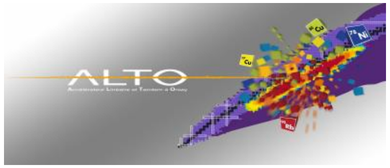
High-precision mass measurements with MLLTRAP at ALTO



MLLTRAP @ ALTO

Workshop LIA COSMA

Enrique Minaya Ramirez
Institut de Physique Nucléaire d'Orsay

Outline

I. MLLTRAP project

II. Penning trap mass spectrometers

III. Status of MLLTRAP@ALTO

Outline

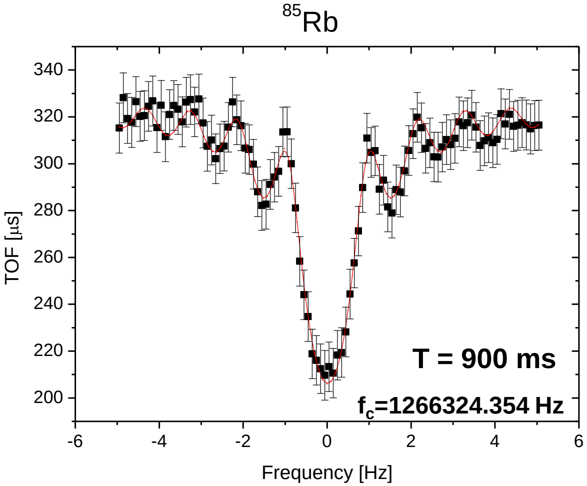
I. MLLTRAP project

II. Penning trap mass spectrometers

III. Status of MLLTRAP@ALTO

MLLTRAP project in Germany

Peter G. Thirolf , Christine Weber



2009 → Off-line commissioning of the double Penning trap system MLLTRAP

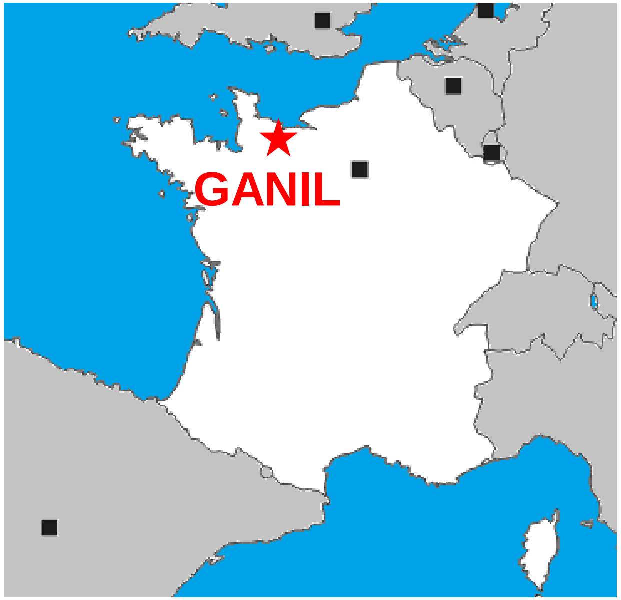
V.S. Kolhinen, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 600 (2009) 391

MLLTRAP → Penning trap mass spectrometer → High-precision mass measurements

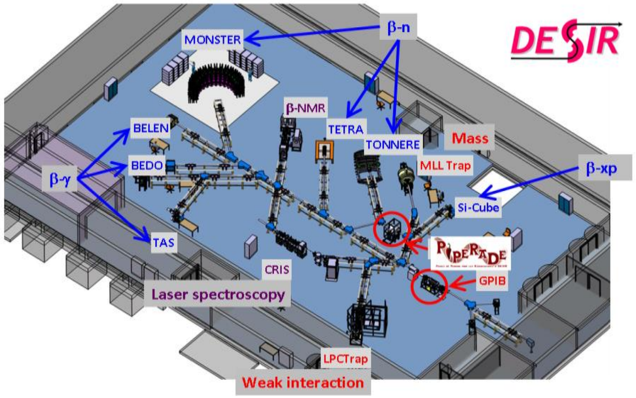
MLLTRAP project in France

The DESIR facility at GANIL-SPIRAL2 :

- β decay spectroscopy
- Laser Spectroscopy
- High-precision mass measurements

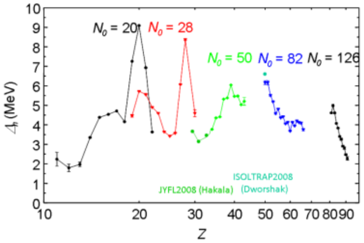


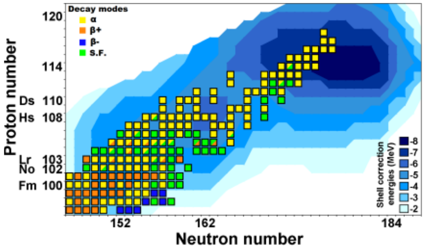
DESIR (Désintégration, Excitation et Stockage d'Ions Radioactifs

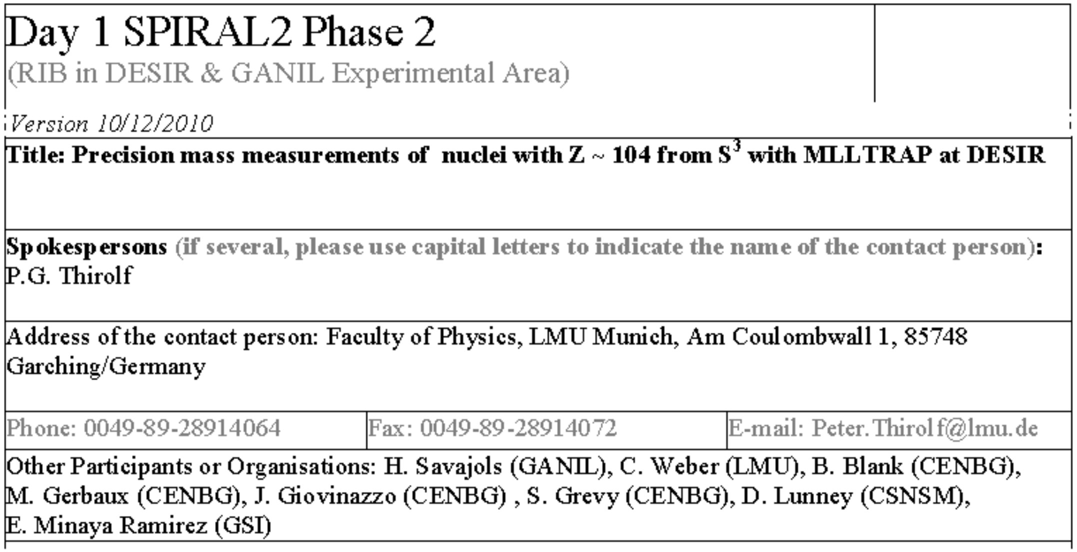


Mass measurements

- **Nuclei with $Z \geq 104$**
- ***N=Z nuclides up to ^{100}Sn***
- ***Quantum phase transitions around A = 100 (N=60)***







Day 1 SPIRAL2 Phase 2

(RIB in DESIR & GANIL Experimental Area)

Version 10/12/2010

Title: Precision mass measurements of nuclei with Z ~ 104 from S^3 with MLLTRAP at DESIR

Spokespersons (if several, please use capital letters to indicate the name of the contact person):
P.G. Thirolf

Address of the contact person: Faculty of Physics, LMU Munich, Am Coulombwall 1, 85748 Garching/Germany

Phone: 0049-89-28914064 | Fax: 0049-89-28914072 | E-mail: Peter.Thirolf@lmu.de

Other Participants or Organisations: H. Savajols (GANIL), C. Weber (LMU), B. Blank (CENBG), M. Gerbaux (CENBG), J. Giovinazzo (CENBG) , S. Grevy (CENBG), D. Lunney (CSNSM), E. Minaya Ramirez (GSI)

MLLTRAP project in France

The ALTO facility at Orsay

First operational RIB facility based on photo-fission →populating the GDR of ^{238}U

- ☐ **30-kV platform**
- ☐ **mass separator (A/ΔA = 1500)**
- ☐ **10 μA, 50 MeV e- beam**
- ☐ **10^{11} – 4 x10^{11} fissions/s**

March 2016 : "Charting Terra Incognita of Exotic Nuclei"

The MoU between MLL and IPNO was signed in May 2016.

Outline

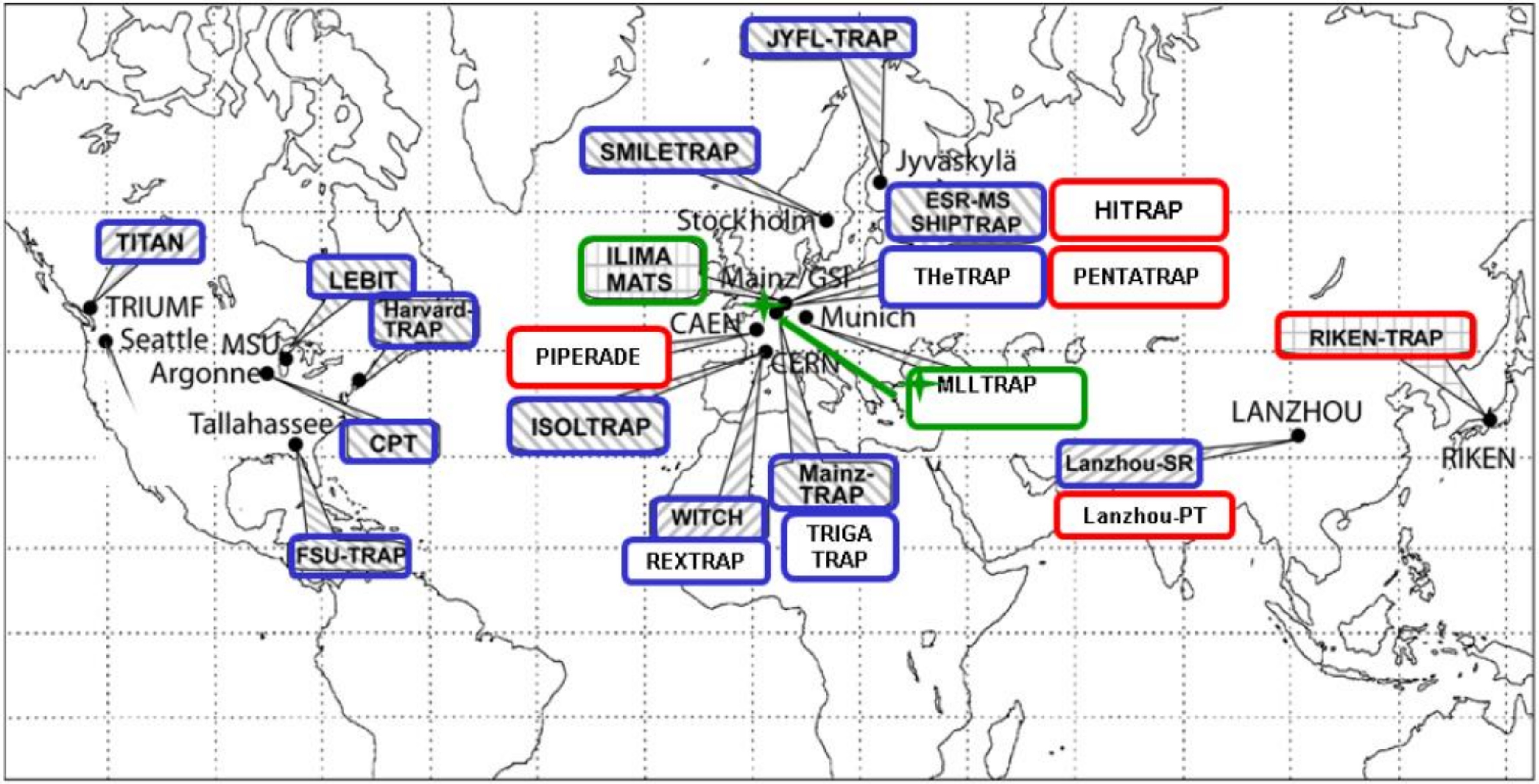
I. MLLTRAP project

II. Penning trap mass spectrometers

III. Status of MLLTRAP@ALTO

Penning traps spectrometers around the world

→**High quality low-energy beams :** low emittance, low energy spread, purified samples



▨ operating facilities

▨ facilities under construction or test

▦ planned facilities

Motivation for mass measurements

Fundamental Property
Tests of nuclear models
and formulas

Physics & Chemistry
Basic information required

Nuclear Structure
Shell closure, pairing,
deformation, halos

Double β-decay

MASS

Neutrino mass

Weak Interaction
symmetry tests,
CVC hypothesis

Nuclear Physics
Nuclear binding energies,
Q-values

Astrophysics
Nucleosynthesis

Motivation for mass measurements

Fundamental Property
Tests of nuclear models
and formulas

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

Physics & Chemistry
Basic information required

$\delta m/m \approx 10^{-5}$

Nuclear Structure
Shell closure, pairing,
deformation, halos

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

Double β-decay

$\delta m/m \approx 10^{-9}$

MASS

Neutrino mass

$\delta m/m \leq 10^{-10}$

Weak Interaction
symmetry tests,
CVC hypothesis

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

Nuclear Physics
Nuclear binding energies,
Q-values

$\delta m/m \approx 10-7$

Astrophysics
Nucleosynthesis

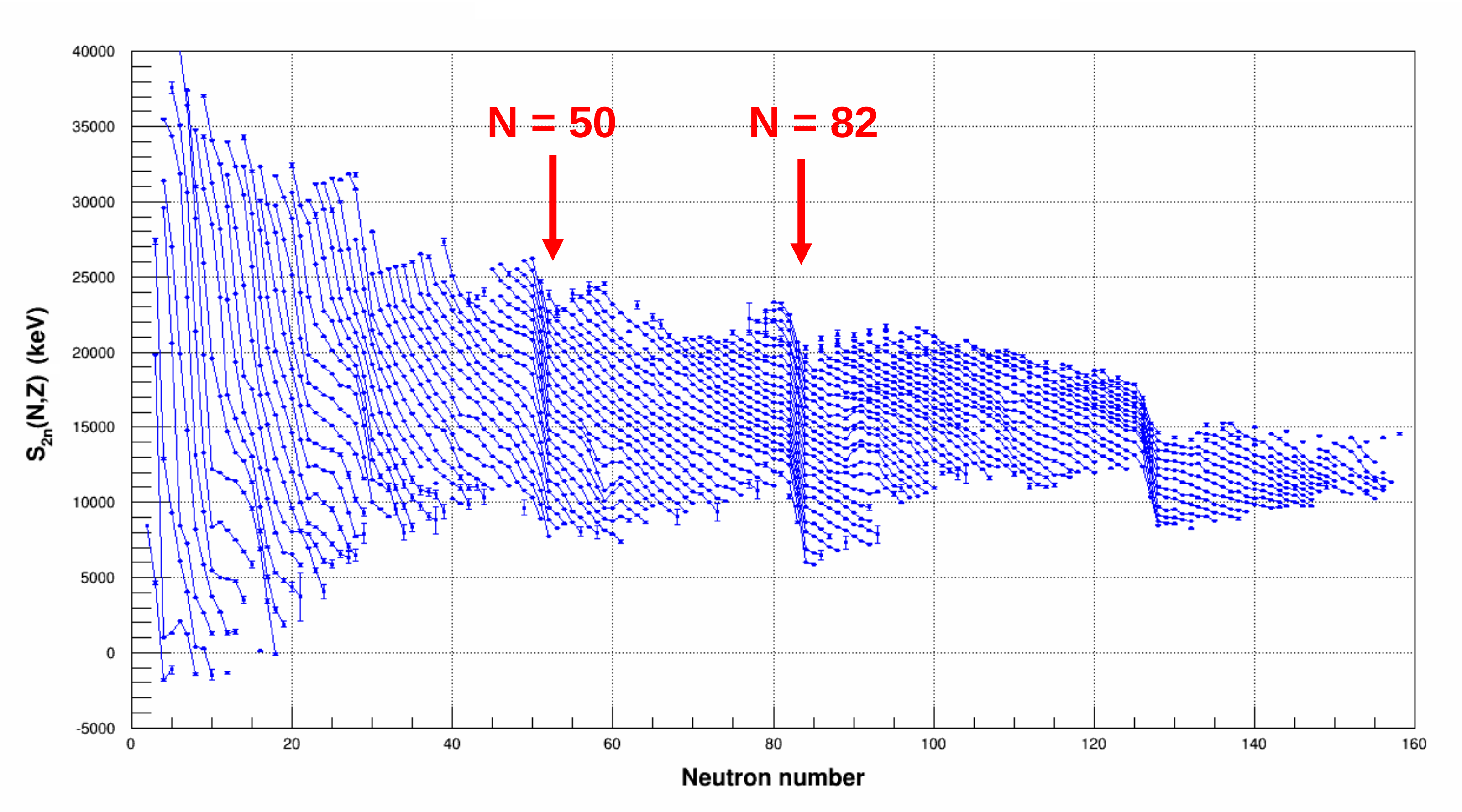
$\delta m/m \approx 10^{-7}$

Masses and nuclear structure

$$M(N,Z) = Z\,M_p + N\,M_n - B(N,Z)$$

→ **absolute nuclear binding energy** → **shell structure evolution**

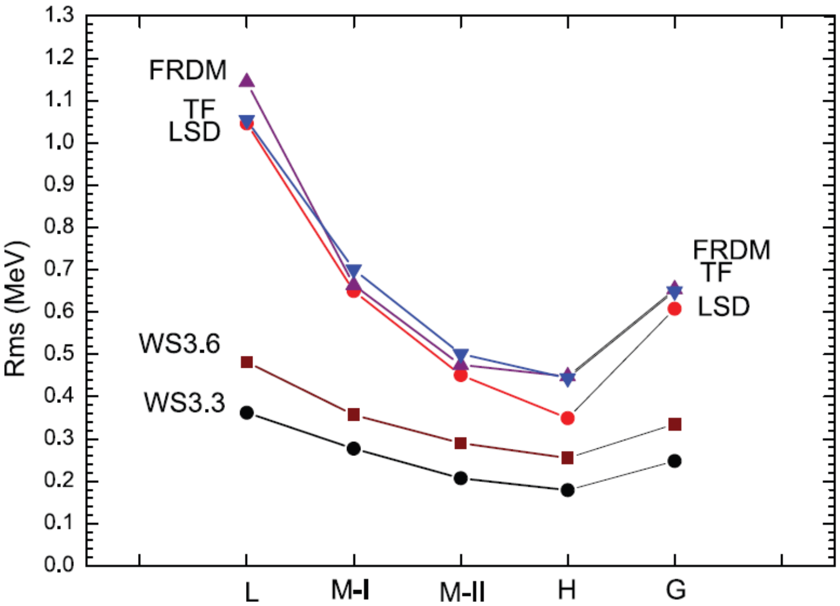
$$S_{2n}(N,Z) = B(N,Z) - B(N-2,Z)$$



Masses and nuclear structure

$$M(N,Z) = Z\,M_p + N\,M_n - B(N,Z)$$

→ **absolute nuclear binding energy** → **shell structure evolution** →**Benchmark nuclear models**



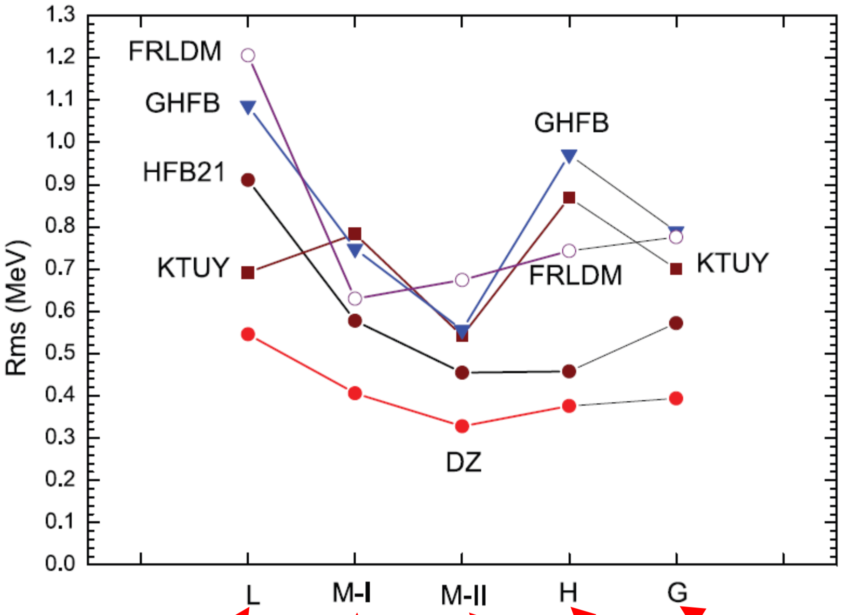
$8 \le Z < 28,\ N \ge 8$

$28 \le Z < 50$

$50 \le Z < 82$

$Z \ge 82$

$Z,\ N \ge 8$



$8 \le Z < 28,\ N \ge 8$

$28 \le Z < 50$

$50 \le Z < 82$

$Z \ge 82$

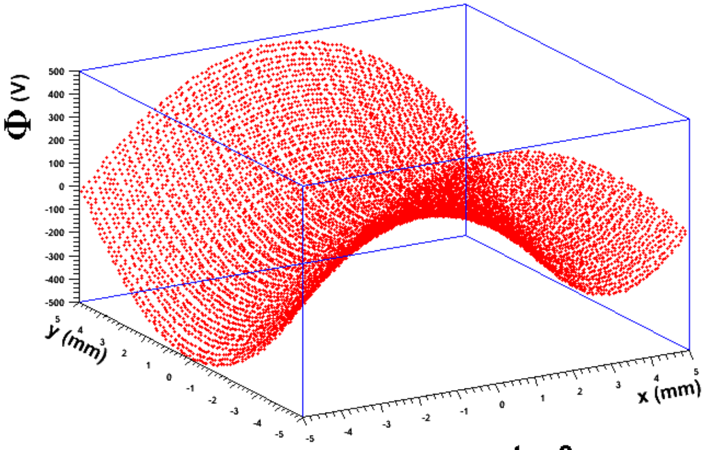
$Z,\ N \ge 8$

A. Sobiczewski and Y. A. Litvinov, Phys. ReV. C 89, 024311 (2014)

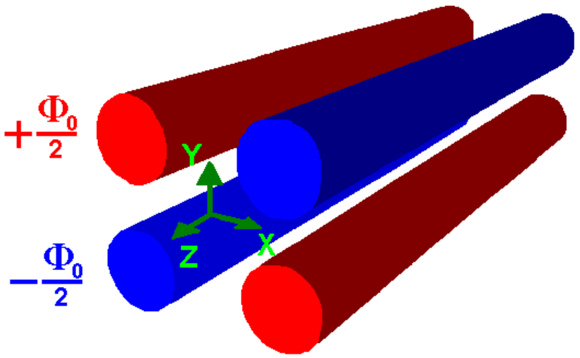
Principle of trapping

Paul trap (dynamic)

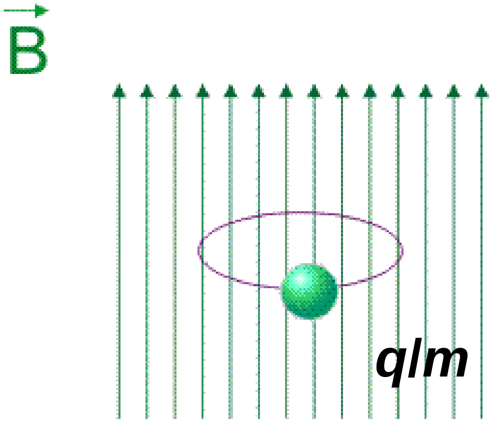
$$\phi_0(t) = V_{DC} - V_{RF}\cos\Omega t$$



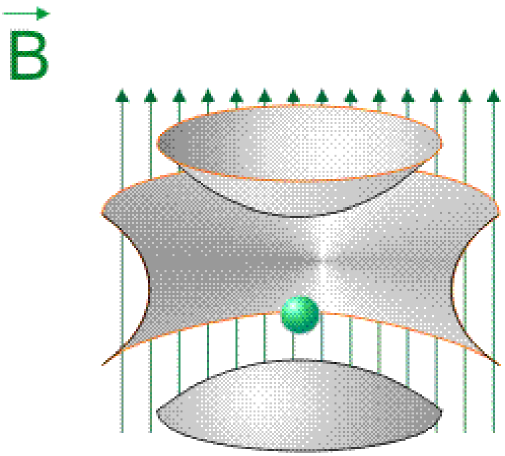
t = 0



Penning trap (static)



strong homogeneous magnetic field



+ weak electrostatic field

Cyclotron frequency

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

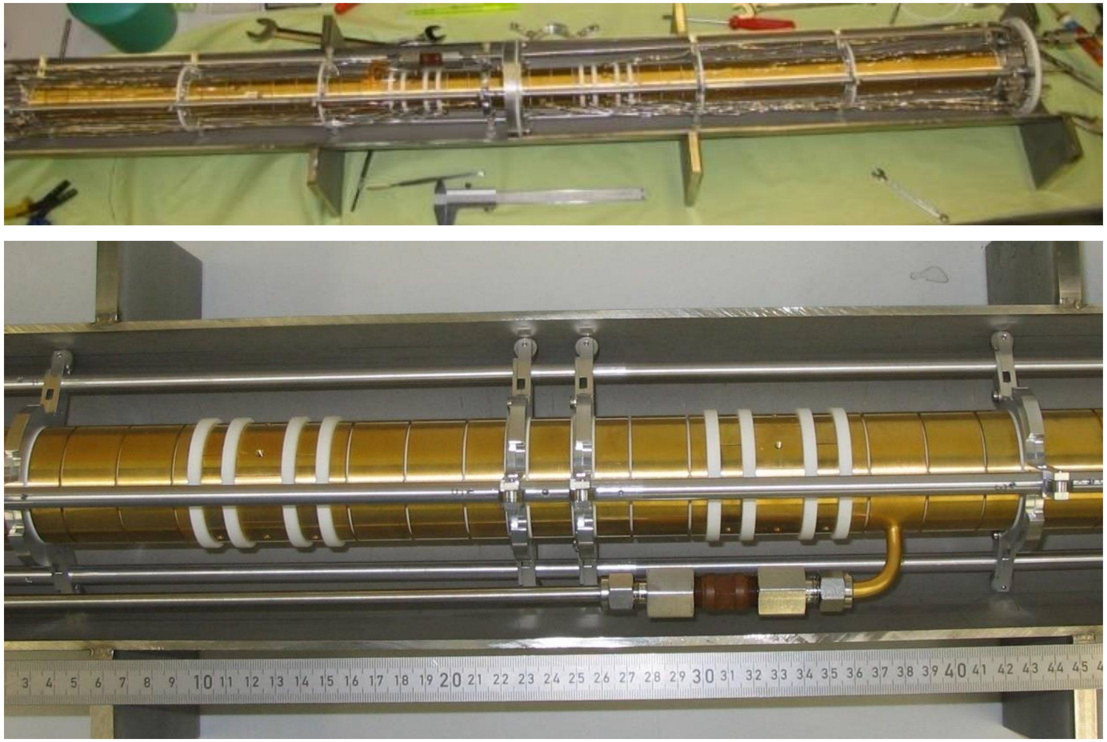
B = 7 T, A = 133, $f_c \approx$ 800 kHz

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

Principle of trapping

Static : Penning trap

7 Tesla superconducting magnet

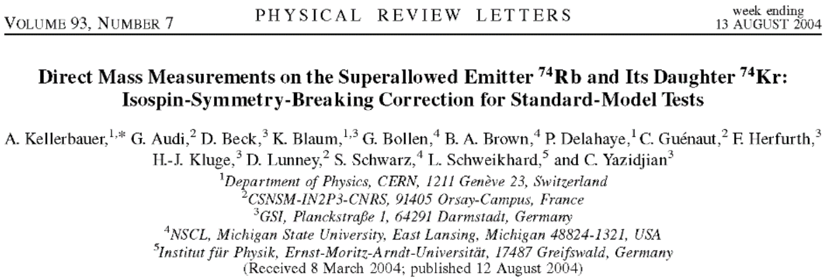


☐ Relative uncertainty	≈ 10^{-8}
☐ Accessible half-lifes	≈ 100 ms
☐ Typical Resolving power	≈ 10^{6}

High-precision mass measurements with Penning traps

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

64.776 ms 0^{+}
M $^{-}$51916 (3)
β^{+}=100%
β^{+}p?


VOLUME 93, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 13 AUGUST 2004

Direct Mass Measurements on the Superallowed Emitter ^{74}Rb and Its Daughter ^{74}Kr: Isospin-Symmetry-Breaking Correction for Standard-Model Tests

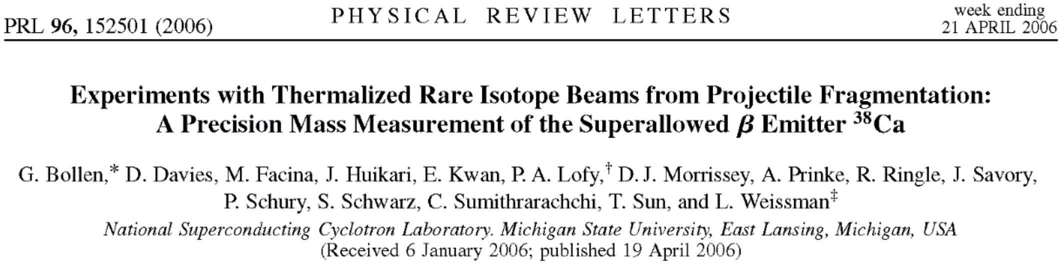
A. Kellerbauer,[1,*] G. Audi,[2] D. Beck,[3] K. Blaum,[1,3] G. Bollen,[4] B. A. Brown,[4] P. Delahaye,[1] C. Guénaut,[2] F. Herfurth,[3]
H.-J. Kluge,[3] D. Lunney,[2] S. Schwarz,[4] L. Schweikhard,[5] and C. Yazidjian[3]
[1]*Department of Physics, CERN, 1211 Genève 23, Switzerland*
[2]*CSNSM-IN2P3-CNRS, 91405 Orsay-Campus, France*
[3]*GSI, Planckstraße 1, 64291 Darmstadt, Germany*
[4]*NSCL, Michigan State University, East Lansing, Michigan 48824-1321, USA*
[5]*Institut für Physik, Ernst-Moritz-Arndt-Universität, 17487 Greifswald, Germany*
(Received 8 March 2004; published 12 August 2004)

ISOLTRAP

$T_{1/2} \approx 64{,}7$ ms
Superallowed β emitter

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

443.77 ms 0^{+}
M $^{-}$22058.50 (0.19)
β^{+}=100%


PRL **96,** 152501 (2006) PHYSICAL REVIEW LETTERS week ending 21 APRIL 2006

Experiments with Thermalized Rare Isotope Beams from Projectile Fragmentation: A Precision Mass Measurement of the Superallowed β Emitter ^{38}Ca

G. Bollen,* D. Davies, M. Facina, J. Huikari, E. Kwan, P. A. Lofy,† D. J. Morrissey, A. Prinke, R. Ringle, J. Savory,
P. Schury, S. Schwarz, C. Sumithrarachchi, T. Sun, and L. Weissman‡
National Superconducting Cyclotron Laboratory. Michigan State University, East Lansing, Michigan, USA
(Received 6 January 2006; published 19 April 2006)

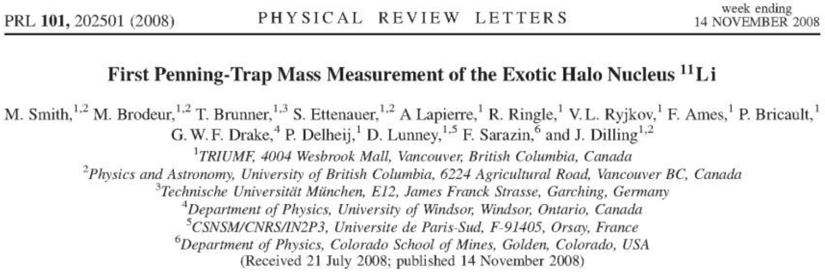
LEBIT

$$\frac{\delta m}{m} = 8 \cdot 10^{-9}$$

Superallowed β emitter

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

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


PRL **101,** 202501 (2008) PHYSICAL REVIEW LETTERS week ending 14 NOVEMBER 2008

First Penning-Trap Mass Measurement of the Exotic Halo Nucleus ^{11}Li

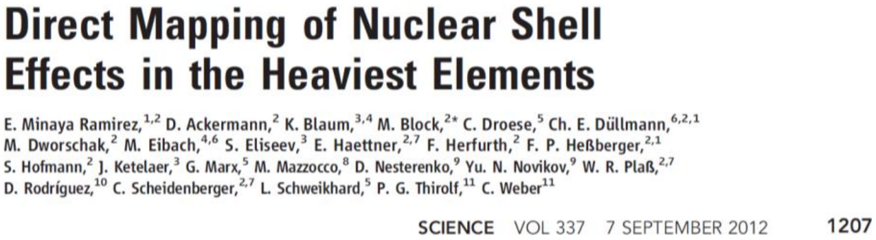
M. Smith,[1,2] M. Brodeur,[1,2] T. Brunner,[1,3] S. Ettenauer,[1,2] A Lapierre,[1] R. Ringle,[1] V.L. Ryjkov,[1] F. Ames,[1] P. Bricault,[1]
G. W. F. Drake,[4] P. Delheij,[1] D. Lunney,[1,5] F. Sarazin,[6] and J. Dilling[1,2]
[1]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada*
[2]*Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver BC, Canada*
[3]*Technische Universität München, E12, James Franck Strasse, Garching, Germany*
[4]*Department of Physics, University of Windsor, Windsor, Ontario, Canada*
[5]*CSNSM/CNRS/IN2P3, Universite de Paris-Sud, F-91405, Orsay, France*
[6]*Department of Physics, Colorado School of Mines, Golden, Colorado, USA*
(Received 21 July 2008; published 14 November 2008)

TITAN

$T_{1/2} \approx 8{,}75$ ms
Halo nucleus

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

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


Direct Mapping of Nuclear Shell Effects in the Heaviest Elements

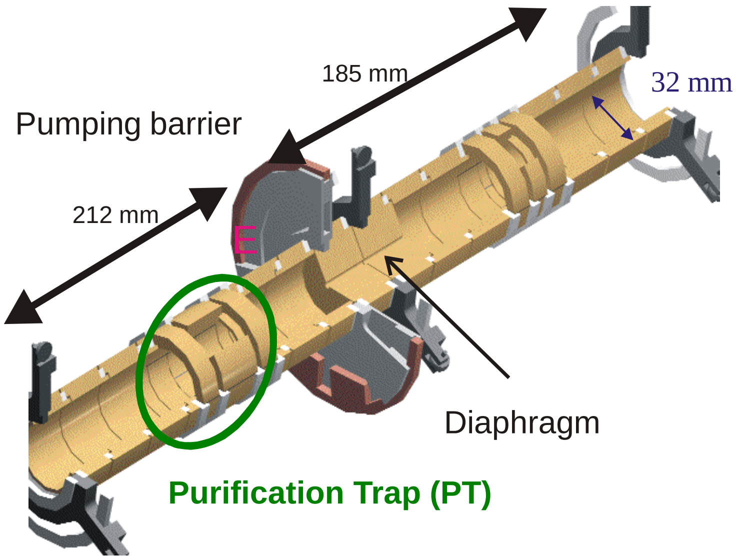
E. Minaya Ramirez,[1,2] D. Ackermann,[2] K. Blaum,[3,4] M. Block,[2*] C. Droese,[5] Ch. E. Düllmann,[6,2,1]
M. Dworschak,[2] M. Eibach,[4,6] S. Eliseev,[3] E. Haettner,[2,7] F. Herfurth,[2] F. P. Heßberger,[2,1]
S. Hofmann,[2] J. Ketelaer,[3] G. Marx,[5] M. Mazzocco,[8] D. Nesterenko,[9] Yu. N. Novikov,[9] W. R. Plaß,[2,7]
D. Rodríguez,[10] C. Scheidenberger,[2,7] L. Schweikhard,[5] P. G. Thirolf,[11] C. Weber[11]

SCIENCE VOL 337 7 SEPTEMBER 2012 1207

SHIPTRAP

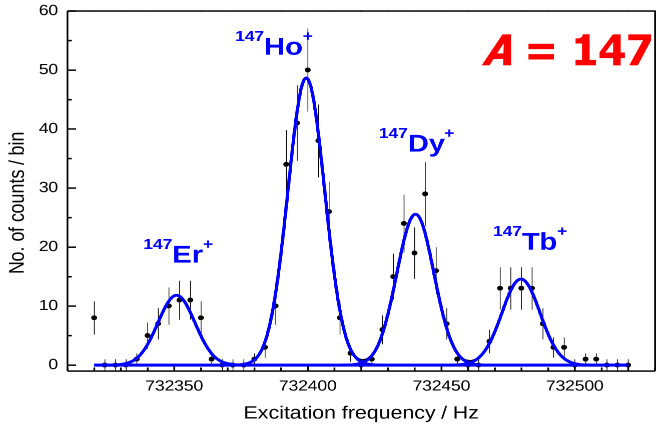
Z = 102,103
σ = 60 nb
Deformed shell gap N = 152

Buffer gas cooling technique



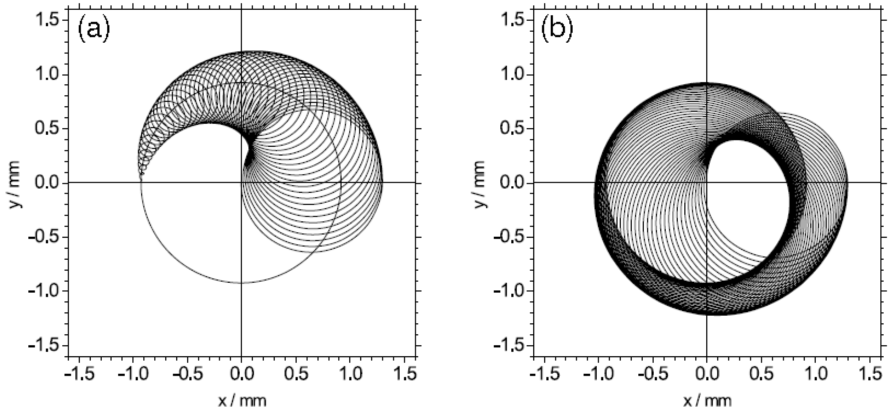
m/Δm ≈ 100 000

⇒ Isobaric separation

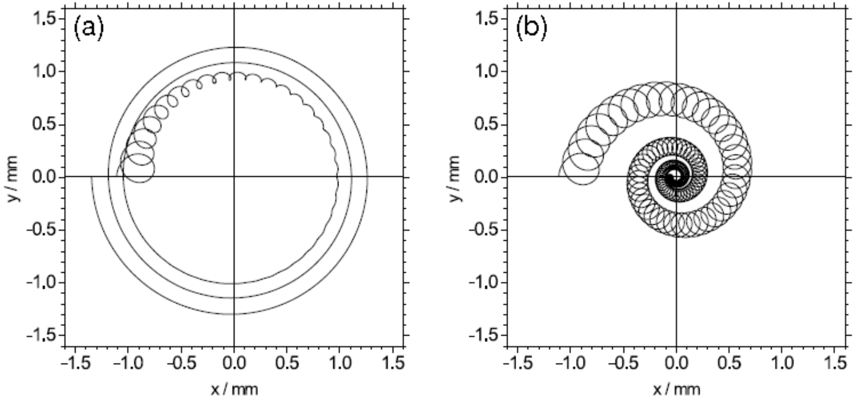


Ion motion in first trap

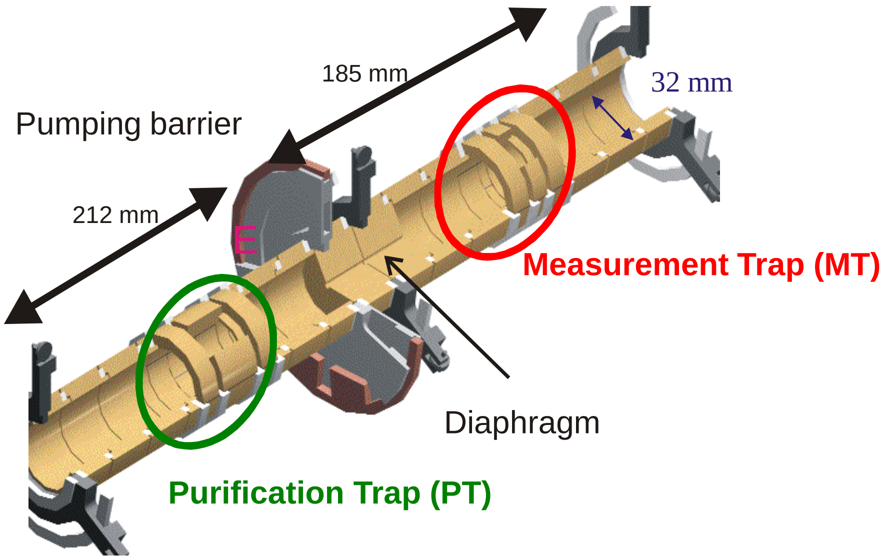
Without buffer gas (Helium)

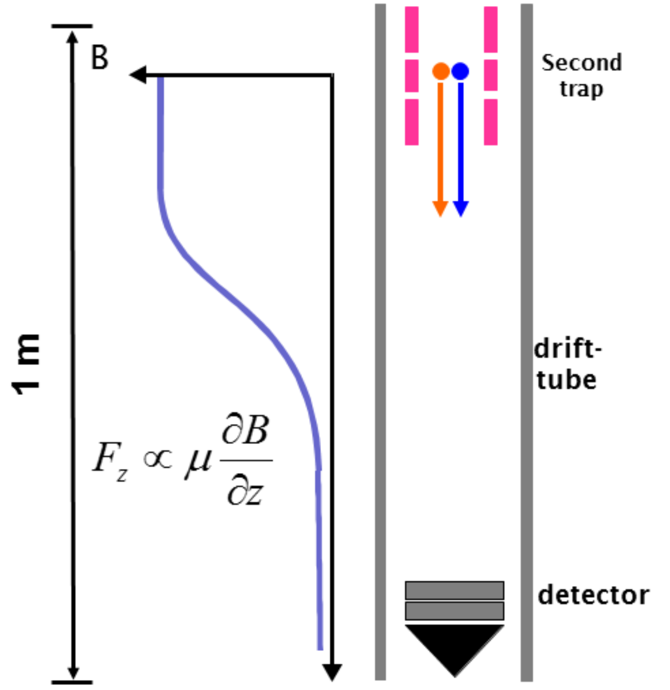


With buffer gas (Helium)



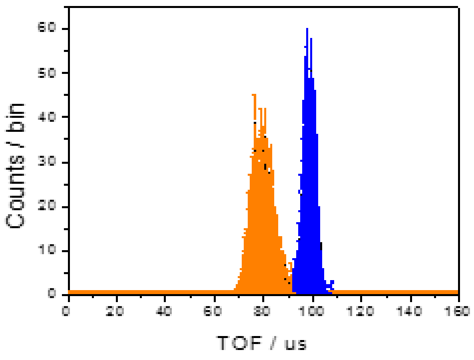
TOF-ICR :Time-of-flight resonance technique

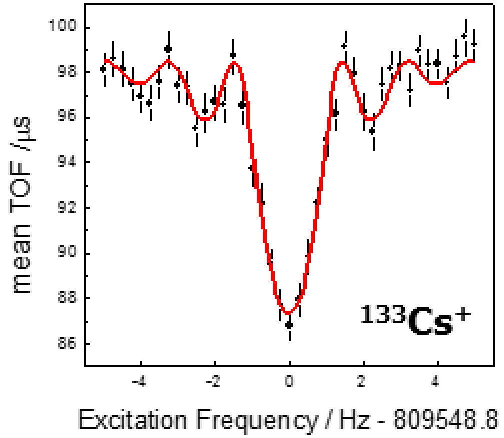




$$F_z \propto \mu \frac{\partial B}{\partial z}$$

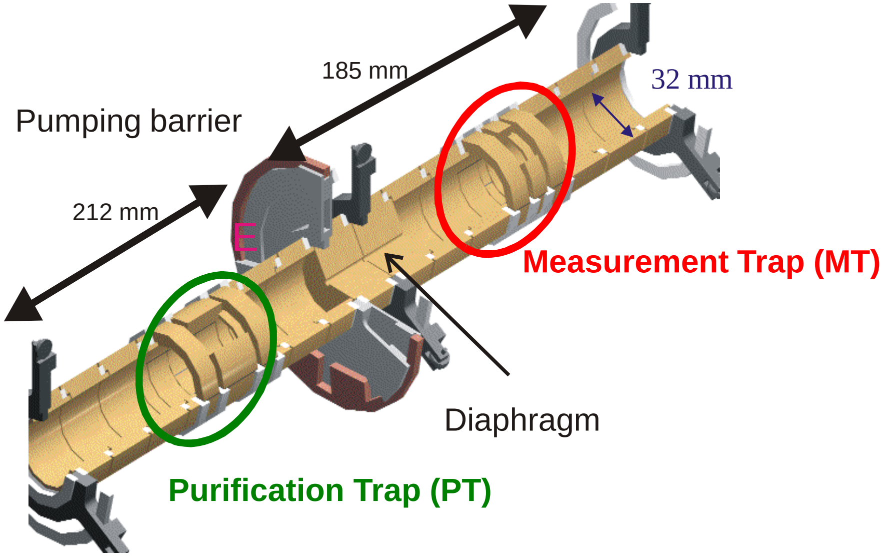
Quadrupolar resonance : m/Δm ≈ 1 000 000

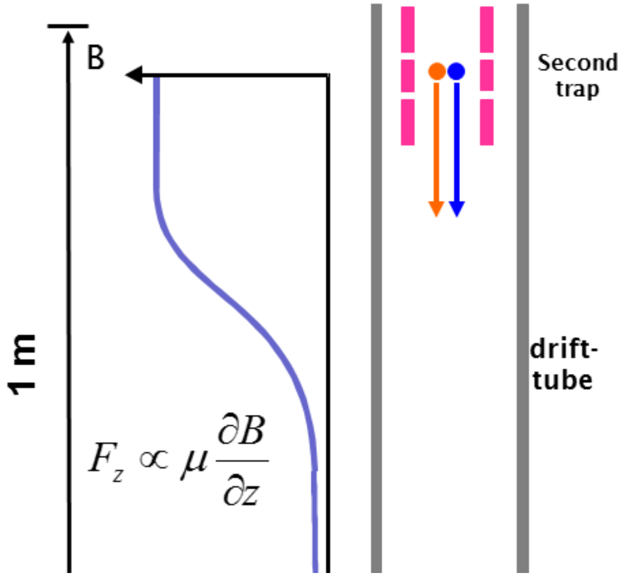




M. König et al., Int. J. Mass Spec. Ion Process. 142 (1995) 95

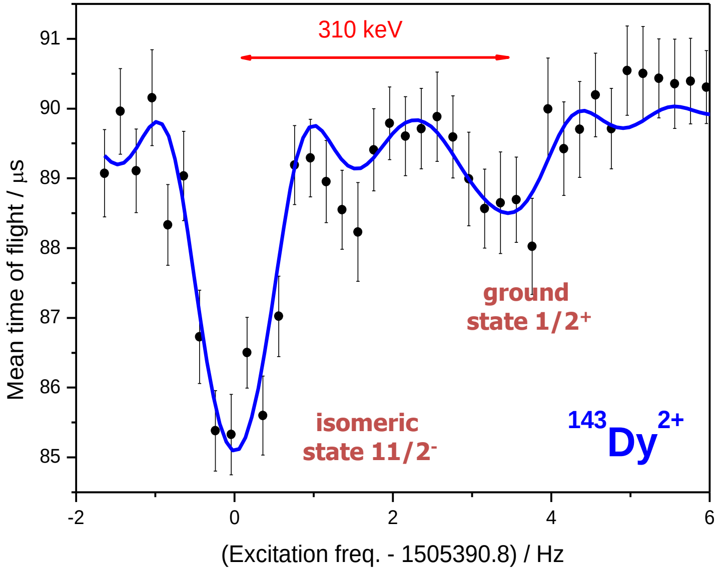
TOF-ICR :Time-of-flight resonance technique





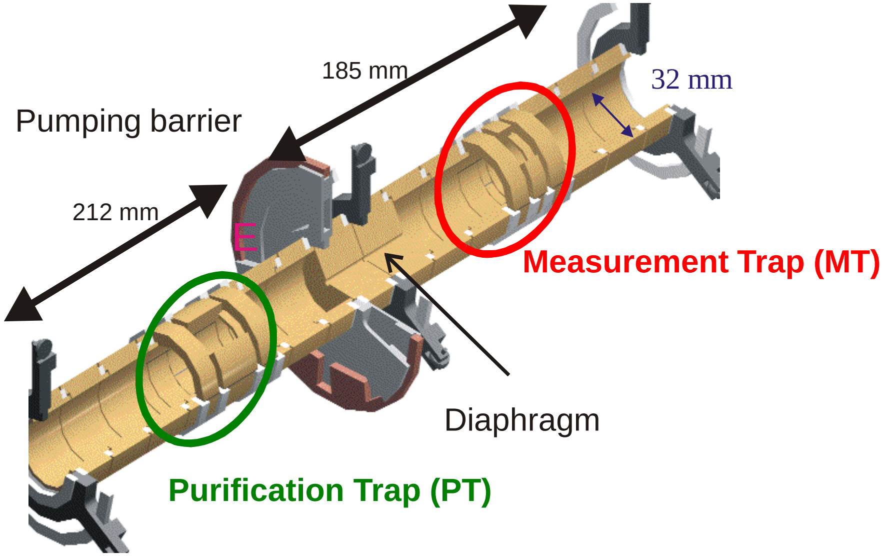
Quadrupolar resonance : m/Δm ≈ 1 000 000

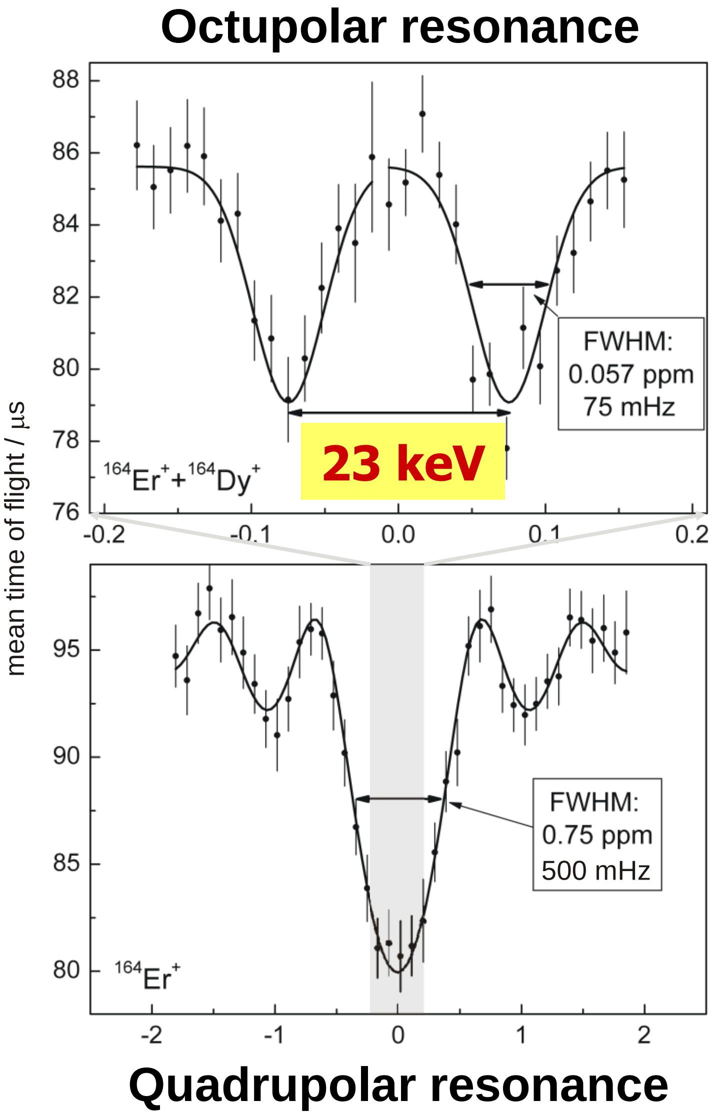
⇒ Separation of isomers



C. Rauth et al., Eur. Phys. J. Special Topics 150 (2007) 329

TOF-ICR :Time-of-flight resonance technique




Octupolar resonance

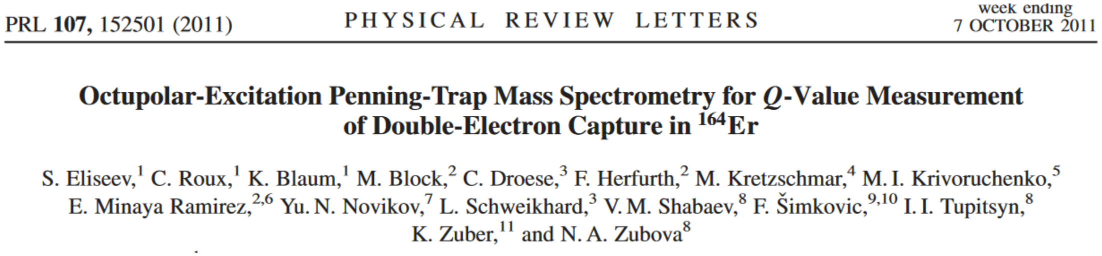
Quadrupolar resonance

Quadrupolar resonance : m/Δm ≈ 1 000 000

⇒ Separation of isomers

Octupolar resonance m/Δm ≈ 20 000 000

⇒ mass-ratio determination of the ^{164}Er-^{164}Dy mass doublet


PRL **107,** 152501 (2011) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2011

Octupolar-Excitation Penning-Trap Mass Spectrometry for *Q*-Value Measurement of Double-Electron Capture in ^{164}Er

S. Eliseev,[1] C. Roux,[1] K. Blaum,[1] M. Block,[2] C. Droese,[3] F. Herfurth,[2] M. Kretzschmar,[4] M. I. Krivoruchenko,[5] E. Minaya Ramirez,[2,6] Yu. N. Novikov,[7] L. Schweikhard,[3] V. M. Shabaev,[8] F. Šimkovic,[9,10] I. I. Tupitsyn,[8] K. Zuber,[11] and N. A. Zubova[8]

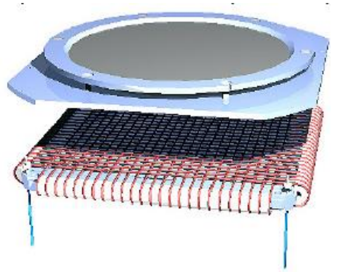
PI-ICR :Phase imaging ion cyclotron resonance

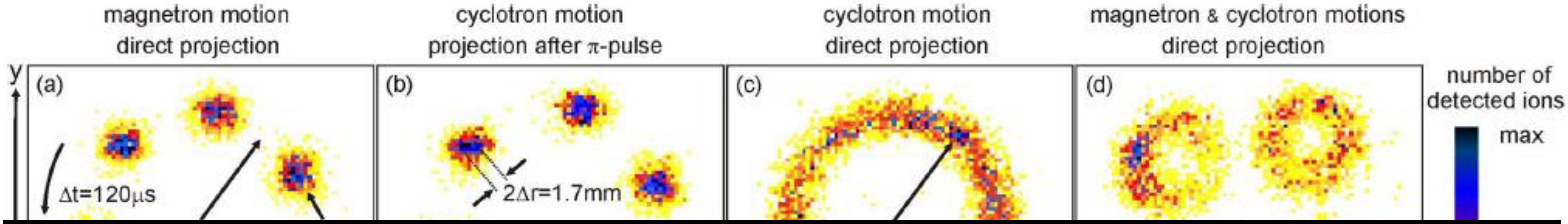
- **Image ion motion**
- **Determine phase of ion motion**
- **Excite ions**
- **Determine phase after evolution time**

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

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

Delay-Line Detector by Roentdek GmbH



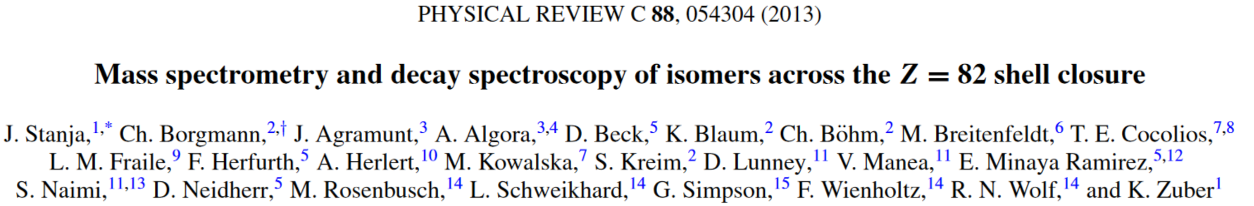


	atomic mass difference	Δm (eV)
S. Eliseev *et al.*, PRL110 (2013)	^{130}Xe / ^{129}Xe	2 ppb
S. Eliseev *et al.*, APB 114 (2014)	^{133}Cs	
E. Minaya Ramirez *et al.*, JPS CP6 (2015)	^{132}Xe / ^{131}Xe	0.2 ppb
D.A. Nesterenko *et al.* PRC90 (2015) → neutrino mass	^{187}Re/^{187}Os	2833 (30_{stat}) (15_{sys})
S. Eliseev *et al.*, PRL115 (2015) → neutrino mass	^{163}Ho/^{163}Dy	2492 (30_{stat}) (15_{sys})
P. Filianin *et al.*, PLB 758 (2016) → s-process nuclide	^{123}Te/^{123}Sb	51.912(67) keV

Trap-assisted Spectroscopy

A system for β- and γ- spectroscopy installed behind a trap can be used for both assisting mass measurements and performing decay spectroscopy on pure samples.

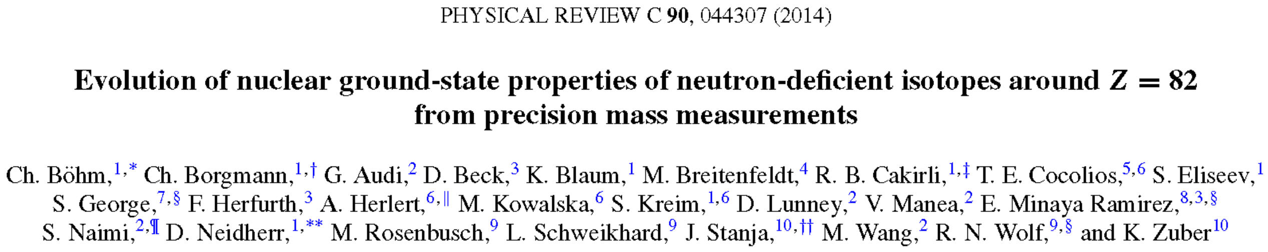
ISOLTRAP



PHYSICAL REVIEW C **88**, 054304 (2013)

Mass spectrometry and decay spectroscopy of isomers across the $Z = 82$ shell closure

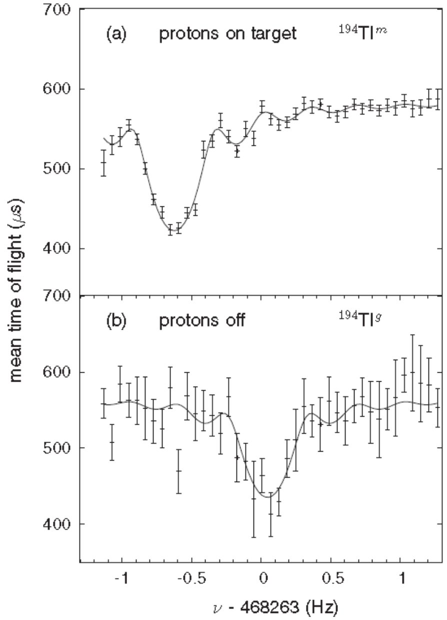
J. Stanja,[1,*] Ch. Borgmann,[2,†] J. Agramunt,[3] A. Algora,[3,4] D. Beck,[5] K. Blaum,[2] Ch. Böhm,[2] M. Breitenfeldt,[6] T. E. Cocolios,[7,8] L. M. Fraile,[9] F. Herfurth,[5] A. Herlert,[10] M. Kowalska,[7] S. Kreim,[2] D. Lunney,[11] V. Manea,[11] E. Minaya Ramirez,[5,12] S. Naimi,[11,13] D. Neidherr,[5] M. Rosenbusch,[14] L. Schweikhard,[14] G. Simpson,[15] F. Wienholtz,[14] R. N. Wolf,[14] and K. Zuber[1]



PHYSICAL REVIEW C **90**, 044307 (2014)

Evolution of nuclear ground-state properties of neutron-deficient isotopes around $Z = 82$ from precision mass measurements

Ch. Böhm,[1,*] Ch. Borgmann,[1,†] G. Audi,[2] D. Beck,[3] K. Blaum,[1] M. Breitenfeldt,[4] R. B. Cakirli,[1,‡] T. E. Cocolios,[5,6] S. Eliseev,[1] S. George,[7,§] F. Herfurth,[3] A. Herlert,[6,‖] M. Kowalska,[6] S. Kreim,[1,6] D. Lunney,[2] V. Manea,[2] E. Minaya Ramirez,[8,3,§] S. Naimi,[2,¶] D. Neidherr,[1,**] M. Rosenbusch,[9] L. Schweikhard,[9] J. Stanja,[10,††] M. Wang,[2] R. N. Wolf,[9,§] and K. Zuber[10]



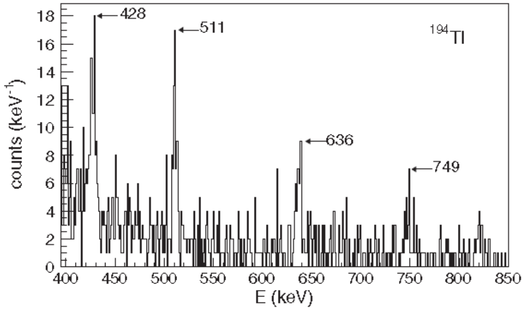


FIG. 3. A β-triggered γ-ray energy spectrum for ^{194}Tl between an HPGe detector and the scintillator at the implantation point after 1.5 h of implantation. The peak at 820 keV does not fit any known transition from the decay of ^{194}Tl.

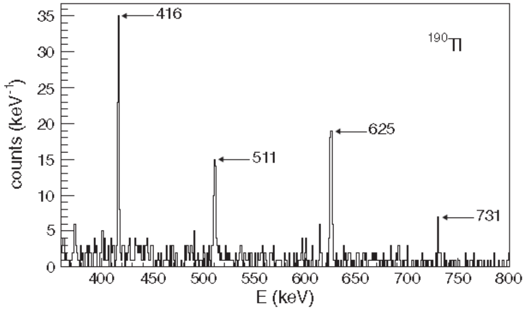
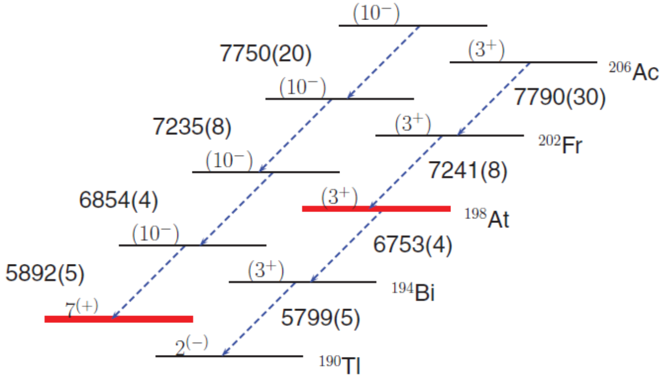
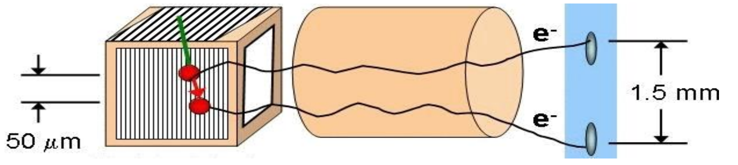


FIG. 4. A β-triggered γ-ray energy spectrum for ^{190}Tl for one HPGe detector at the implantation point after 2×15 min of implantation.



In-trap decay spectroscopy for MLLTRAP

TRAPPED SHORT-LIVED ISOTOPE
EMITS α PARTICLE AND ELECTRONS



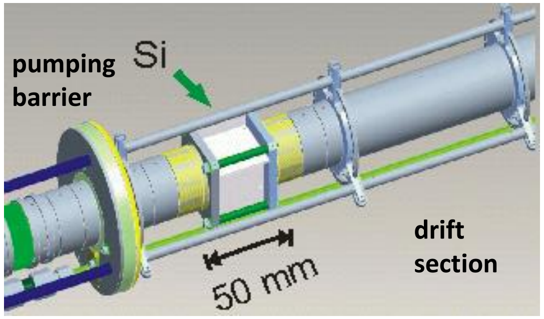
DETECTOR TRAP OF Si-STRIP SENSORS

DRIFT SECTION

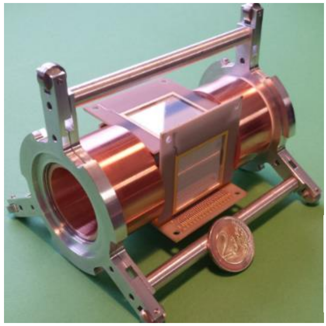
POSITION-SENSITIVE ELECTRON DETECTOR

MAGNETIC FIELD STRENGTH ALONG THE TRAP AXIS

C. Weber et al., Int. J. Mass Spectrom. 349-350, 270 (2013)
C. Weber et al., Nucl. Instr. Meth. B 317, 532 (2013)



Conceptual layout



Detector trap

- ‘detector trap’: α-detectors act as trap electrodes
- customized α detectors were developed and characterized for the cryogenic and UHV-conditions (single-sided Si-strip detector, active area 30x30 mm², 30 strips, α-energy resolution ~ 20 keV)

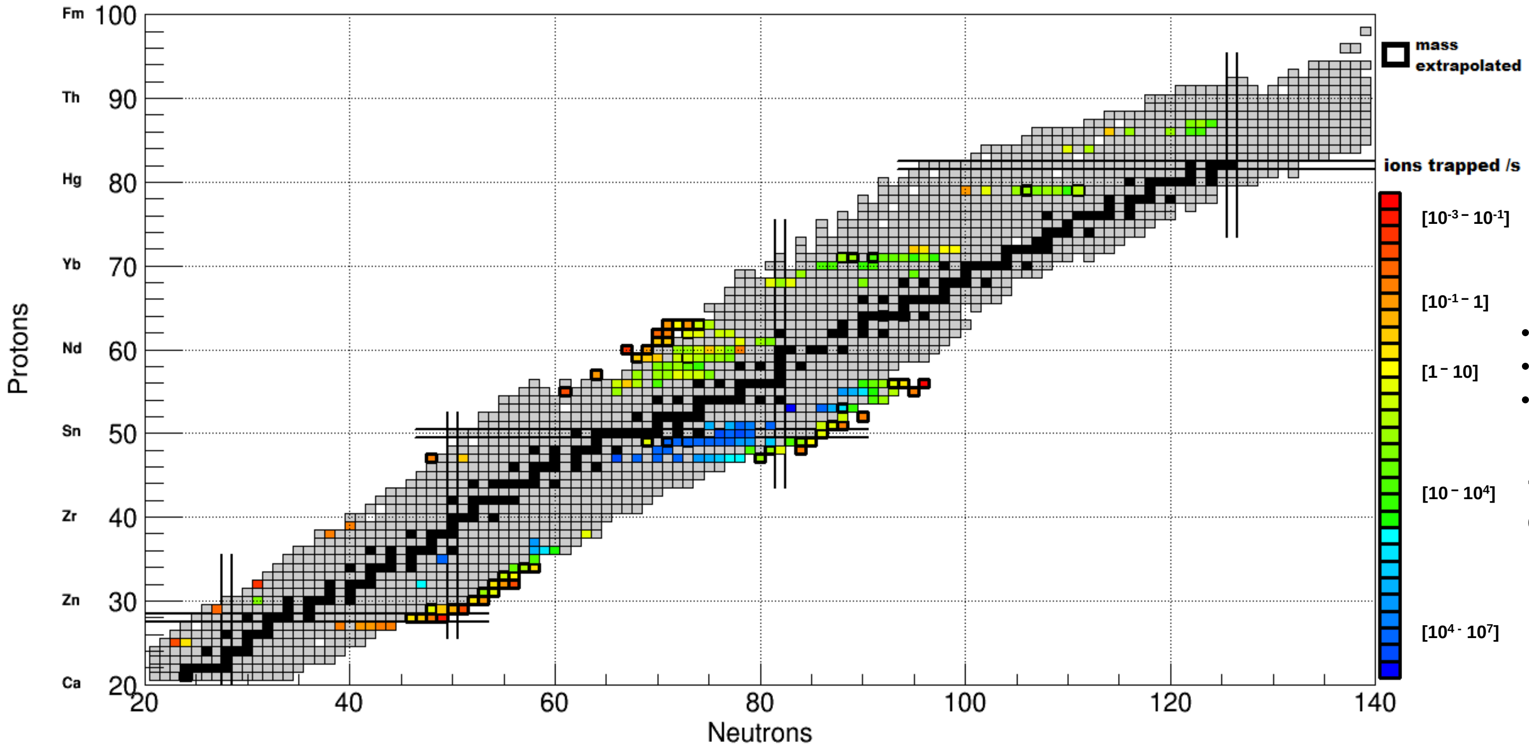
Advantages:

- Decay experiments with carrier-free particles stored in a Penning trap enable studies on ideal ion samples.
- The improved energy resolution can be exploited for high-resolution α- and electron-decay spectroscopy.

Physics Goals :

- From lifetime measurements of the first excited 2^+ states in heavy nuclei, nuclear quadrupole moments Q_0 can be derived
- Similar experiments on 0^+ states allow for a determination of E0 decay strengths r^2 (E0)
- Shape coexistence of 0^+ configurations as present in mid-shell regions around magic proton numbers

High-precision mass measurements at ALTO

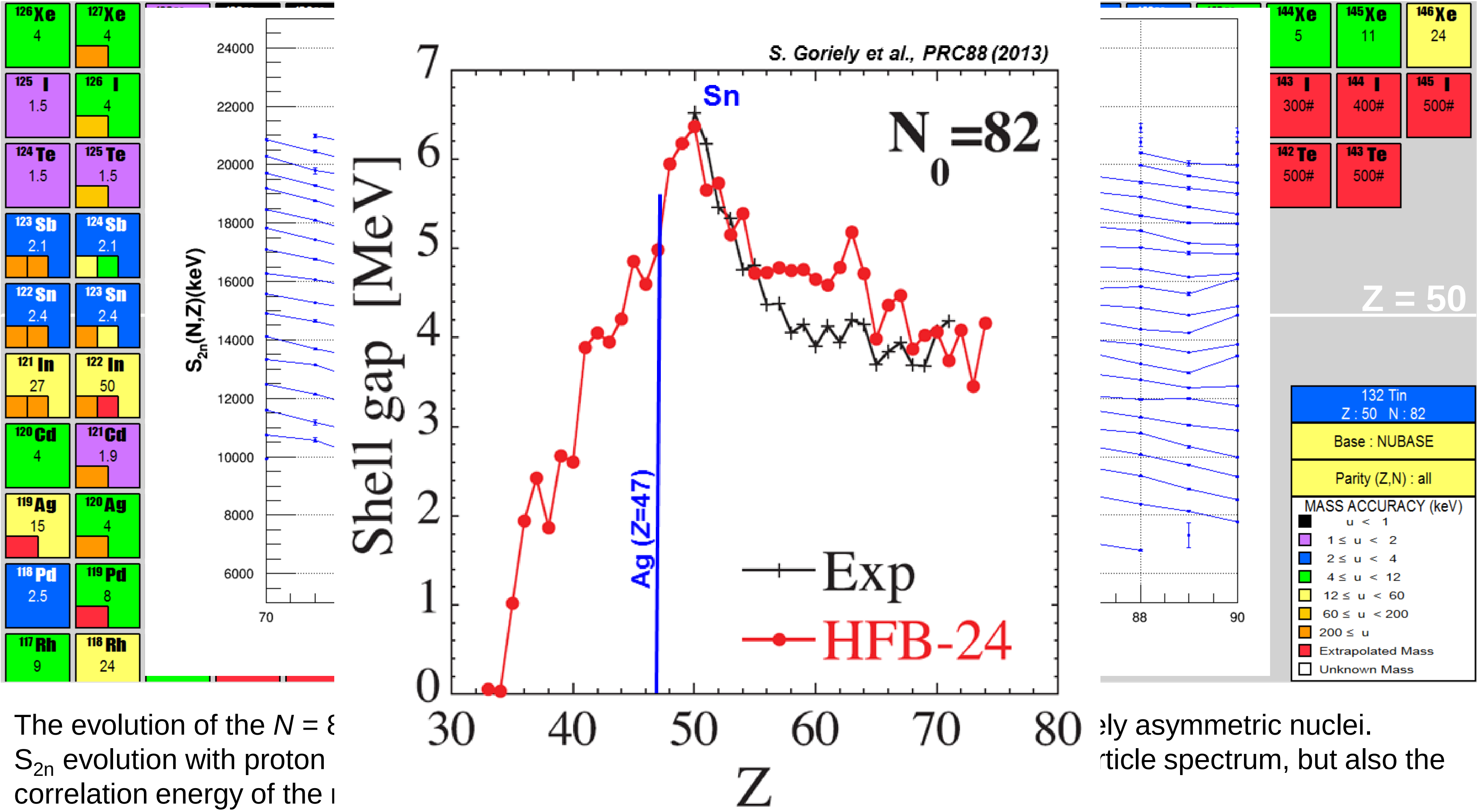


- δm > 10 keV
- $T_{1/2}$ > 80 ms
- Trapped ions in 10h > 100

+ Fusion evaporation cases

- High-precision mass measurements in the region of the magic numbers 50 and 82 are of high interest for nuclear astrophysics (r and rp process)
- Masses of neutron-rich Ag and In isotopes would allow to investigate a possible weakening of the shell gap for Z < 50 and its impact on the A = 130 r-process abundances

High-precision mass measurements at ALTO



The evolution of the *N* = ely asymmetric nuclei.
S_{2n} evolution with proton rticle spectrum, but also the
correlation energy of the

Ground-state correlations allowed → lower the two-neutron gap with respect to the spherical shell gap and upon approaching the magic Z = 50 the reduction of collectivity gives it an apparent enhancement. With further reduction of the spherical gap for Z < 50, ground-state collectivity is predicted to determine a quenching of the two-neutron shell gap towards Z = 40.

Outline

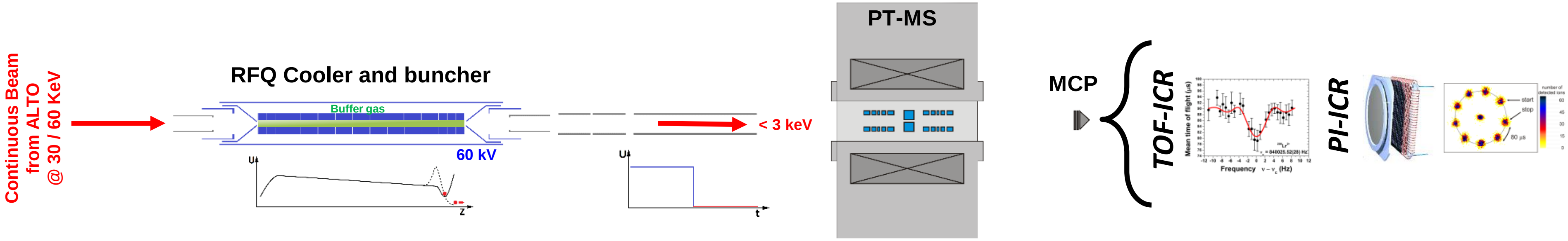
I. MLLTRAP project

II. Penning trap mass spectrometers

III. Status of MLLTRAP@ALTO

MLLTRAP@ALTO

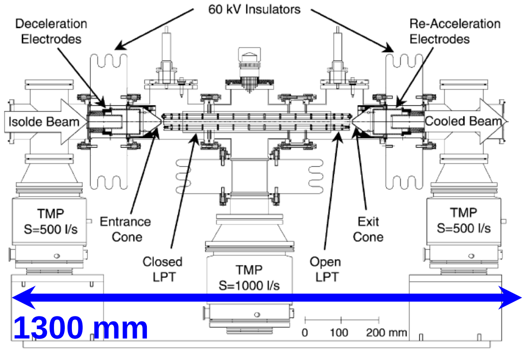
Paul trap



RFQ Design →COLETTE

$2r_0$ = 14 mm, 15 segments

COLETTE : RFQ cooler and buncher

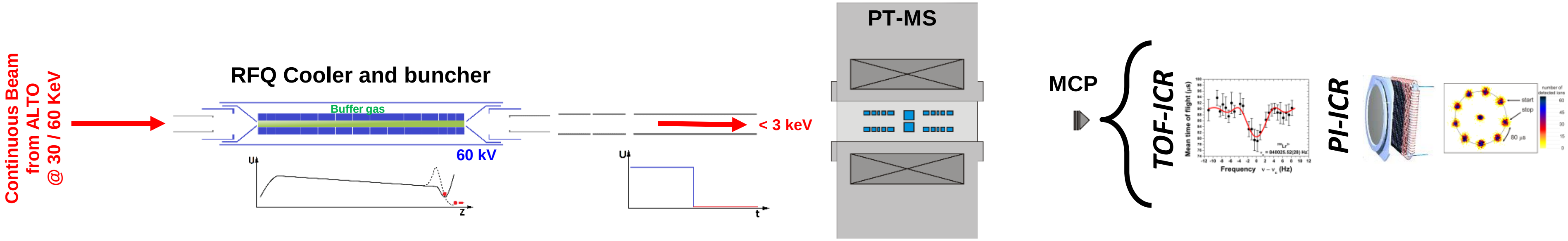


$2r_0$ = 14 mm
L = 40 mm (9 segments - center)
L = 20 mm (6 segments - first and last)

Transverse emittance : ~ 20 π.mm.mrad @ 1 keV
Longitudinal emittance : ~ 10 eV.μs

MLLTRAP@ALTO

Paul trap



Continuous Beam from ALTO @ 30 / 60 KeV

RFQ Cooler and buncher

PT-MS

MCP

TOF-ICR

PI-ICR

RFQ Design →COLETTE

$2r_0$ = 14 mm, 15 segments

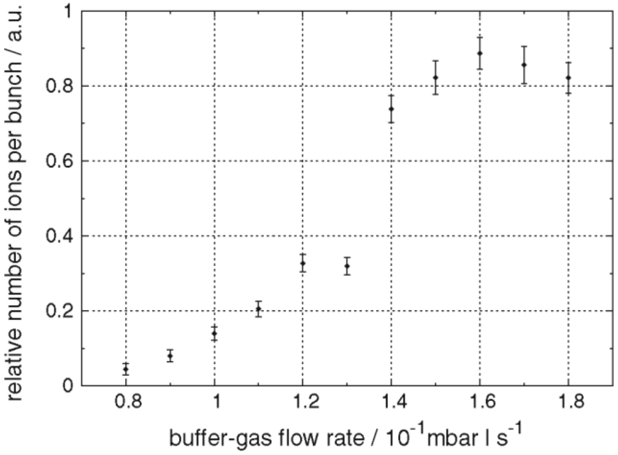
$^{39}K^{+}$ @ 30 keV,

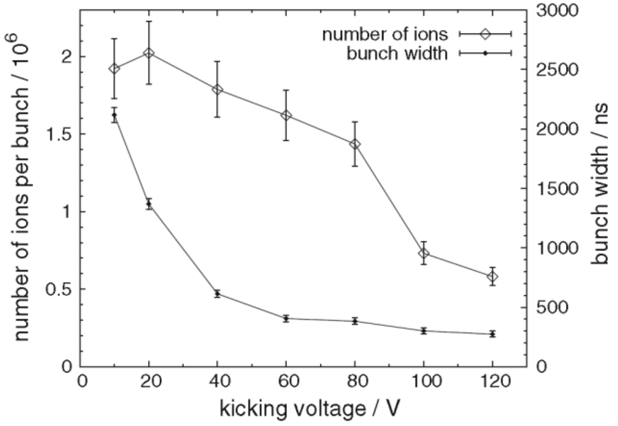
V_{RF} = $85V_{pp}$ F_{RF}= 1 MHz

Bunching efficiency = 54%

COLETTE@TRIGA

T. Beyer et al., Appl. Phys. B 114 (2014) 129

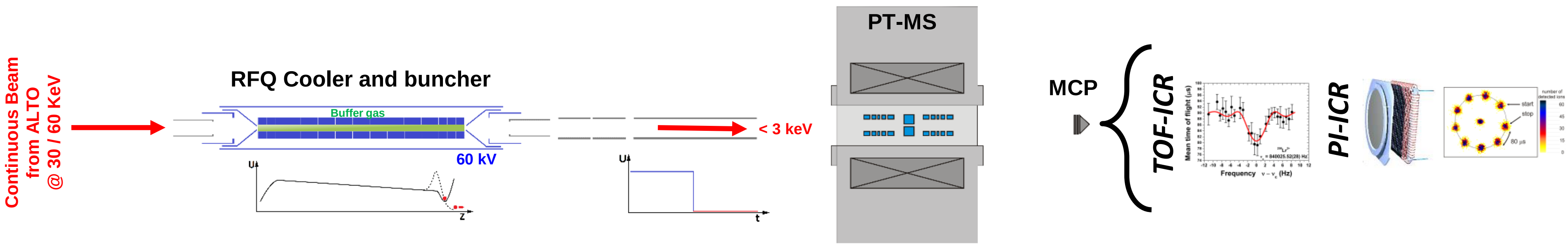




MLLTRAP@ALTO

Paul trap

Penning trap



Continuous Beam from ALTO @ 30 / 60 KeV

RFQ Cooler and buncher

Buffer gas

60 kV

< 3 keV

PT-MS

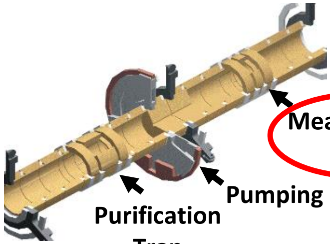
MCP

TOF-ICR

PI-ICR

RFQ Design →COLETTE

$2r_0$ = 14 mm, 15 segments

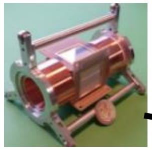


Measurement Trap

Pumping barrier

Purification Trap

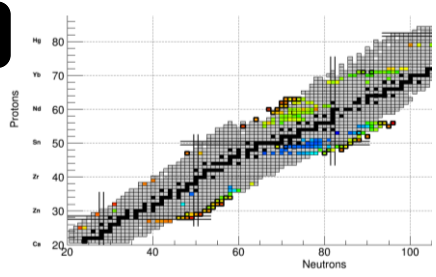
Detector Trap



High-precision mass measurements

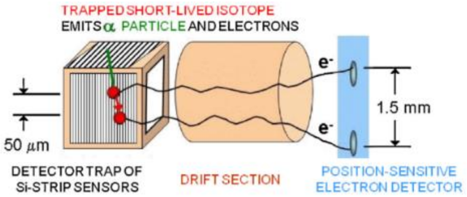
$10^{-10} \leq \delta m/m \leq 10^{-6}$

- Nuclear fine structure
- Astrophysics
- Weak interaction studies
- Atomic physics



Trap-assisted spectroscopy

In-trap decay spectroscopy



Enrique Minaya Ramirez, Serge Franchoo, Marion MacCormick

Araceli Lopez-Martens, Joa Ljungvall, David Lunney, Pierre Chauveau

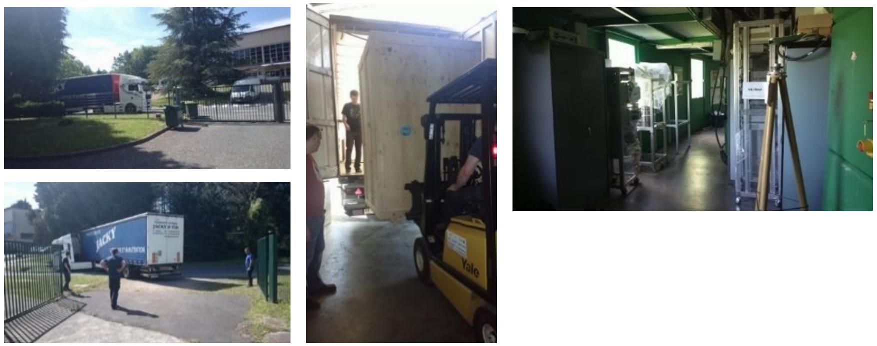
Move of MLLTRAP from MLL to Alto

February – April 2016

July 2016

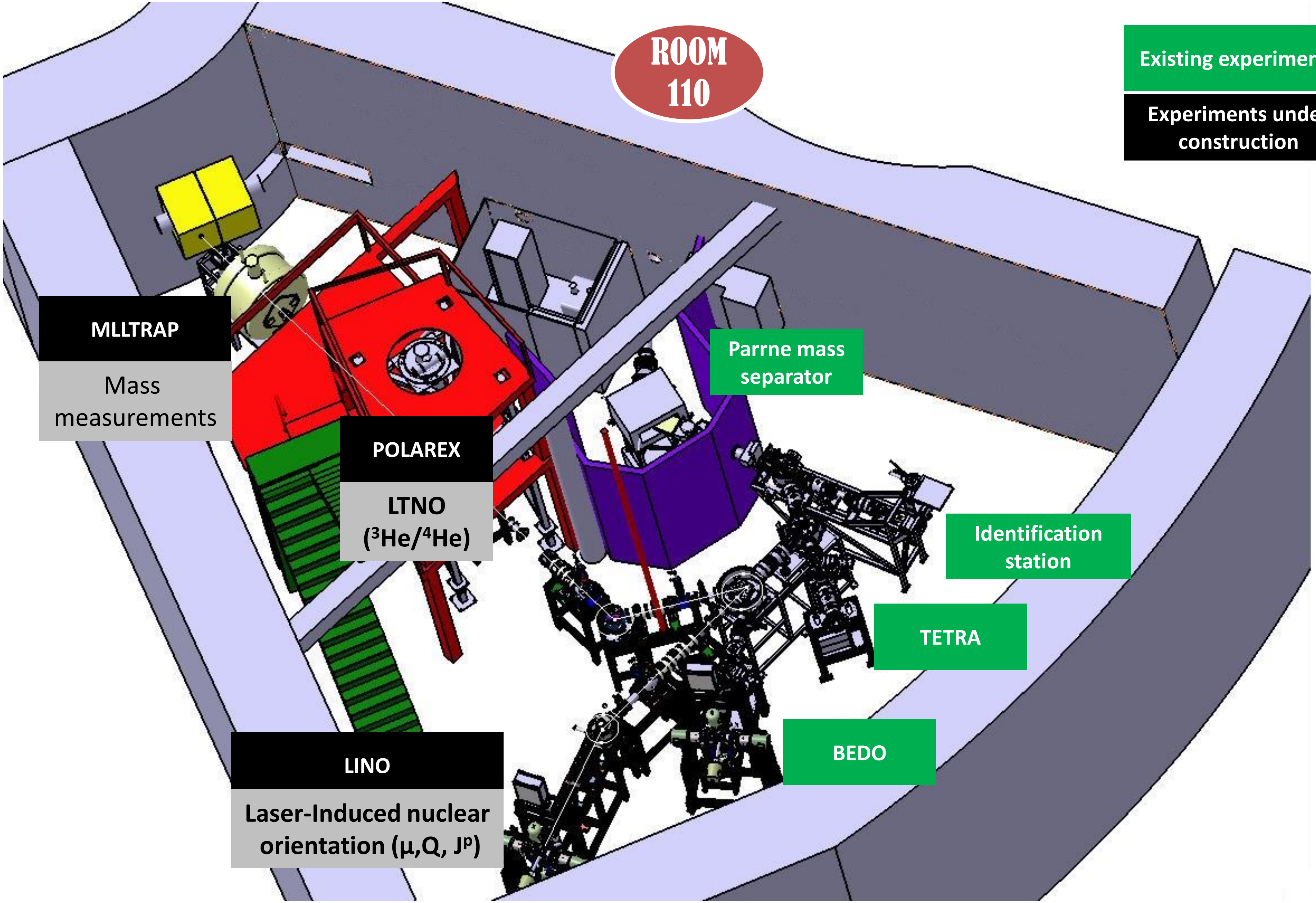
The truck left MLL the ***14th of July 2016***

July 2016



MLLTRAP is now at ALTO

MLLTRAP beam line at ALTO



Existing experiments

Experiments under construction

MLLTRAP

Mass measurements

POLAREX

LTNO (^{3}He/^{4}He)

LINO

Laser-Induced nuclear orientation (µ,Q, J^p)

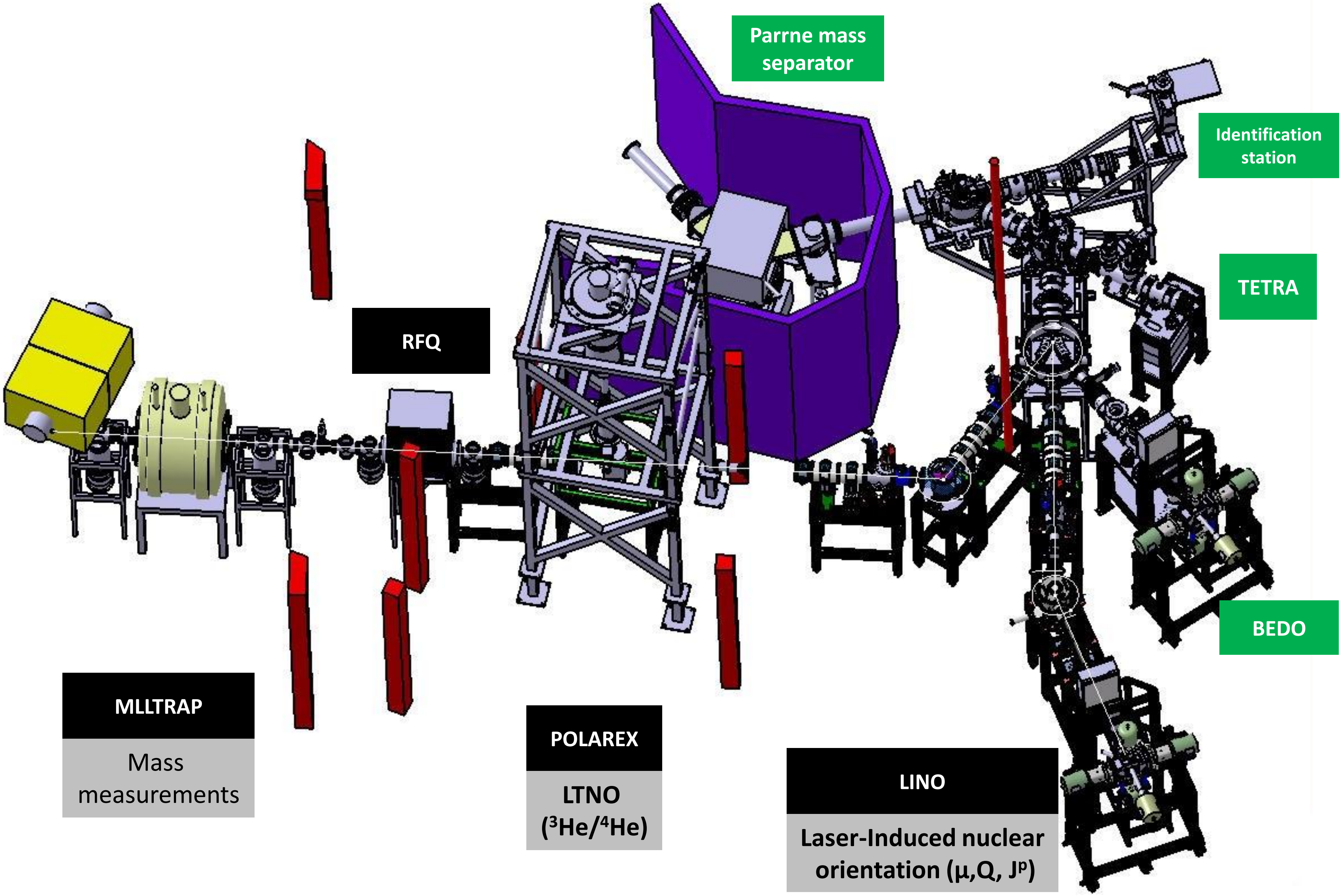
Parrne mass separator

Identification station

TETRA

BEDO

Radioactive beams at ALTO



Parrne mass separator

Identification station

TETRA

BEDO

RFQ

MLLTRAP

Mass measurements

POLAREX

LTNO (^{3}He/^{4}He)

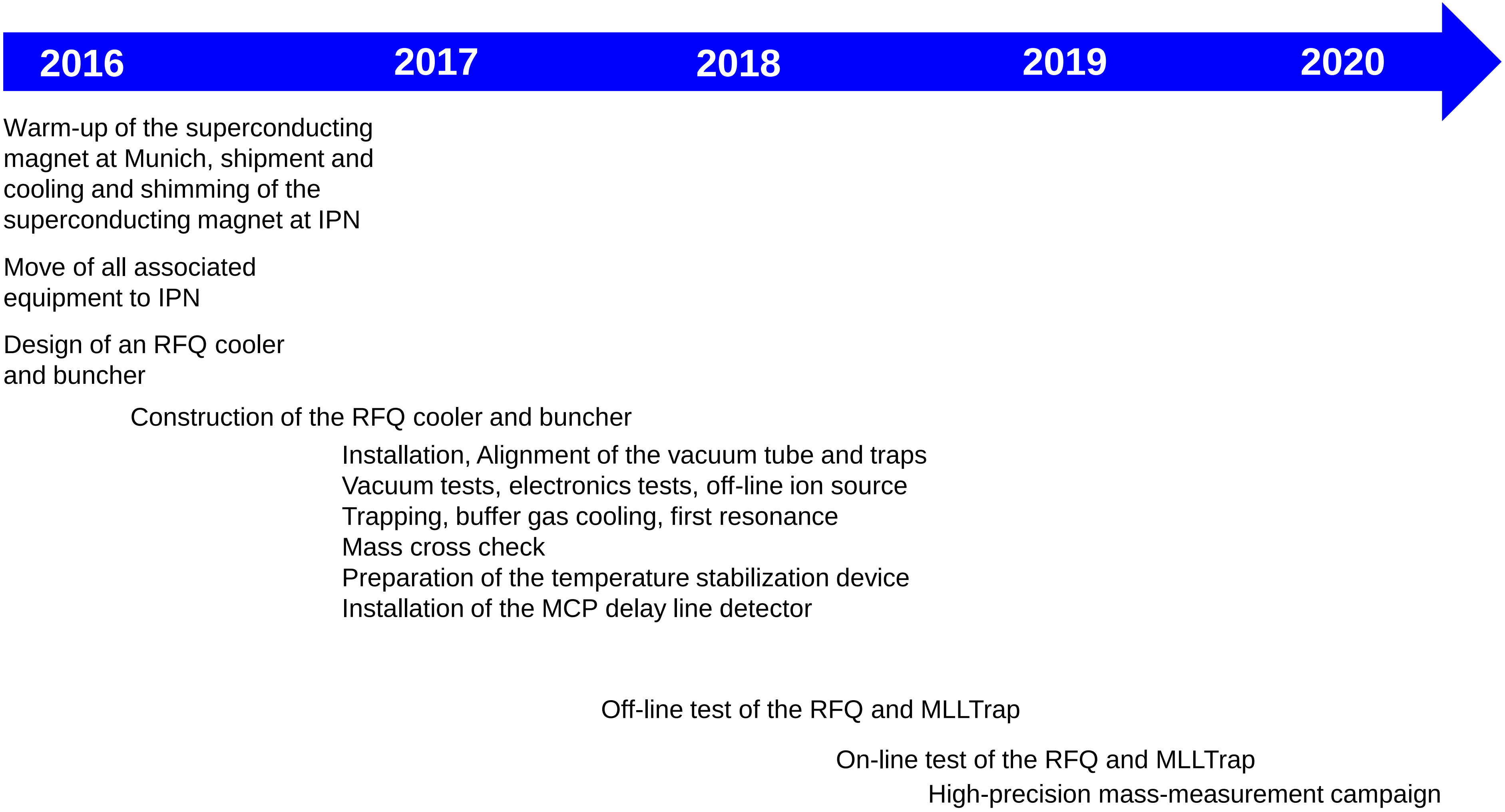
LINO

Laser-Induced nuclear orientation (μ,Q, J^p)

Alignment in Room 110

The radioactive beam for MLLTRAP will be sent with a 59° bender.
The alignment is almost finalized (the area is still being prepared).
The magnet will be energized by an engineer of Agilent in the next months.

Present status of MLLTRAP@ALTO



2016 2017 2018 2019 2020

Warm-up of the superconducting magnet at Munich, shipment and cooling and shimming of the superconducting magnet at IPN

Move of all associated equipment to IPN

Design of an RFQ cooler and buncher

Construction of the RFQ cooler and buncher

Installation, Alignment of the vacuum tube and traps
Vacuum tests, electronics tests, off-line ion source
Trapping, buffer gas cooling, first resonance
Mass cross check
Preparation of the temperature stabilization device
Installation of the MCP delay line detector

Off-line test of the RFQ and MLLTrap

On-line test of the RFQ and MLLTrap

High-precision mass-measurement campaign

Thank you for your attention!