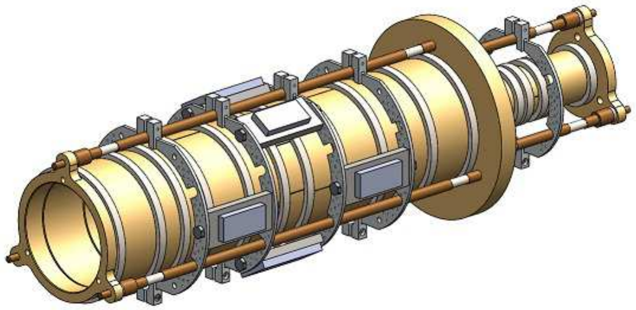
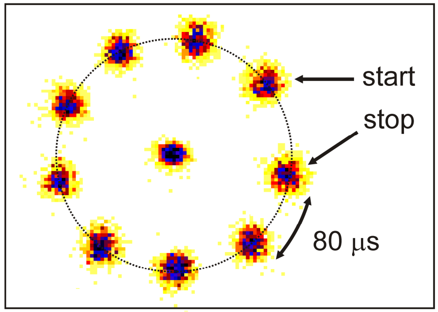
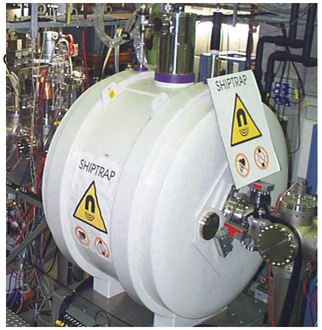
Recent developments in ion detection techniques and high-capacity separation for Penning trap mass spectrometers







NUSTAR Week 2014

22-26 September 2014
Valencia
Europe/Madrid timezone

Enrique MINAYA RAMIREZ

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

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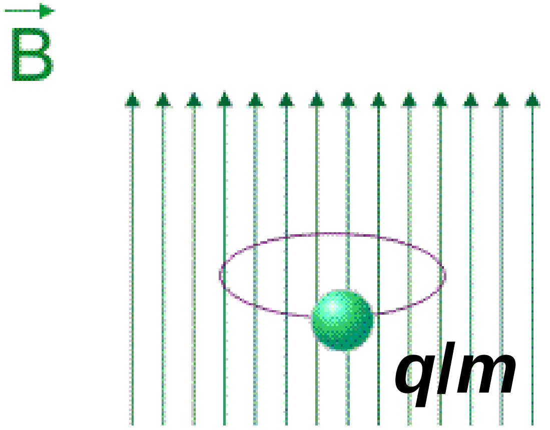
Outline

☐ **How to perform a high-precision mass measurements ?**

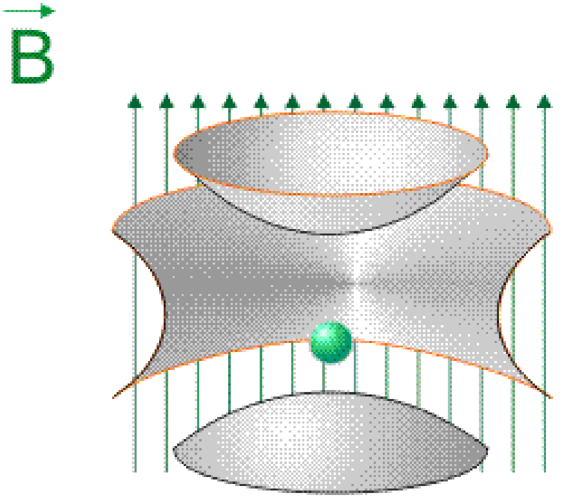
☐ **Increasing the sensitivity and the resolving power**

☐ **Resolving large samples of contaminants**

High-precision mass measurements with Penning traps



strong homogeneous magnetic field

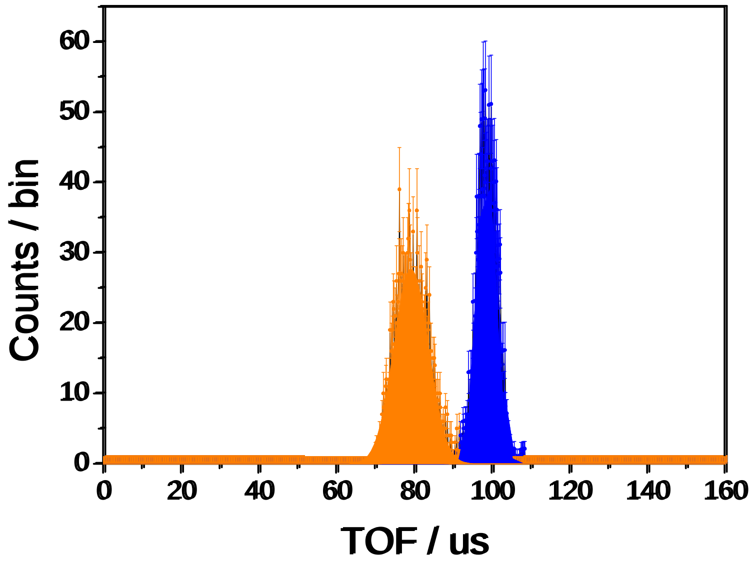


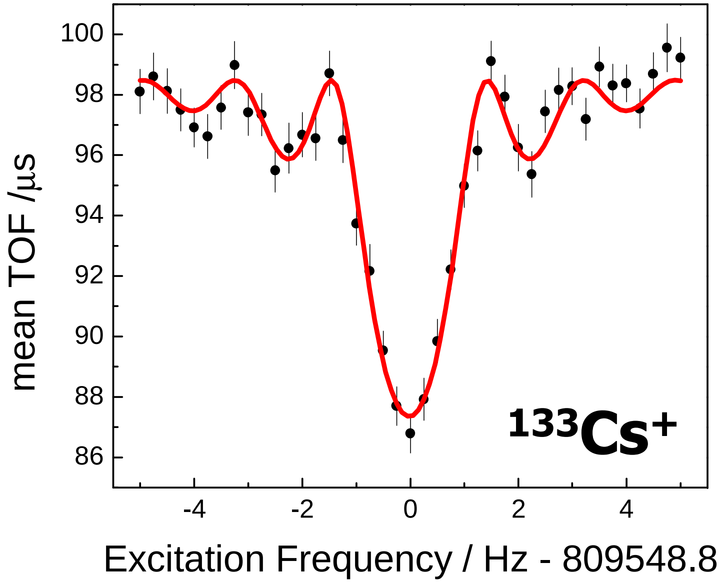
\+ weak electrostatic field

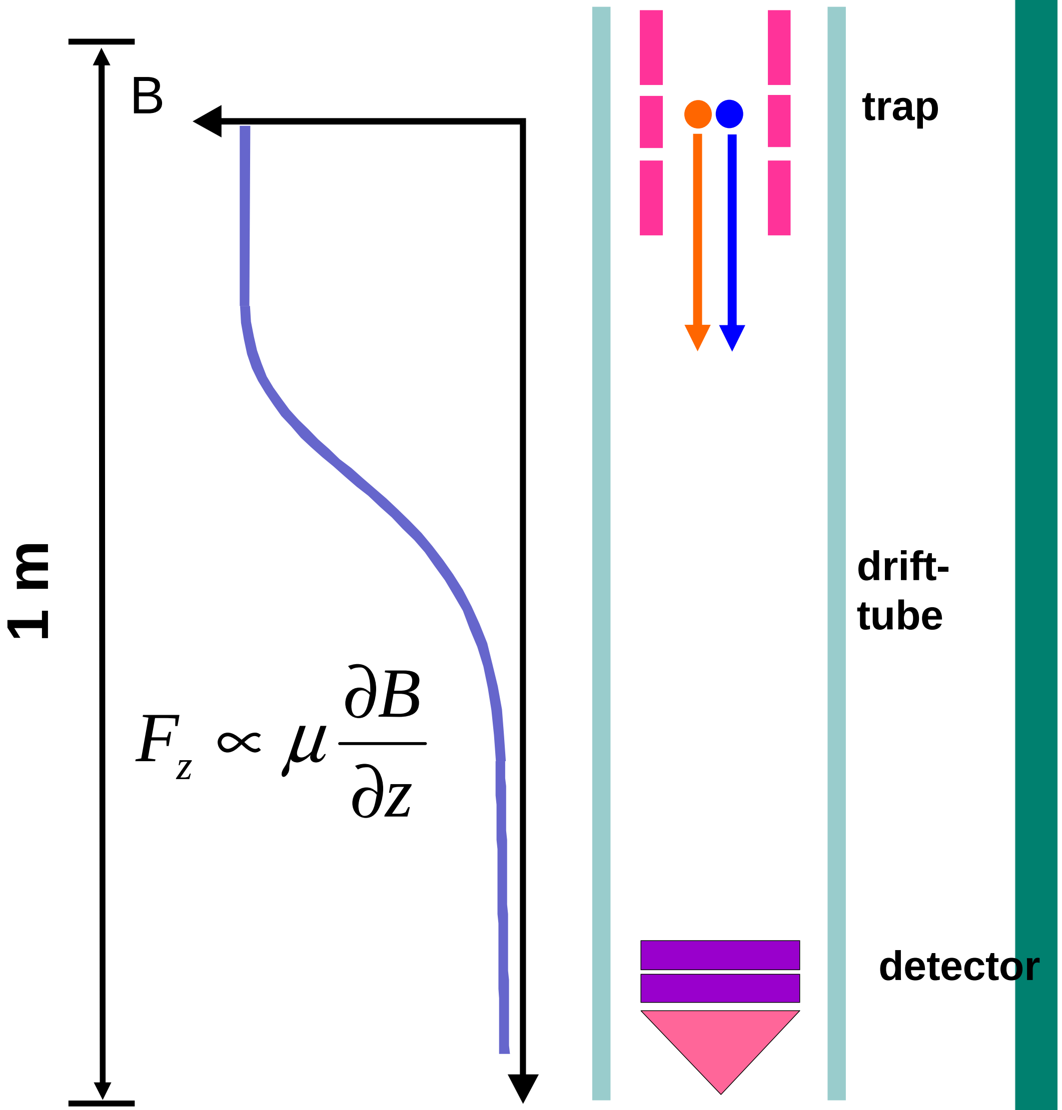
Cyclotron frequency

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

TOF-ICR : Time-of-flight resonance technique







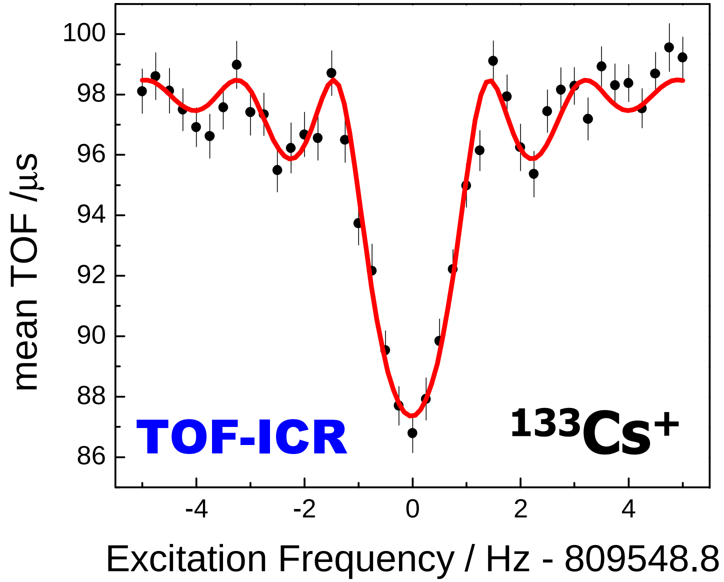
$$F_z \propto \mu \frac{\partial B}{\partial z}$$

M. König et al., Int. J. Mass Spec. Ion Process. 142 (1995) 95

High-precision mass measurements with Penning traps

Cyclotron frequency $$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

(B = 7 T, A = 133, $f_c \approx$ 800 kHz)



- ❑ Relative uncertainty $\approx 10^{-8}$
- ❑ Accessible half-lifes > 10 ms
- ❑ Typical Resolving power $\approx 10^{7}$

$$R = f_c \cdot T_{exc}$$ (T_{exc} = 2 s)

Resolving power and Statistical uncertainty

Resolving power

$$R = f_c \cdot T_{exc}$$

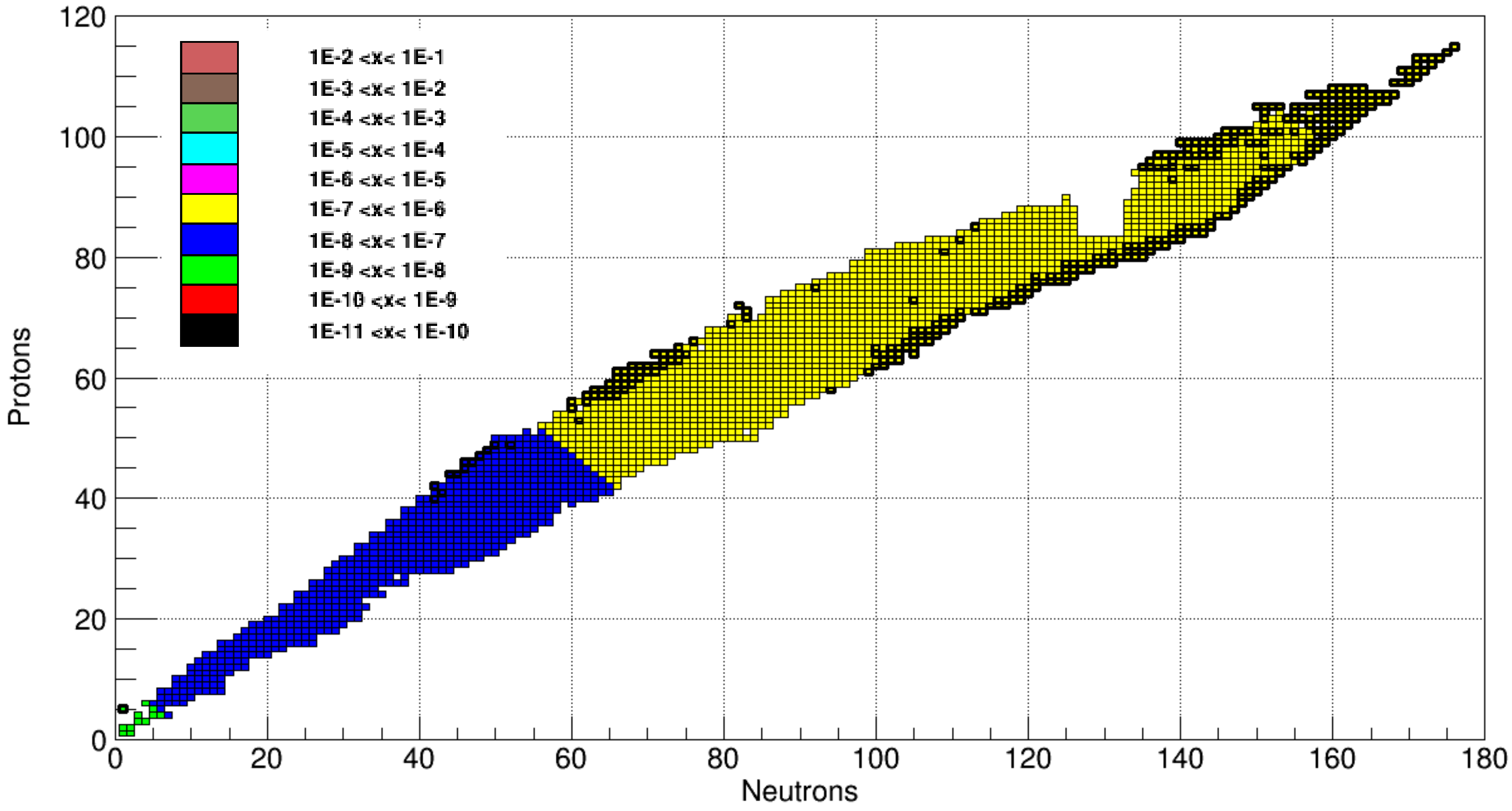
$$R = \frac{q \cdot B}{2 \cdot \pi \cdot m} \cdot T_{exc}$$

Statistical uncertainty

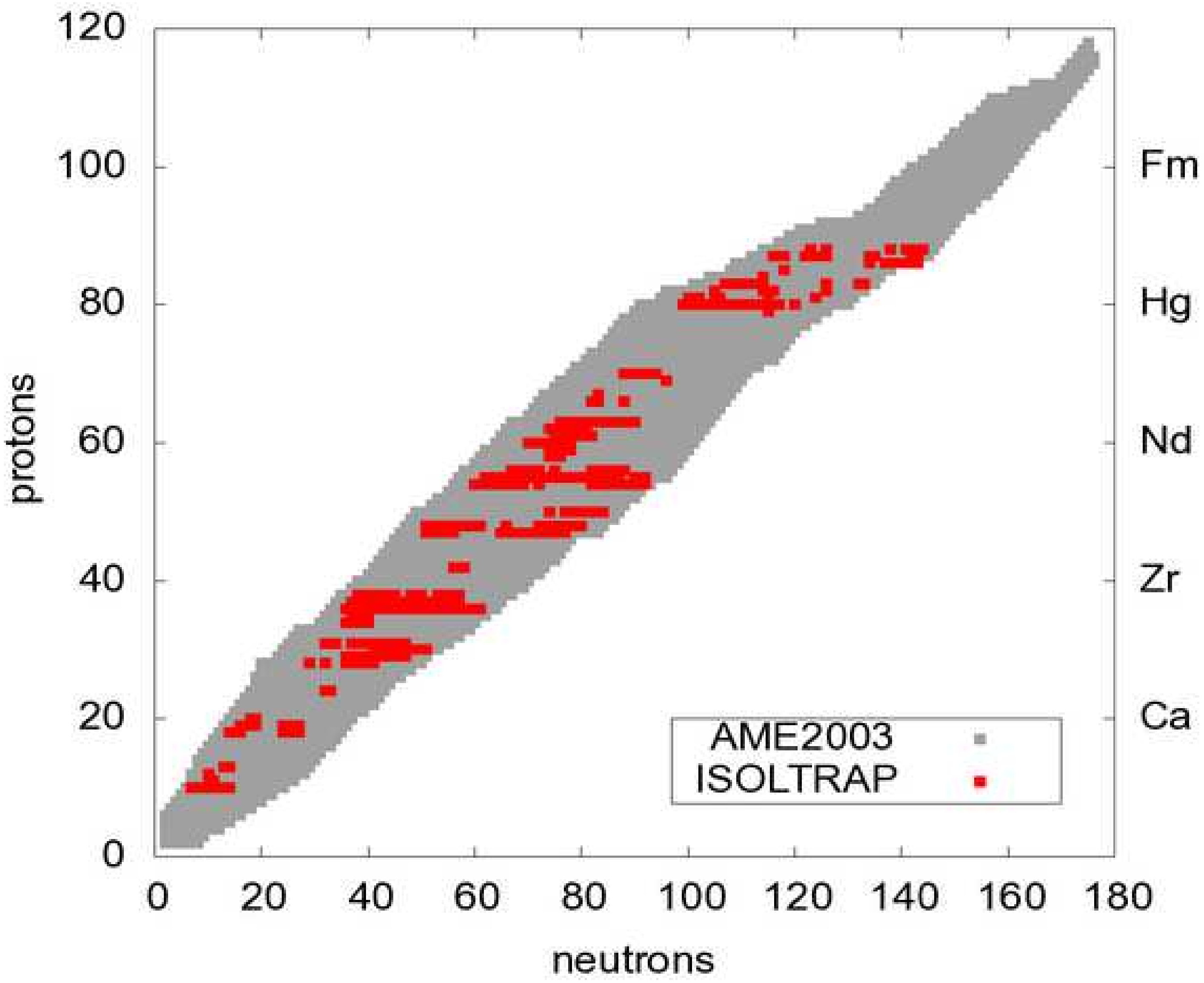
$$\frac{\delta m}{m} \approx \frac{1}{R\sqrt{N}}$$

Statistical uncertainty

T_{exc} = 1 s, N=100 AME [$T_{1/2}$ => 1s]



High-precision mass measurements with Penning traps



High-precision mass measurements with Penning traps

$^{74}_{37}\text{Rb}\ 37$

64.776 ms 0^+
M −51916 (3)
β^+=100%
β^+p?

ISOLTRAP

A. Kellerbauer et al., PRL 93 (2004) 072502

$^{38}_{20}\text{Ca}\ 18$

443.77 ms 0^+
M −22058.50 (0.19)
β^+=100%

LEBIT

G. Bollen et al., PRL 96 (2006) 152501

$^{11}_{3}\text{Li}\ 8$

8.75 ms $3/2^-$
M 40728.3 (0.6)
β^-=100%
β^-n=86.3 (9)%...

TITAN

M. Smith et al., PRL 101 (2008) 202501

$^{256}_{103}\text{Lr}\ 153$

27 s
M 91750 (80)
α=85 (10)%
β^+=15 (10)%...

SHIPTRAP

E. Minaya Ramirez et al., Science 337 (2012) 1207

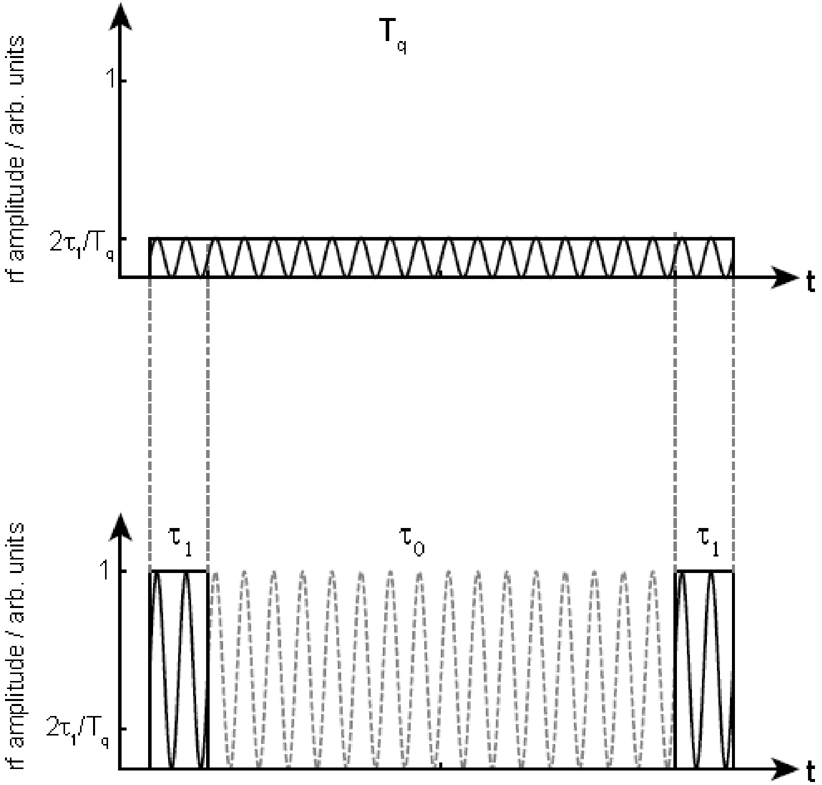
Outline

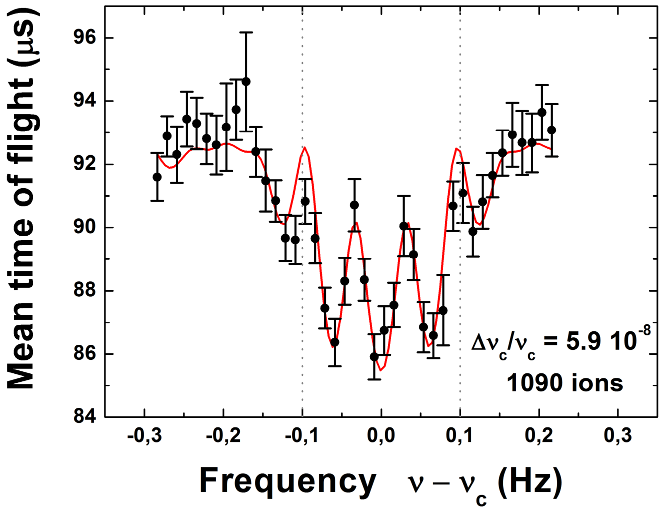
- ☐ How to perform a high-precision mass measurements ?
- ☐ **Increasing the sensitivity and the resolving power**
- ☐ Resolving large samples of contaminants

Increasing sensitivity and resolving power

→ Excitation schemes

Ramsey excitation : 3 fold gain in precision compare to TOF-ICR





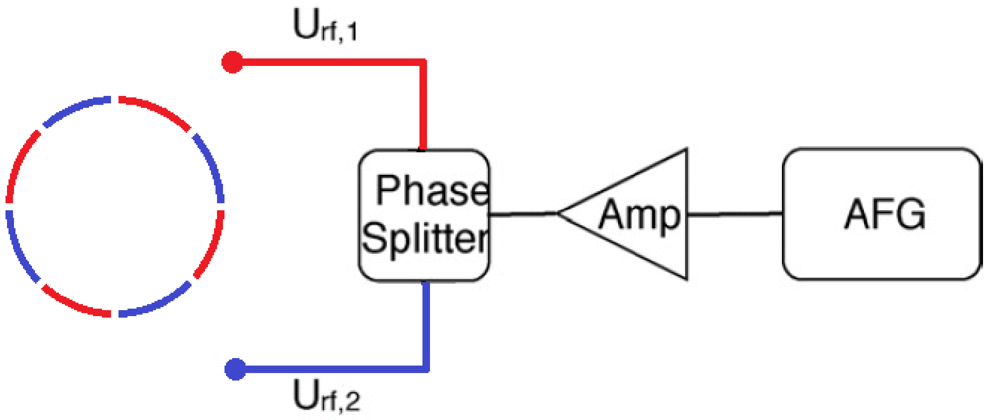
Ramsey resonance
T = 10 + 5 + 10 s, $^{133}Cs^+$

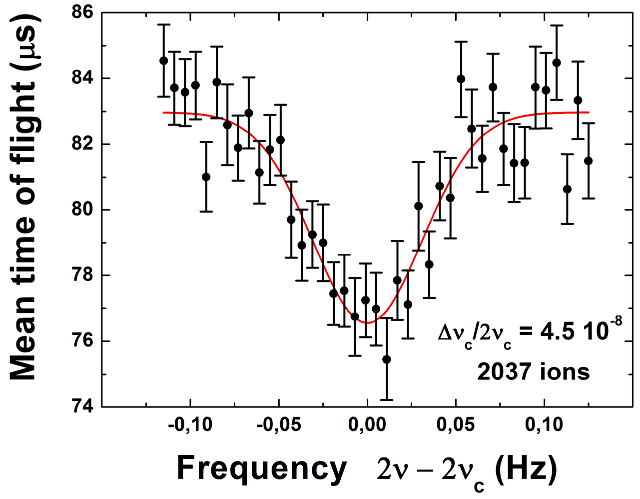
S. George et al., Phys. Rev. Lett. 98 (2007) 162501.
S. George et al., Int. J. Mass. Spectrom. 264 (2007) 110.

Increasing sensitivity and resolving power

→ Excitation schemes

Octupolar excitation :



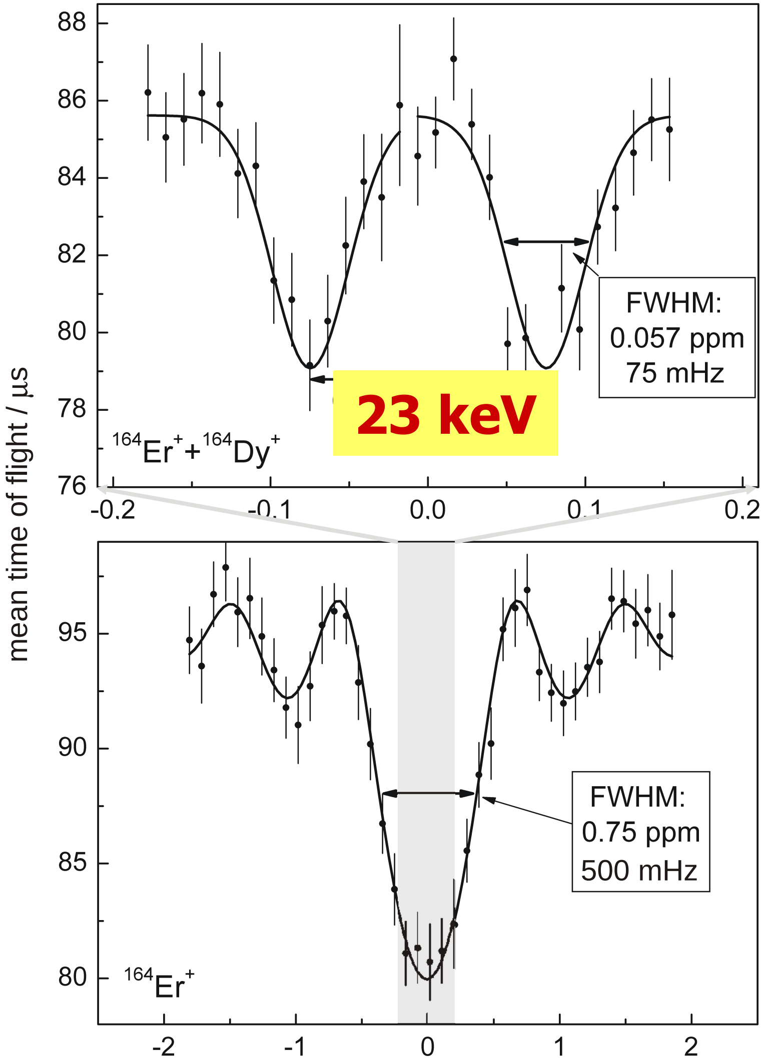


Octupolar resonance
T = 1 s, $^{133}Cs^+$

LEBIT: R. Ringle et al., Int. J. Mass Spectrom. 262, 33 (2007).
SHIPTRAP: S. Eliseev et al., Int. J. Mass Spectrom. 262, 45 (2007).
S. Eliseev et al., Phys. Rev. Lett. 107, 152501 (2011)

Increasing sensitivity and resolving power

Octupolar

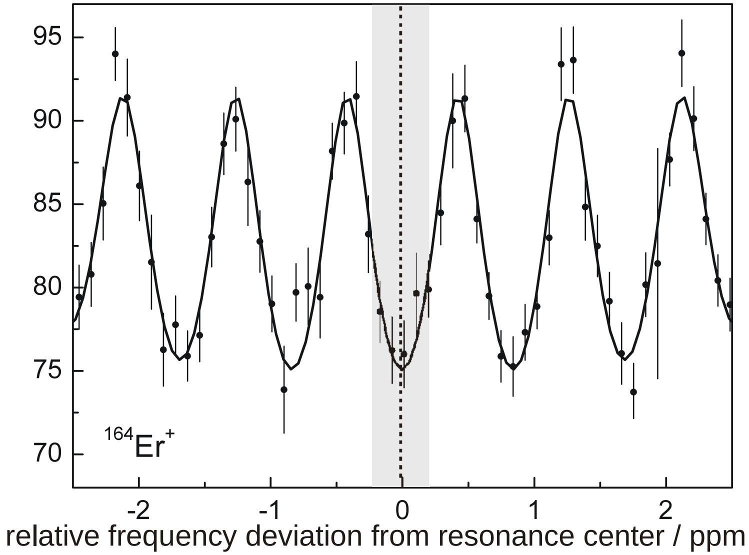


23 keV

Quadrupolar

Octupolar excitation scheme leads to gain in resolving power by a factor of 10

$R = 2 \cdot 10^7$ (for $T_{exc} = 2$ s)



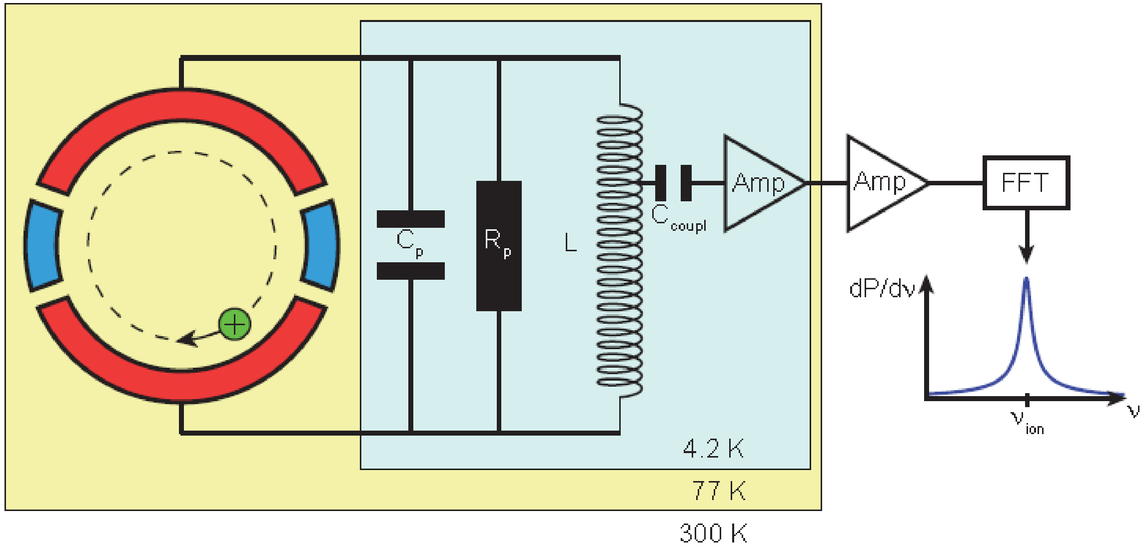
Quadrupolar Ramsey

S. Eliseev et al., Phys. Rev. Lett. 107, 152501 (2011)

FT-ICR: non-destructive detection system

➔ Increase sensitivity of detection

Narrow-band FT-ICR (Fourier Transform Ion Cyclotron Resonance)



High Q-inductor

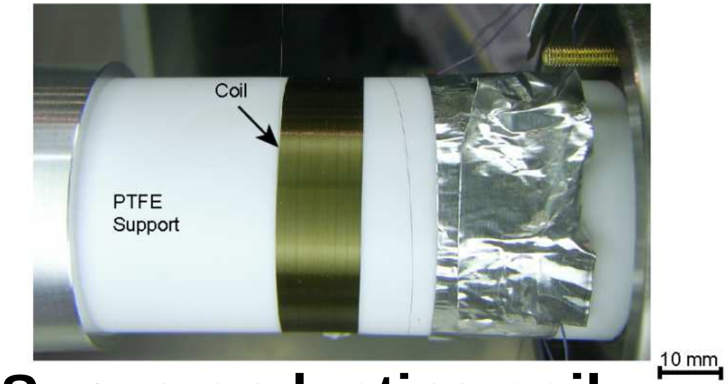
Induced signal → only a few fA

high precision mass measurements
with a single ion: $\Delta m/m < 10^{-11}$

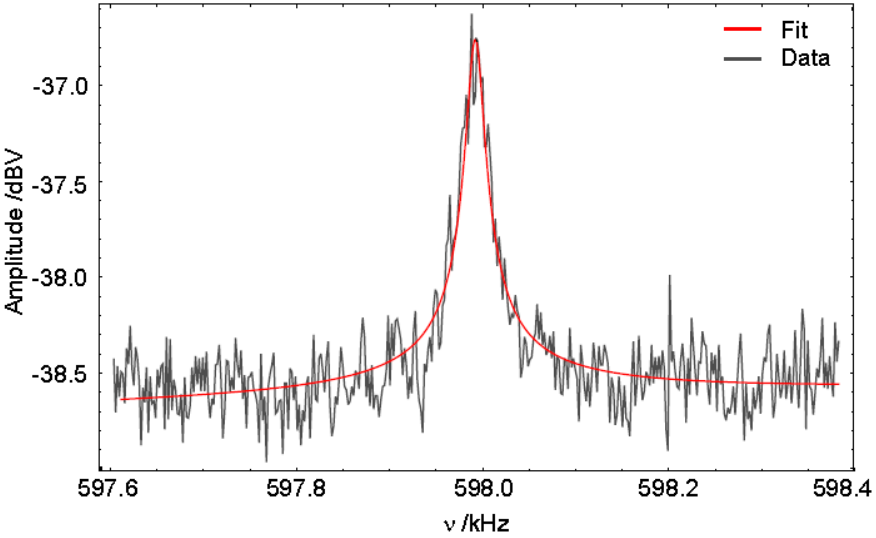
→ Possibility to use the same ion for others measurements

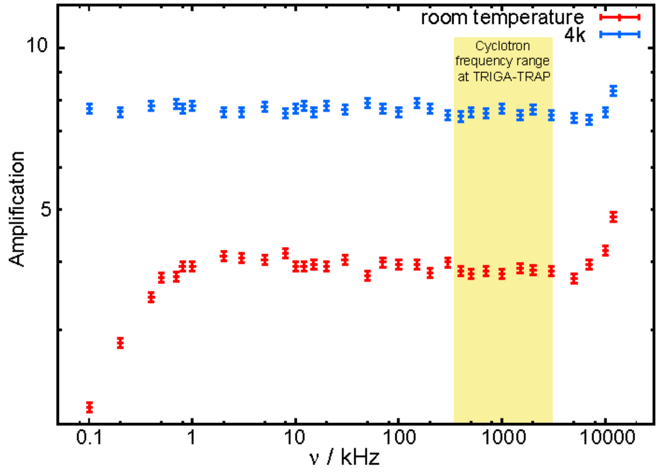
FT-ICR: non-destructive detection system

TRIGA-TRAP (MAINZ)



Superconducting coil





Resonance spectrum

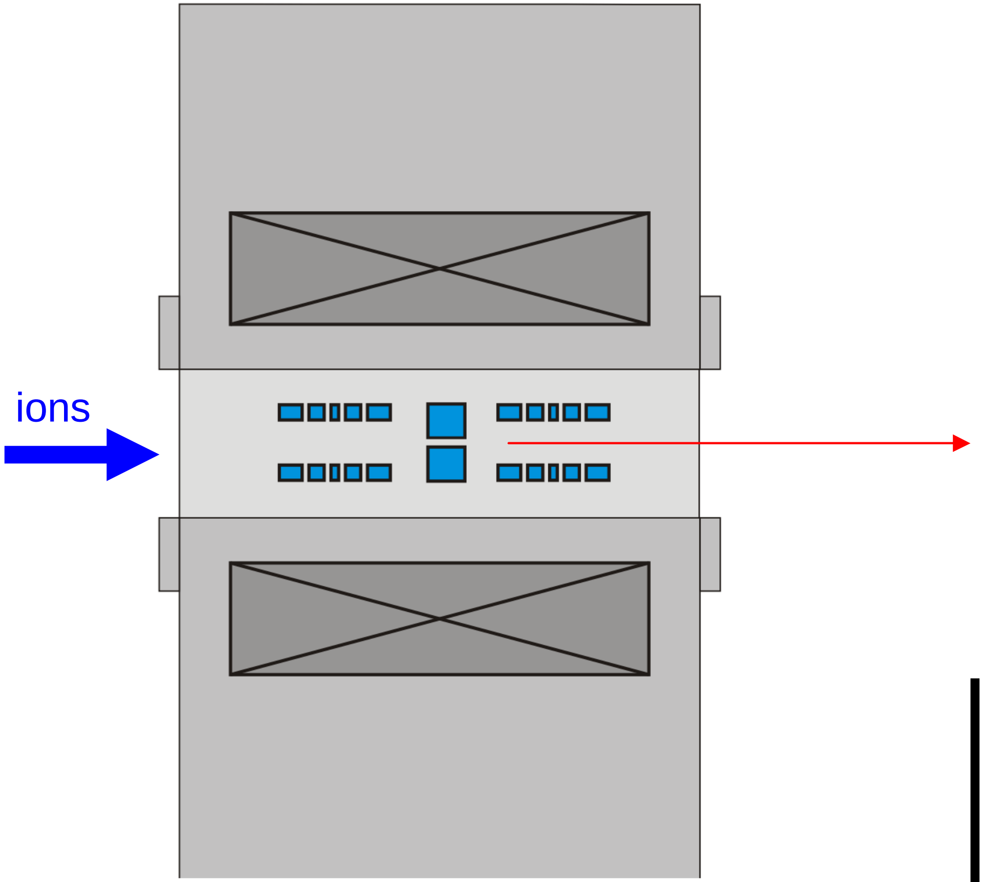
Q= 27(2) 103, V_{LC} = 597992.1(6)Hz

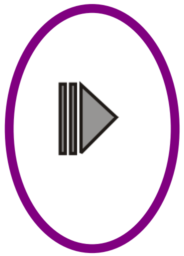
L_{coil} = 2.9(5) mH, C_{coil} = 14.1(4.6) pF

Frequency response of the cryogenic amplifier

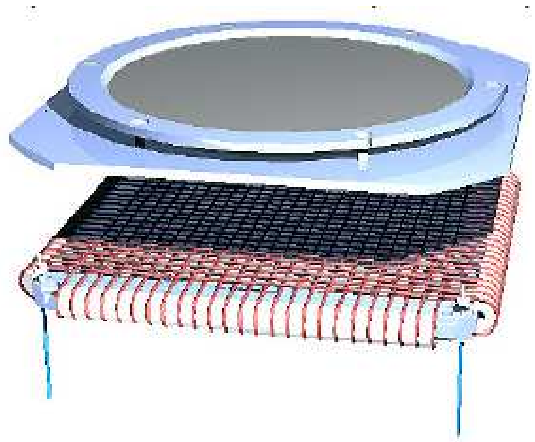
M. Eibach Phd thesis

Phase Imaging Ion Cyclotron Resonance (PI-ICR)

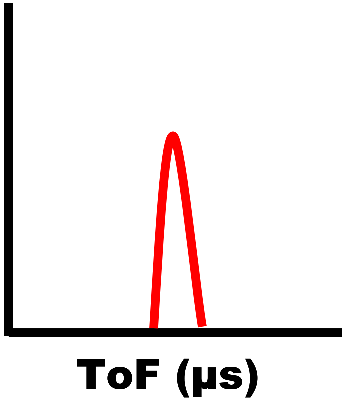


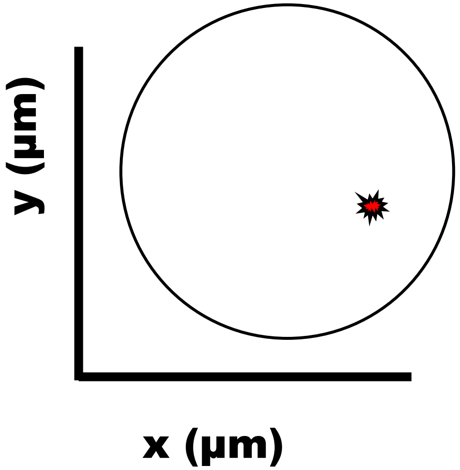


Delay-Line Detector by Roentdek GmbH



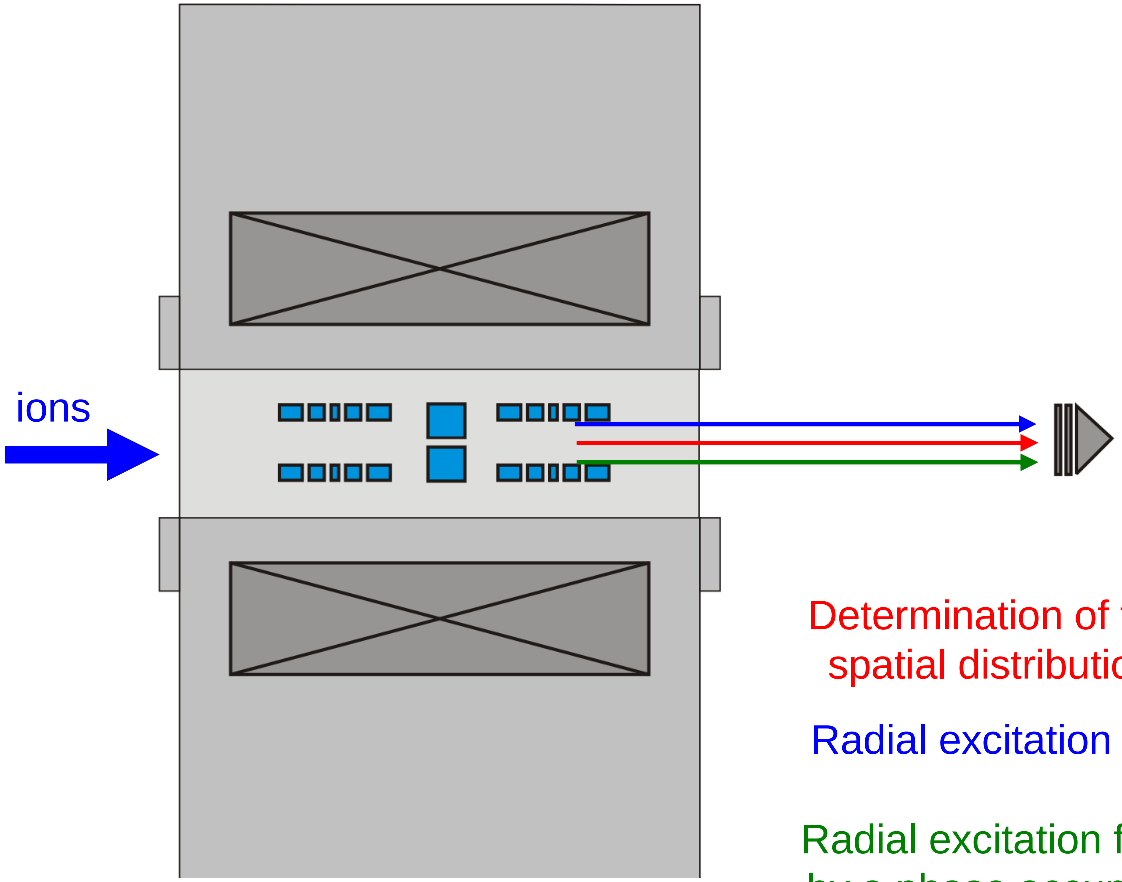
Position sensitive detector



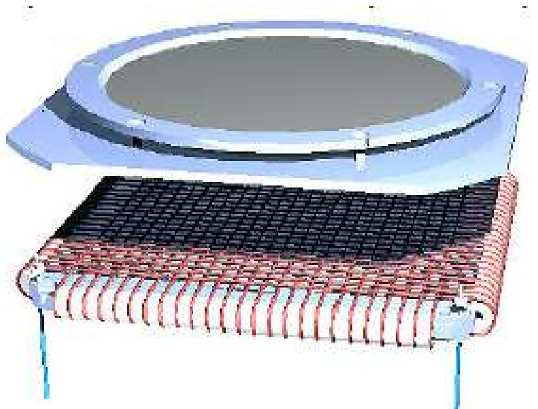


- **position resolution : 70 μm**
- **active diameter : 42 mm**

Phase Imaging Ion Cyclotron Resonance (PI-ICR)



Delay-Line Detector by Roentdek GmbH

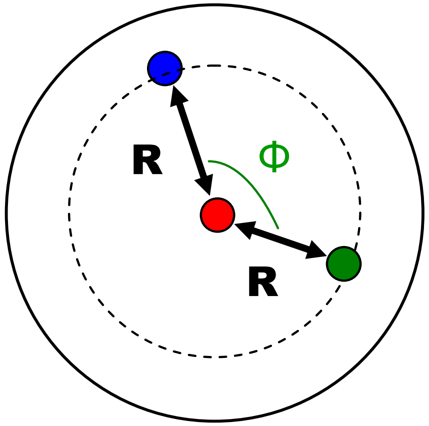


Independent Measurements of Eigenfrequencies ν_+ and ν_-

Determination of the spatial distribution

Radial excitation

Radial excitation followed by a phase accumulation time



$$\phi + 2\pi n = 2\pi \nu t$$

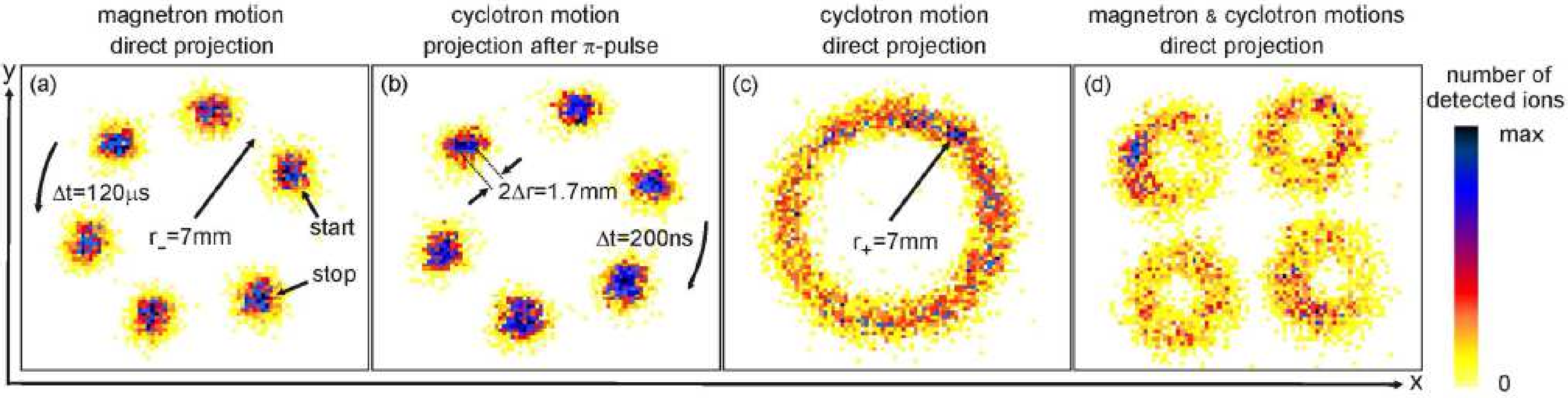
$$\Delta\nu = \frac{\Delta\phi}{2\pi t} = \frac{\Delta R}{\pi t R}$$

Phase Imaging Ion Cyclotron Resonance (PI-ICR)

- Image ion motion
- Determine phase of ion motion
- Excite ions
- Determine phase after evolution time

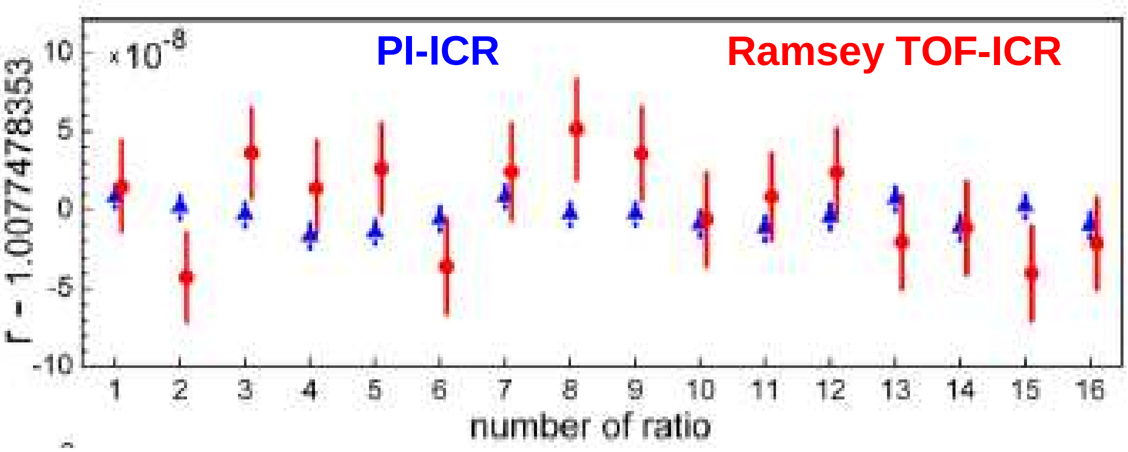
$$\phi + 2\pi n = 2\pi \nu t$$

$$\Delta \nu = \frac{\Delta \phi}{2\pi t} = \frac{\Delta R}{\pi t R}$$



S. Eliseev et al., Appl. Phys B 114 (2014) 107

Phase Imaging Ion Cyclotron Resonance (PI-ICR)



$\Delta M_{shiptrap} = M(^{130}Xe^{+}) - M(^{129}Xe^{+})$

$\Delta M_{FSU} - \Delta M_{shiptrap} = 690\ (880)\ \mathrm{eV}$

$\Delta M_{FSU} - \Delta M_{shiptrap} = 180\ (240)\ \mathrm{eV}$

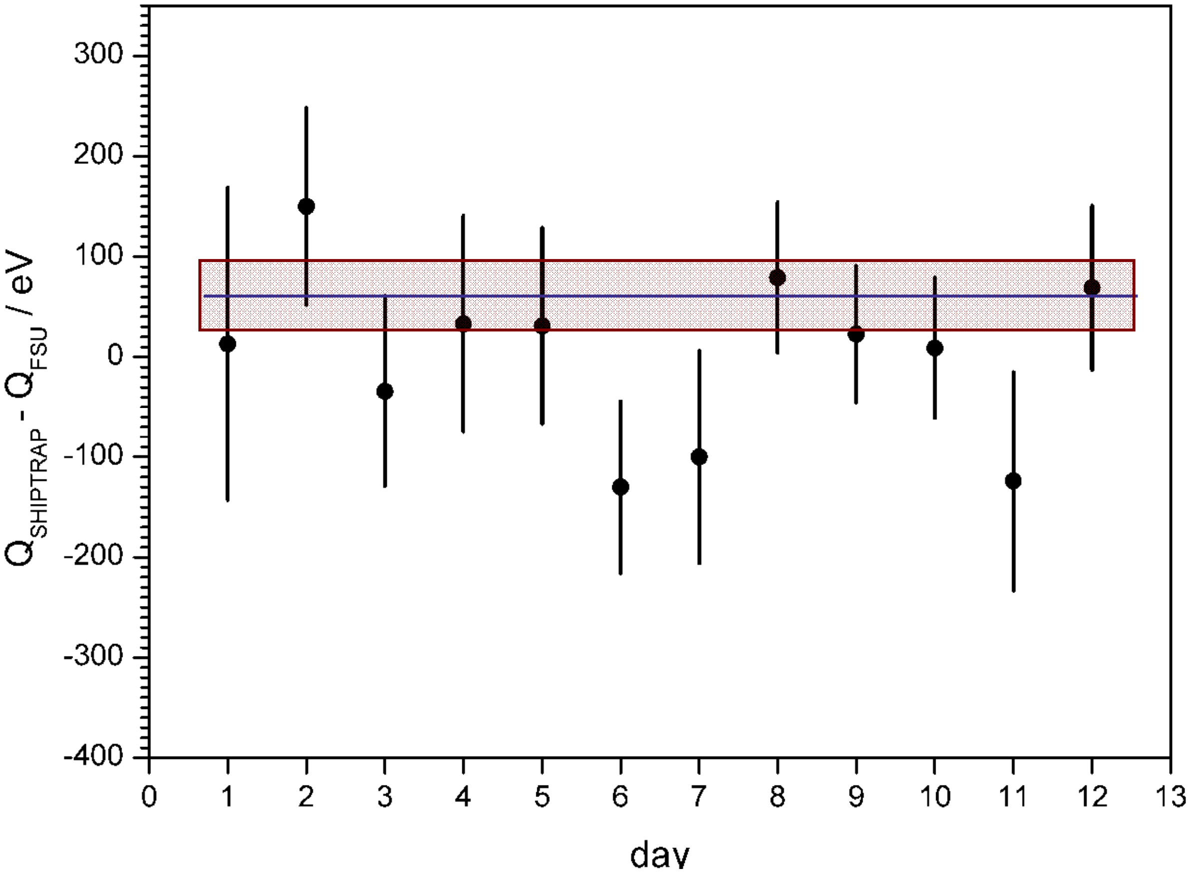
S. Eliseev et al., Phys. Rev. Lett. 110, 082501 (2013)

compared to standard technique:
→ 40 fold gain in resolving power
→ 5 fold gain in precision
→ 25 faster than the Ramsey TOF-ICR

High precision mass measurements of short-lived nuclides and produced with low production rates.

PI-ICR technique at SHIPTRAP

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

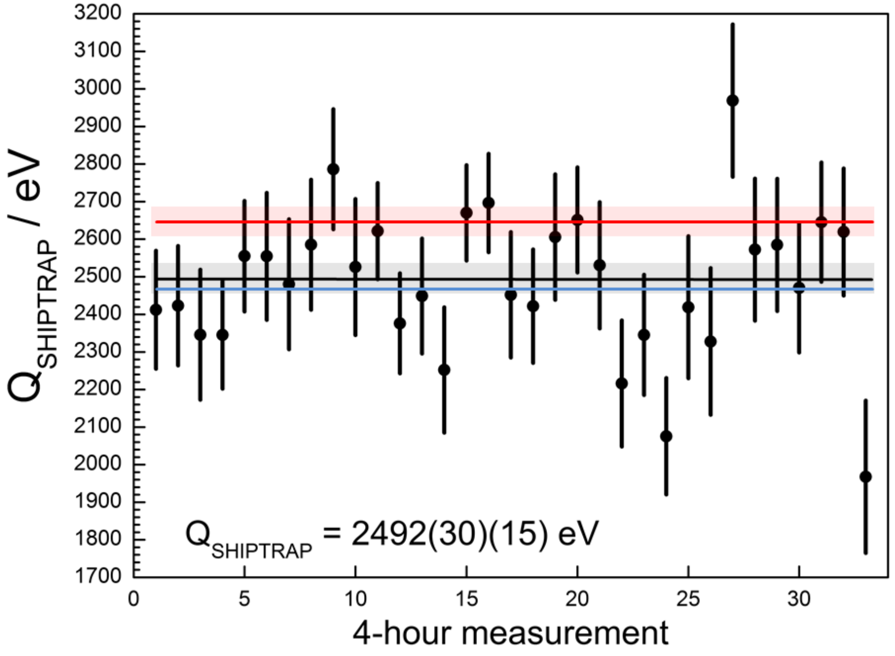


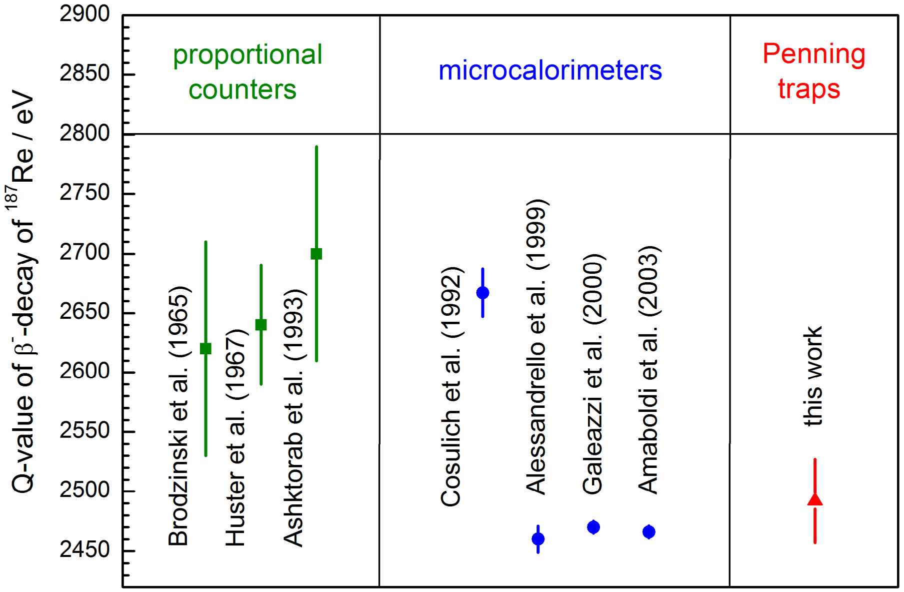
first ever measurement of mass difference
of ***singly charged*** medium-heavy **non-mass-doublets**
with a relative accuracy of $2 \cdot 10^{-10}$!!!

Q-value of the β^-- decay of ^{187}Re

SHIPTRAP measurement (April 2014) of

$M(^{187}\mathrm{Re})-M(^{187}\mathrm{Os}) = 2492\ (30_{stat})\ (15_{sys})$ eV





$\delta R/R < 3 \times 10^{-10}$

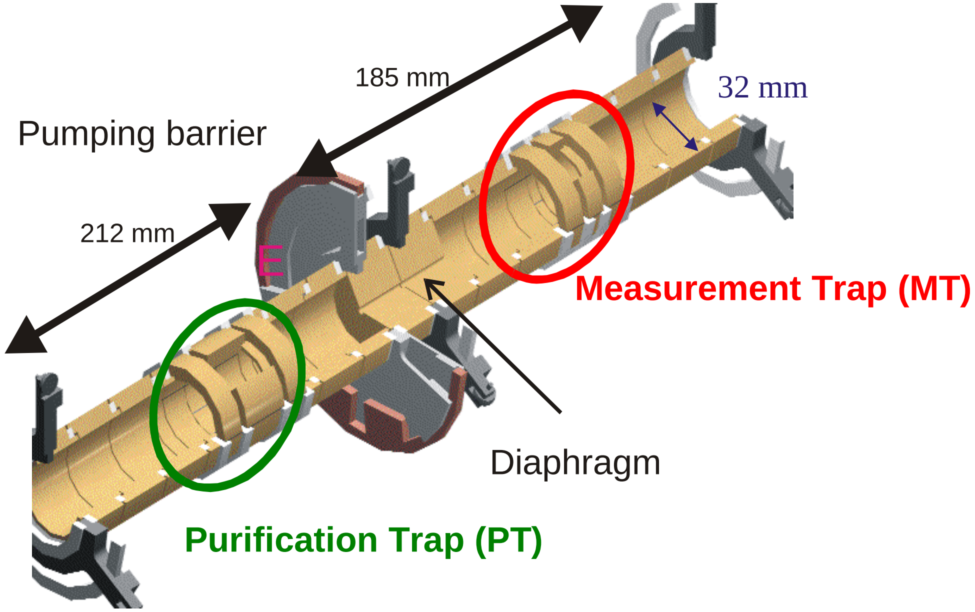
Outline

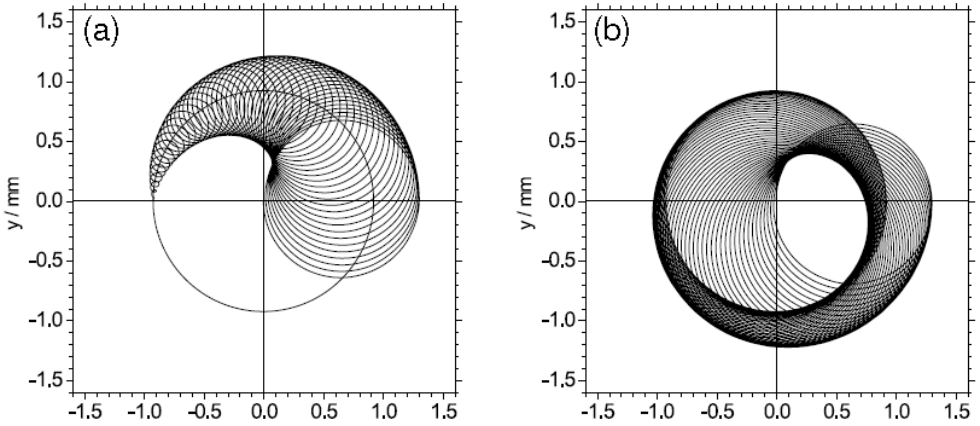
- ☐ How to perform a high-precision mass measurements ?
- ☐ Increasing the sensitivity and the resolving power
- ☐ **Resolving large samples of contaminants**

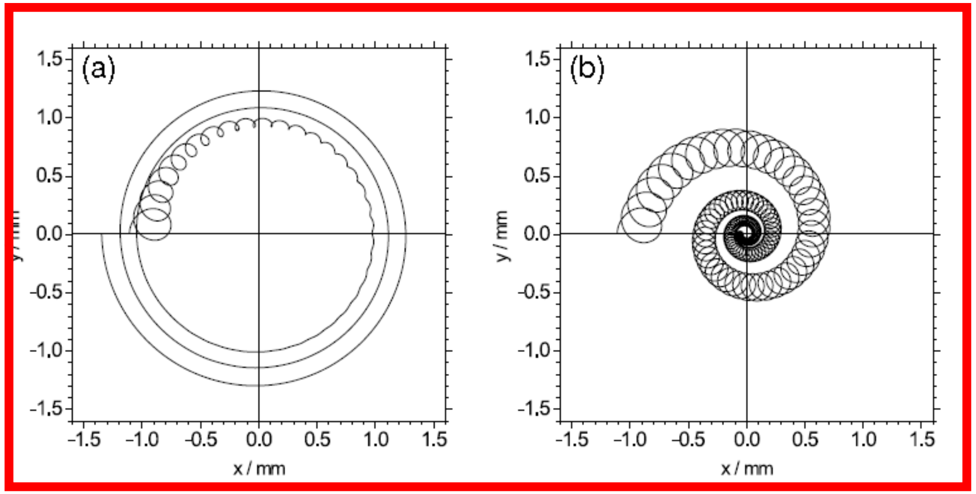
High-capacity separation

Double penning trap

→ Buffer gas cooling technique







Limitation ≈ 10^3 ions/bunch

The space charge changes the total potential seen by the ions

High-capacity separation

- Resolving power : $m/\Delta m = 10^5$
- Purify very large samples > 10^5 ions / bunch
- Cleaning process : a few ms

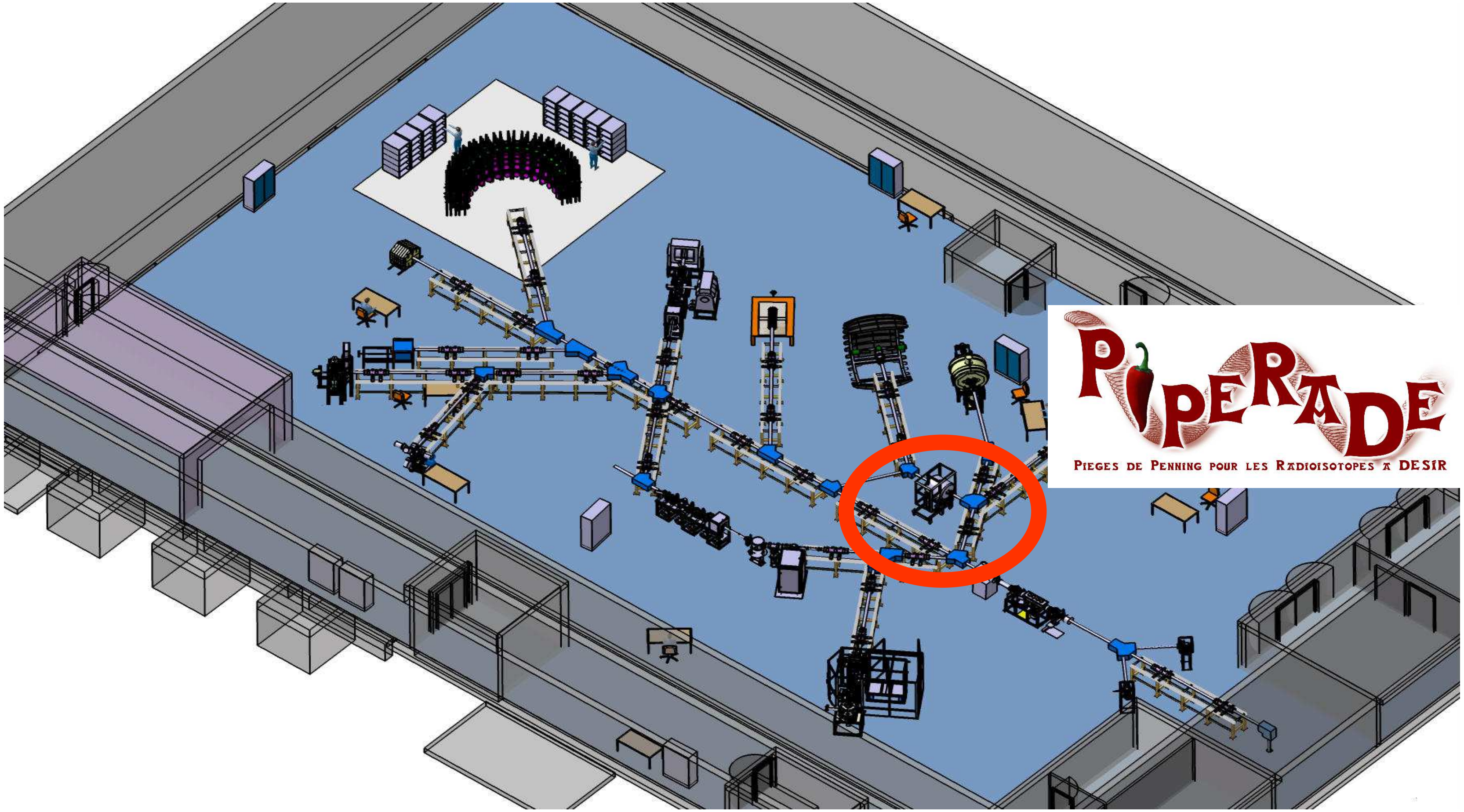
→ **New separation techniques**
→ **Special geometry for the trap**

PIPERADE @ DESIR

PIEGES DE PENNING POUR LES RADIOISOTOPES A DESIR

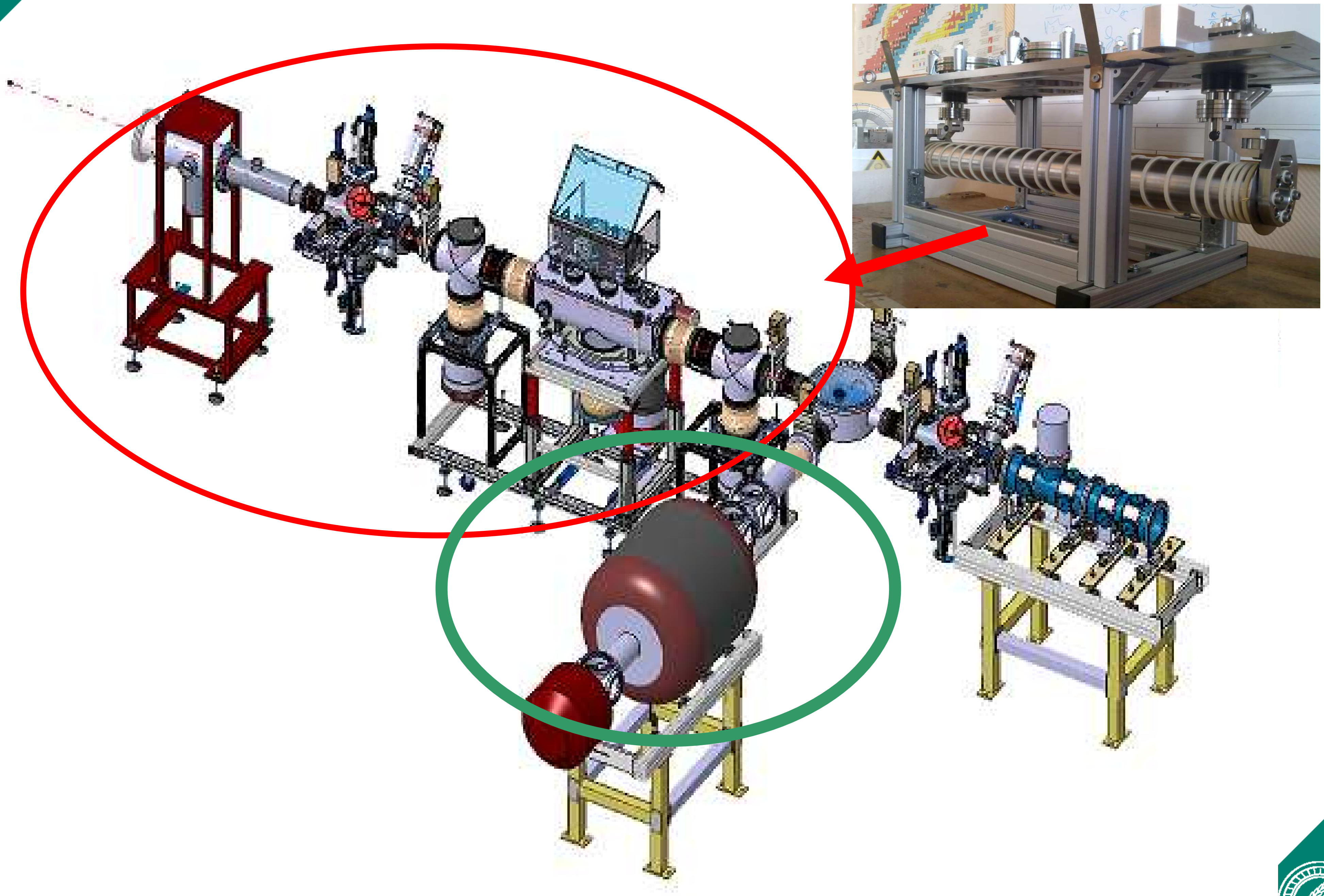
DESIR @ SPIRAL2

A low-energy RIB facility dedicated to the study of the fundamental properties of the nucleus in its ground and isomeric states

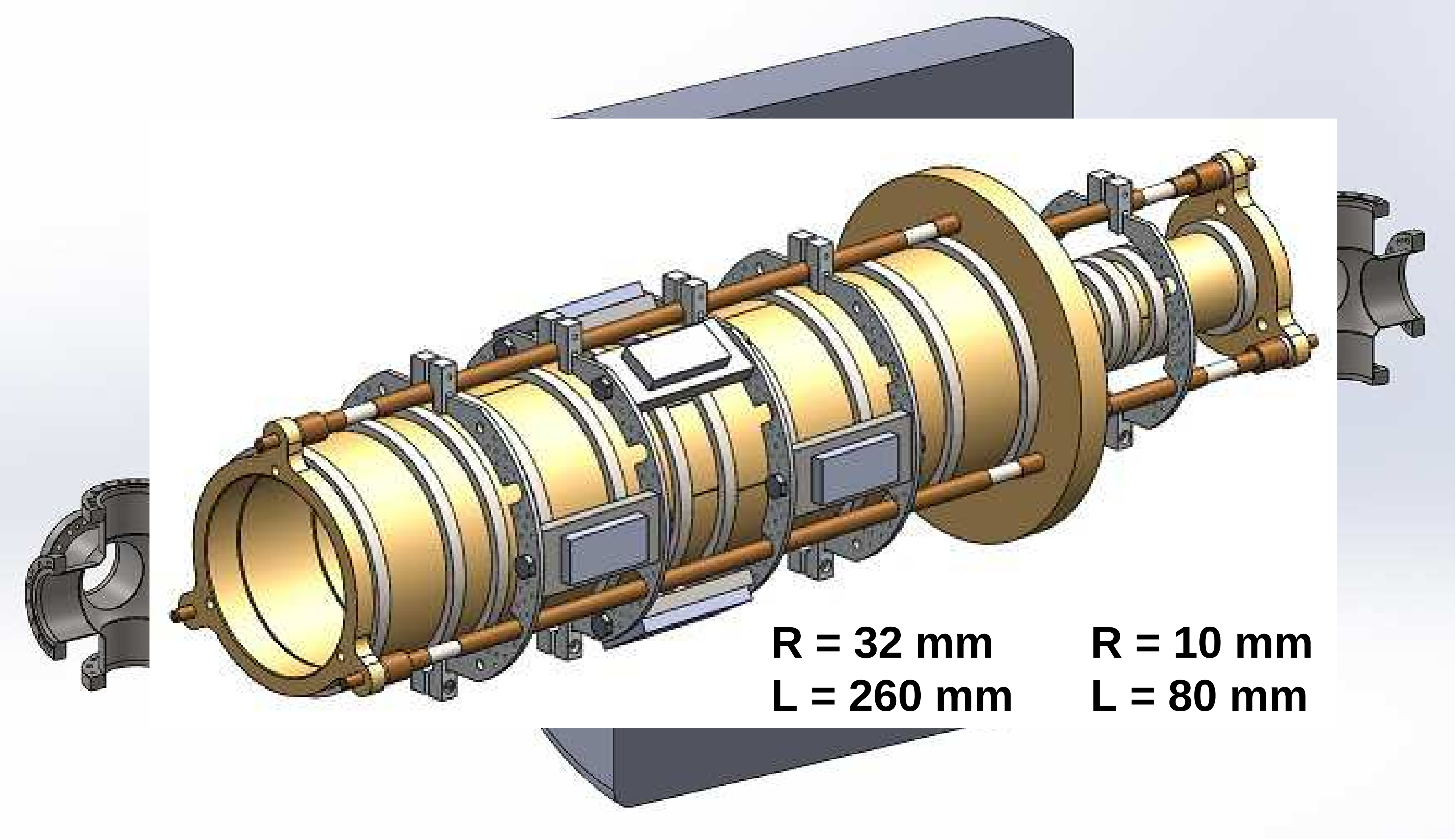


Collaboration Spokesperson: *B. Blank, CENBG*
Facility coordinator: *J.-C. Thomas, GANIL*

PIPERADE @ CENBG



PIPERADE @ MPIK



R = 32 mm
L = 260 mm

R = 10 mm
L = 80 mm

A double Penning trap for purification and accumulation

SIMULATIONS : Space charge effects

SIMBUCA code : **S**imulation of **I**on **M**otion in a Penning trap with realistic **BU**ffer gas collisions and **C**oulomb interaction using **A** Graphics Card

→ Study of the space charge effects

→Study of existing techniques with a high number of ions

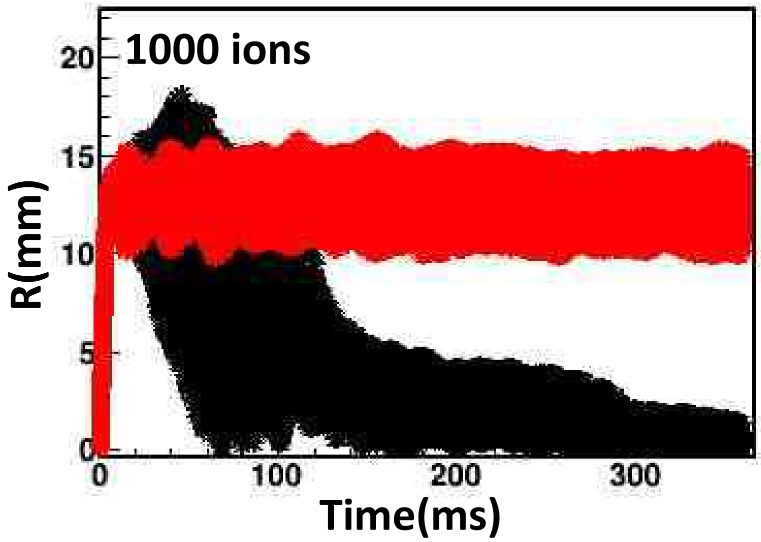
→ Simulations of new isobaric separation techniques

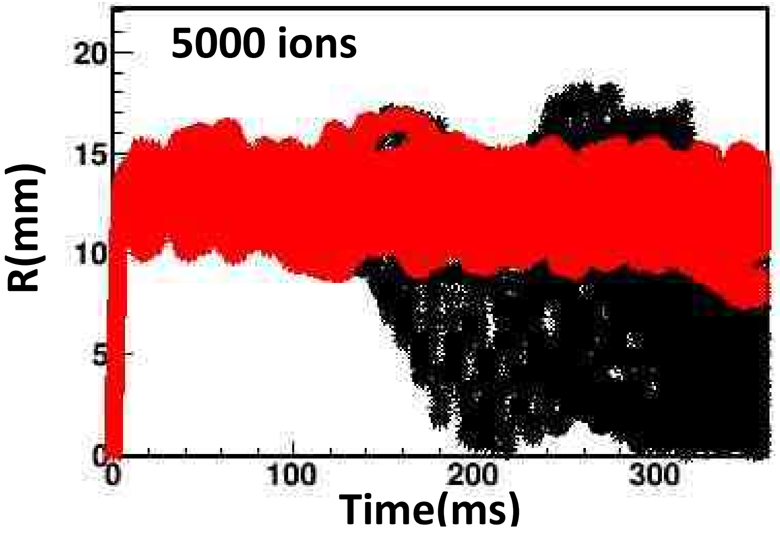
S. Van Gorp et al., NIM A 638, 192200 (2011)

S. Van Gorp and P. Dupré, AIP Conf. Proc. 1521 300 (2013)

SIMULATIONS : Space charge effects

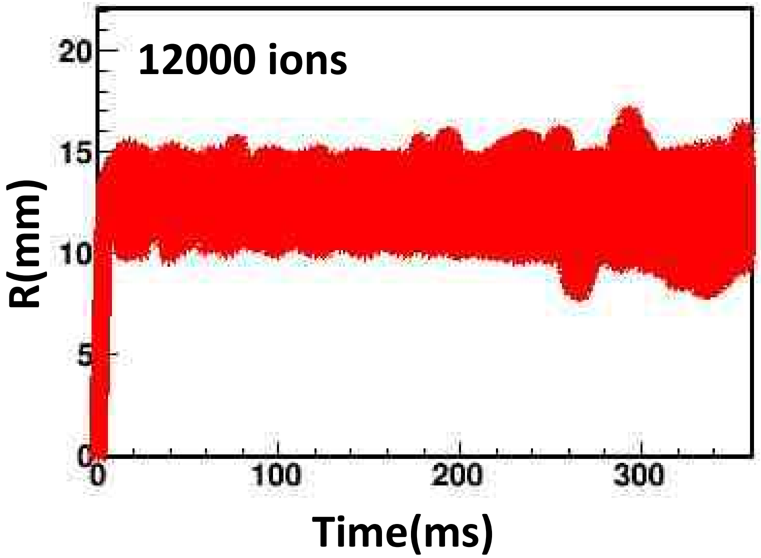
90% ^{136}Te, 10% ^{136}Sb P = 10^{-4} mbar





Increasing the number of ions

makes the re-centering inefficient



Additional potential created by the cloud itself

→ f-shifts

→ peak broadening

→ screening effects

Expand the cloud to decrease the density

SIMULATIONS : isobaric separation

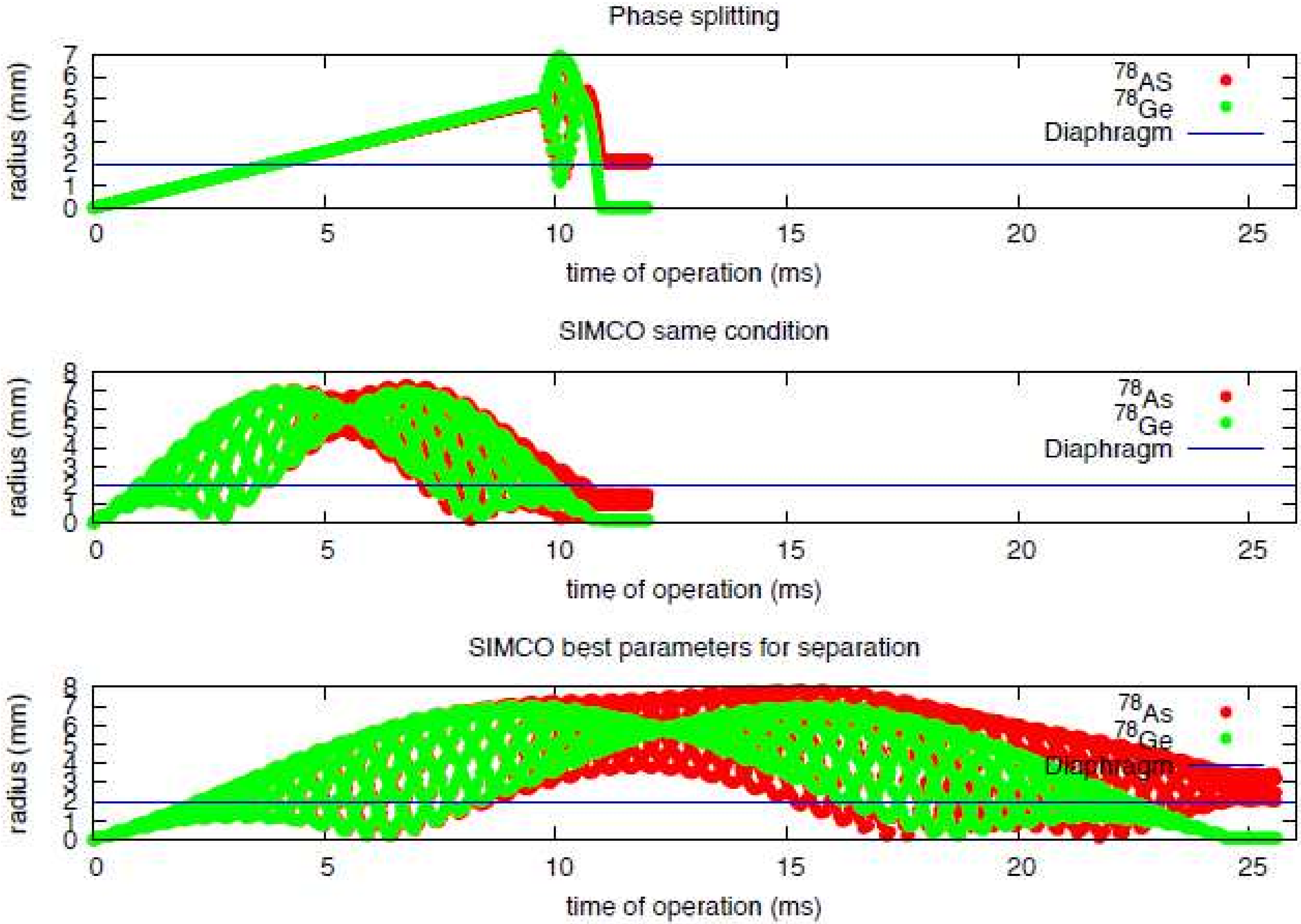
Existing techniques

- Dipole cleaning
- SWIFT technique
- SIMCO Excitation
- Anti Rotating Wall Technique

Exploring new techniques

phase splitting technique
→ no dependence on the contaminants
→ no buffer gas
→ great power of separation
→faster by a factor 2 than the SIMCO technique

SIMULATIONS : isobaric separation



Outlook

High accurate masses of exotic nuclides have been performed using the TOF-ICR method

Different excitation schemes can improve the resolving power of the standard technique

The implementation of new detection techniques will further increase the mass measurements of very exotic nuclides

PIPERADE will develop new isobaric separation techniques for high-capacity separation