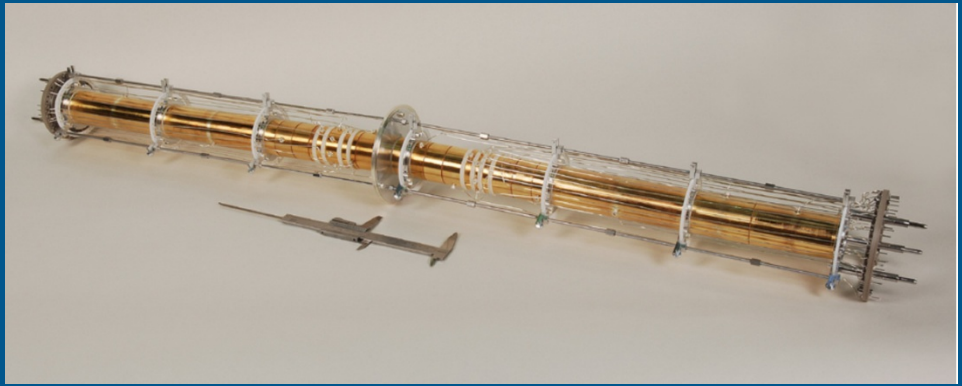
FUSHE Workshop, Weilrod 2012

Ground state properties of the heaviest elements

Lasers spectroscopy and mass measurements

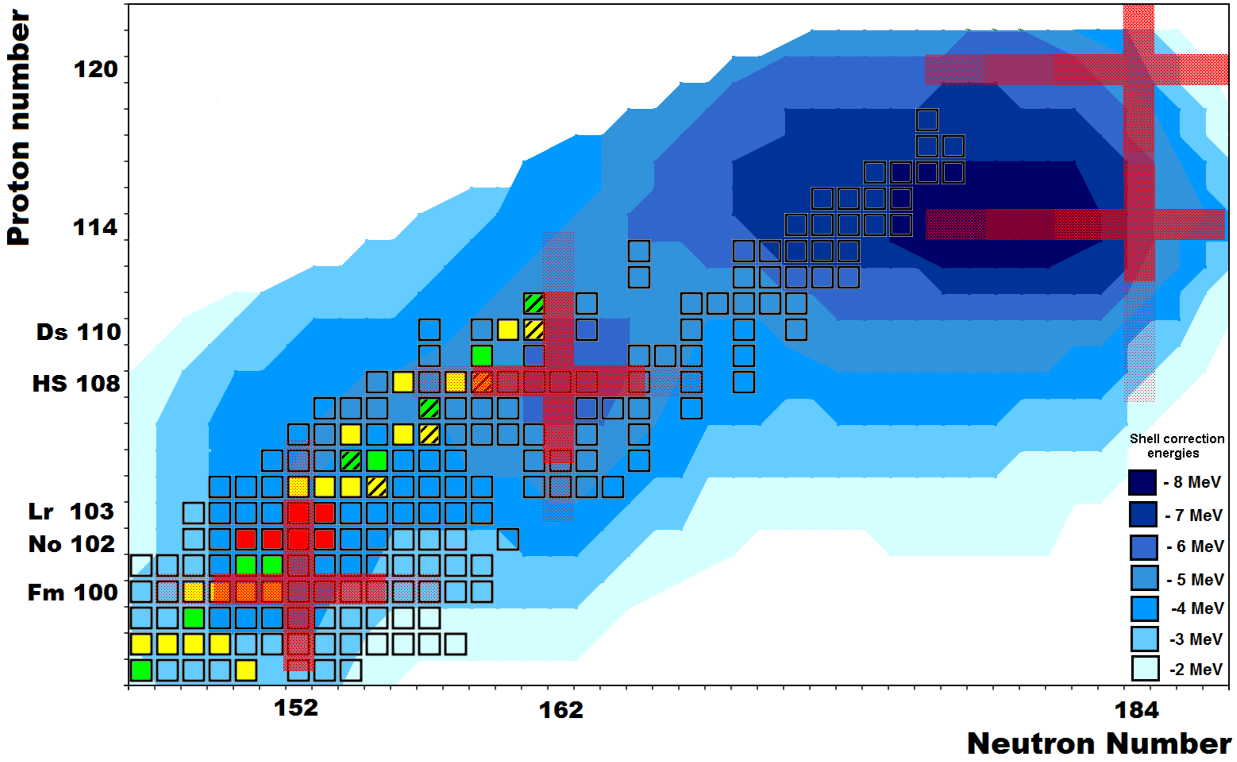


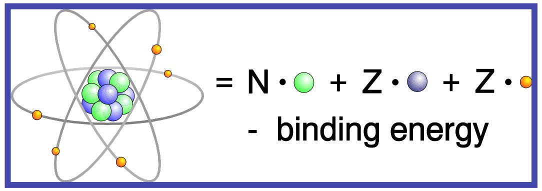
Michael Block, GSI

Outline

- What do we learn from ground state properties
- Techniques for mass measurements of rare isotopes
  - Buffer-gas stopping and beam preparation of rare isotopes
  - Penning traps, Multi-Reflection-ToF mass spectrometers
  - Pushing towards higher precision and higher sensitivity
- Laser spectroscopy of the heaviest elements
  - Laser resonance ionization spectroscopy in gas cells
- New approaches
- Summary and Conclusions

Importance of Masses for Z > 100

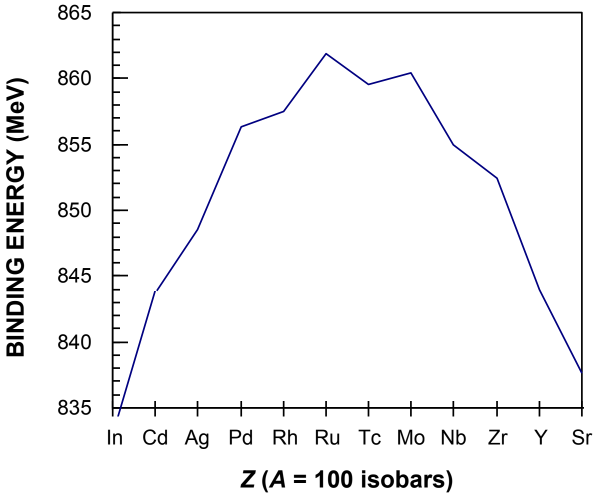




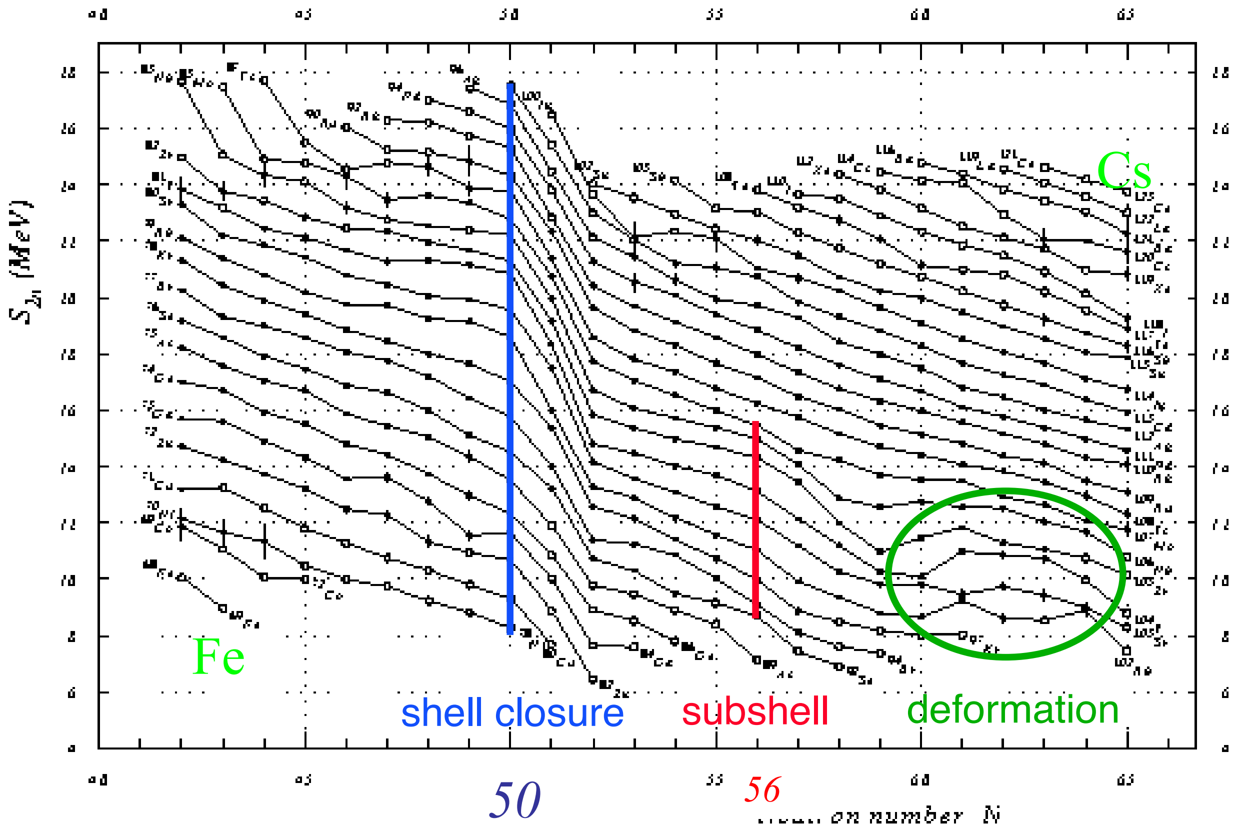
- masses provide absolute nuclear binding energies
- masses allow studies of the shell structure evolution
- high-precision mass measurements provide anchor points to fix decay chains
- benchmark nuclear models

Masses and Nuclear Structure

total
binding energies



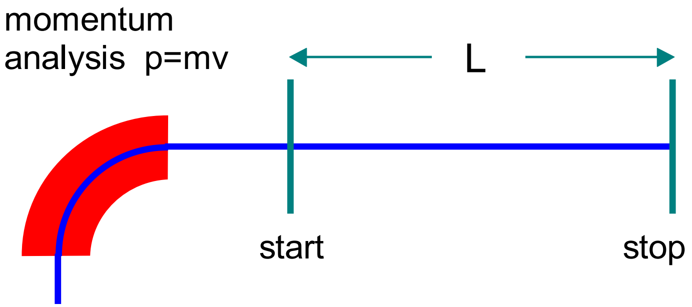
two-neutron
separation energies



Systematic study of masses –indicator of new nuclear structure effects

Tools for mass measurements on rare isotopes

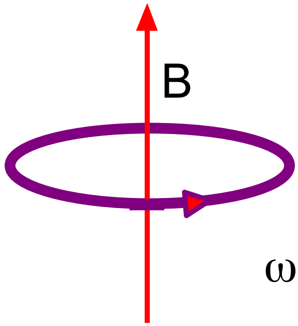
Time-of-flight spectrometry



single turn: SPEG/GANIL, S800/NSCL

multi turn: ESR/GSI, CSR/Lanzhou, RIBF ring
electrostatic MR-ToF

Frequency measurements



$\omega_c = q/m\ B$

storage rings	ESR/GSI, CSR/Lanzhou, RIBF rings
Penning traps	LEBIT/NSCL, ISOLTRAP/ISOLDE JYFLTRAP/JYFL, CPT/ANL SHIPTRAP/GSI, TITAN/TRIUMF, TRIGATRAP/ Mainz, …

β-decays: masses from long-decay chains MUST be replaced by direct measurements

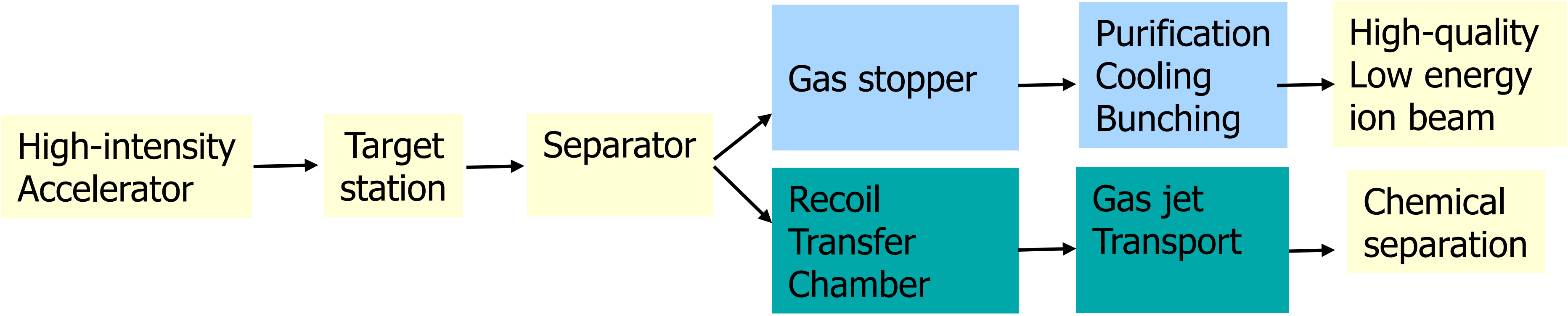
Proton and alpha decays: needed for fast proton emitters, super heavy elements

Reactions: (p,d) for masses (+excited states) of unbound nuclei beyond p-dripline

Courtesy G. Bollen

Slowing down rare isotopes with Gas catchers

prepare SHE for experiments at low-energy: fast, universal, efficient


High-intensity Accelerator

Target station

Separator

Gas stopper

Purification Cooling Bunching

High-quality Low energy ion beam

Recoil Transfer Chamber

Gas jet Transport

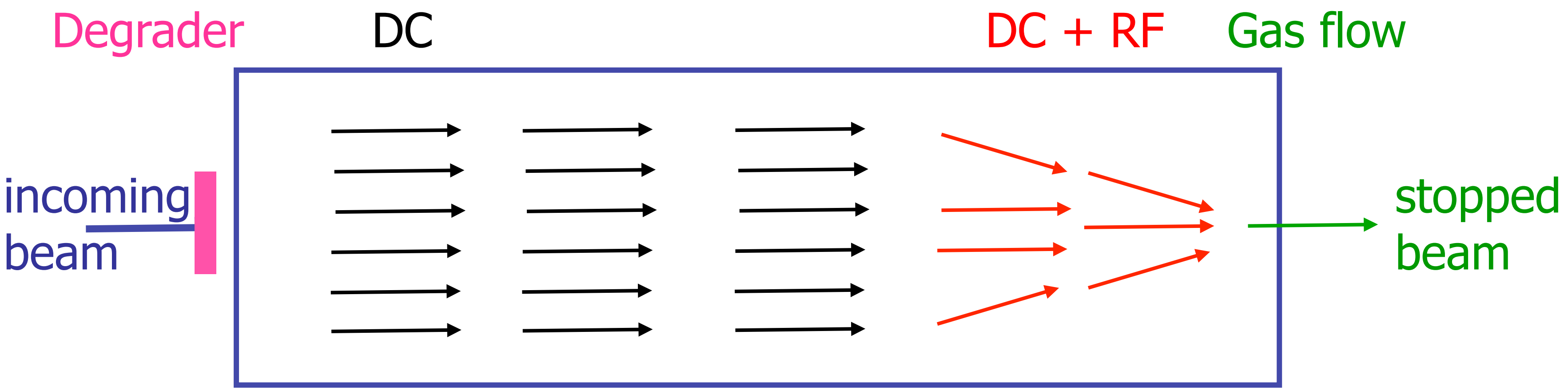
Chemical separation

High quality low-energy beams: low emittance, low energy spread, purified

- High-precision mass measurements
- Laser spectroscopy
- Trap-assisted decay studies
- Chemistry

Successfully employed at CPT/Argonne, SHIPTRAP/GSI, IGISOL/JYFL, LISOL/Louvain-la-Neuve, and for fragment beams at NSCL/MSU, SLOWRI/RIKEN, first tests at FRS/GSI

Schematic of Gas Stopper



Degrader

DC

DC + RF

Gas flow

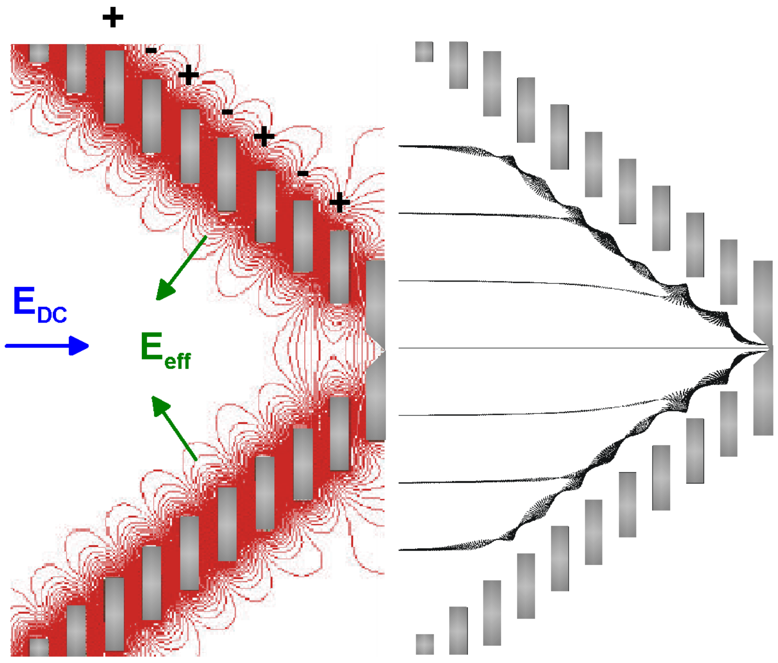
incoming beam

stopped beam

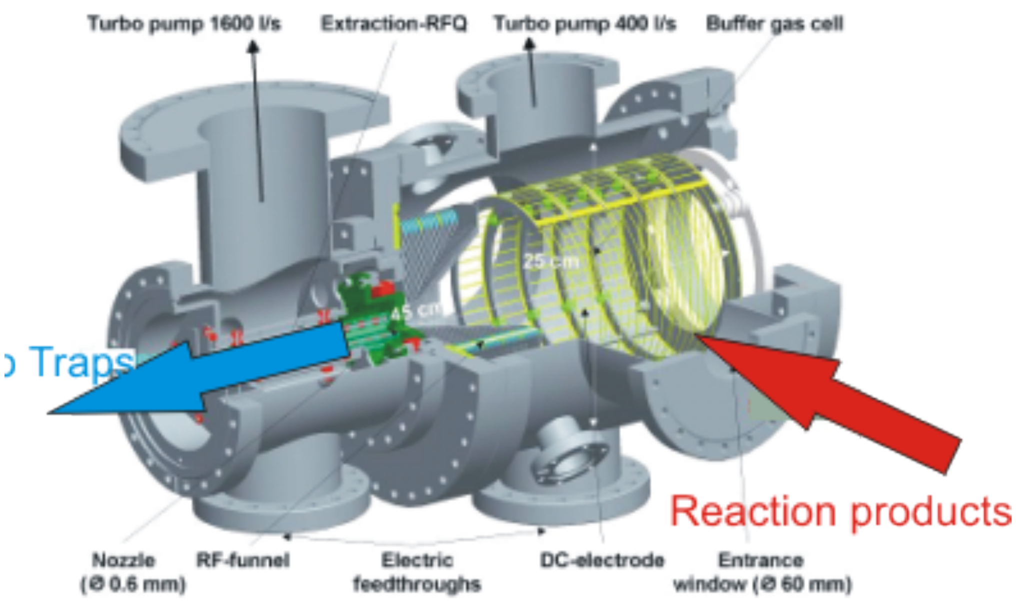
- stopping in high-purity buffer gas
- DC drag field for fast extraction
- RF funnel for efficient transport
- extraction through nozzle

Present systems:

Overall efficiency ≈10%



SHIPTRAP buffer gas stopping cell



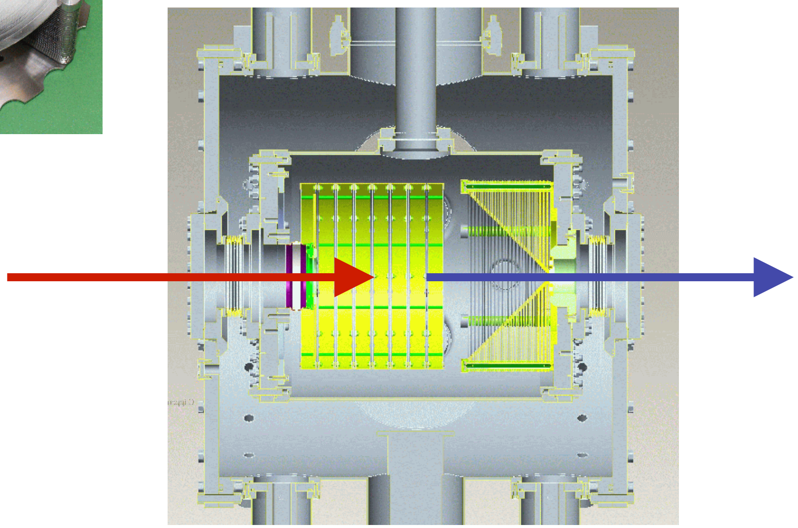
- stopping in ultrahigh-purity helium at 50-100 mbar
- extraction electrode system with DC cage and RF funnel
- extraction time 5-10 ms
- overall efficiency about 10%

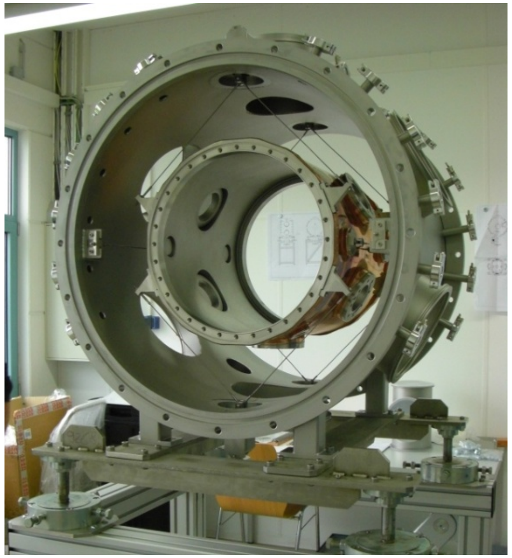
Difficulty: Beam is injected from the side

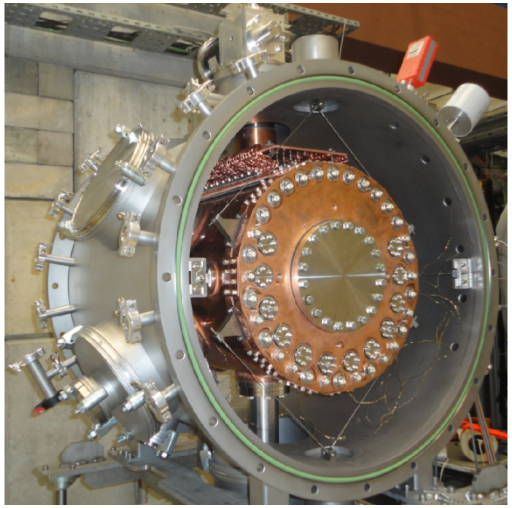
- ➢ matching of stopping distribution to extraction region
- ➢ *dead zone* between window and electrode structure

J.B. Neumayr *et al.*, Nucl. Instr. Meth. B 244 (2006) 489.
S. Eliseev *et al.*, Nucl. Instr. Meth. B 258 (2007) 479.

Future: SHIPTRAP cryogenic gas stopper







outer chamber ≈ 650 mm long / 500 mm in diameter

Gain in overall efficiency factor: 3-5

S. Eliseev et al., Nucl. Instr. and Meth. B 266 (2008) 4475–4477

Max-Planck-Institut für Kernphysik

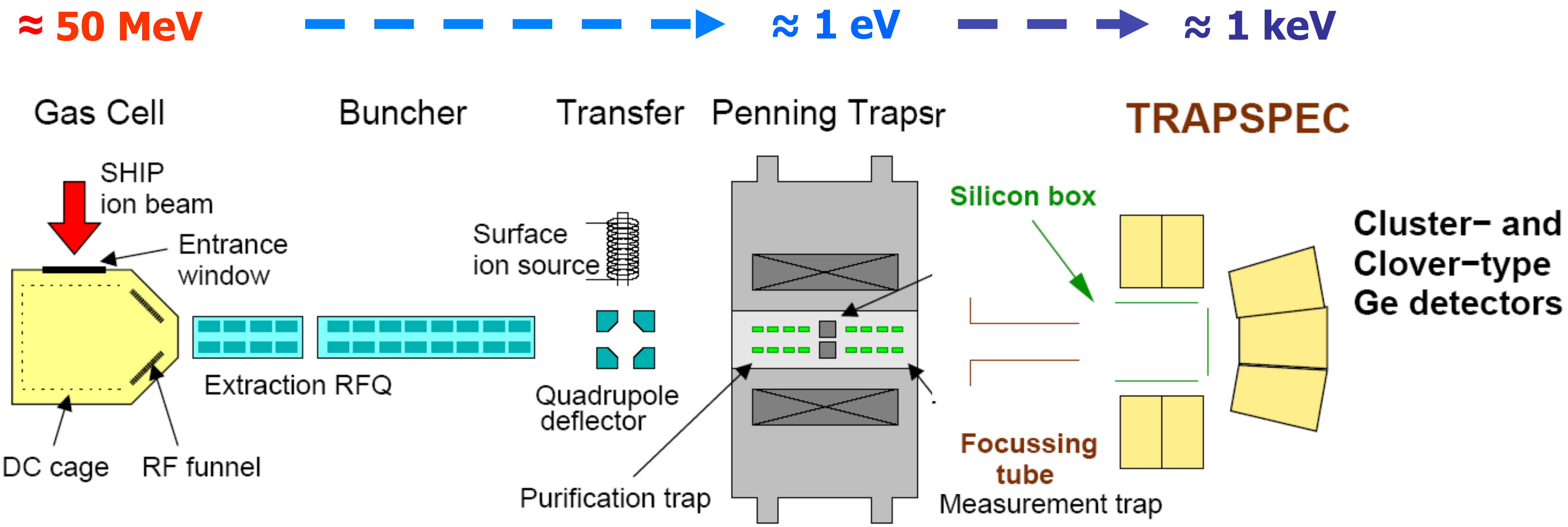
LMU

S. Eliseev, C Droese,
M. Laatiaoui, E. Minaya et al.

HELMHOLTZ ASSOCIATION

GSI

SHIPTRAP Setup



≈ 50 MeV → ≈ 1 eV → ≈ 1 keV

Gas Cell

Buncher

Transfer

Penning Trapsr

TRAPSPEC

SHIP
ion beam

Entrance
window

Extraction RFQ

DC cage

RF funnel

Surface
ion source

Quadrupole
deflector

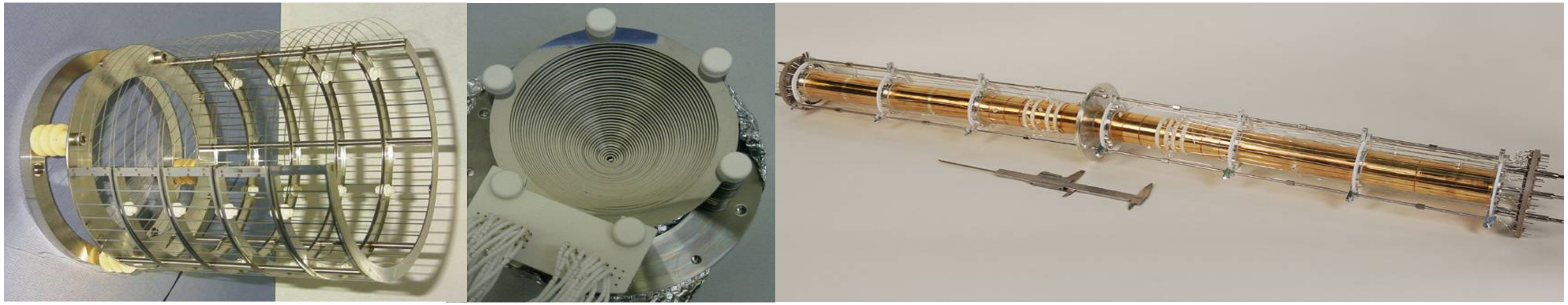
Purification trap

Silicon box

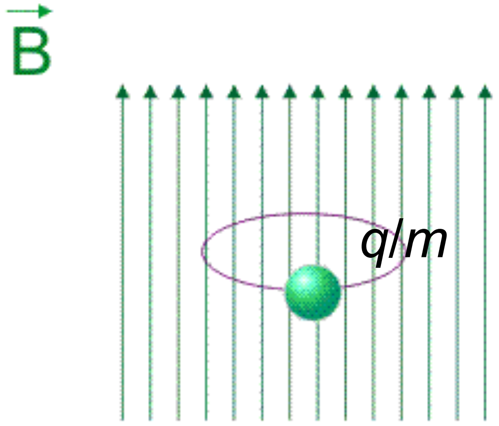
**Focussing
tube**

Measurement trap

**Cluster- and
Clover-type
Ge detectors**

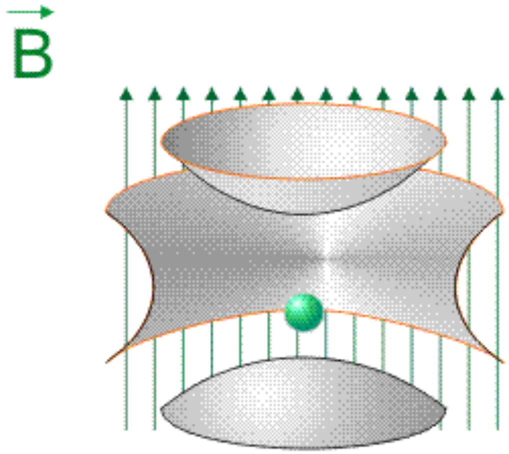


Principle of Penning Traps



PENNING trap

- Strong homogeneous magnetic field
- Weak electric 3D quadrupole field

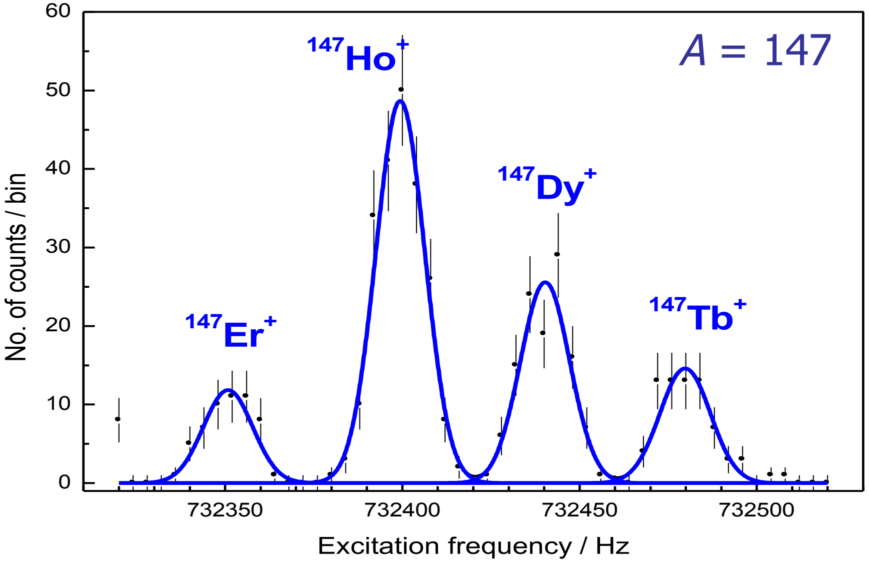


Cyclotron frequency: $$f_c = \frac{1}{2\pi}\cdot\frac{q}{m}\cdot B$$

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

L. S. Brown and G. Gabrielse, Rev. Mod. Phys. 58 (1986) 233
G. Gabrielse, Int. J. Mass Spectr. 279, (2009) 107

SHIPTRAP Performance

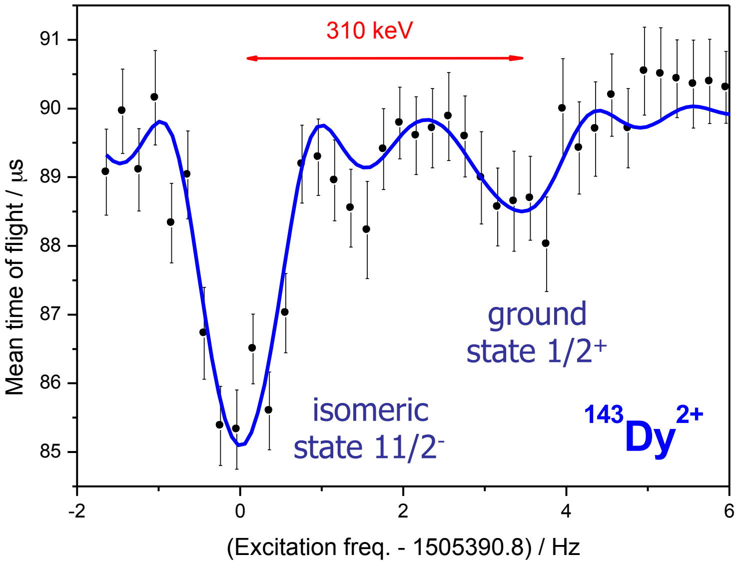


Mass resolving power of

m/δm ≈ 100,000

in purification trap:

⇒ separation of isobars



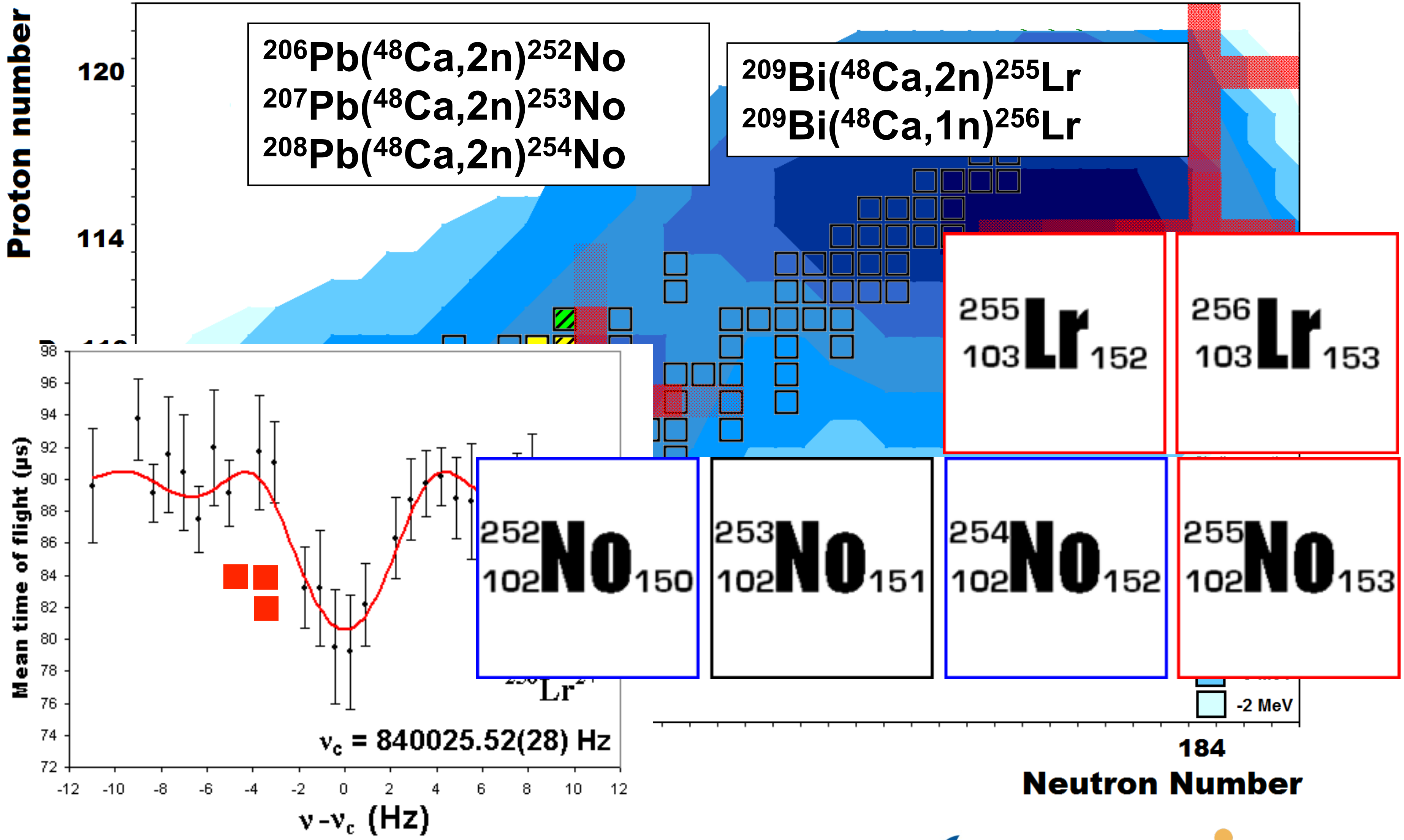
Mass resolving power of

m/δm ≈ 1,000,000

in measurement trap:

⇒ separation of isomers

Direct mass measurements with SHIPTRAP



$^{206}\mathrm{Pb}(^{48}\mathrm{Ca},2n)^{252}\mathrm{No}$
$^{207}\mathrm{Pb}(^{48}\mathrm{Ca},2n)^{253}\mathrm{No}$
$^{208}\mathrm{Pb}(^{48}\mathrm{Ca},2n)^{254}\mathrm{No}$

$^{209}\mathrm{Bi}(^{48}\mathrm{Ca},2n)^{255}\mathrm{Lr}$
$^{209}\mathrm{Bi}(^{48}\mathrm{Ca},1n)^{256}\mathrm{Lr}$

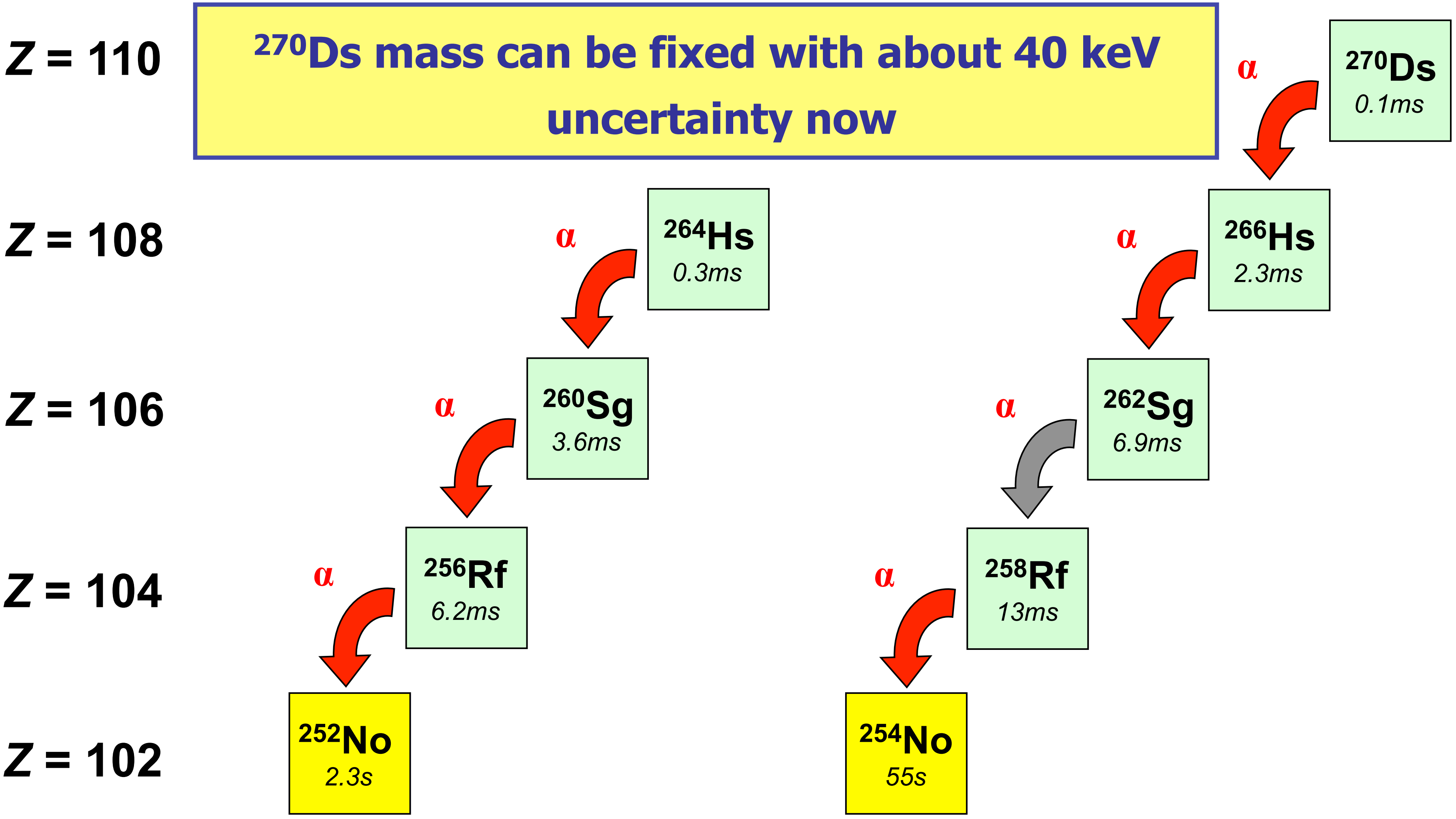
$^{255}_{103}\mathrm{Lr}_{152}$ $^{256}_{103}\mathrm{Lr}_{153}$

$^{252}_{102}\mathrm{No}_{150}$ $^{253}_{102}\mathrm{No}_{151}$ $^{254}_{102}\mathrm{No}_{152}$ $^{255}_{102}\mathrm{No}_{153}$

ν_c = 840025.52(28) Hz

Follow up α-decay chains

^{270}Ds mass can be fixed with about 40 keV uncertainty now



Z = 110

Z = 108

Z = 106

Z = 104

Z = 102

^{270}Ds
0.1ms

α

^{266}Hs
2.3ms

α

^{262}Sg
6.9ms

α

^{258}Rf
13ms

α

^{254}No
55s

^{264}Hs
0.3ms

α

^{260}Sg
3.6ms

α

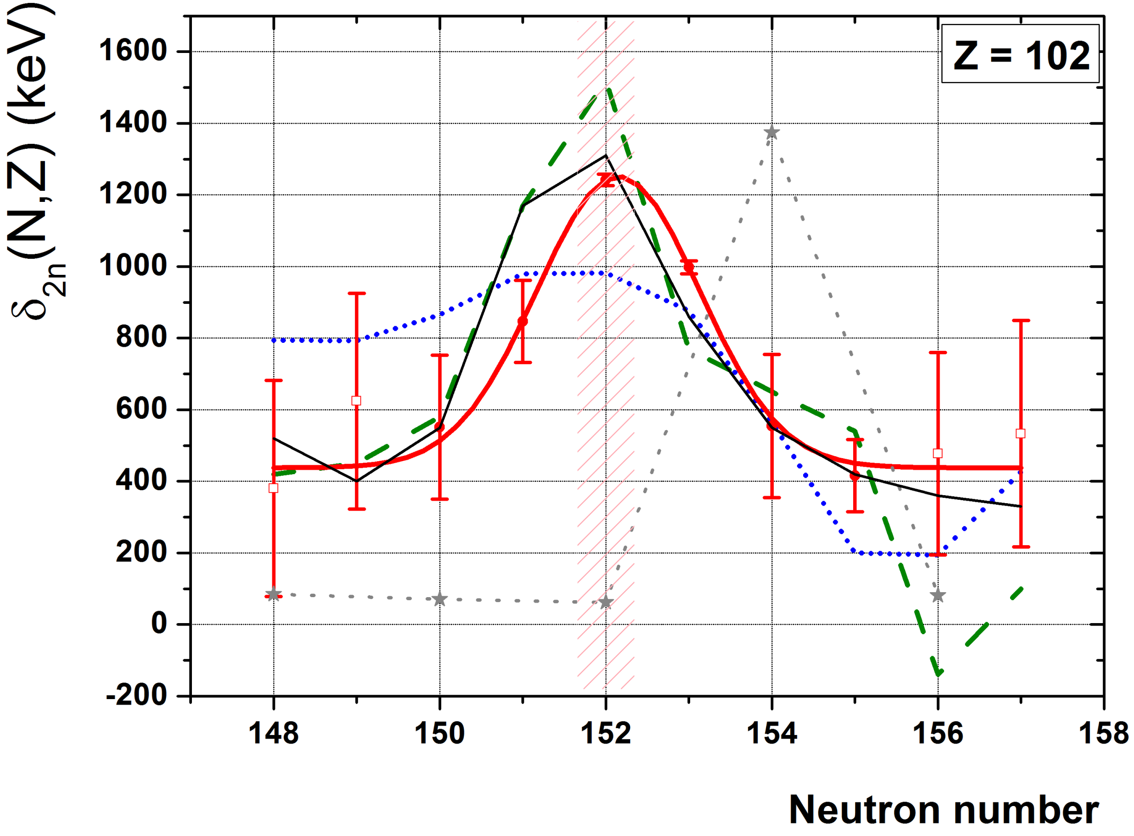
^{256}Rf
6.2ms

α

^{252}No
2.3s

Mapping the shell gap at N=152

$\delta_{2n}(N,Z) = 2B(N,Z) - B(N-2,Z) - B(N+2,Z)$



Experiment

Moeller et al.

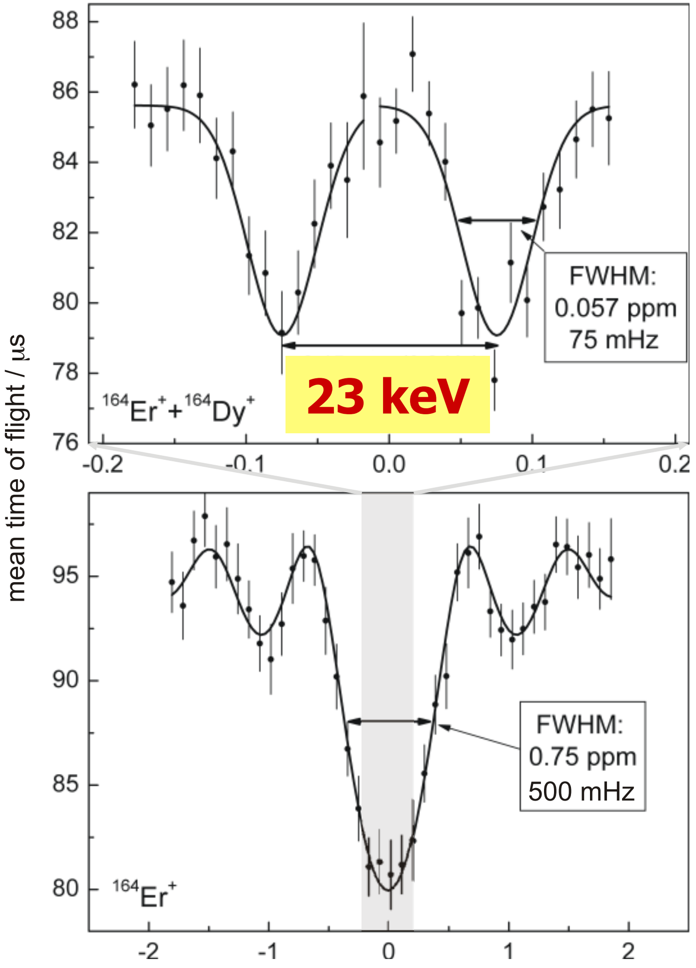
Sobiczewski et al.

SkM*

Typel et al.

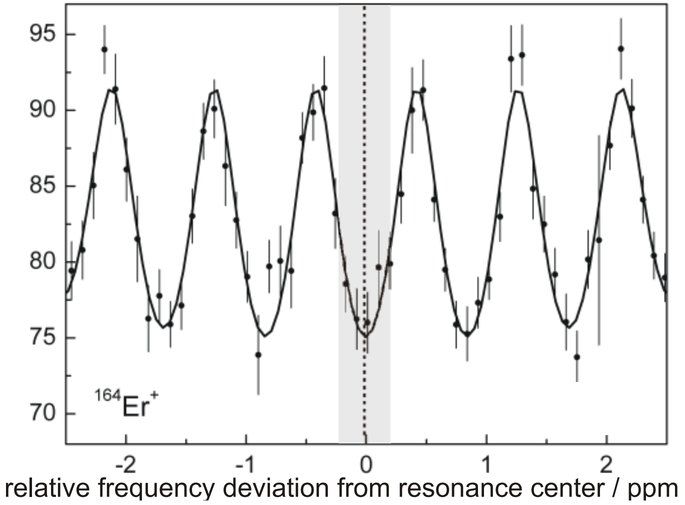
Enrique Minaya Ramirez et al.

Improving the resolving power



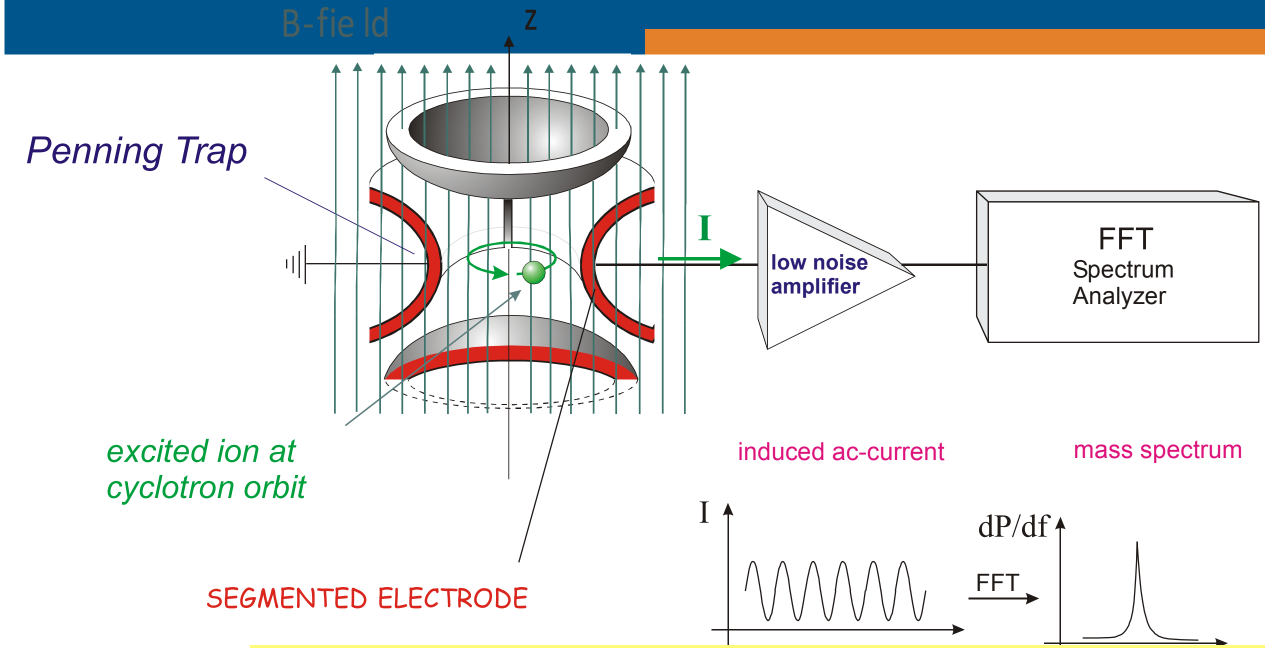
New excitation schemes result in higher resolving power for the same measurement time.

Gain factor: 10 in resolving power



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

Future: single ion sensitivity



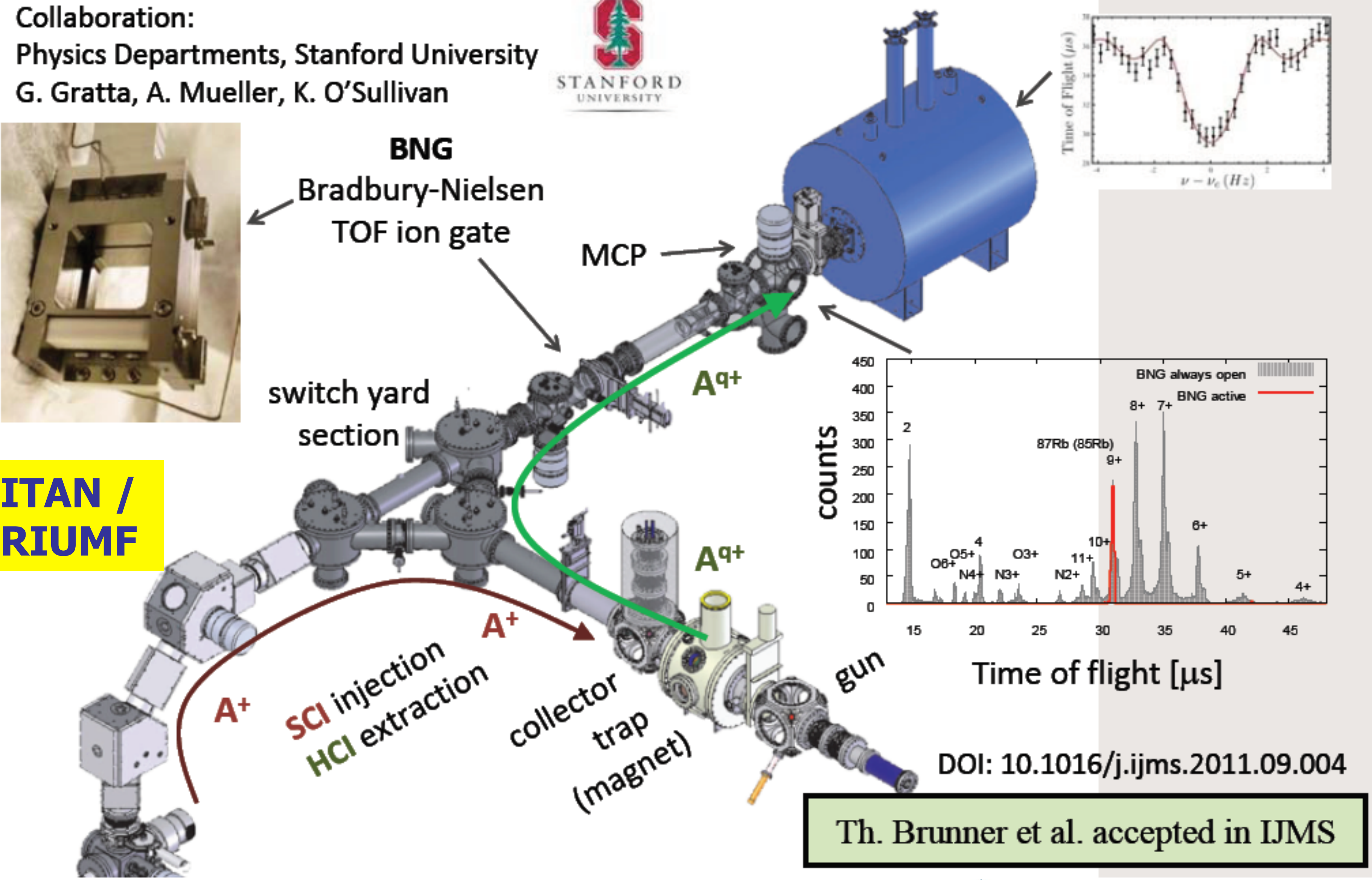
in collaboration with TRIGA-TRAP

$$\frac{S}{N} \propto \frac{r_{ion}}{D} \cdot q \cdot \sqrt{\frac{\nu}{\Delta\nu}} \cdot \sqrt{\frac{Q}{kT \cdot C}}$$

Gain factor: 1 detected ion instead of 30 for a mass value

Going to higher charge states

Collaboration:
Physics Departments, Stanford University
G. Gratta, A. Mueller, K. O'Sullivan



TITAN / TRIUMF

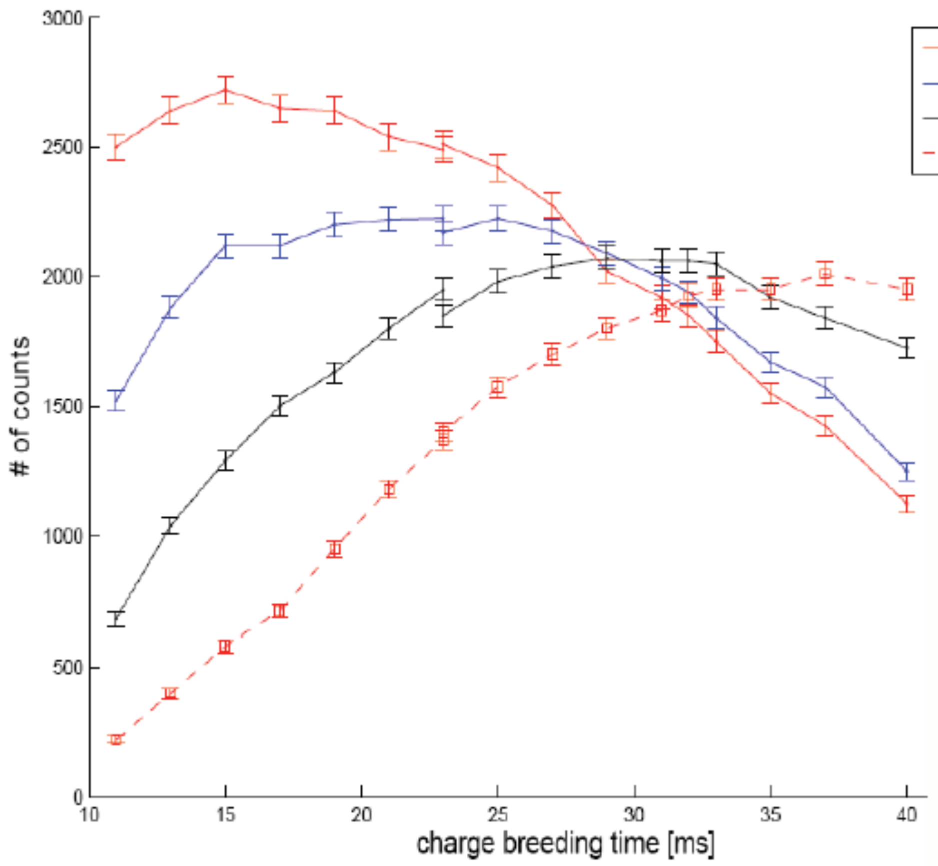
DOI: 10.1016/j.ijms.2011.09.004

Th. Brunner et al. accepted in IJMS

Courtesy J. Dilling

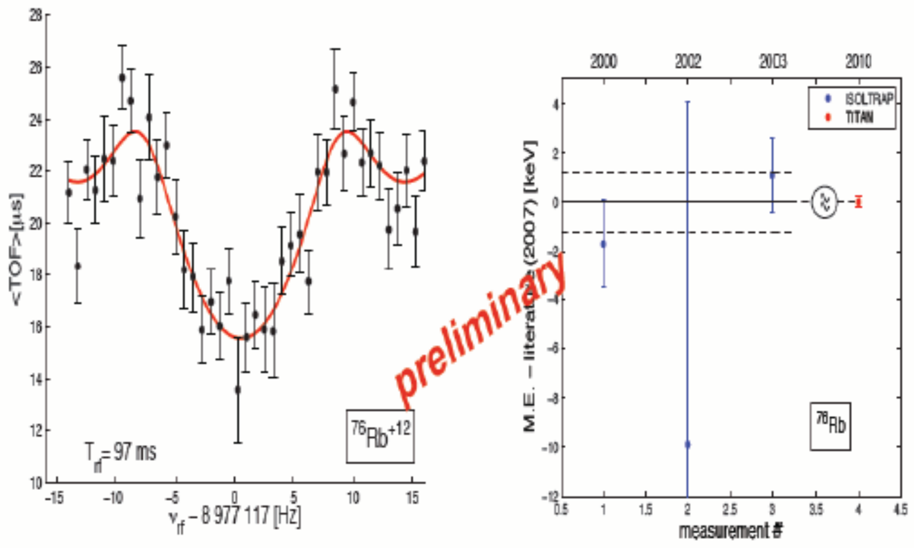
Going to higher charge states

Charge state distribution in the EBIT



First mass measurement
of charge bred ions
in an on-line PT system

**TITAN /
TRIUMF**

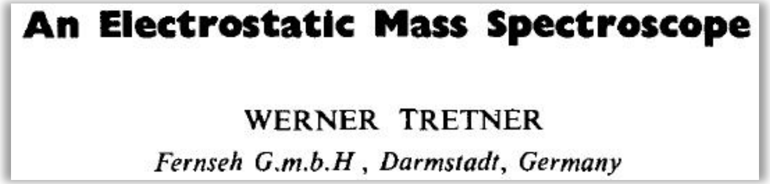


S. Ettenauer et al., Phys. Rev. Lett. **107**, 272501 (2011)

Courtesy J. Dilling

Multi-Reflection Time-of-Flight Mass Analyzers

“Farvitron” in 1959

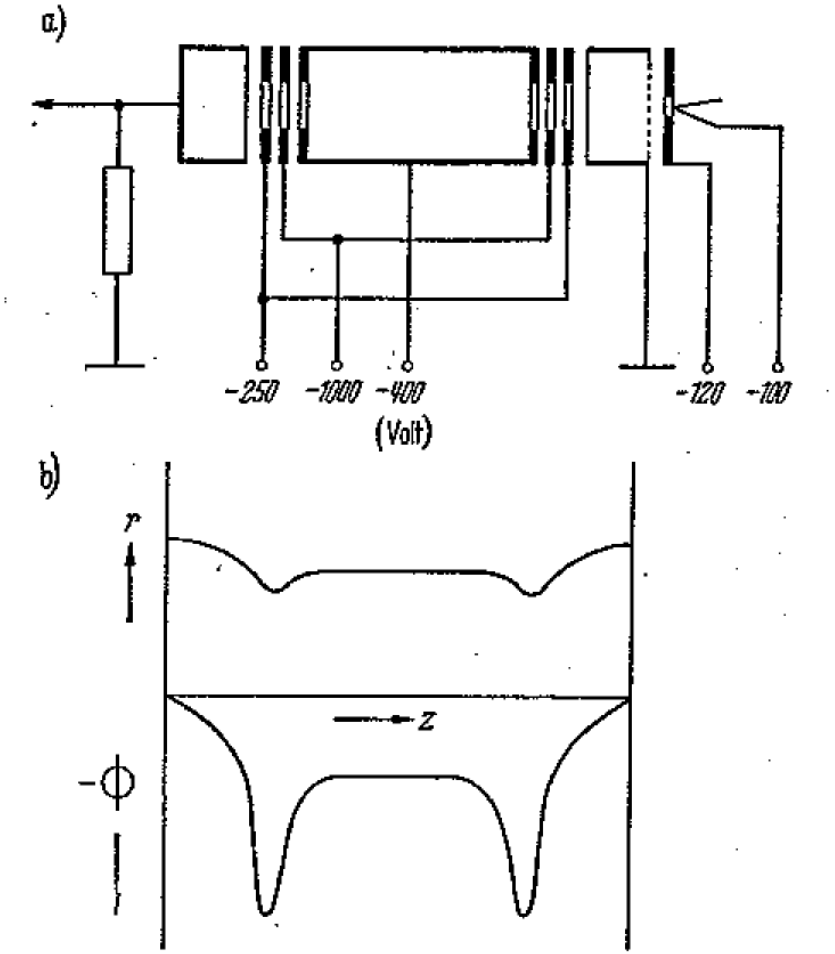


An Electrostatic Mass Spectroscope

WERNER TRETNER

Fernseh G.m.b.H., Darmstadt, Germany

- Electrostatic tube for mass analysis in UHV pressure 10^{-8}mbar
- 2 cylindrical ion mirrors separated by drift path, overall length 36mm
- Ionization via electron collision inside the mirror
- No single ion detector needed, only HF amplifier
- 50Hz spectra acquisition rate
- Mass resolving power $m/\Delta m=20$

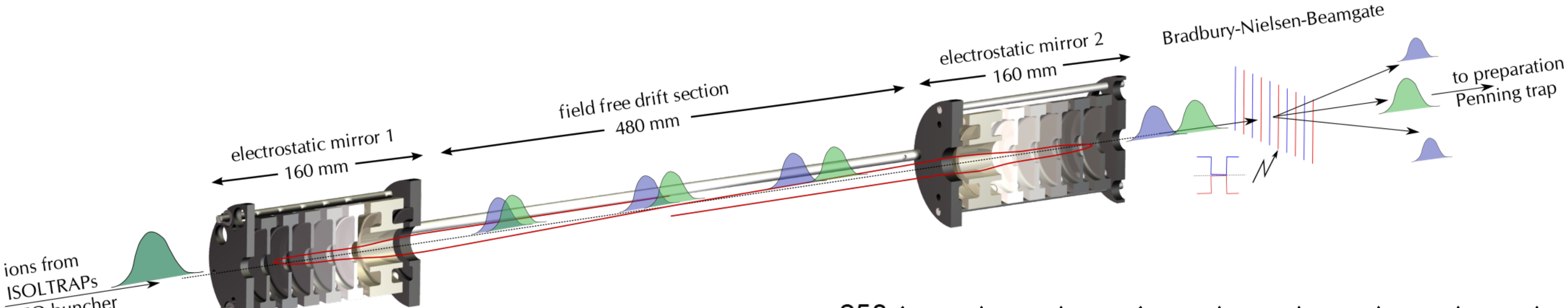


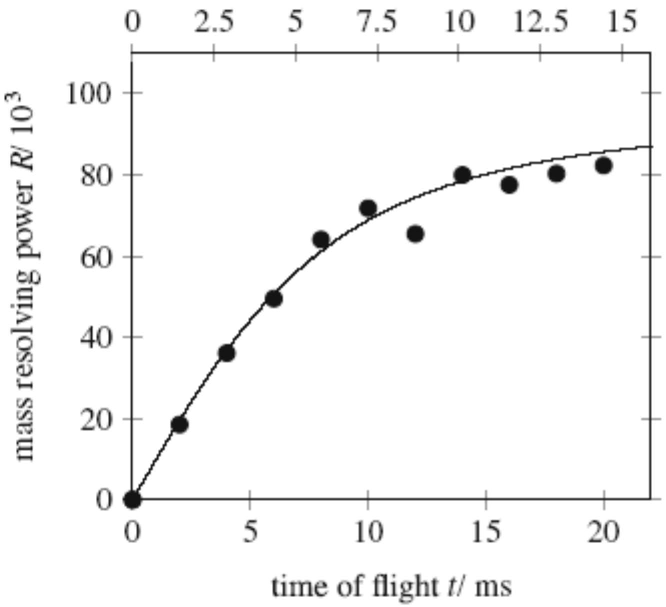
4a u. b. a Längsschnitt durch die Elektroden der Röhre von Abb. 3. Der Verlauf des Potentials und eine spezielle Elektronenbahn

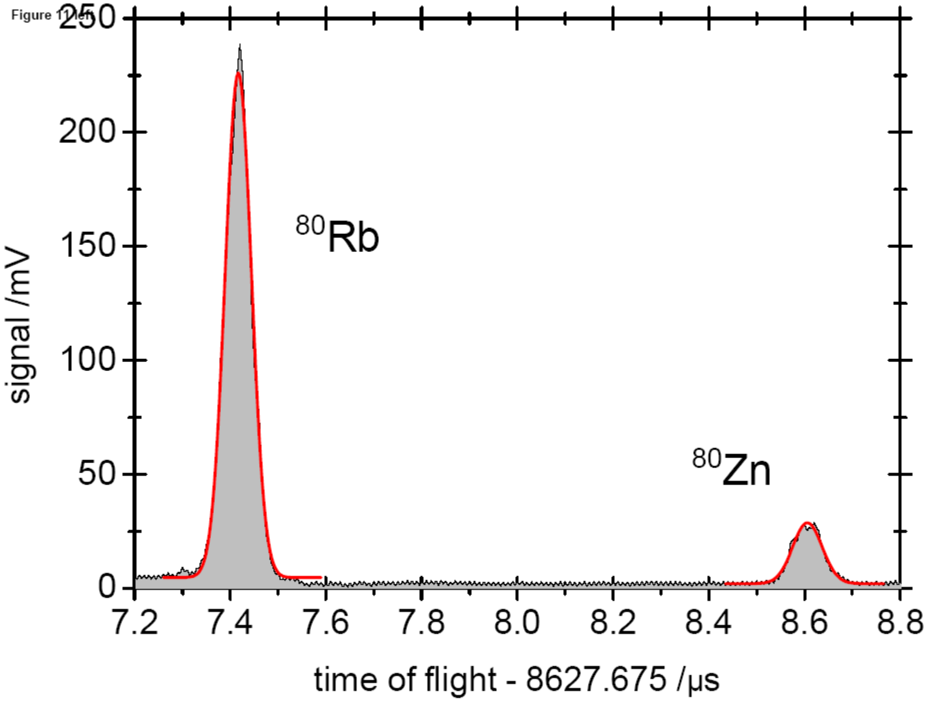
W. Tretner, Z. angew. Phys. **11**, 395 (1959)

Courtesy R. N. Wolf

MR-ToF isobar separator at ISOLTRAP/CERN





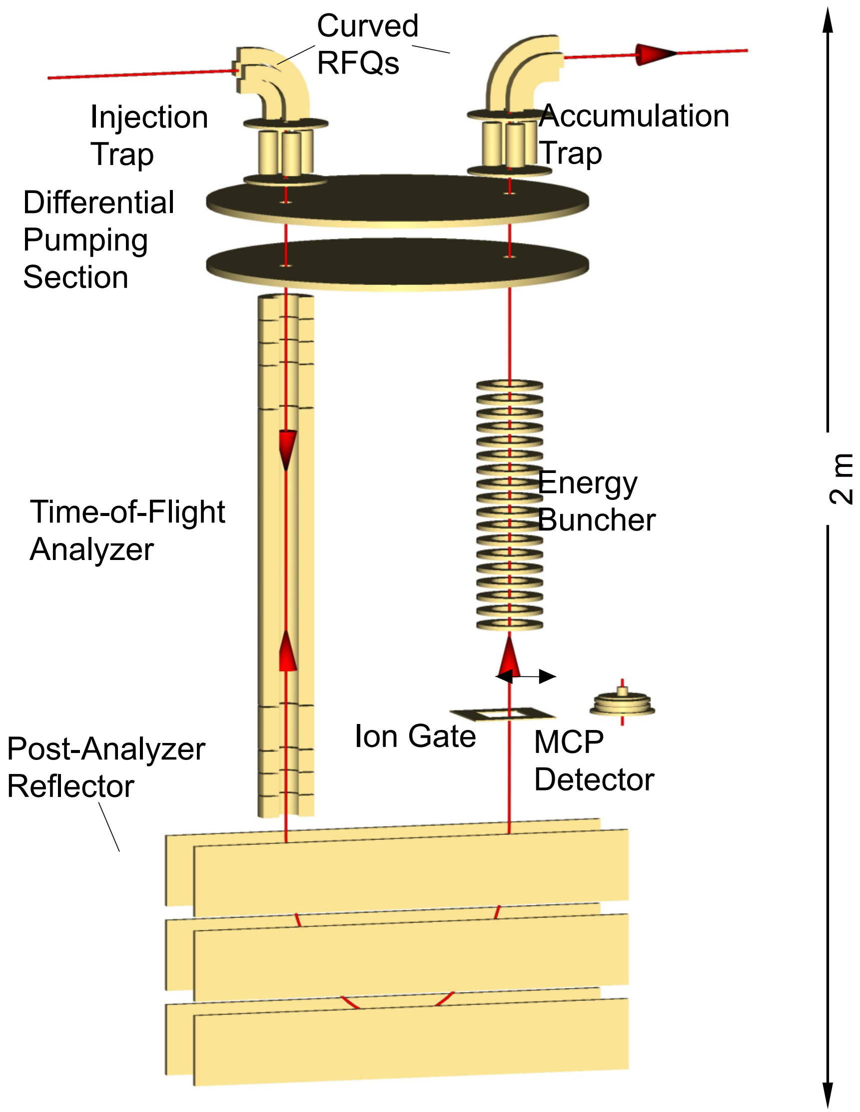


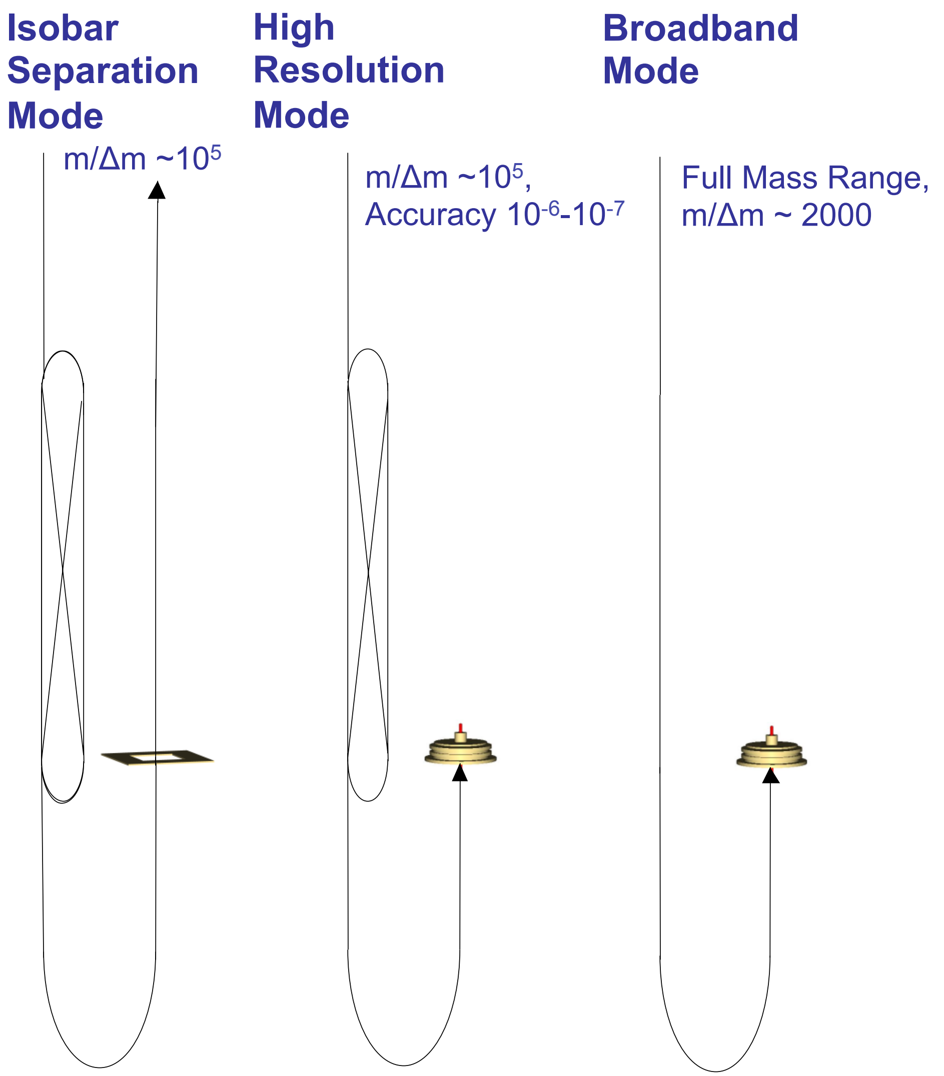
R.N. Wolf et al. Hyperfine Interact (2011) 199:115-122

R.N. Wolf et al. submitted to NIMA

Adapted from R. N. Wolf

Giessen MR-TOF-MS Setup





Isobar Separation Mode

m/Δm ~10^5

High Resolution Mode

m/Δm ~10^5,
Accuracy 10^{-6}-10^{-7}

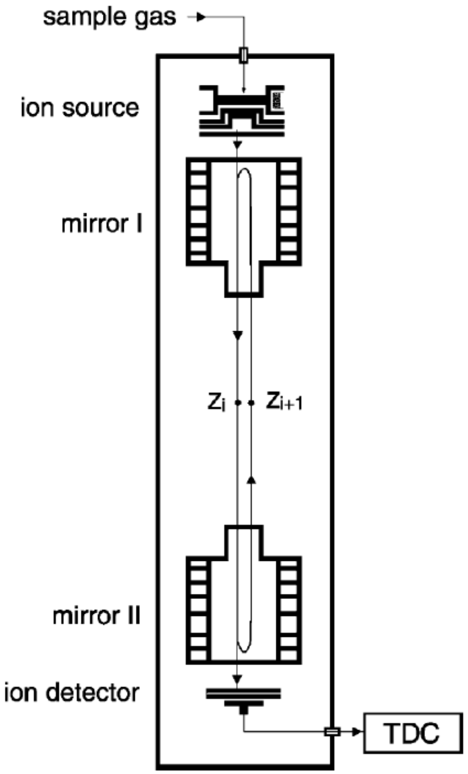
Broadband Mode

Full Mass Range,
m/Δm ~ 2000

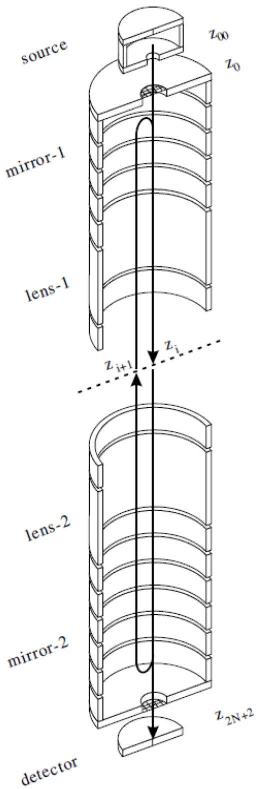
W.R. Plaß et al., Nucl. Instrum. Methods B 266 (2008) 4560

Courtesy W.R. Plaß

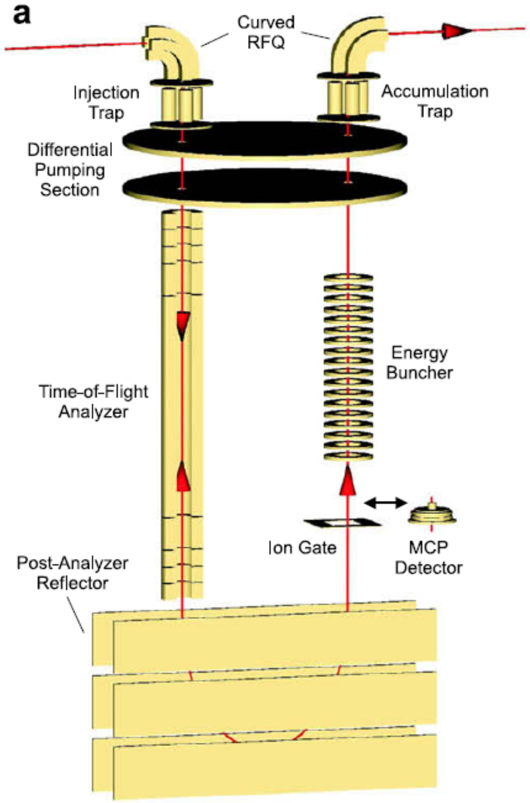
Multi-Reflection Time-of-Flight Mass Analyzers



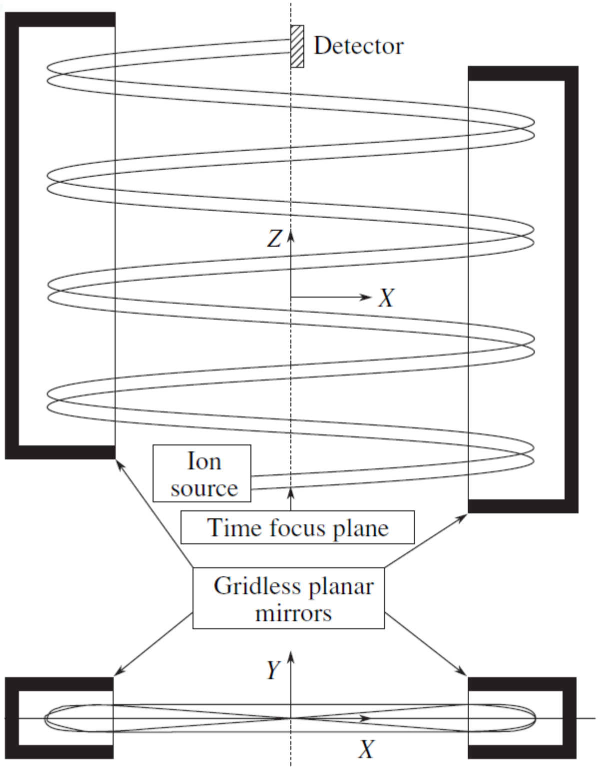
H. Wollnik and A. Casares, Int. J. Mass. Spectrom. **227**, 217 (2003)



Y. Ishida *et al.*, NIM B **219-220**, 468 (2004)
H. Wollnik *et al.*, NIM A **519**, 373 (2004)
A. Piechaczek *et al.*, NIM B **266**, 4510 (2008)



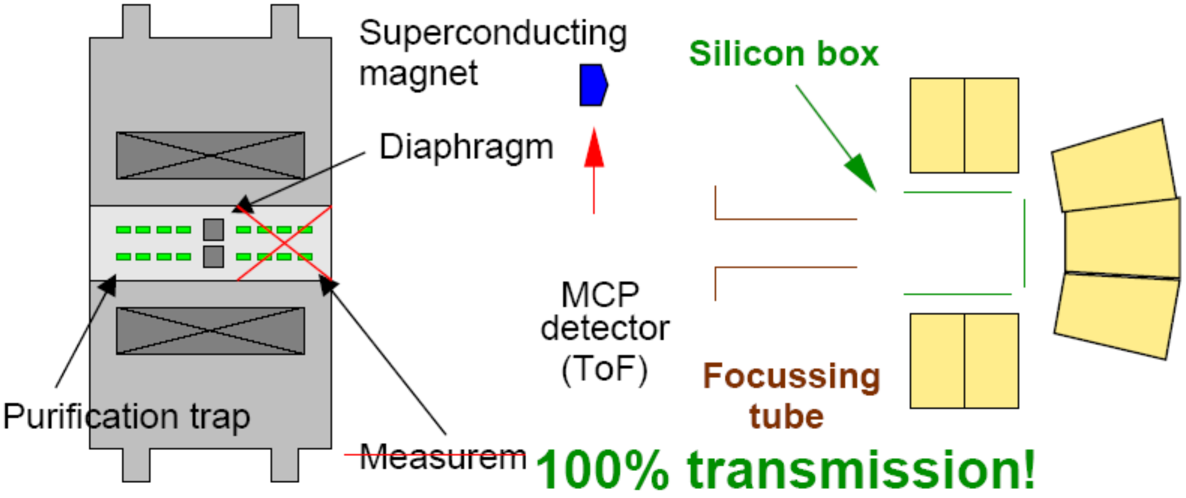
W. R. Plaß *et al.*, NIM B **266**, 4560 (2008)
W. R. Plaß *et al.*, Eur. Phys. J. Special Topics **150**, 367 (2007)



A. N. Verentchikov *et al.*, Tech. Phys. **50**, 73 (2005)

Courtesy R. N. Wolf

TRAPSPEC: Trap-assisted Spectroscopy



Penning Traps

Detector

TRAPSPEC

Superconducting magnet

Diaphragm

Purification trap

~~Measurem~~

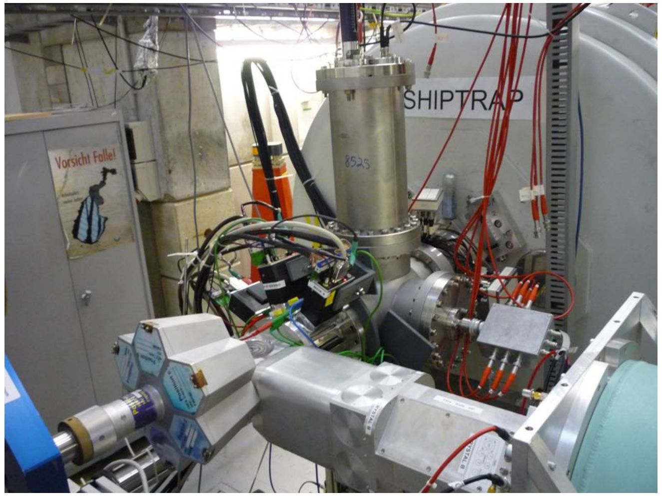
MCP detector (ToF)

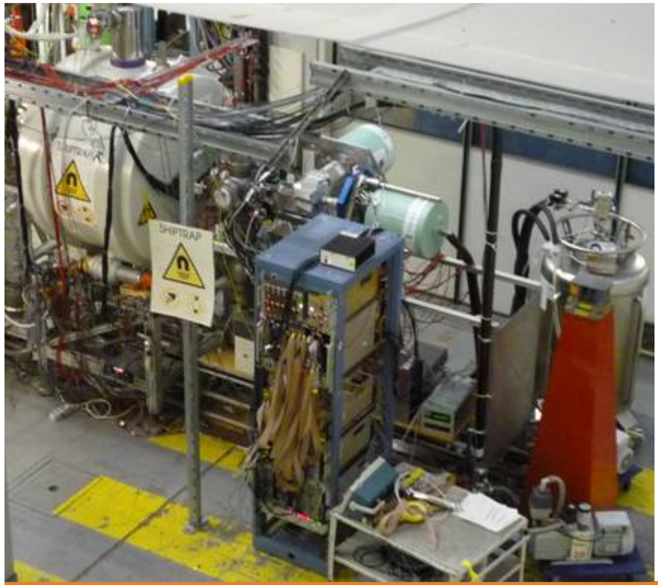
Silicon box

Focussing tube

100% transmission!

Cluster- and Clover-type Ge detectors

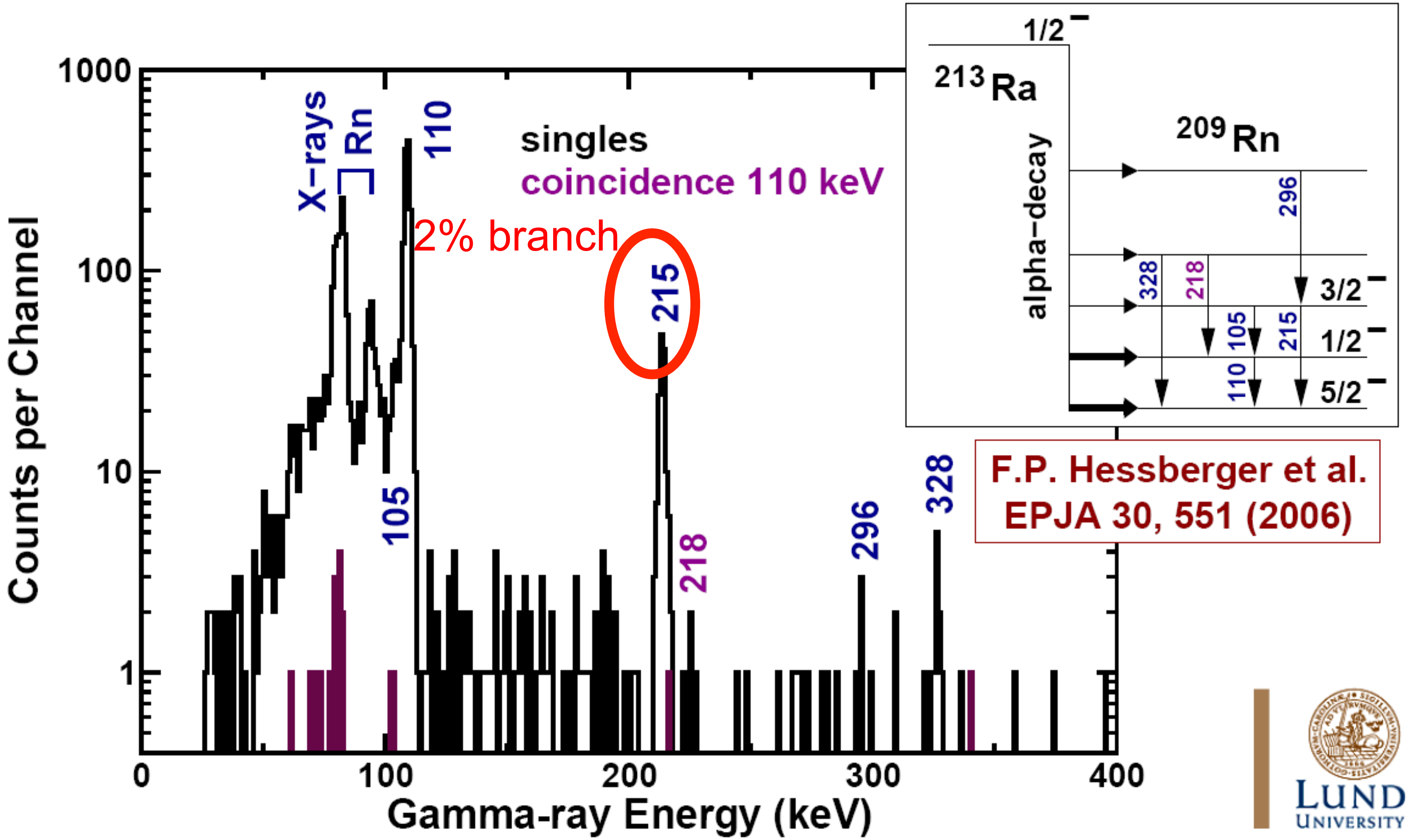




Penning trap as high-resolution mass separator to prepare state-selected pure sample

M. B., D. Rudolph et al.

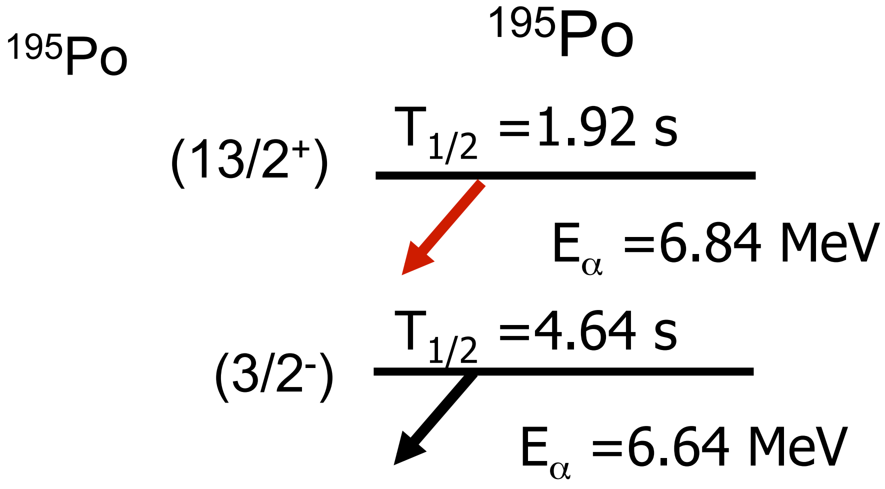
TRAPSPEC – Decay studies ^{213}Ra



F.P. Hessberger et al.
EPJA 30, 551 (2006)

D. Rudolph al., GSI Scientific Report, NUSTAR-SHE-08, 177 (2009)

TRAPSPEC – State selection by half-life



^{195}Po

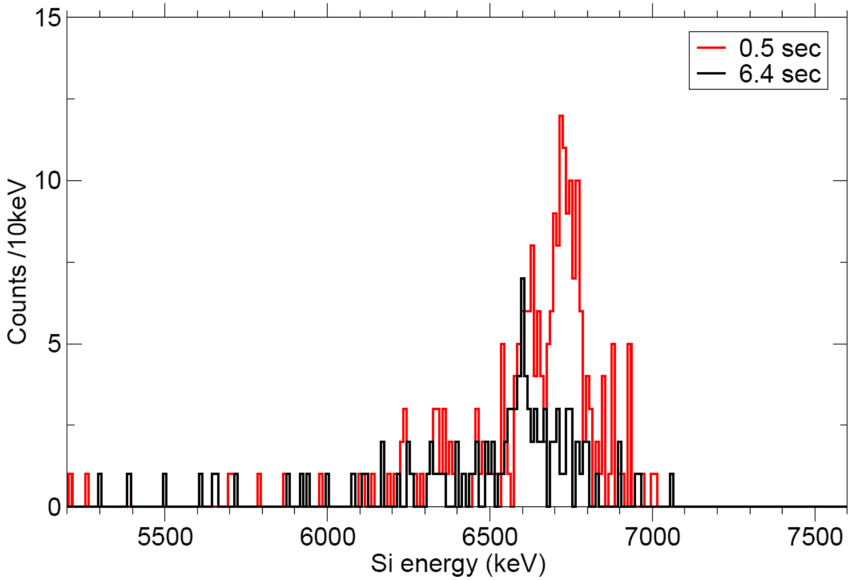
^{195}Po

(13/2$^+$) $T_{1/2}$ =1.92 s

E_α =6.84 MeV

(3/2$^-$) $T_{1/2}$ =4.64 s

E_α =6.64 MeV

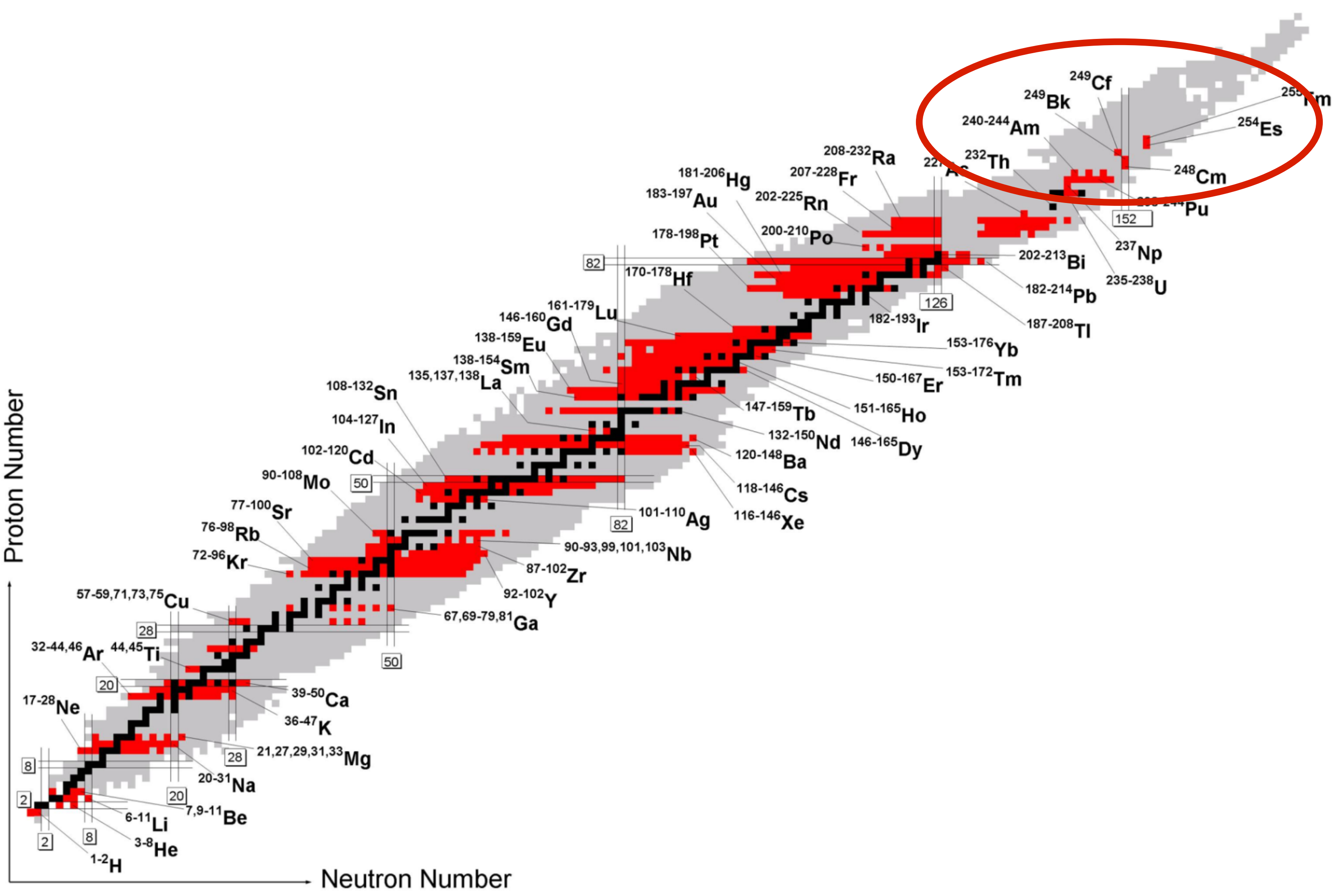


α-spectrum for different storage time in the Penning trap:

- short-lived state decays
- α-daughter not captured due to high recoil
- preparation of a single state
- in addition: mass spectrometric cleaning possible

L.-L. Andersson al., GSI Scientific Report, NUSTAR-SHE (2011)

Laser spectroscopy of radionuclides – Overview



W. Nörtershäuser et al., http://www.gsi.de/forschung/ap/projects/laser/survey.html

Nuclear properties from laser spectroscopy

Hyperfine structure interaction

1. Magnetic Dipole HFS

$$A = \frac{\mu_I \langle H_e(0) \rangle}{IJ} \Rightarrow \text{Nuclear magnetic moment } \mu_I$$

2. Electric Quadrupole HFS

$$B = eQ_S < \varphi_{jj}(0) > \Rightarrow \text{Spectroscopic quadrupole moment } Q_S$$

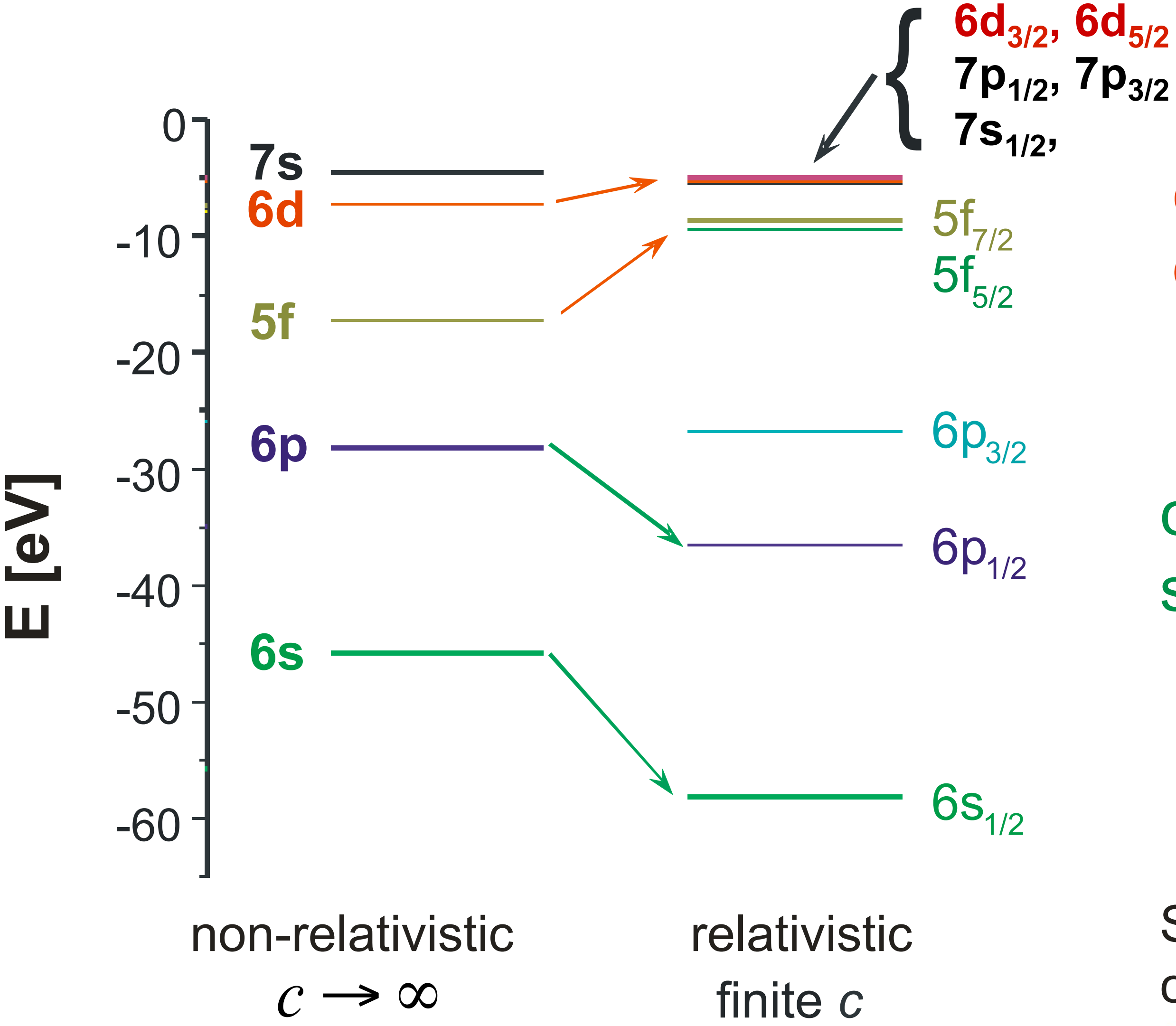
3. Coupling

$$\vec{J} + \vec{I} = \vec{F} \Rightarrow \text{Nuclear spin } I$$

Isotope shift

$\delta < r^2 >^{A,A'} \Rightarrow$ change of mean square charge radius

Relativistic Effects in Uranium



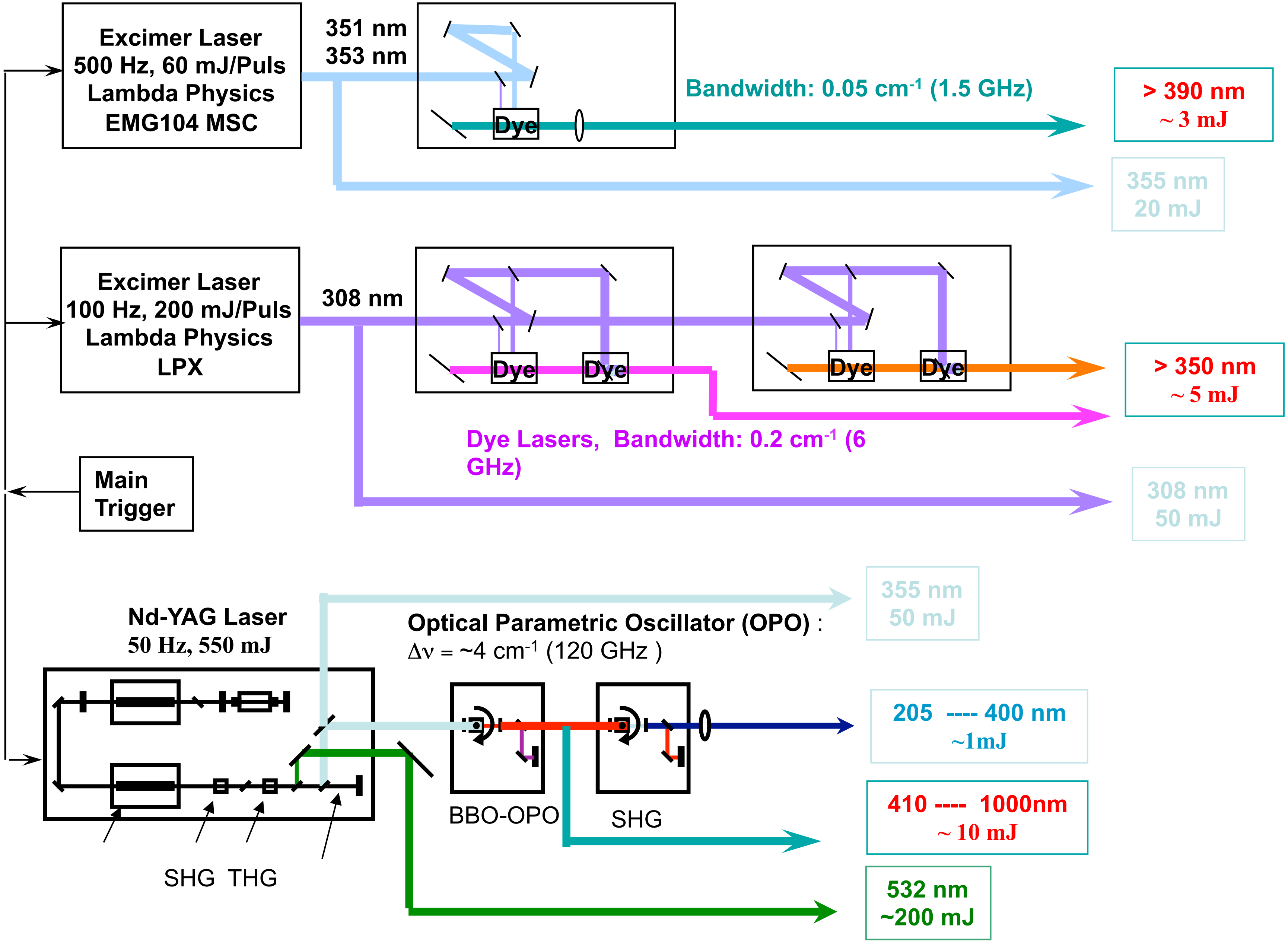
expansion of
d, f orbitals

contraction of
$s_{1/2}$, $p_{1/2}$ orbitals

Spin-orbit
coupling

J.P. Desclaux, At. Data Nucl. Data Tables **12**, 311 (1973)

Laser Systems



Excimer Laser
500 Hz, 60 mJ/Puls
Lambda Physics
EMG104 MSC

351 nm
353 nm

Bandwidth: 0.05 cm^{-1} (1.5 GHz)

> 390 nm
~ 3 mJ

355 nm
20 mJ

Excimer Laser
100 Hz, 200 mJ/Puls
Lambda Physics
LPX

308 nm

> 350 nm
~ 5 mJ

Dye Lasers, Bandwidth: 0.2 cm^{-1} (6 GHz)

308 nm
50 mJ

Main Trigger

Nd-YAG Laser
50 Hz, 550 mJ

Optical Parametric Oscillator (OPO) :
Δν = ~4 cm^{-1} (120 GHz)

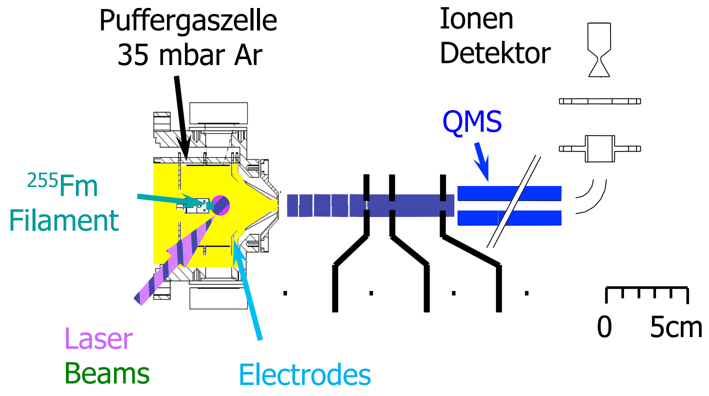
355 nm
50 mJ

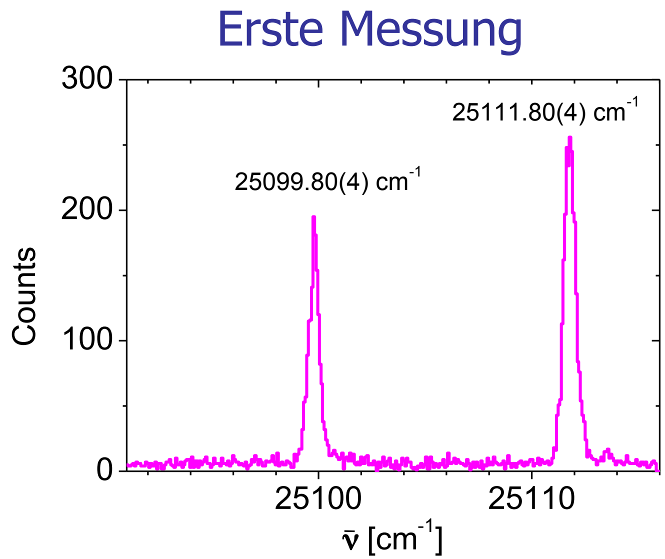
205 ---- 400 nm
~1mJ

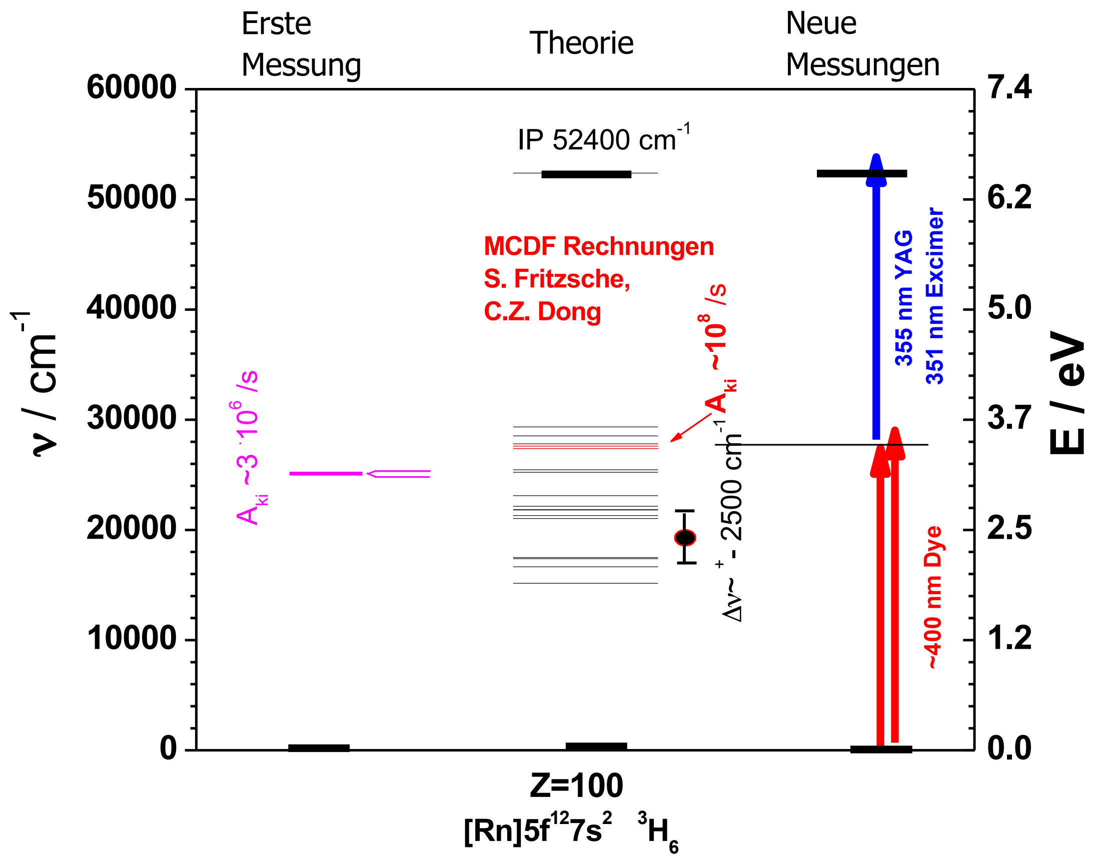
410 ---- 1000nm
~ 10 mJ

532 nm
~200 mJ

Search for Atomic Levels in Fermium (Z=100)

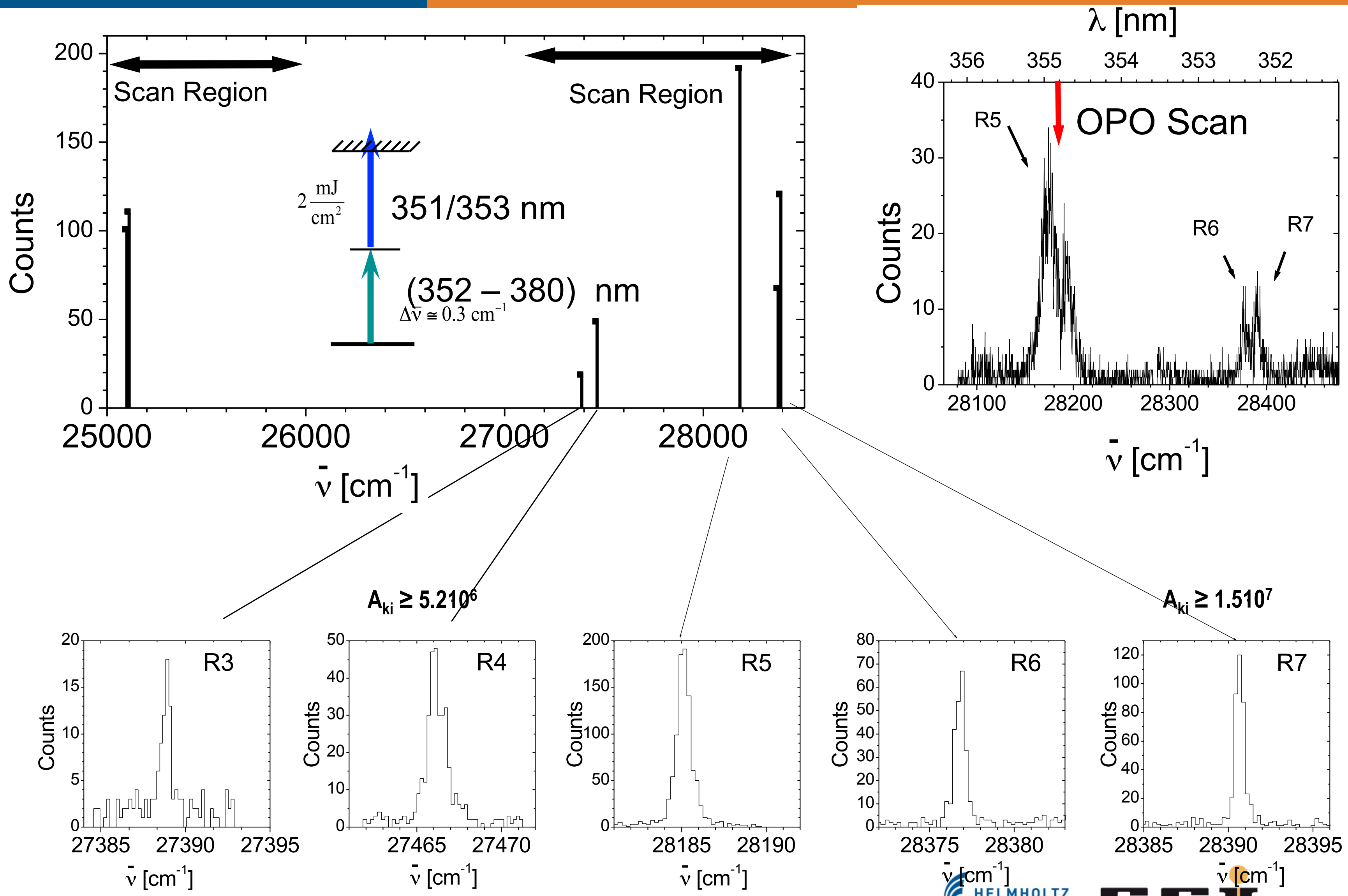






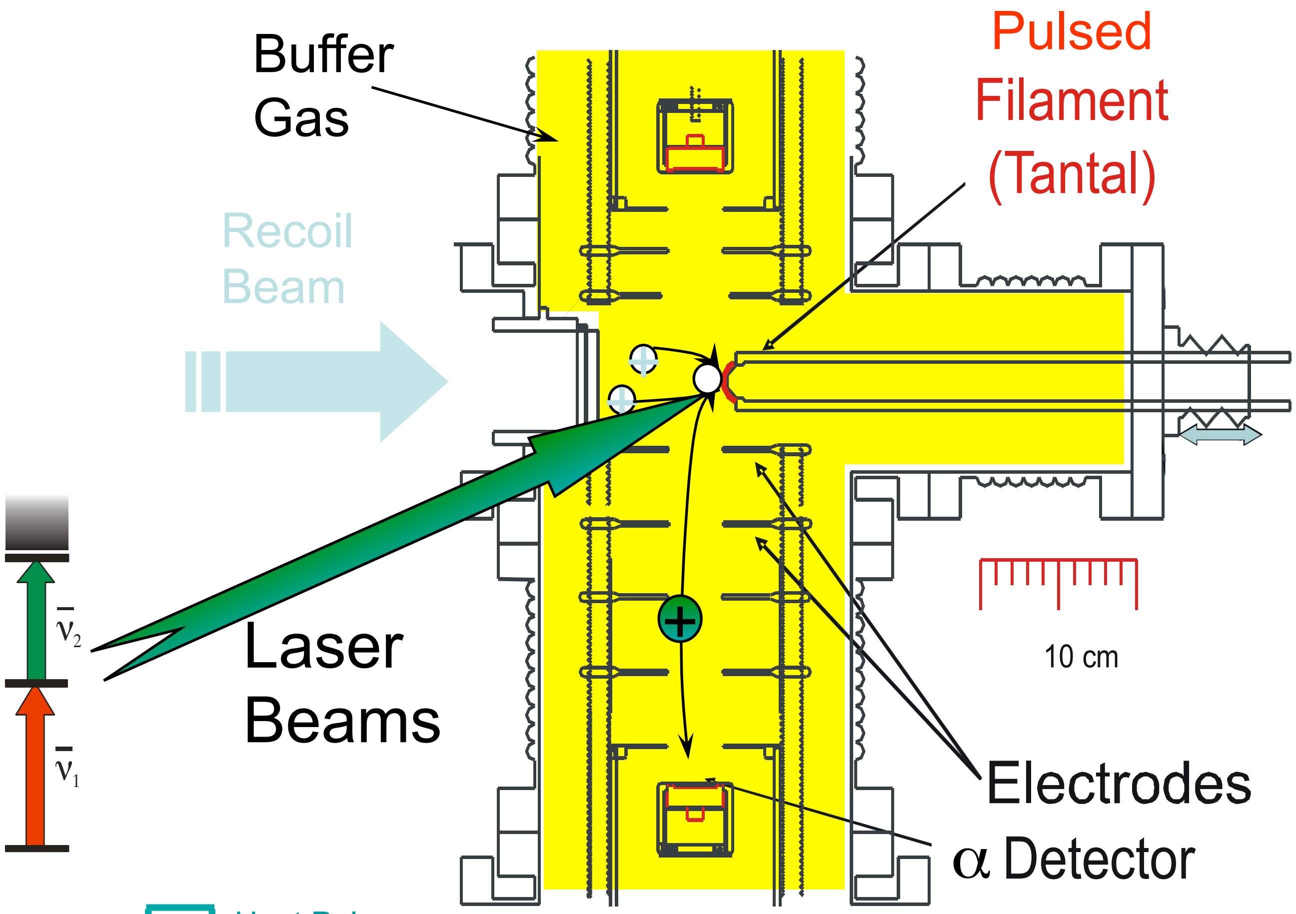
M. Sewtz, H.Backe, A. Dretzke, G. Kube, W. Lauth et al.,
Phys. Rev. Lett. 90, (2003), 163002-1

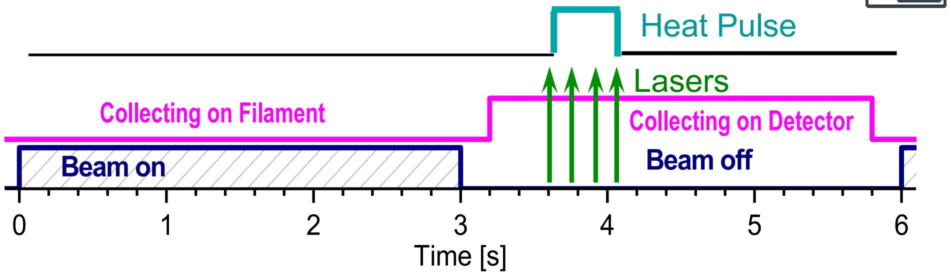
Search for Atomic Levels in Fermium (Z=100)



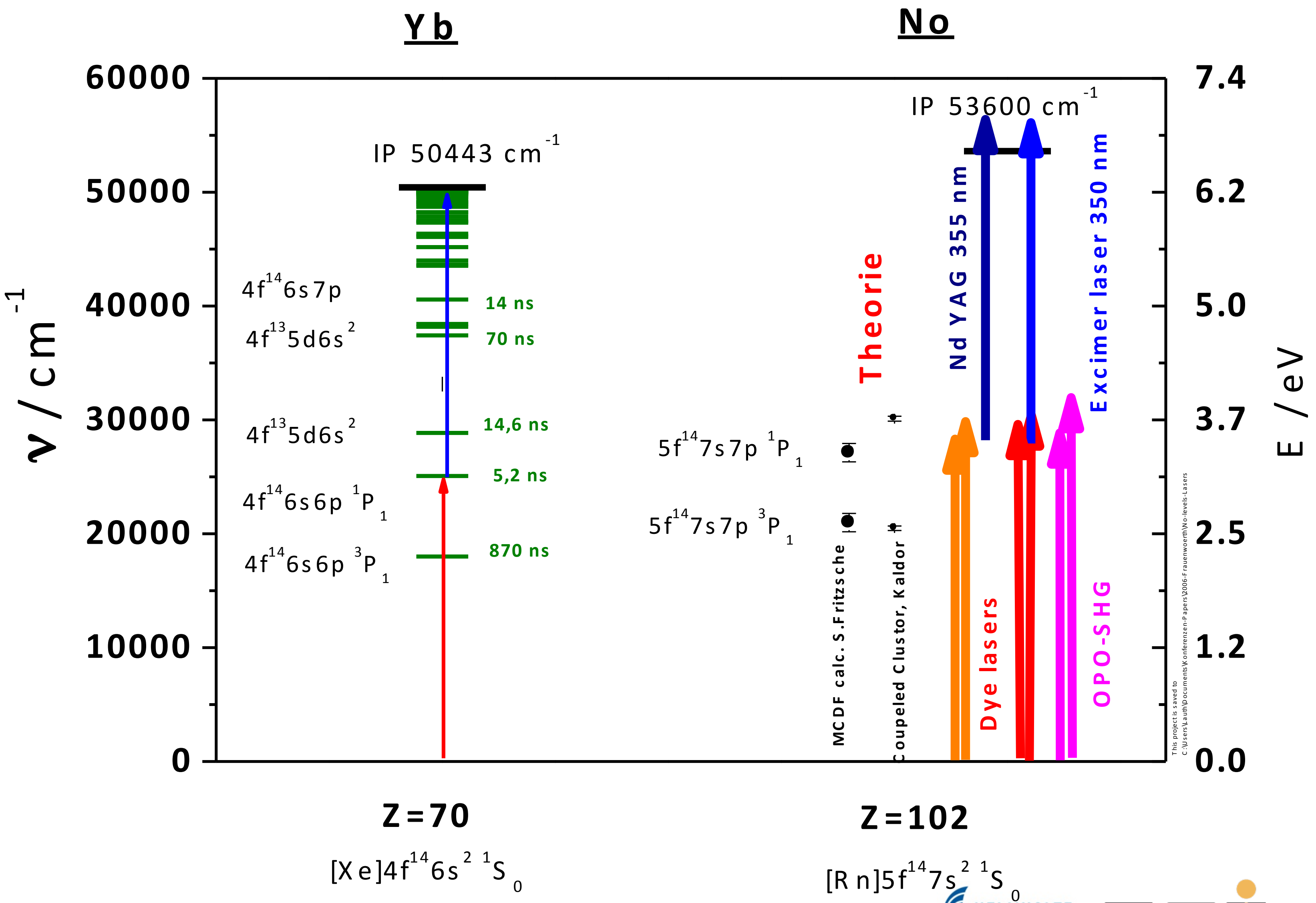
Hyp. Int. 162 (2005) 3, 1DOI 10.1007/s10751-005-9209-x

Radioactive Detected Resonance Ionization



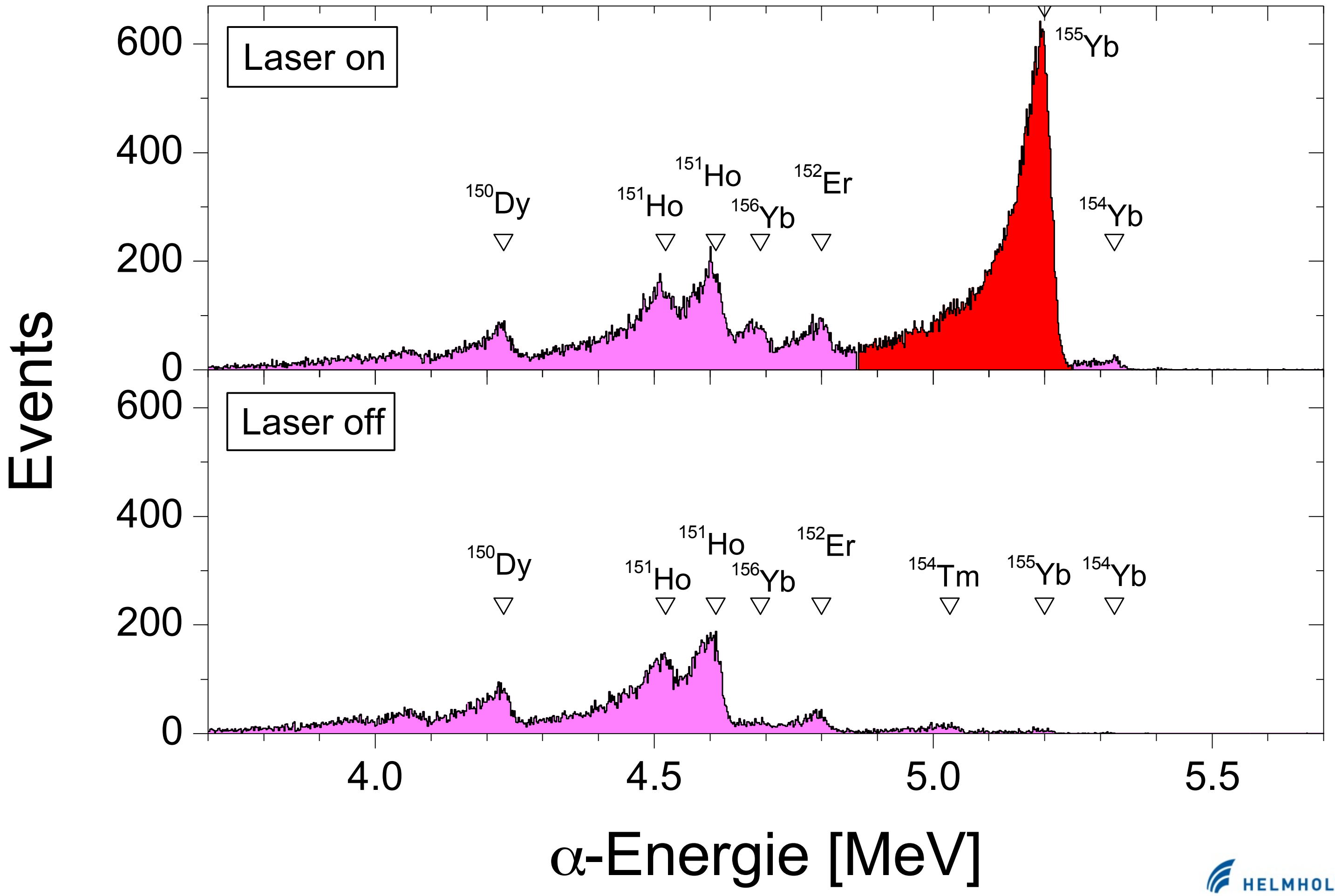


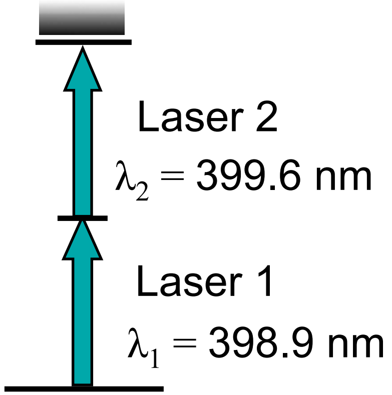
Excitation Schemes for Yb and No



On-line Experiment on ^{155}Yb at SHIP

Z=70 $^{107}Ag(^{52}Cr,p3n)^{155}Yb$ ($t_{1/2}$=1.75 s, α) $4 \cdot 10^4$ Ions/s

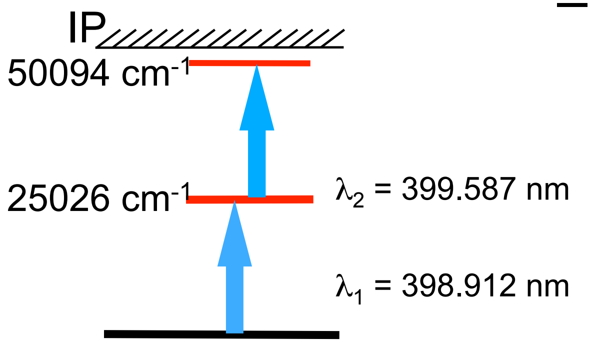


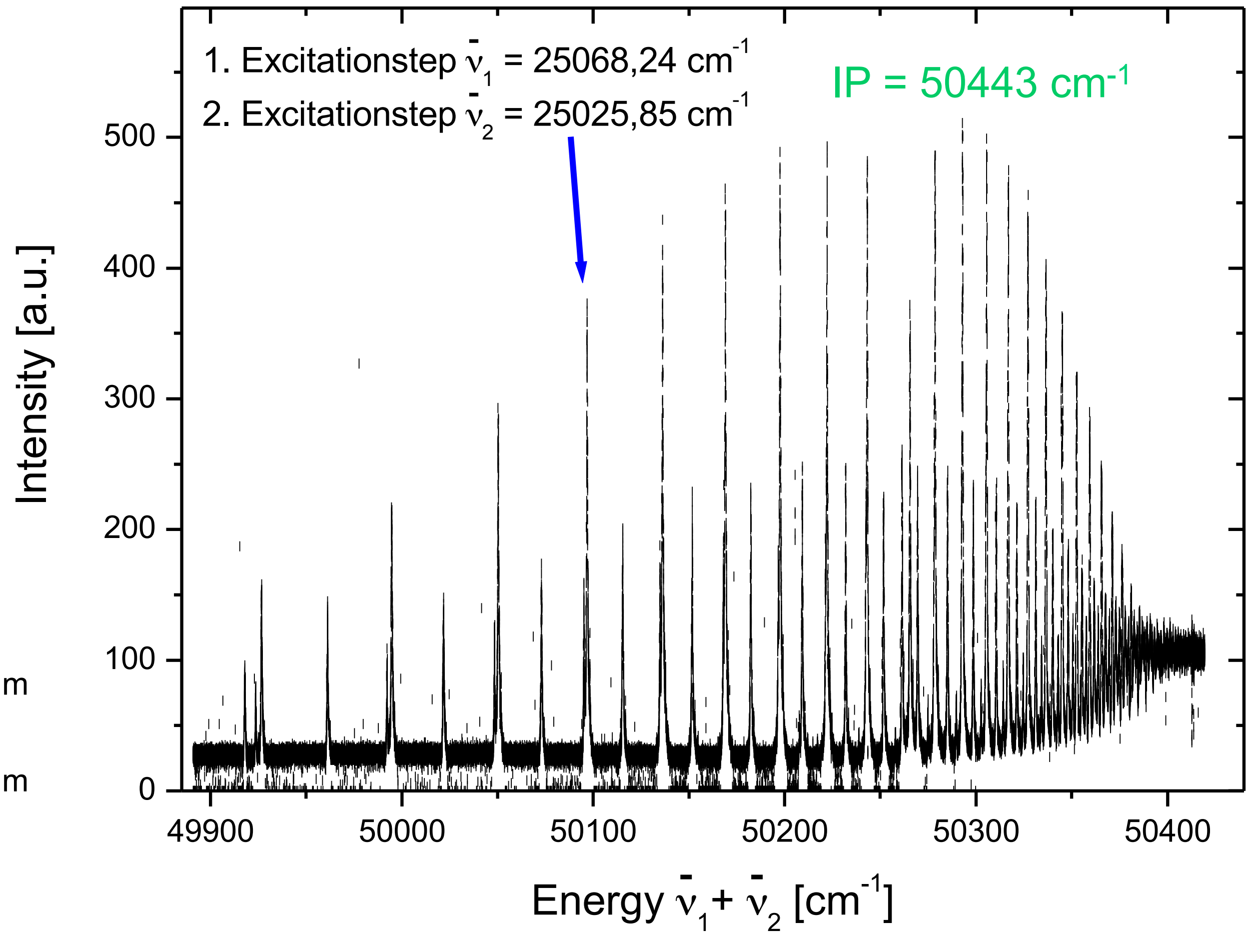


$$\frac{\text{Signal}}{\text{Background}} = \frac{30}{1}$$

Rydberg series for Yb

Rydberg state provides higher ionization efficiency



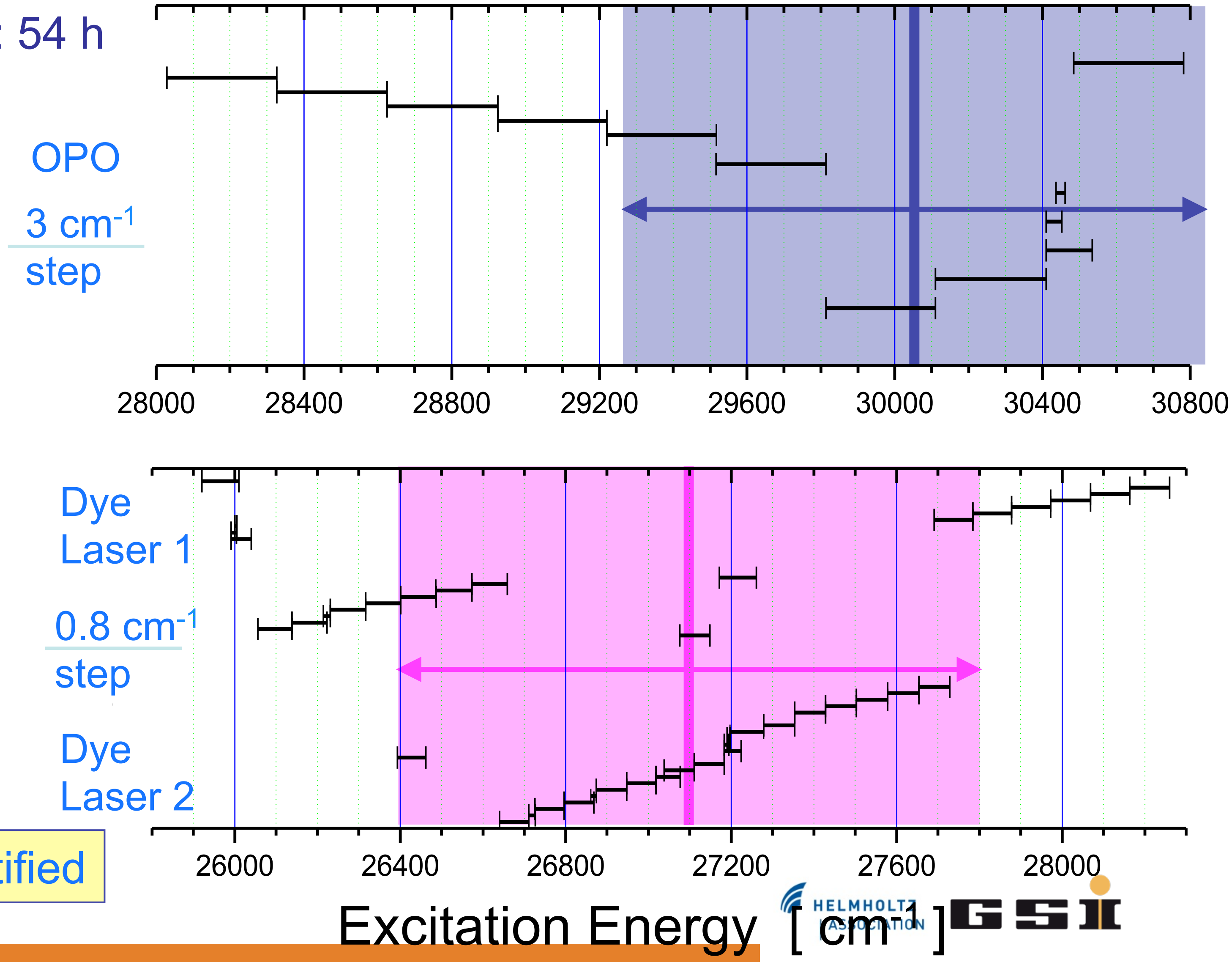


First search for the $5f^{14}7s7p\ ^1P_1$ Level of ^{254}No

5 Days Beam Time
Search Time : 54 h

Waiting Time per Step : **44 s**

Expected Resonance Count Rate : **4/step**



no level identified

Move setup permanently to GSI

Laser shack set up: 2 Excimer lasers and 4 Dye lasers

M. Laatiaoui, F. Lautenschlager,
Th. Walther, H. Backe, W. Lauth et al.

Summary and Conclusions

- high-precision mass measurements at about 50 nb demonstrated
- Technical and methodical developments promise ga y factor 10-100
- gain by higher beam intensity factor 10
- Novel experiments become possible
  - Combination of gas stopper and m pectrometry for yield measurements
  - trap-assisted decay spectr y
- Laser spectroscopy to provid omplementary data about spins and charge radii elements around nobelium

Thank you for your attention !

HELMHOLTZ ASSOCIATION GSI