Manipulation of slow radioactive ions by trapping

Gas-filled RFQ: principle
Penning trap: principle

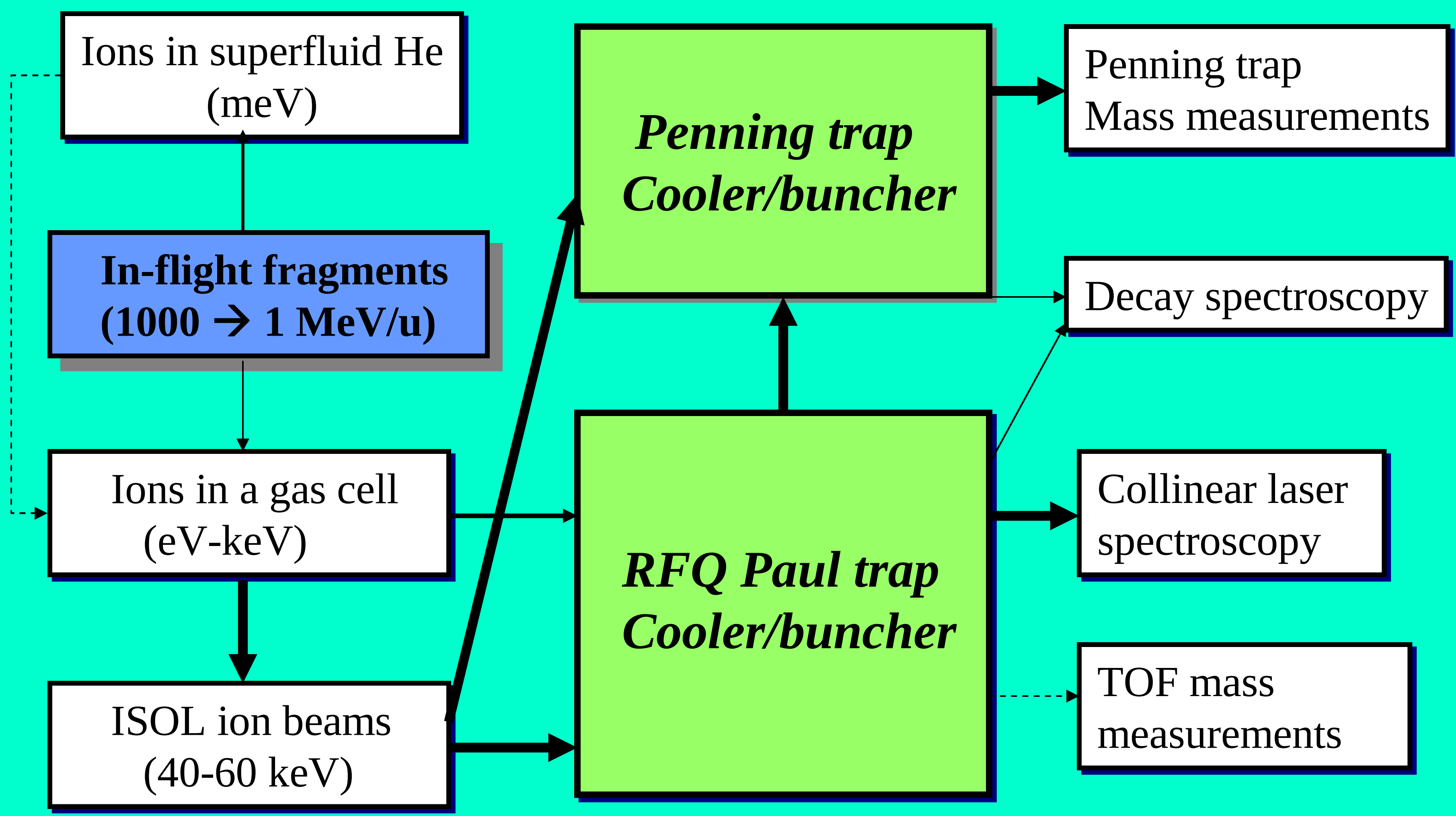
What can we do with these devices?

- Cooling and bunching (RFQ and PT)
- Isobar separation (PT)
- Yield or cross section measurements
- Trap-assisted spectroscopy
  - in-trap decay
  - post-trap decay spectroscopy

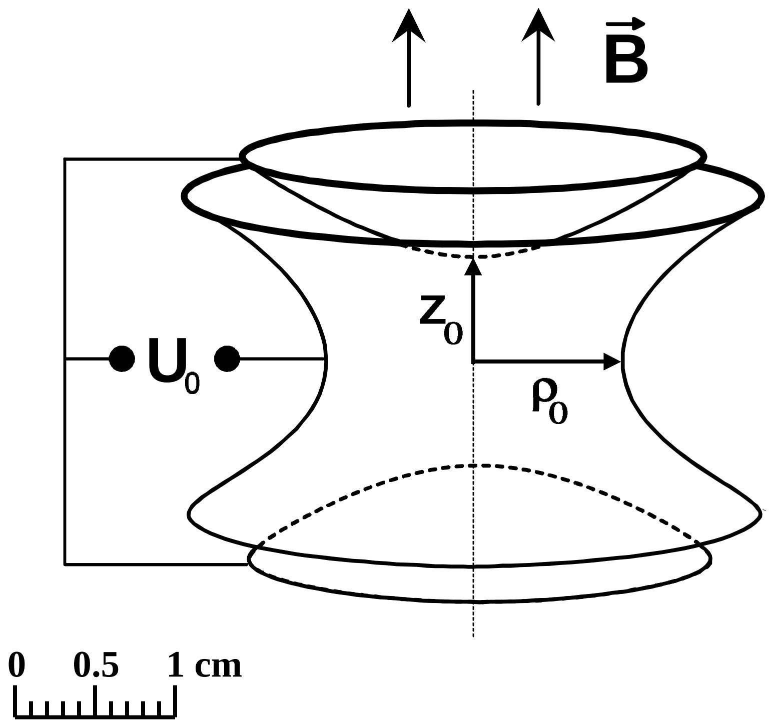
- Direct mass measurements
- Optical pumping (RFQ)
- Isomer separation (PT)

Thanks to many colleagues at IGISOL group + K. Blaum, G. Bollen, J. Kluge,

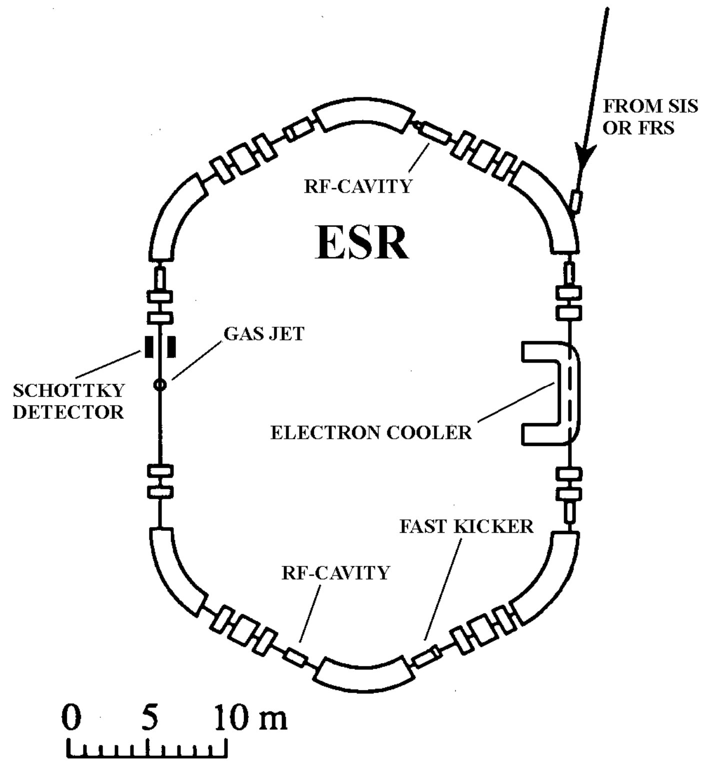
Ion Manipulation in Spectroscopy of Exotic Nuclei



PENNING (PAUL) TRAP



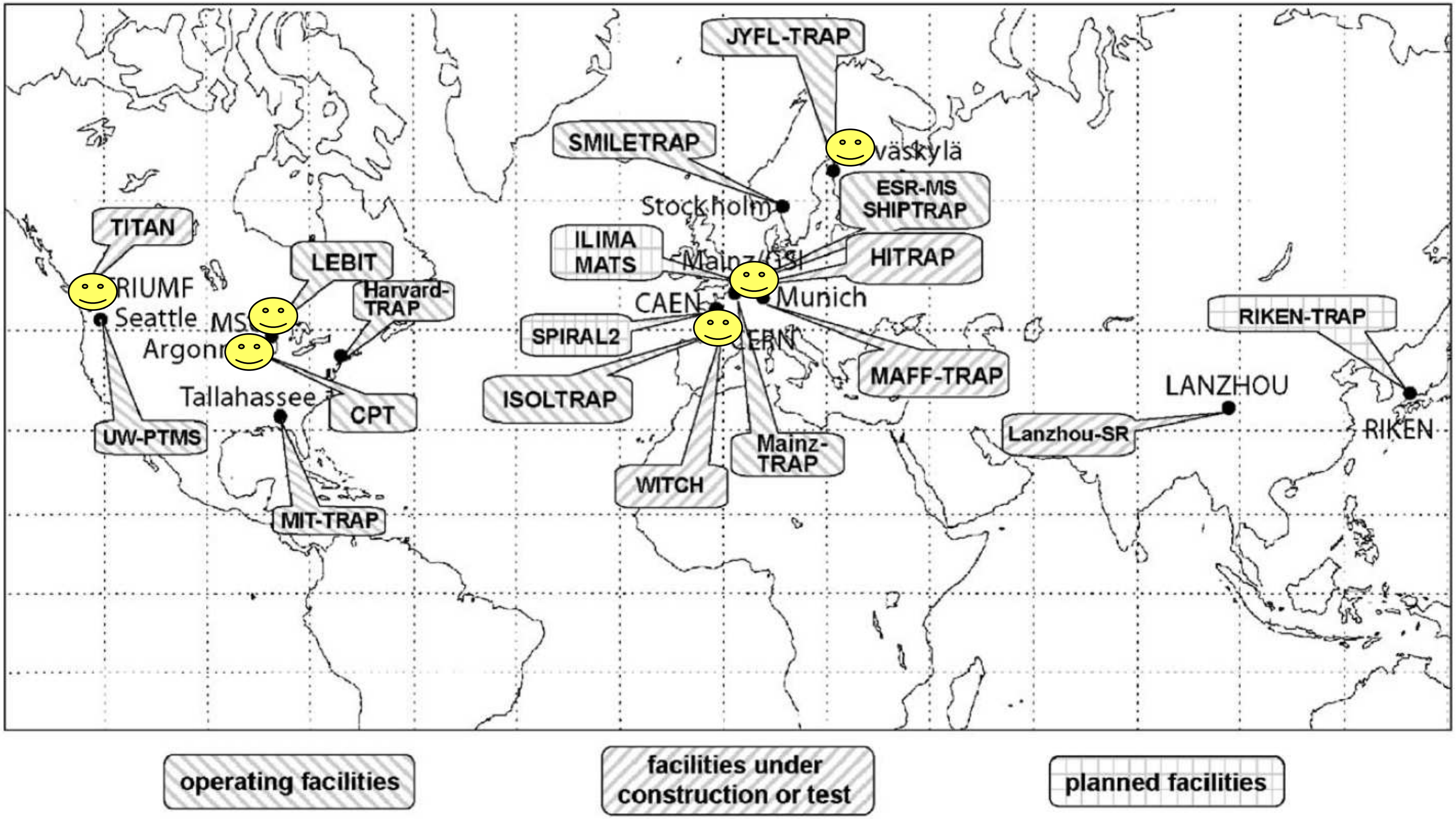
STORAGE RING



particles: at nearly rest in space **at relativistic energies**

See for a nice review article: K. Blaum, Phys. Rep. 425 (2006) 1

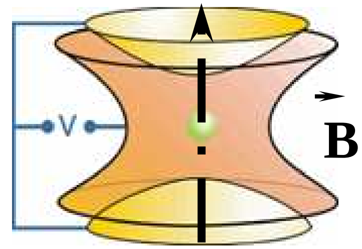
Storage rings and Penning traps for high-accuracy measurements worldwide

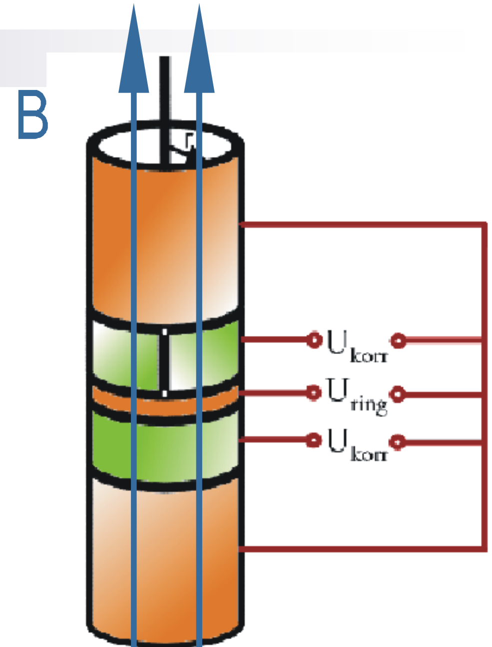


K. Blaum / Physics Reports 425 (2006) 1–78

Ion motion in a Penning trap

$$\sum \vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$





- Three harmonic eigenmotions

1. **Axial** motion:

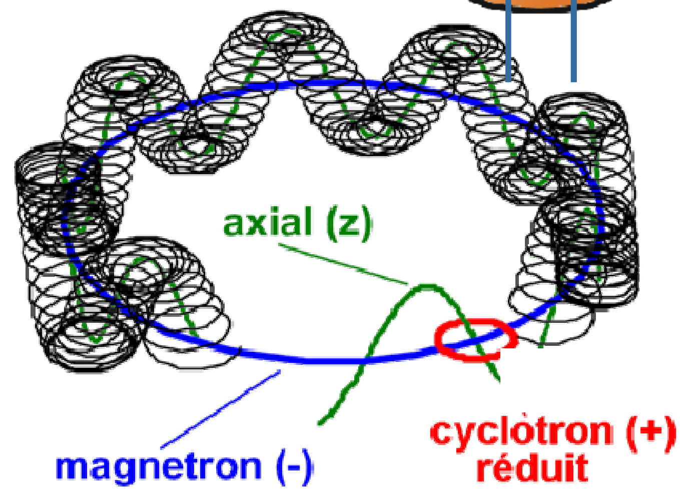
$$\omega_z = \sqrt{\frac{qV_0}{md^2}}$$

2. **Magnetron** motion (slow):

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

3. **Reduced Cyclotron** motion (fast):

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$



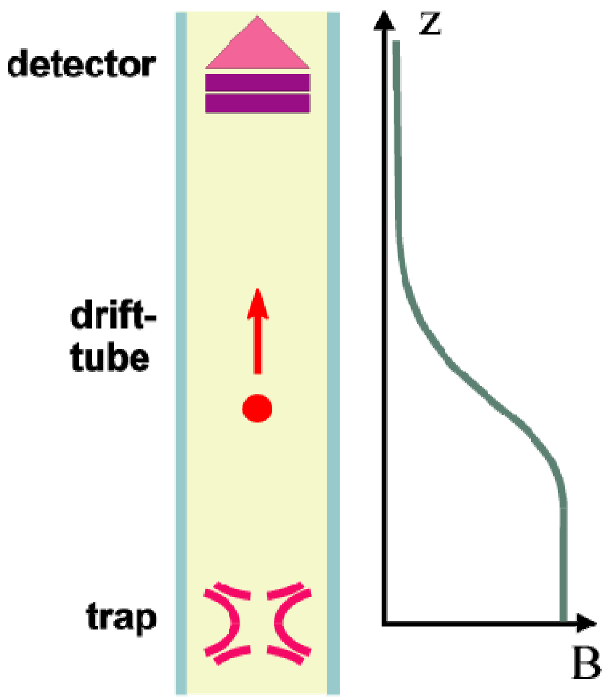
$$\omega_c = \omega_+ + \omega_- = \frac{q}{m} \cdot B$$

A=100, q=1, B=7 T

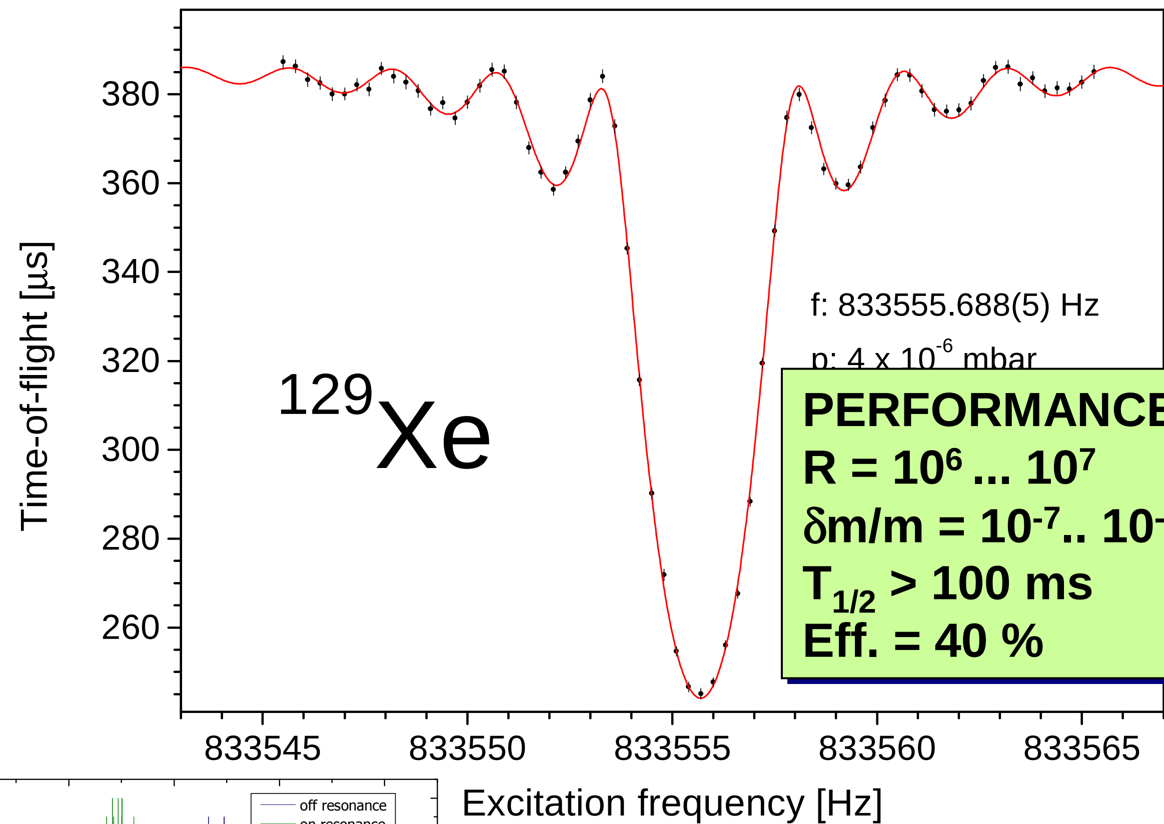
- $f_+ \approx$ 1 MHz
- $f_- \approx$ 1 kHz
- $f_z \approx$ 44 kHz

Resonance frequency measurement – the time of flight technique

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

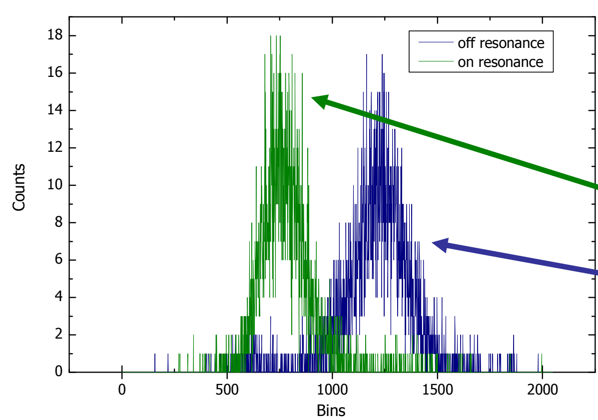


$$\vec{F} = \vec{\mu}\ \vec{\nabla} B$$



PERFORMANCE:
R = 10^6 ... 10^7
$\delta m/m = 10^{-7} .. 10^{-8}$
$T_{1/2}$ > 100 ms
Eff. = 40 %

^{129}Xe time of flight spectrum



On resonance
Off resonance

Injection of ions into a Penning trap ?

Solution: buffer-gas filled RFQ trap

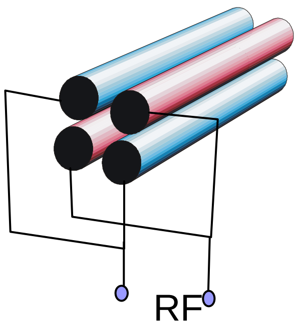
Combination of buffer gas cooling and RF-confinement

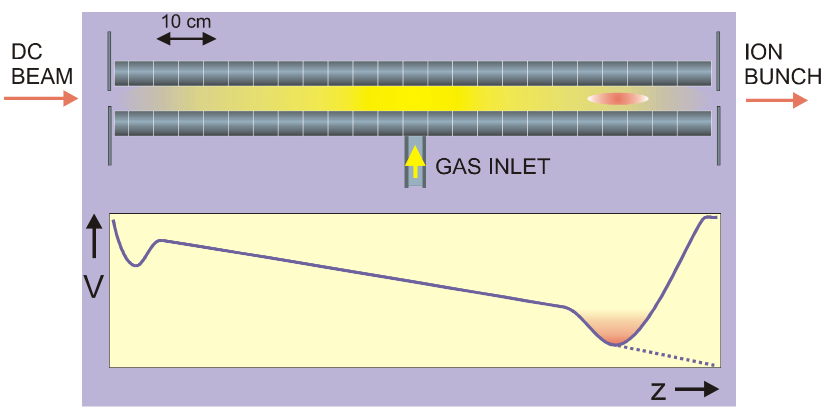
- To reduce the emittance and the energy spread
- Optional bunching the DC-beam

RF-multipole structure

A. Nieminen, JYFL
F. Herfurth, ISOLTRAP
D. Lunney, MISTRAL cooler

Emittance 3 π mm mrad
Energy spread 0.5 eV
Bunch width 10 μs
Transmission 70 %

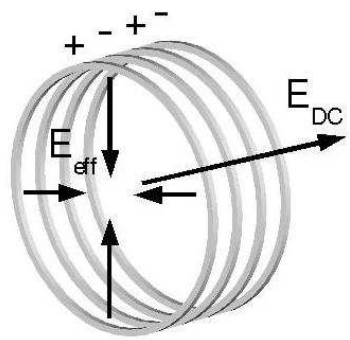


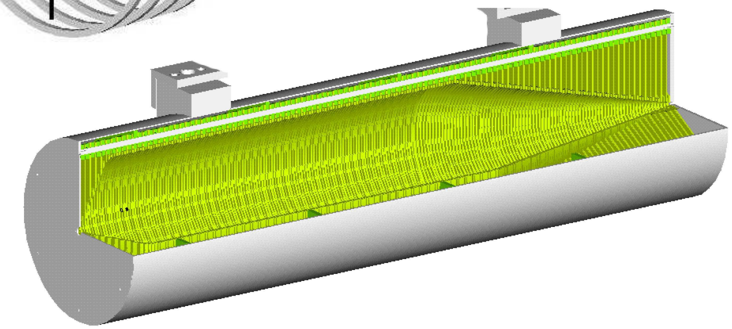


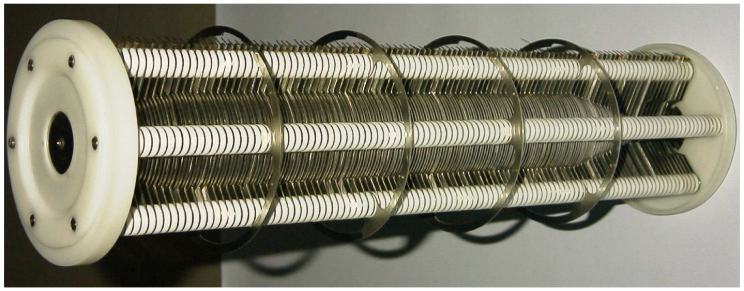
RF-wall with the funnel

S. Heinz, LMU

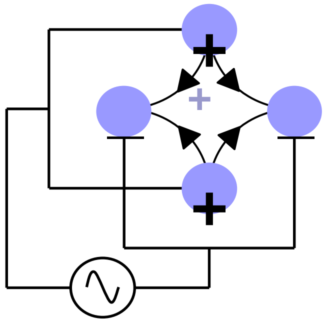
Tested on-line at JYFL

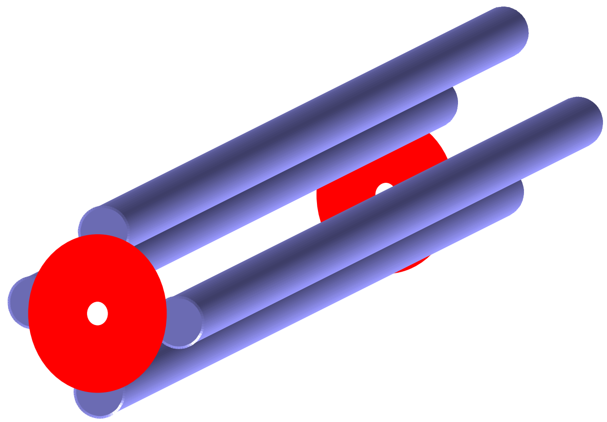


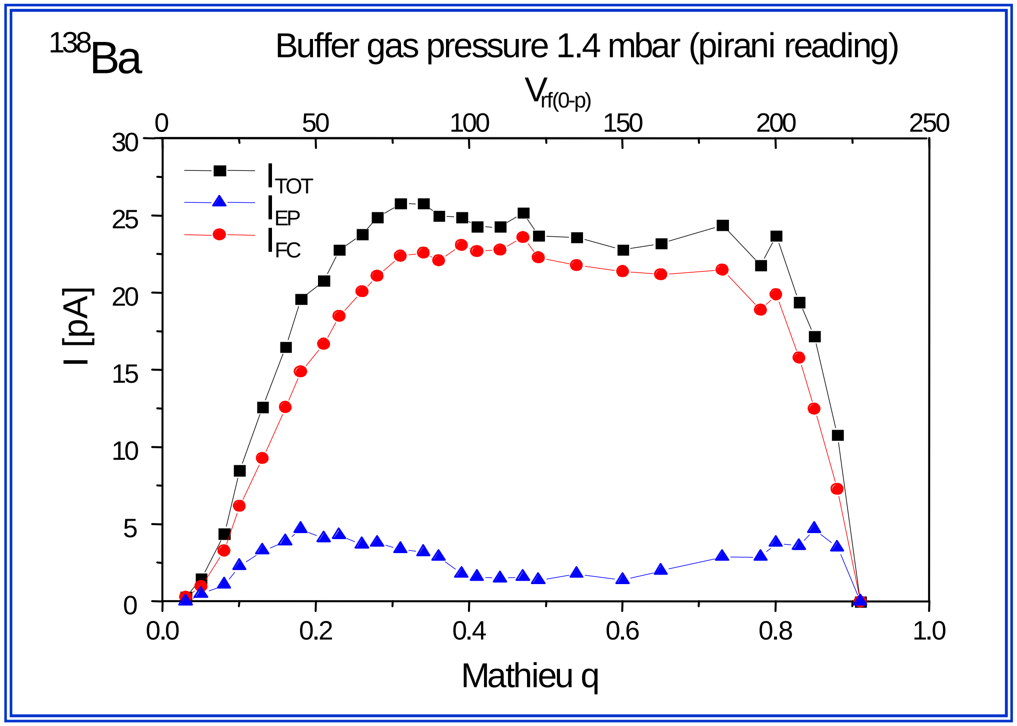




Ion beam cooler: RF confinement







Mathieu parameter

$$q = \frac{4\,Q\,V_{RF}}{m\,r_0^2\,\Omega_{RF}^2}$$

Ion motion is stable when $0 < q < 0.91$

Cooling and bunching of low-energy RIBs

Nucl. Instr. Meth. A469, Issue 2

A linear radiofrequency ion trap for accumulation, bunching, and emittance improvement of radioactive ion beams

F. Herfurth[a,*], J. Dilling[a], A. Kellerbauer[a,b], G. Bollen[c], S. Henry[d], H.-J. Kluge[a], E. Lamour[a], D. Lunney[d], R.B. Moore[e], C. Scheidenberger[a], S. Schwarz[a,b], G. Sikler[a], J. Szerypo[f]

ISOLTRAP

JYFLTRAP

Beam cooler for low-energy radioactive ions

A. Nieminen[a,*], J. Huikari[a], A. Jokinen[a], J. Äystö[a,1], P. Campbell[b], E.C.A. Cochrane[c,2]

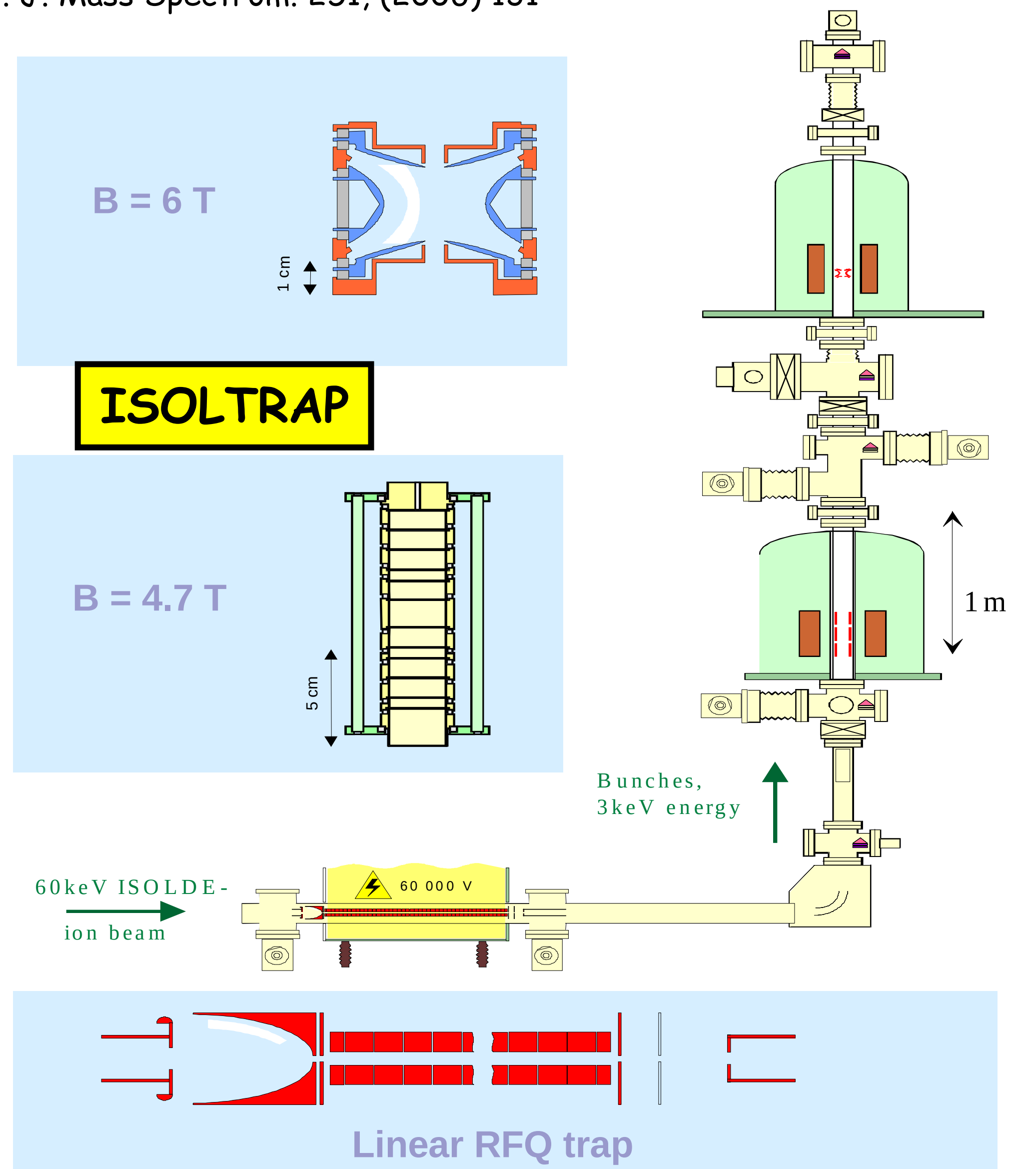
Buffer gas cooling of ion beams

A. Kellerbauer*, T. Kim, R.B. Moore, P. Varfalvy

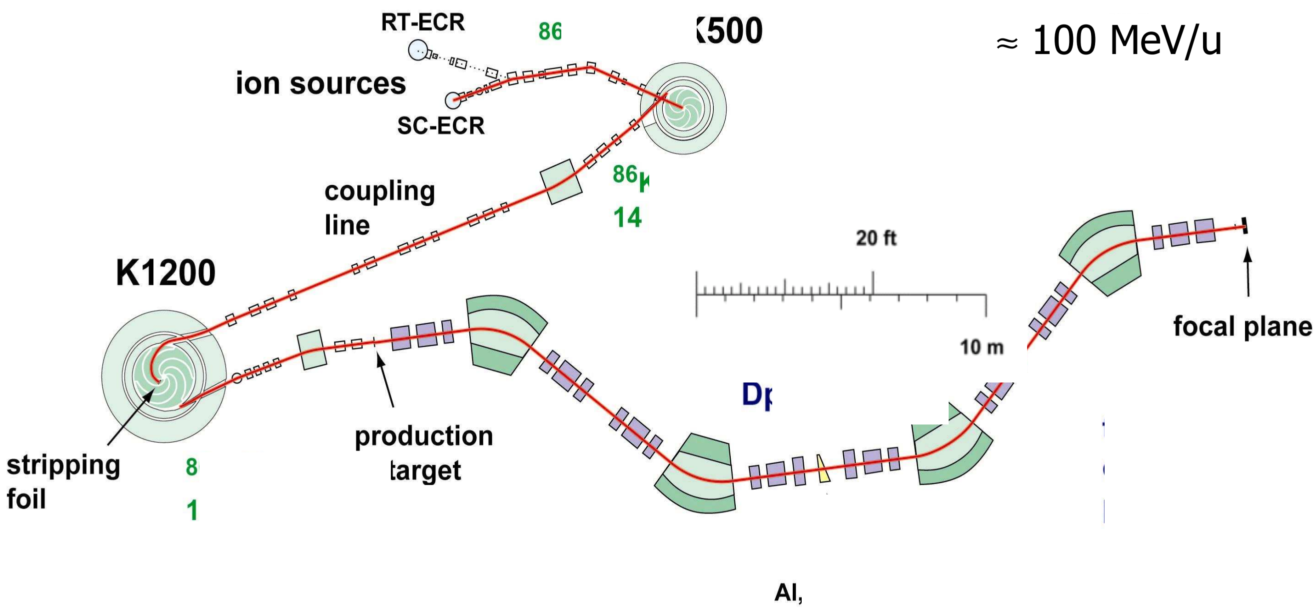
McGill at Montreal

Huge impact on:
- sensitivity in collinear laser spectrocopy (x 10^5)
- optical pumping applications
- fast/efficient injection into Penning traps

A. Herlert, et al., Int. J. Mass Spectrom. 251, (2006) 131



NSCL-MSU



≈ 100 MeV/u

LEBIT

≈ 1 eV

Gas stopping

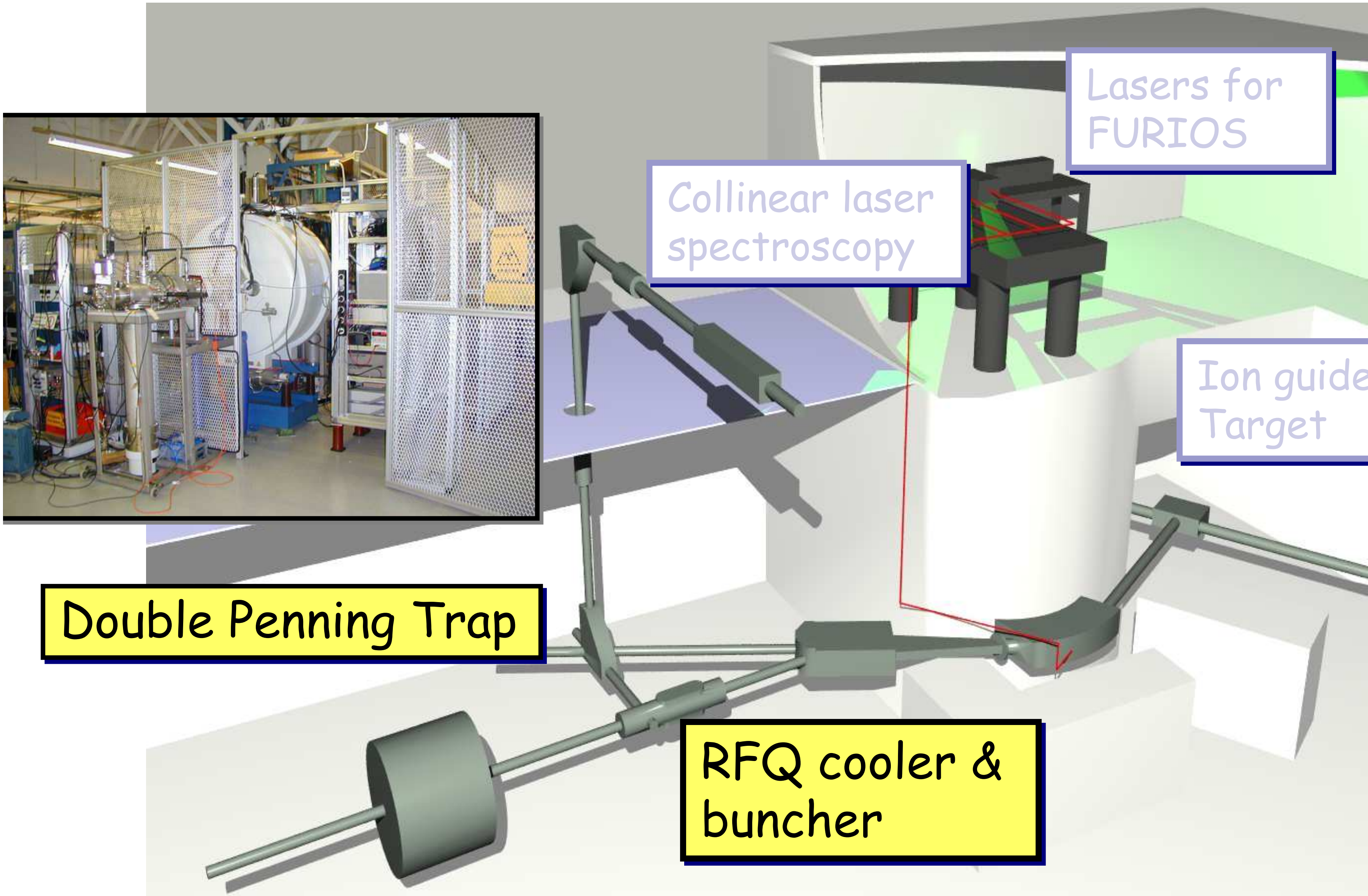
Beam preparation

Penning trap mass measurements

Laser spectroscopy soon

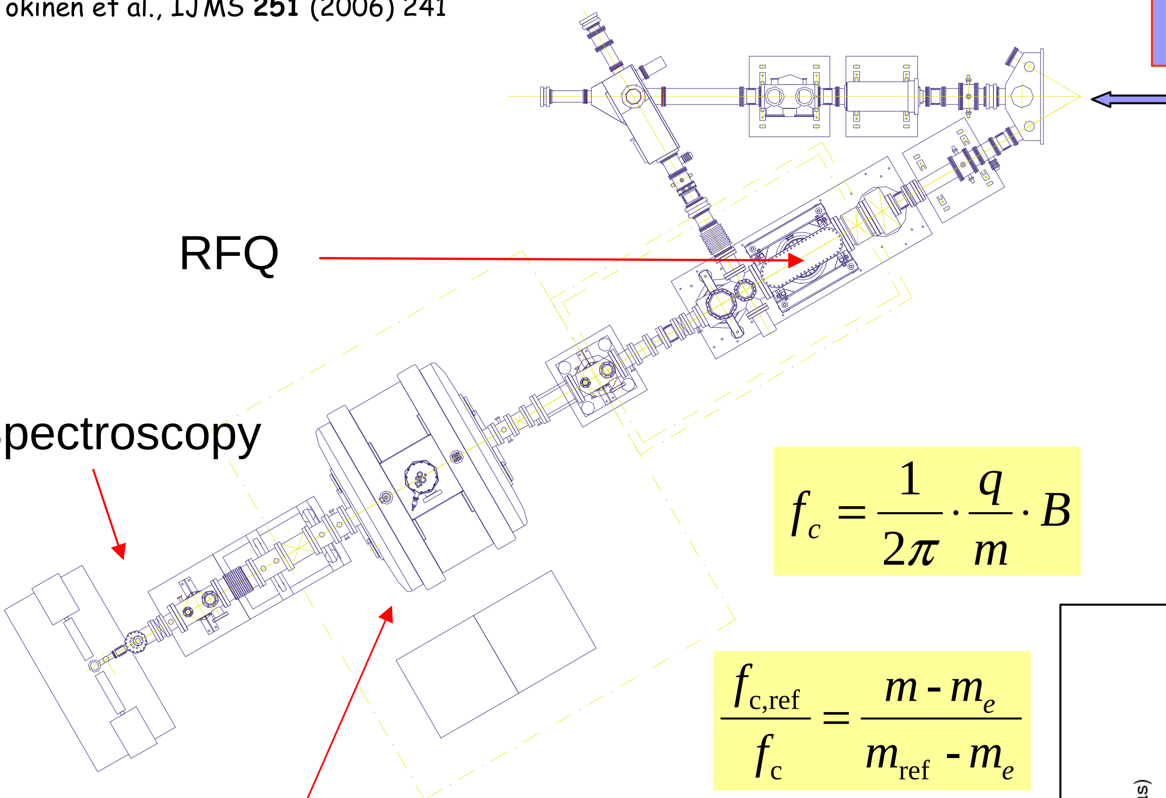
[18] G. Bollen, D. Davies, M. Facina, et al., Phys. Rev. Lett. 96, 152501 (2006).

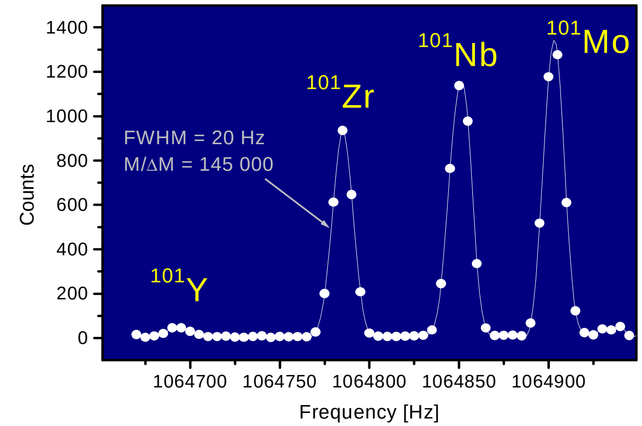
JYFLTRAP-facility



V. Kolhinen et al., NIM A **528** (2004) 776
S. Rinta-Antila et al., PRC **70** (2004) 011301(R)
A. Jokinen et al., IJMS **251** (2006) 241

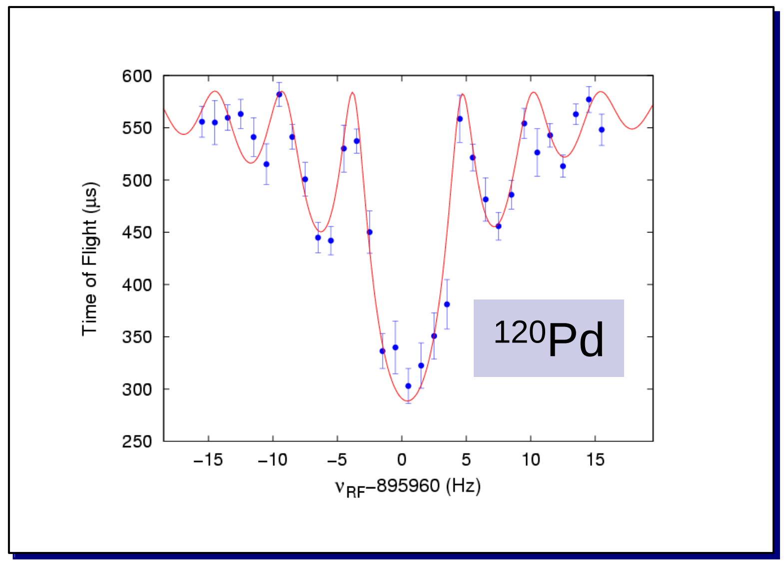
K130-accelerator + IGISOL:
✓ Mass-separated 1+ DC ion beam at 30 keV of all elements.





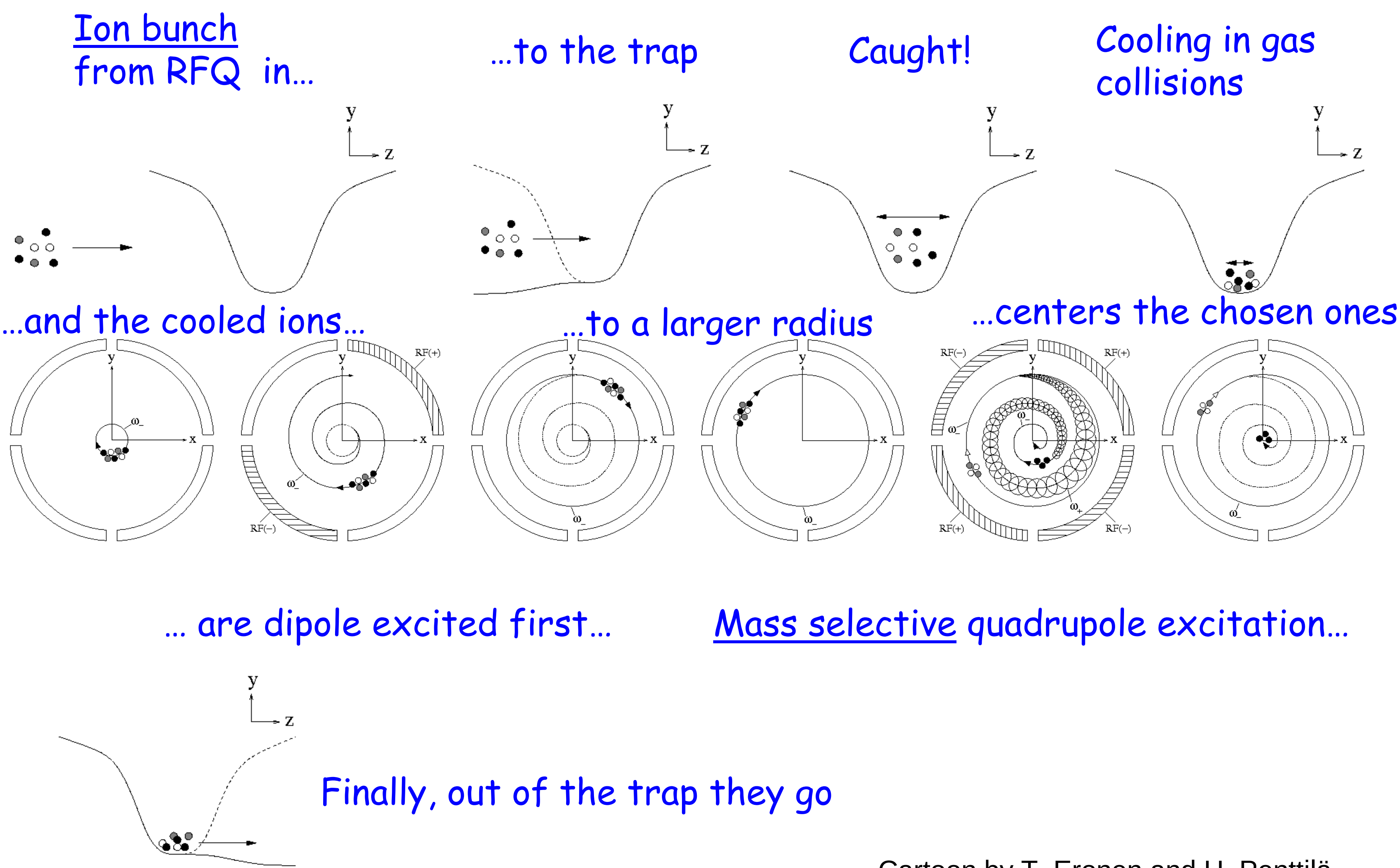
$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$

$$\frac{f_{\mathrm{c,ref}}}{f_{\mathrm{c}}} = \frac{m - m_e}{m_{\mathrm{ref}} - m_e}$$



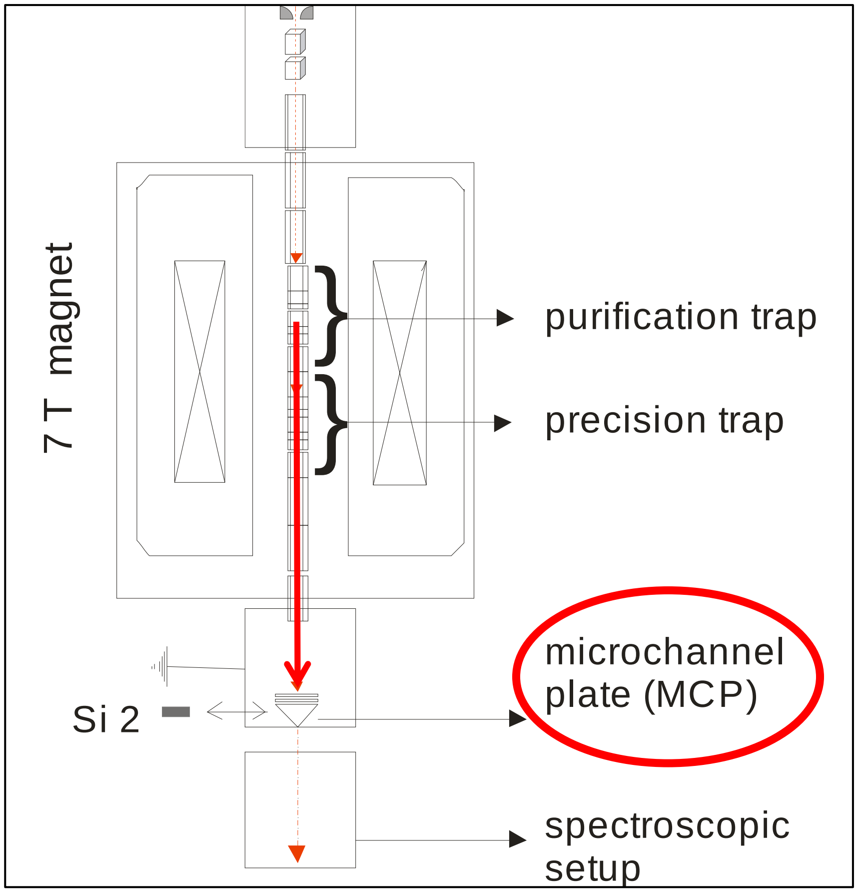
7 T superconducting solenoid @ 30 kV:
Purification trap ($\Delta M/M < 10^{-5}$):
Precision trap ($\Delta M/M < 10^{-6}$):

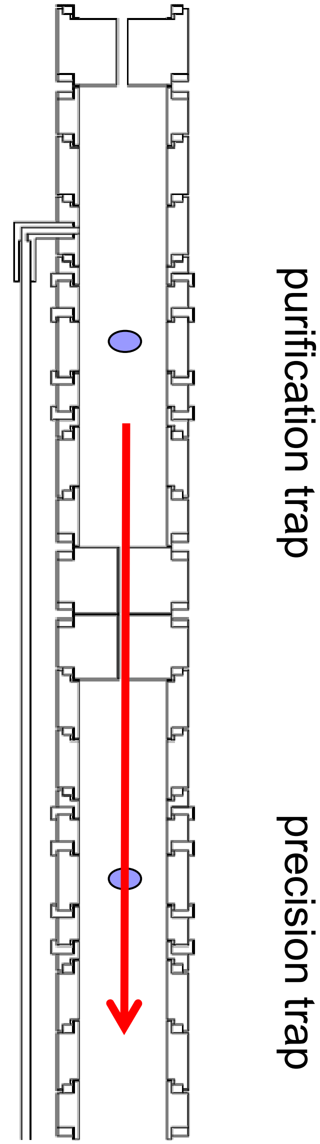
Penning trap purification cycle



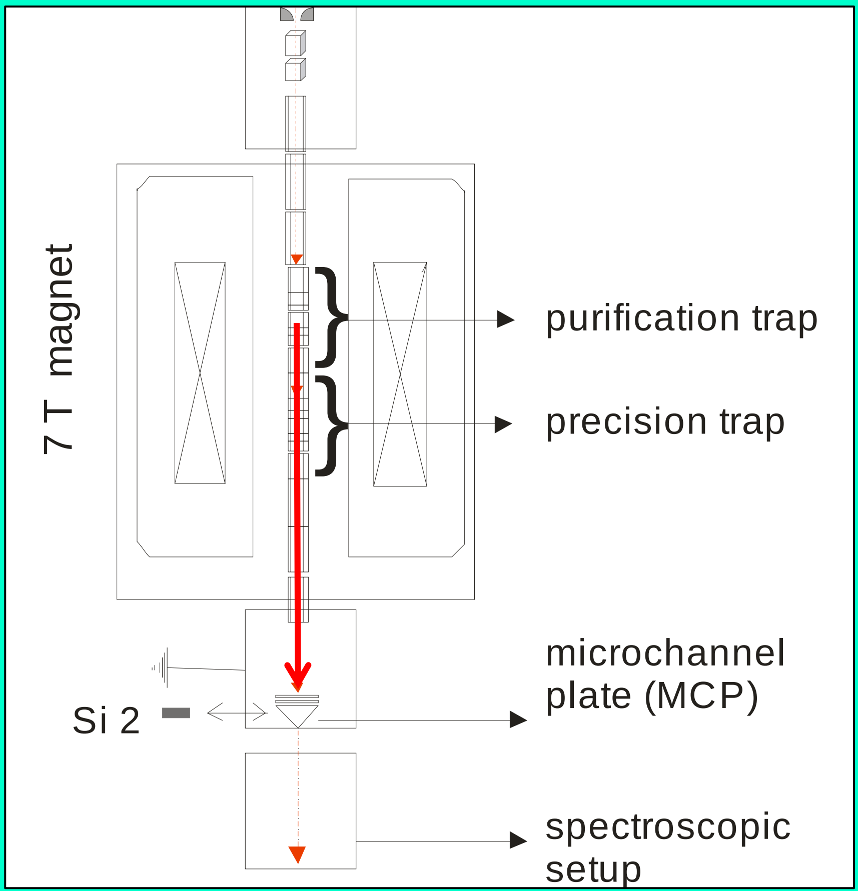
Cartoon by T. Eronen and H. Penttilä

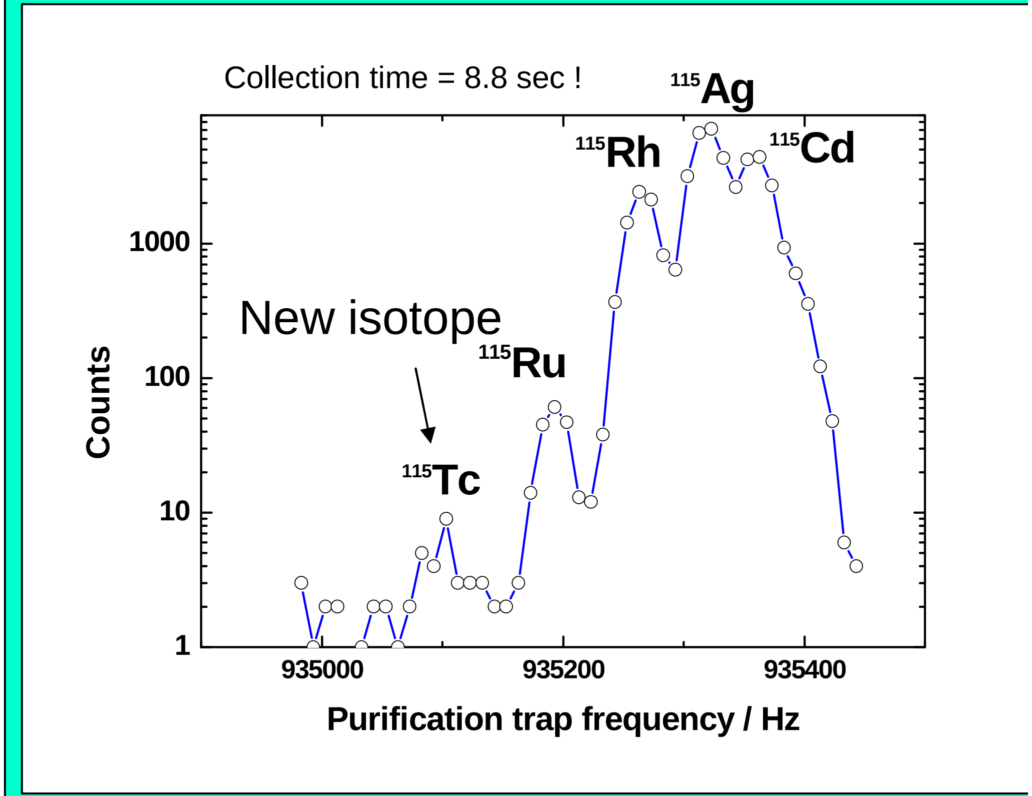
Selection of the good ones: eye of a needle





Example: A= 115 mass scan





Purification cycle: 110 ms
Mass Resolving Power ~ 30000

Independent fission yields

Easy as 1-2-3:

All primary isotopes directly from reaction

Isotopes of all produced elements

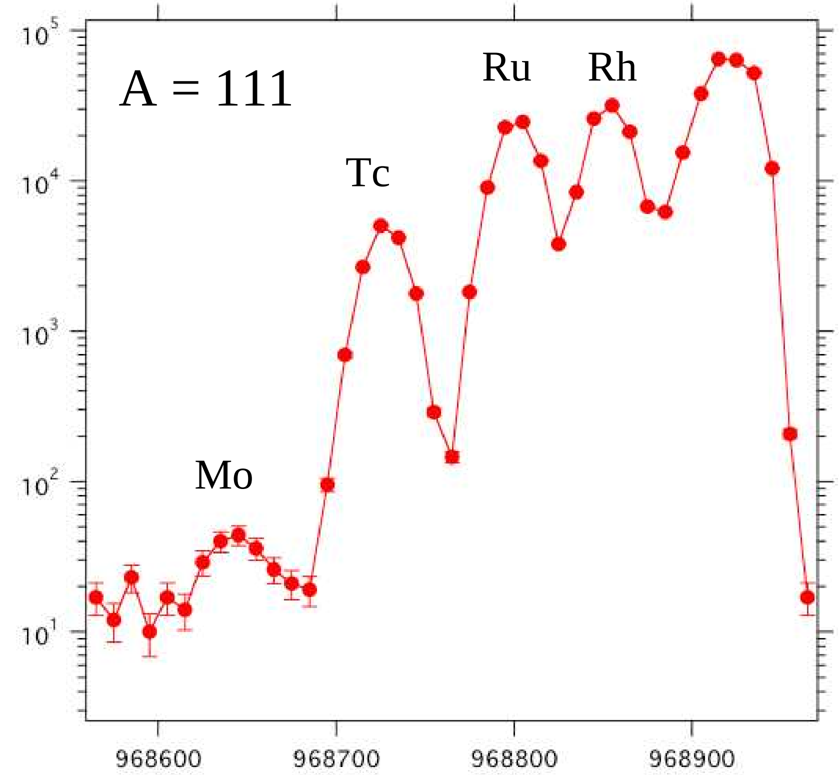
Yield disrtibution related to the independent fission cross sections

But:

Chemical effects: ion guide (**and trap!**) efficiency NOT same for all elements

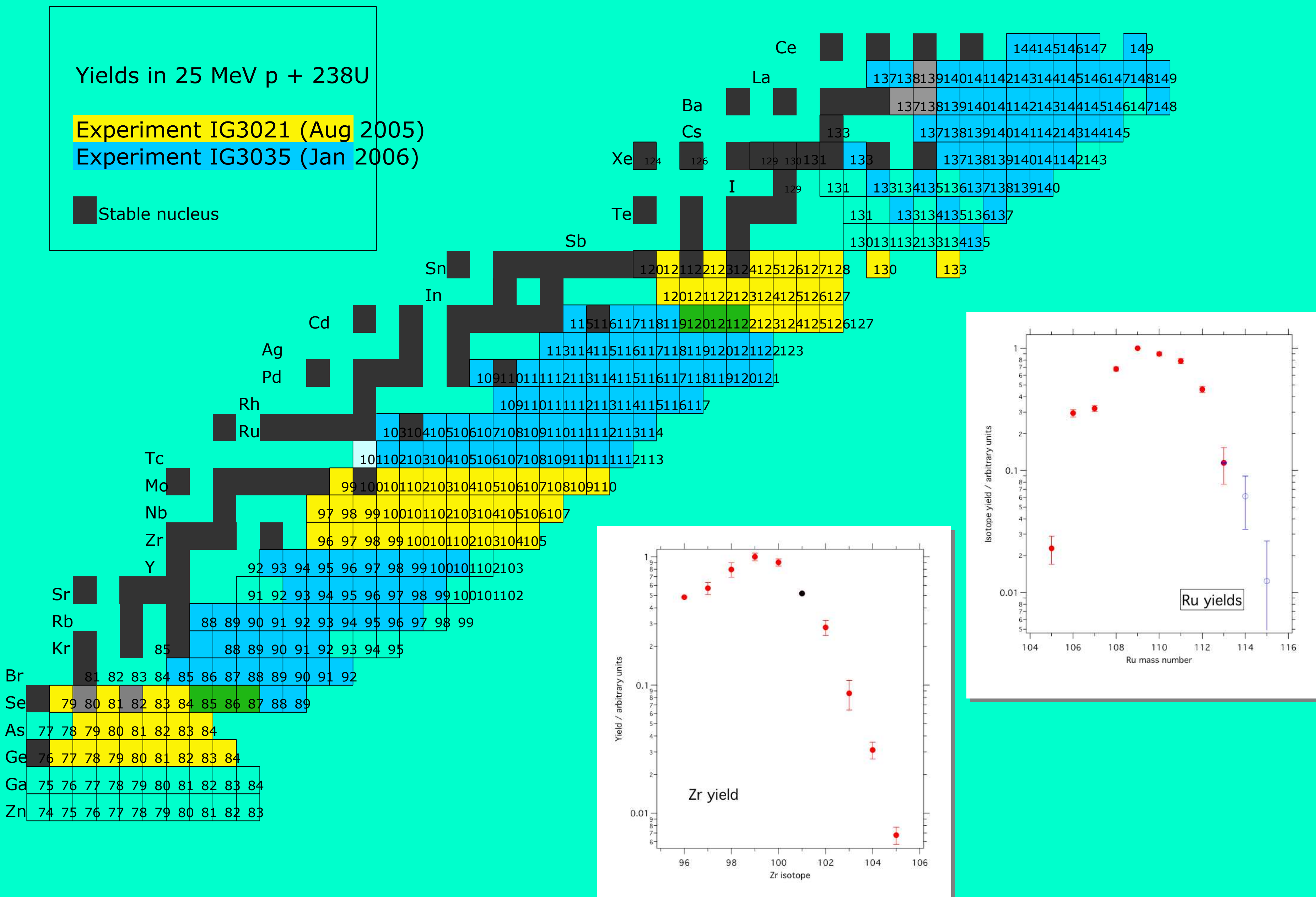
Measured: **relative** isotope yield dirstibutions for each element

Mass cross sections needed for absolute independent cross sections

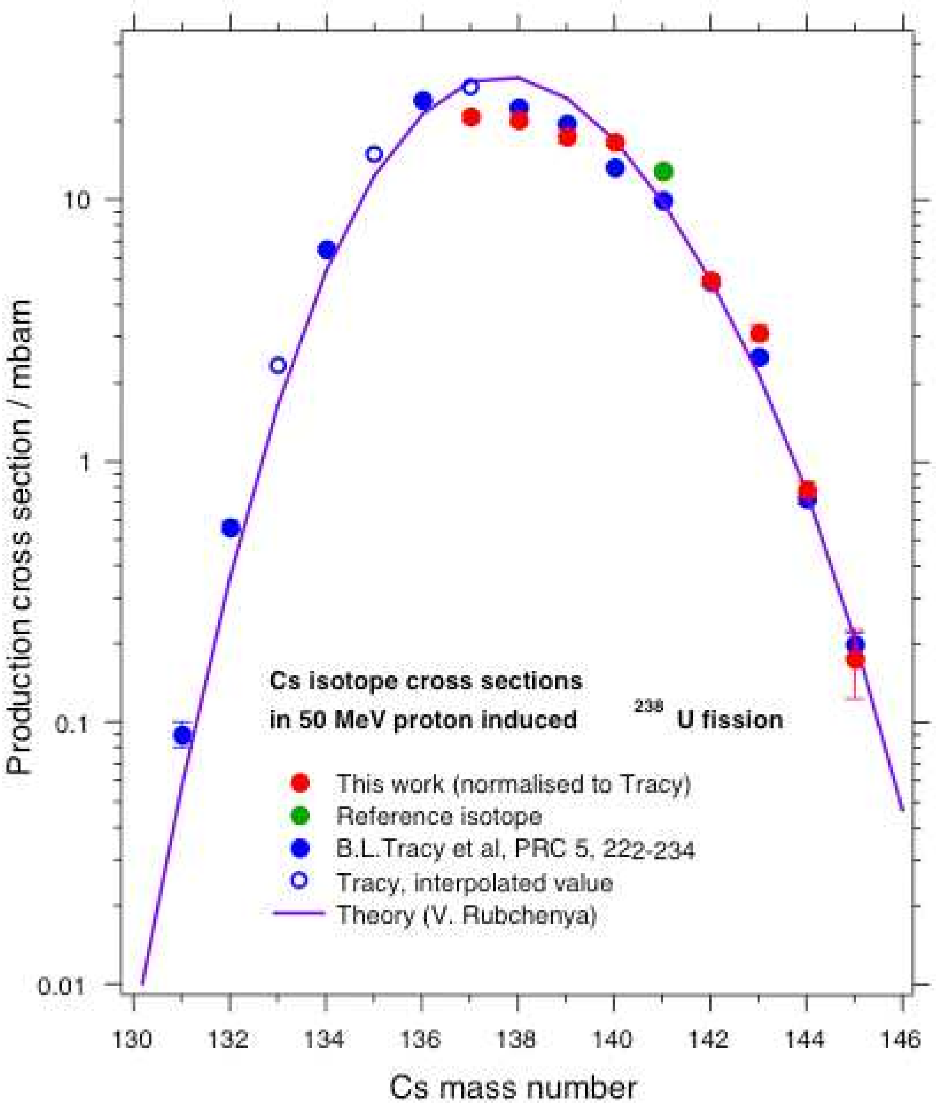


Quadrupole frequency (mass selective centering)

Prompt fission yields for 25 MeV p + ^{238}U



Comparison to existing data



Data on proton induced fission in these projectile energies sparse!

Most reasonable data set from 1972
B.L.Tracy et al, Phys Rev C 5, 222

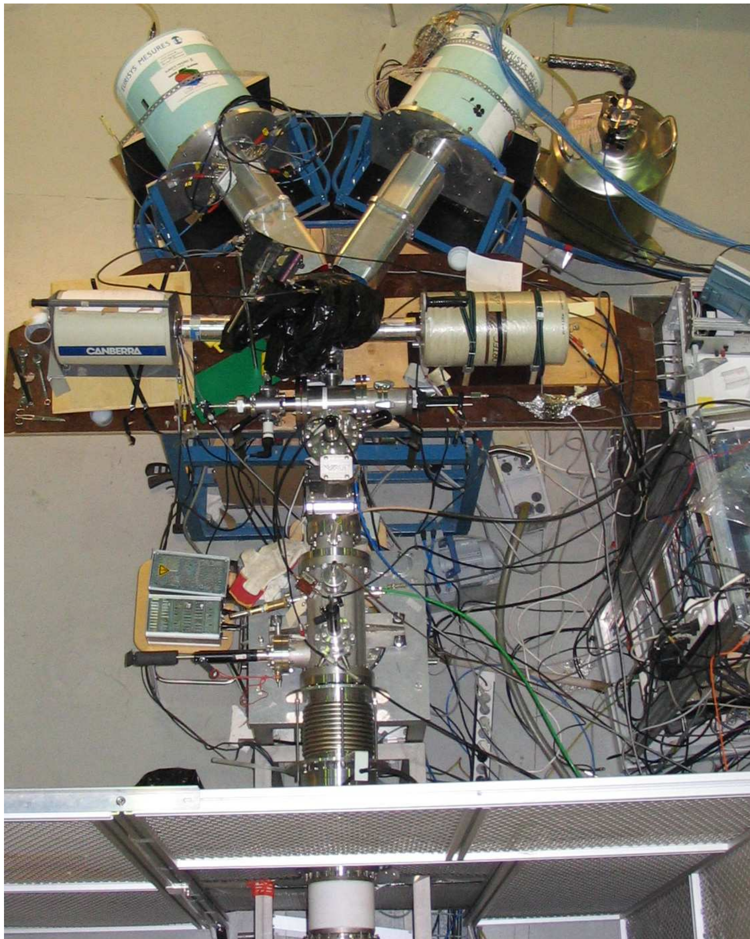
Also based on directly counting ions

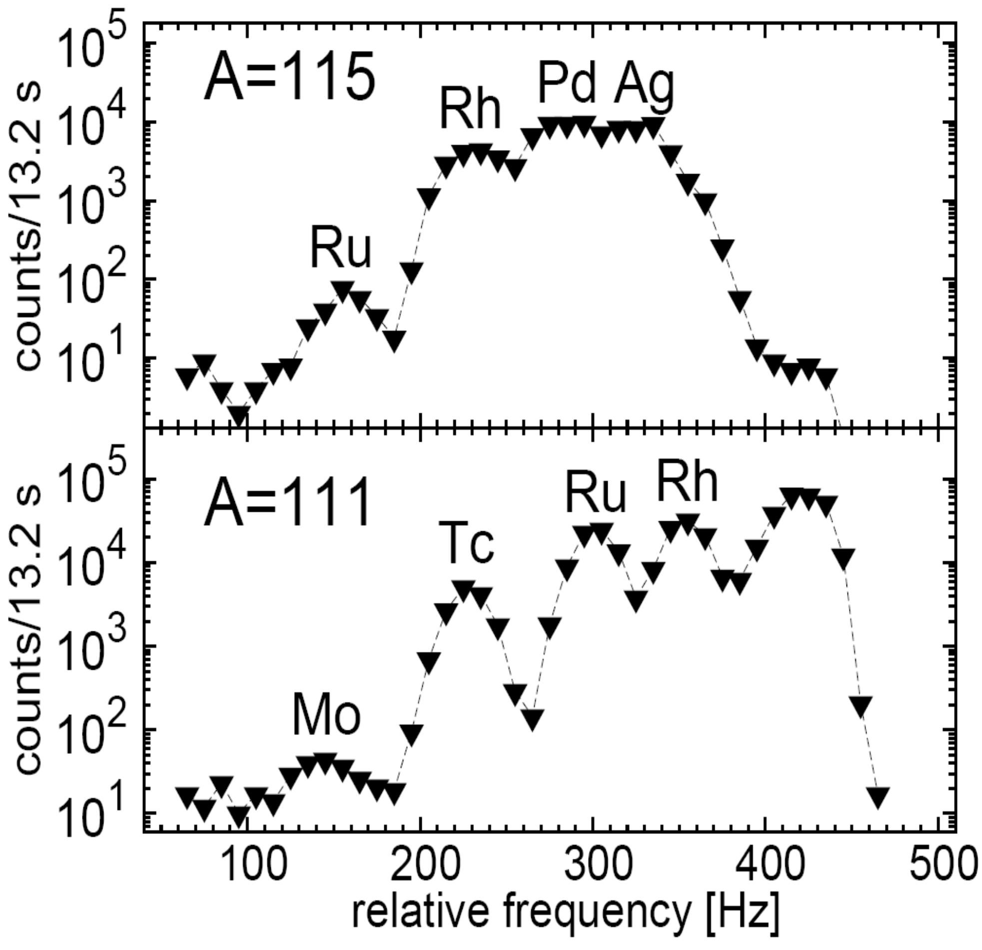
Agreement between data depends pretty much which error you apply on the data points

Post-trap spectroscopy

Isotopically and isomerically pure sources

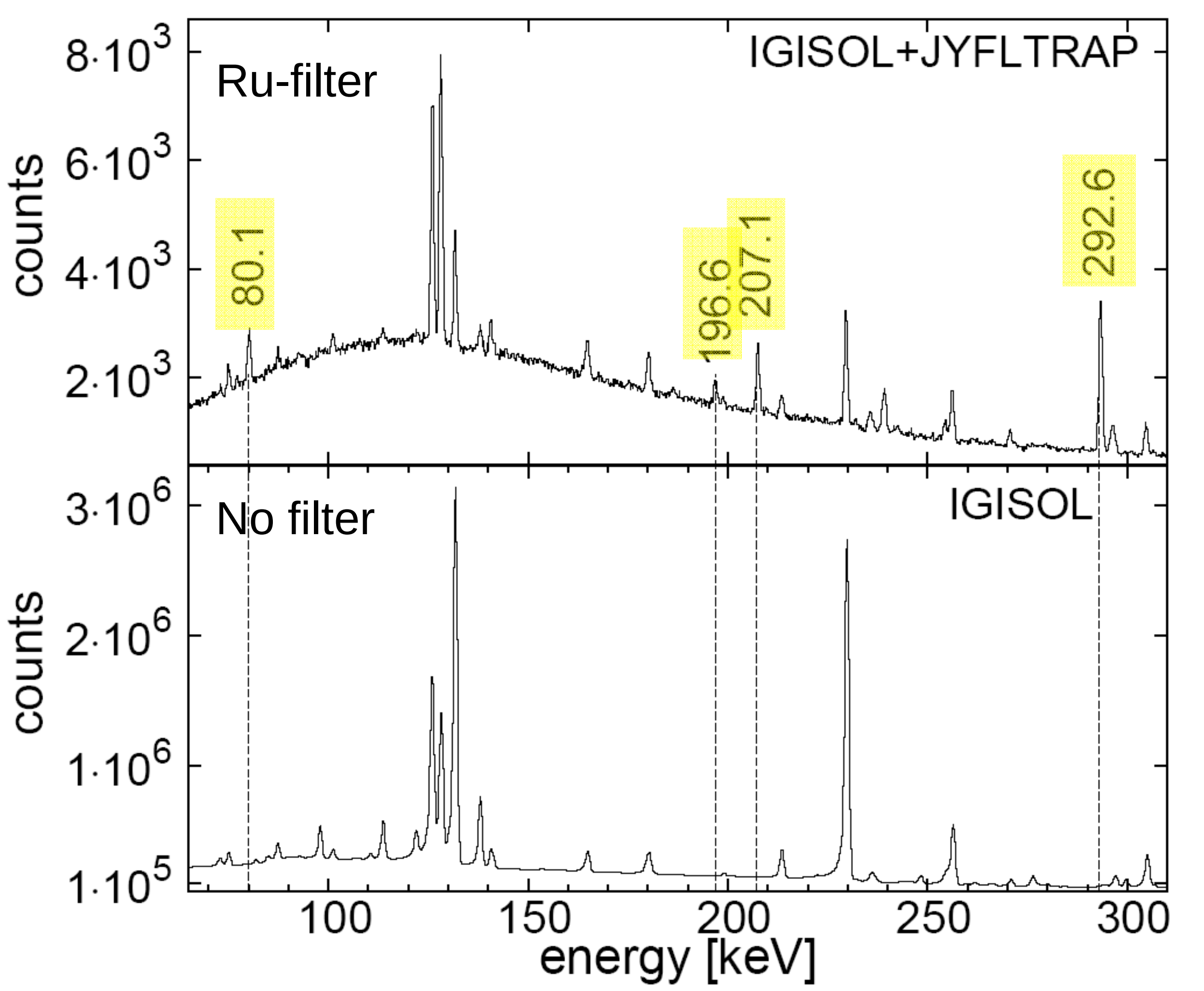
Decay spectroscopy on mass-purified samples of exotic nuclei

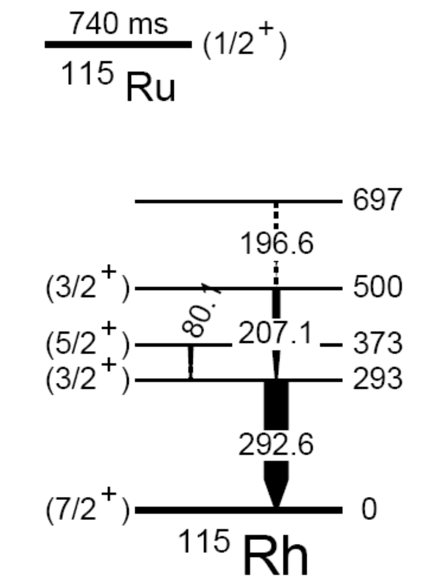




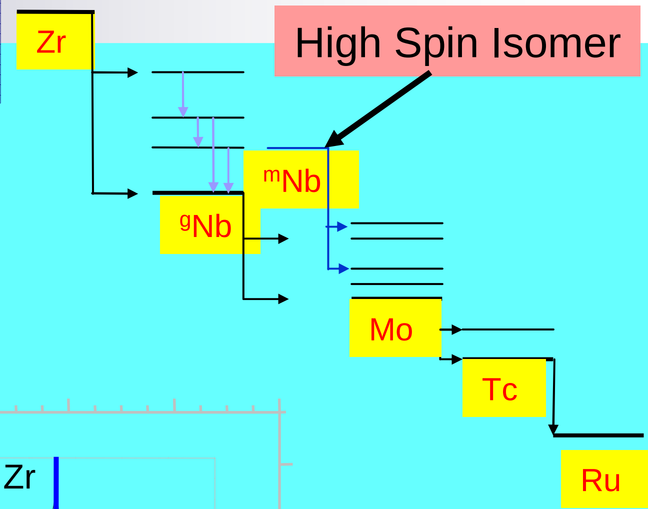
J. Rissanen et al. (2006)

The first decay study of ^{115}Ru

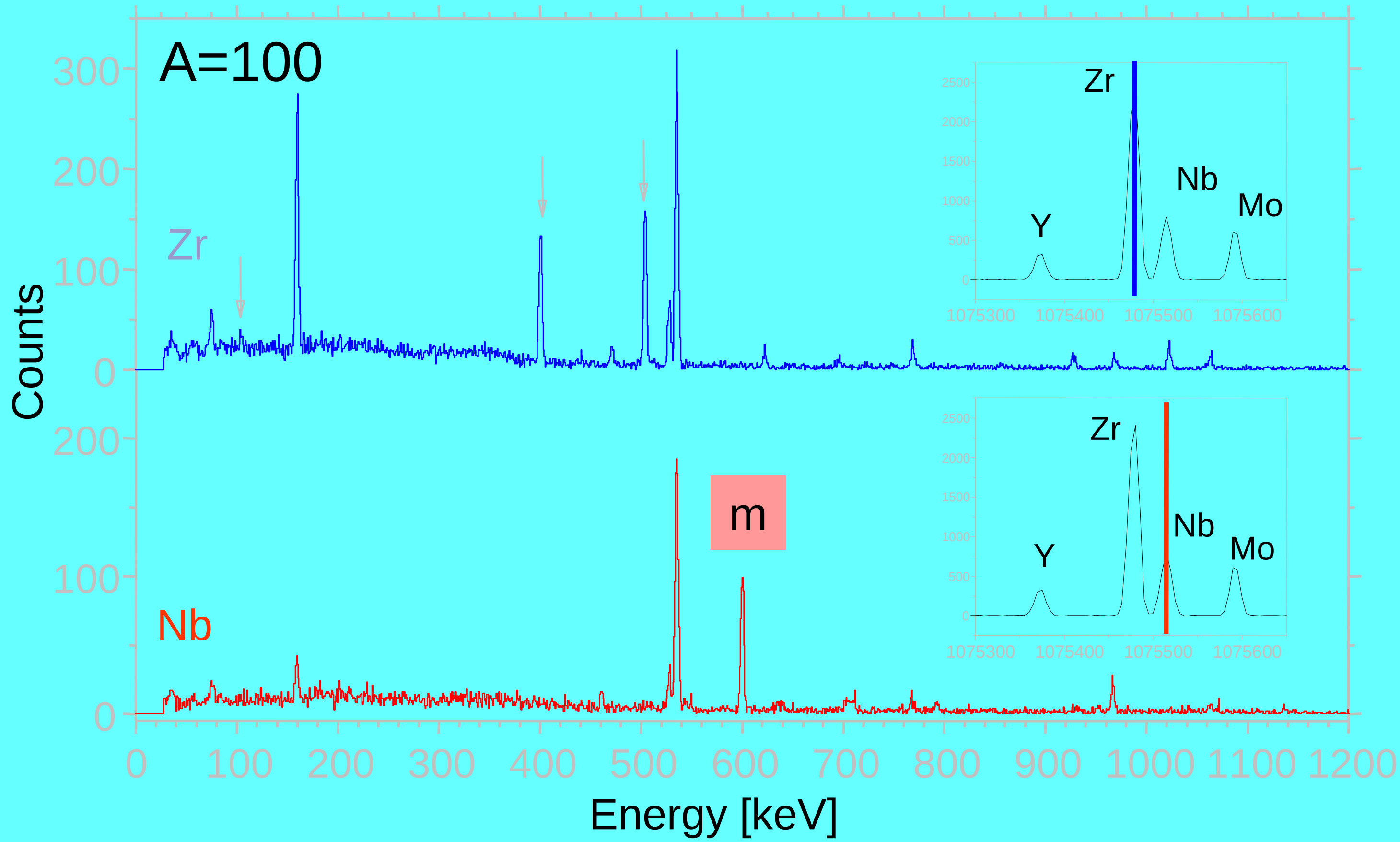




Decay of strongly deformed $^{100,102,104}Zr$



Transmission 40 %
Excellent ion optics after the trap



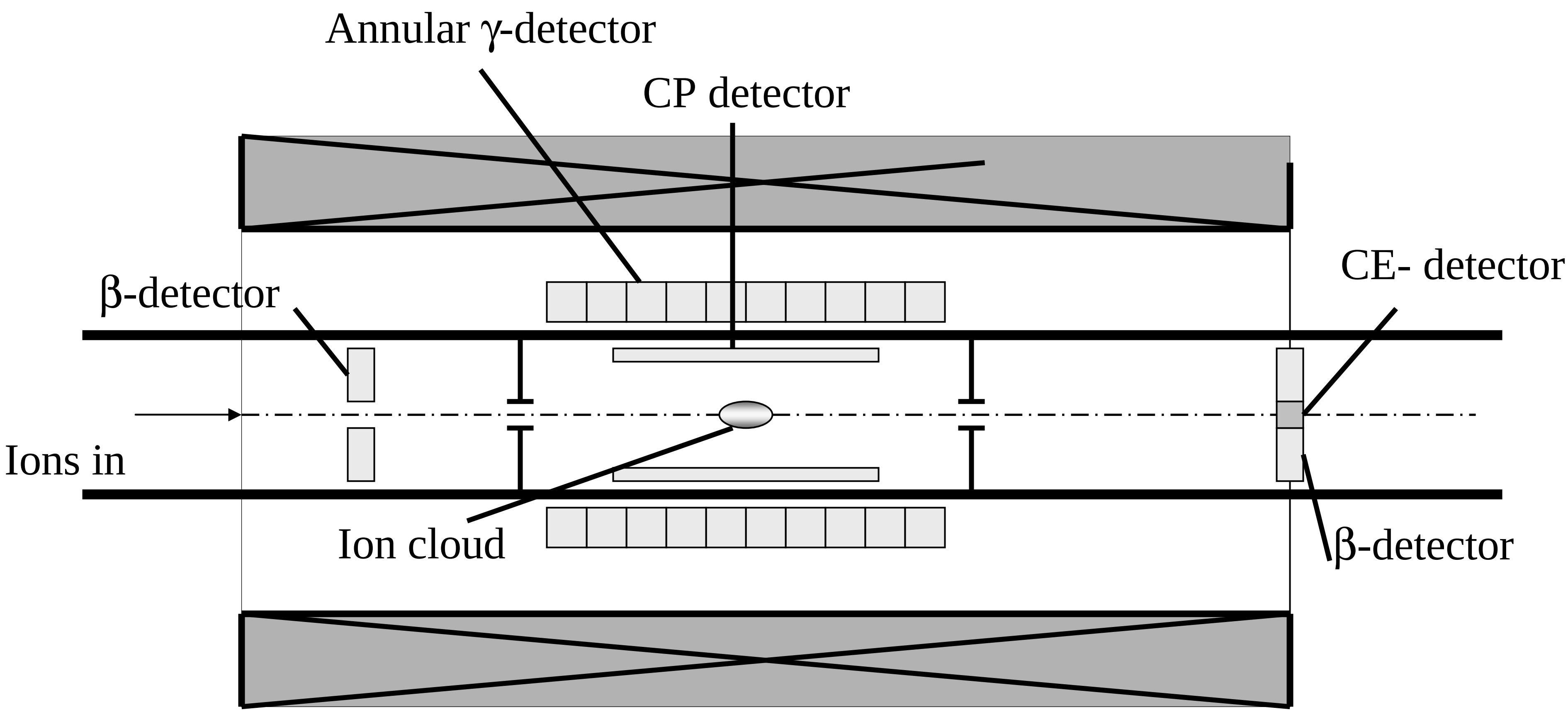
S. Rinta-Antila et al., EPJA

In-trap spectroscopy

In-trap spectroscopy

free of source effects
high efficiency

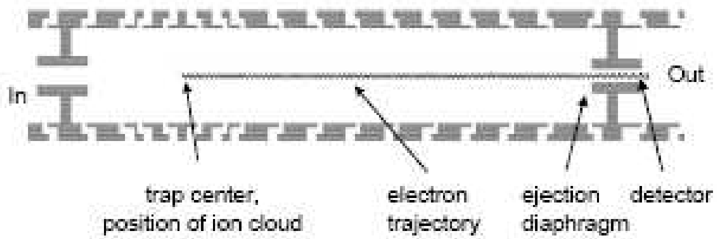
Ion beam coolers in nuclear physics,
J. Äystö and A. Jokinen
J. Phys. B 36 (2003) 573



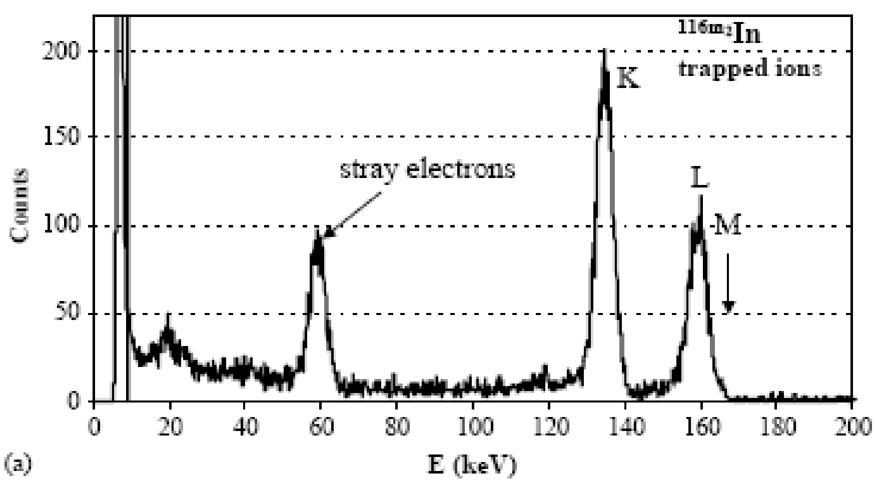
Nuclear Instruments and Methods in Physics Research A 492 (2002) 451–463

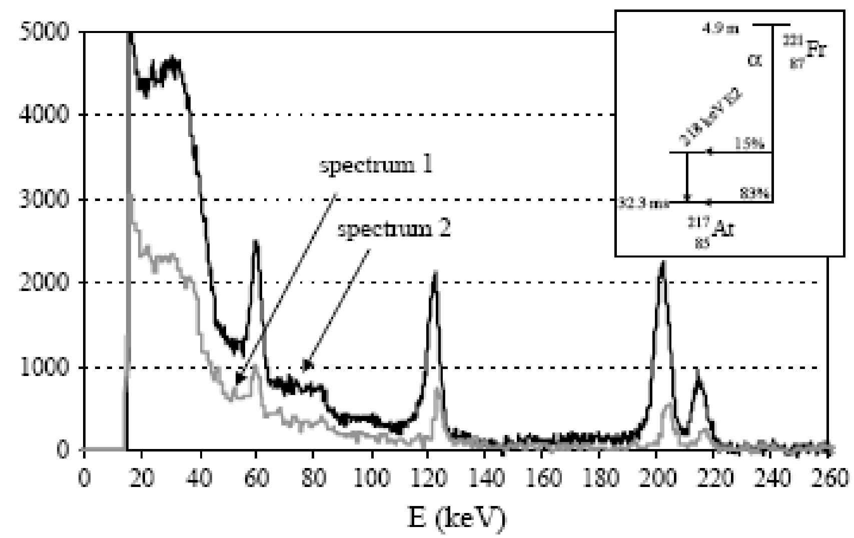
In-trap conversion electron spectroscopy

L. Weissman[a,*], F. Ames[a,b], J. Äysto[a,c], O. Forstner[a], K. Reisinger[a,b], S. Rinta-Antila[d]



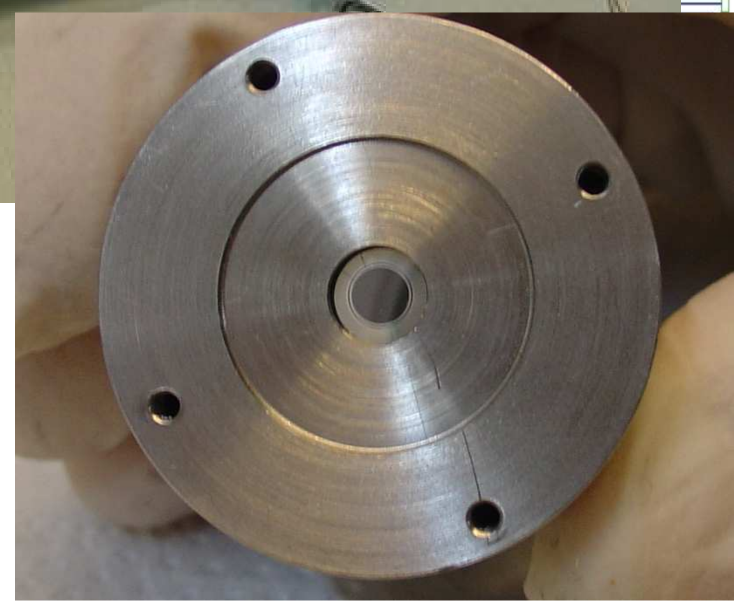
(α,e$^-$) position information
→ τ(E2) transition





JYFLTRAP in conversion electron spectroscopy

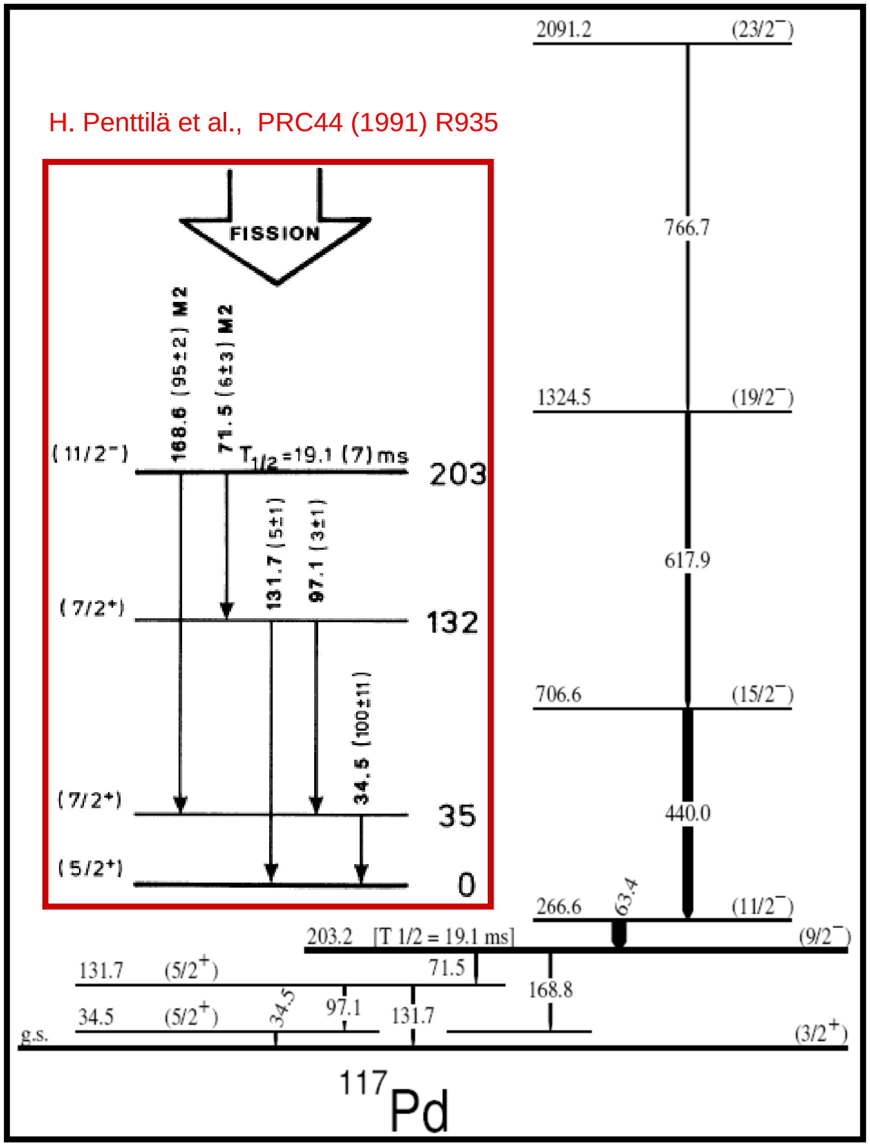
center of the purification trap



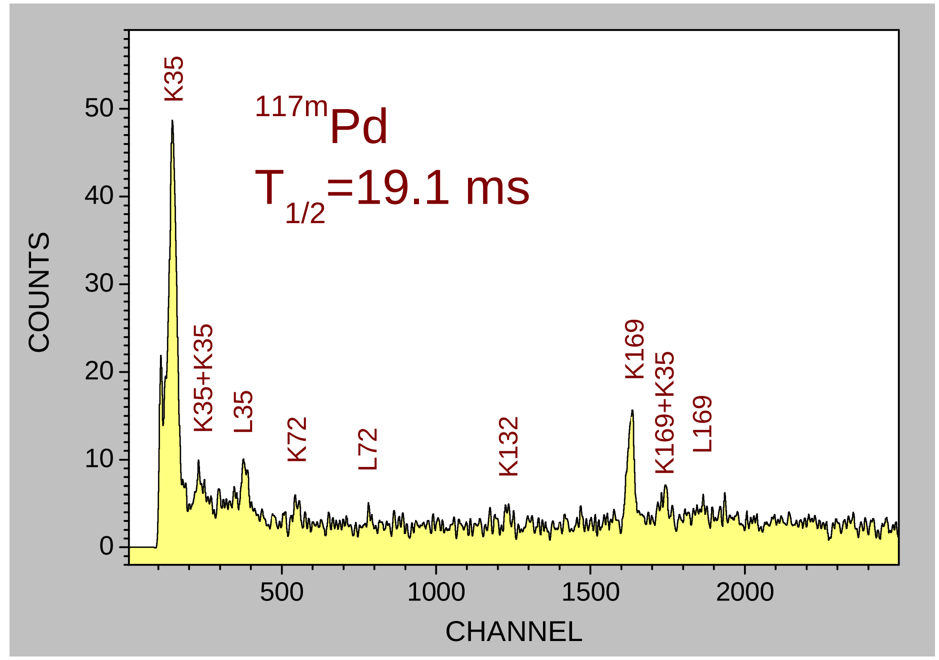
Canberra RD EB 10GC-500P
Thickness 500 µm
Active area 10 mm^2 (r = 1.78 mm)
Dead layer 250 Å
PA 1201 Pre amp
Resolution less than 1 keV for 59.5 Xray ^{241}Am

J. Rissanen Diploma thesis 2005

In-trap spectroscopy; commissioning run for ^{117m}Pd



W. Urban et al., EPJA 22 (2004) 157



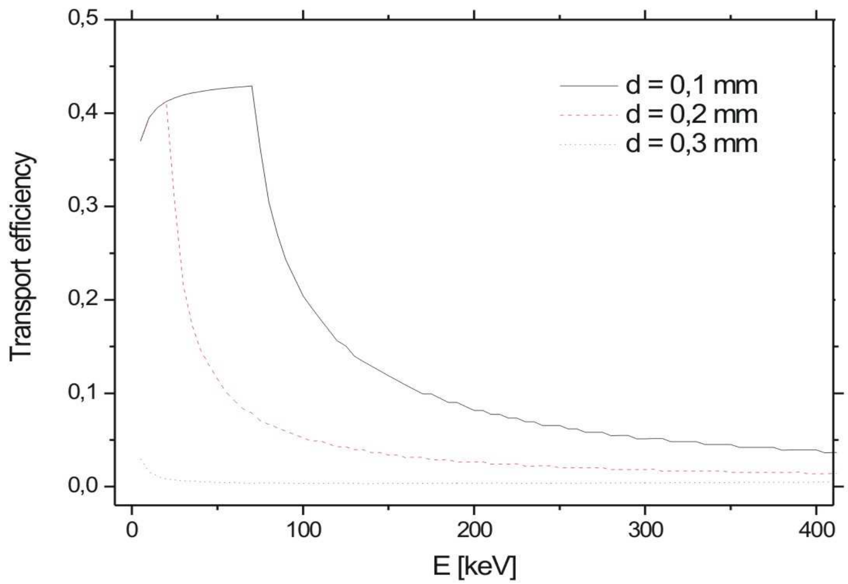
- ✓ ^{238}U(p,f) @ 25 MeV
- ✓ 10 mm^2 Si-detector @ B=0.7 T
- ✓ Excellent lineshape
- ✓ Efficient collection of electrons
- ✓ Background-free spectra
- ✓ Extends to very low energies
- ✓ No X-rays !
- ✓ Applicable to rather short-lived states

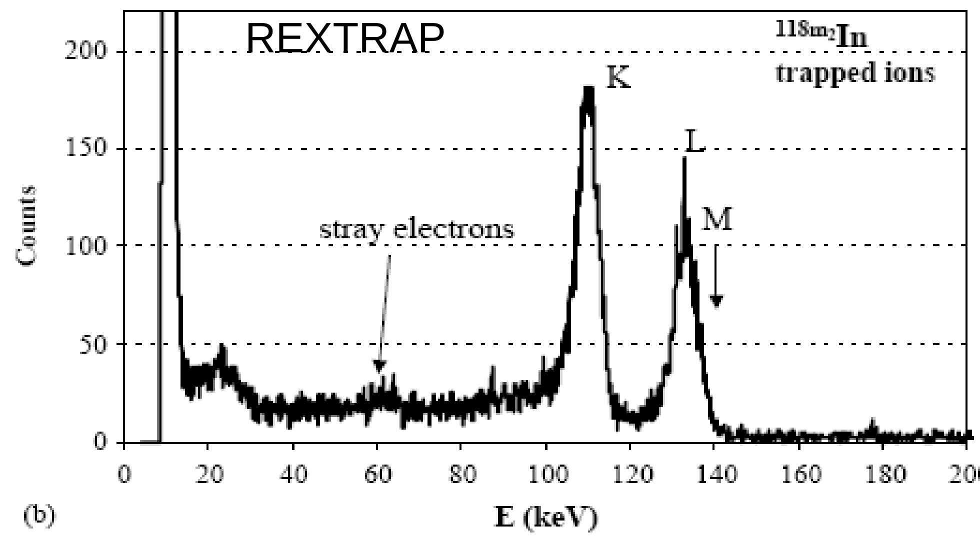
J. Rissanen et al. (2006)

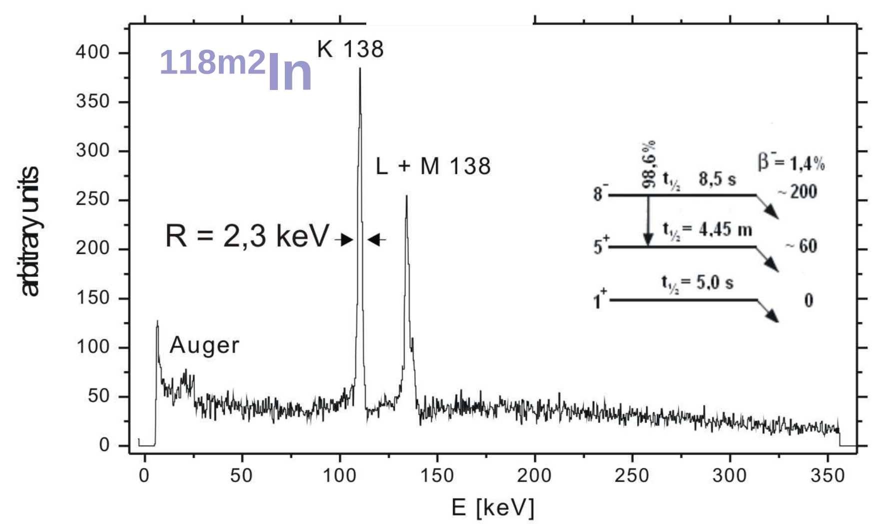
Online Results: ^{117m}Pd and ^{118m2}In

a)

Transport efficiency







J. Rissanen et al. to be published