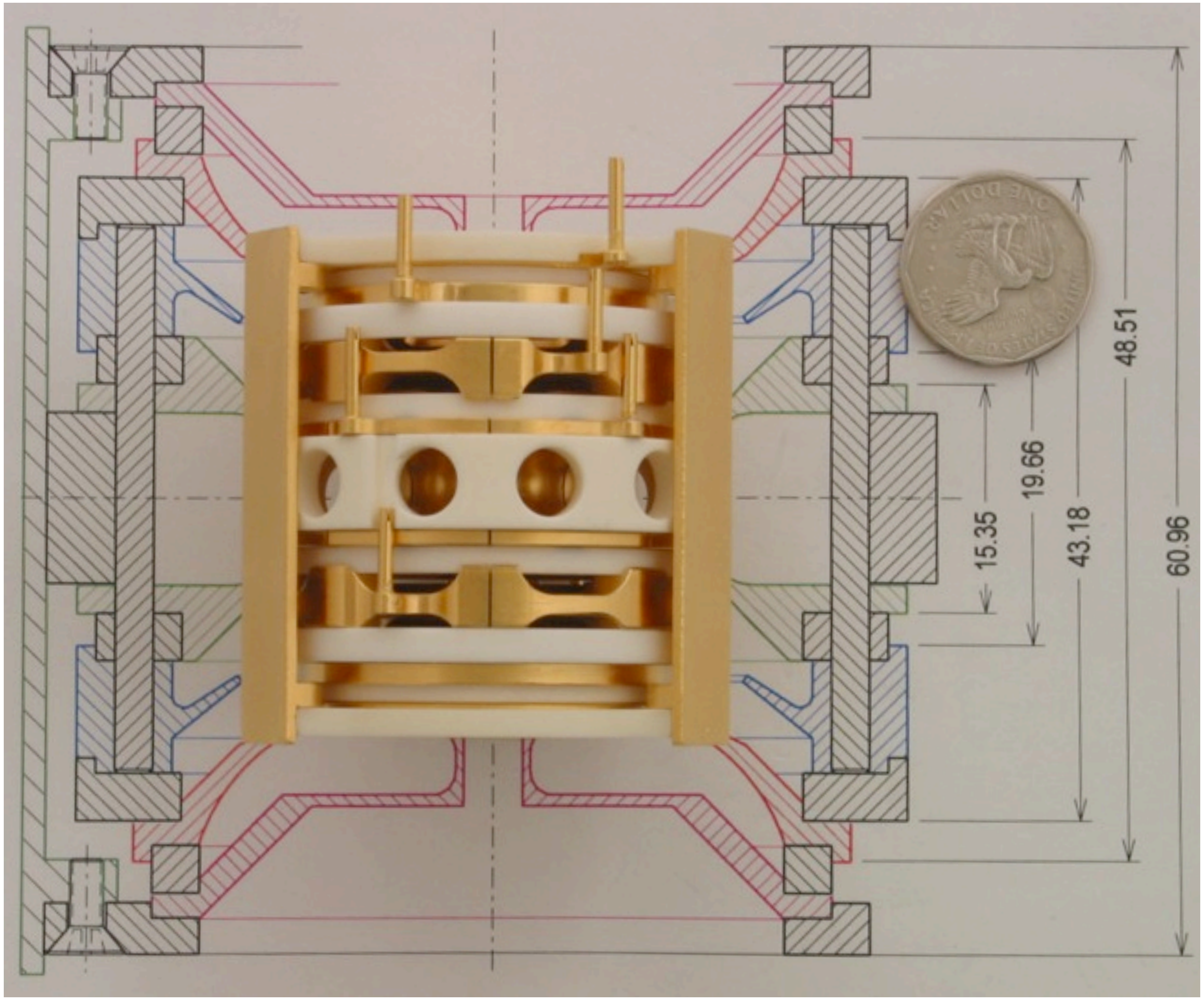
Plans for further technical development and improvements in trap-based mass measurements



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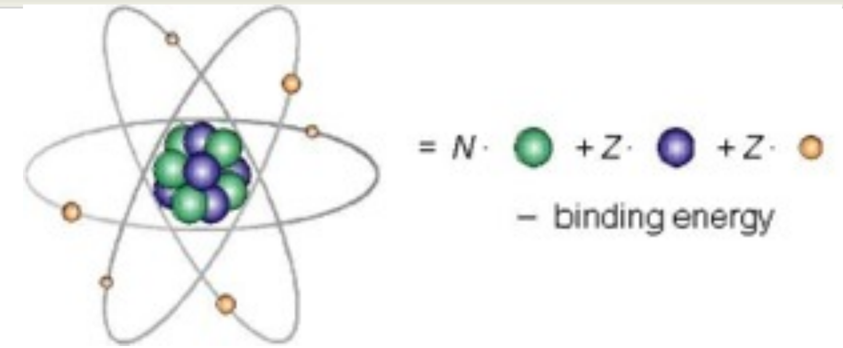
May 25th, 2010

Outline



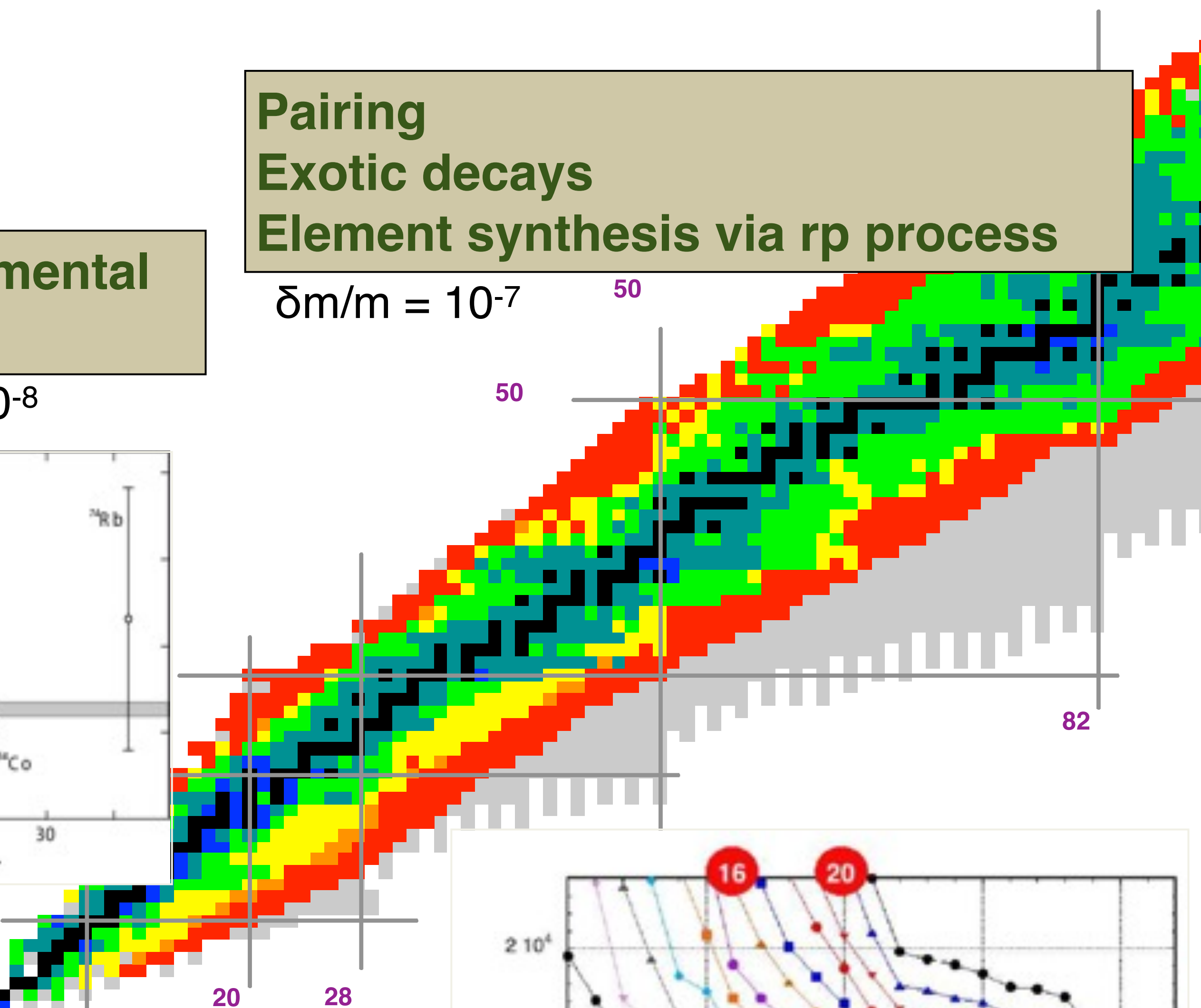
•Range of relative mass precisions required for mass measurements of rare isotopes

•Principles of Penning trap operation
  •confining fields
  •multipolar RF fields to drive ion motion
  •time-of-flight resonant detection technique
  •mass resolution

•State of the art and future technical developments
 - Short and long term implementation
 - NSCL's possible contributions

Masses of rare isotopes

Mass Uncertainties
δm/m
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
unknown

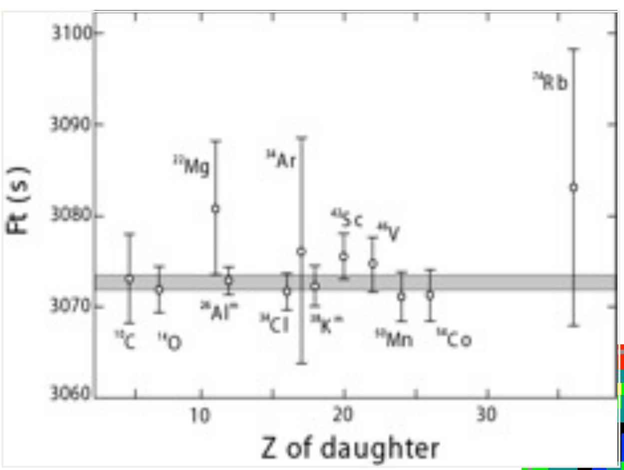


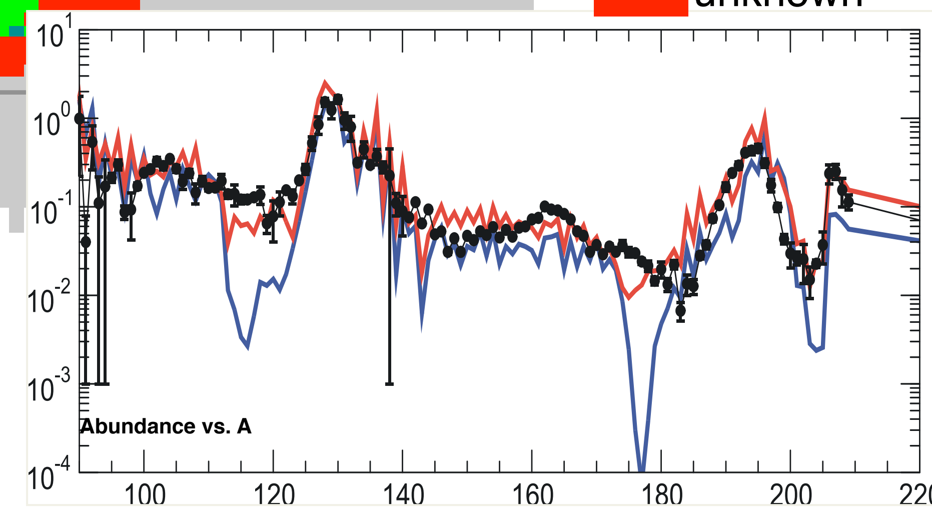
Pairing
Exotic decays
Element synthesis via rp process

$\delta m/m = 10^{-7}$

Tests of Fundamental Interactions

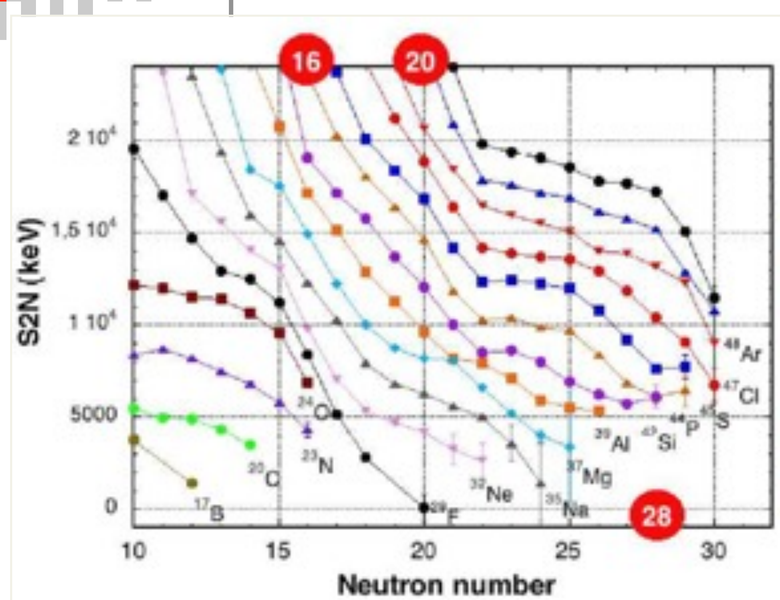
$\delta m/m < 10^{-8}$





Element synthesis via r process

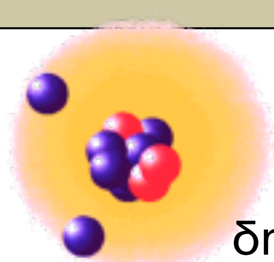
$10^{-7} < \delta m/m < 10^{-6}$



Evolution of nuclear shell structure

$10^{-6} < \delta m/m < 10^{-5}$

Halos and skins



$\delta m/m = 10^{-7}$

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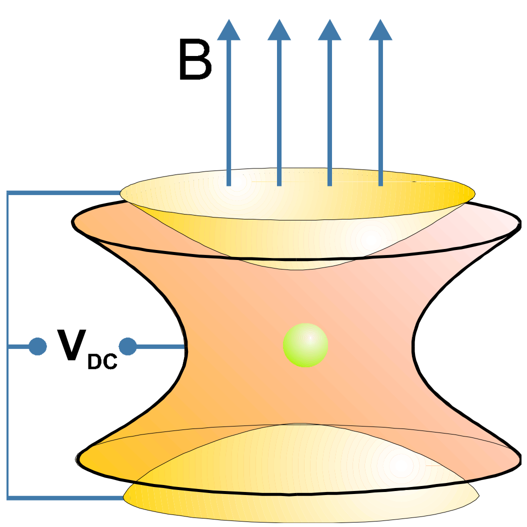
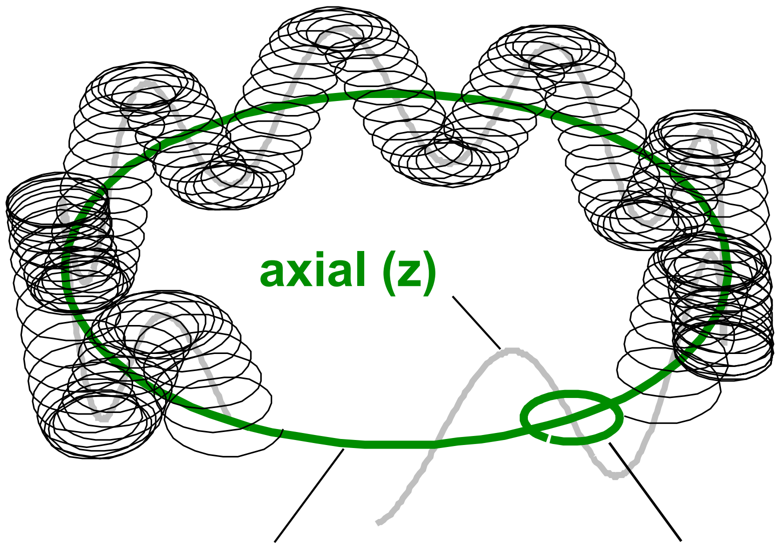
Penning trap basics

homogenous magnetic field



electrode structure

trapped ions execute three independent eigenmotions[1,2]



Important relation:

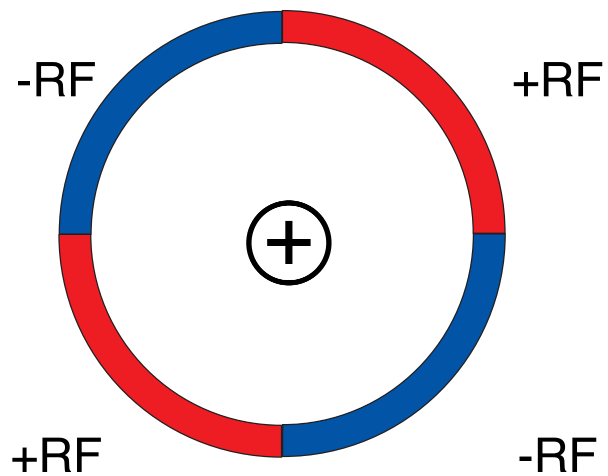
$$\nu_c = \frac{q}{2\pi m} \cdot B = \nu_+ + \nu_-$$

eigenmotions can be driven with the application of RF fields

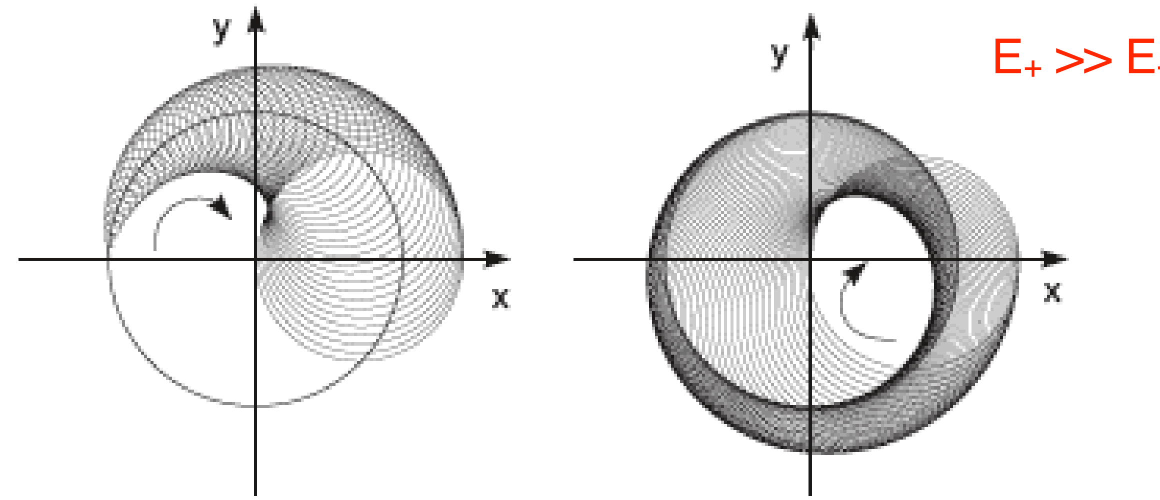
- mass measurements
- isobaric/isomeric purification
- cooling/centering of beam

1. L. S. Brown and G. Gabrielse, *Reviews of Modern Physics* **58**, 233-311 (1986).
2. M. König *et al.*, *Int. J. Mass Spectrom.* **142**, 95-116 (1995).

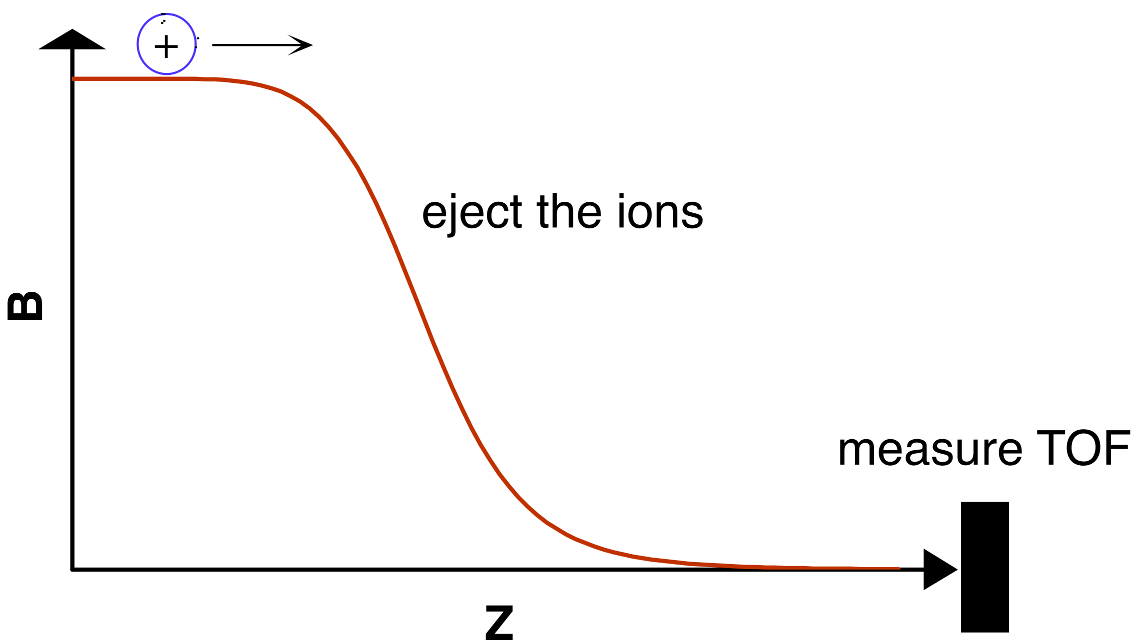
Quadrupolar excitation and resonance time-of-flight detection



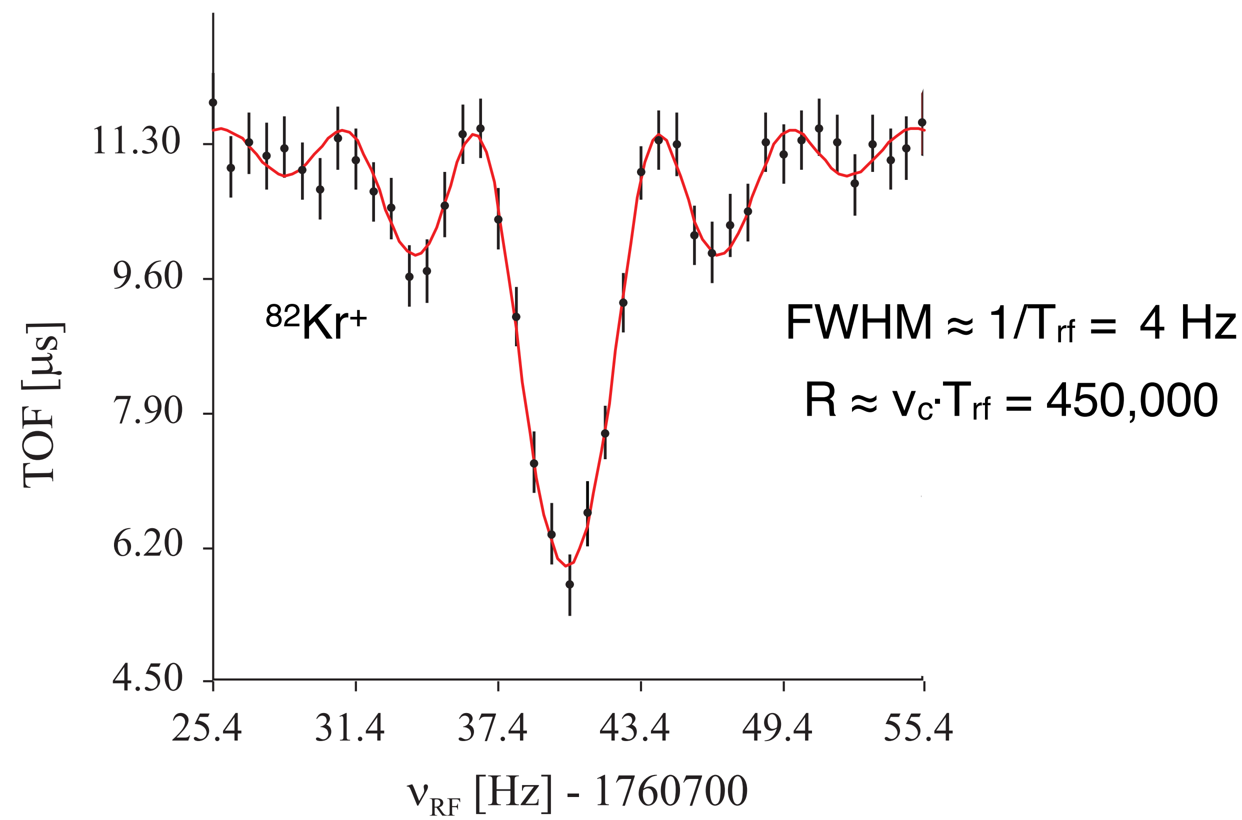
trap ions and apply RF excitations



quadrupolar excitation: beating of motions when $\nu_{rf} \approx \nu_c$



$$F = -\mu \frac{\partial B}{\partial z} = -\frac{E_r}{B_o} \cdot \frac{\partial B}{\partial z}$$



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What goes into relative mass precision?

$$\frac{\delta m}{m} = \frac{\gamma}{R \cdot \sqrt{N}}$$

ϒ - system-specific scaling factor

- initial ion distribution
- extraction conditions
- length of flight path
- contaminant ions

optimized injection
optimized ejection
efficient purification

R - resolving power of excitation

- function of T_{rf} and ν_c

improved with: →

better excitation schemes
charge breeding

N - number of detected ions

- detection efficiency
- yield, total experiment time
- measurement overhead

large duty cycle
fast purification

Fast, efficient purification

Isobaric purification of contaminant species

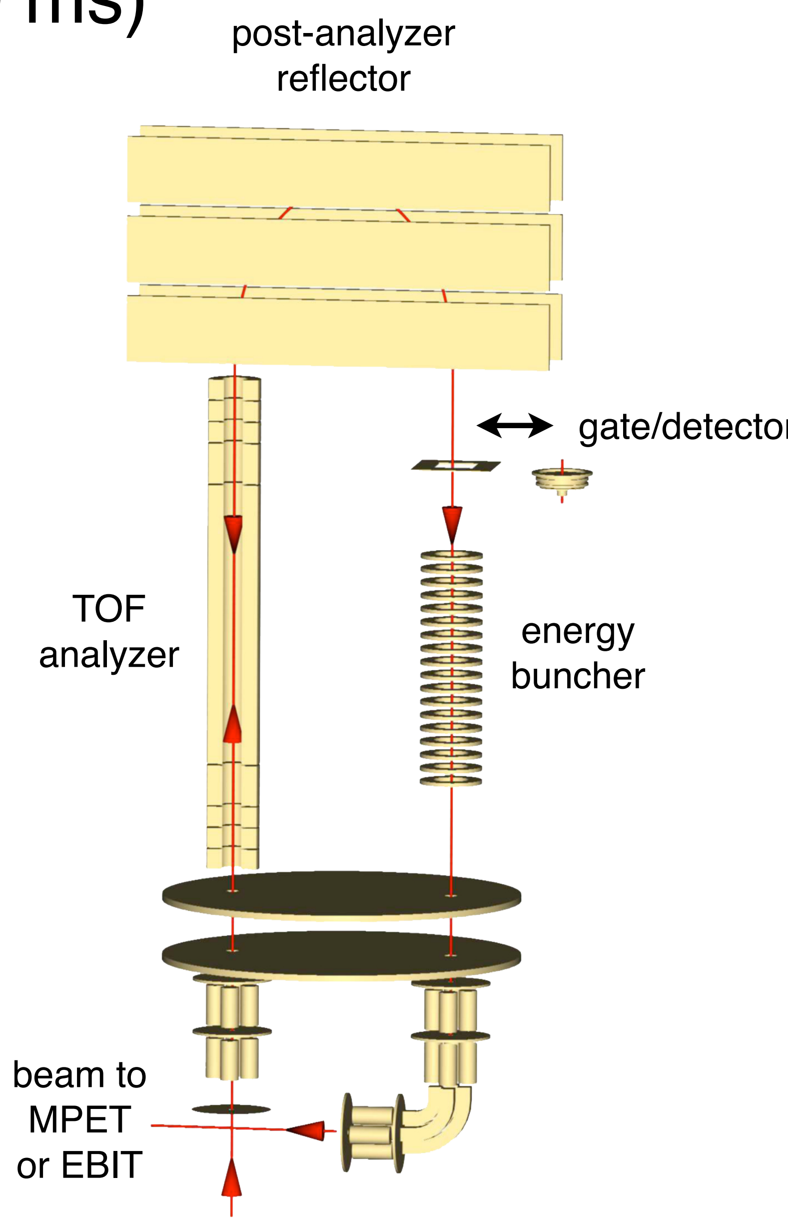
- sideband cooling in a gas-filled Penning trap[1] (t ~ 100 ms)
  (broadband, no knowledge of contaminant required)
- dipolar excitation of contaminants (t ~ 10 ms)
  (contaminant species need to be identified)

MR-TOF-MS Isobar Separator[2]

Principle: electrostatic mirror system drastically increases the ion flight path

Advantages:

1. extremely short measurement times (100 ns to 10 ms)
2. broad mass range
3. large ion capacity
4. high resolving power ($m/\Delta m \sim 100{,}000$)
5. compact setup

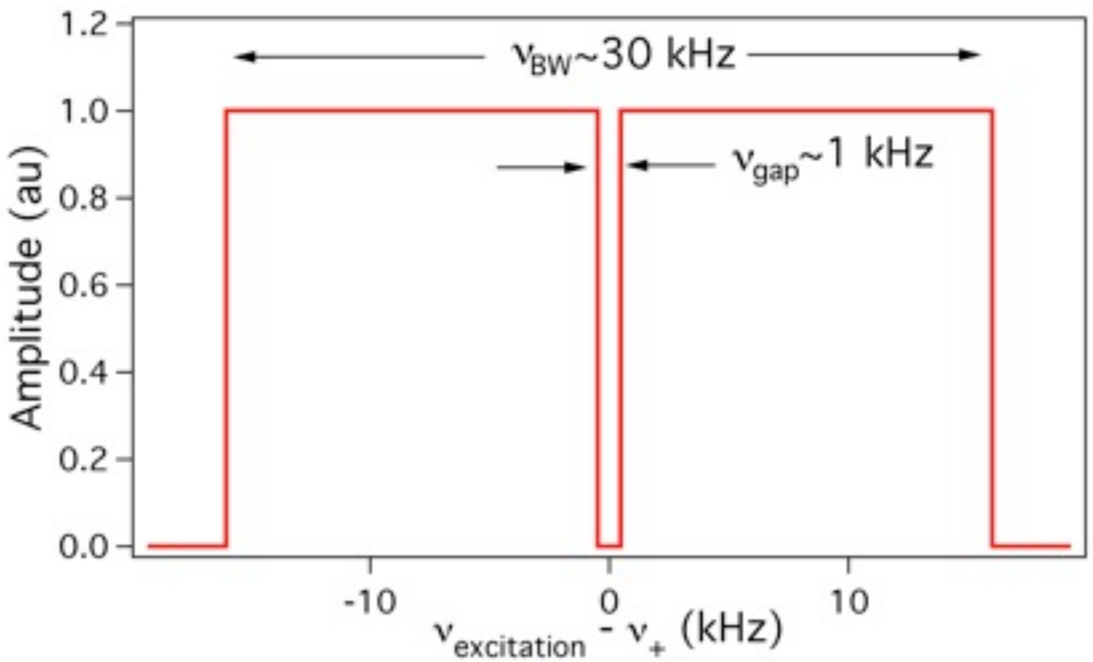


1. G. Bollen *et al.*, *J. Appl. Phys.* **68**, 4355-74 (1990).
2. W. R. Plaβ *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. B* **266**, 4560-4 (2008).

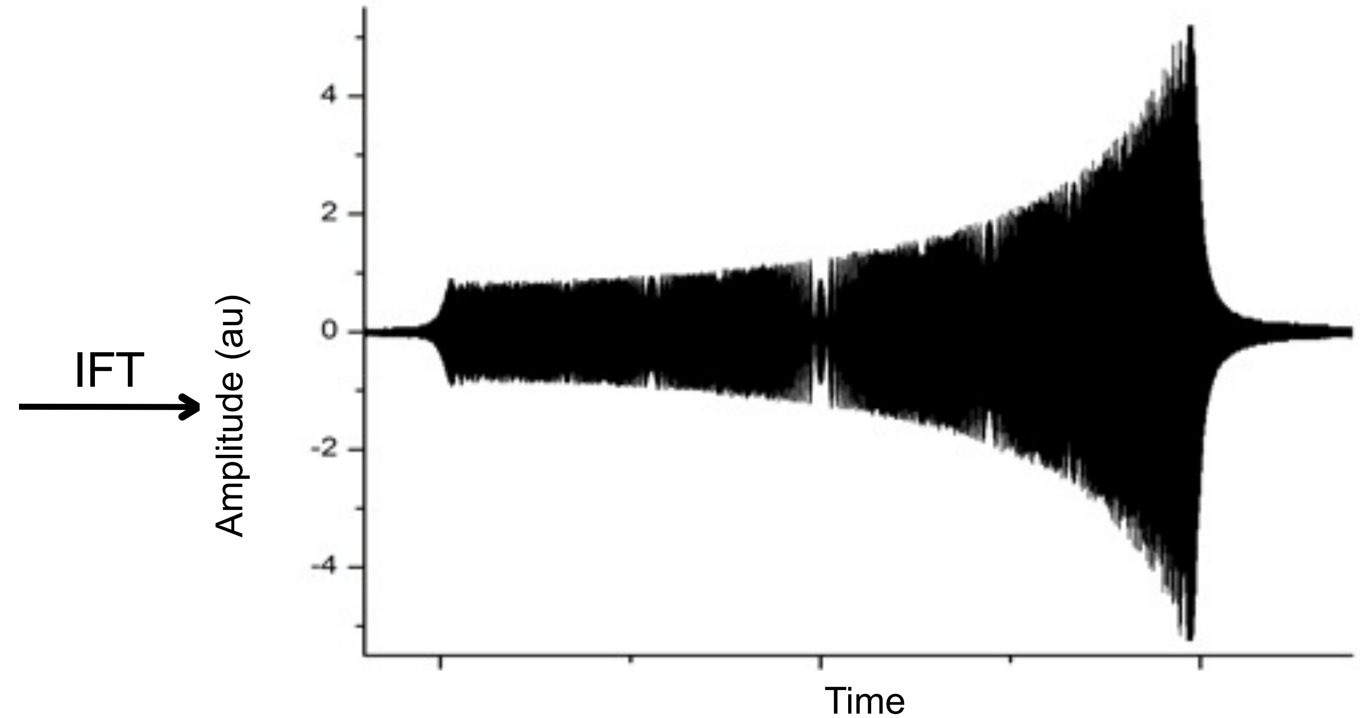
Fast, efficient purification

Implement SWIFT[1] Technique used in FT-ICR

Frequency domain signal



Time domain signal



Requirements for LEBIT

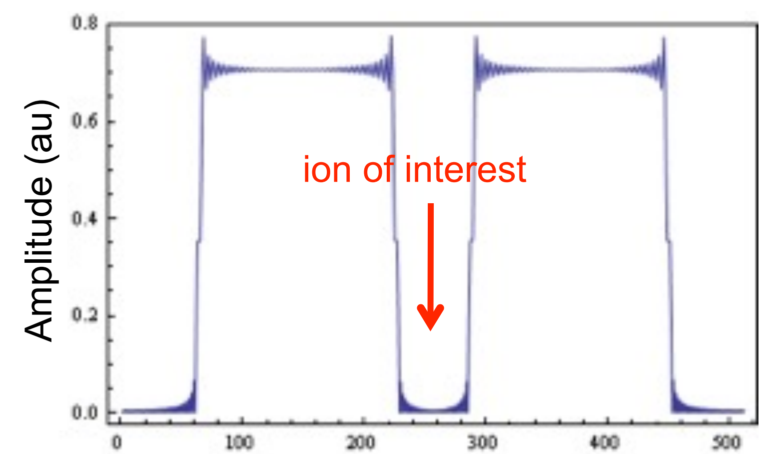
- Isobaric Purification — Molecular Isobars => Mass bandwidth ±0.1 u
  Nuclear Isobars => $\Delta m/m \sim 10^{-4}$

Challenge

- Minimize power leakage into gap

Requirements

- Programming, function generator, amplifier



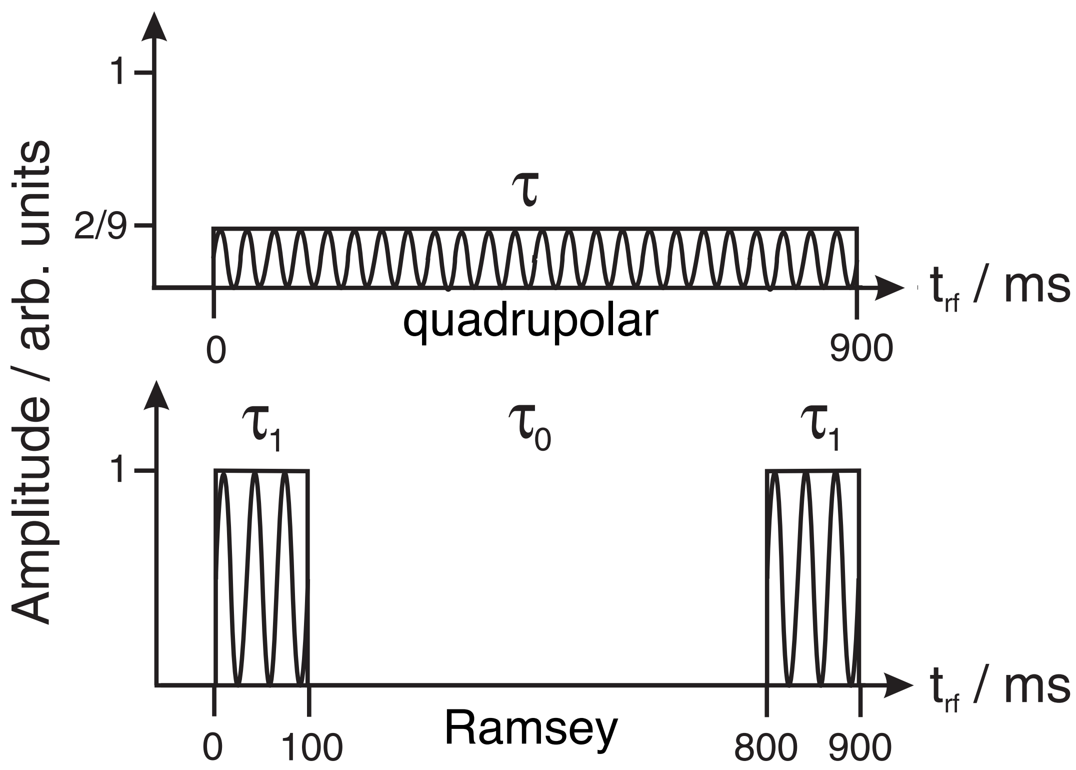
Reduced cyclotron frequency (au)

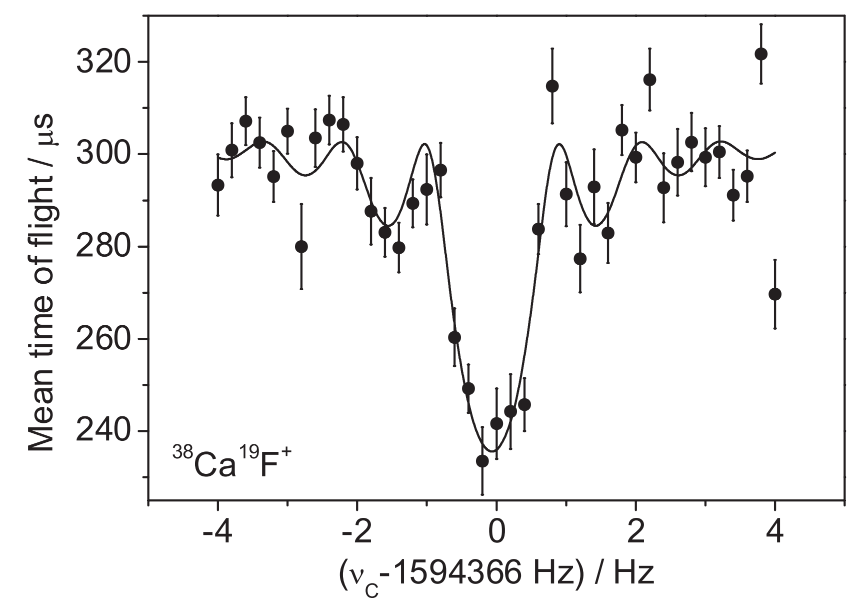
SWIFT is a cheap, efficient and fast solution

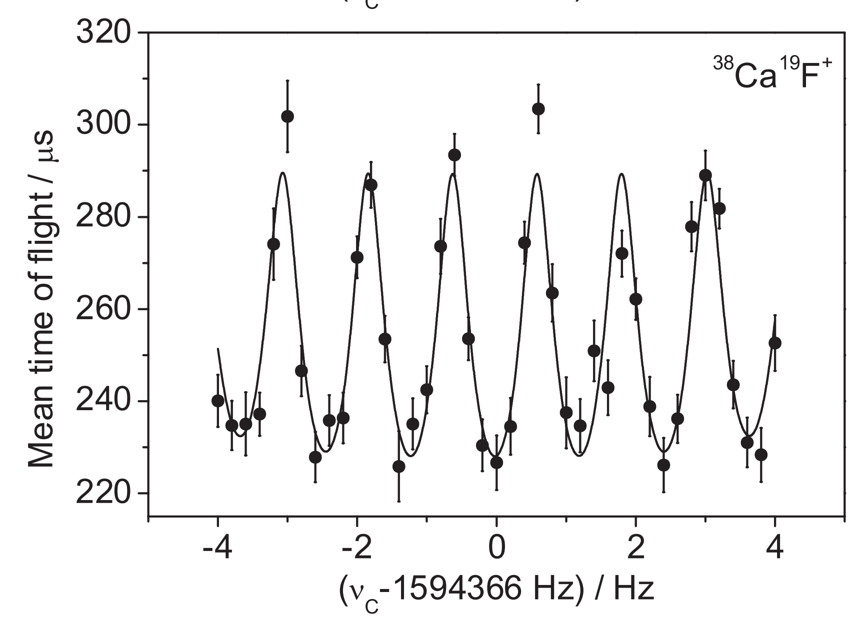
1. S. Guan and A. Marshall, *Int. J. Mass Spectrom.* , 5-37 (1996).

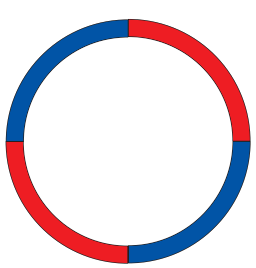
Excitation schemes
(using quadrupolar RF field)

Goal: highest resolving power for given T_{rf}









Quadrupolar: $R \sim Trf \cdot \nu_c$

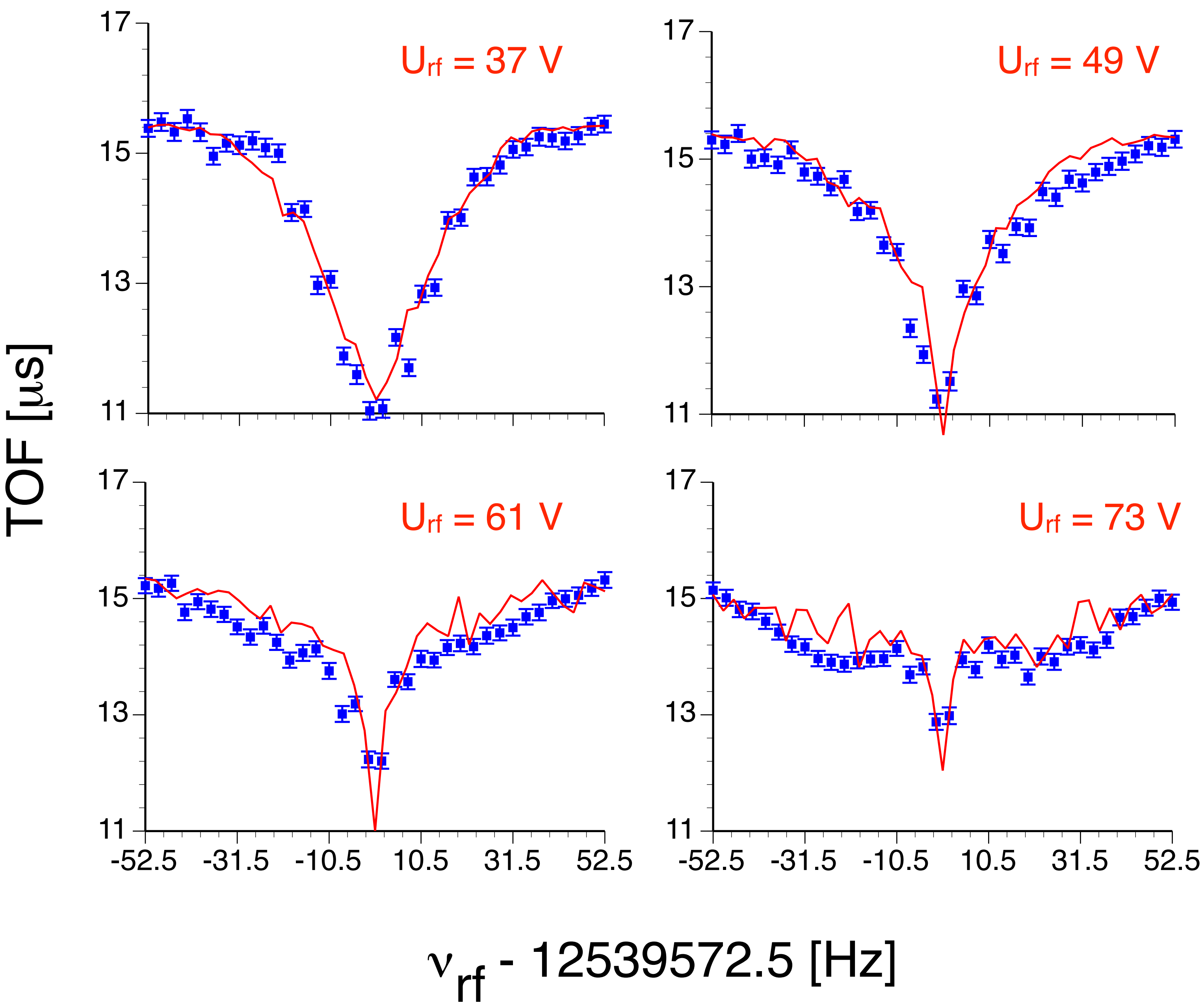
Ramsey[1,2,3]: $R \sim 3 \cdot Trf \cdot \nu_c$

Ramsey offers greater resolving power free of charge

- issues with isomer resolution, center freq. determination

1. N. F. Ramsey, *Reviews of Modern Physics* **62**, 541-52 (1990).
2. S. George *et al.*, *Phys. Rev. Lett.* **98**, 162501 (2007).
3. M. Kretzschmar, *Int. J. Mass Spectrom.* **264**, 122-45 (2007).

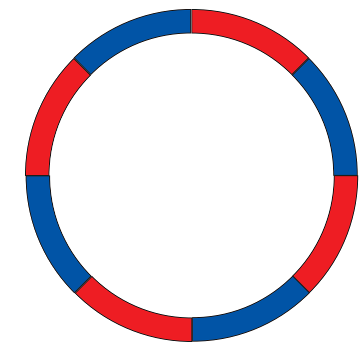
Excitation scheme
(using octupolar RF field)



$^{23}Na^{+}$, T_{rf} = 50 ms

requires eight-fold ring segmentation

$\nu_{rf} \approx 2\nu_c$



quadrupolar excitation:
- FWHM $\approx 1/T_{rf}$

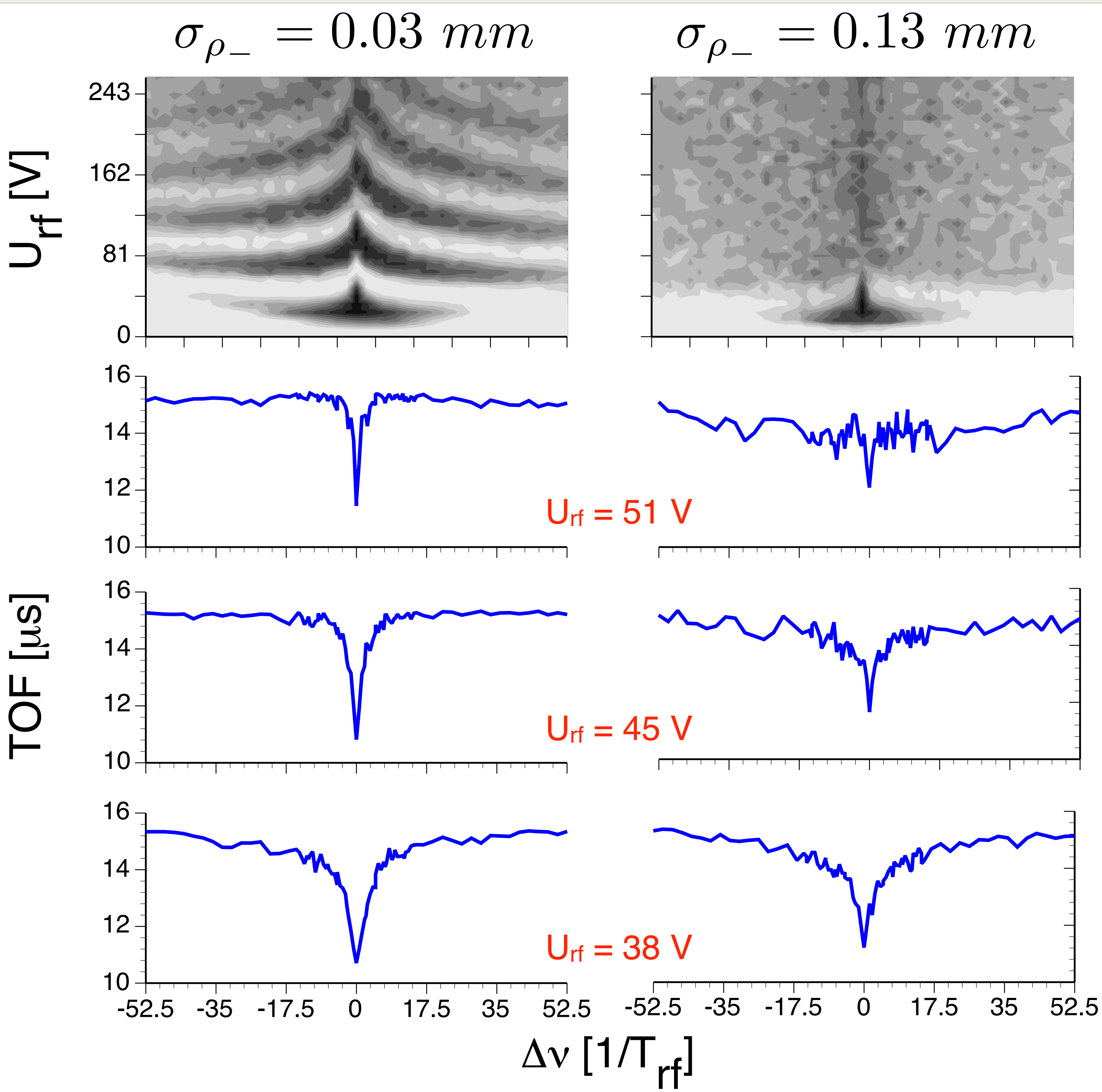
octupolar excitation[1,2]:
- FWHM $\approx 0.2/T_{rf}$ @ U_{rf} = 73 V

→ $R_{oct} = 10 \cdot R_{quad}$

Note:
ultimate gain in R is highly dependent on initial ion cloud distribution

1. R. Ringle *et al.*, *Int. J. Mass Spectrom.* **262**, 33-44 (2007).
2. S. Eliseev *et al.*, *Int. J. Mass Spectrom.* **262**, 45 - 50 (2007).

Excitation scheme
(using octupolar RF field)



Realistic multi-ion simulations:

- conversion frequency is dependent on amplitude
- smaller magnetron distribution yields higher resolving power
- increases in resolving powers of ≈ 20 within reach of current system
- preliminary results, further studies required
- no theoretical line shape

Experimental results:

- accuracy of ~ 5×10^{-9} experimentally verified
- $R_{oct} \sim 10 \cdot R_{quad}$

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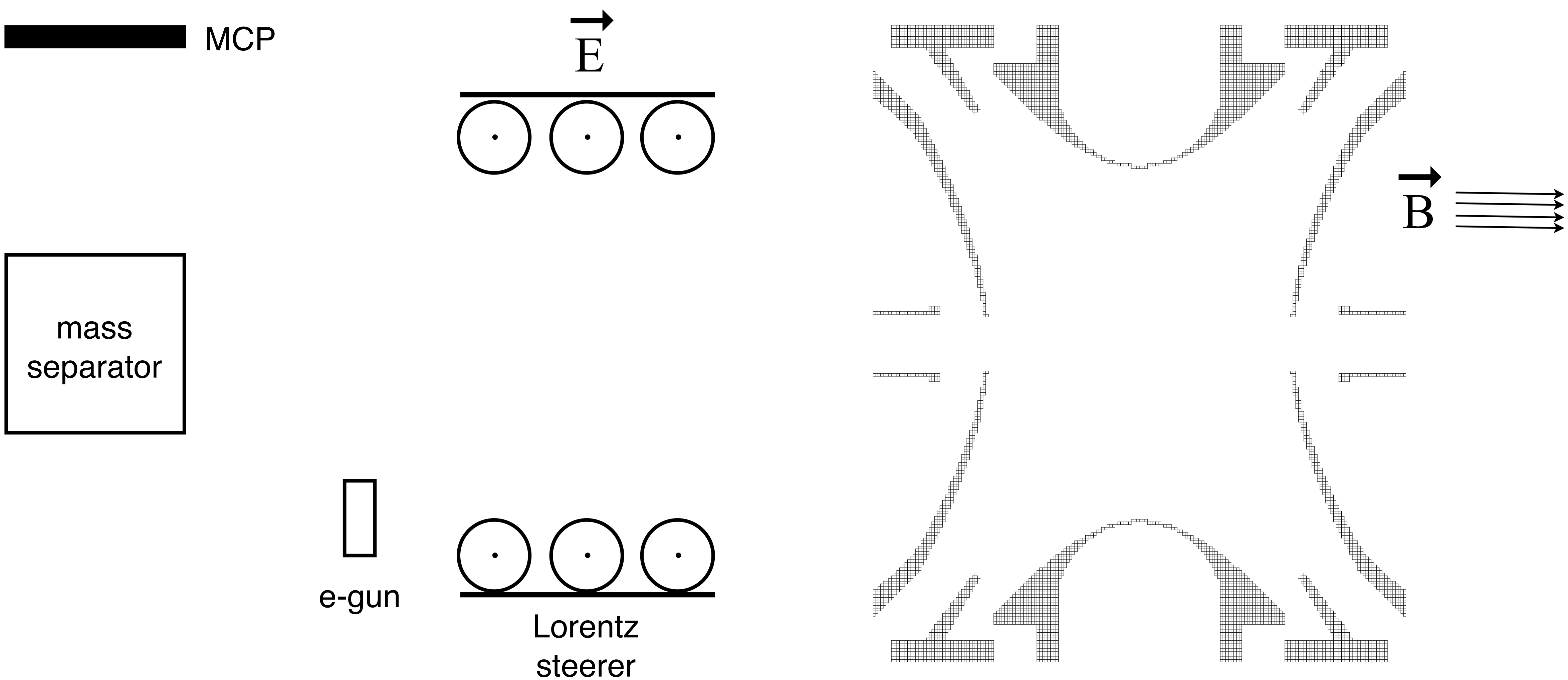
Charge breeding

Moderate charge breeding on a budget

- no EBIT and separate cooler trap required
- efficient use of all charge states produced
- less complicated

$$\nu_c = \frac{q}{2\pi m} \cdot B = \nu_+ + \nu_-$$

Increasing q increases ν_c
larger ν_c increases R for given T_{rf}



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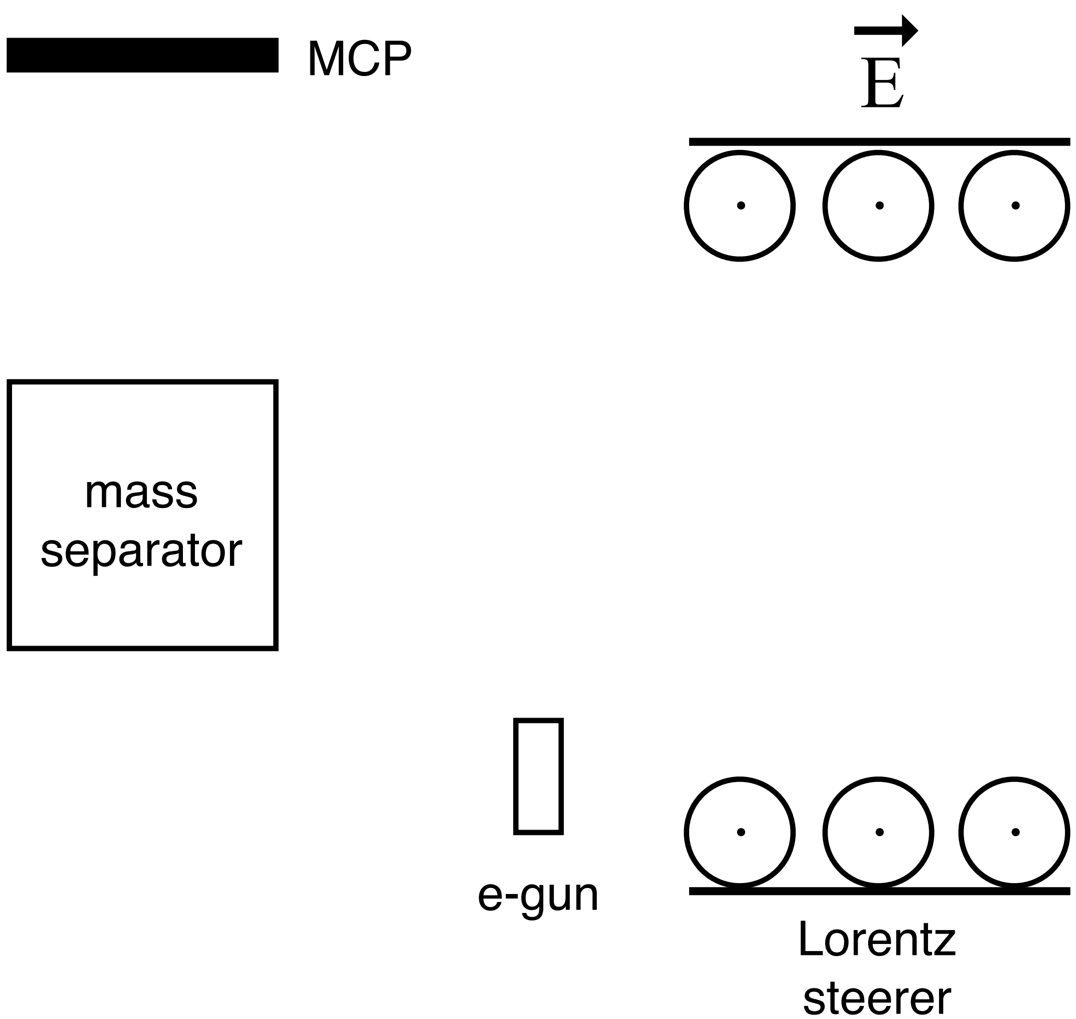
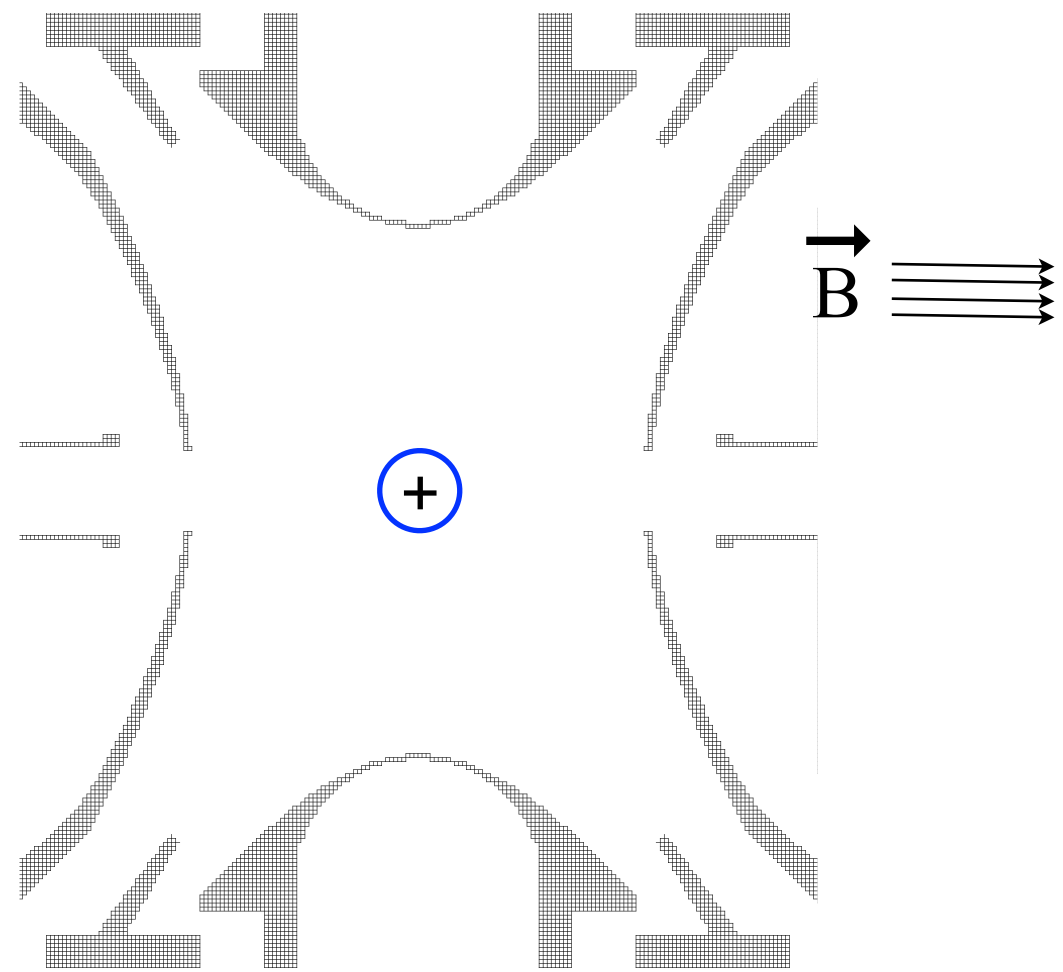
Increasing q increases v_c
larger v_c increases R for given T_{rf}





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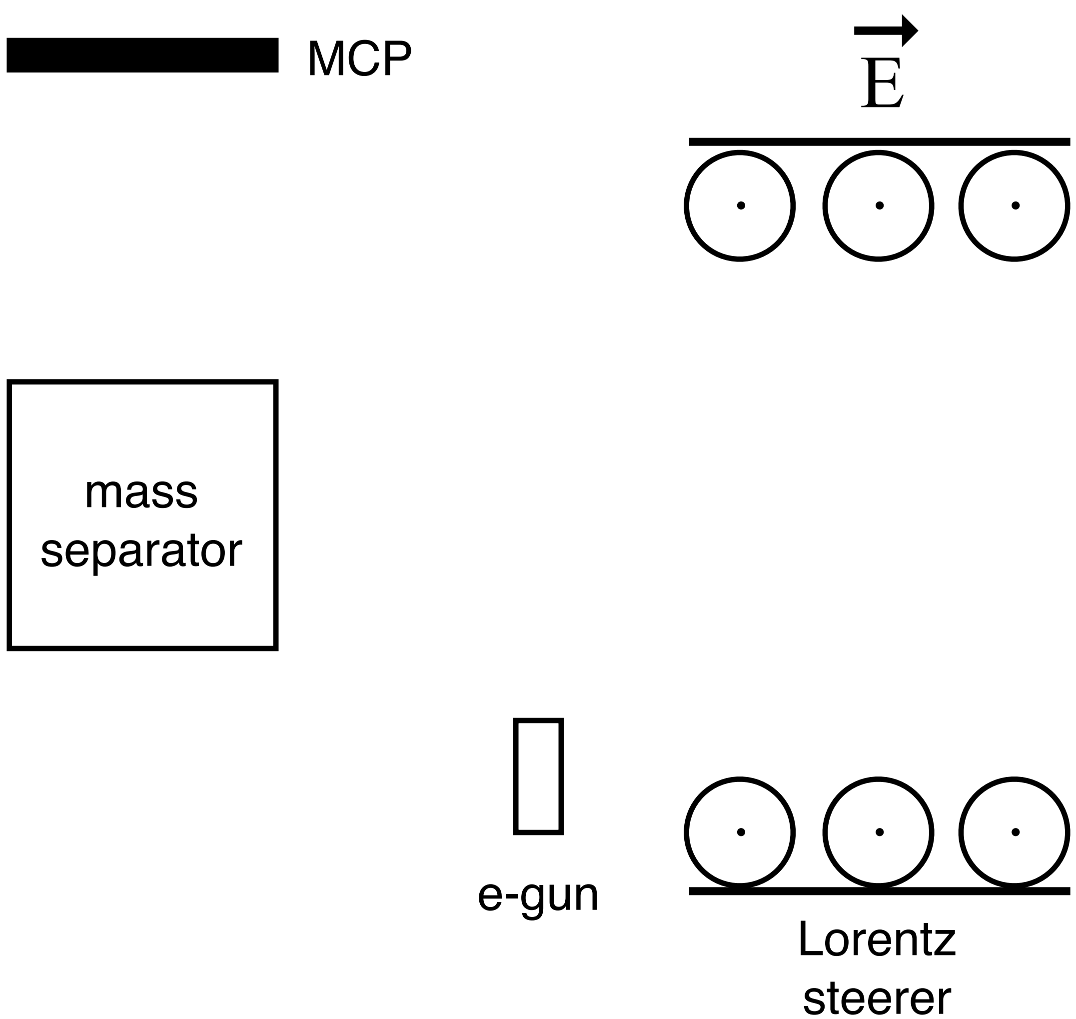

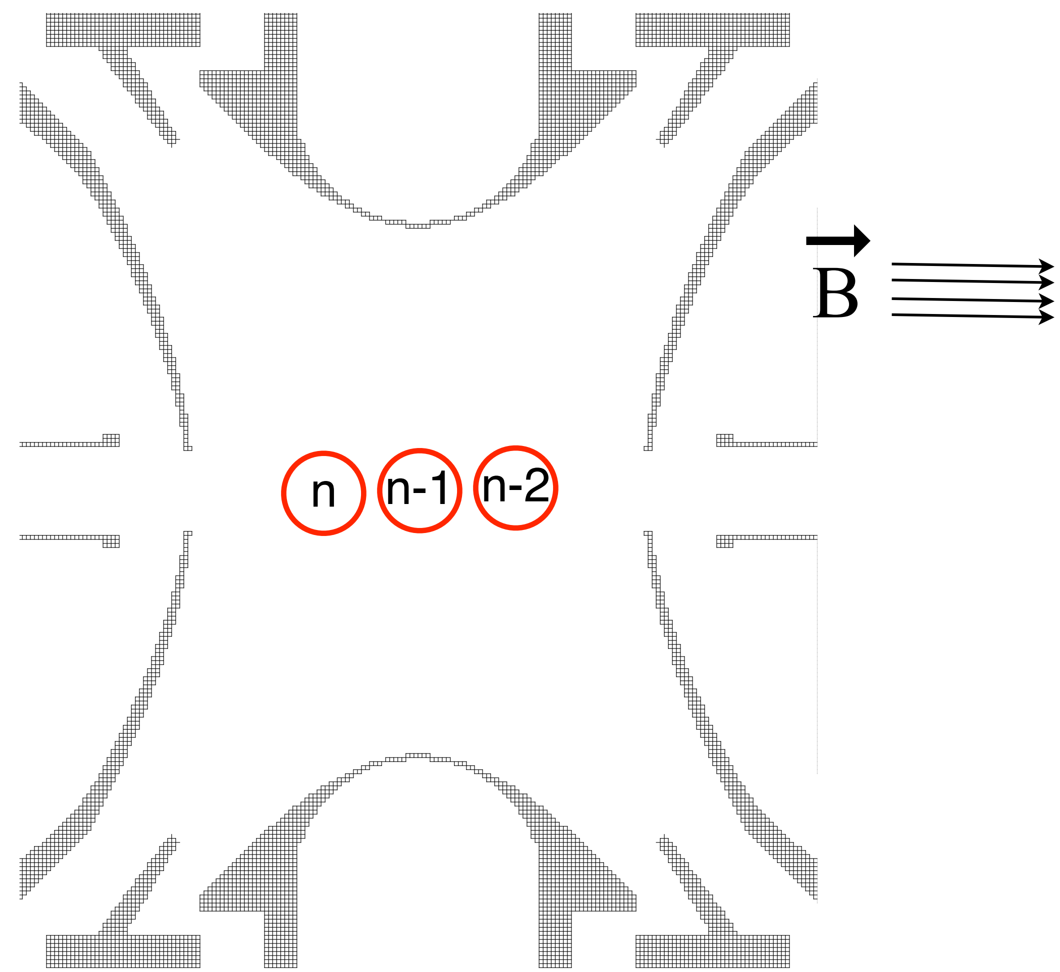

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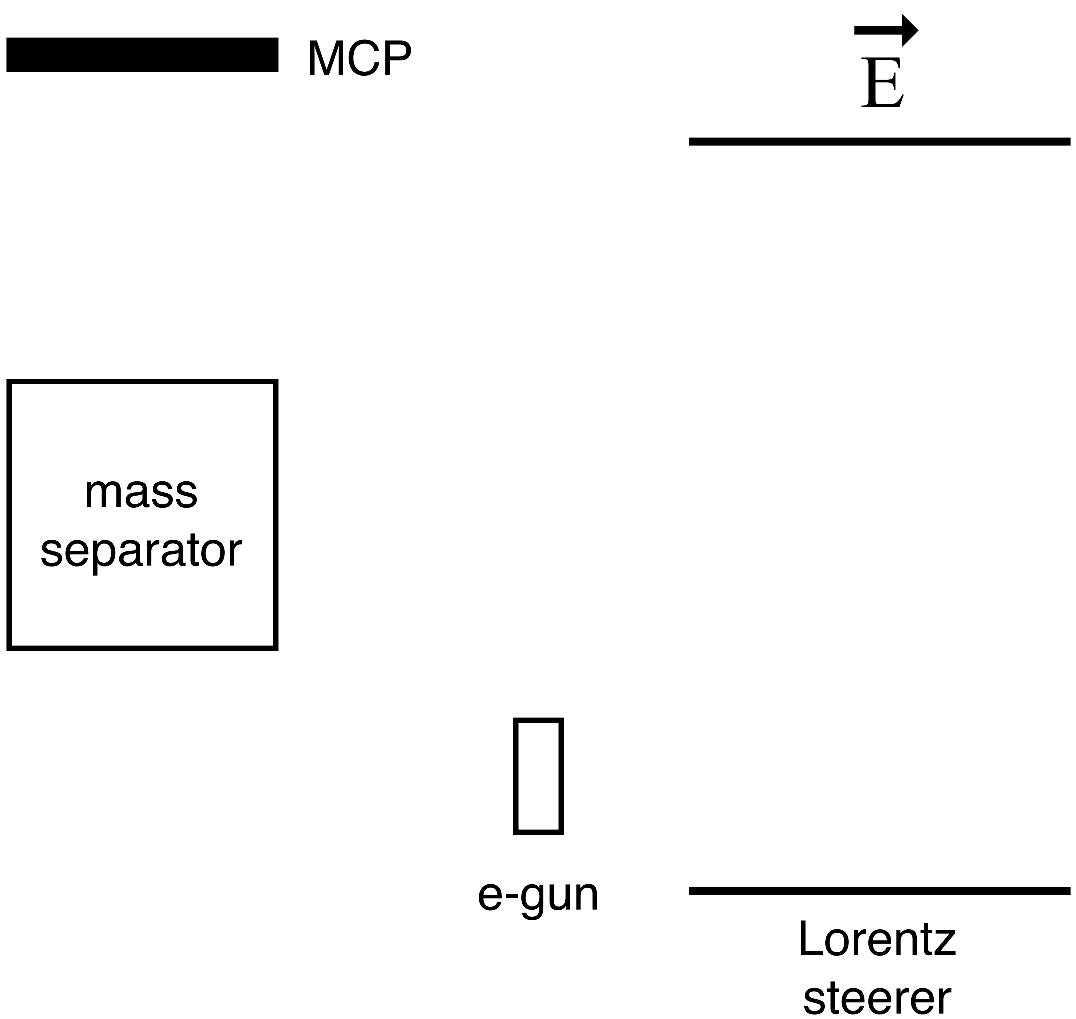

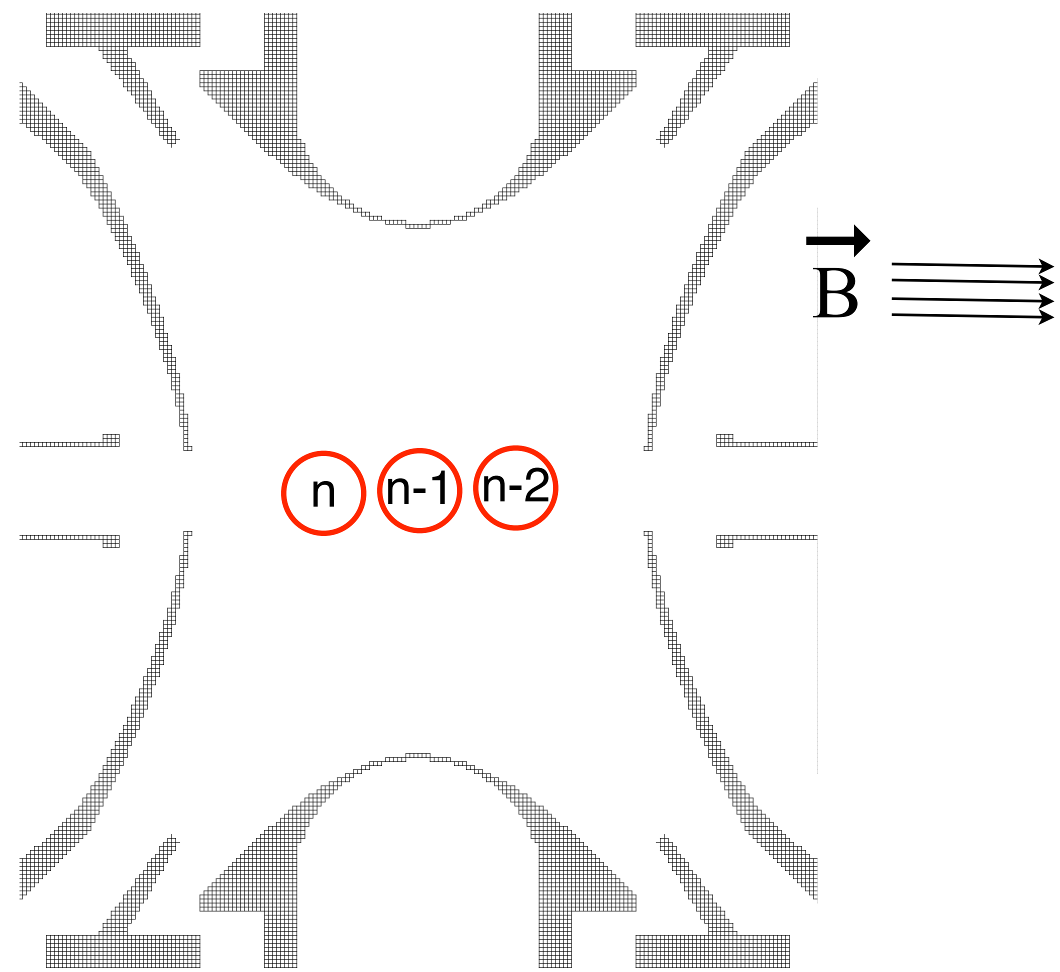

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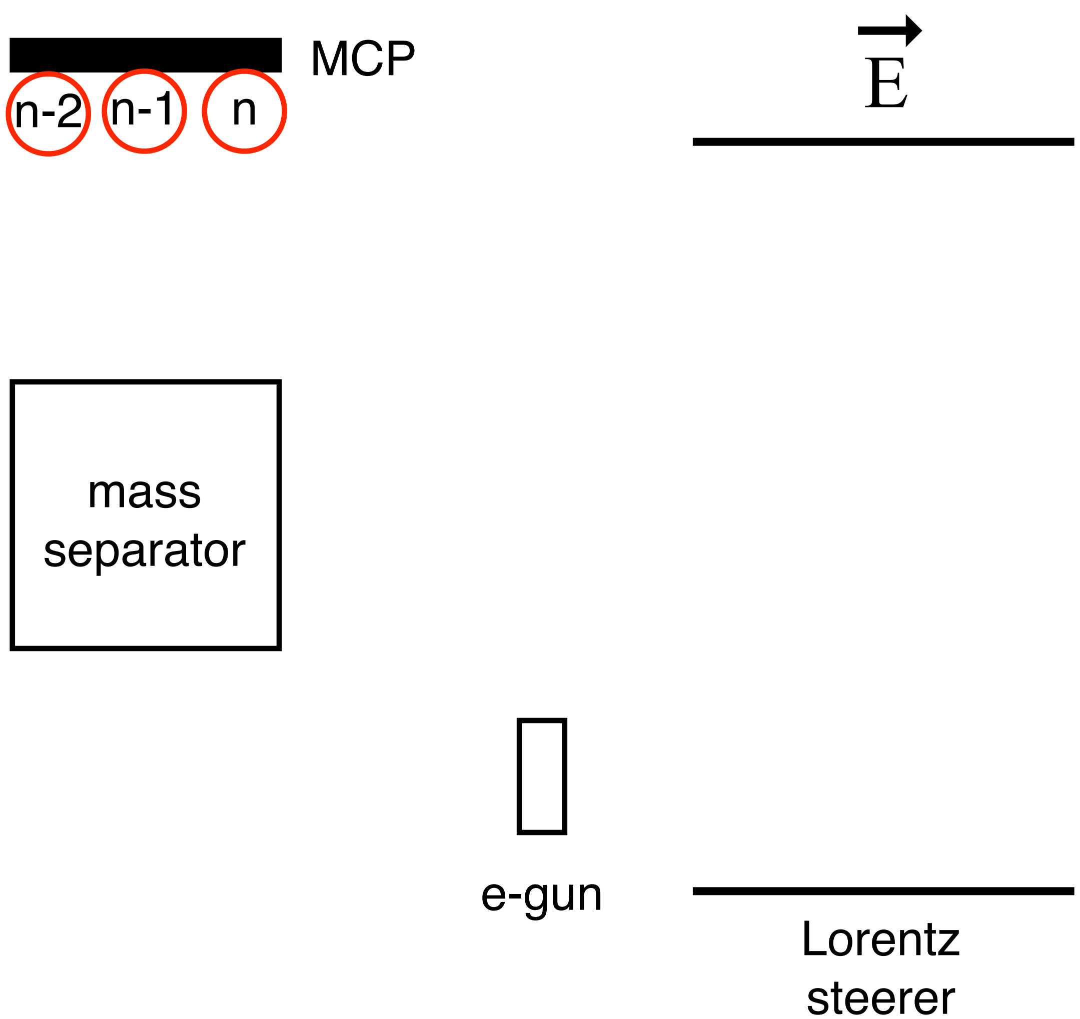
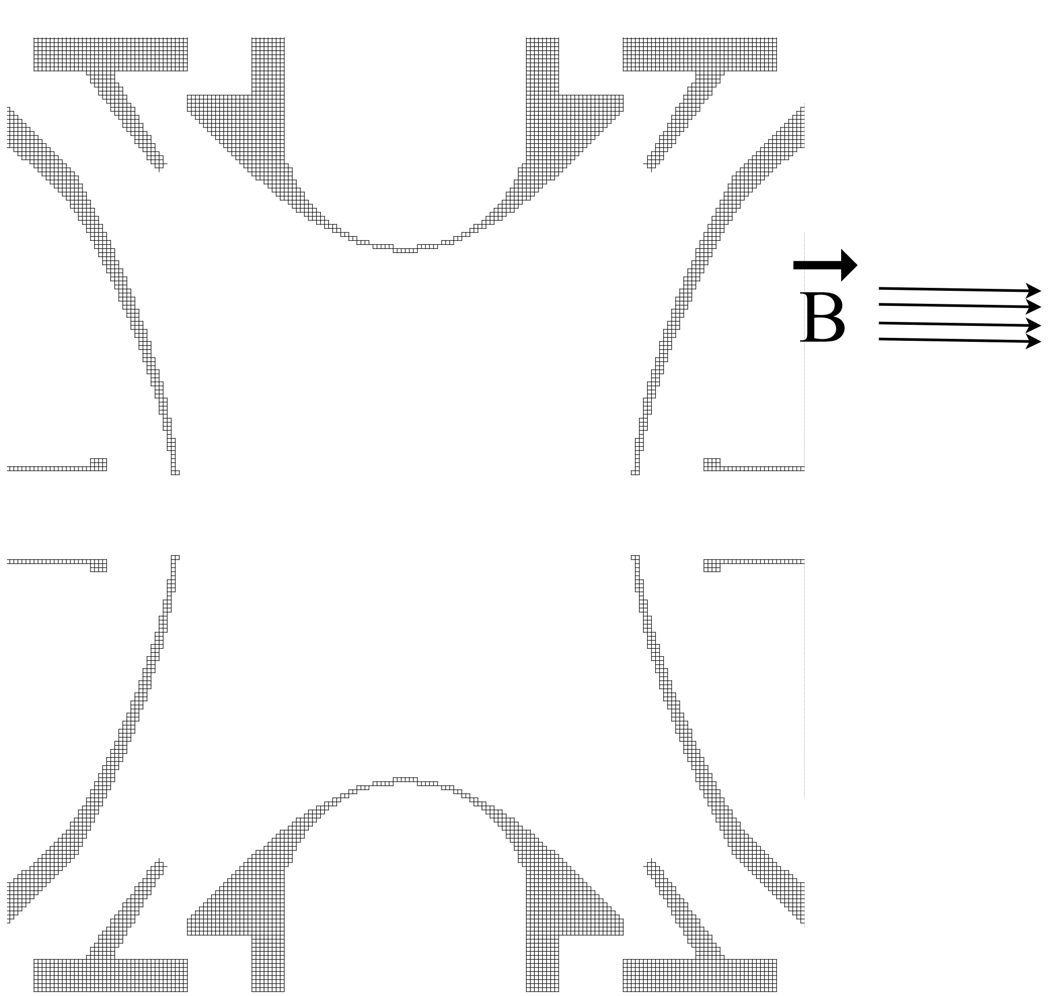
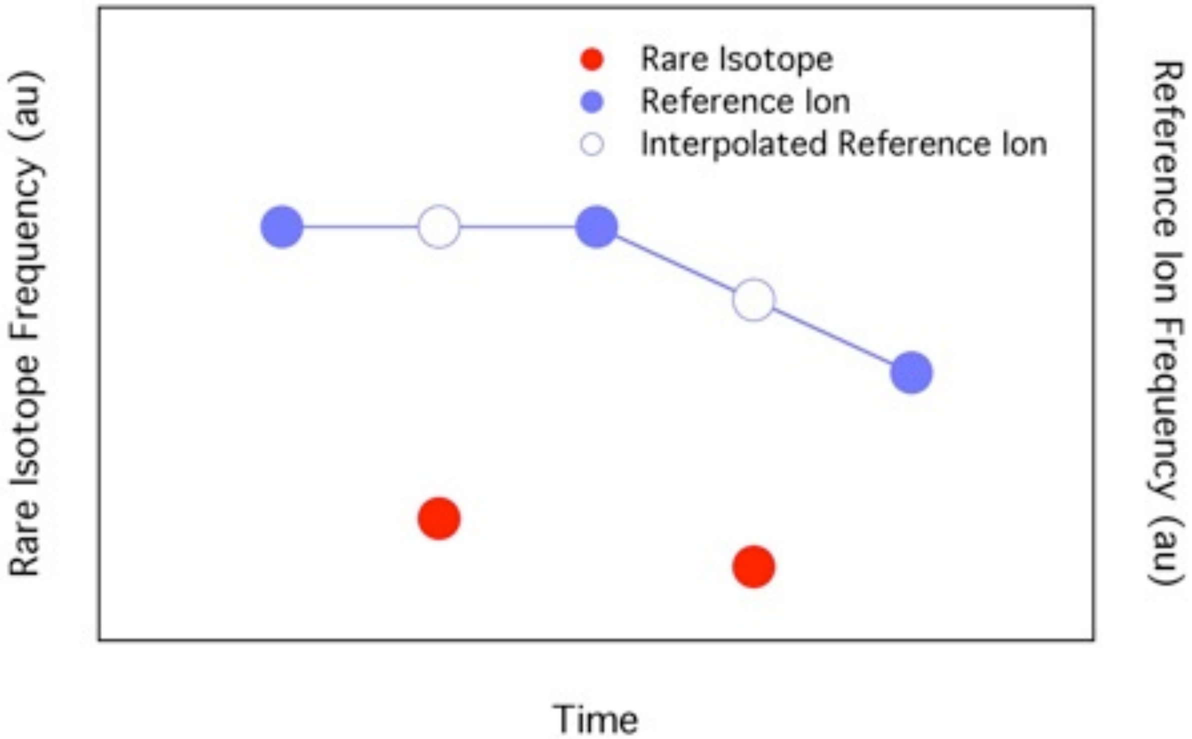




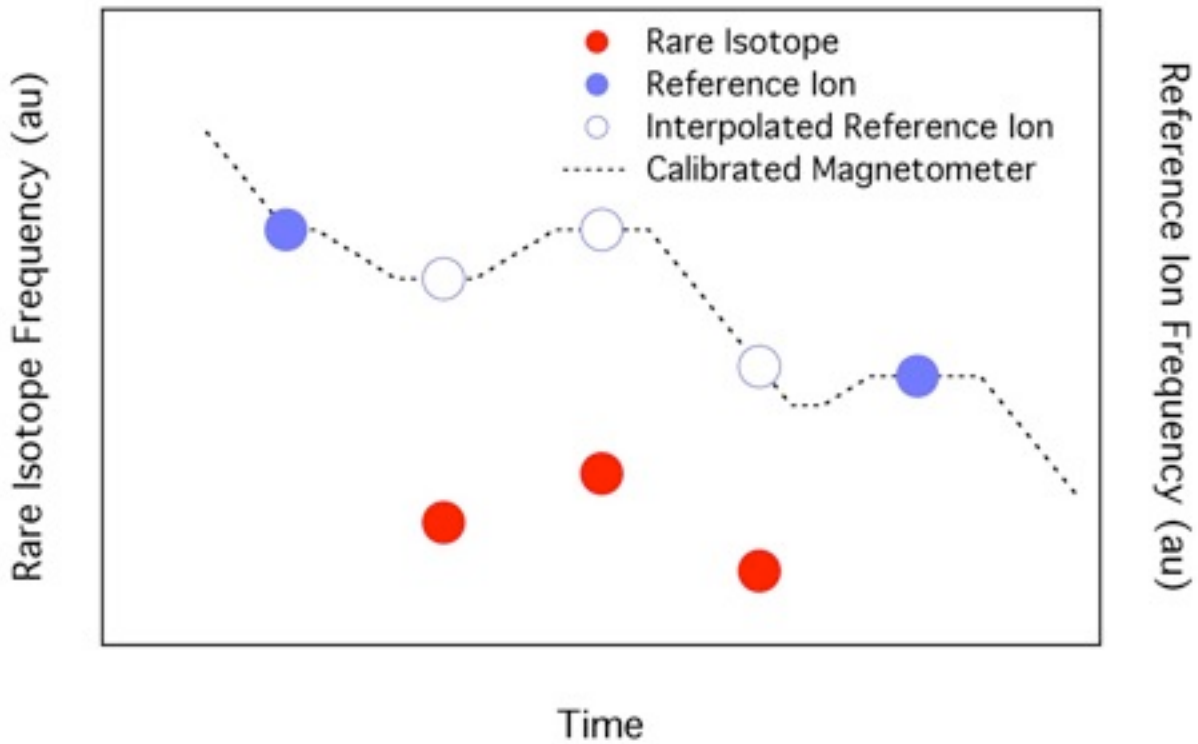
Mini Penning trap magnetometer



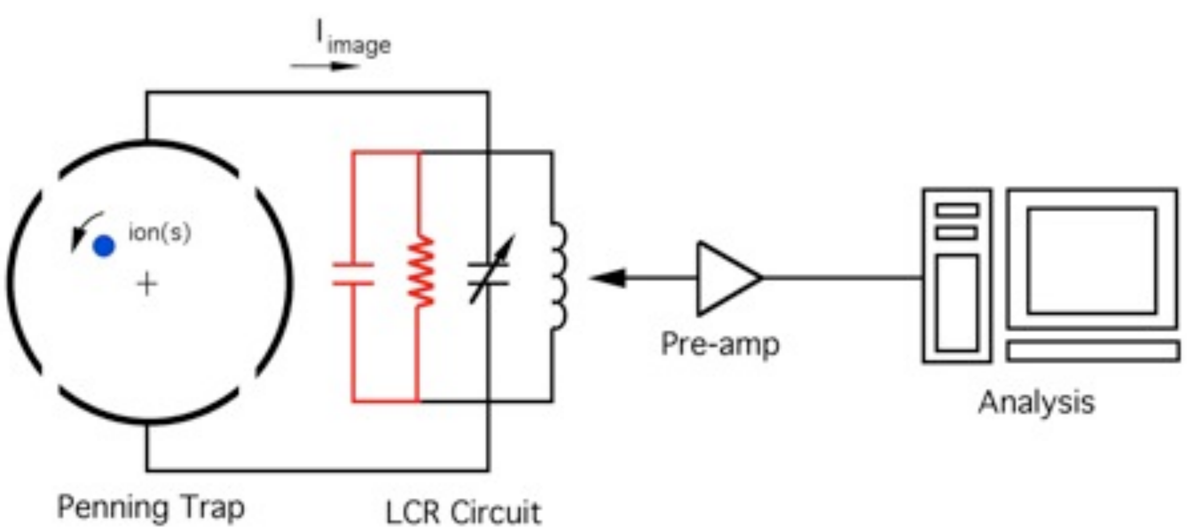
- Beam time is “wasted” on measuring reference ions
- Does not account for non-linear field drifts

Magnetic field is calibrated with a mass measurement of a reference ion before and after each RI ion measurement

Mini Penning trap magnetometer



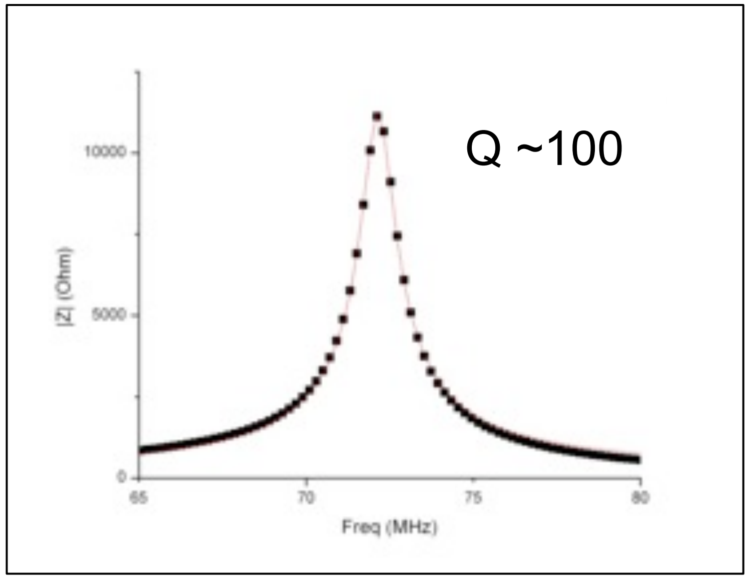
- Magnetic field is actively monitored during measurements
- Nonlinear drifts are systematically tracked



- Precision goal: $<10^{-8}$
- Aim to work with room temperature trap and detection

Trap size: ~0.5 cm
Detector Q ~ 100
 # ions ~ 100-1000

$$\frac{S}{N} \sim Nq\left(\frac{\rho}{\rho_0}\right)\sqrt{\frac{\nu}{\Delta\nu}}\sqrt{\frac{Q}{kTC}}$$



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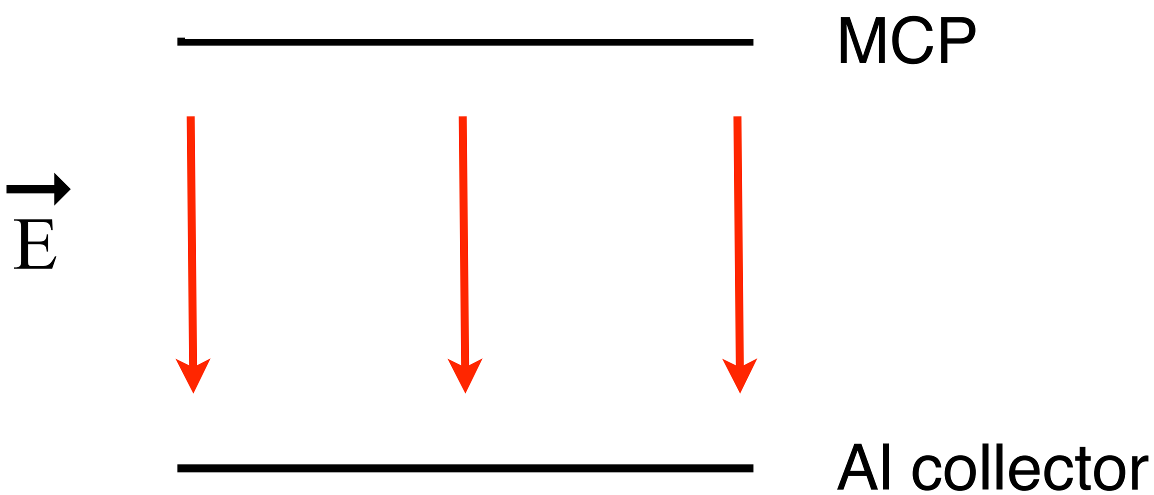
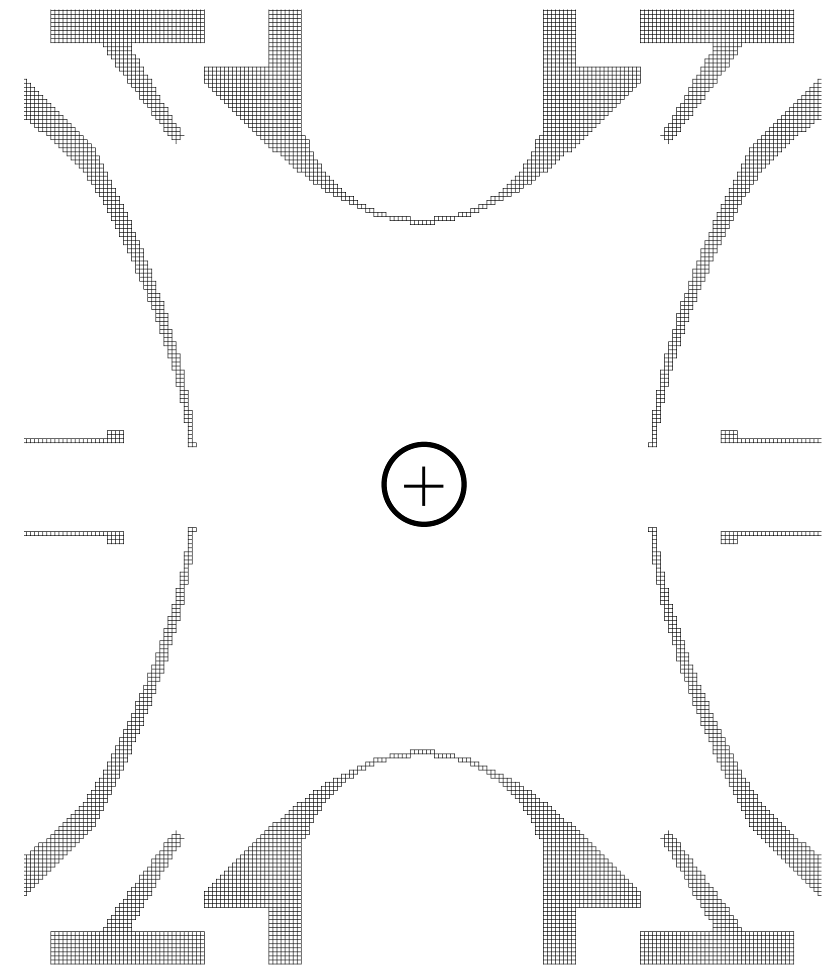
β-coincidence time of flight detection

background suppression for species with short half-life, low yield

$^{14}Be \sim 4$ ms
$^{19}C \sim 46$ ms
$^{70}Kr \sim 57$ ms





N. R. Daly, *Review of Scientific Instruments* **31**, 264-7 (1960).

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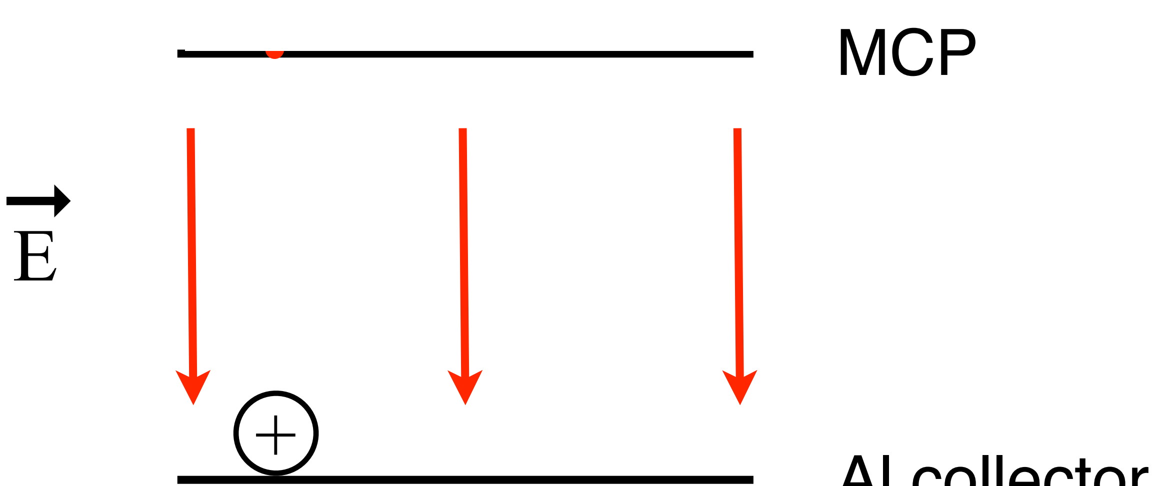

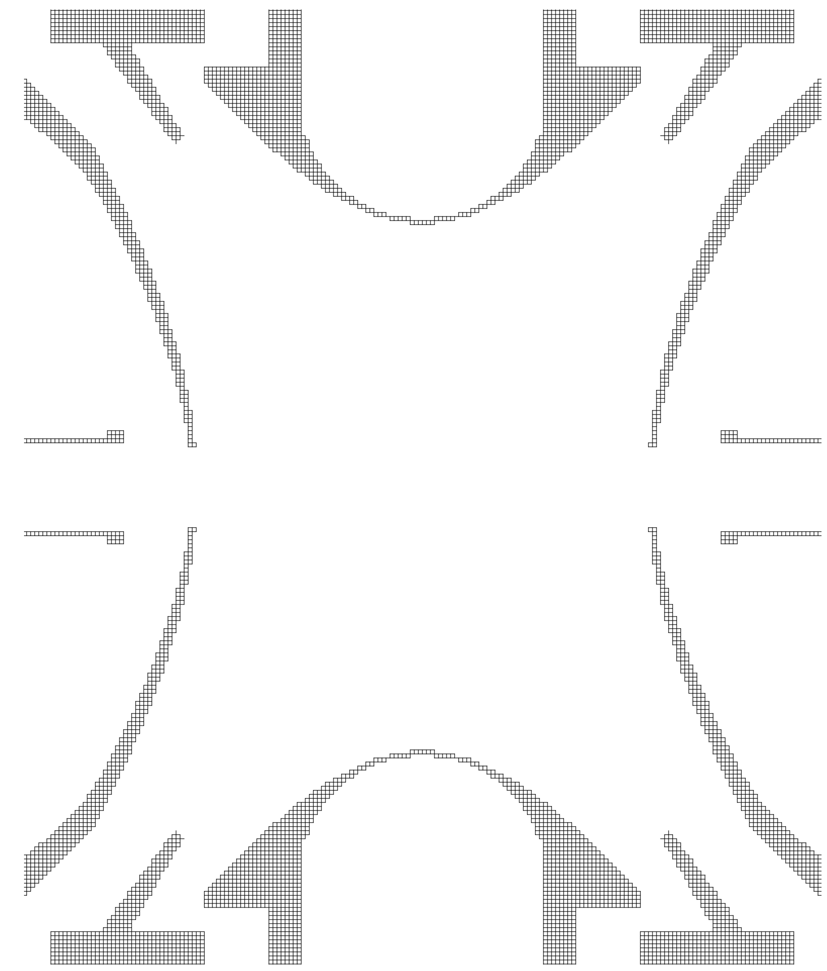

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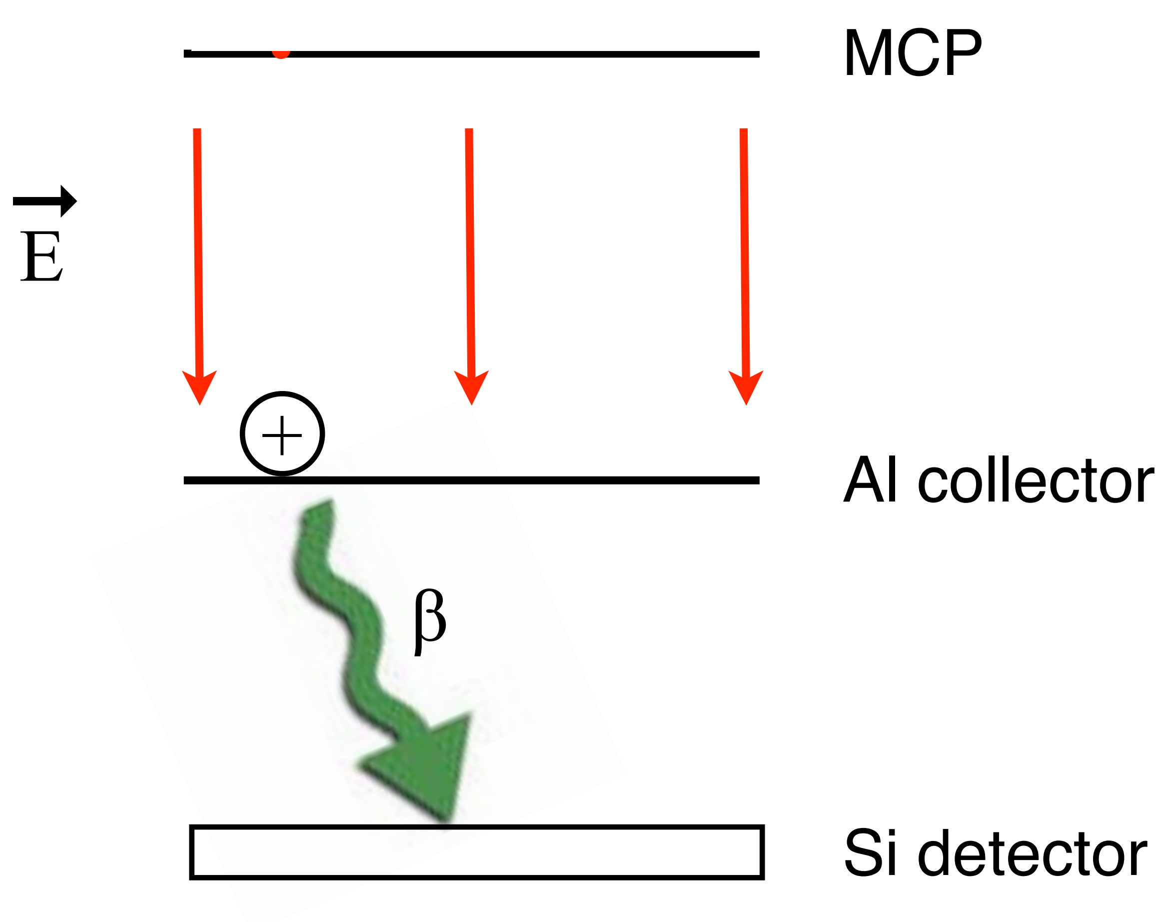

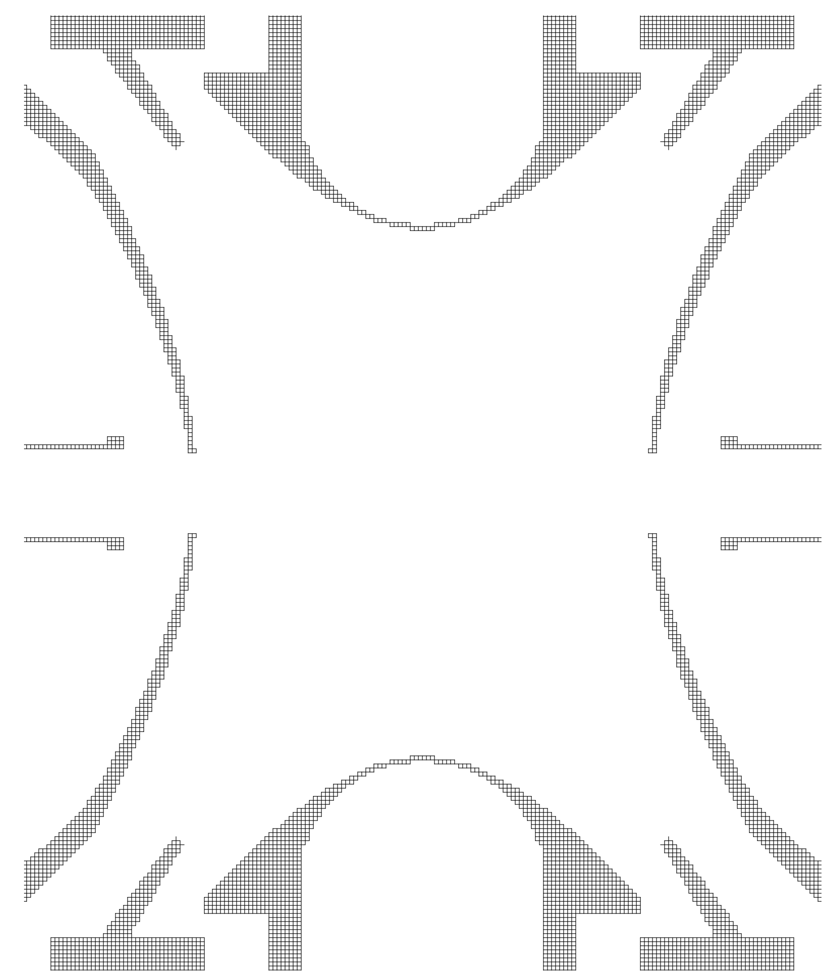

N. R. Daly, *Review of Scientific Instruments* **31**, 264-7 (1960).

3D cylindrical PIC code

Need to study space charge in traps for a variety of applications

Brute force: simulate ~ 1000 particles and scale Coulomb interaction for buffer gas cooling in Penning trap[1]

3D cubic PIC: 10^6 ions in cubic domain used to study image-charge detection in FT-ICR[2]

Problems with these approaches

brute force: not very realistic, ignores image charges, gets expensive
cubic PIC: not a natural geometry for our traps, uniform cell volume

Benefits of 3D cylindrical PIC

- high cell density near origin
- natural boundary geometry
- ability to apply RF on boundaries
- add in physics (scattering, charge breeding, etc.)

Possible applications

- plasma evolution in trap
- side band or rotating wall cooling
- proton/electron cooling of HCI's
- thermalization in gas cells

1. D. Beck *et al.*, *Hyperfine Interactions.* **132**, 473-8 (2001).
2. E. N. Nikolaev *et al.*, *Rapid Communications in Mass Spectrometry* **21**, 3527-46 (2007).