MR-ToF precision mass measurements of short-lived nuclides

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for the ISOLTRAP Collaboration

NAVI Annual Meeting
17.12.2013, GSI Darmstadt

- *Mass measurements of short-lived nuclides*
- *MR-ToF mass spectrometry*
- *MR-ToF-MS at ISOLTRAP for ...*
- *... isobar separation: ^{82}Zn and Penning-trap stacking*
- *... ion-beam analysis: target/ion source development*
- *... precision mass measurements: n-rich Ca isotopes*
- *Summary*

Mass measurements of short-lived nuclides

$$m(Z,N) = Z \cdot m_\mathrm{p} + Z \cdot m_\mathrm{e} + N \cdot m_\mathrm{n} - BE/c^2$$

➔ **input for nuclear physics and astrophysics models and calculations**

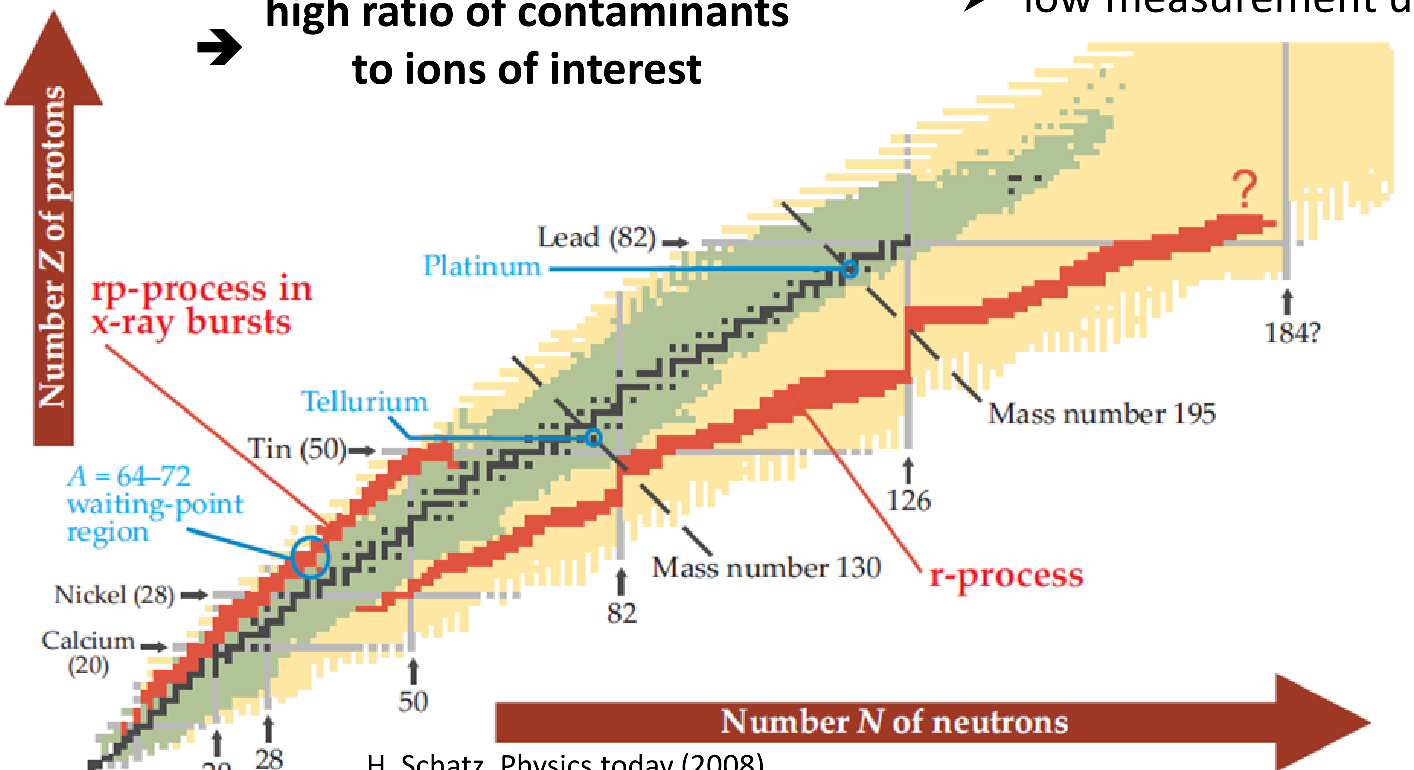
Challenges for experiments on short-lived nuclides:

- half-life: <1s
- production: <100 ions/s
- contaminats: long lived, high yield

➔ **high ratio of contaminants to ions of interest**

Aims and requirements:

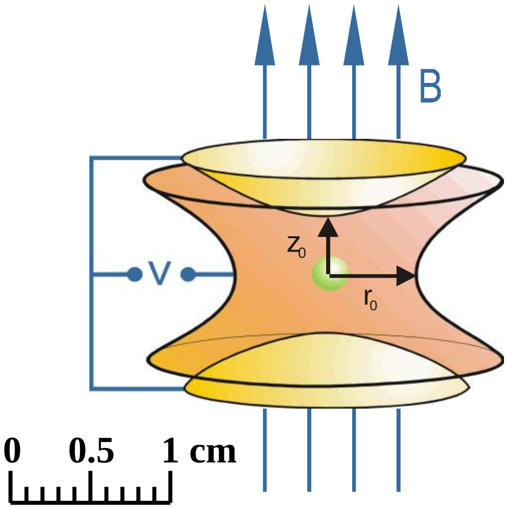
- high mass resolving power
- high contamination suppression
- fast measurement cycle
- low measurement uncertainty



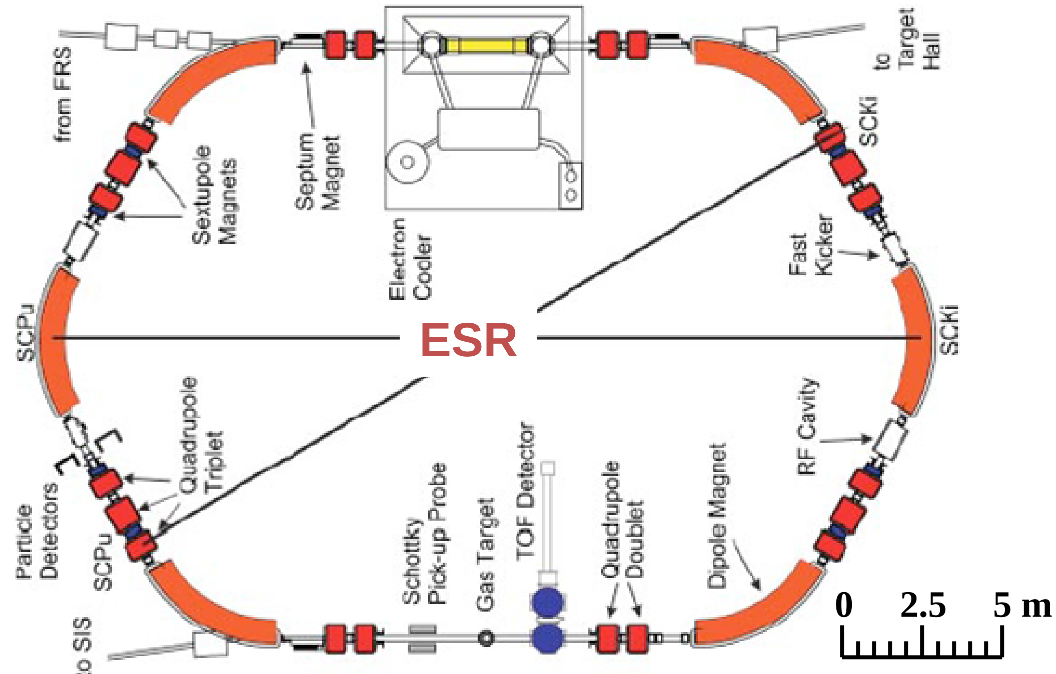
H. Schatz, Physics today (2008)

Direct mass measurements techniques – the well-known

Penning trap

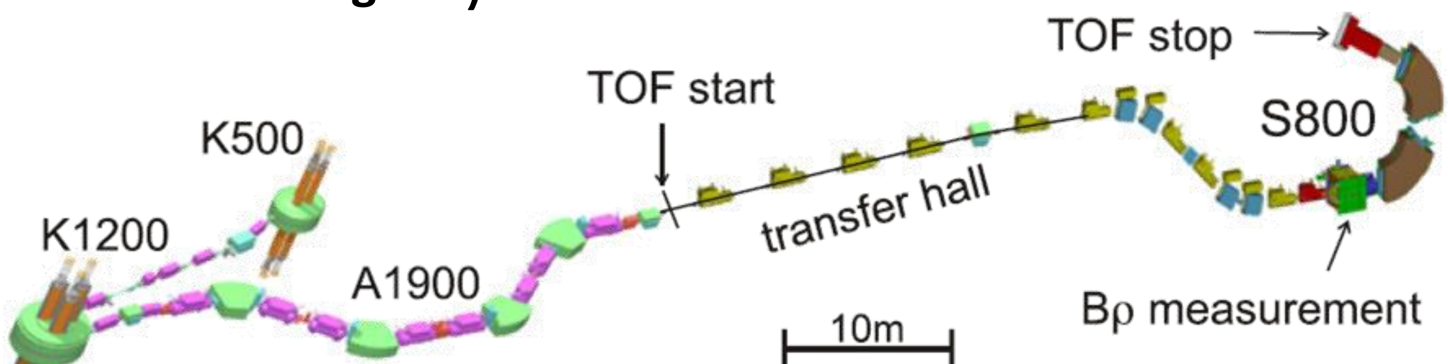


Storage ring



Franzke *et al.*, MSR 27, 428 (2008)

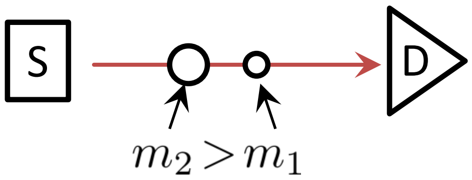
Time-of-flight-$B\rho$



NSCL: Matos *et al.*, NIM A 696, 171 (2012)

Multi-Reflection Time-of-Flight Mass Spectrometry

1950s: ToF-MS



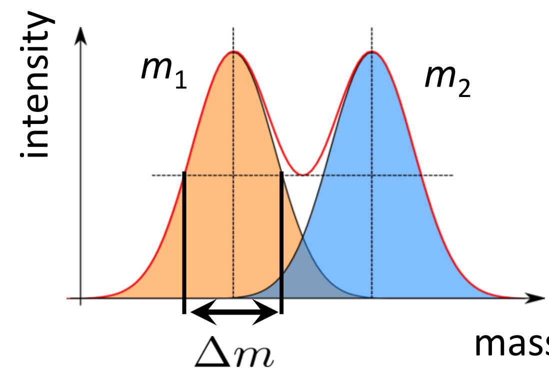
$t \sim 0.01\,\mathrm{ms}, \;\; R \sim 500$

ion flight time:

$$t \propto \sqrt{\frac{m}{q}}$$

mass resolving power:

$$R = \frac{m}{\Delta m} = \frac{t}{2\Delta t}$$

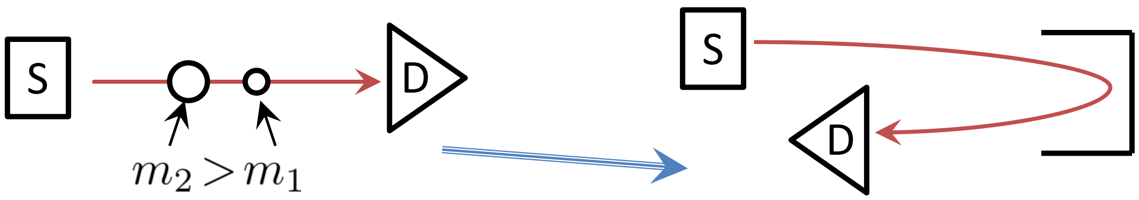


Wollnik & Przewloka, Int. J. Mass Spectrom. Ion Proc. 96, 267 (1990)

Multi-Reflection Time-of-Flight Mass Spectrometry

1950s: ToF-MS

1970s: R-ToF-MS



$t \sim 0.01\,\mathrm{ms}, \;\; R \sim 500$

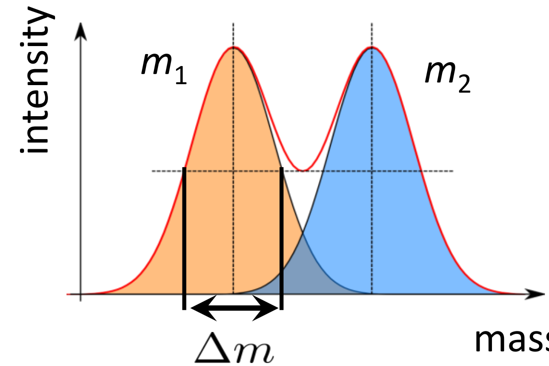
$t \sim 0.1\,\mathrm{ms}, \;\; R \sim 5000$

ion flight time:

$$t \propto \sqrt{\frac{m}{q}}$$

mass resolving power:

$$R = \frac{m}{\Delta m} = \frac{t}{2\Delta t}$$



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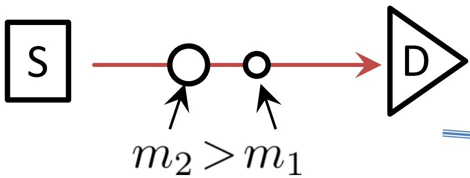

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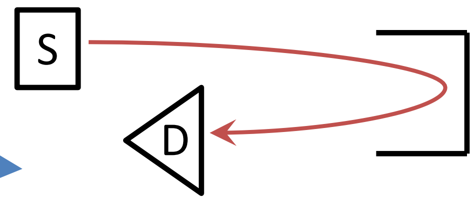
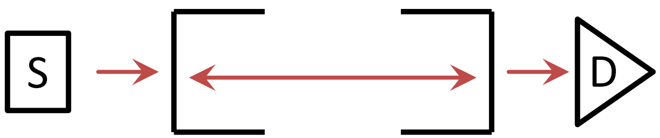
1970s: R-ToF-MS



$t \sim 0.1\,\mathrm{ms}, \;\; R \sim 5000$

1990s: MR-ToF-MS



$t \sim 10\,\mathrm{ms}, \;\; R \sim 100\,000$

ion flight time:

$$t \propto \sqrt{\frac{m}{q}}$$

mass resolving power:

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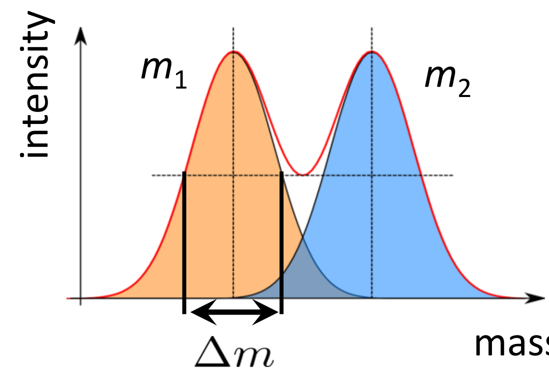

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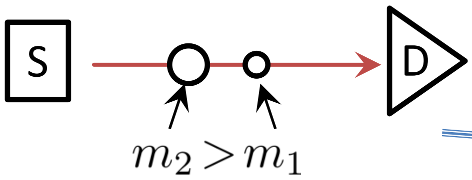

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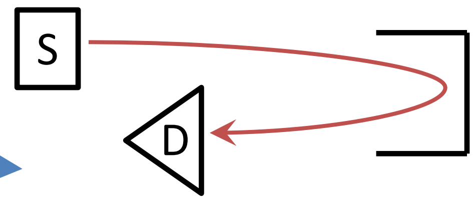
1970s: R-ToF-MS



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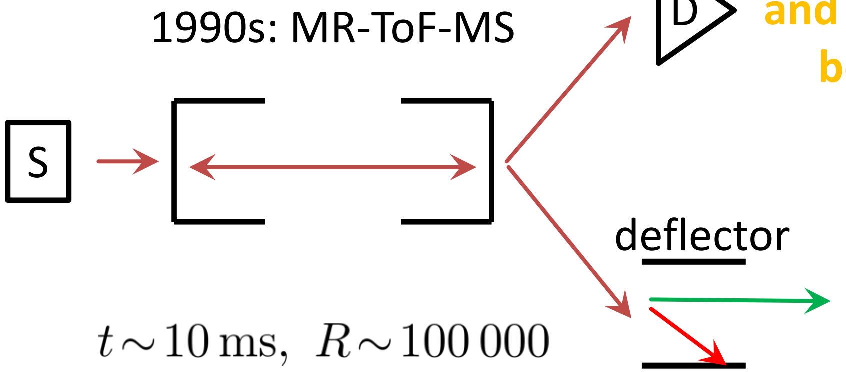

$t \sim 10\,\text{ms}, \;\; R \sim 100\,000$

TODAY:

mass measurement and high-resolution beam analysis

mass purification for subsequent experiments → Penning traps, decay stations, ...

ion flight time:

$$t \propto \sqrt{\frac{m}{q}}$$

mass resolving power:

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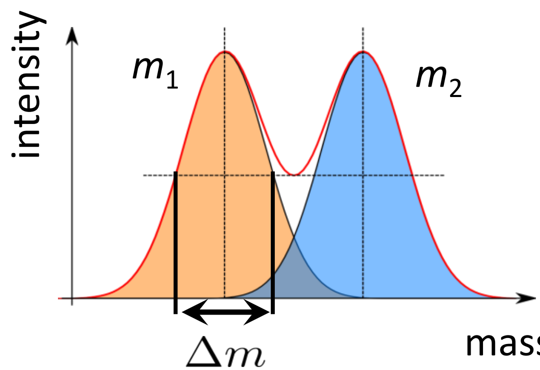
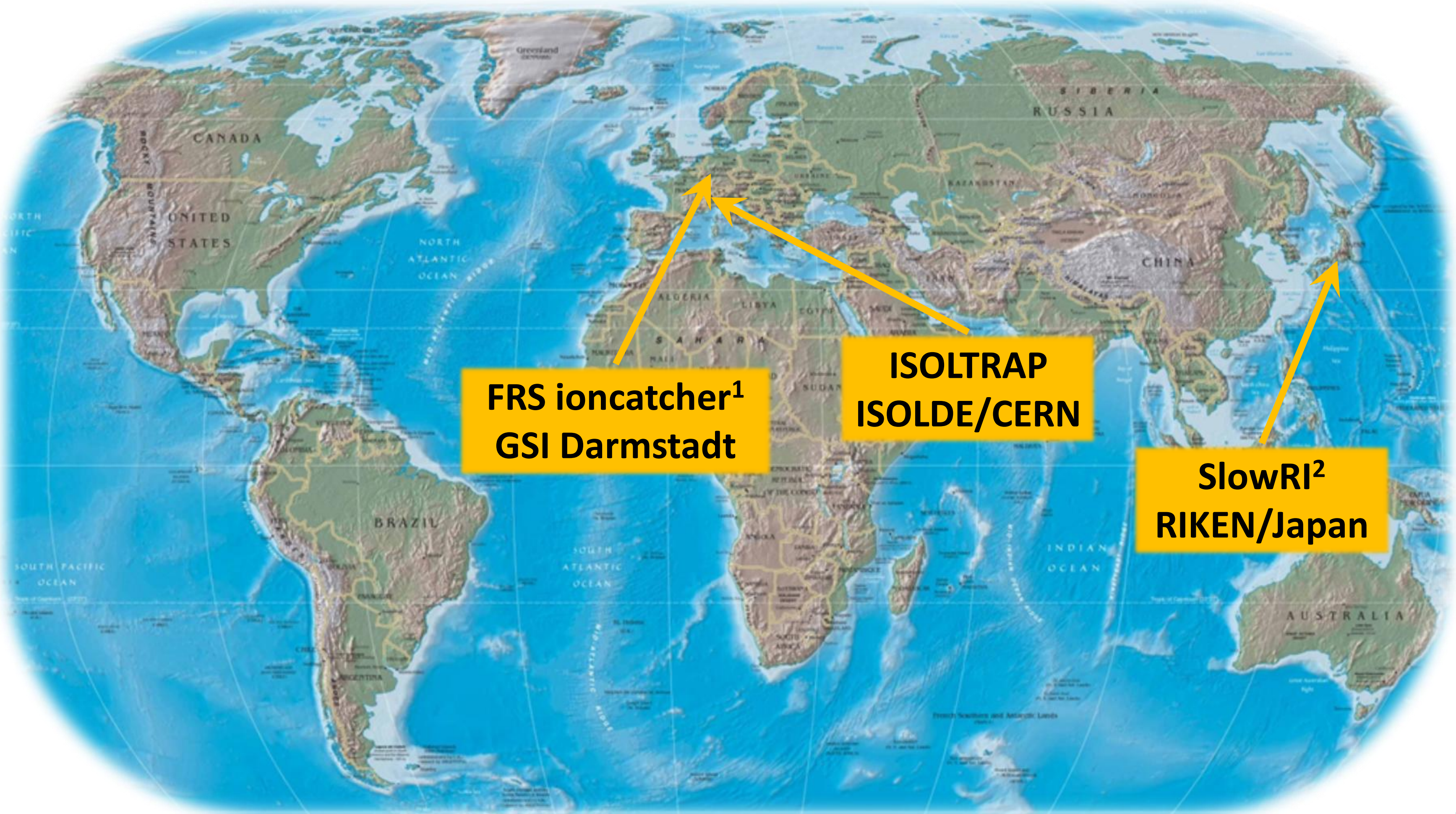


Wollnik & Przewloka, Int. J. Mass Spectrom. Ion Proc. 96, 267 (1990)

Multi-Reflection Time-of-Flight Mass Spectrometry for short-lived nuclides

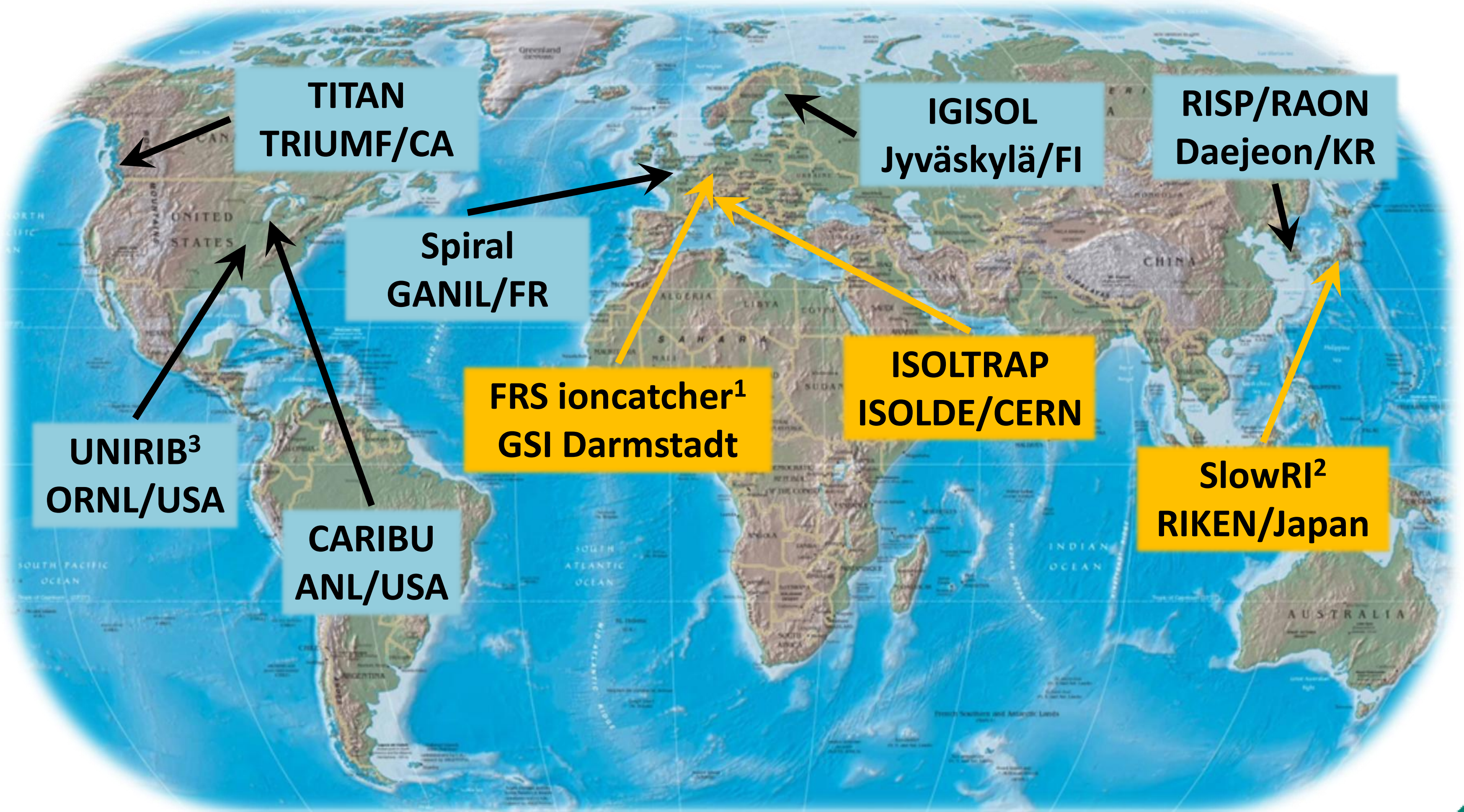
Systems in operation



1: Plaß *et al.*, IJMS 349-350, 134 (2013); NIM B 317, 457 (2013); NIM B 266, 4560 (2008); EPJ ST 150, 367 (2007)
2: Schury *et al.*, NIM B 317, 537 (2013); EPJ A 42, 343 (2009); Ito *et al.*, PRC 88, 011306R (2013); Ishida *et al.*, NIM B 241, 983 (2005)

Multi-Reflection Time-of-Flight Mass Spectrometry for short-lived nuclides

Systems in operation and under construction/development



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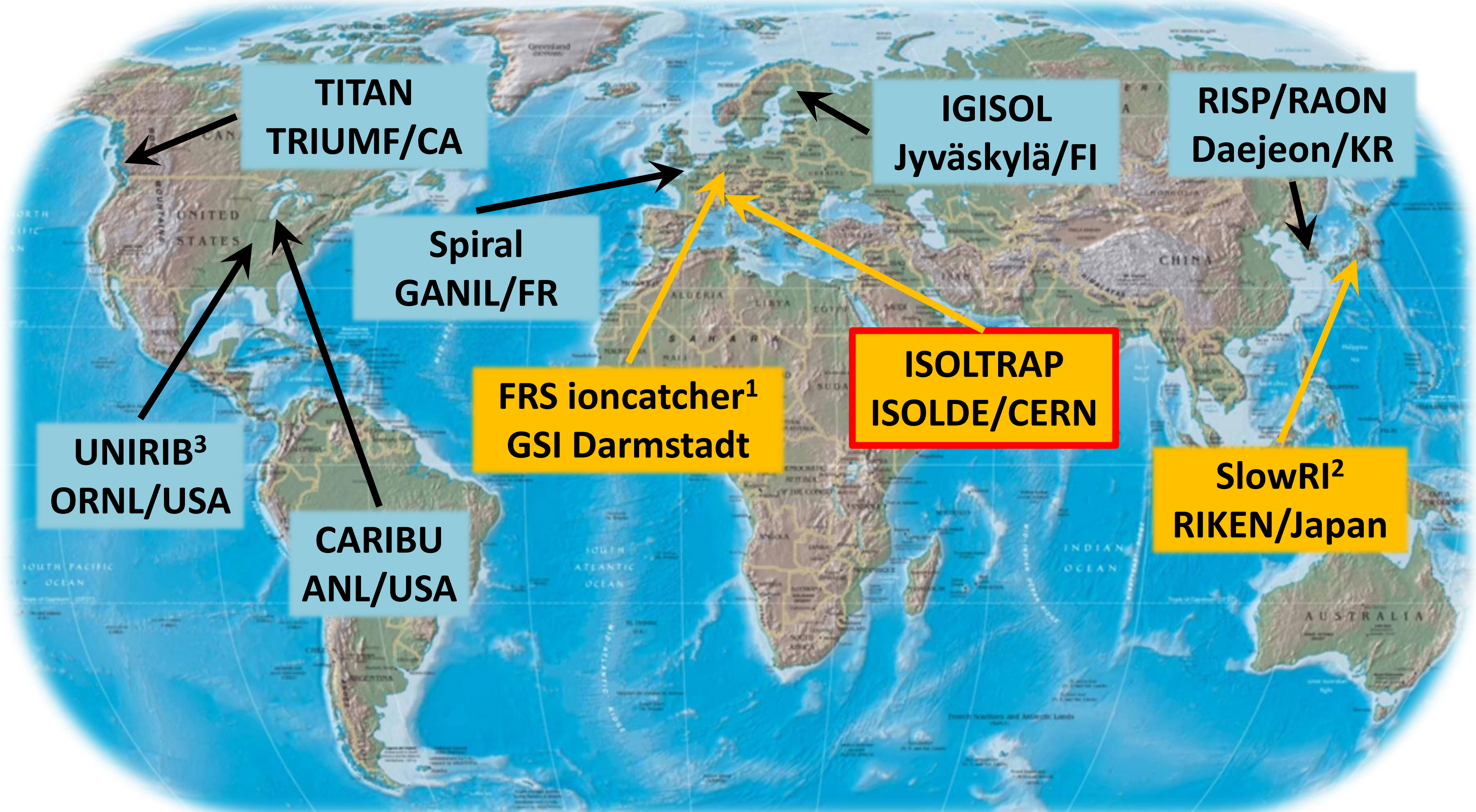

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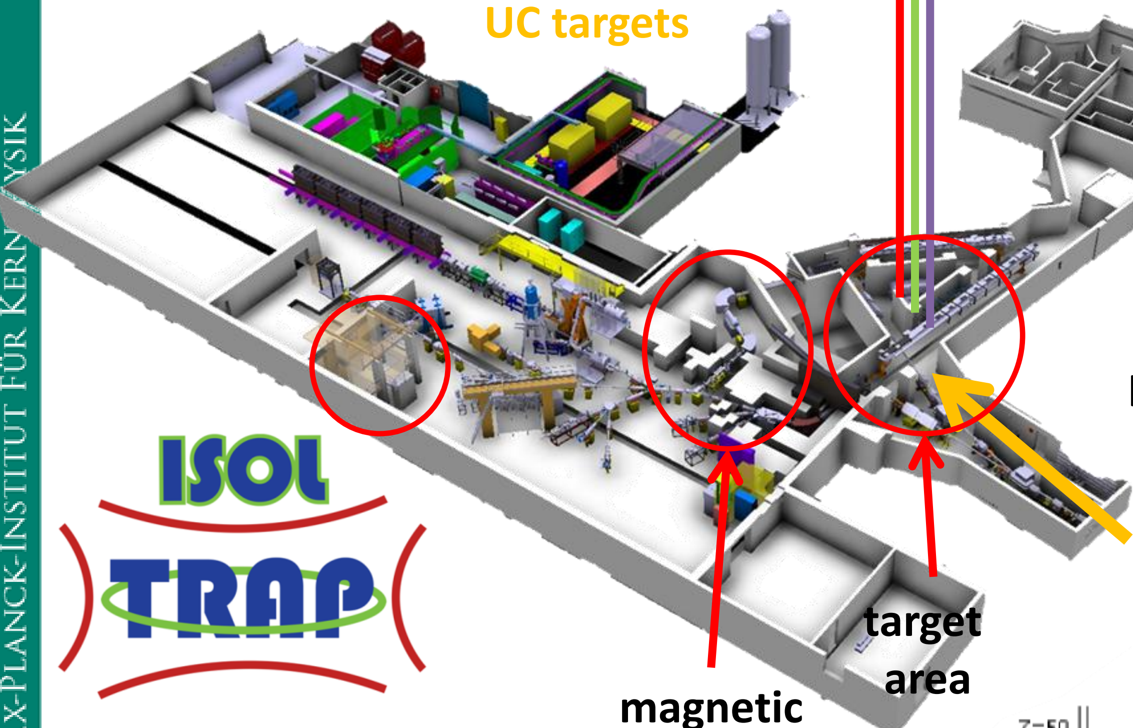
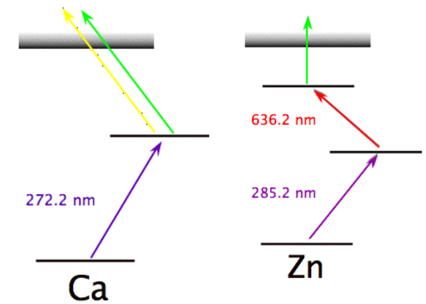
ISOLDE – Isotope Separator On-Line @ CERN

spallation, fission, fragmentation of UC targets

resonance laser ionization



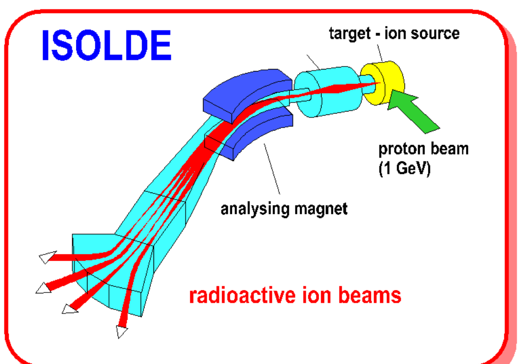


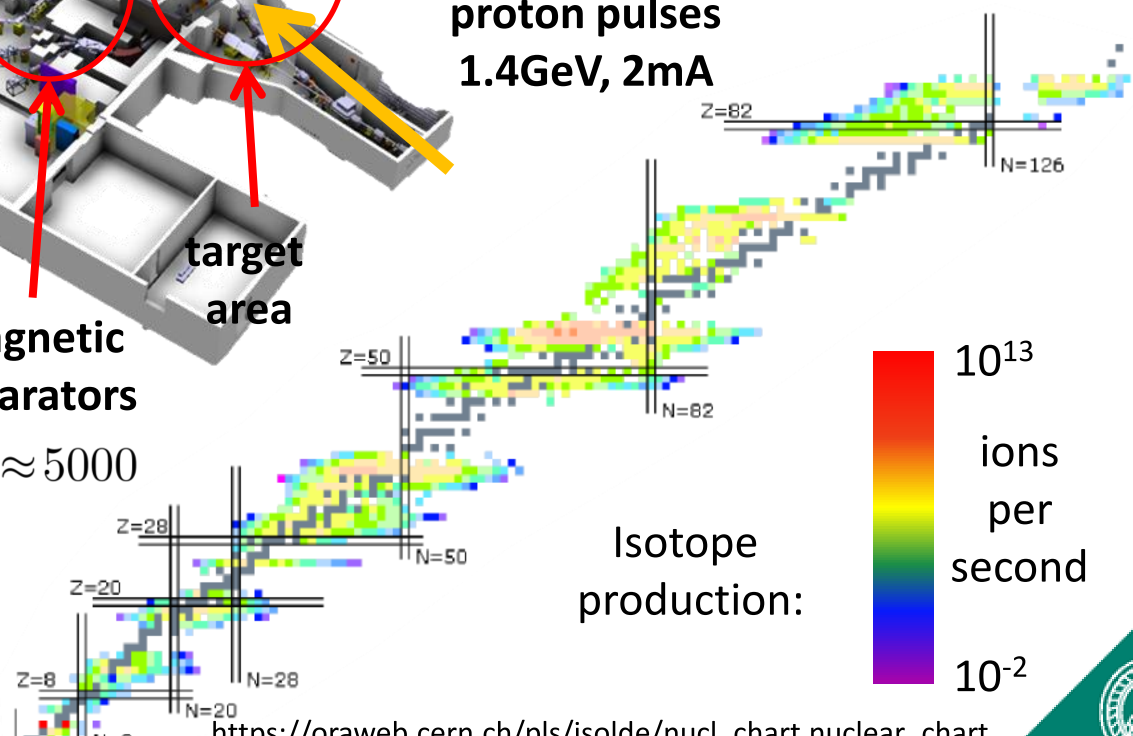
proton pulses 1.4GeV, 2mA

target area

magnetic separators

$$\frac{m}{\Delta m} \approx 5000$$

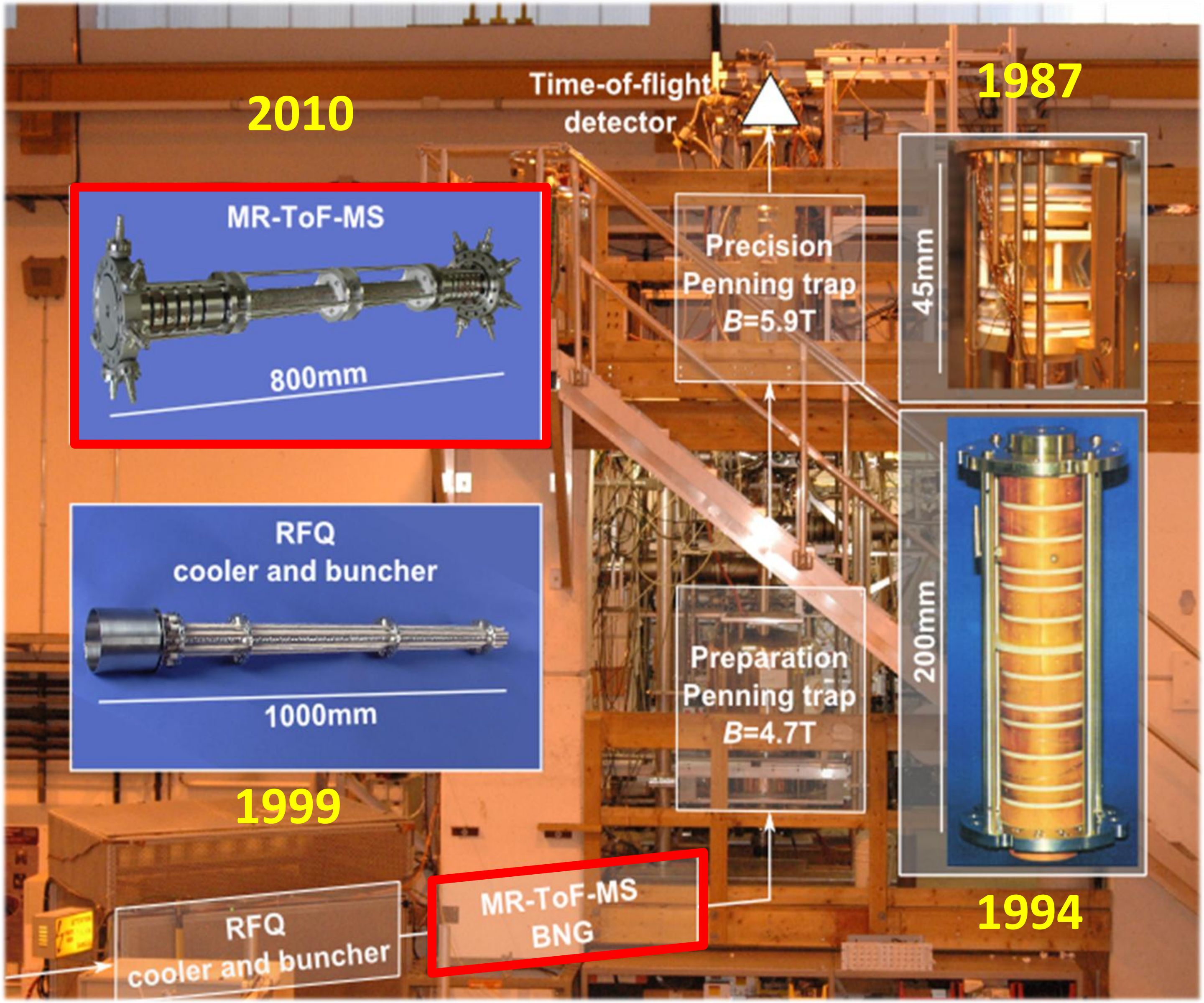




Isotope production:

https://oraweb.cern.ch/pls/isolde/nucl_chart.nuclear_chart

The ISOLTRAP mass spectrometer for short-lived nuclides



Mukherjee *et al.*, Eur. Phys. J. A 35, 1 (2008)

The ISOLTRAP mass spectrometer for short-lived nuclides

4 ion traps for ion accumulation, selection, cooling and mass measurement

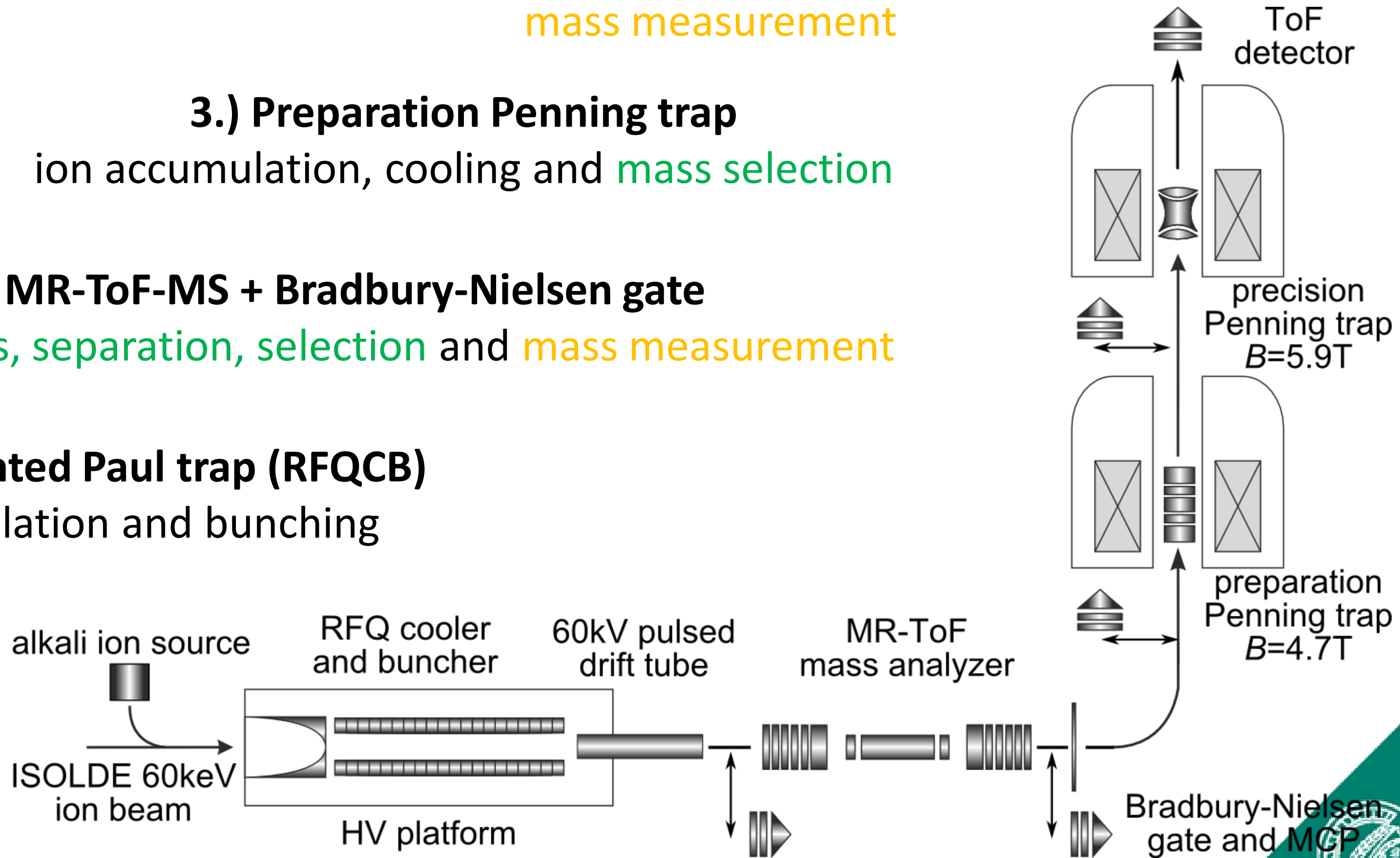
4.) Precision Penning trap
mass measurement

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

3.) Preparation Penning trap
ion accumulation, cooling and mass selection

2.) MR-ToF-MS + Bradbury-Nielsen gate
mass analysis, separation, selection and mass measurement

1.) Linear segmented Paul trap (RFQCB)
ion accumulation and bunching



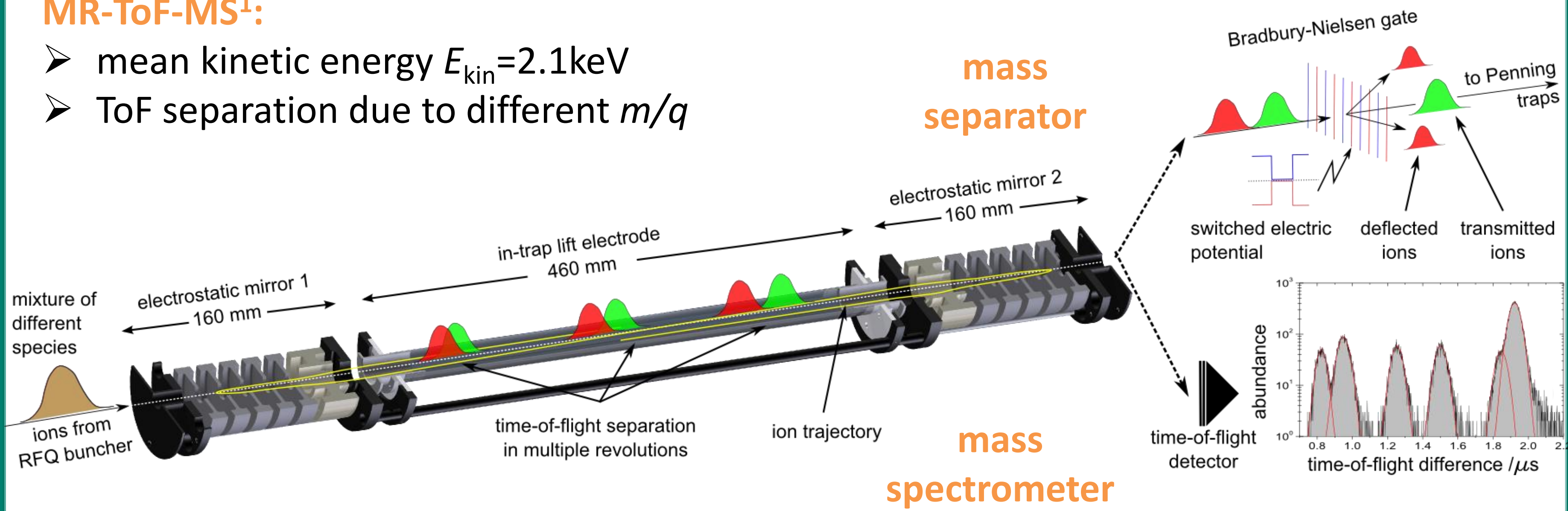
Mukherjee *et al.*, Eur. Phys. J. A 35, 1 (2008)

The MR-ToF-MS at ISOLTRAP

4 ion traps for ion accumulation, selection, cooling and mass measurement

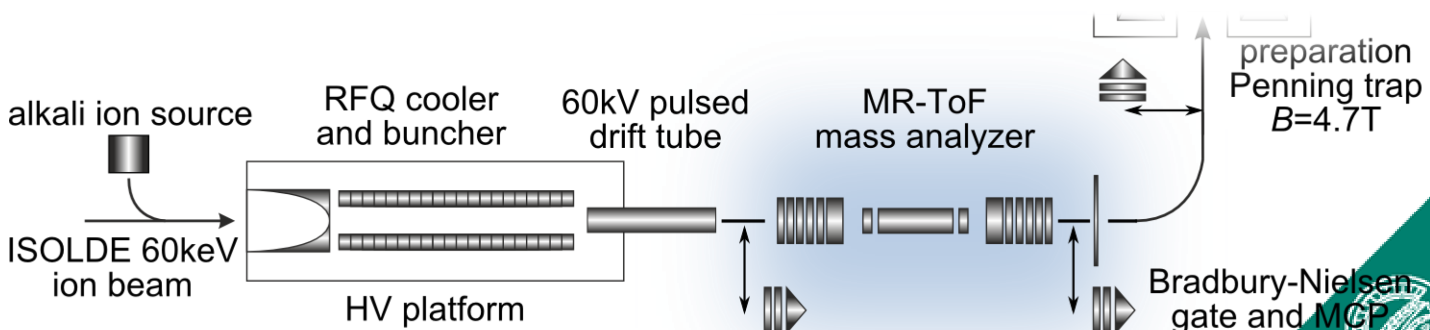
MR-ToF-MS[1]:

- mean kinetic energy E_{kin}=2.1keV
- ToF separation due to different m/q



RFQCB:

- Δt≈60ns
- $\Delta E_{kin}/E_{kin}$≈3%



Wolf *et al.*, NIM A 686, 82 (2012); 1: Wollnik & Przewloka, Int. J. Mass Spectrom. Ion Proc. 96, 267 (1990)

The MR-ToF-MS at ISOLTRAP

MR-ToF-MS

mass resolving power (FWHM)

$m/\Delta m$=100 000 at 12ms

$m/\Delta m$=200 000 at 30ms

transmission

≈50% at 30ms

ion capacity for multiple species

≈1000 per cycle

≈100 000 per second

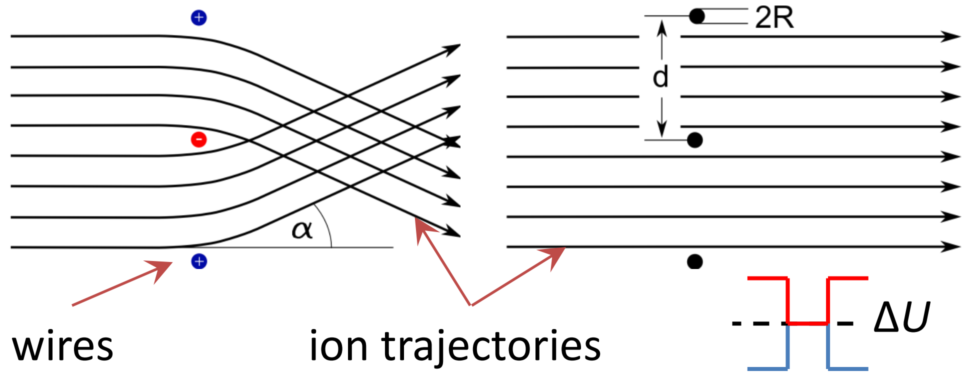
Bradbury-Nielsen gate (BNG)[1,2]

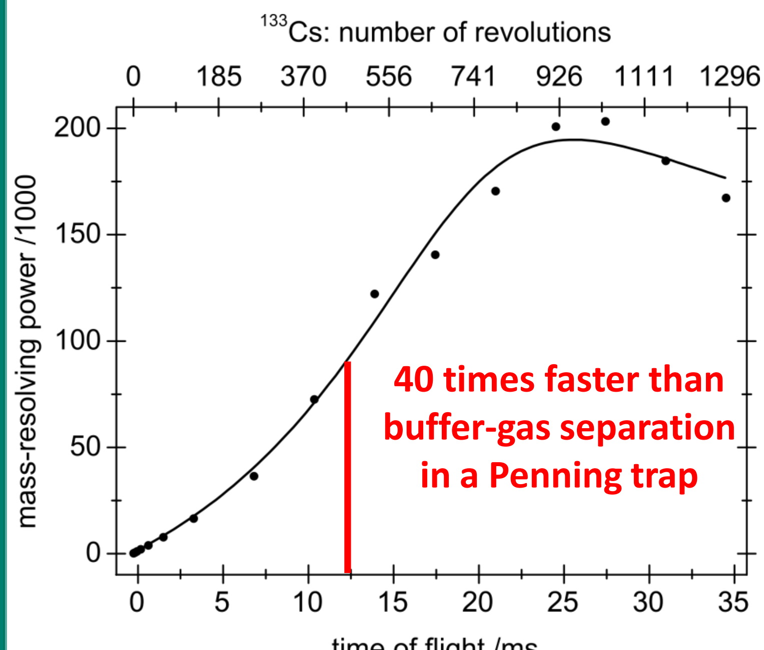
contamination suppression

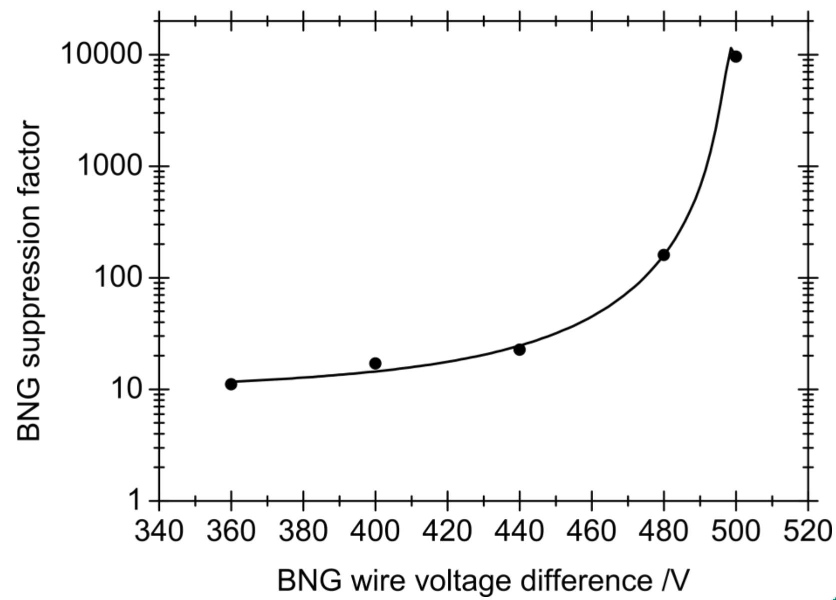
1:10 000

R=0.005mm

d=0.5mm







Wolf *et al.*, NIM A 686, 82 (2012); 1: Bradbury & Nielsen, Phys. Rev. 49, 388 (1936); 2: Plass *et al.*, NIM B 266, 4560 (2008)

Purification of isobaric masses

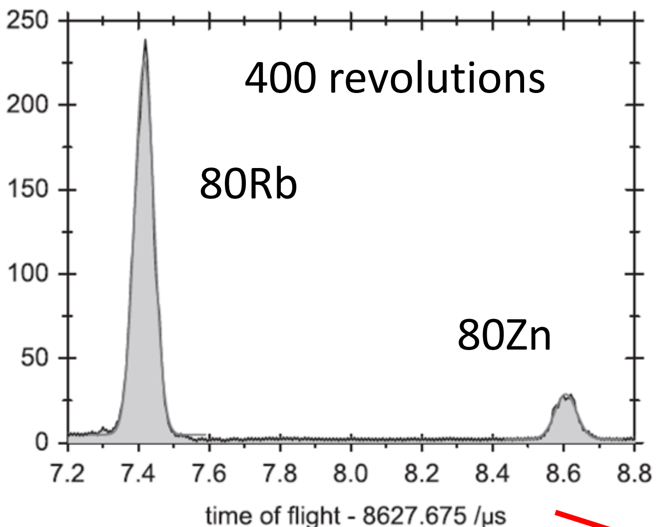
64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83

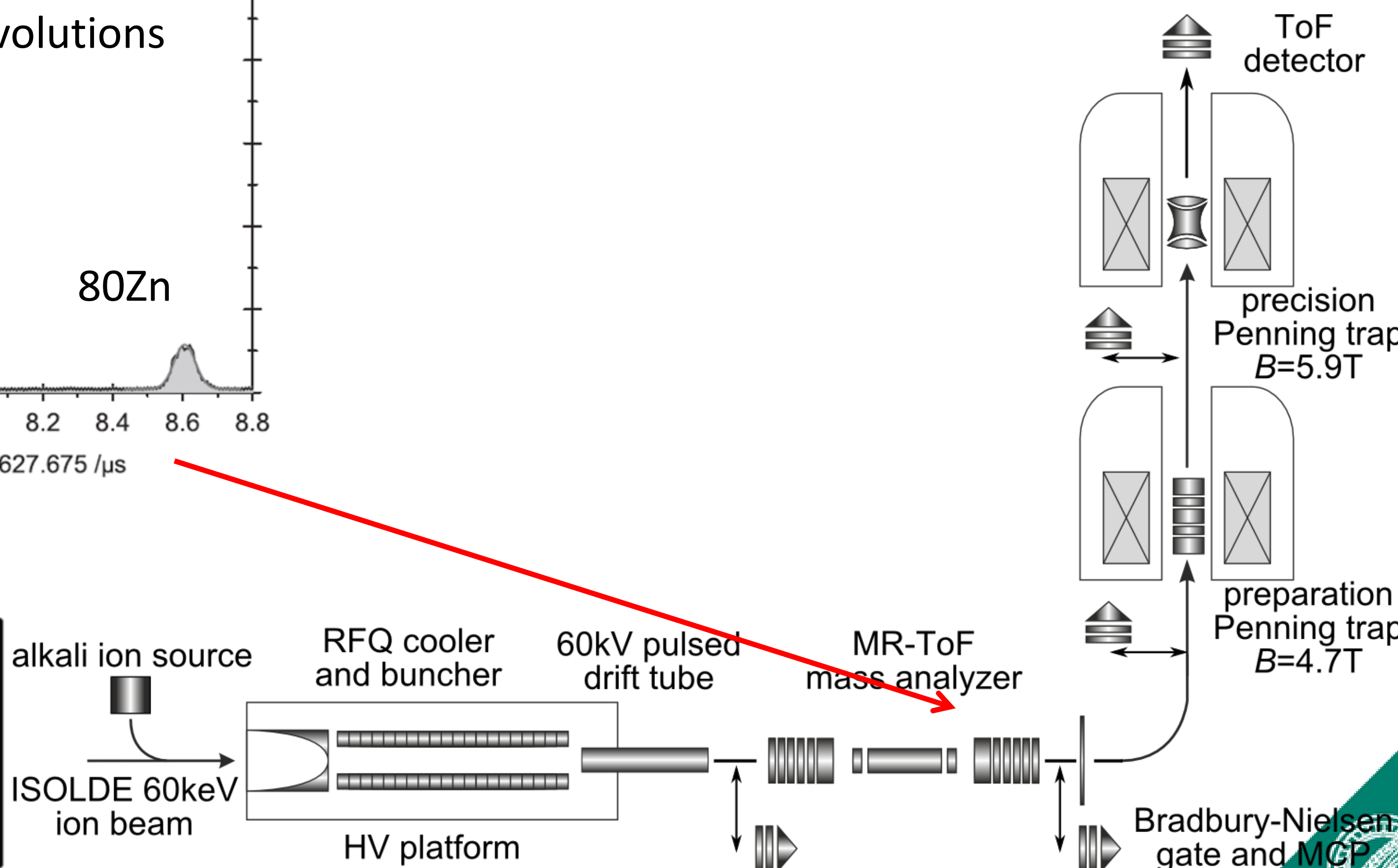
N=50

0.1s ... 3s
3s ... 2m
2m ... 1h
1d ... 1y
>1Gy

Isobar separation: n-rich Zn isotopes

MR-ToF spectrum





80Zn:
1000/s, $T_{1/2}$=0.55s
80Rb:
10000/s, $T_{1/2}$=33.4s

Wolf *et al.*, PRL 110, 041101 (2013); NIM A 686, 82 (2012)

64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83

N=50

■	0.1s ... 3s
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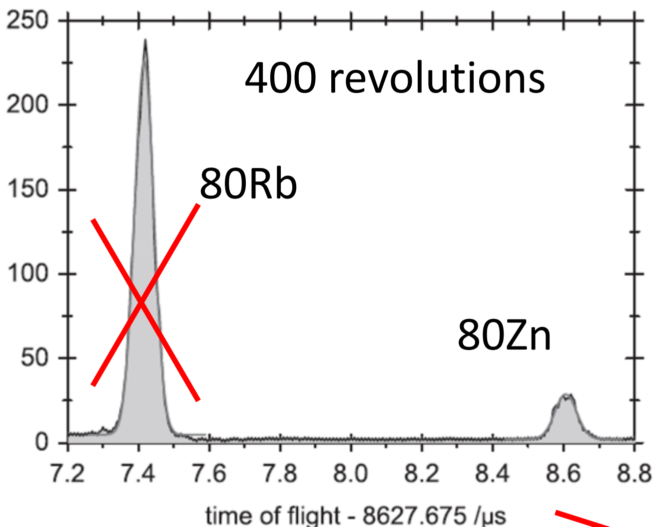
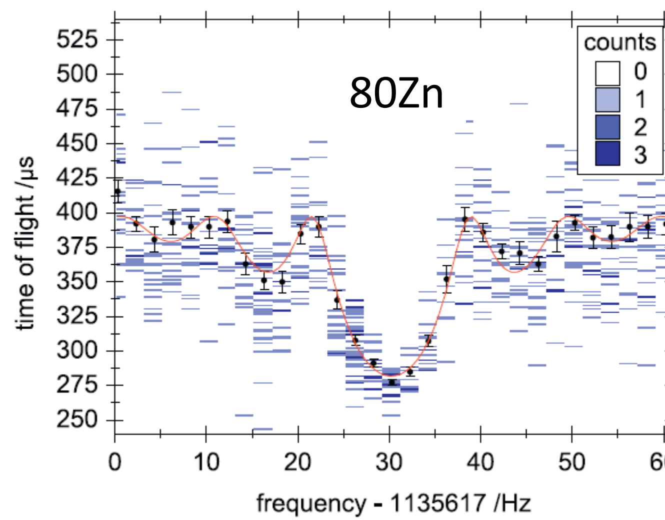
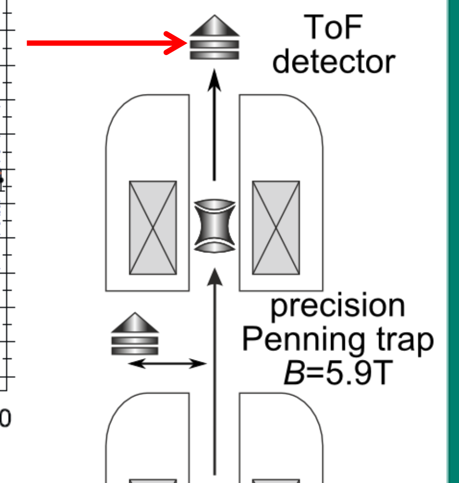
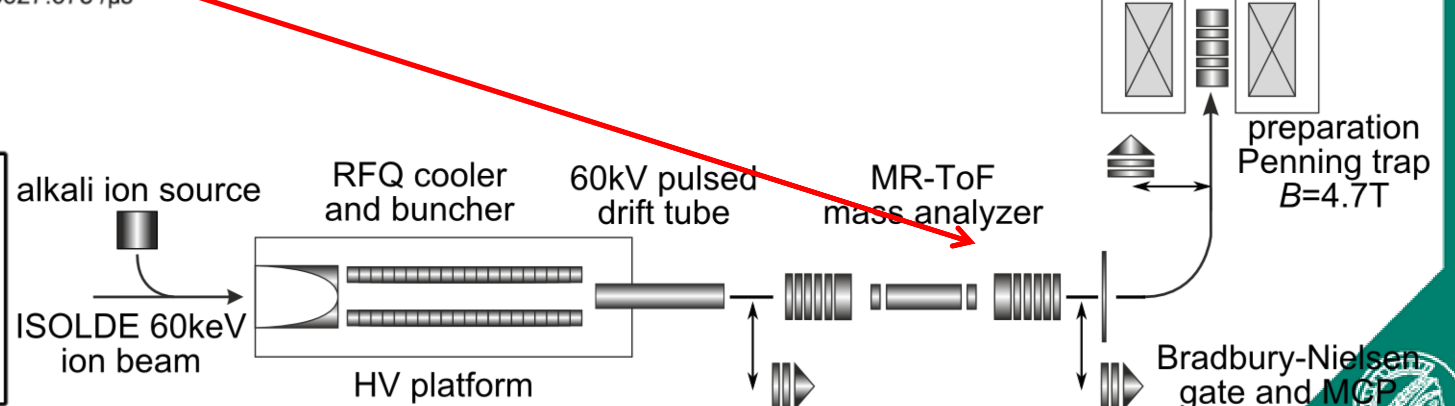


ToF-ICR mass measurement



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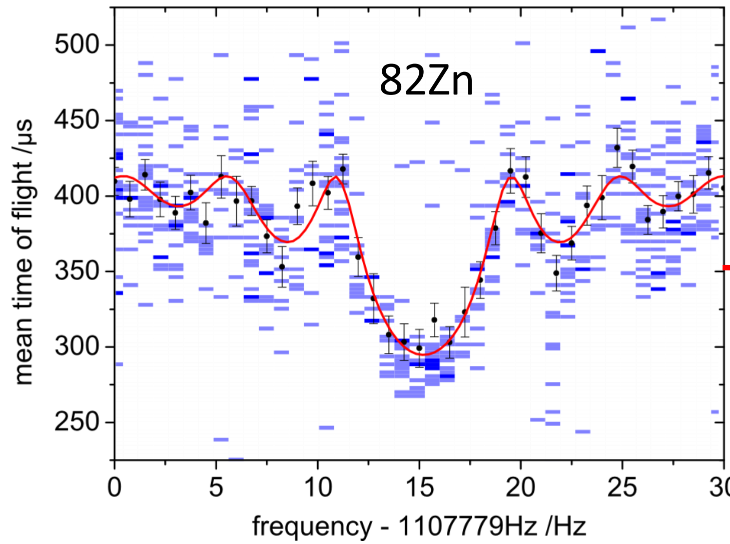
64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83

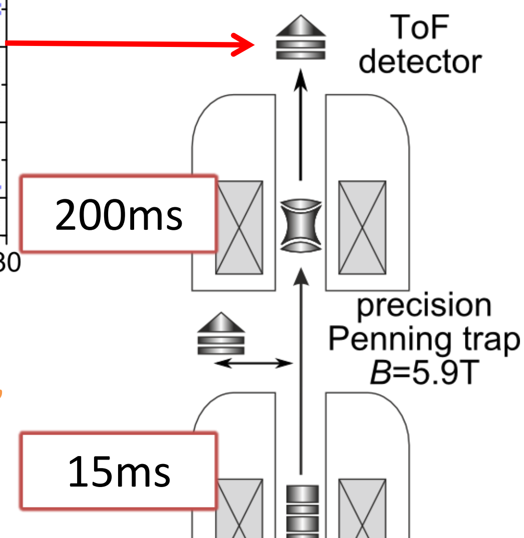
N=50

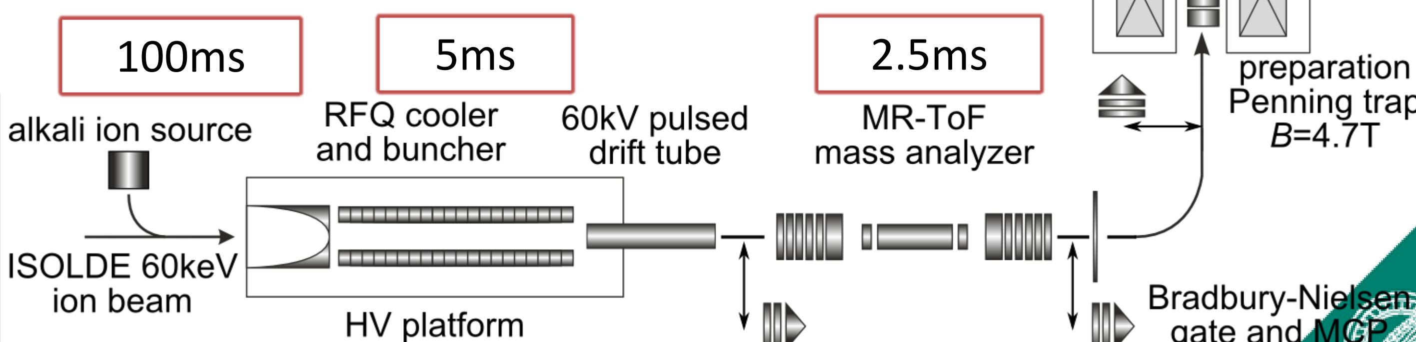
orange	0.1s ... 3s
dark yellow	3s ... 2m
yellow	2m ... 1h
blue	1d ... 1y
black	>1Gy

Isobar separation: n-rich Zn isotopes



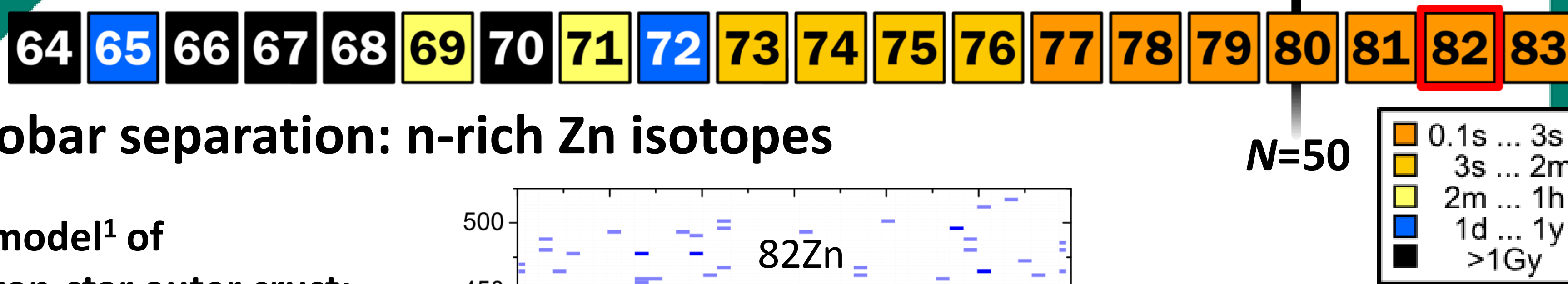
MR-ToF separation in only 2.5ms, <25ms for complete preparation





82Zn:
200/s, $T_{1/2}$=228ms
82Rb:
6000/s, $T_{1/2}$=1.3min

1: Baym, Pethick & Sutherland, ApJ 170, 299 (1971); 2: Pearson *et al.*, PRC 83, 065810 (2011); Wolf *et al.*, PRL 110, 041101 (2013)



Isobar separation: n-rich Zn isotopes

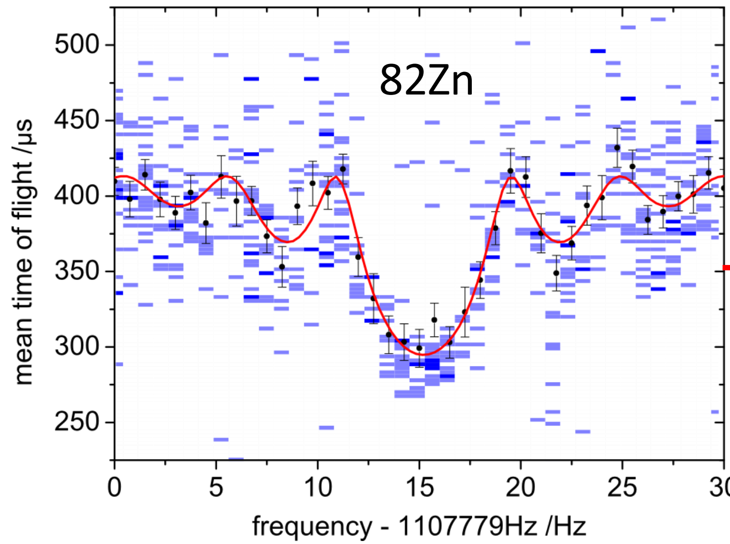
BPS-model[1] of neutron-star outer crust:

- masses of n-rich nuclei
- 82Zn predicted by some mass models[2]

➔ first mass measurement: 82Zn is not part of the outer crust

ISOLDE techniques:

- resonant laser ionization
- neutron converter
- quartz transfer line



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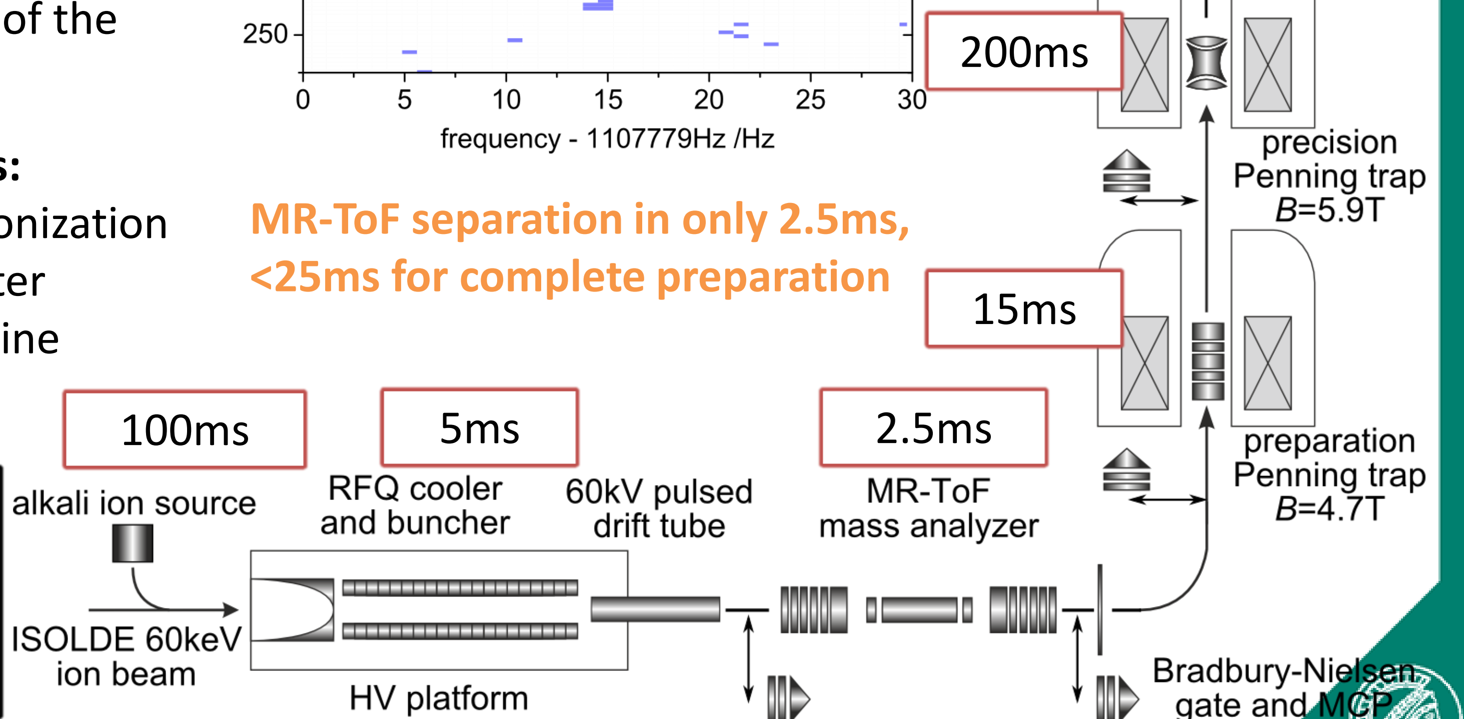

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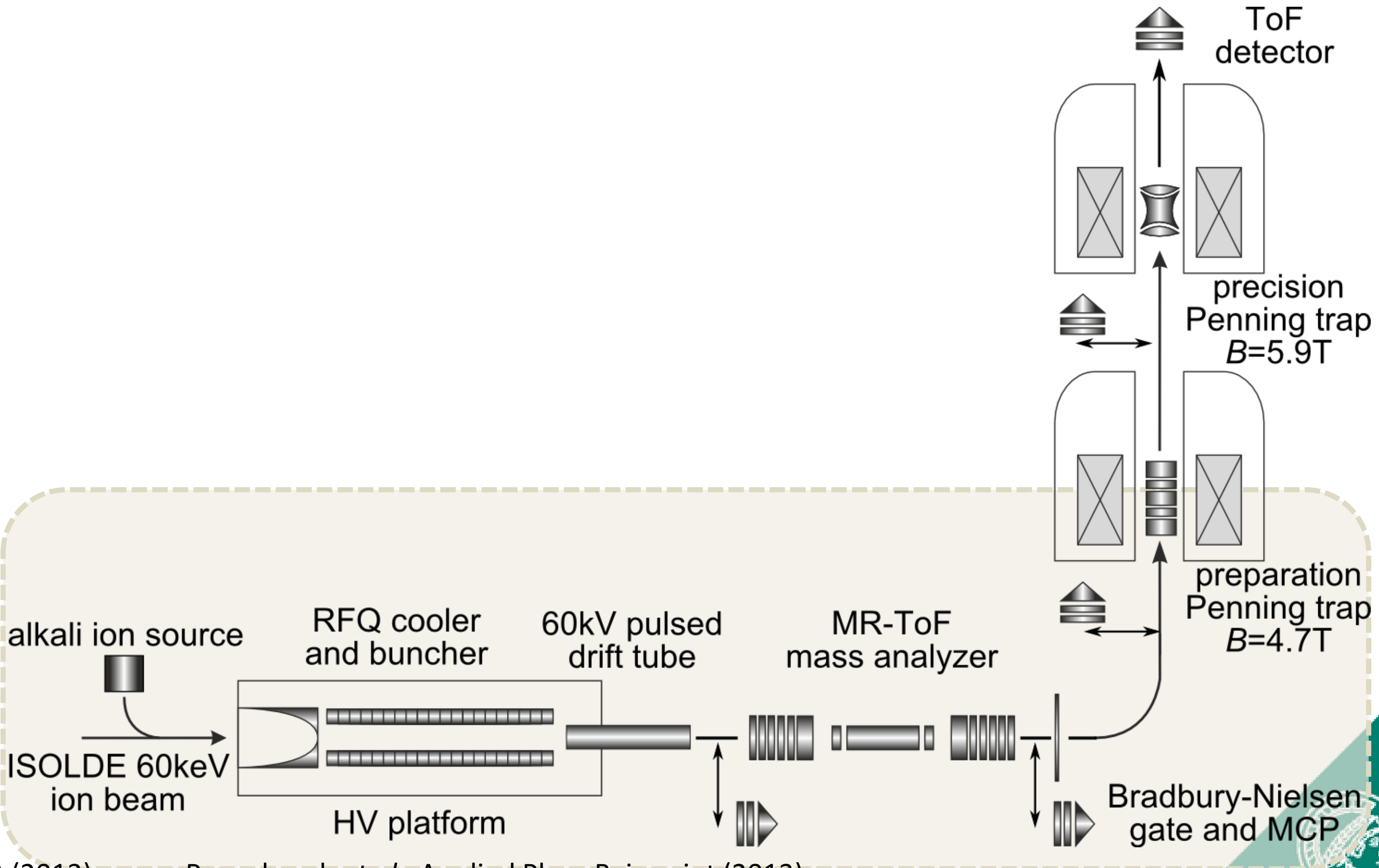
Isobar separation: preparation Penning trap stacking

- Space-charge effects lead to peak coalescence – limited number of ions
- Multiple MR-ToF-MS separation cycles within one experiment cycle
- Accumulation of isobarically purified bunches in the preparation Penning trap



Wolf *et al.*, IJMS 349-350, 123 (2013); Rosenbusch *et al.*, Applied Phys. B, in print (2013)

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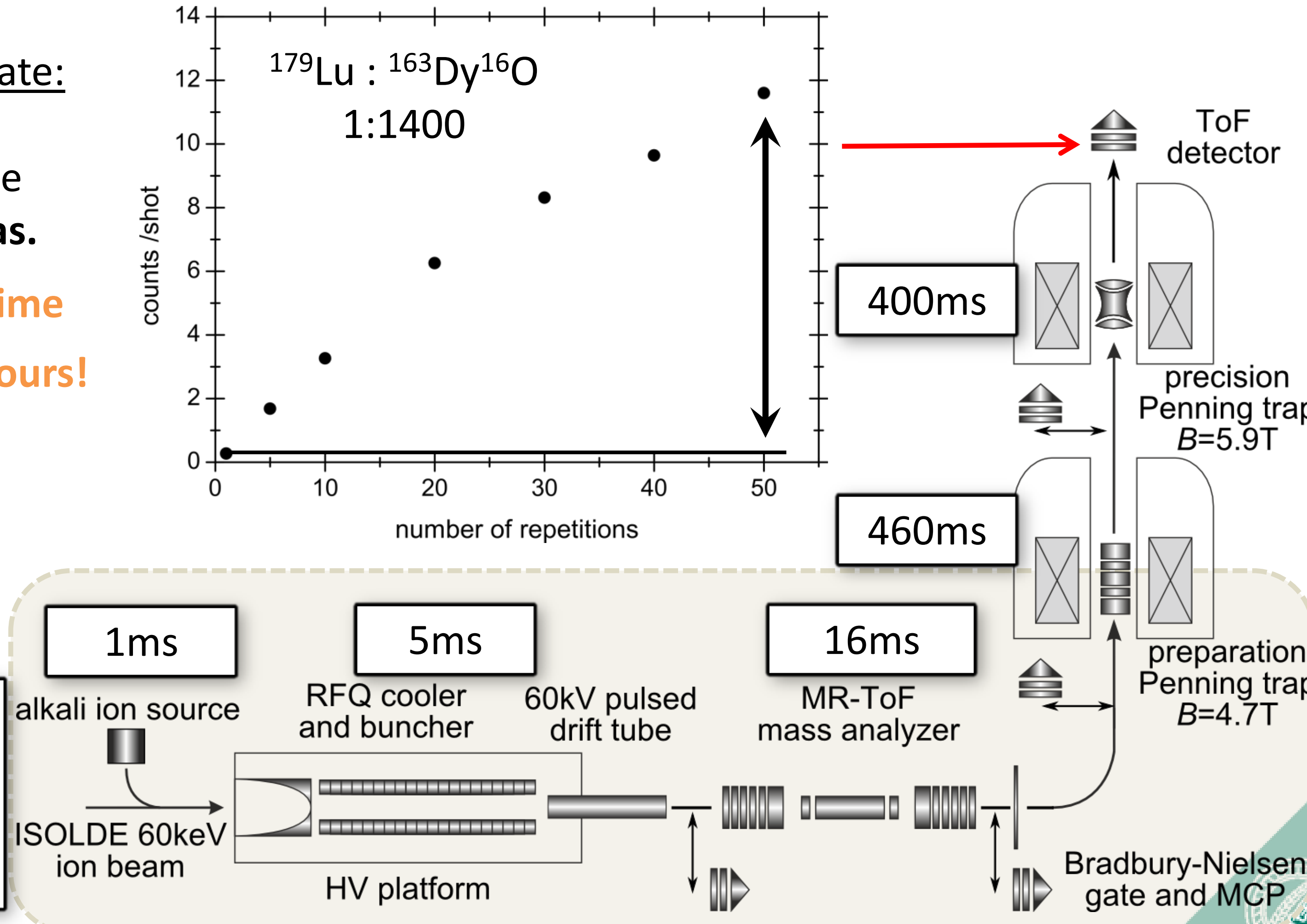
- Accumulation of isobarically purified bunches in the preparation Penning trap

<u>20Hz repetition rate:</u>

- x40 count rate
- x3.6 meas. time
- **x11 faster meas.**

measurement time

≈1 day ⟶ 2 hours!



179Lu:
$3x10^5$/s, $T_{1/2}$=4.6h
179DyO:
$4.5x10^8$/s, stable

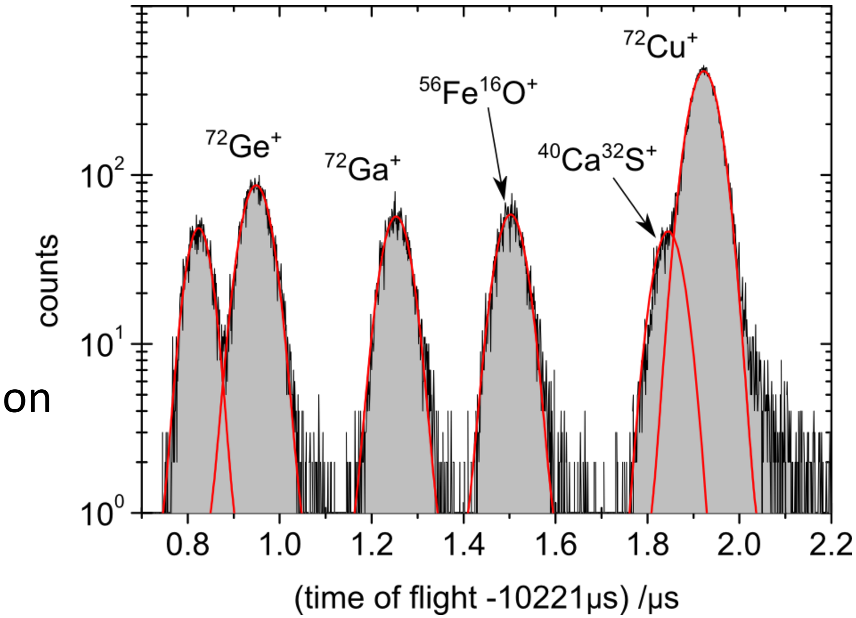
Wolf *et al.*, IJMS 349-350, 123 (2013); Rosenbusch *et al.*, Applied Phys. B, in print (2013)

Ion beam analysis

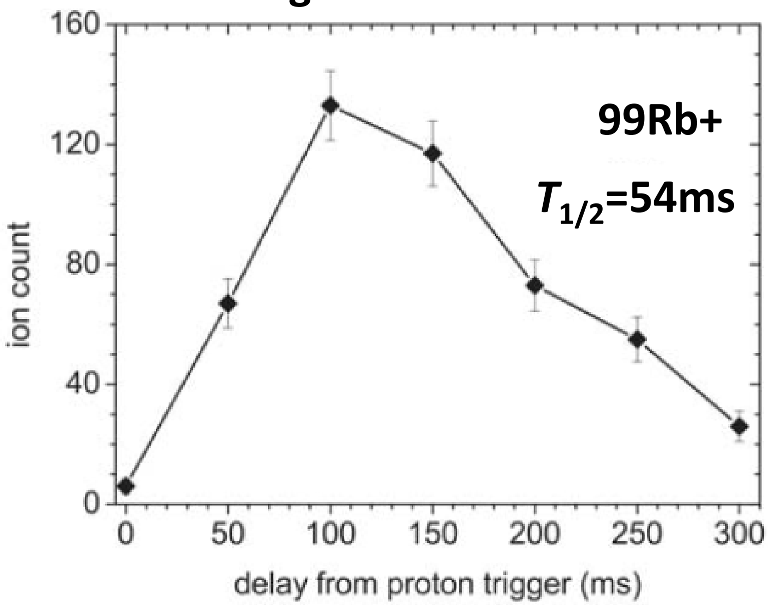
MR-ToF ion-beam analysis

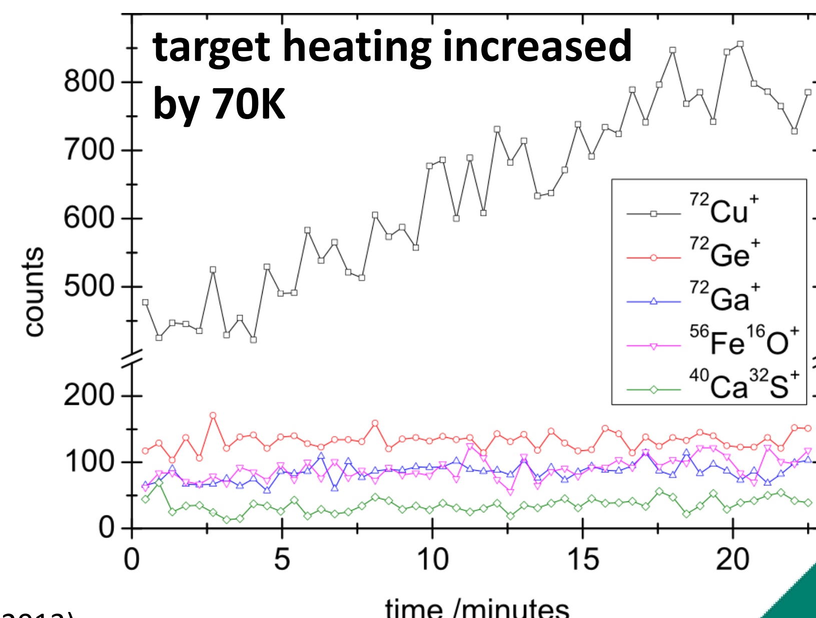
Ion-beam composition analysis

- direct feedback for target/line optimization
- sampling of release curve possible
- single ion sensitivity to detect lowest yields
- no upper limit on half-life as with decay station
- not hindered by decay branching ratio



target release curve



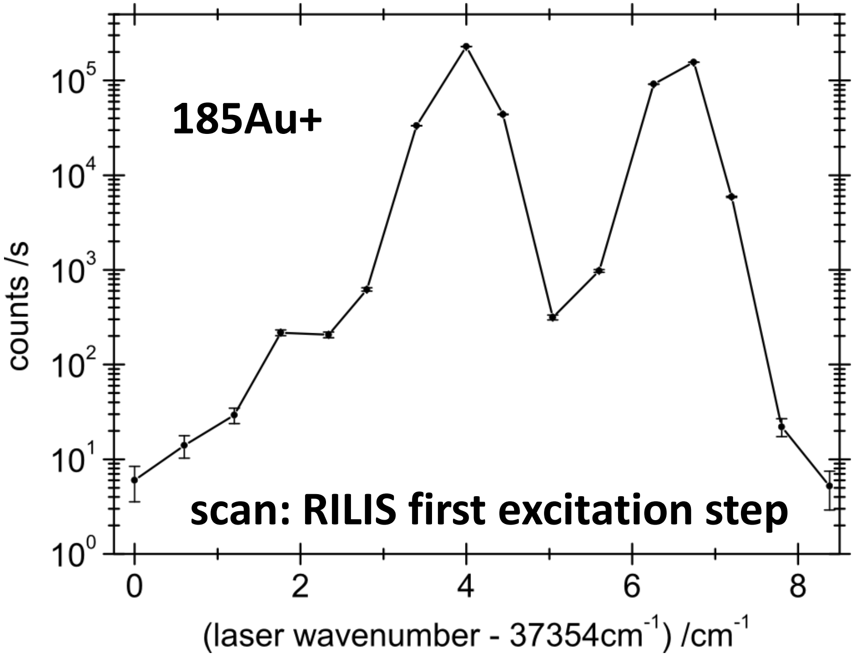


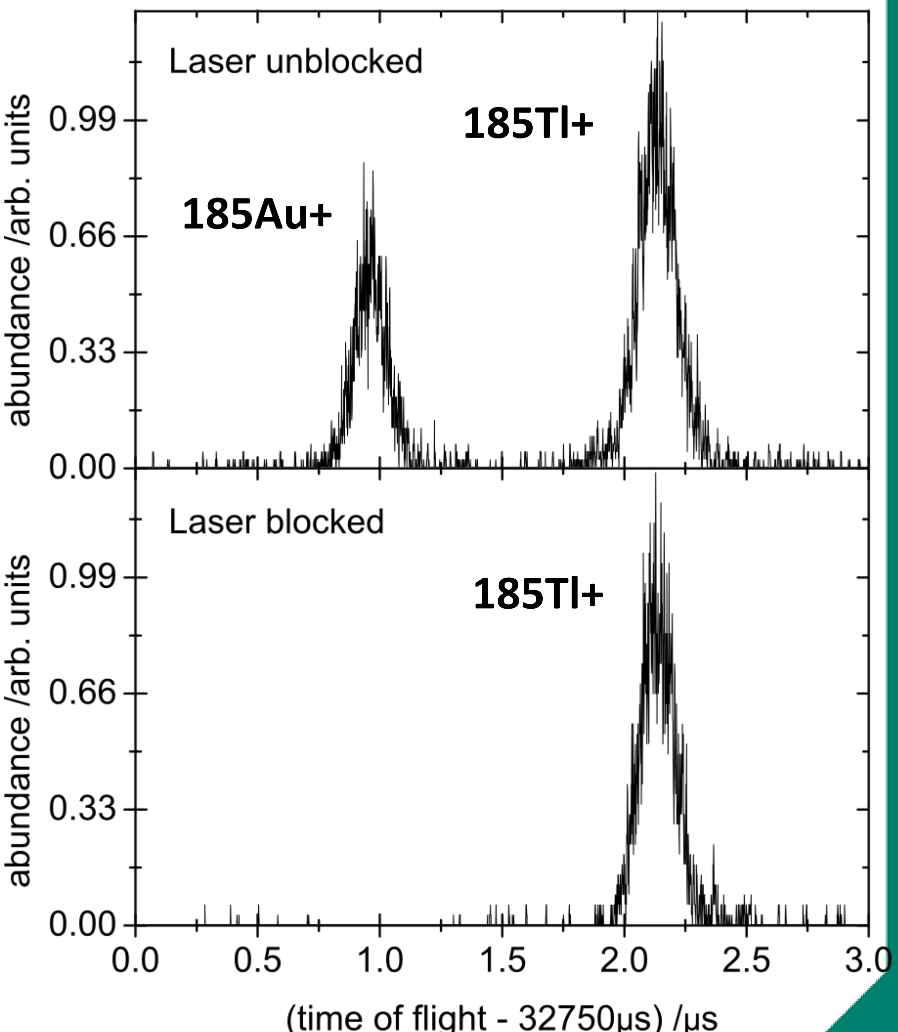
Wolf *et al.*, IJMS 349-350, 123 (2013); Kreim *et al.*, NIM B 317, 492 (2013)

MR-ToF ion-beam analysis

MR-ToF analyzer to investigate resonant laser ionization of nuclides far from stability

- fast, sensitive tool to improve ionization eff.
- high dynamic range: 1-10e5 counts/s
- counts free from background contamination
- not limited by decay branching ratio
- help to provide isomerically pure beams





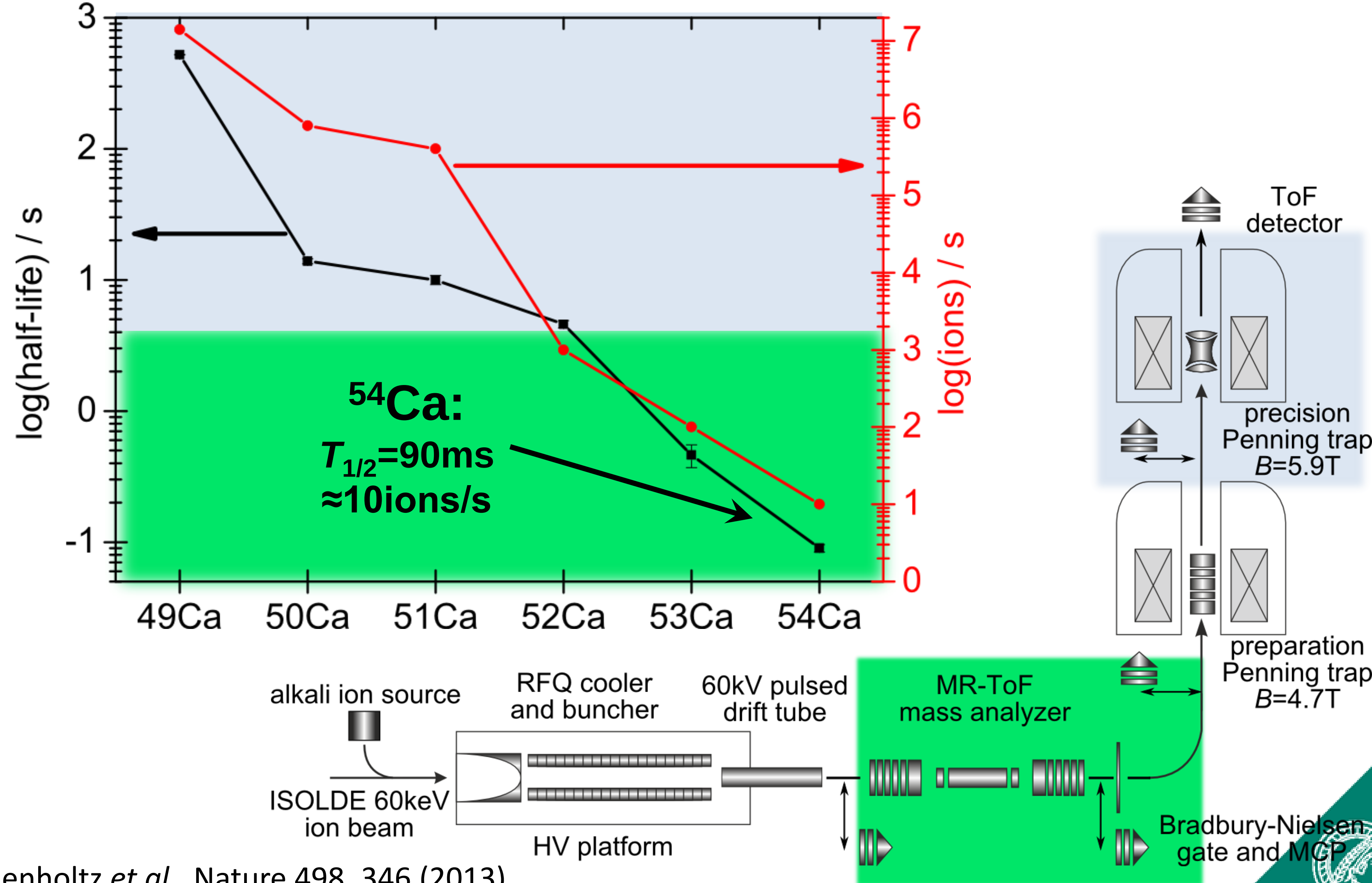
Wolf *et al.*, IJMS 349-350, 123 (2013); Kreim *et al.*, NIM B 317, 492 (2013); Marsh *et al.*, NIM B 317, 550 (2013);

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Precision mass measurements

Z=20 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55

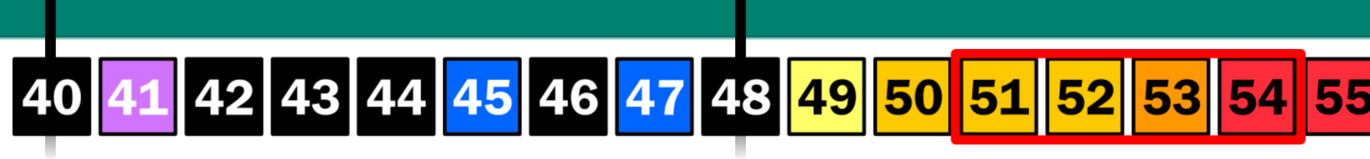
MR-ToF mass spectrometer: n-rich Ca isotopes



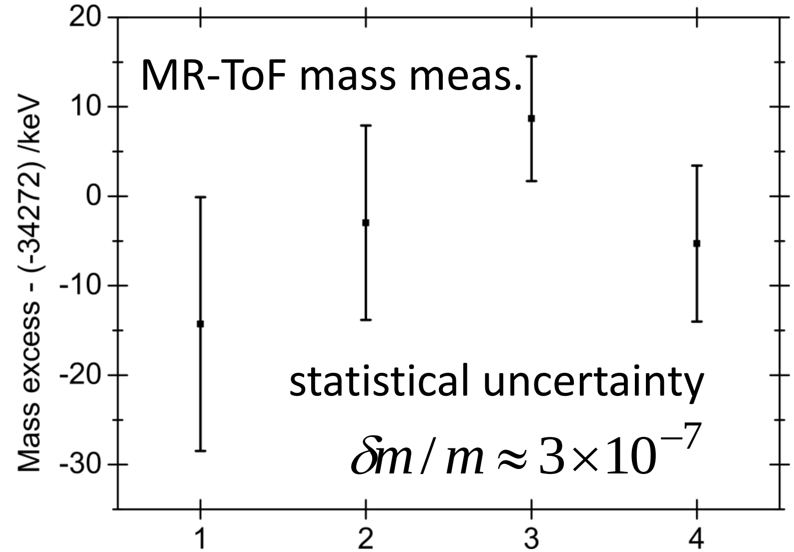
Wienholtz *et al.*, Nature 498, 346 (2013)

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

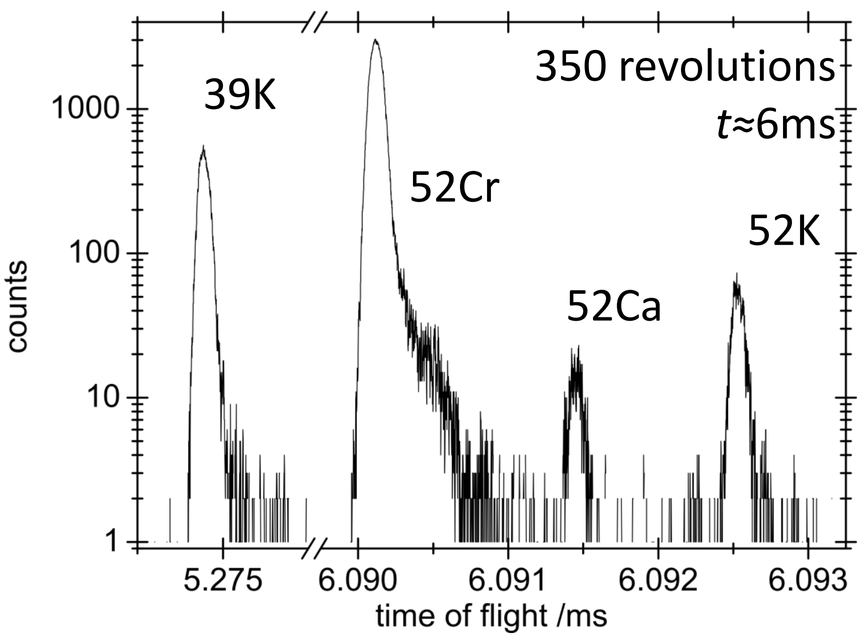
Z=20

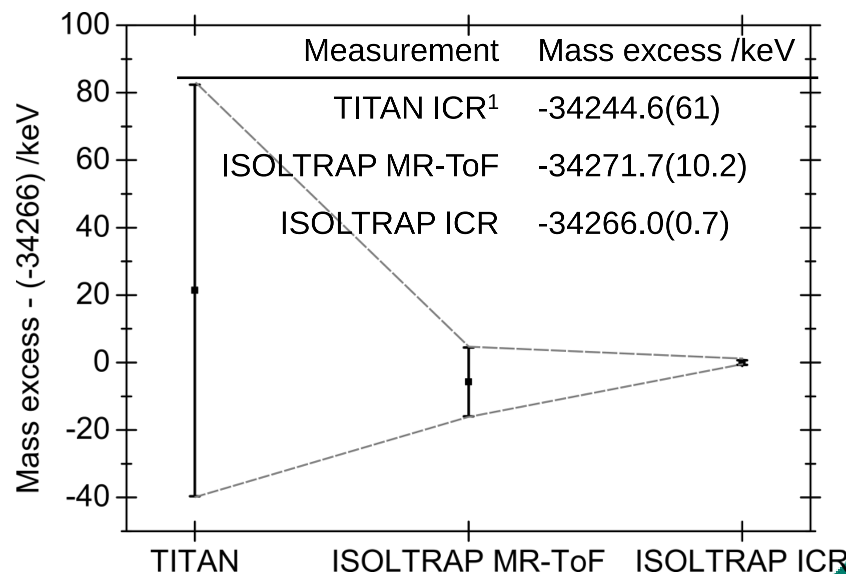


- TITAN/TRIUMF measurements of 51,52Ca[(1)]
- ISOLTRAP measurement agrees with TITAN
- 51,52Ca measured with Penning trap
- 52,53,54Ca measured with MR-ToF-MS
  - ➔ MR-TOF-MS agrees with PT measurements
  - ➔ sub-ppm statistical mass uncertainty



MR-ToF spectrum



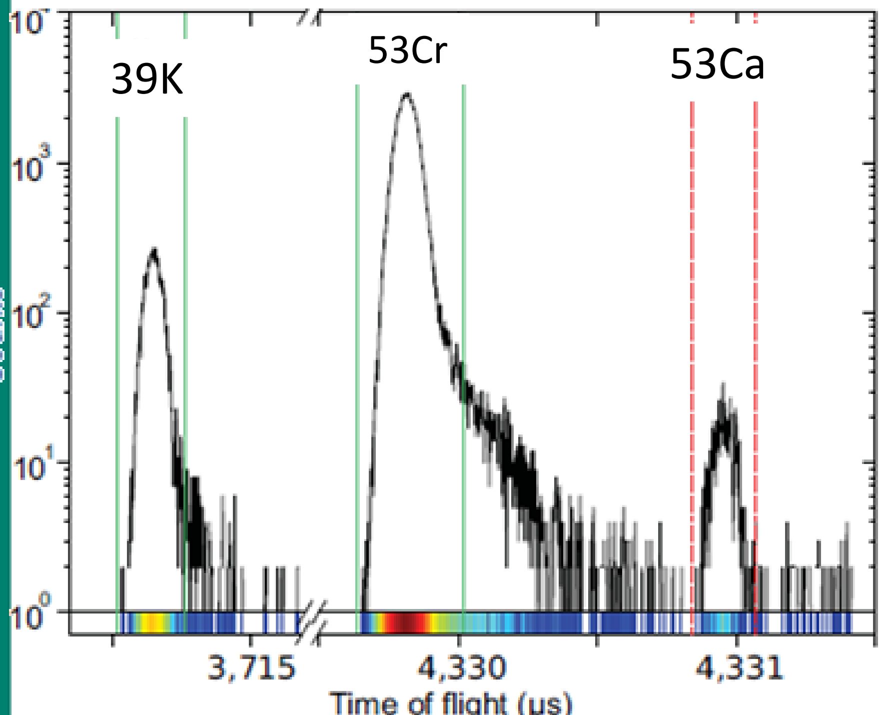


1: Gallant *et al.*, PRL 109, 032506 (2012) Wienholtz *et al.*, Nature 498, 346 (2013)

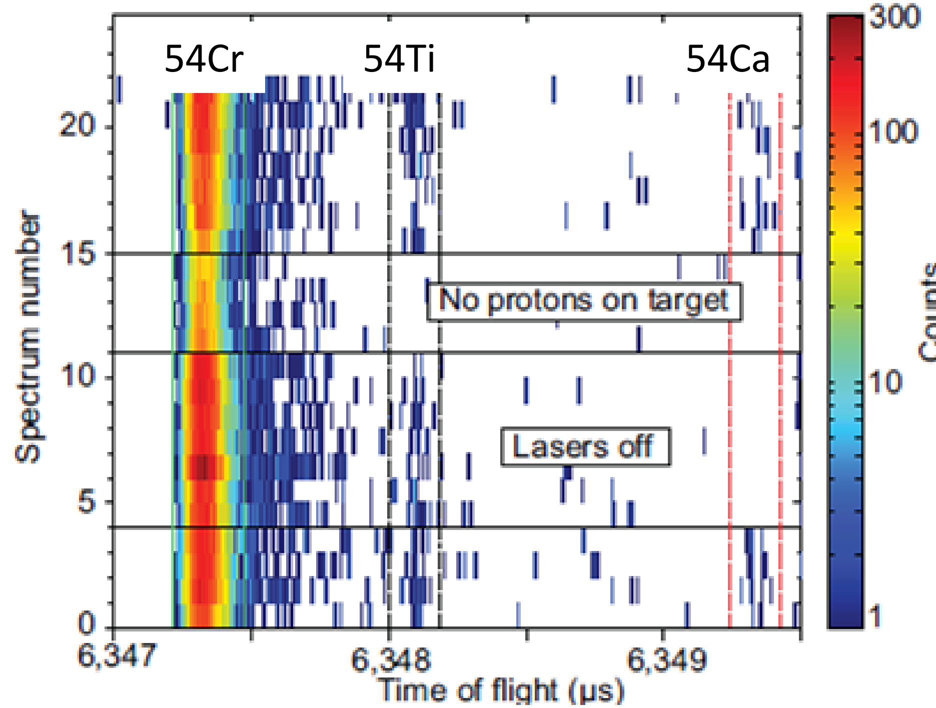
Z=20 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55

MR-ToF mass spectrometer: n-rich Ca isotopes

***A*=53:** measurement cycle ≈ 4ms



***A*=54:** measurement cycle ≈ 6ms



6413 counts/12.6h ➔ 9 counts/minute

2314 counts/18.2h ➔ 2 counts/minute

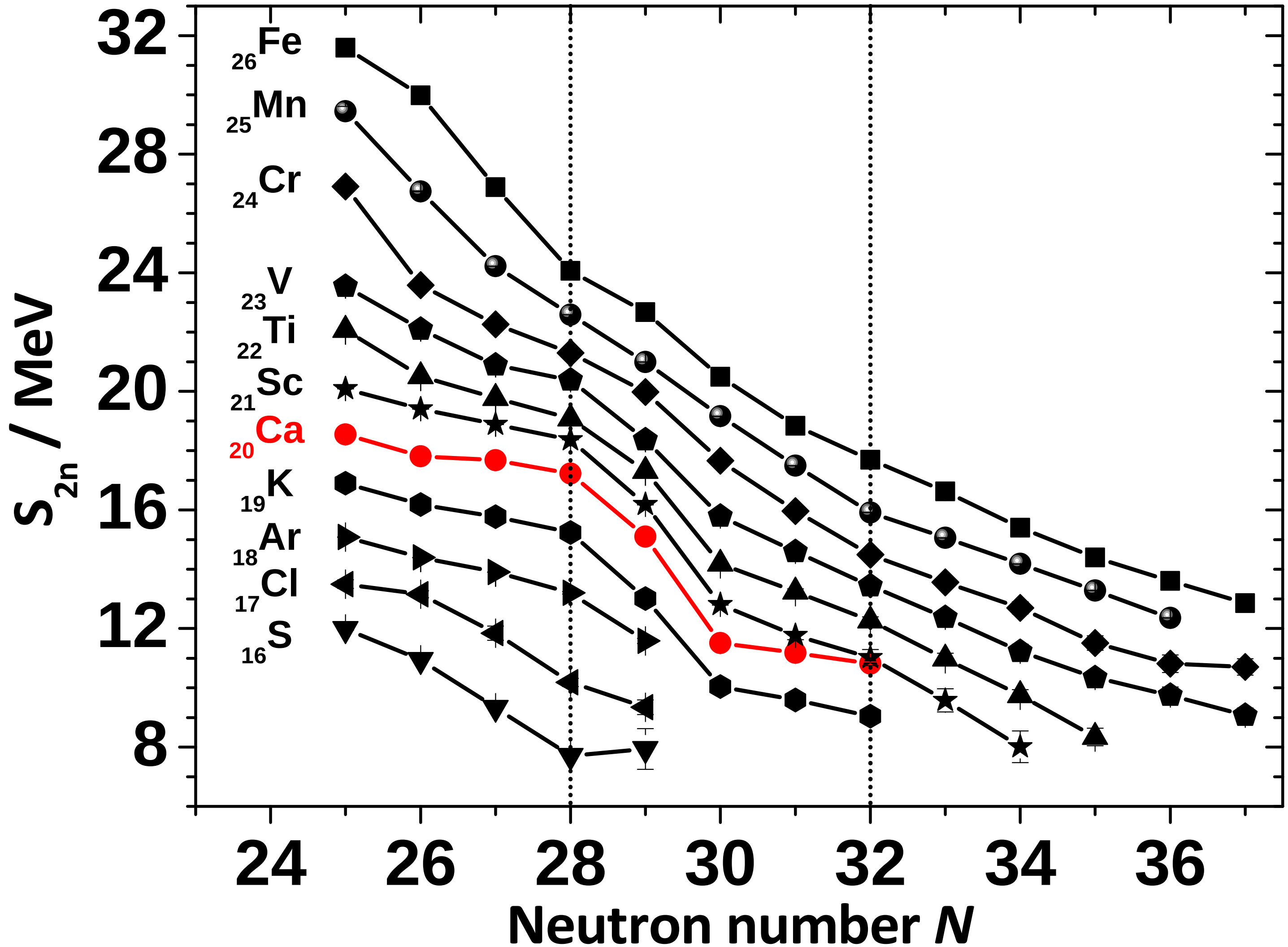
statistical uncertainty ≈ 45keV ➔ $\delta m/m \approx 9\text{x}10^{-7}$

Wienholtz *et al.*, Nature 498, 346 (2013)

Z=20 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55

MR-ToF mass spectrometer: n-rich Ca isotopes

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

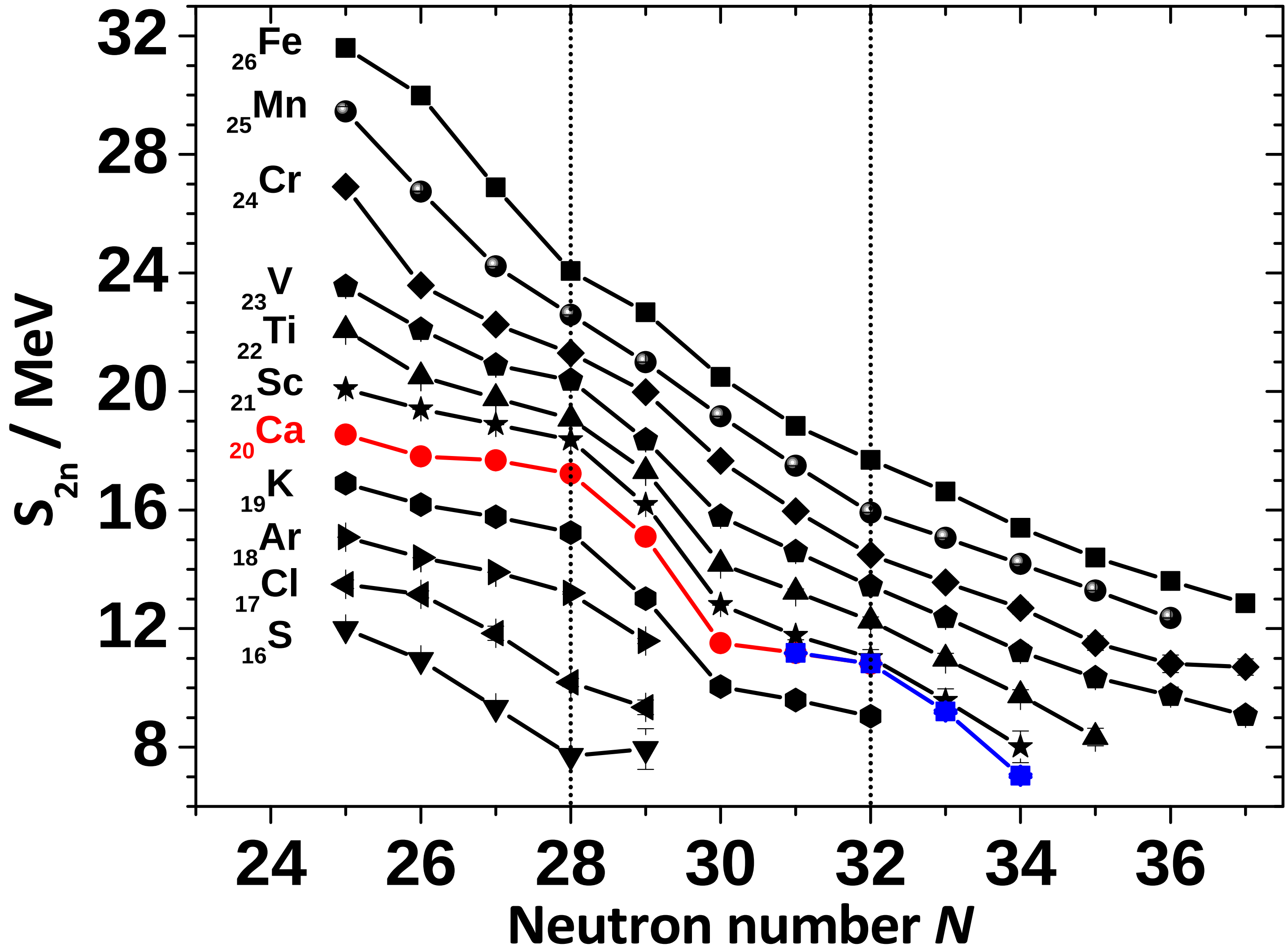


Wienholtz *et al.*, Nature 498, 346 (2013)

Z=20	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55

MR-ToF mass spectrometer: n-rich Ca isotopes

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

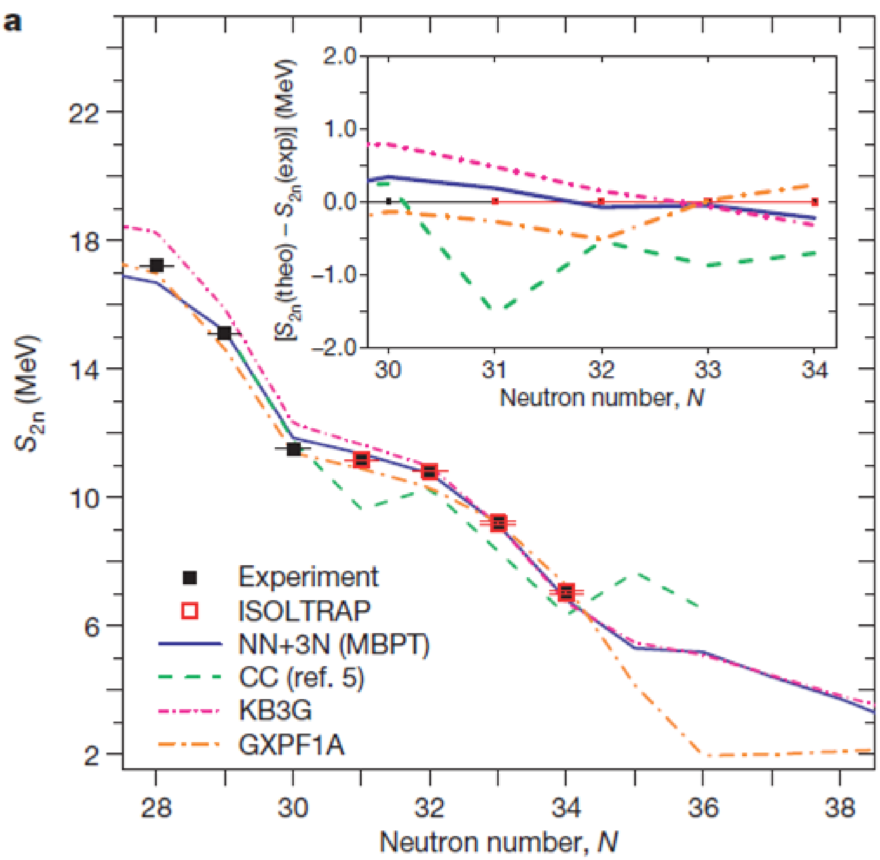


Wienholtz *et al.*, Nature 498, 346 (2013)

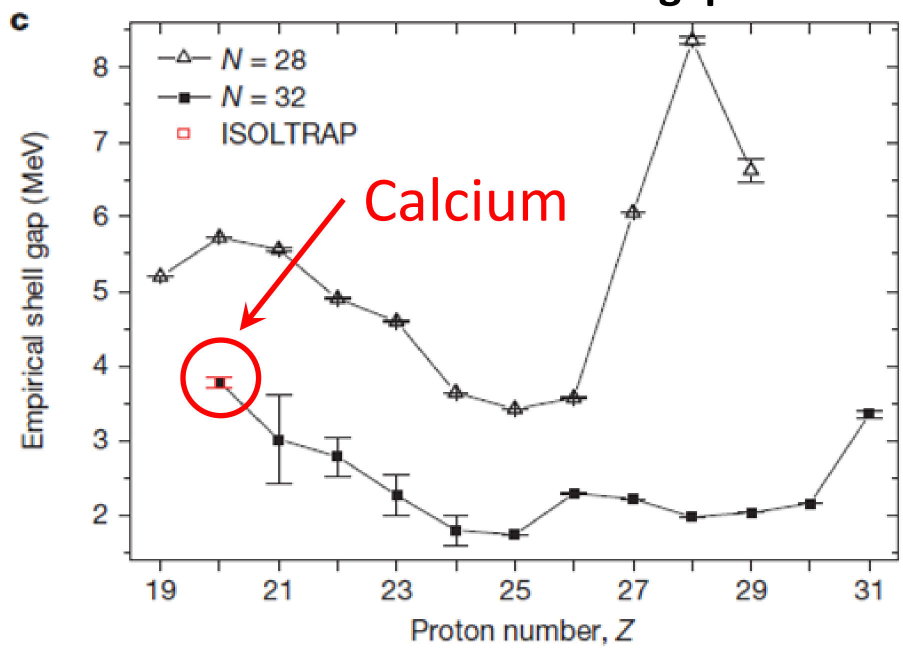
Z=20 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55

MR-ToF mass spectrometer: n-rich Ca isotopes

Two-neutron separation energy



Two-neutron shell gap



N=32 shell closure

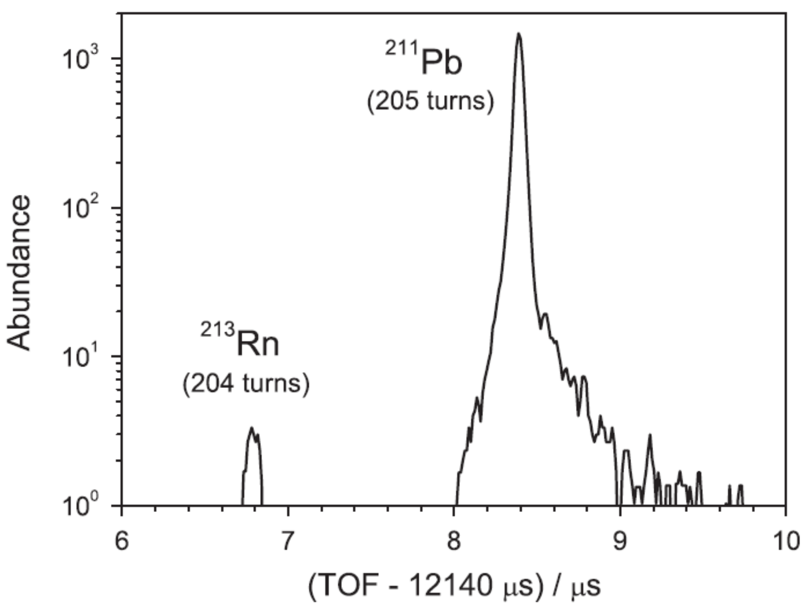
excellent agreement with predictions from microscopic valence-shell calculations with three-nucleon forces (NN+3N) based on chiral effective field theory

Wienholtz *et al.*, Nature 498, 346 (2013)

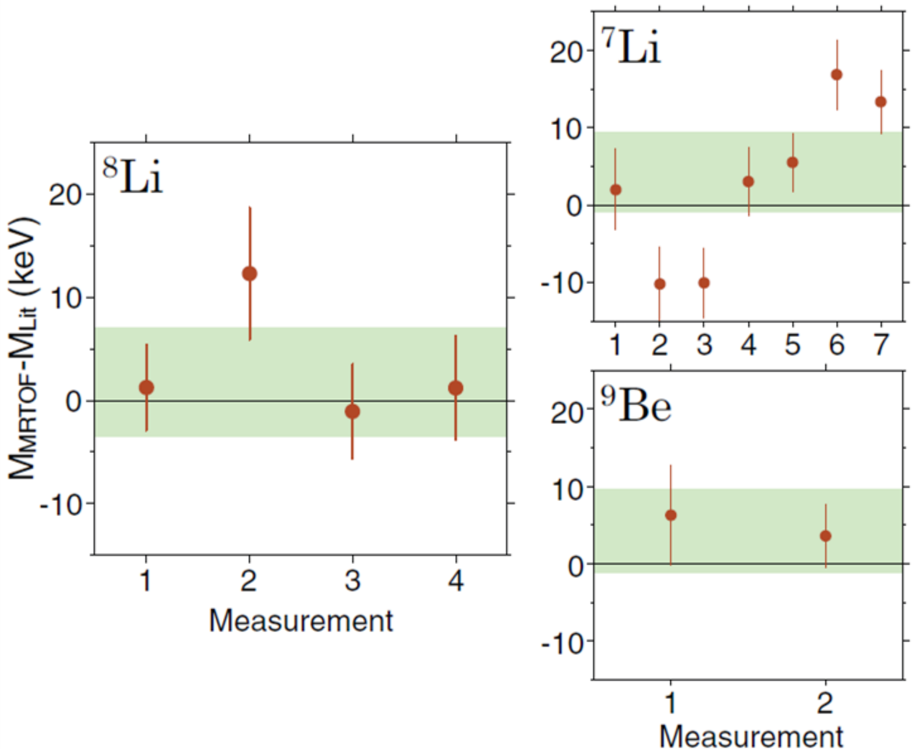
MR-ToF mass spectrometer at GSI and RIKEN

- first direct mass measurements of $^{211}Rn^+$, $^{213}Rn^+$, $^{211}Po^+$ at GSI
- half-life $^{213}Rn^+$: 19.5ms
- measurement time 12ms

- mass measurements of $^{8}Li^+$ at RIKEN
- mass resolving power R≈200000
- measurement time 8ms
- relative mass uncertainty 6.6×10^{-7}



Plaß *et al.*, NIM B 317, 457 (2013)



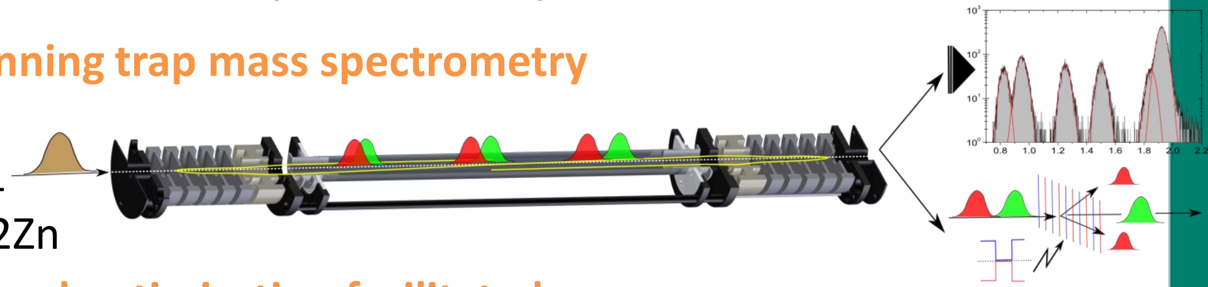
Ito *et al.*, PRC 88, 011306R (2013)

Summary

Precision and fast measurement cycle makes the MR-TOF-MS a promising approach for MS on short-lived isotopes with low production

MR-ToF mass purification for Penning trap mass spectrometry

- *R*=200000 after 30ms
- contam. suppression 10000:1
- first mass measurement of 82Zn



Target/ion source development and optimization facilitated

MR-ToF mass measurements on very short-lived isotopes with very small production rates

- successful mass measurements of 52-54Ca, sub-ppm uncertainty
- in addition: 52-53K, half-life 30ms, publication in preparation

Other groups and activities (for short-lived nuclei):
FRS ioncatcher (GSI, Gießen), SlowRI (RIKEN), ORNL (Oak Ridge), CARIBU (Argonne), IGISOL (Jyväskylä), GANIL (Caen), TITAN/TRIUMF (Vancouver), RISP (S. Korea)

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the ISOLDE collaboration, CERN

http://isoltrap.web.cern.ch