PI-ICR technique for high-precision measurements of nuclide masses

(development at SHIPTRAP)

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Petersburg Nuclear Physics Institute, Russia

NUSTAR Meeting, March 5th

high-precision measurements of masses of exotic nuclides

Field	Examples	$\delta m/m$
nuclear structure physics astrophysics	shell closures, shell quenching, regions of deformation, drip lines, halos, island of stability *rp*-process and *r*-process path, waiting-points nuclei, astrophysical reaction rates, neutron stars	10^{-6} - 10^{-7}
weak interaction studies	CVC hypothesis, CKM matrix unitarity, *Ft* of superallowed *ß*-emitters	10^{-8}
metrology, fundamental const. neutrino physics	α $(h/m_{Cs}, m_{Cs}/m_p, m_p/m_e)$, m_{Si} $0\nu\beta\beta$, $0\nu 2EC$	10^{-9} -10^{-10}
neutrino mass CPT tests QED in highly-charged ions	*β*-decay, *EC* m_p and $m_{\bar{p}}$ m_{e-} and m_{e+} m_{ion}, electron binding energy	$<10^{-11}$

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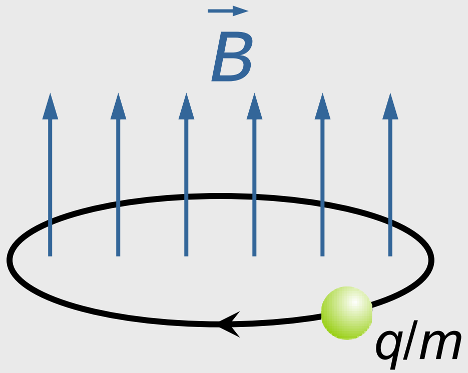
Penning trap ⟶ the most accurate mass spectrometer

strong uniform
static B-field



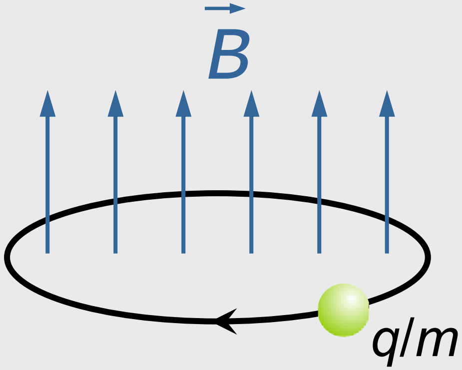
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

Penning trap ⟶ the most accurate mass spectrometer

SHIPTRAP
JYFLTRAP
TRIGATRAP
MLLTRAP

$$\frac{\Delta B}{B} < 5 \cdot 10^{-9}\ h^{-1}$$

strong uniform
static B-field



$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

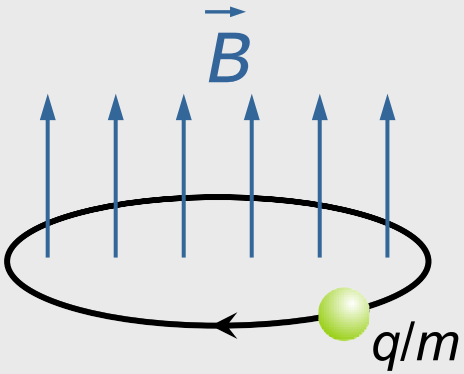
THe-TRAP

Max-Planck Institute for Nuclear Physics,
Heidelberg

$$\frac{\Delta B}{B} < 10^{-11}\ h^{-1}$$

Penning trap ⟶ the most accurate mass spectrometer

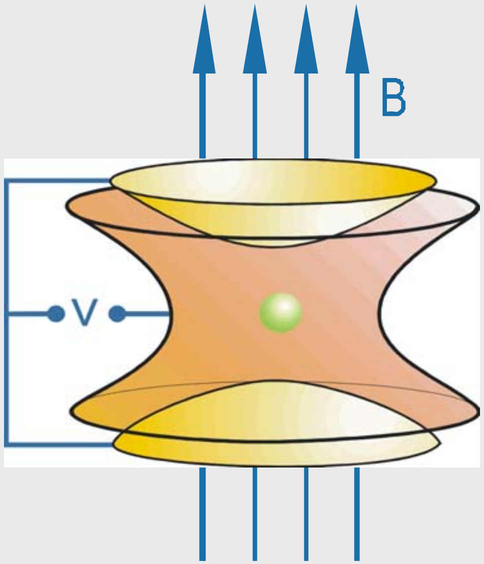
uniform B-field



$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

+

quadrupole E-field



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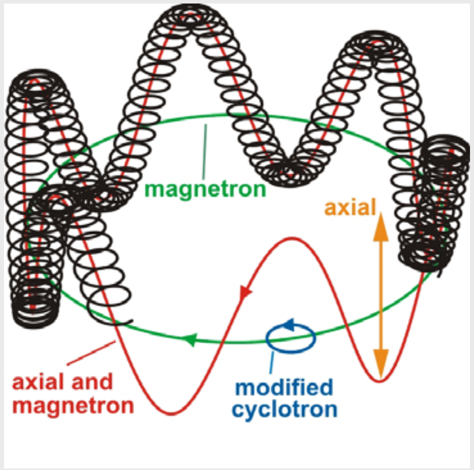
Penning Trap



ν_+ - modified cyclotron

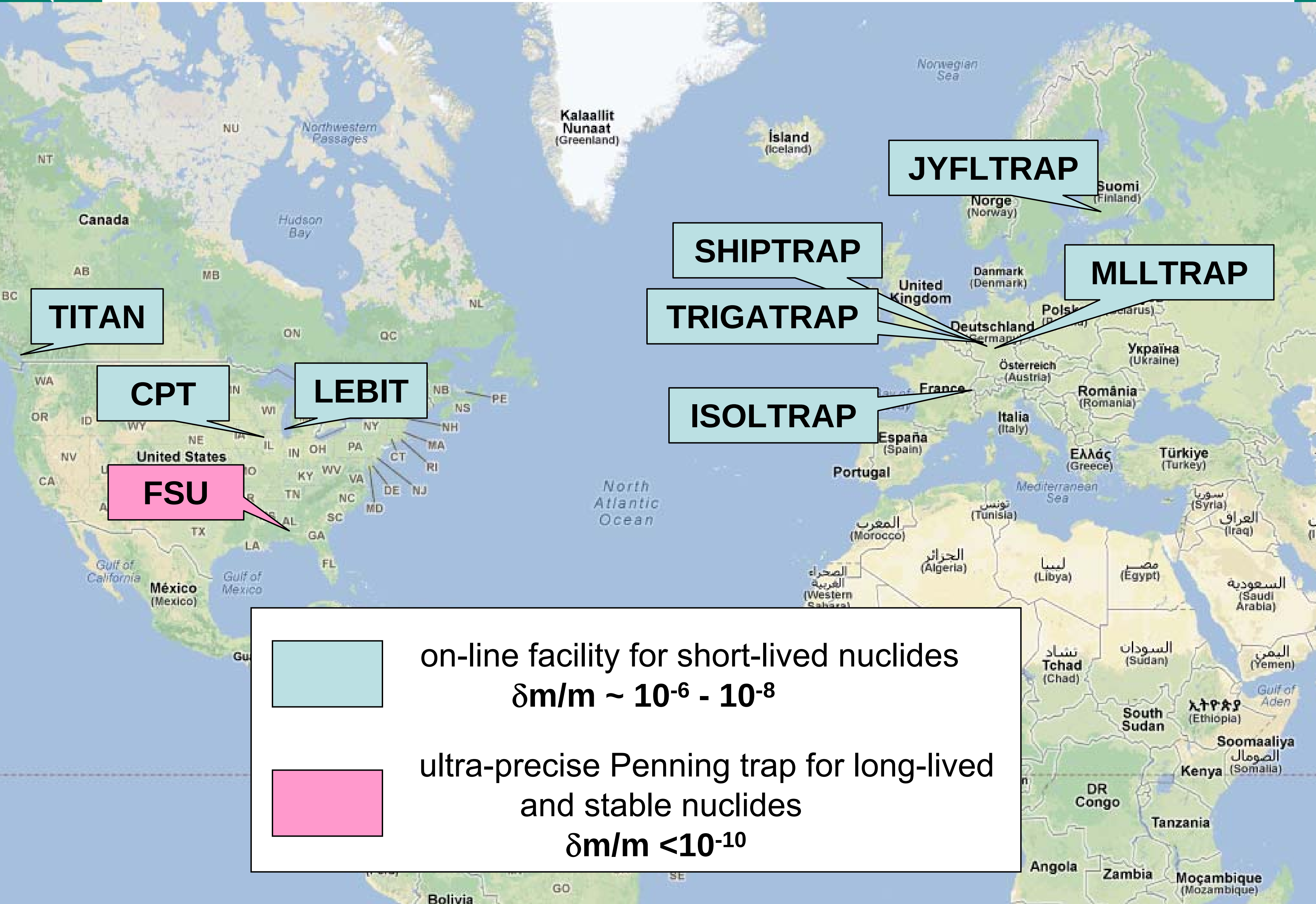
ν_- - magnetron

ν_z - axial

$$\nu_c = \nu_+ + \nu_-$$

$$\frac{\Delta\nu_c}{\nu_c} > 10^{-10}$$

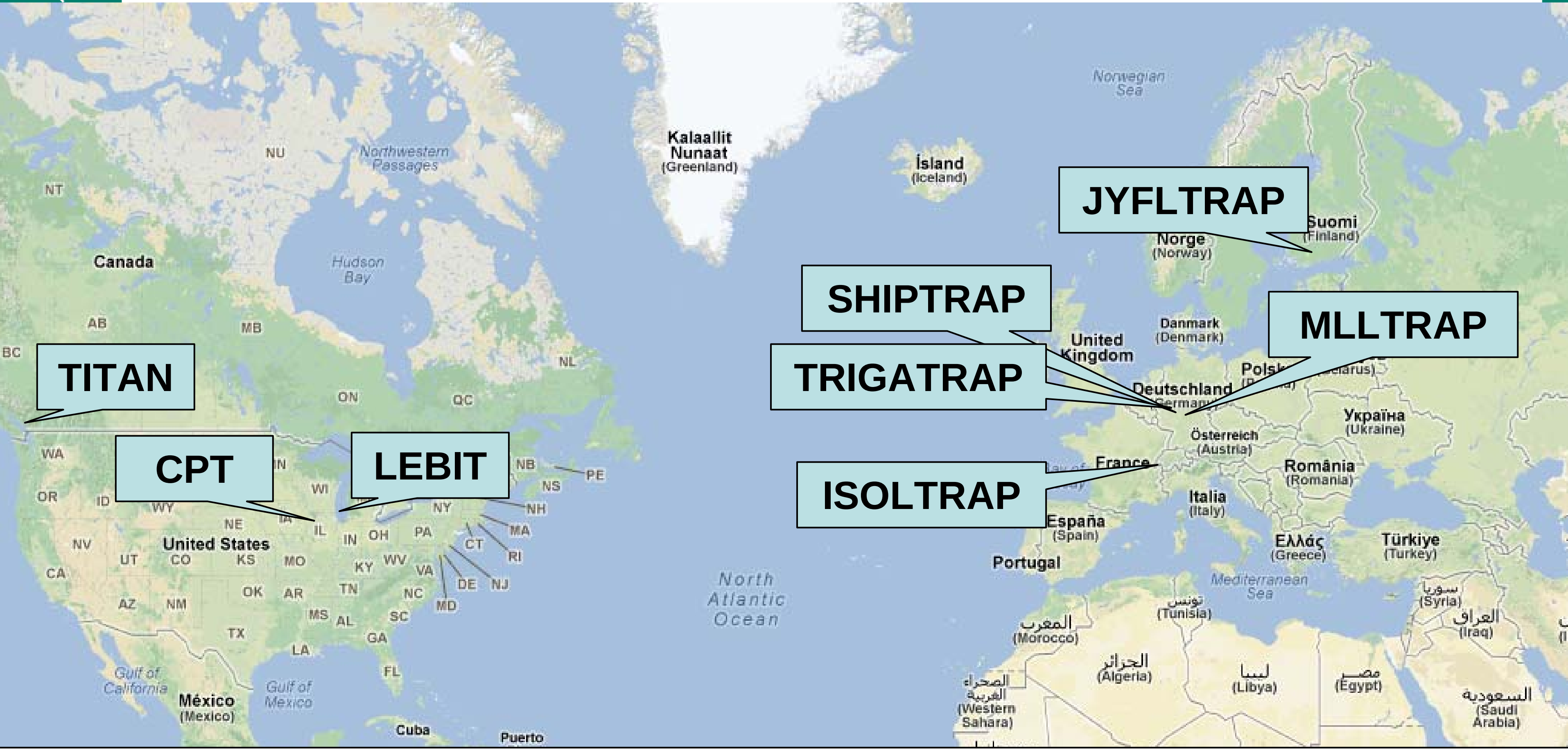
Penning-Traps worldwide



🟦 on-line facility for short-lived nuclides
$\delta m/m \sim 10^{-6} - 10^{-8}$

🟥 ultra-precise Penning trap for long-lived and stable nuclides
$\delta m/m < 10^{-10}$

Penning-Traps worldwide



on-line facilities (short-lived nuclides)

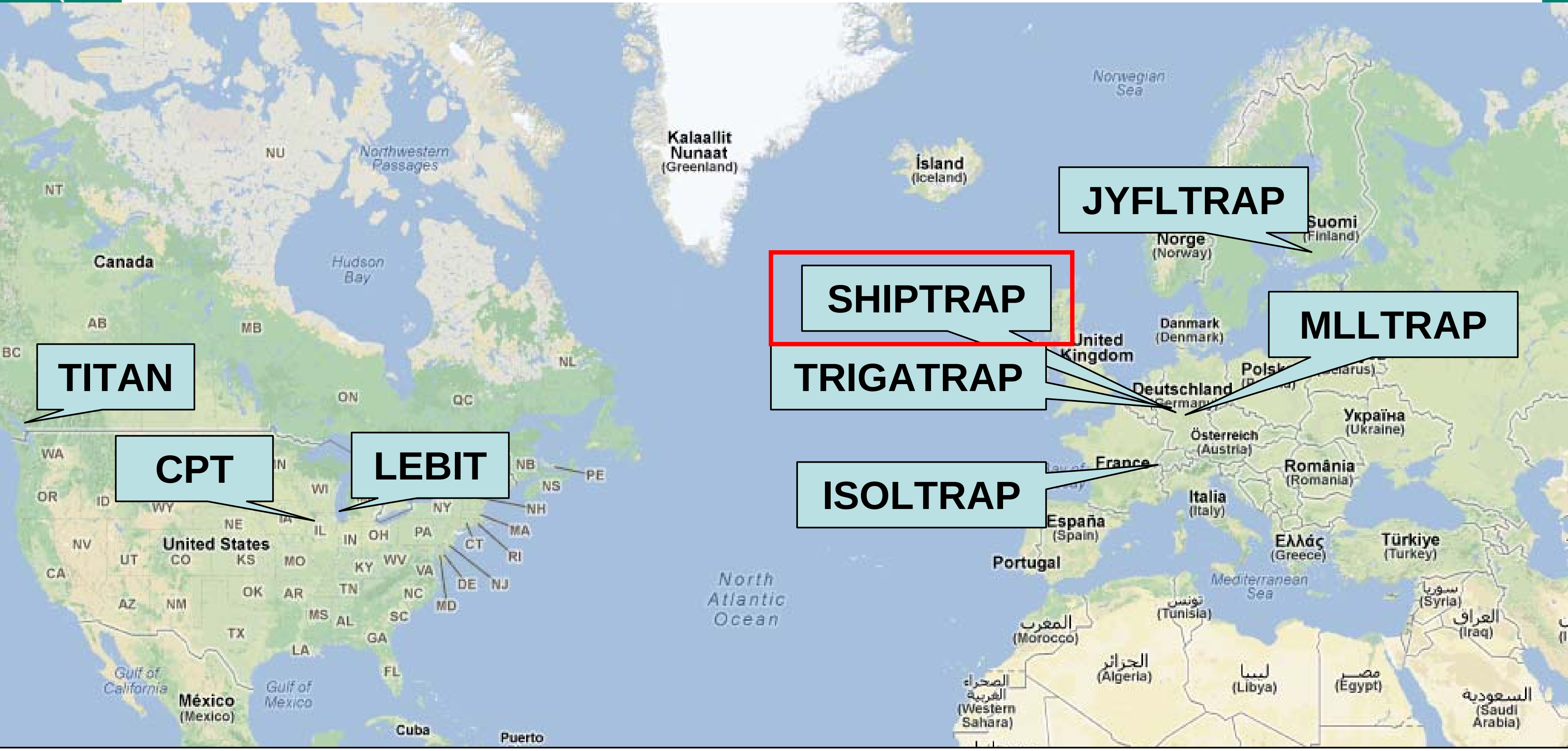
$\delta m/m \sim 10^{-6} - 10^{-8}$

until now
ToF-ICR technique

→

future ?
PI-ICR technique

Penning-Traps worldwide



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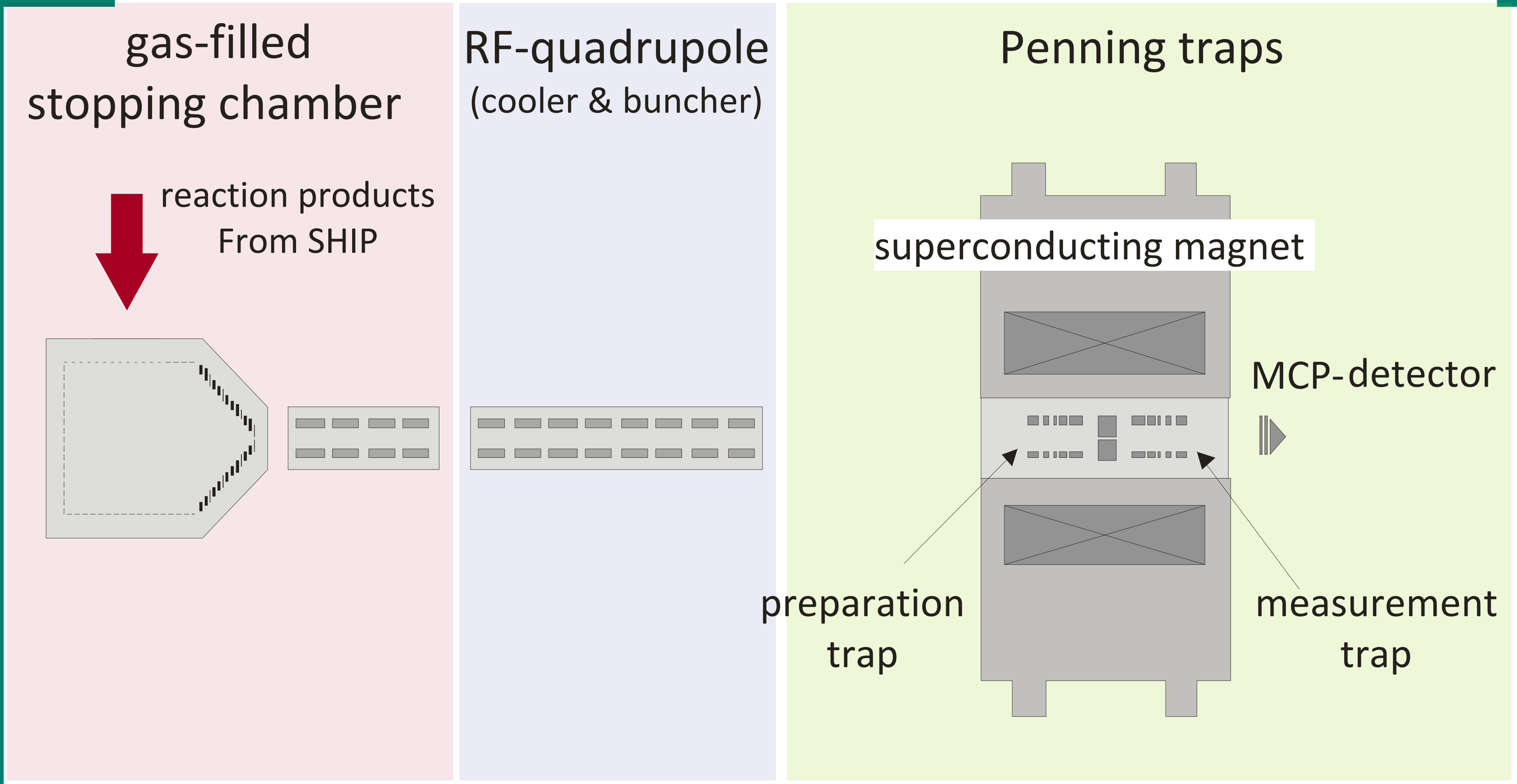
future ?
PI-ICR technique

SHIPTRAP

150-1000 keV/u → ≈ 1 eV



gas-filled
stopping chamber

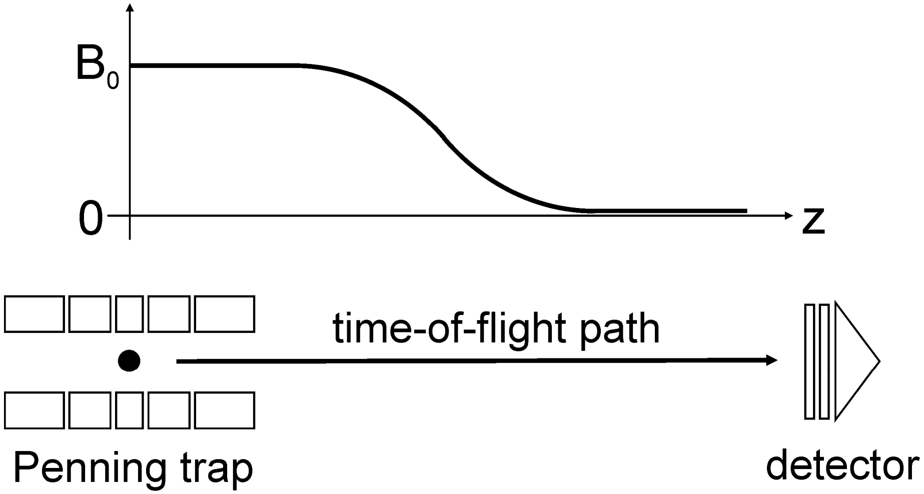
RF-quadrupole
(cooler & buncher)

Penning traps

M. Block et al., *Eur. Phys. J. D* 45 (2007) 39

Currently used **ToF-ICR** technique

(**T**ime-**o**f-**F**light **I**on-**C**yclotron-**R**esonance)



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

larger $\mu \rightarrow$ shorter ToF

Currently used **ToF-ICR** technique

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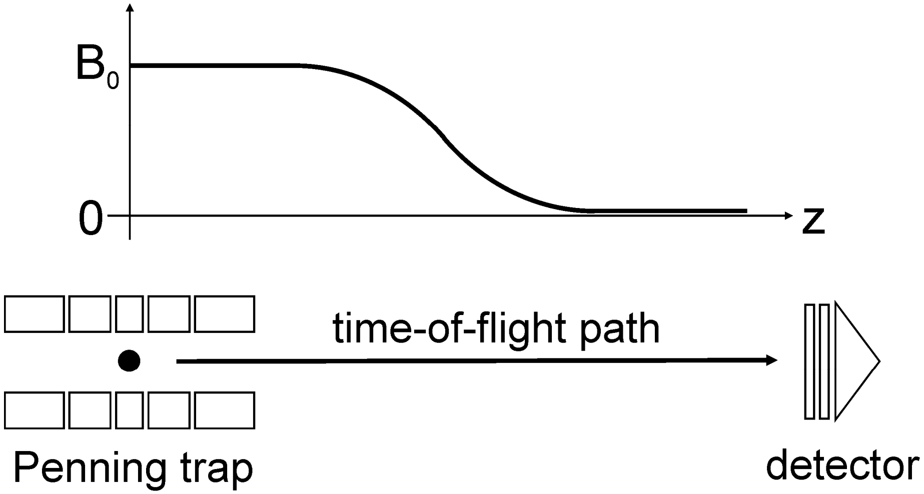

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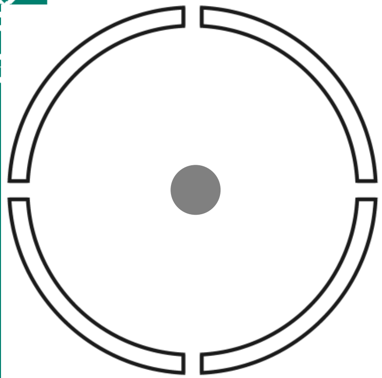
larger $\mu \rightarrow$ shorter ToF

injection



Currently used **ToF-ICR** technique

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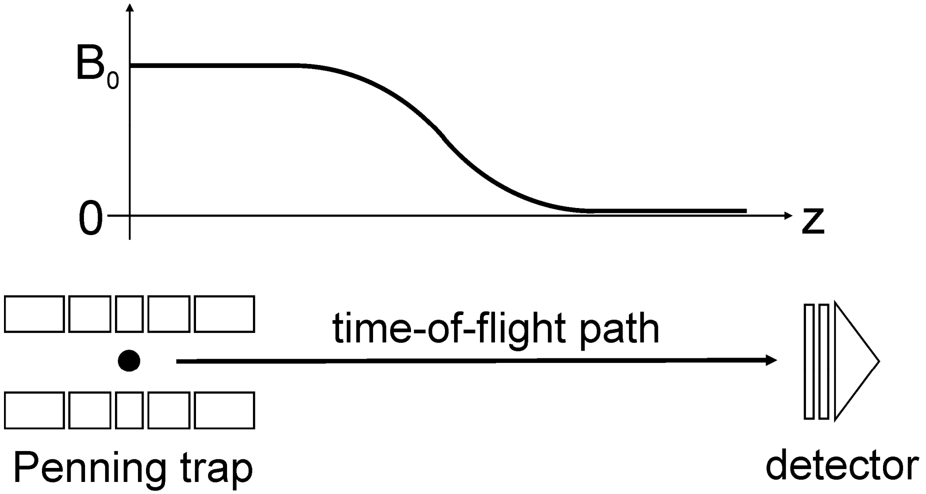
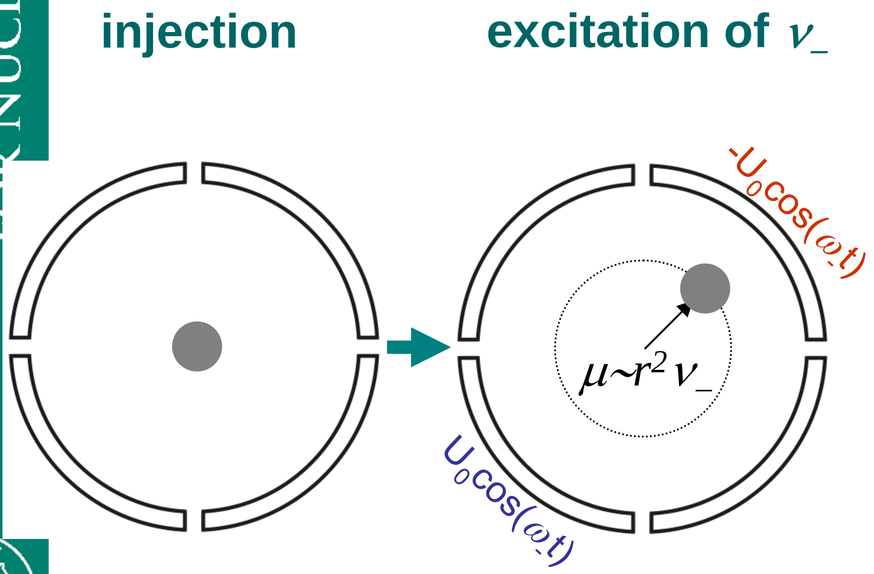


$$\vec{F} = -\vec{\mu}\cdot\frac{\partial \vec{B}}{\partial z}$$

larger μ → shorter ToF



Currently used **ToF-ICR** technique

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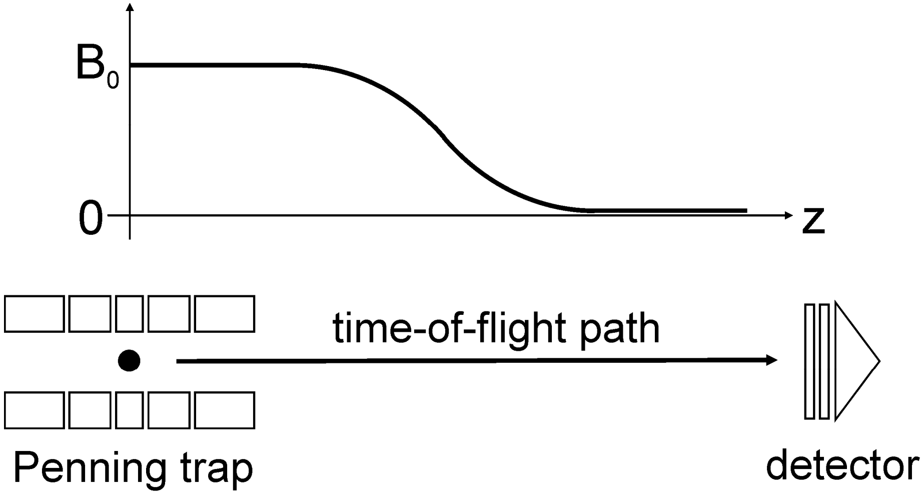

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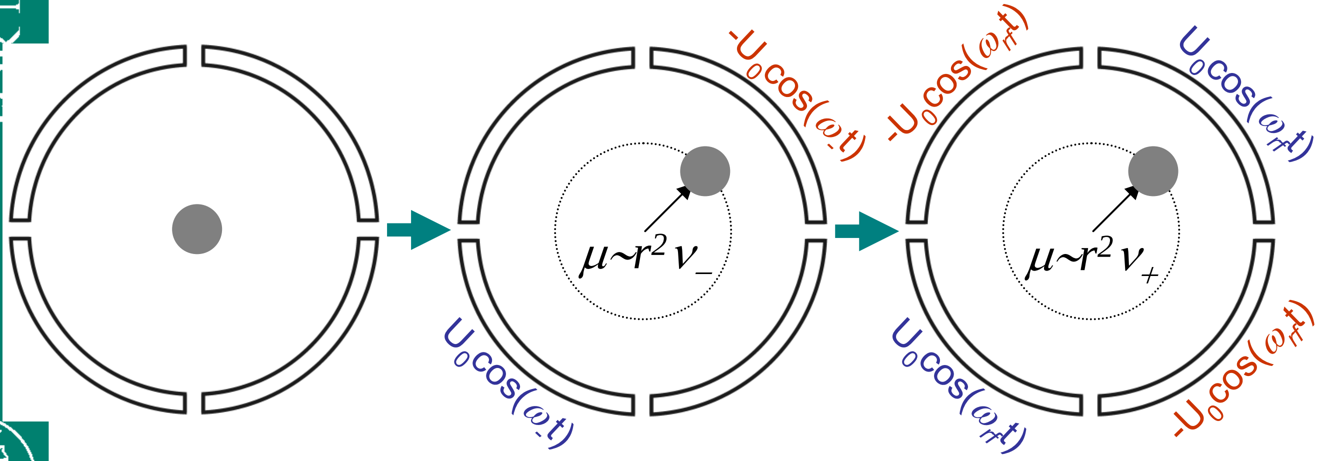
injection **excitation of ν_-** π–pulse **at $\nu_{rf} \approx \nu_c$**



Currently used **ToF-ICR** technique

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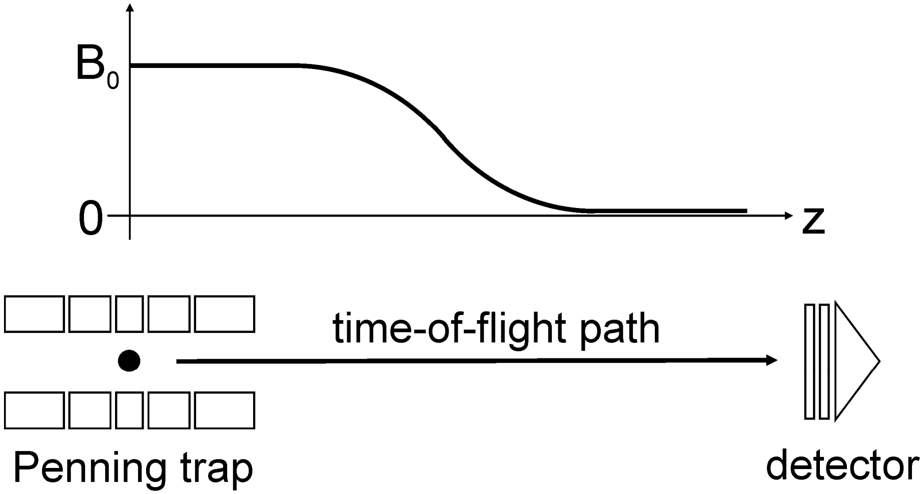

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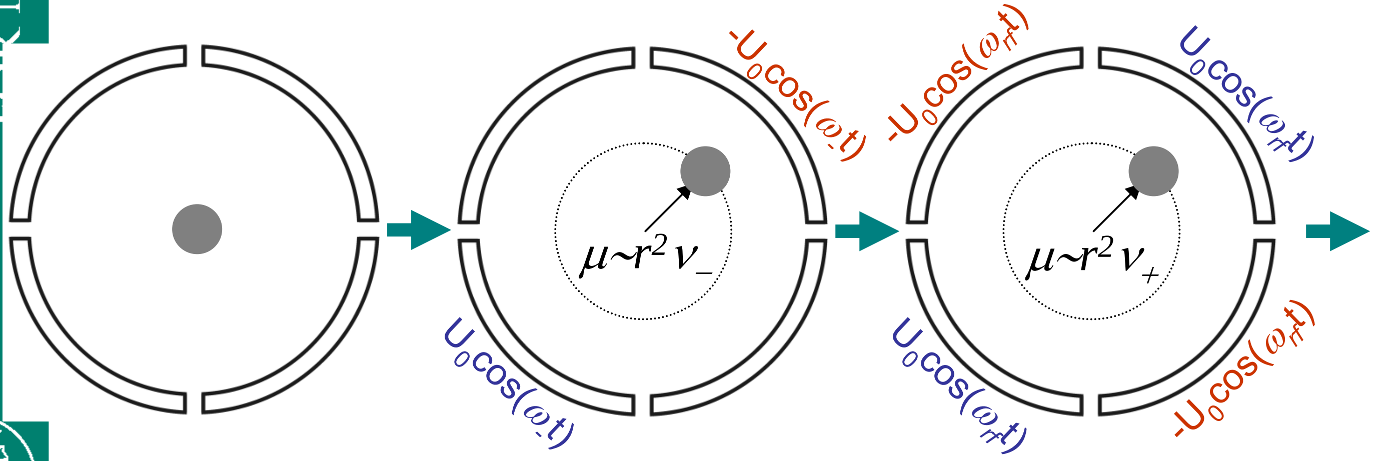
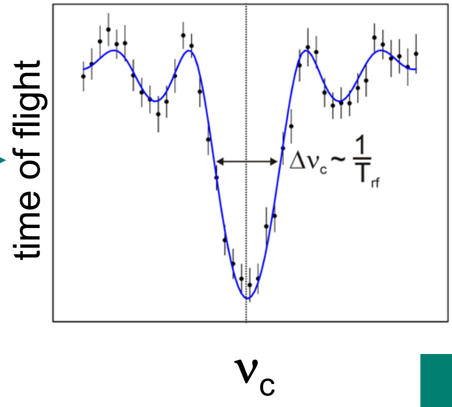
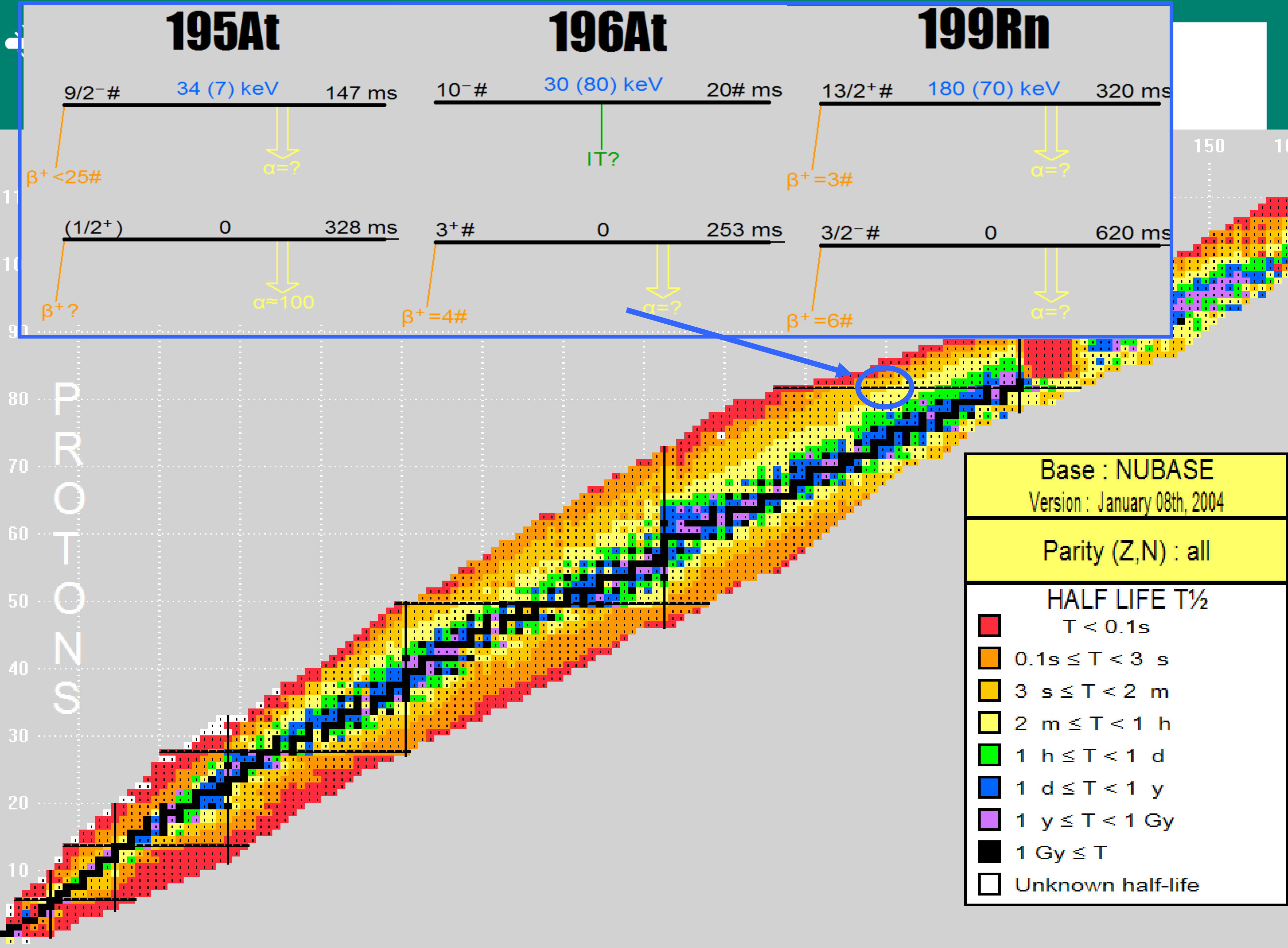
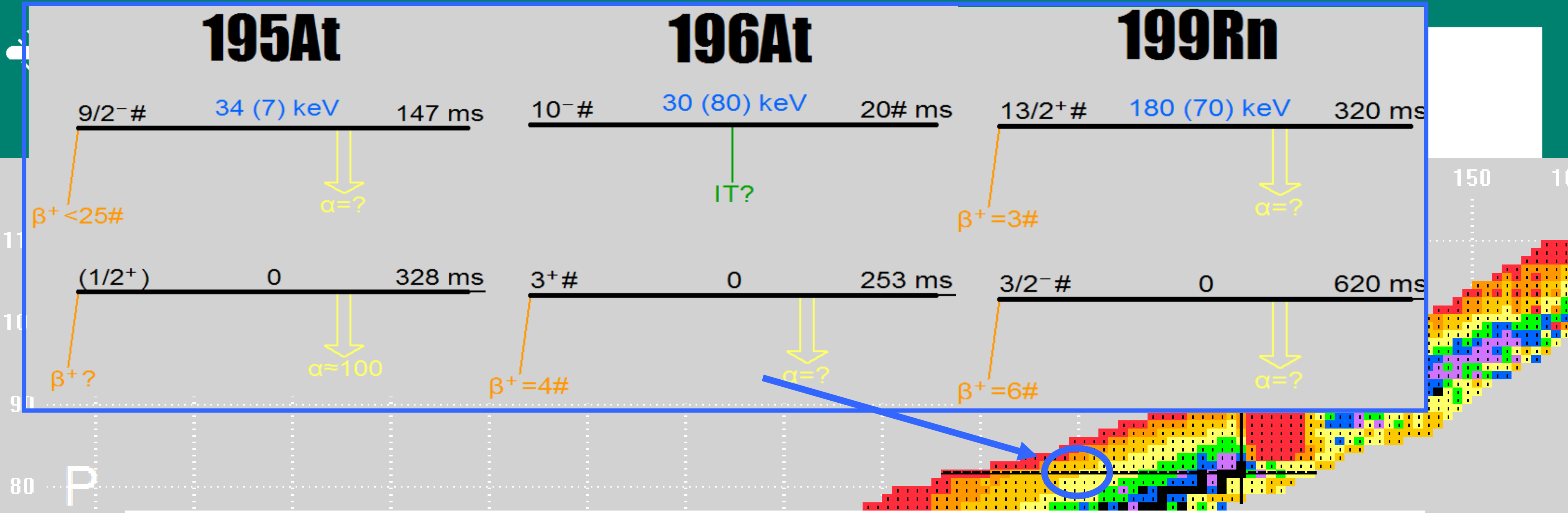





195At
196At
199Rn
9/2⁻#
34 (7) keV
147 ms
β+<25#
α=?
(1/2+)
0
328 ms
β+?
α≈100
10⁻#
30 (80) keV
20# ms
IT?
3+#
0
253 ms
β+=4#
α=?
13/2+#
180 (70) keV
320 ms
β+=3#
α=?
3/2⁻#
0
620 ms
β+=6#
α=?
150
80
70
60
50
40
30
20
10
PROTONS
Base : NUBASE
Version : January 08th, 2004
Parity (Z,N) : all
HALF LIFE T½
🟥 T < 0.1s
🟧 0.1s ≤ T < 3 s
🟨 3 s ≤ T < 2 m
🟨 2 m ≤ T < 1 h
🟩 1 h ≤ T < 1 d
🟦 1 d ≤ T < 1 y
🟪 1 y ≤ T < 1 Gy
⬛ 1 Gy ≤ T
⬜ Unknown half-life

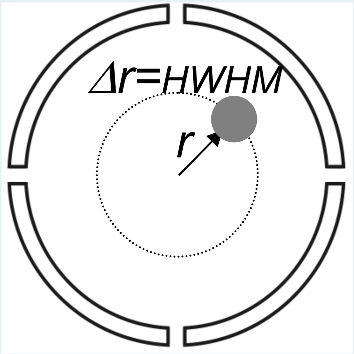


we want to

measure masses of nuclides with $T_{1/2}$~100 ms with a few keV accuracy ($\delta m/m \sim 10^{-8}$)

be able to resolve isomeric states with a few ten keV energy

Perfomance of **ToF-ICR** technique



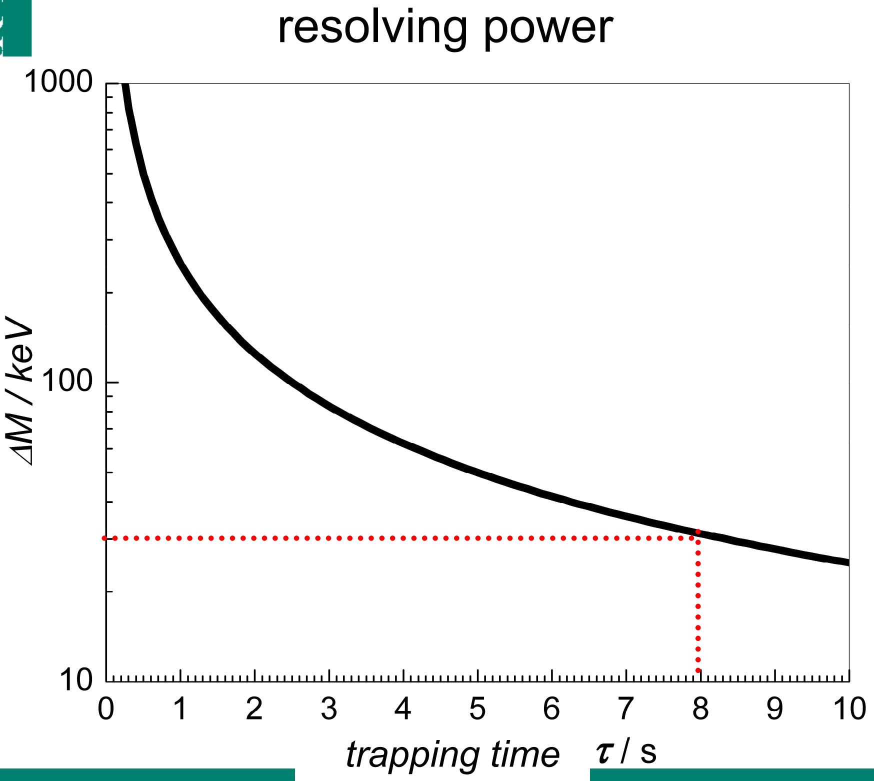
$$\frac{\nu_c}{\Delta\nu_c} = 1.6\cdot\nu_c\cdot\tau$$

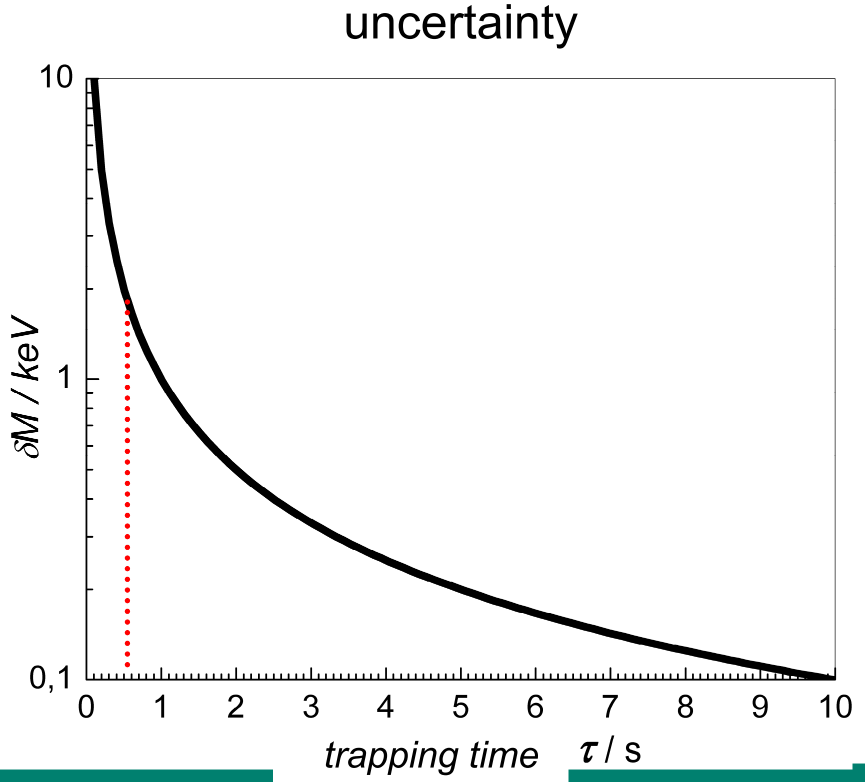
$$\delta\nu_c \approx \frac{1.6}{\tau\sqrt{N}}\,\frac{\Delta r}{r}$$

singly charged ions of *M=200*

$\nu_c \approx 500$ kHz

$N=1000$





new technique for singly-charged ions

- gain in resolving power: ~ 50
- much faster measurements
- gain in precision: ~ 5

determination of neutrino mass with accuracy of 0.2 eV

ECHo - Project → Analysis

EC in ^{163}Ho

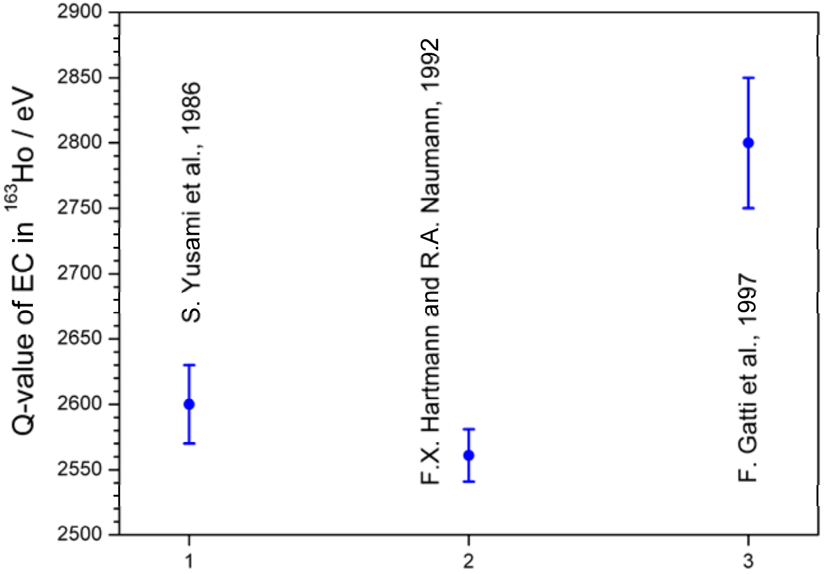
β^{-}decay of ^{187}Re

$\delta Q \sim 1$ eV ($\delta Q/m < 10^{-11}$) → neutrino-mass value (PENTATRAP)

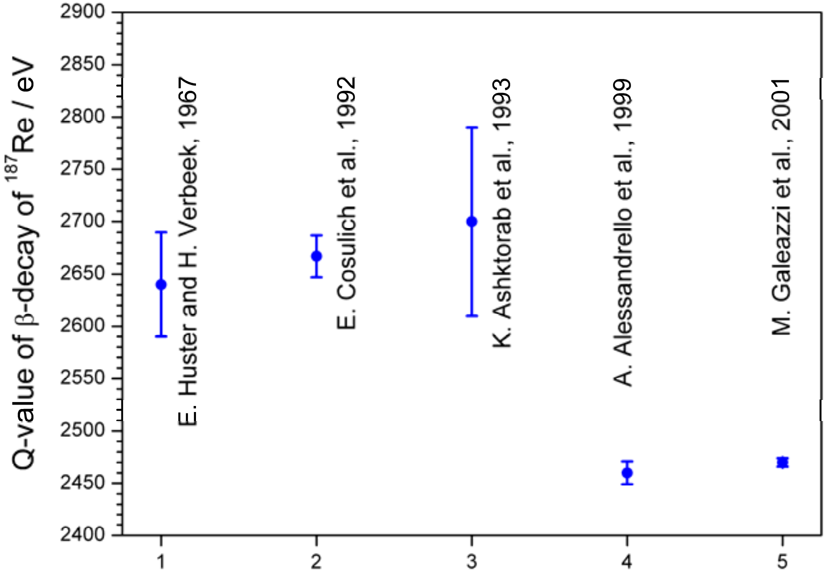
$\delta Q \sim 50$ eV ($\delta Q/m < 3 \cdot 10^{-10}$) → development of experiment

Development of the ECHo-Project
(scale of experiment)

^{163}Ho



^{187}Re



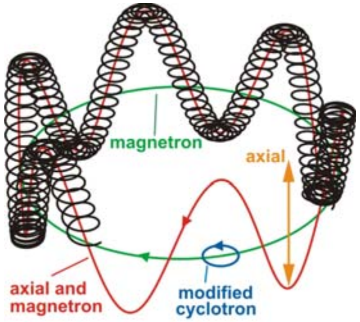
SHIPTRAP in 2014-2015

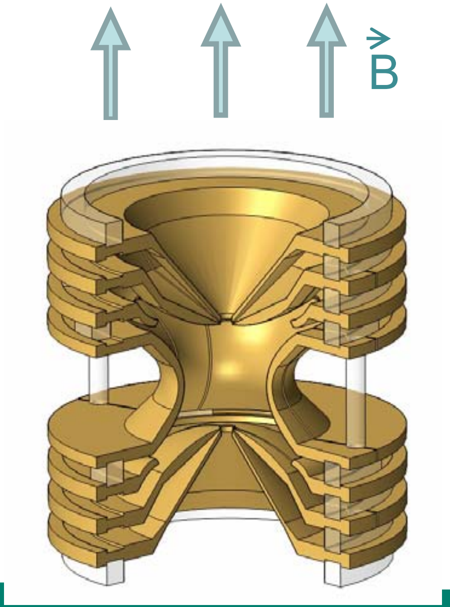
Measurement of *Q*-values
of ^{187}Re β-decay & EC in ^{163}Ho
with 50 eV-uncertainty

New **PI-ICR** technique

(**P**hase-**I**maging **I**on-**C**yclotron-**R**esonance)

$$\nu_c = \nu_+ + \nu_-$$





New **PI-ICR** technique

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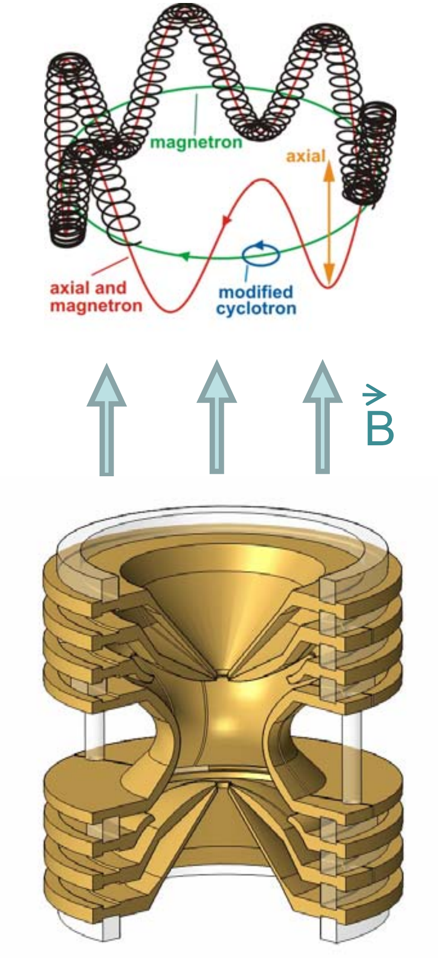
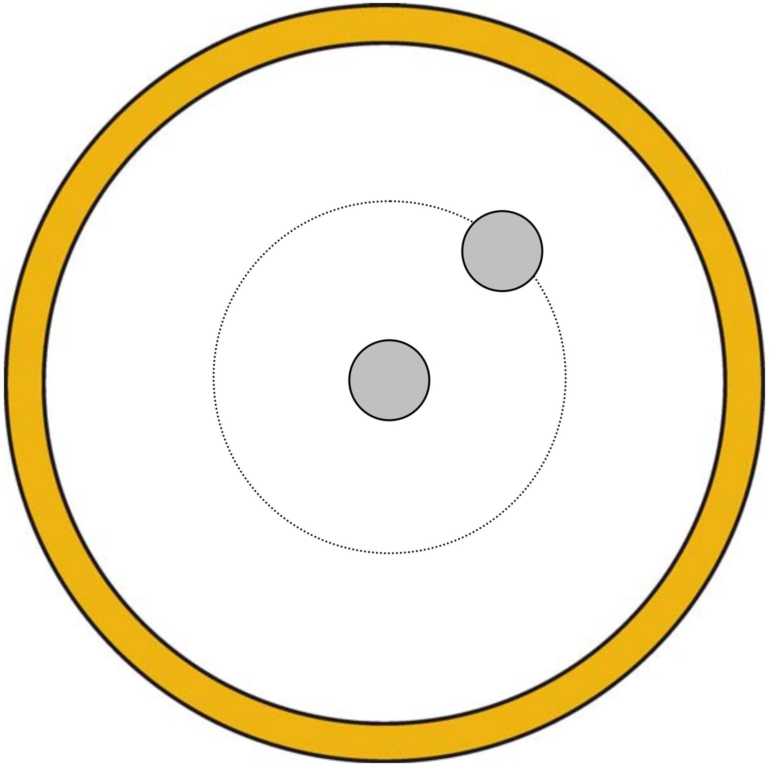
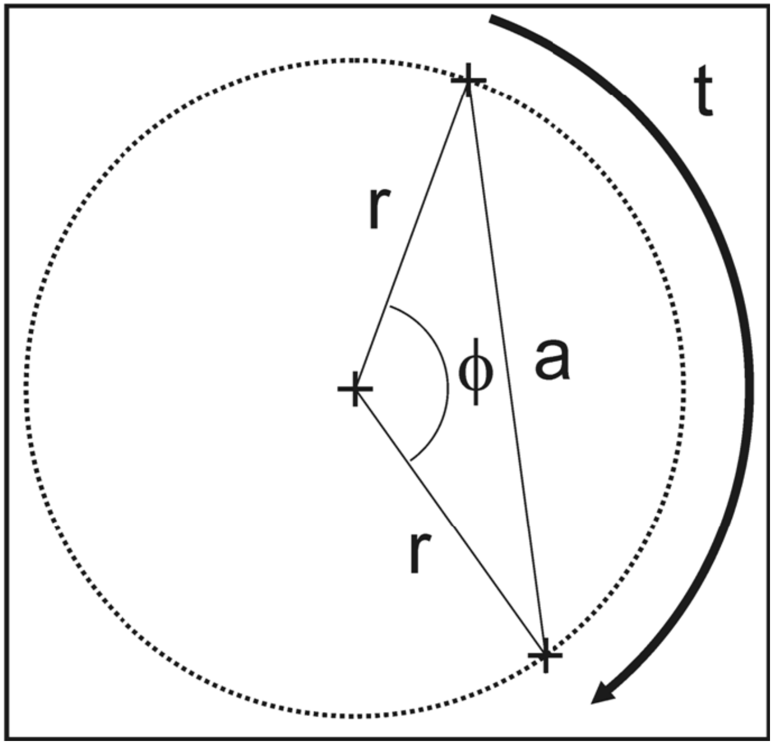


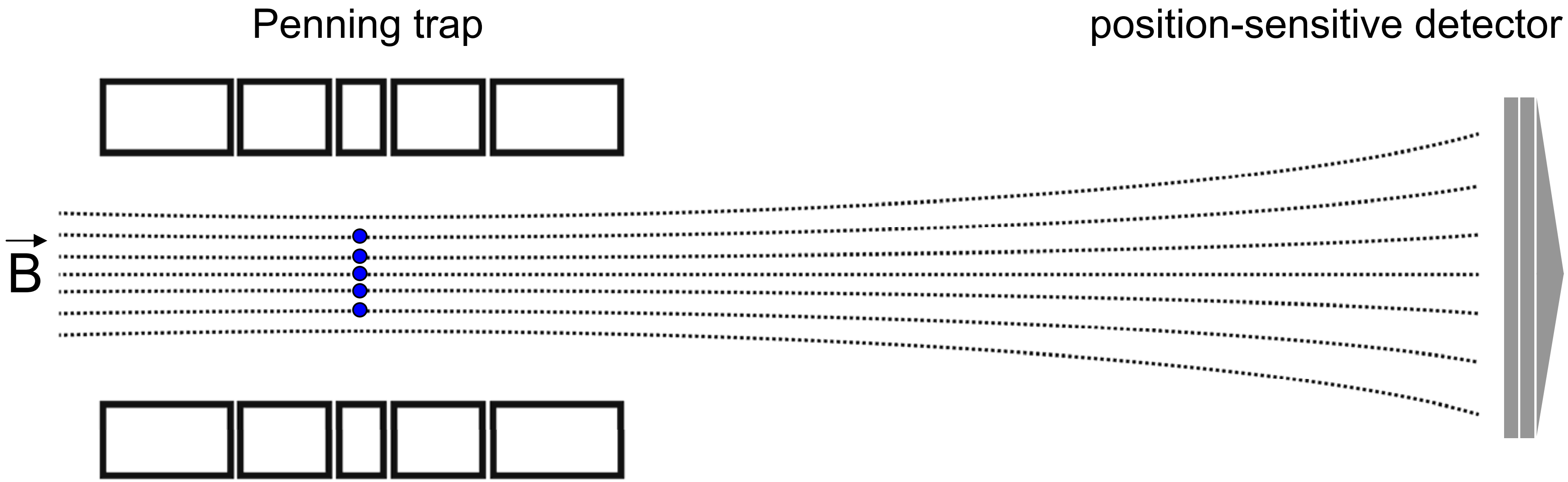




$$\nu_- = \frac{\phi_- + 2\pi n_-}{2\pi t_-}$$

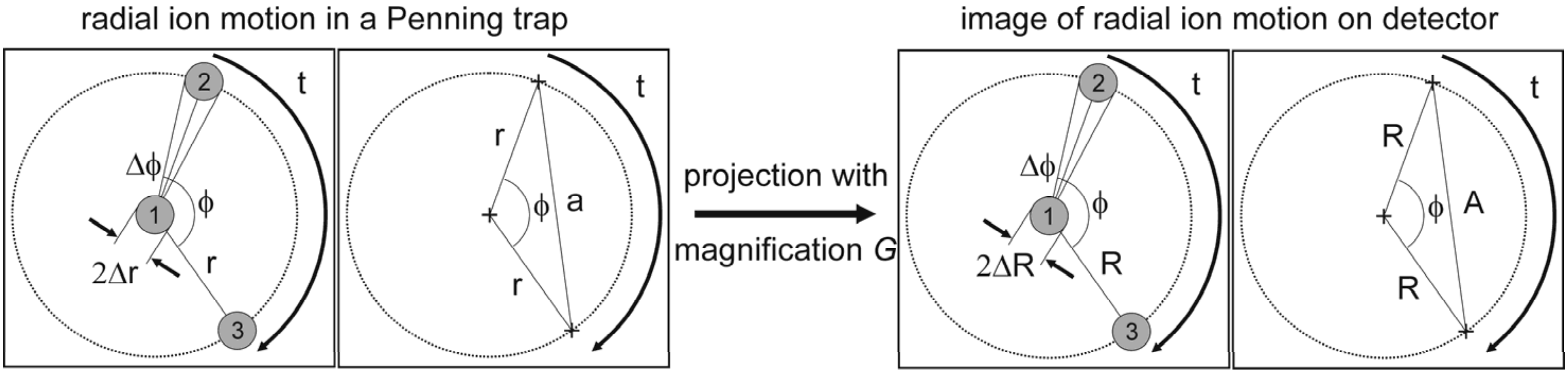
$$\nu_+ = \frac{\phi_+ + 2\pi n_+}{2\pi t_+}$$

$$\nu_c = \nu_+ + \nu_-$$



Penning trap

position-sensitive detector



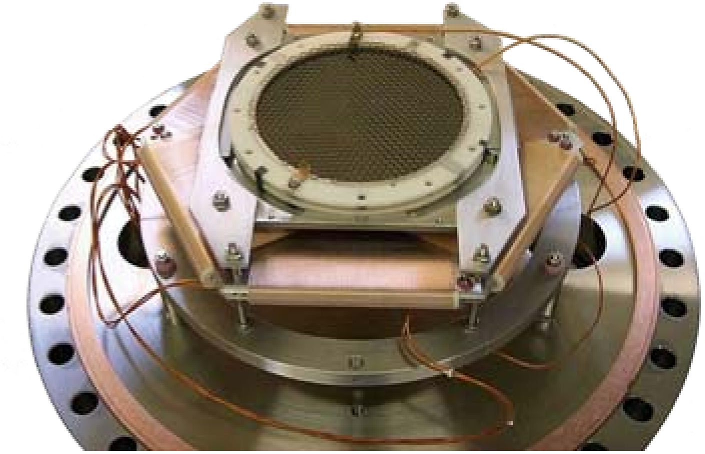
radial ion motion in a Penning trap

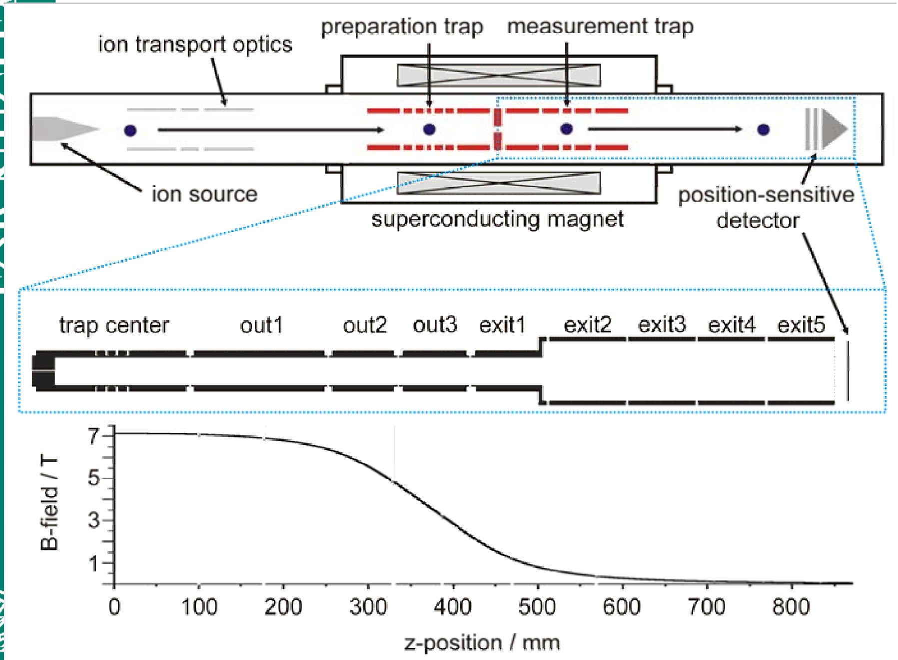
projection with magnification *G*

image of radial ion motion on detector

delayline position-sensitive detector RoentDek GmbH DLD40

Active diameter	42 mm
Channel diameter	25 µm
Open area ratio	>50 %
Position resolution	**70 µm**
Max. B-field	**a few mT**
Time resolution	~ 10 ns





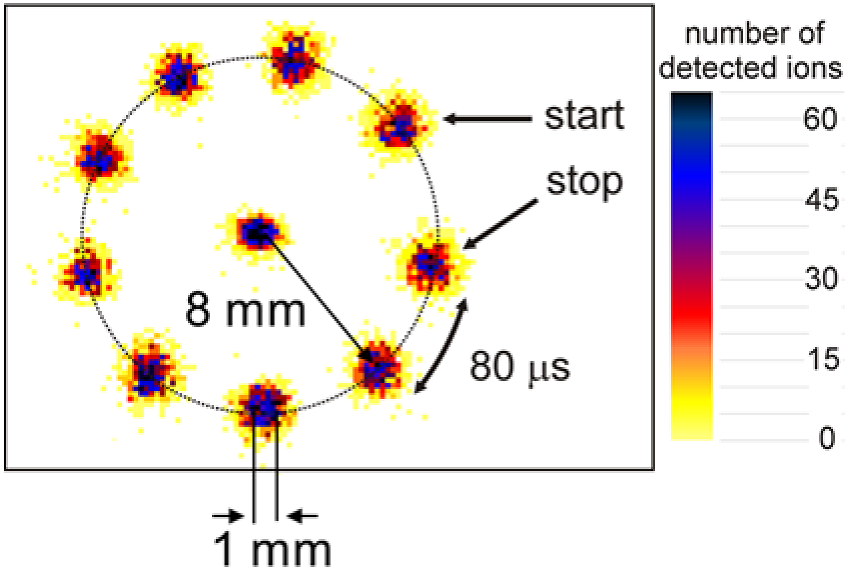
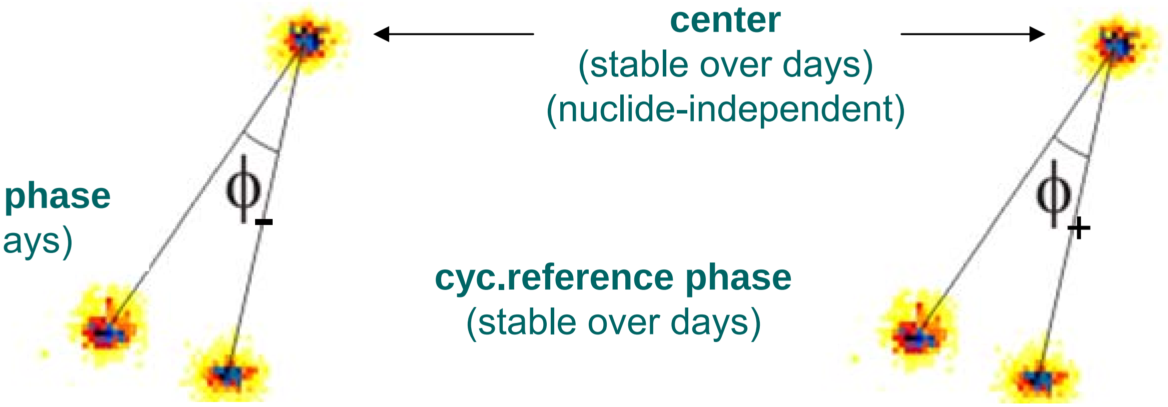


image of magnetron motion ($G \approx 20$)

measurement of free cyclotron frequency: $\nu_c = \nu_+ + \nu_-$

magnetron frequency ν_- **modified cyclotron frequency ν_+**



center
(stable over days)
(nuclide-independent)

mag.reference phase
(stable over days)

cyc.reference phase
(stable over days)

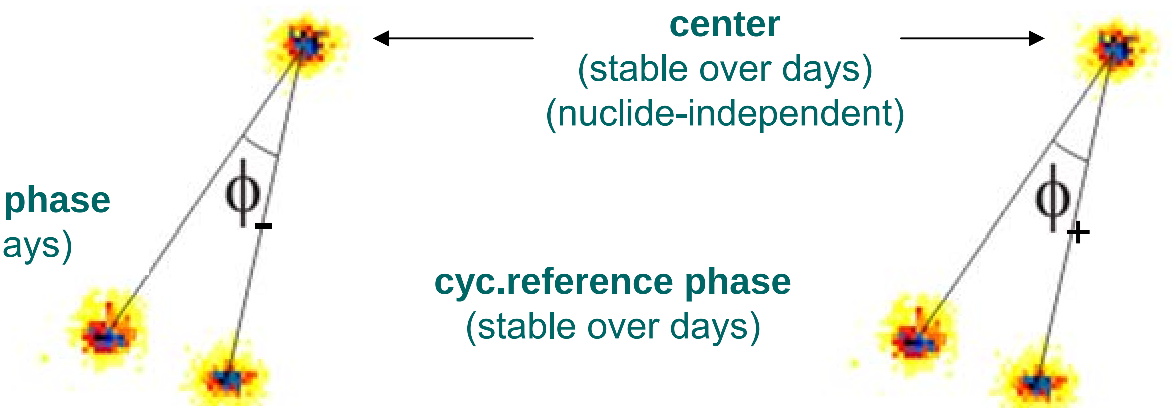
mag. final phase

cyc. final phase

measurement of free cyclotron frequency: $\nu_c = \nu_+ + \nu_-$

magnetron frequency ν_-

modified cyclotron frequency ν_+



center
(stable over days)
(nuclide-independent)

mag.reference phase
(stable over days)

cyc.reference phase
(stable over days)

mag. final phase

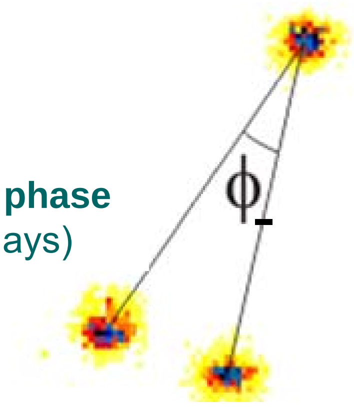
cyc. final phase

if production rates of exotic nuclides are extremely low and experiment time is limited?

it is desirable to skip the measurement of the reference phases

measurement of free cyclotron frequency: $\nu_c = \nu_+ + \nu_-$

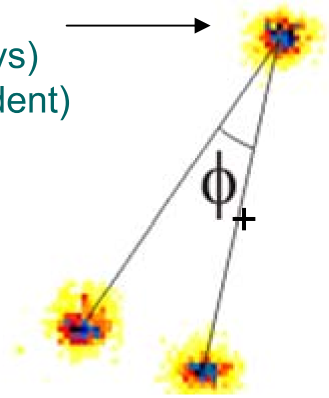
magnetron frequency ν_- | **modified cyclotron frequency ν_+**



center
(stable over days)
(nuclide-independent)

mag.reference phase
(stable over days)

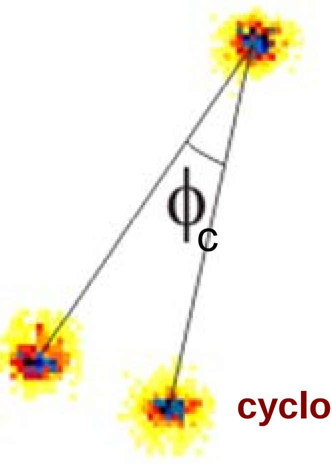
mag. final phase



cyc.reference phase
(stable over days)

cyc. final phase

free cyclotron frequency ν_c

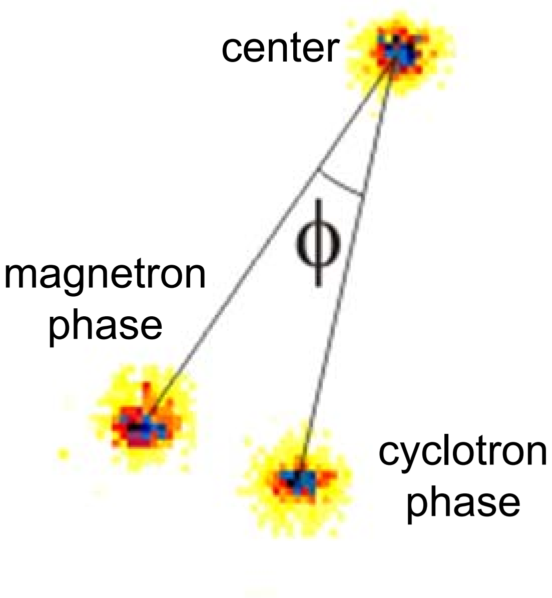


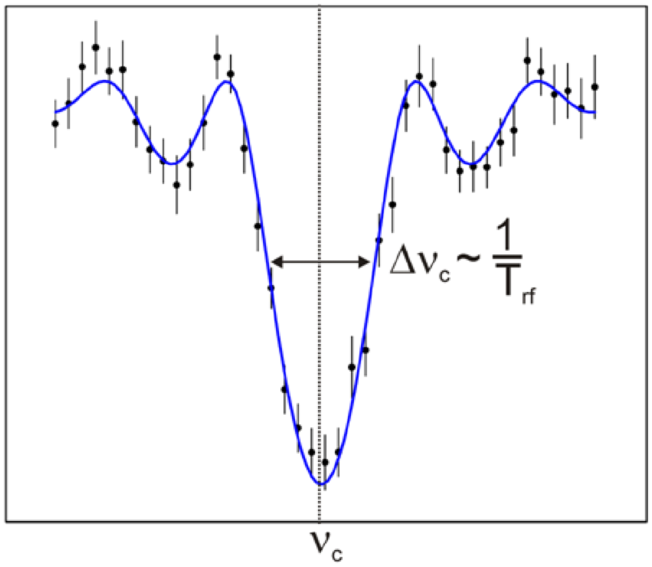
magnetron phase

cyclotron phase

$$\nu_c = \frac{\phi_c + 2\pi n}{2\pi t}$$

PI-ICR vs. ToF-ICR





- gain in precision $= \dfrac{(\delta\nu_c)_{ToF-ICR}}{(\delta\nu_c)_{PI\ ICR}} = 1.6\cdot\pi \cong 5$

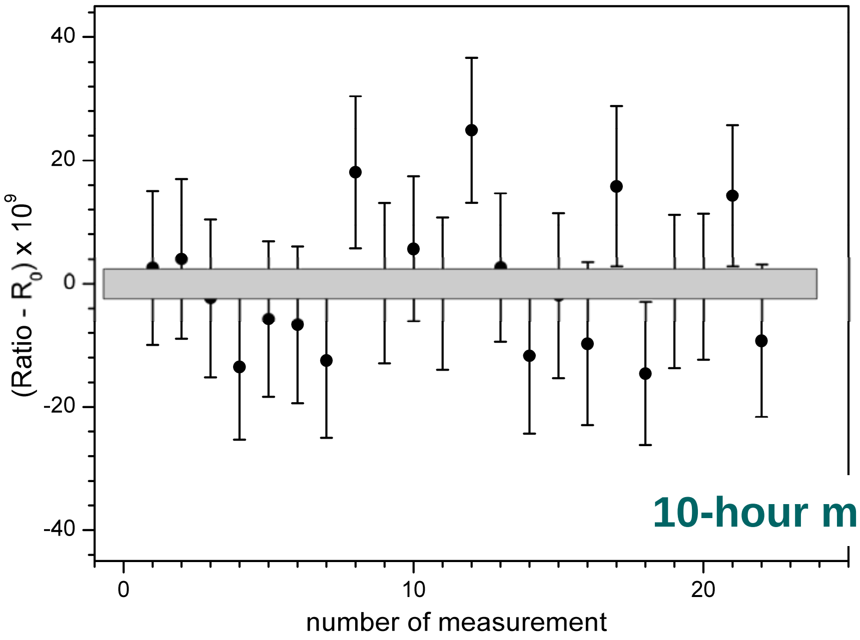
- gain in resolving power $= \dfrac{0.6\pi r}{\Delta r} = \dfrac{0.6\cdot\pi\cdot 1}{0.05} \cong 40$

- higher sensitivity

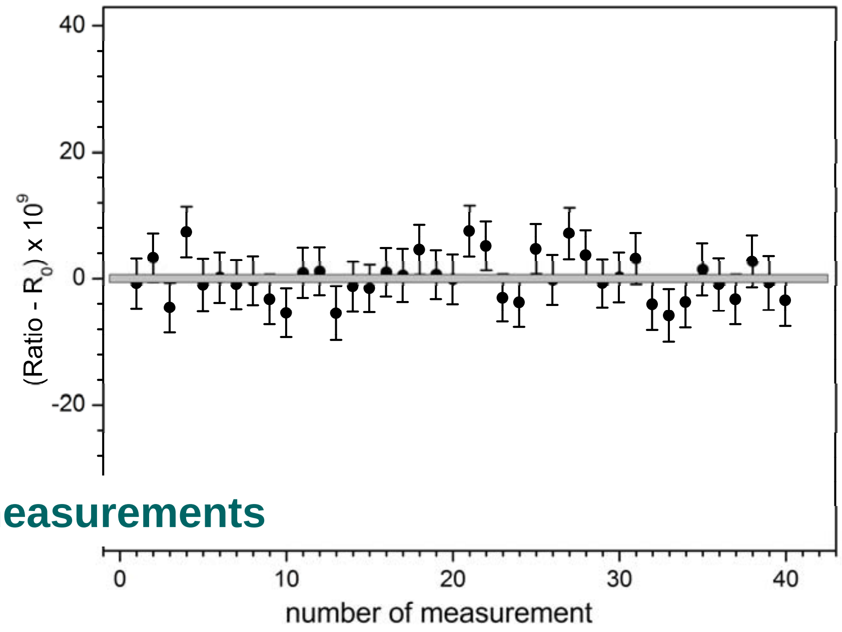
!

PI-ICR vs. ToF-ICR in experiment

ToF-ICR



PI-ICR



10-hour measurements

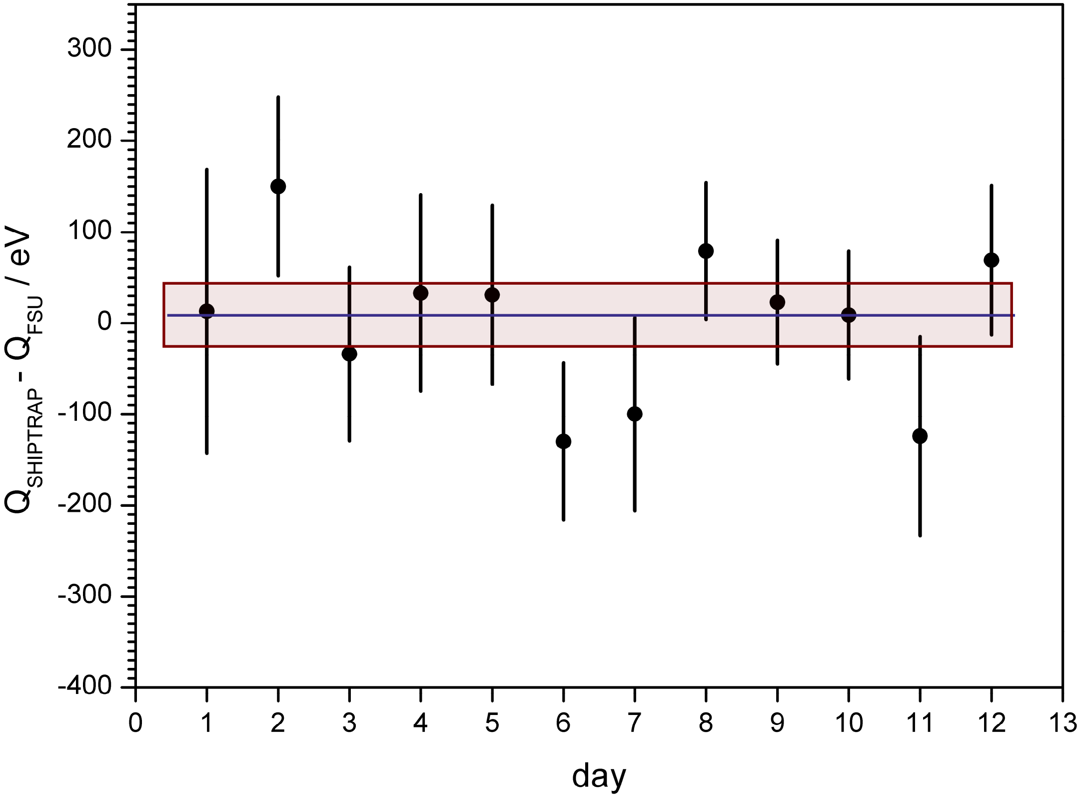
$\delta[M(^{124}Xe) - M(^{124}Te)] \sim 300$ eV

$\delta[M(^{132}Xe) - M(^{131}Xe)] \sim 70$ eV !!!

Gain in Precision ~ 4.5 !!!

PI-ICR in experiment

$$\Delta M = M(^{132}Xe) - M(^{131}Xe)$$

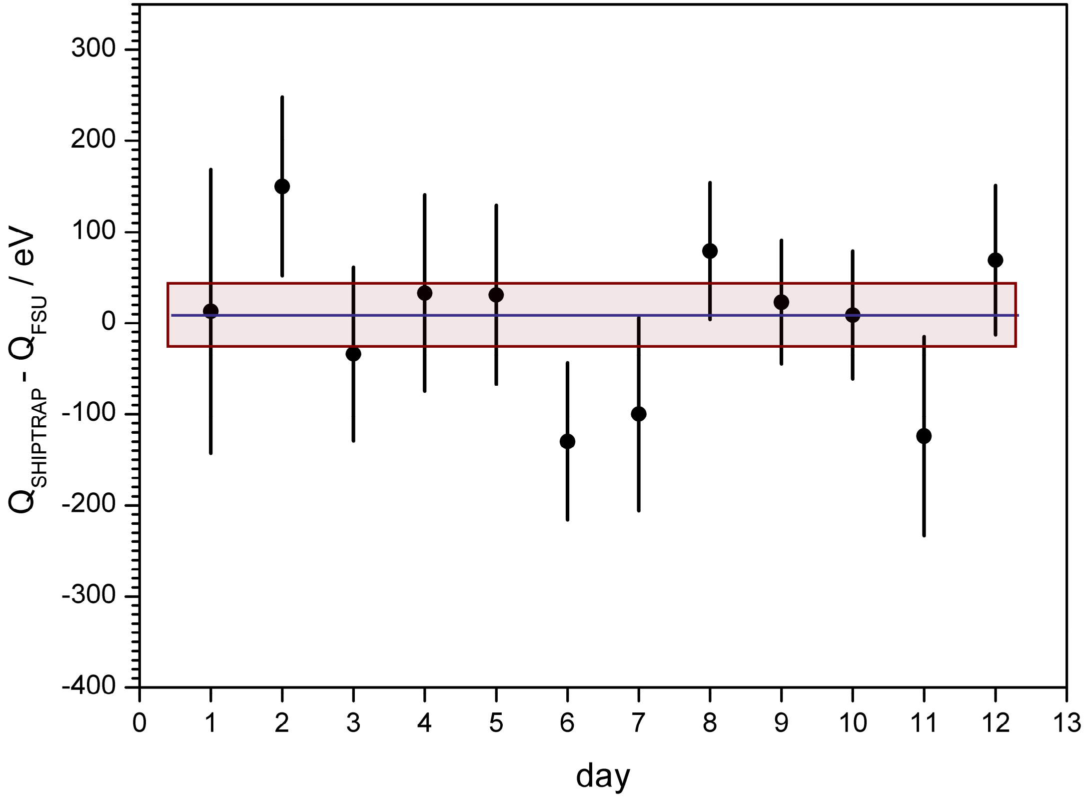


$$\delta(\Delta M)_{SHIPTRAP} = (30_{stat})(12_{sys})\ eV$$

$$\Delta M_{SHIPTRAP} - \Delta M_{reference} = (8 \pm 35)\ eV$$

PI-ICR in experiment

$\Delta M = M(^{132}Xe) - M(^{131}Xe)$



first ever measurement of mass difference
of *singly charged* medium-heavy non-mass-doublets
with a relative accuracy of $2 \cdot 10^{-10}$!!!

SHIPTRAP in 2014-2015

We are preparing for the measurement of the *Q*-value of:

(1) β^{-}-decay of ^{187}Re

(2) EC in ^{163}Ho

with an uncertainty of ~ 50 eV

Summary

- PI-ICR has been developed at SHIPTRAP for mass measurements on singly-charged short-lived nuclides
- PI-ICR is much faster than ToF-ICR and offers very high mass resolving power
- Performance at SHIPTRAP:

$$\delta(M(^{132}\mathrm{Xe}) - M(^{131}\mathrm{Xe})) = \pm\ 30\ \mathrm{eV}$$

- Plans at SHIPTRAP: Q-values of EC in ^{163}Ho and β-decay of ^{187}Re

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EMMI

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(HA 216)

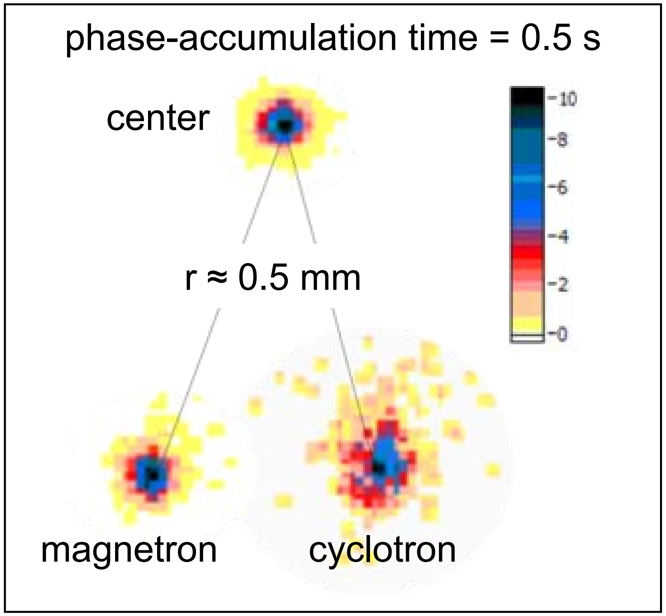
Thank you for your attention !

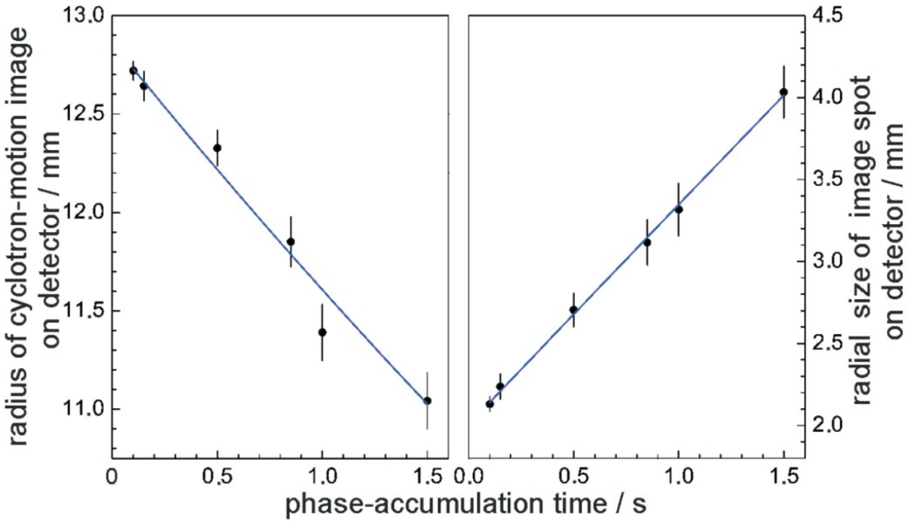
Effects that limit Resolving Power and Maximum Precision of PI-ICR

- Presence of Helium in the Trap
- Anharmonicity of the Trap Potential
- Instability of the Trap Potential in Time
- Instability of the B-Field in Time
- Error due to Conversion

Presence of Helium in the Trap

collisions with He atoms in trap increase the size of *cyclotron* phase spot





$P_{He} \approx 3\cdot10^{-7}$ mbar

$$\left(\frac{\nu_c}{\Delta\nu_c}\right)^{max} \approx \left(\frac{\nu_+}{\Delta\nu_+}\right)^{max} \approx 5\cdot10^6$$

(M = 200 u
ΔM=40 keV)

Anharmonicity of the Trap Potential

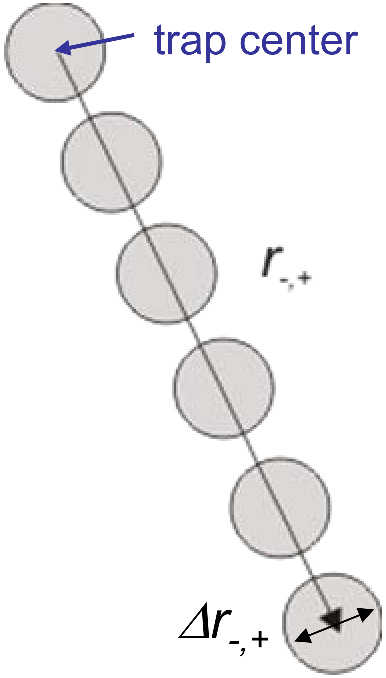
$$\nu_- = \nu_-^{harmonic} + C_4' r_-^2 + C_6' r_-^4 + \dots$$

$$\nu_+ = \nu_+^{harmonic} - C_4' r_+^2 - C_6' r_+^4 - \dots$$

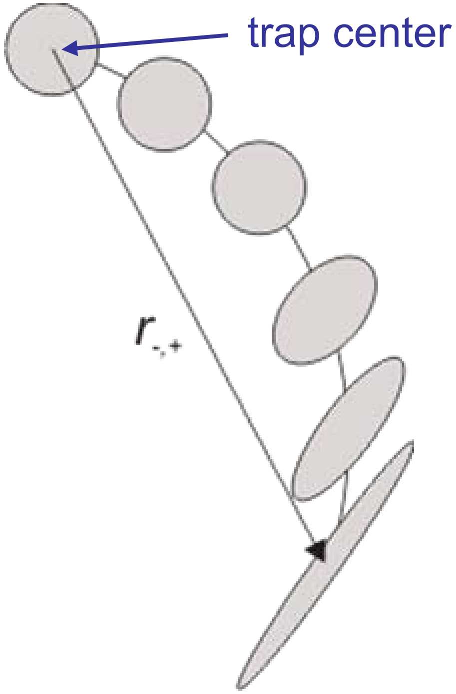
$$U_{trap} = C_2 \frac{U_0}{2d^2} z^2 + C_4 \frac{U_0}{2d^4} z^4 + C_6 \frac{U_0}{2d^6} z^6 + \dots$$

harmonic trap

anharmonic trap



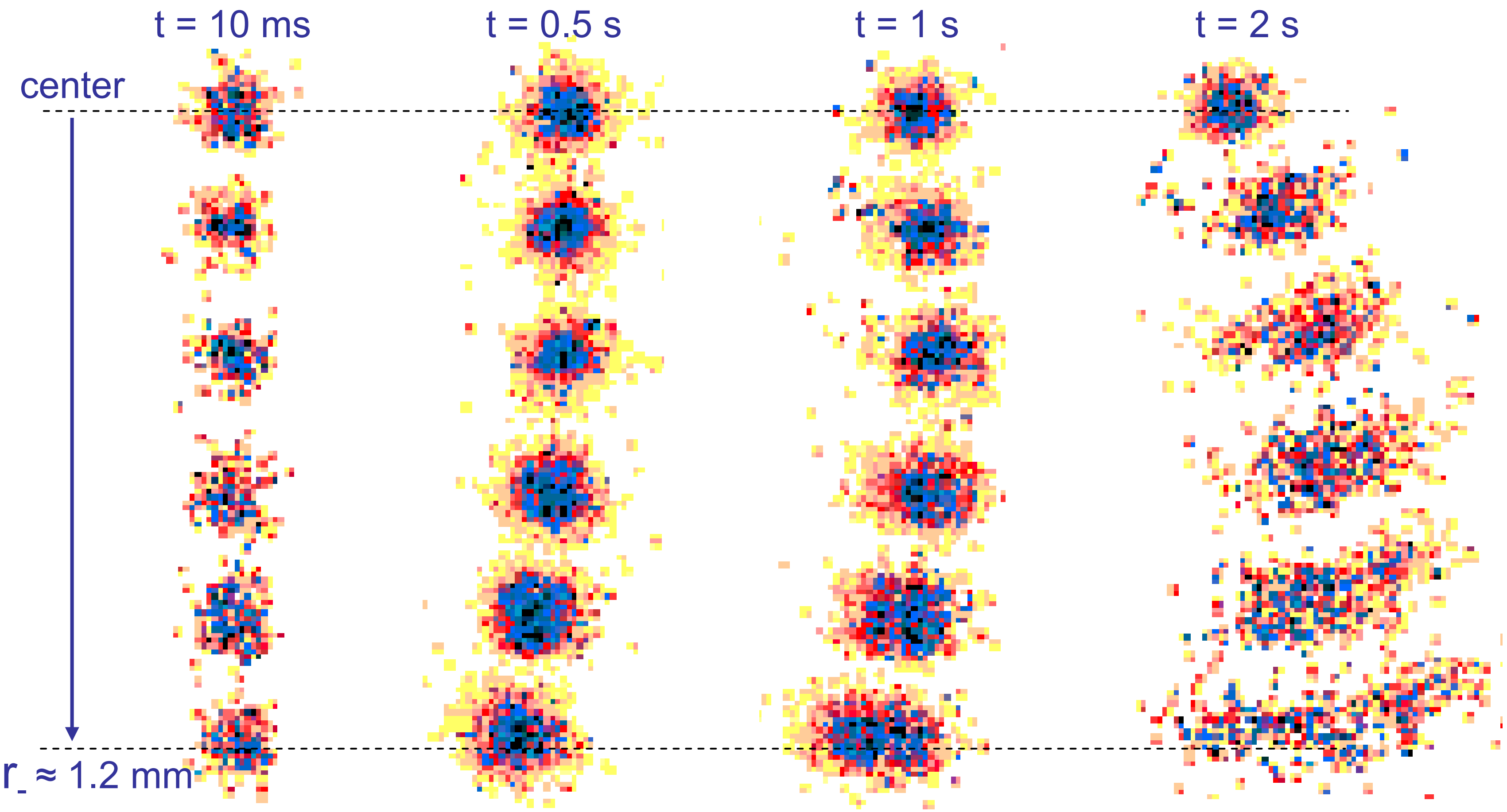
$$\Delta\nu = \frac{\Delta\phi}{2\pi t} \approx \frac{1}{\pi t}\frac{\Delta r}{r}$$



Anharmonicity of the Trap Potential

real trap

magnetron phase spots

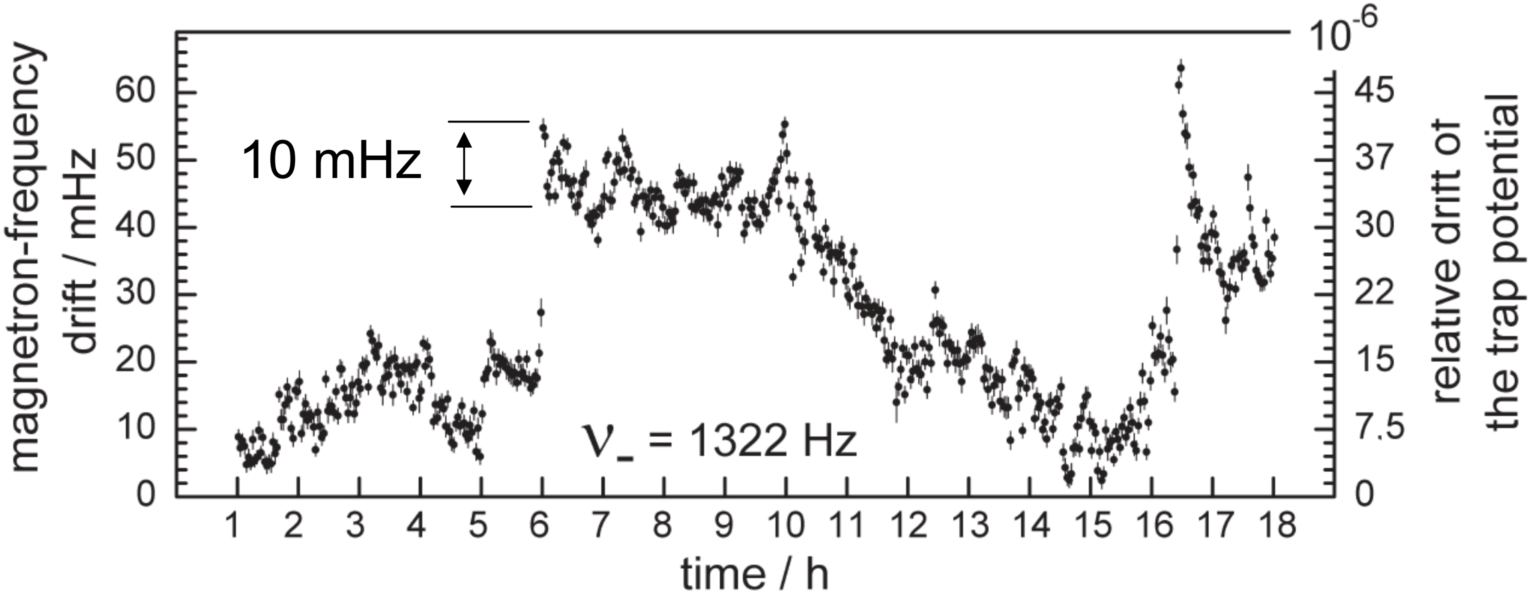


$$\Delta\nu_{-,+}^{max} \approx 50mHz \qquad \left(\frac{\nu_c}{\Delta\nu_c}\right)^{max} \approx \left(\frac{\nu_+}{\Delta\nu_+}\right)^{max} \approx 10^7$$

(M = 200 u
ΔM=20 keV)

Instability of Trap Potential in Time

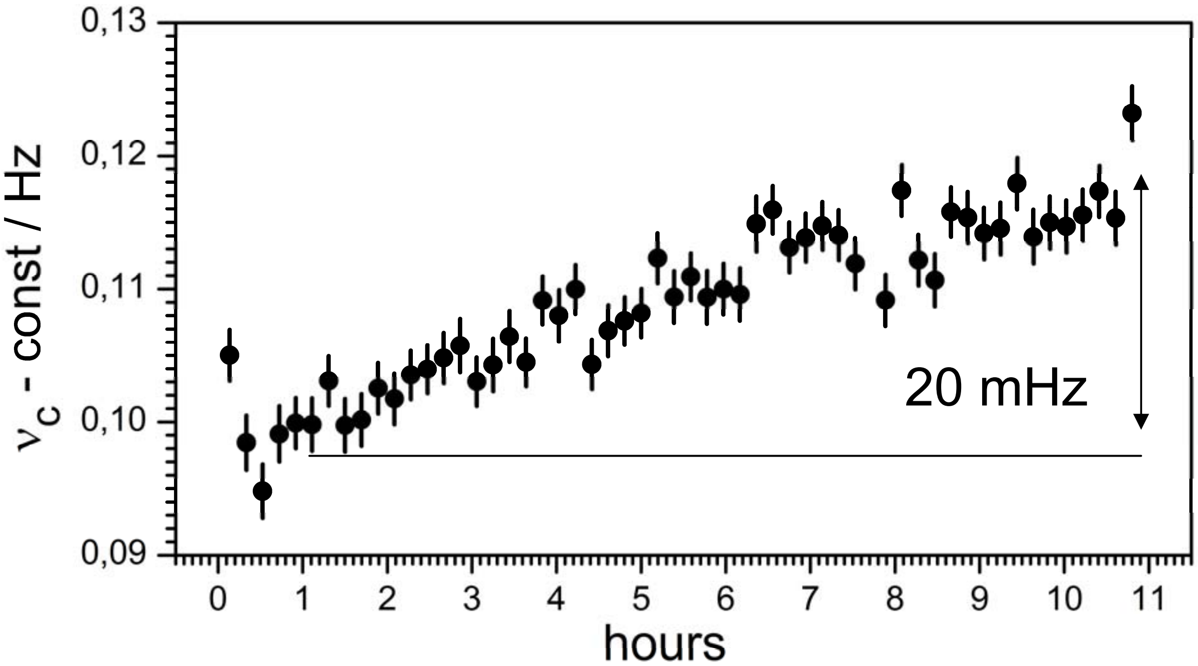
temporal instability of trapping voltage causes
angular smearing of both phase spots



$$\left(\frac{\nu_c}{\Delta\nu_c}\right)^{max} \approx \left(\frac{\nu_+}{\Delta\nu_+}\right)^{max} \approx 5\cdot 10^7 \qquad (M = 200\ \mathrm{u})$$

Instability of B-Field in Time

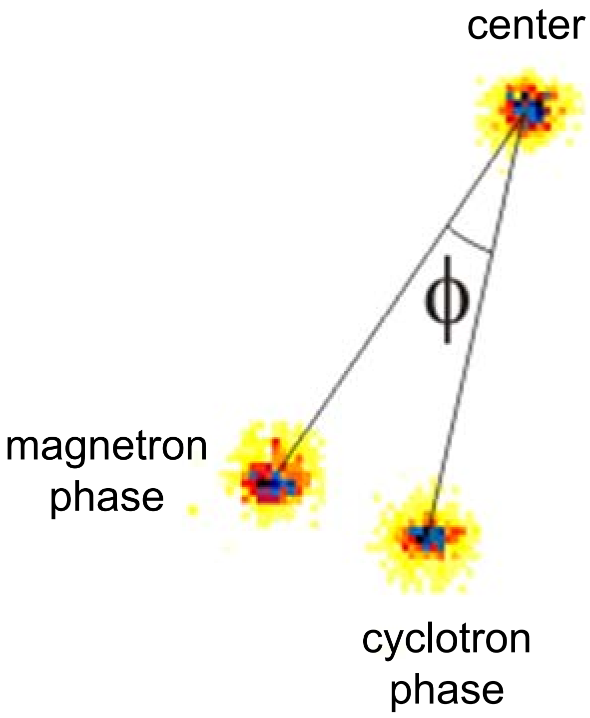
temporal instability of B-field causes
angular smearing of *cyclotron* phase spot



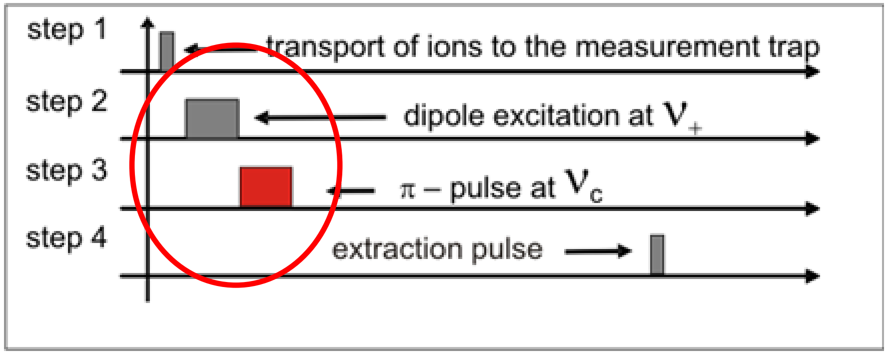
$$\left(\frac{\nu_c}{\Delta\nu_c}\right)^{max} \approx \left(\frac{\nu_+}{\Delta\nu_+}\right)^{max} \approx 2\cdot 10^7$$

(M = 200 u)

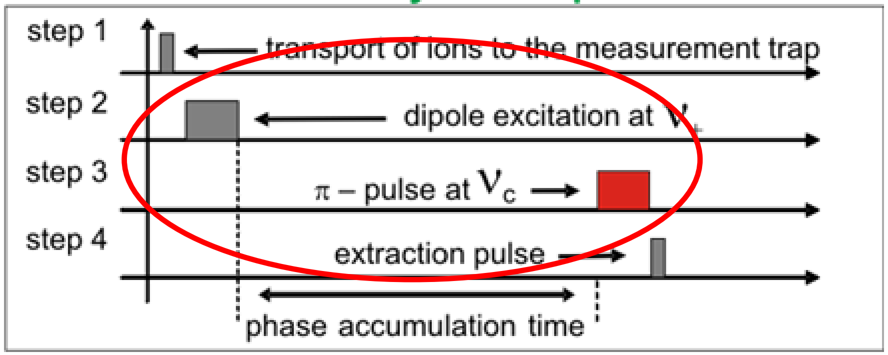
error in ν_c determination due to conversion of cyclotron motion to magnetron motion



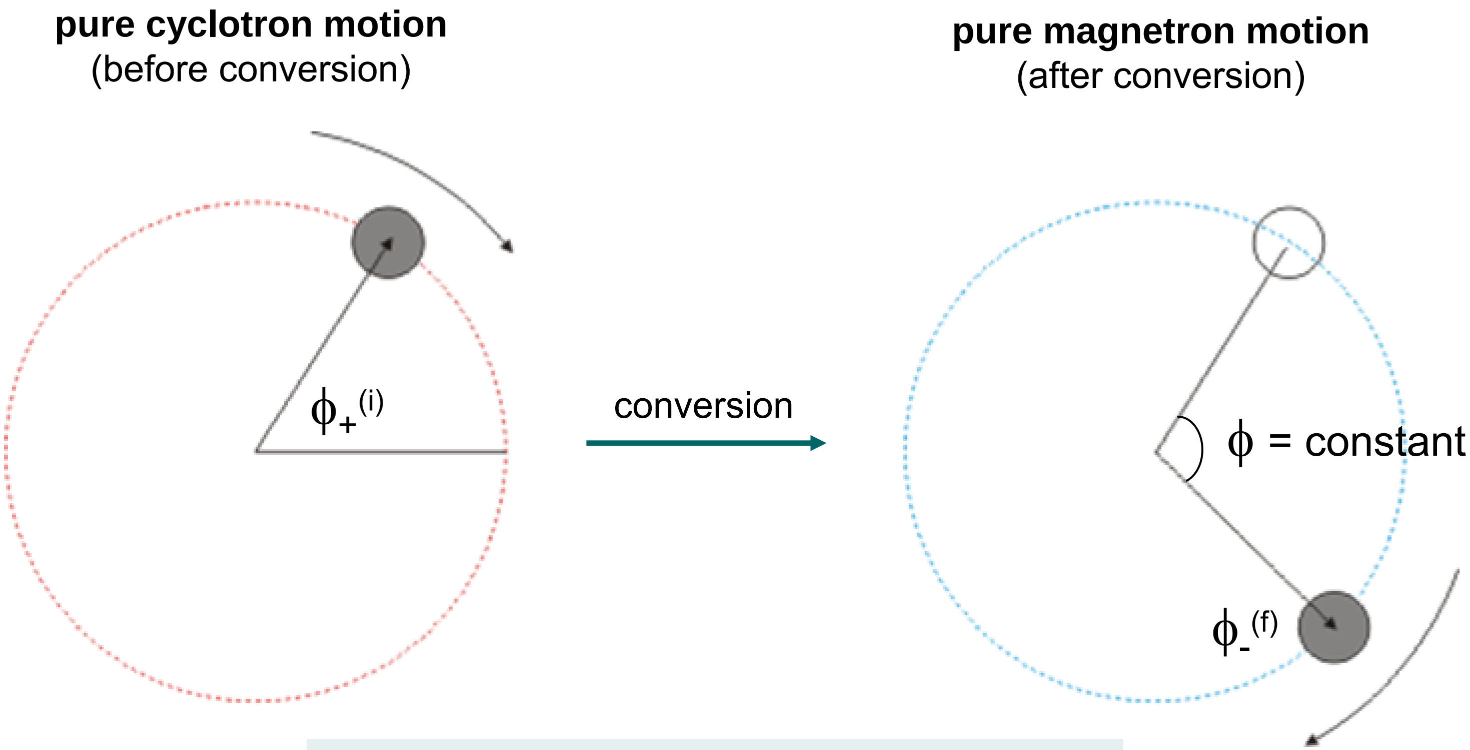
magnetron phase



modified cyclotron phase



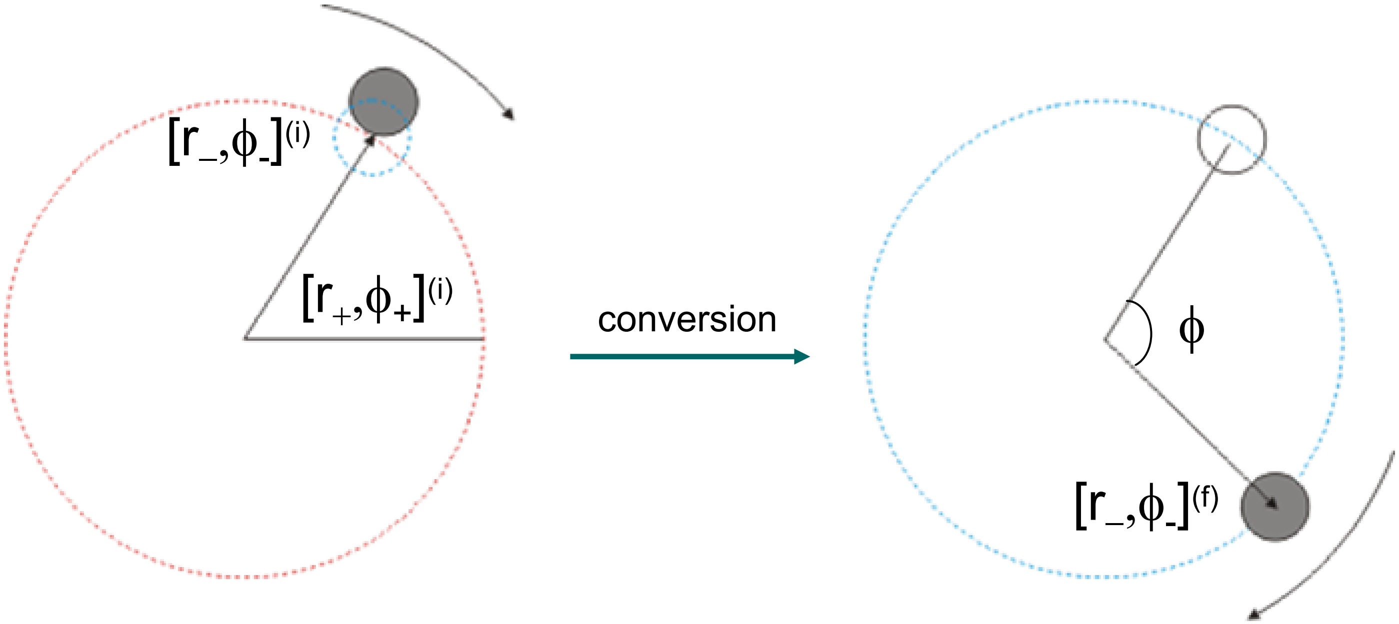
error in ν_c determination due to conversion of cyclotron motion to magnetron motion



$$\phi_-^{(f)} = -\,\phi_+^{(i)} + \phi$$

$$\Delta\phi_-^{(f)} = -\,\Delta\phi_+^{(i)}$$

error in ν_c determination due to conversion of cyclotron motion to magnetron motion



cyclotron and magnetron motions
(before conversion)

pure magnetron motion
(after conversion)

$$\phi_-^{(f)} = -\phi_+^{(i)} + \phi\left(\phi_-^{(i)}, \phi_+^{(i)}, r_-/r_+\right)$$

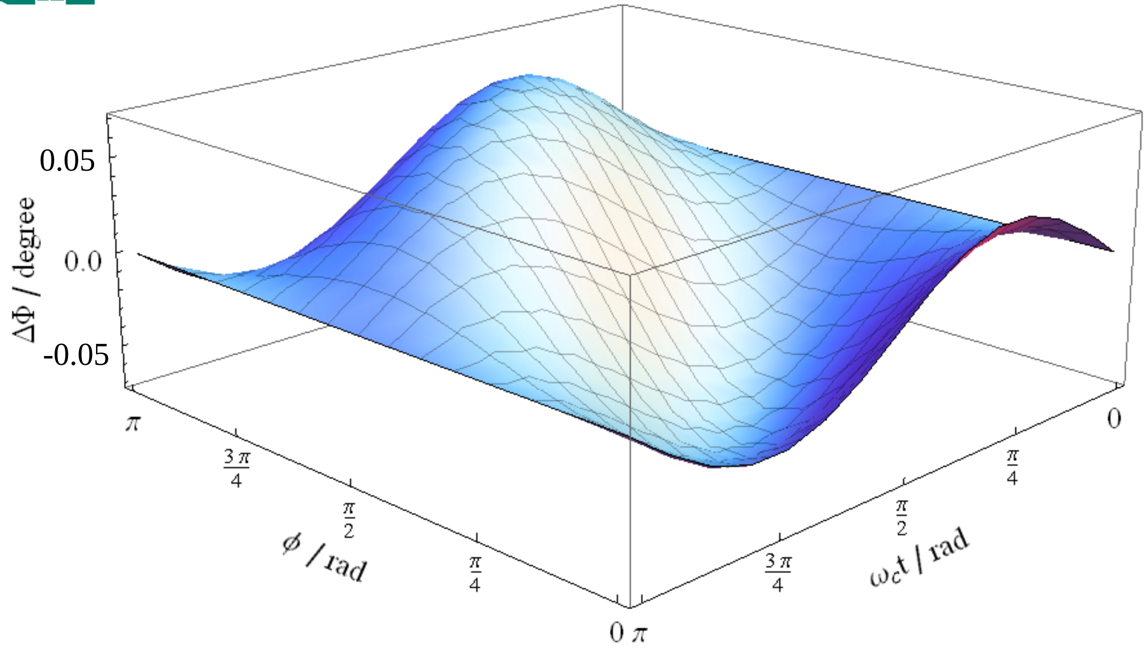
$$\Delta\phi_-^{(f)} = -\Delta\phi_+^{(i)} + \Delta\Phi$$

error in ν_c determination due to conversion of cyclotron motion to magnetron motion

$$\Delta\Phi = f(\phi, \omega_c t, S)$$

$$\phi = \phi_{rf}^{(i)} - \phi_-^{(i)} - \phi_+^{(i)}$$

$$S = r_-^{(i)} / r_+^{(i)}$$



$$\Delta\Phi_{max} \approx 60 \cdot S^2 \text{ [deg]}$$

$r_+^{(i)} = 1$ mm, $r_-^{(i)} = 0.025$ mm

↓

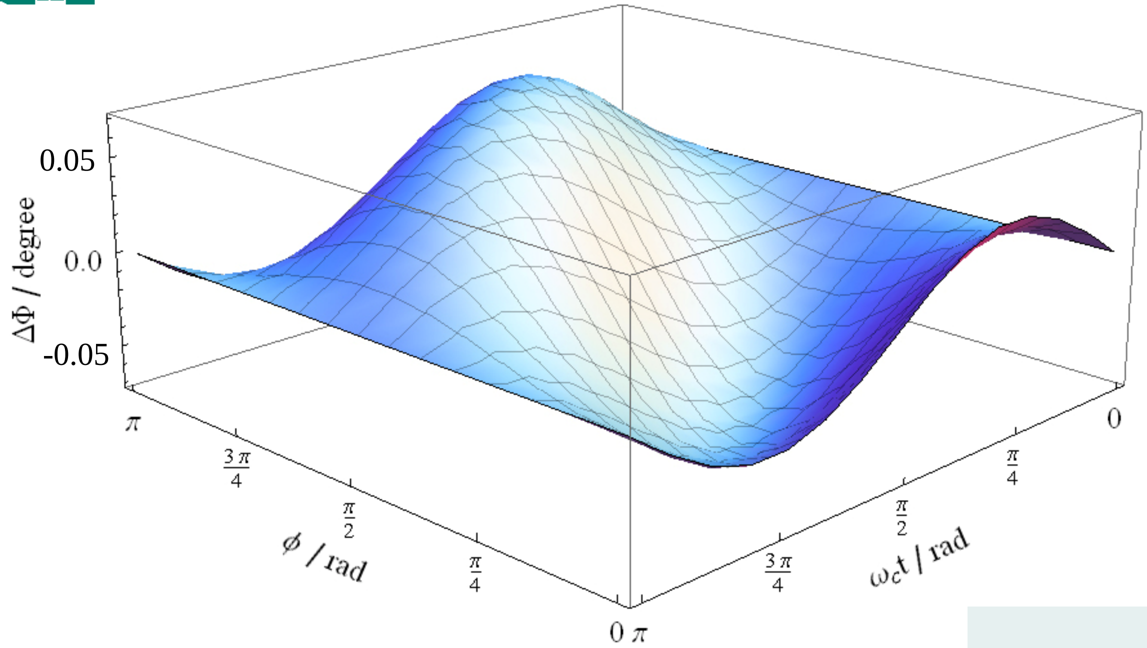
$$\left(\frac{\Delta\nu_c}{\nu_c}\right)^{max} \approx \frac{10^{-10}}{t[s]}$$

error in ν_c determination due to conversion of cyclotron motion to magnetron motion

$$\Delta\Phi = f(\phi, \omega_c t, S)$$

$$\phi = \phi_{rf}^{(i)} - \phi_{-}^{(i)} - \phi_{+}^{(i)}$$

$$S = r_{-}^{(i)} / r_{+}^{(i)}$$



$$\Delta\Phi_{max} \approx 60 \cdot S^2 \text{ [deg]}$$

$r_{+}^{(i)} = 1$ mm, $r_{-}^{(i)} = 0.025$ mm

↓

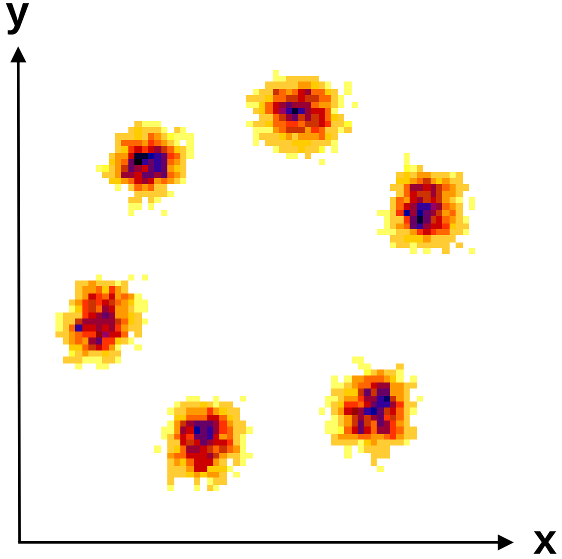
$$\left(\frac{\Delta\nu_c}{\nu_c}\right)^{max} \approx \frac{10^{-10}}{t[s]}$$

$\Delta\Phi = 0 \longleftarrow$ If $t = N \cdot T_c/2$

magnetron motion vs. **modified cyclotron** motion

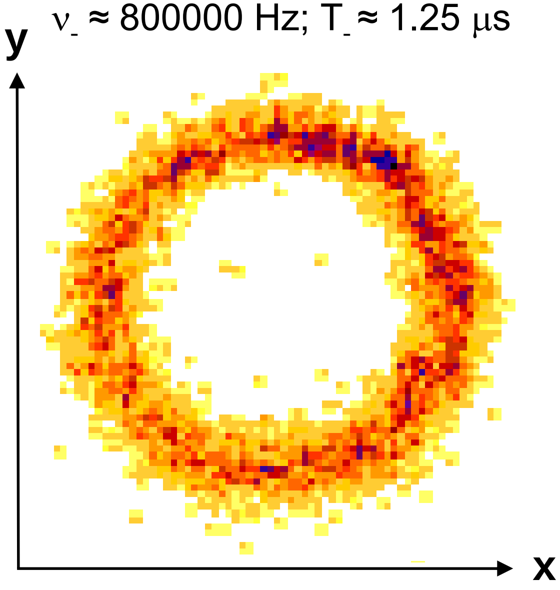
magnetron motion

$\nu_- \approx 1335$ Hz; $T_- \approx 750$ µs

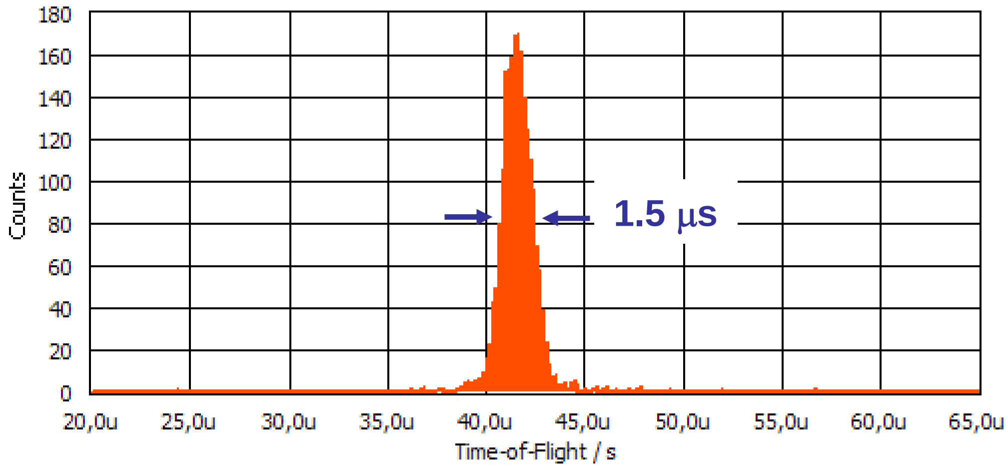


modified cyclotron motion

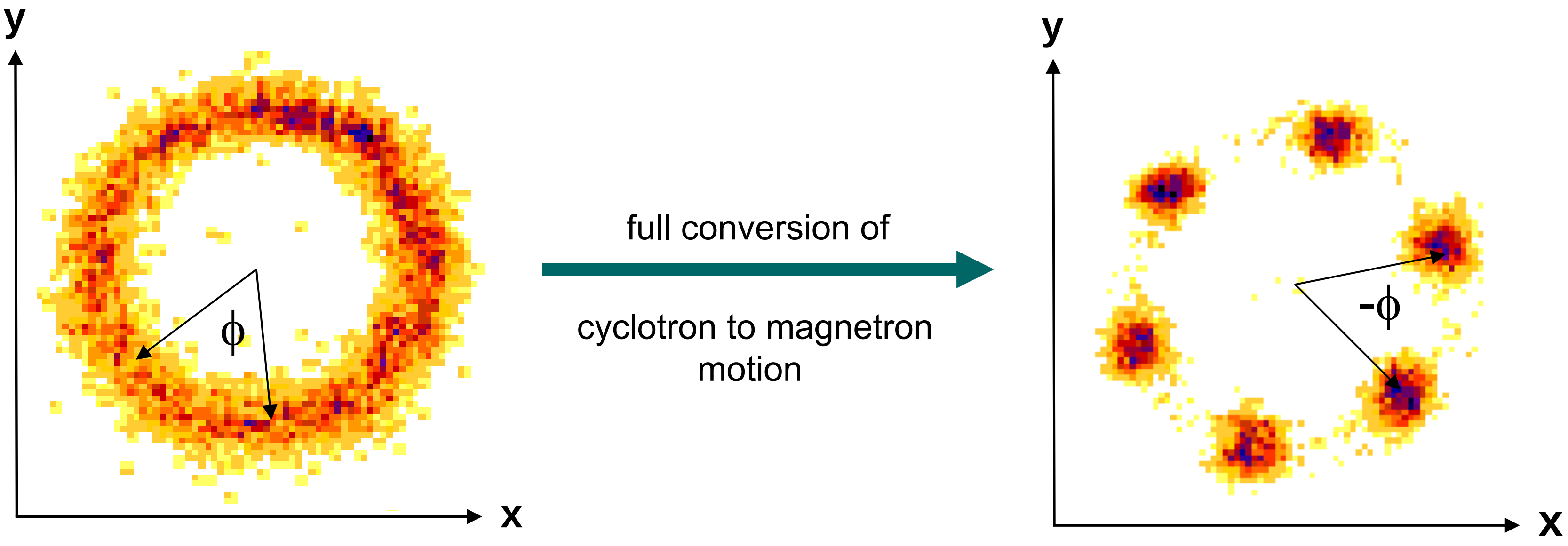
$\nu_- \approx 800000$ Hz; $T_- \approx 1.25$ µs



time of flight of ^{132}Xe ions between the trap and the detector



projection of modified cyclotron motion



modified cyclotron motion
direct projection

full conversion of

cyclotron to magnetron motion

magnetron motion
projection after full conversion

Phase (after conversion) = - Phase (before conversion) + Const

↓

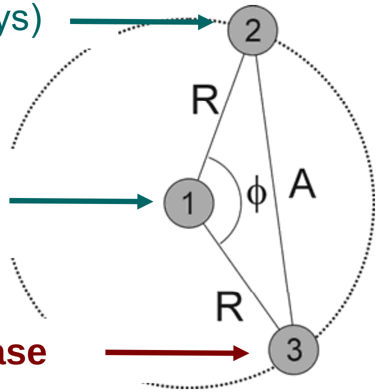
ϕ (after conversion) = - ϕ (before conversion)

measurement sequence Nr. 1

reference phase (stable over days)

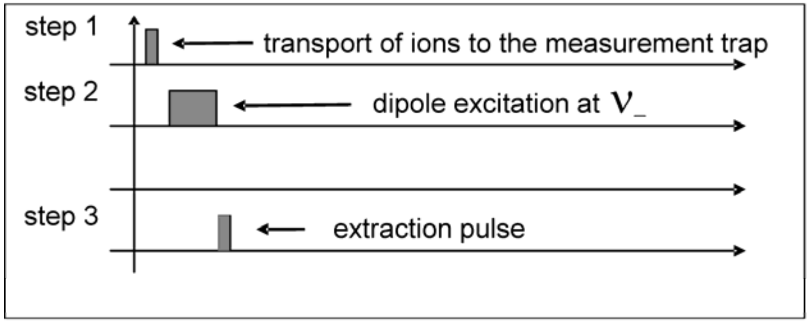
projection of trap center onto detector
(nuclide-independent)

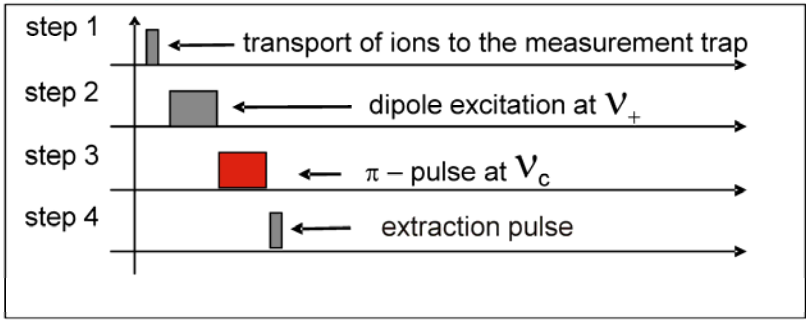
final phase



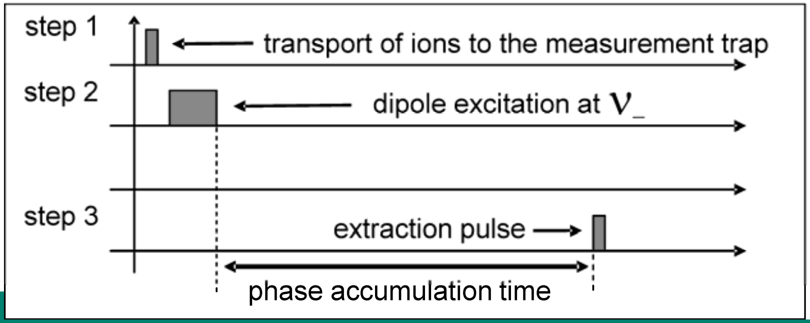
magnetron frequency ν_- | modified cyclotron frequency ν_+

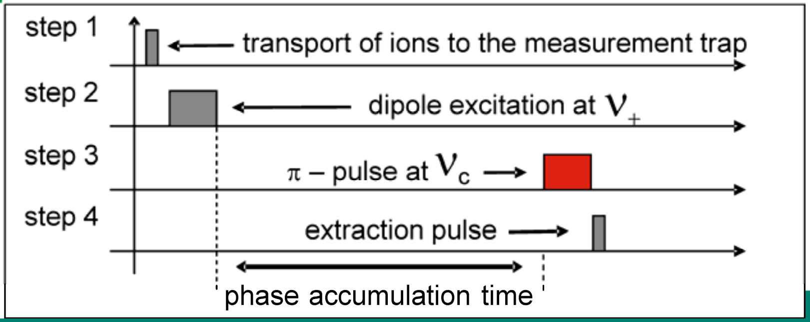
reference phase





final phase

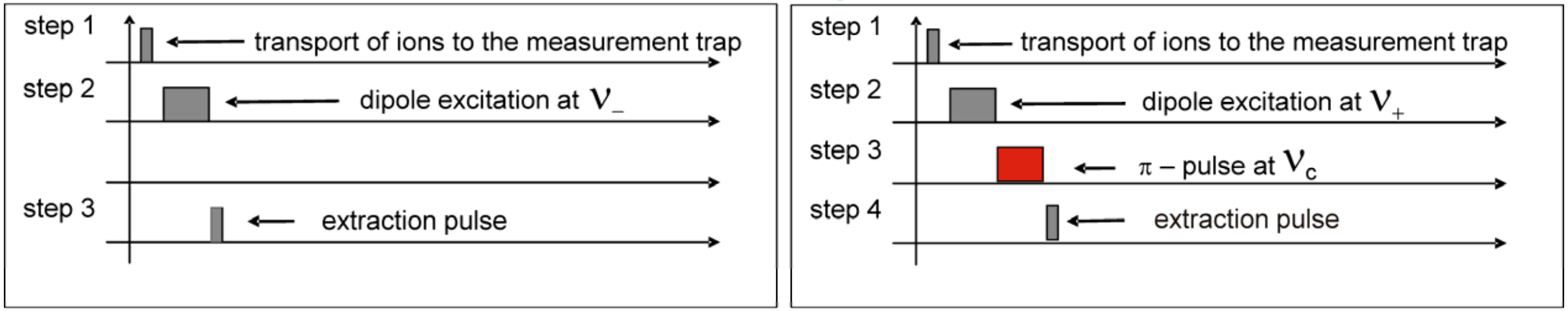




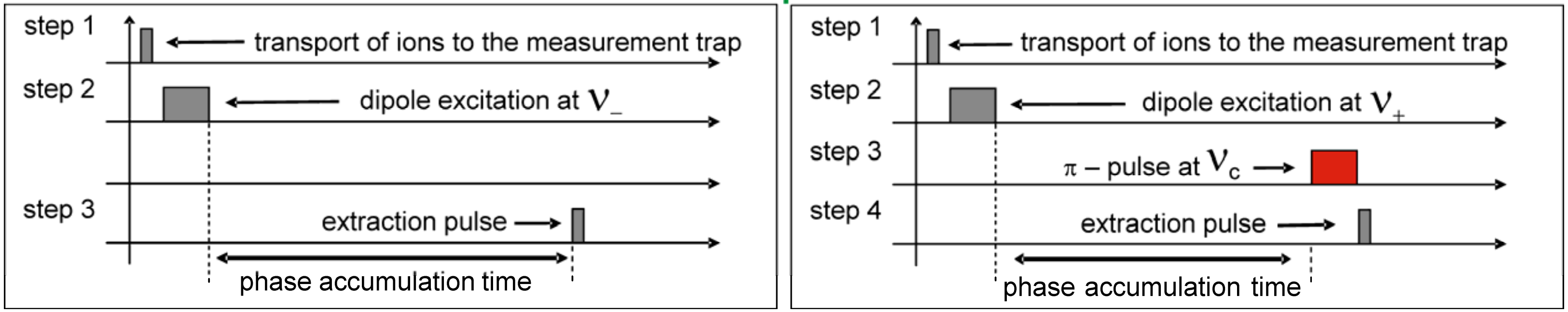
if production rates of exotic nuclides are extremely low and experiment time is limited?

magnetron frequency ν_- | **modified cyclotron frequency ν_+**

reference phase



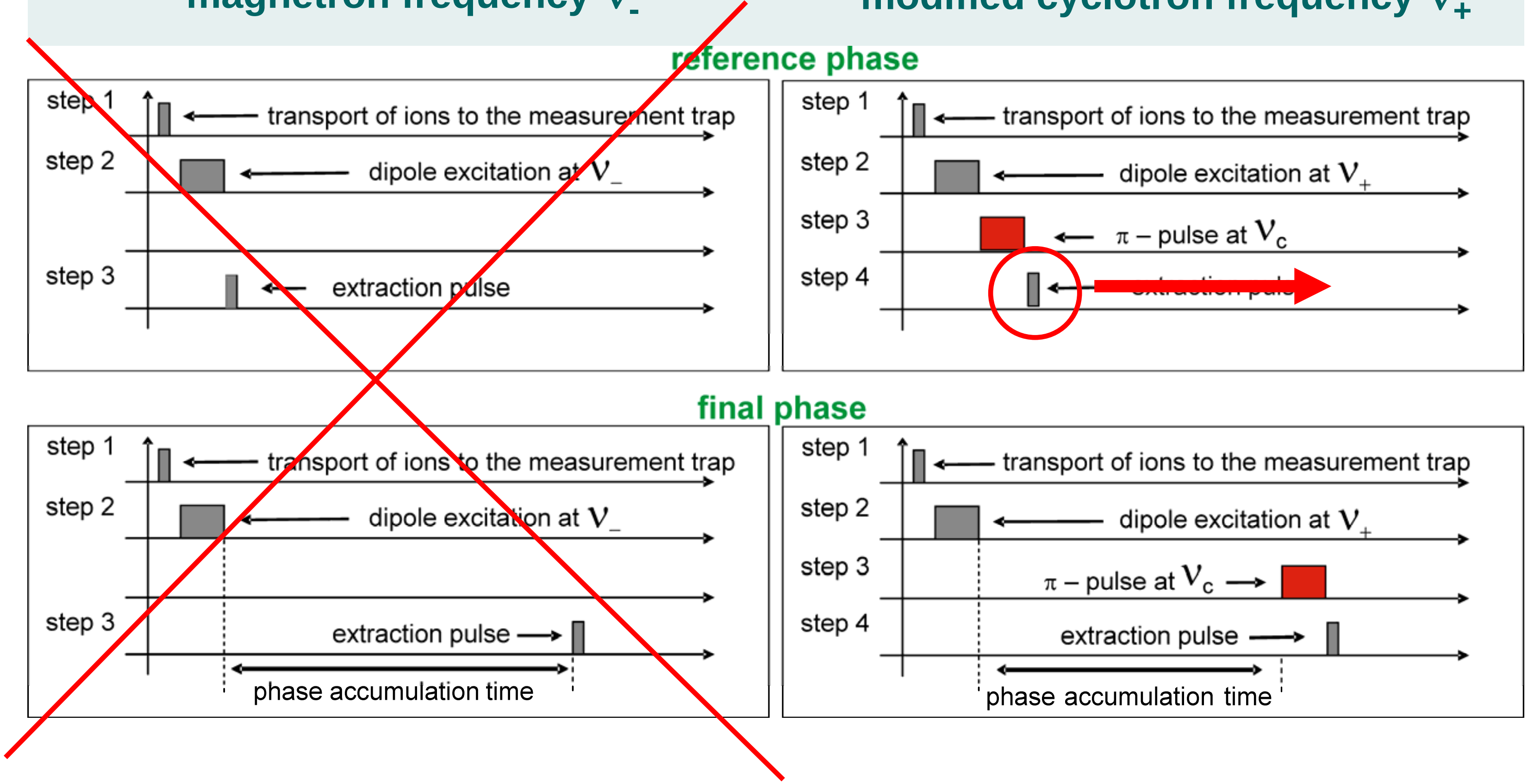
final phase



measurement sequence Nr. 2

~~**magnetron frequency ν_-**~~

modified cyclotron frequency ν_+



reference phase

~~step 1 transport of ions to the measurement trap~~
~~step 2 dipole excitation at ν_-~~
~~step 3 extraction pulse~~

step 1 transport of ions to the measurement trap
step 2 dipole excitation at ν_+
step 3 π – pulse at ν_c
step 4 extraction pulse

final phase

~~step 1 transport of ions to the measurement trap~~
~~step 2 dipole excitation at ν_-~~
~~step 3 extraction pulse~~
~~phase accumulation time~~

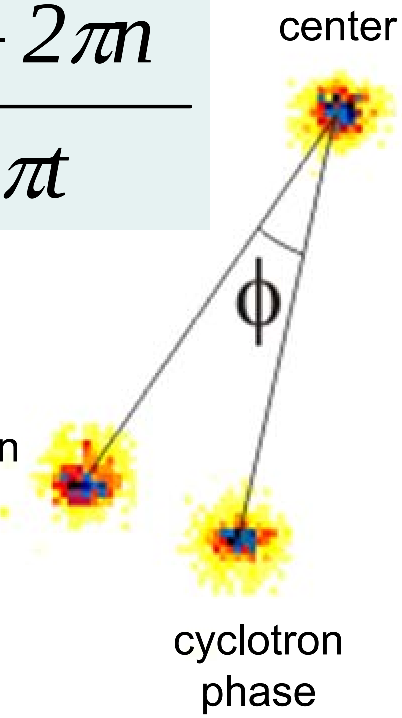
step 1 transport of ions to the measurement trap
step 2 dipole excitation at ν_+
step 3 π – pulse at ν_c
step 4 extraction pulse
phase accumulation time

measurement sequence Nr. 2

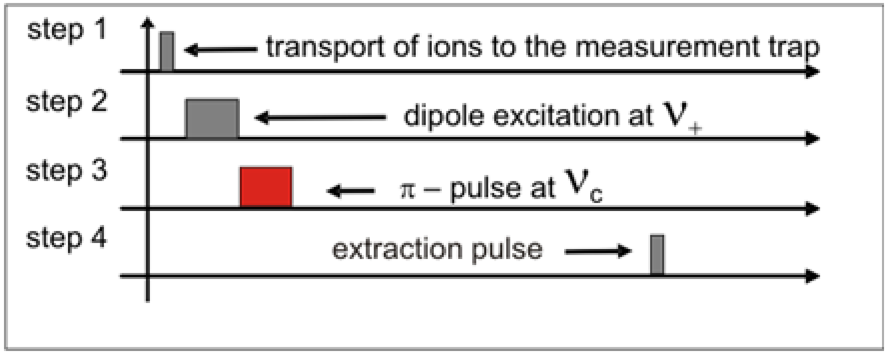
if production rates of exotic nuclides are extremely low
and experiment time is limited?

free cyclotron frequency ν_c

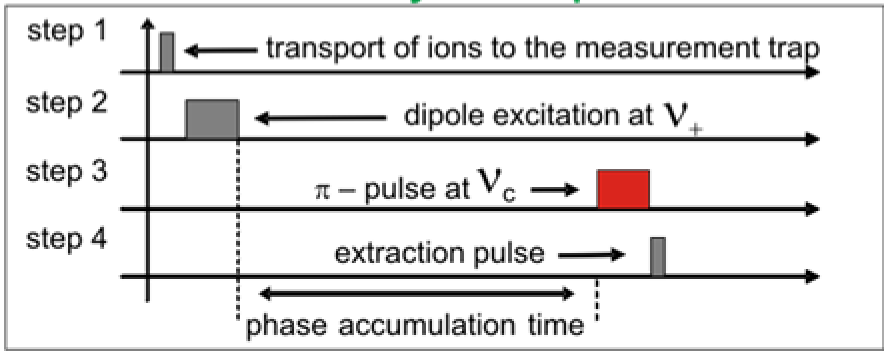
$$\nu_c = \frac{\phi + 2\pi n}{2\pi t}$$



magnetron phase



modified cyclotron phase

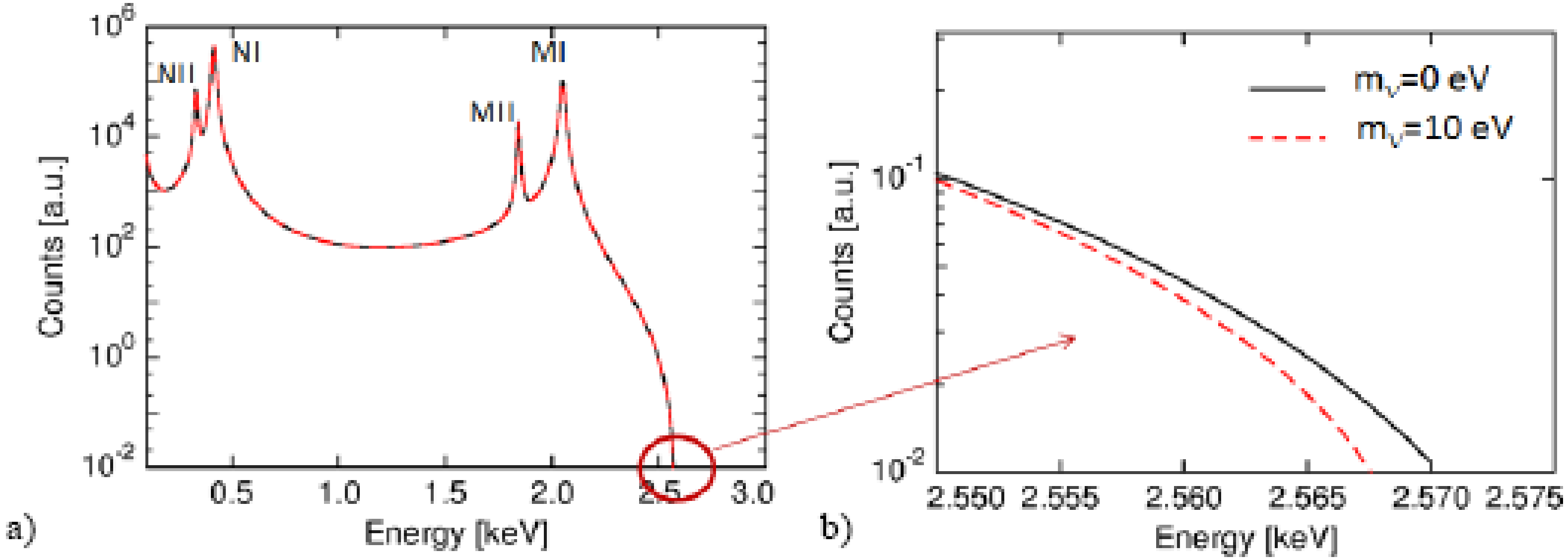


determination of neutrino mass with accuracy of 0.2 eV

$$^{163}\mathrm{Ho} \longrightarrow {}^{163}\mathrm{Dy}^h + \nu_e\,(E_\nu)$$

$$\hookrightarrow {}^{163}\mathrm{Dy} + E_c$$

$$\xrightarrow{\text{ANALYSIS of DE-EXCITATION SPECTRUM}} m_\nu$$



$$\text{Factor of Merit} = \frac{S_{\text{end point}}}{S_{\text{full spectrum}}} = f\,(\text{Q-value})$$