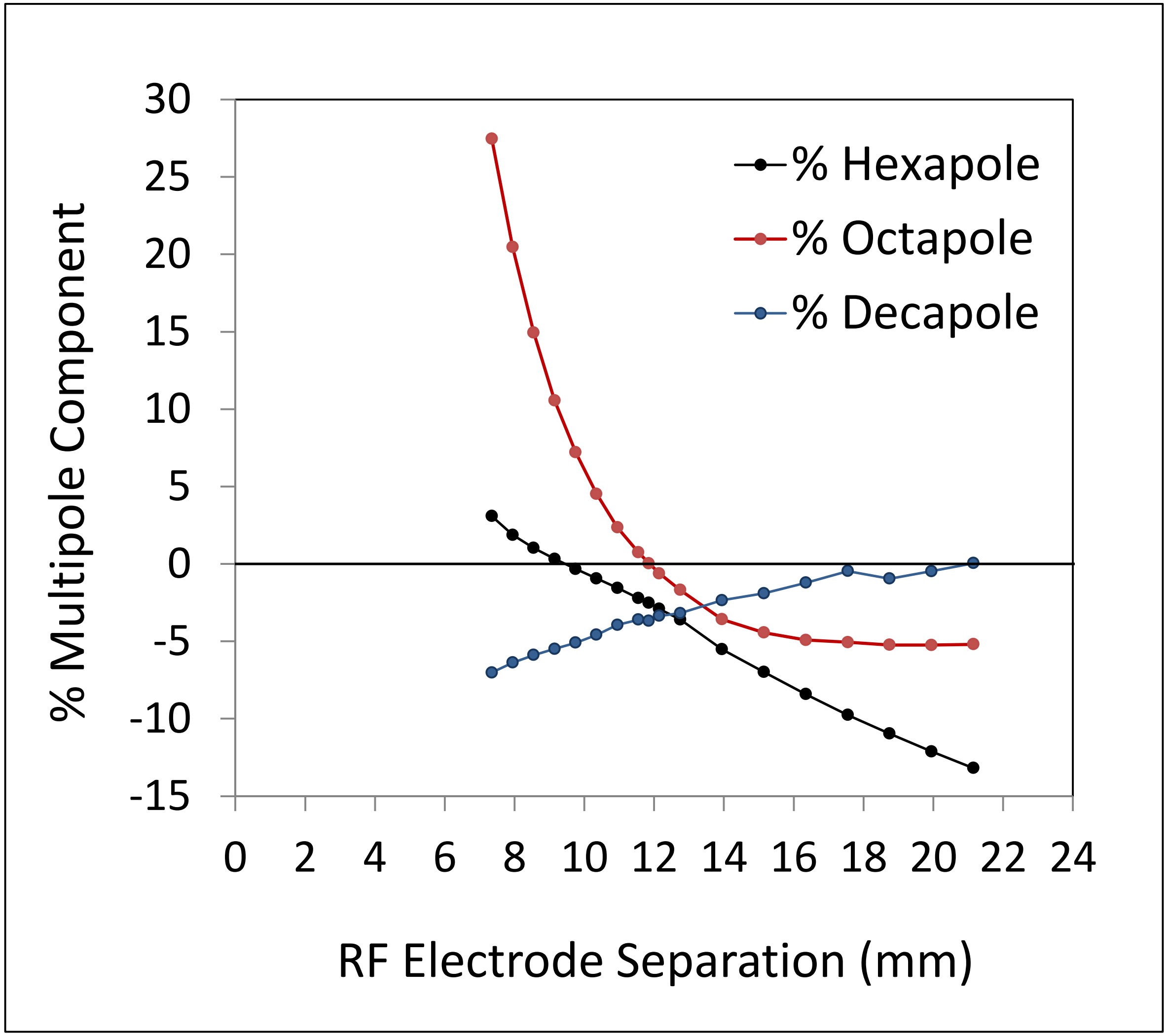
G. Wu et al. *Int. J. Mass Spectrom.* 241 (**2005**) 119-132.



These dimensions
can also be adjusted

All of these dimensions have asymmetric effect on trapping fields

Effect of stretching the RF electrode spacing



0 % Stretch
% Hexapole = -2.3 %
% Octapole = 0.0 %
% Decapole = -3.4 %

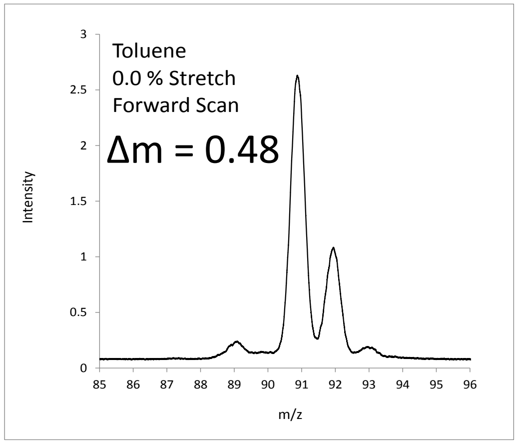
-2 % Stretch
% Hexapole = -2.2 %
% Octapole = +0.7 %
% Decapole = -3.6 %

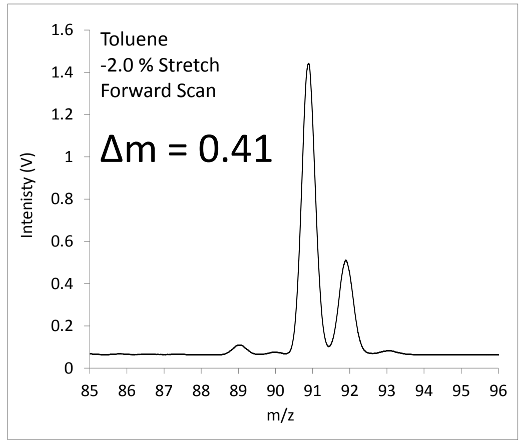
-5 % Stretch
% Hexapole = -2.0 %
% Octapole = +1.0 %
% Decapole = -3.7 %

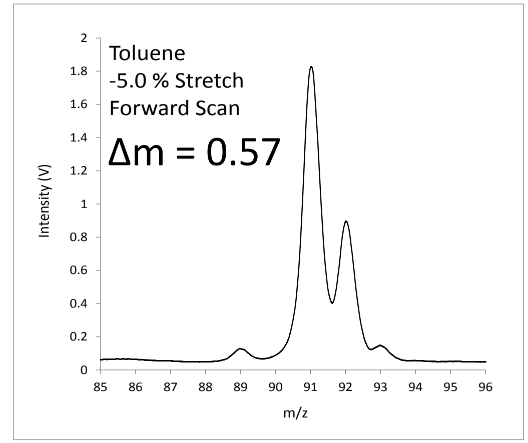
Evaluation of Resolution (Δm) of Toluene

0.0 % Stretch | -2.0 % Stretch | -5.0 % Stretch

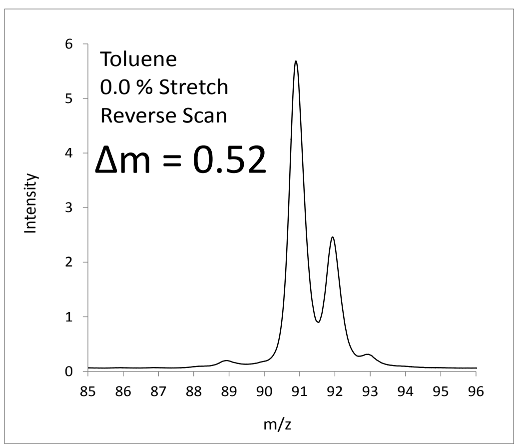
Forward Scan

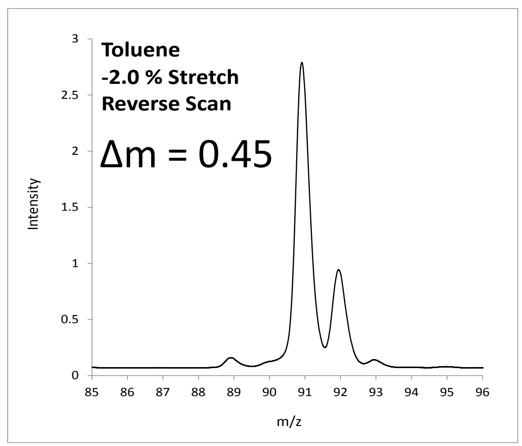


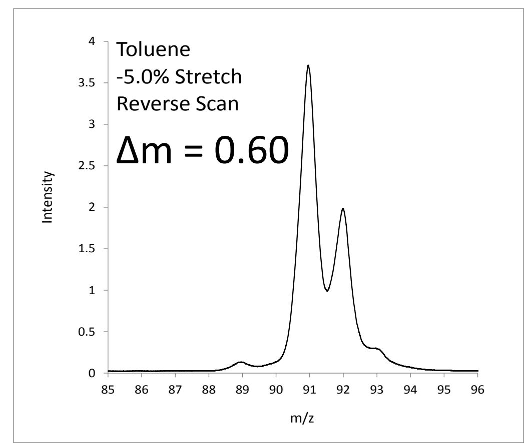




Reverse Scan



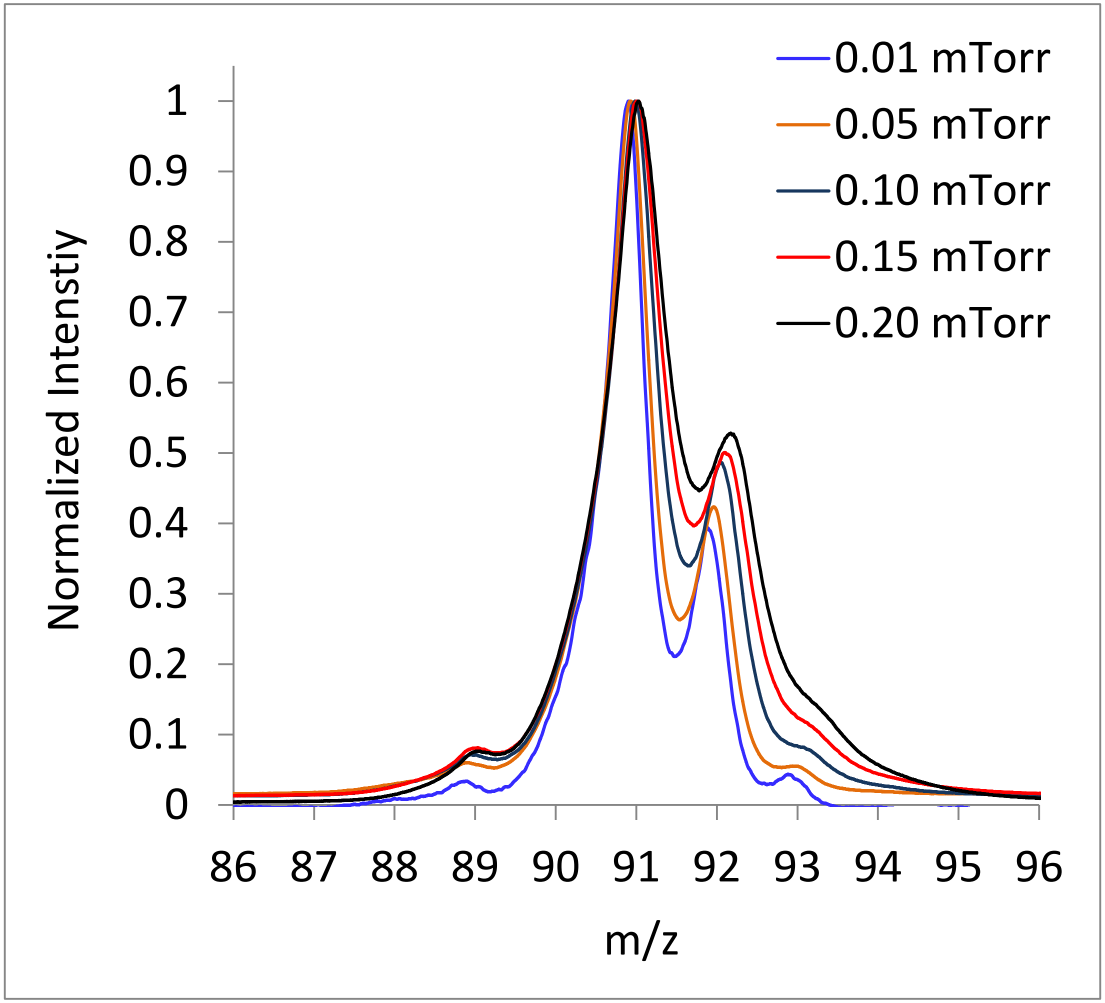




Mass resolution compares well with other toroidal ion traps

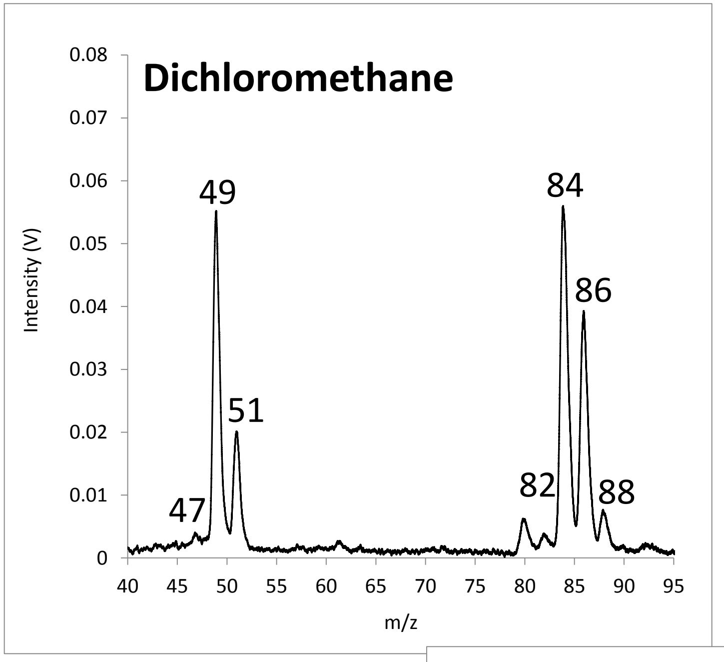
Study	Trapping Radius (mm)	Test Molecule	Ion Mass	Resolution (Δm)
Original toroidal IT (Lammert *et al.*)	7.83	n-butylbenzene	91	0.4 - 0.5
Miniaturized toroidal IT (Lammert *et al.*)	2.00	n-butylbenzene	91	0.4
Guardion 7 (Contreras *et al.*)	2.00	Toluene	91	0.42
Halo ion trap	3.50	Toluene	91	1.3
CTIT	6.00	Toluene	91	0.41

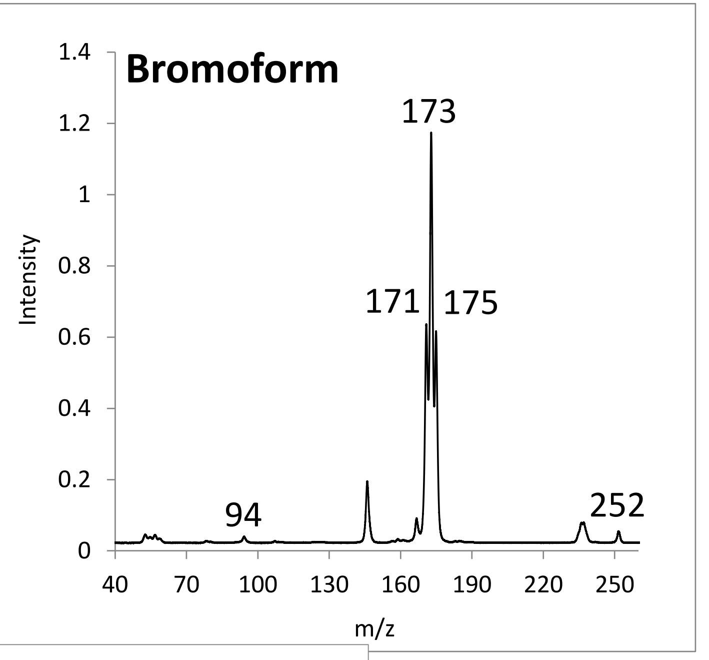
Ion Capacity: Effect on Resolution and Mass Accuracy

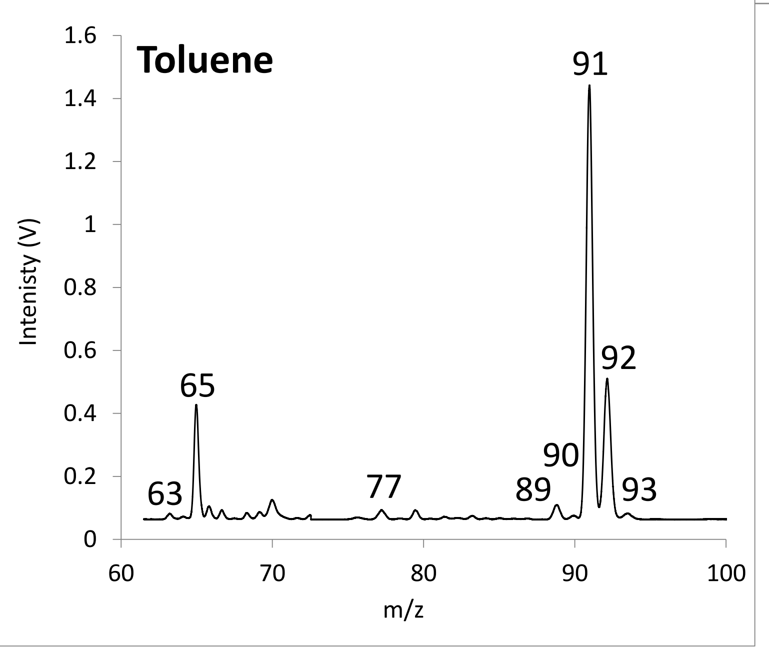


Reverse Scan mode
Resonance ejection used
AC = 215 kHz, 3.50 $V_{p\text{-}p,}$ 3.25 V_{DC}
Can only speak on terms of the sample partial pressure not on the absolute ion populations

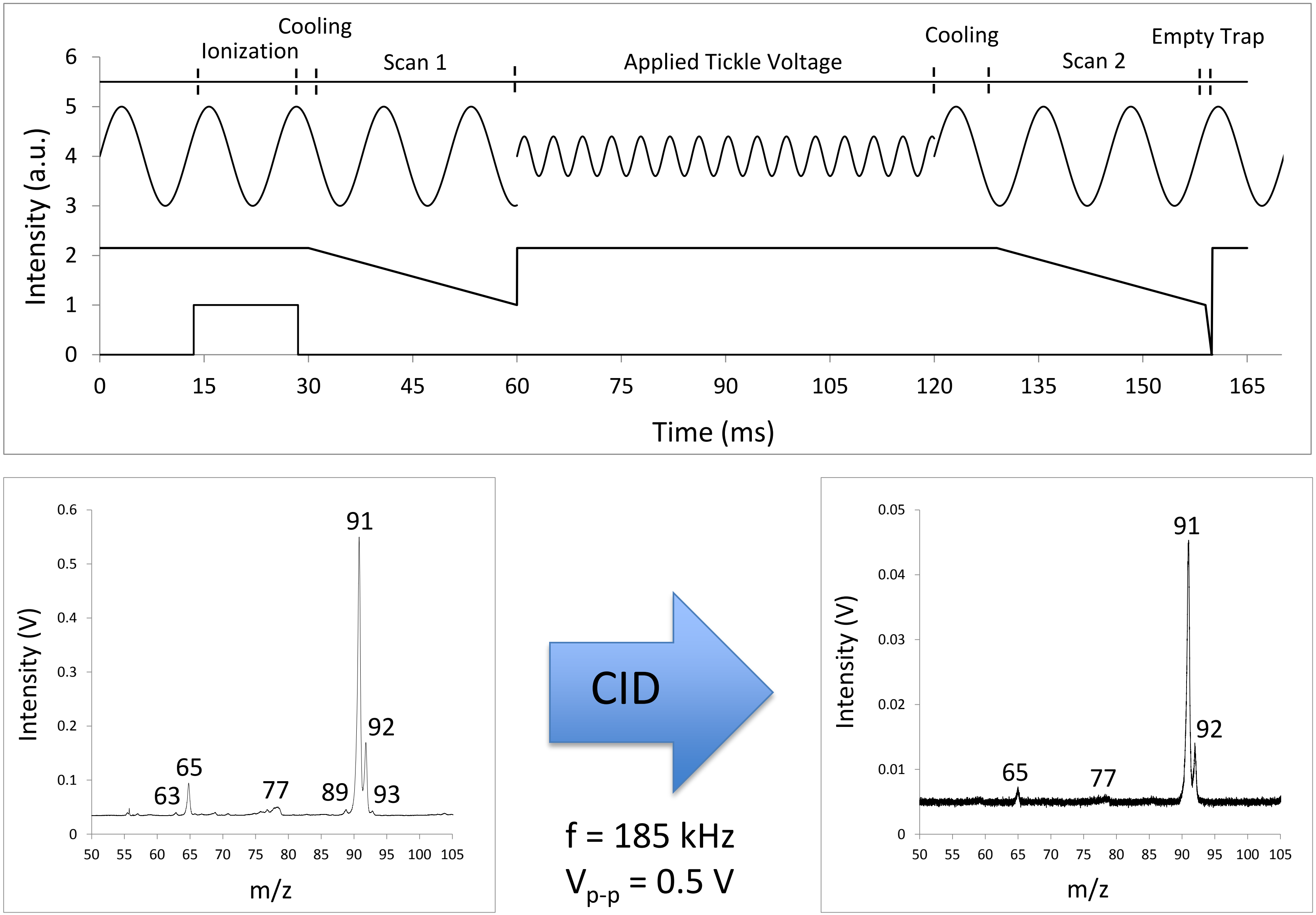
Other Mass Spectra



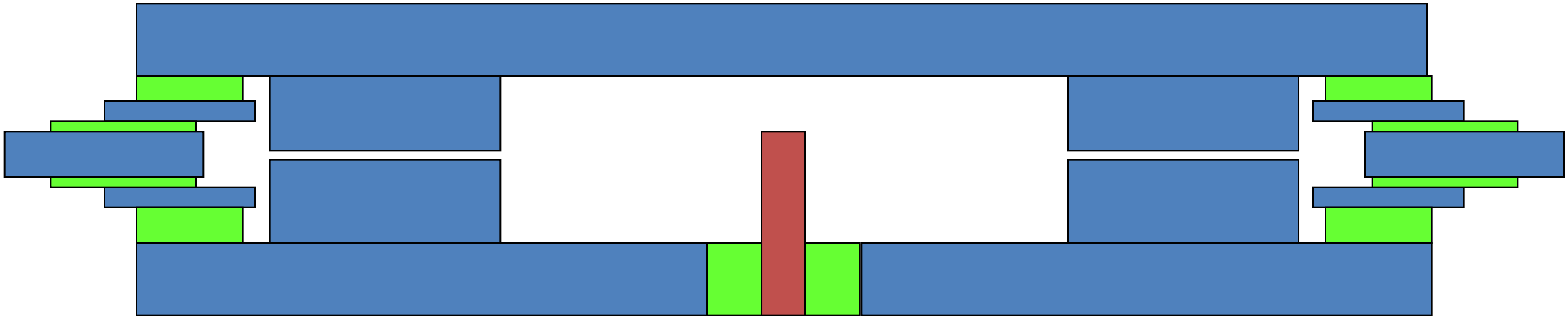




Tandem Mass Spectrometry (MS^2) of the m/z 134 Molecular Ion of Iso-butylbenzene



Next Step: miniaturized CTIT made from sheet materials



Sheet materials (stainless steel, teflon, etc.) available with thickness down to tens of microns—excellent uniformity of thickness

Inexpensive materials

Laser cutting or pressed-stack milling provides high accuracy of shape in 2 dimensions

Alignment of individual pieces using jigs

Integrated ion guide and ion optics with ¾-circle CTIT

Only minor radius needs to be reduced

In Conclusion….

We have demonstrated a toroidal ion trap mass spectrometer made with cylindrical electrodes

Asymmetry of electrode arrangement compensates for toroidal curvature

All ions ejected to a single point for improved detection

Mass resolution comparable to other toroidal ITs reported in the literature

Higher-order multipoles optimized by changing thickness of insulator layers

Tandem mass analysis demonstrated

Miniaturization facilitated by simplified electrode geometry

Questions?