ISOLTRAP's MR-ToF mass separator/spectrometer

Robert Wolf
– University of Greifswald –
for the ISOLTRAP Collaboration

530. WE-Heraeus-Seminar:
Nuclear masses and nucleosynthesis,
Bad Honnef, 2013-04-24

- Limitations for on-line precision Penning-trap mass spectrometry
- MR-ToF mass **separator**: 82Zn mass measurement
- Upgrade: stacking of multiple purified ion bunches
- MR-ToF mass **spectrometer**: n-rich Ca mass measurement
- Future applications
- Summary

http://isoltrap.web.cern.ch

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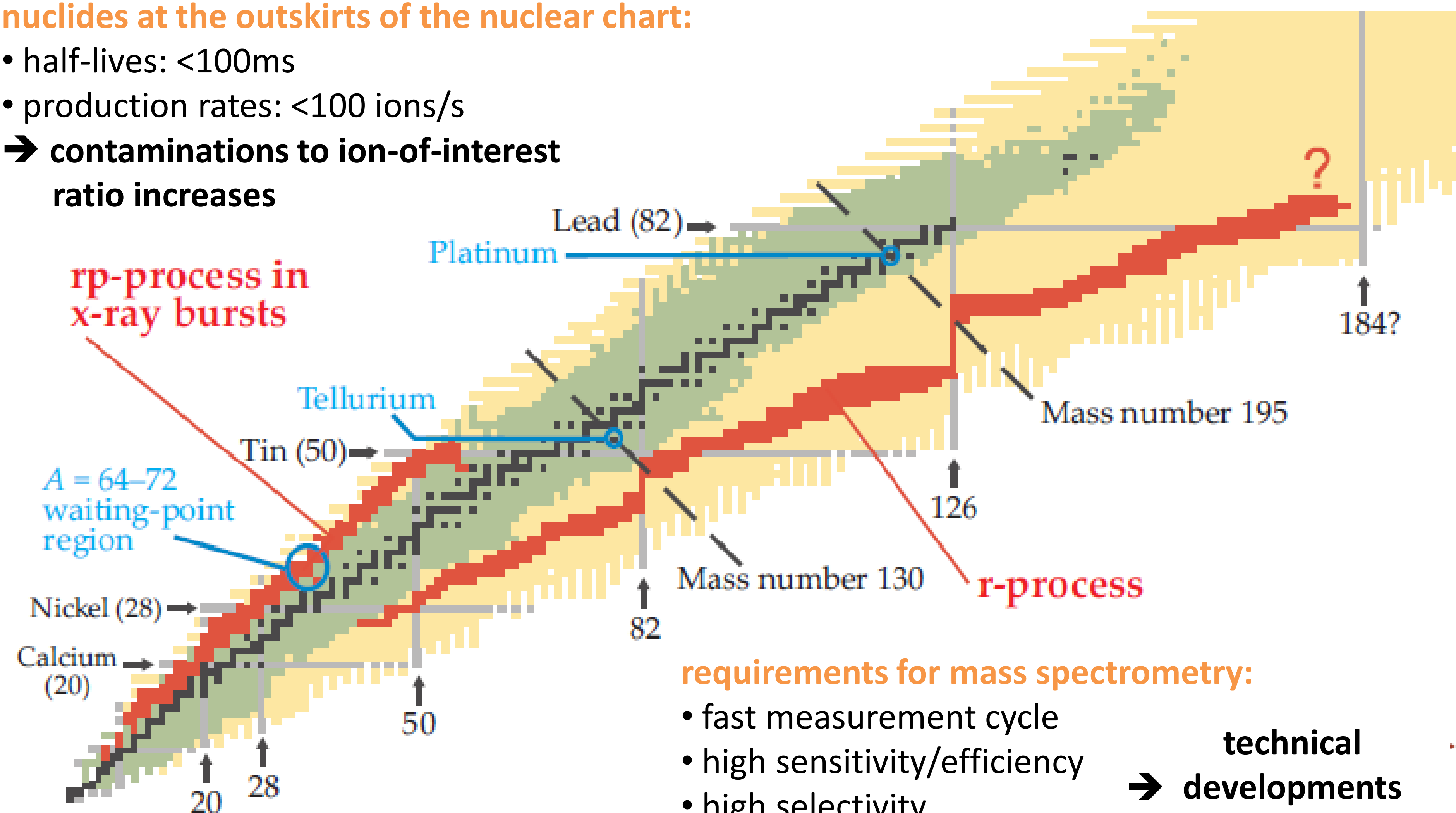
Masses for nucleosynthesis

Precise masses needed to constrain nuclear and astrophysical models

nuclides at the outskirts of the nuclear chart:

- half-lives: <100ms
- production rates: <100 ions/s

➔ **contaminations to ion-of-interest ratio increases**



requirements for mass spectrometry:

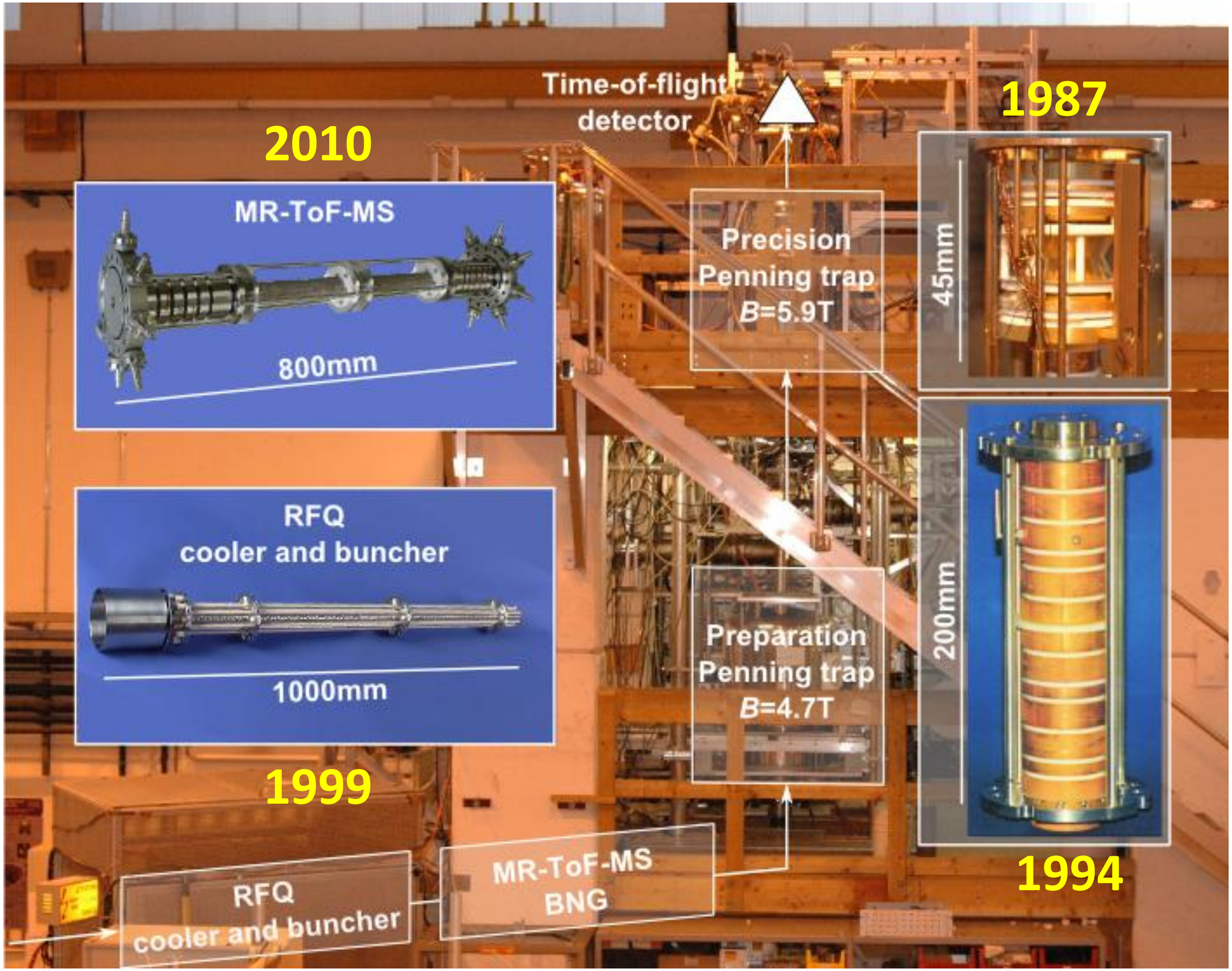
- fast measurement cycle
- high sensitivity/efficiency
- high selectivity
- sub-ppm uncertainty

➔ **technical developments necessary**

H. Schatz, Physics Today 61, 40 (2008)

ISOLTRAP overview

ISOLTRAP uncertainty: $\frac{\delta m}{m} \approx 10^{-8}$; >500 short-lived nuclides investigated



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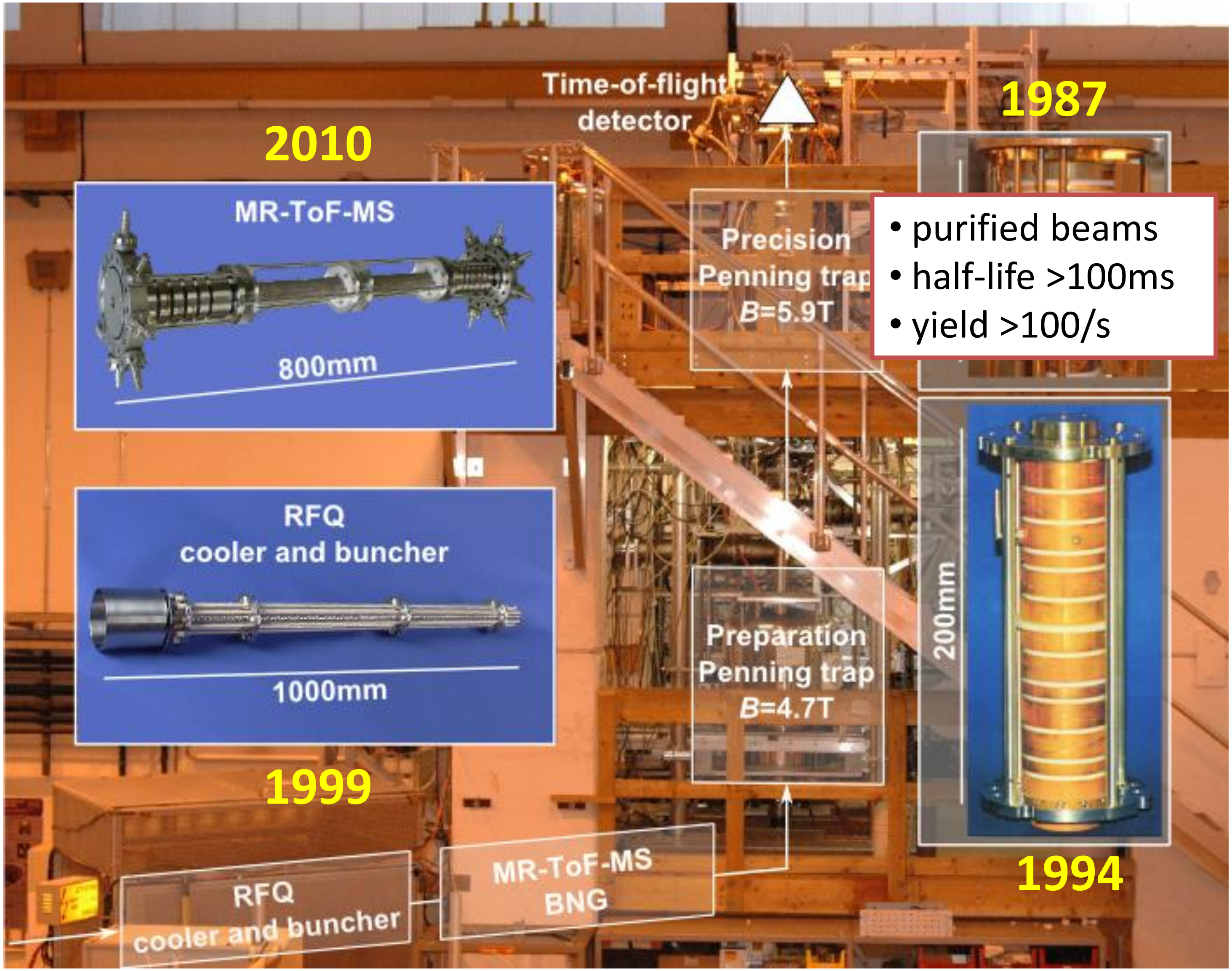
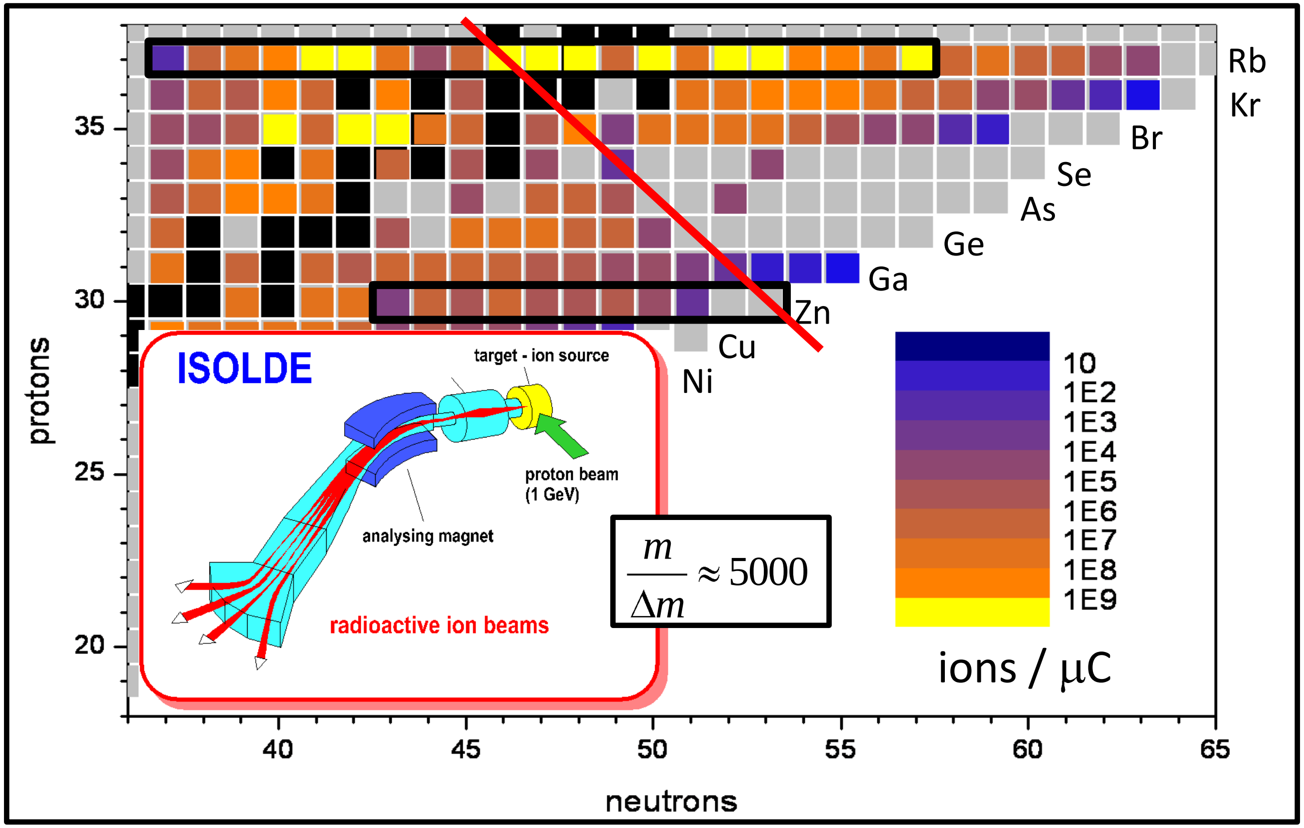
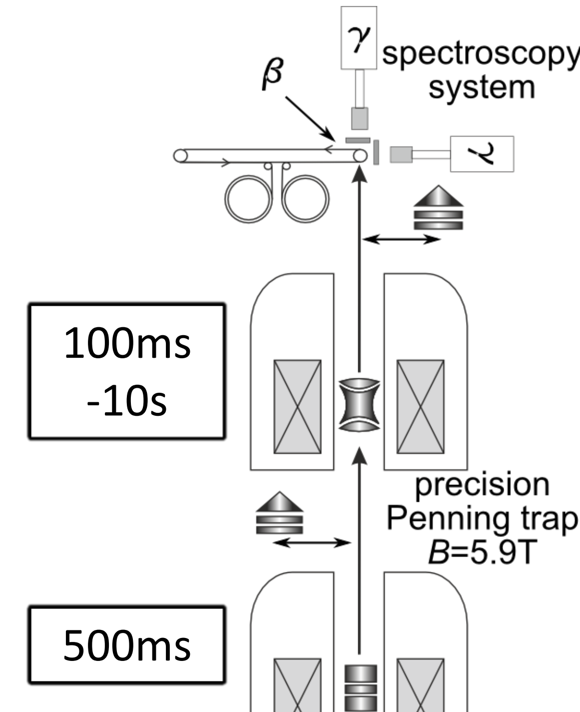
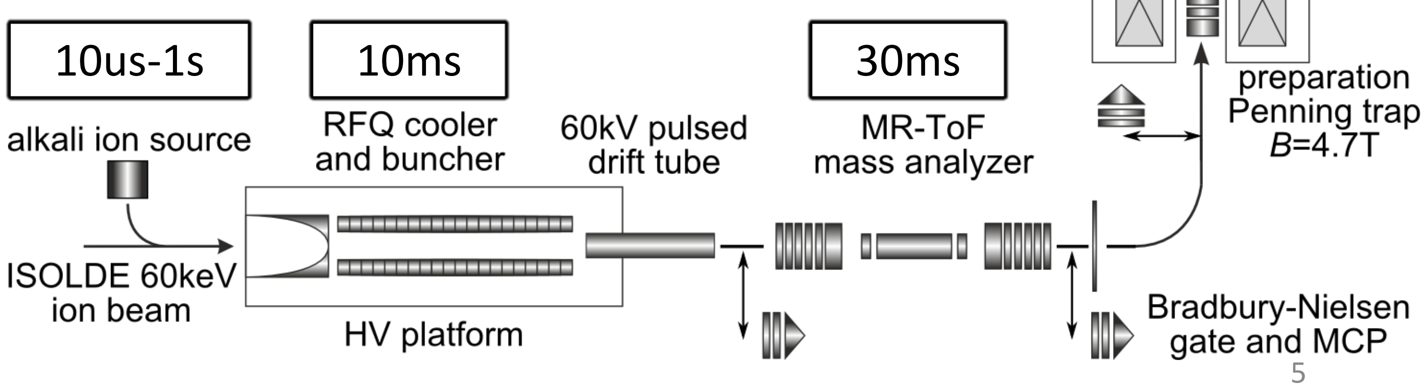


Isobar purification

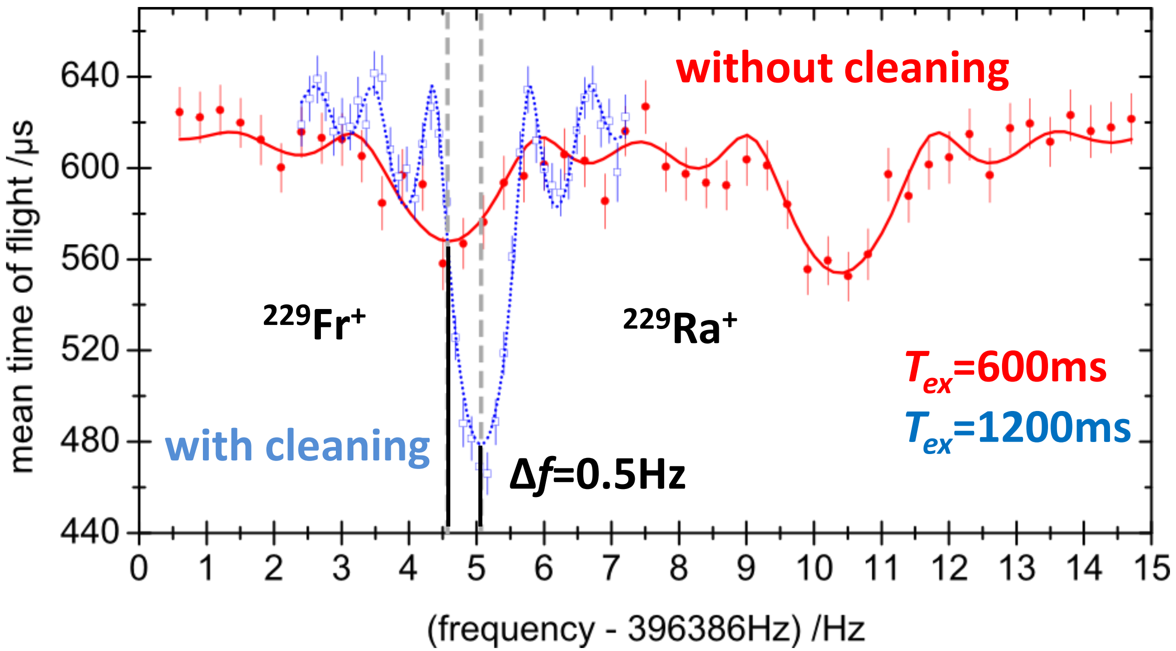






ISOLDE delivers a **mixture of isobaric species**

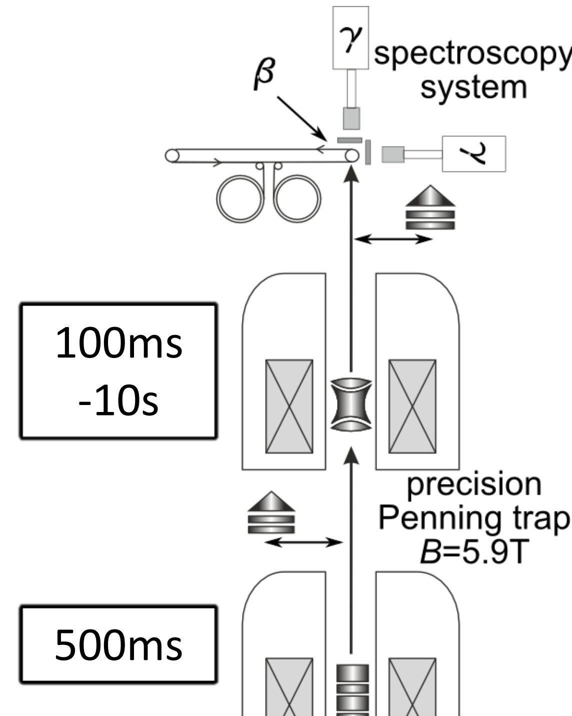
Isobar purification

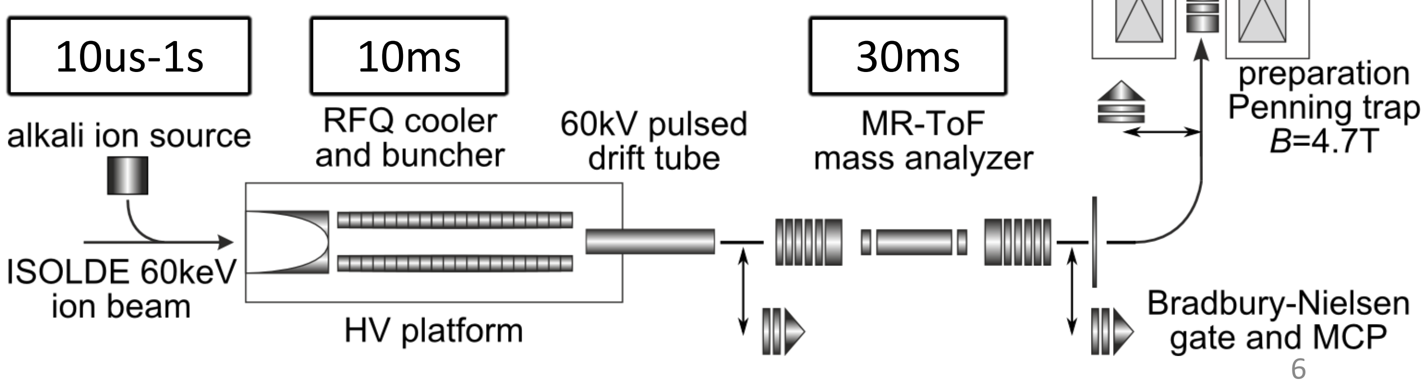


frequency shifts due to contaminated ensemble

➔ **Incorrect mass values**

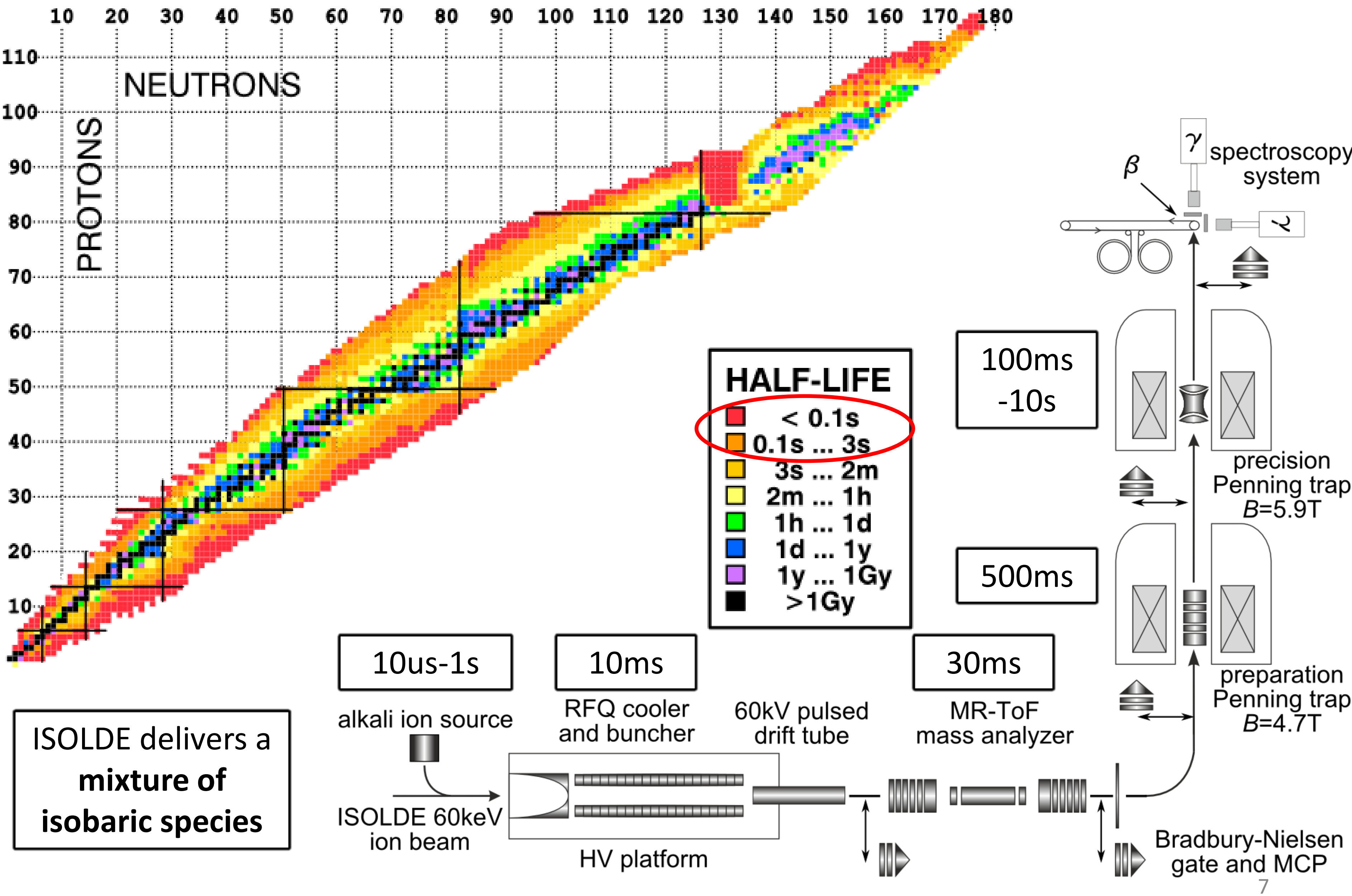
ISOLDE delivers a **mixture of isobaric species**





Wolf *et al*, IJMS, in print

Isobar purification



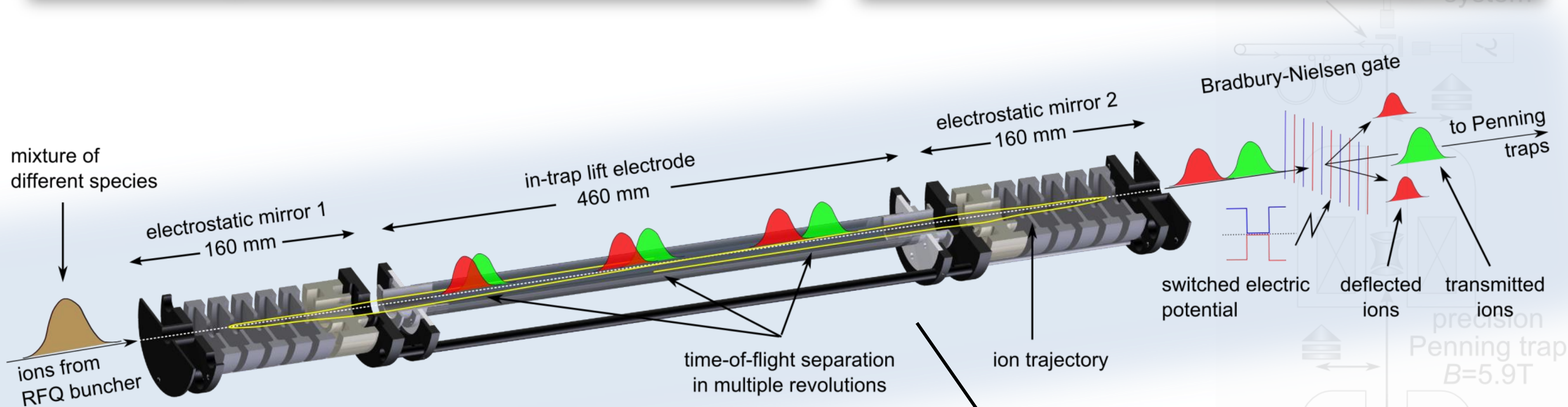
ISOLDE delivers a **mixture of isobaric species**

Multi-reflection time-of-flight (MR-ToF) isobar separator

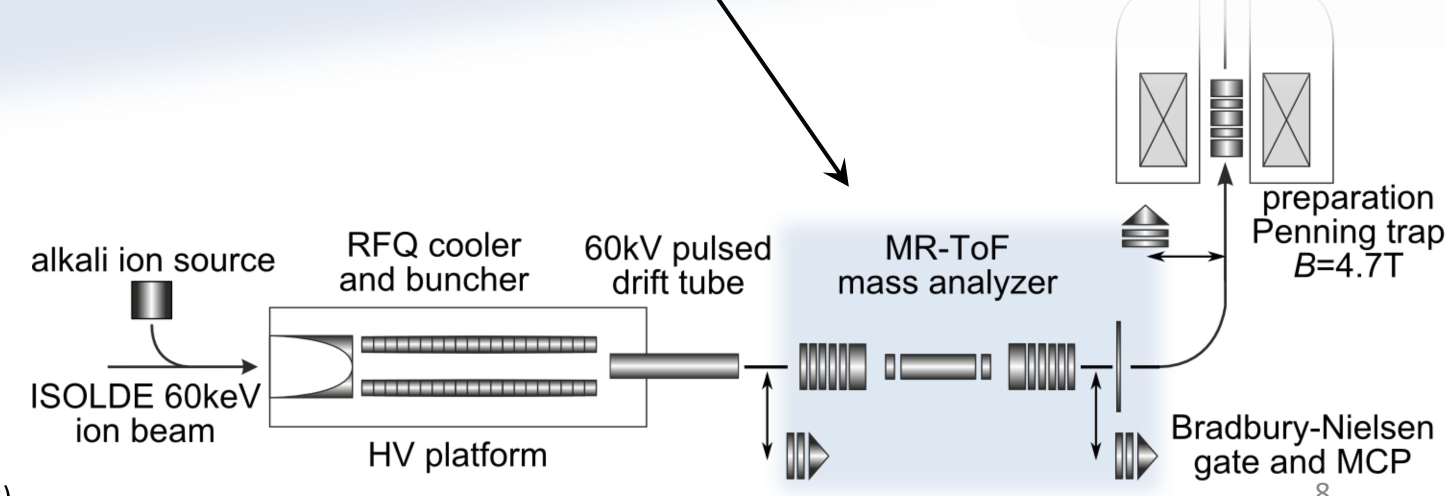
\\\\ **Wolf *et al.*, Hyperf. Inter. 199, 115 (2011); IJMS 313, 8 (2012); NIM A 686, 82 (2012); IJMS in print**

MR-ToF isobar separator[1,2]
- mean kinetic energy E_{kin}=2.1keV
- time-of-flight separation due to different *m/q*

Bradbury-Nielsen ion gate (BNG)[2,3]
- selection of wanted species
- further transport to first Penning trap



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



[1]Wollnik, IJMS 96, 267 (1990)
[2]Plass *et al.*, NIM B 266, 4560 (2008)
[3]Bradbury and Nielsen, Phys. Rev. 49, 388 (1936)

MR-ToF isobar separator performance

MR-ToF mass separator

Mass resolving power (FWHM)

$m/\Delta m$=100 000 after 10ms

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

Transmission

50%-70% for up to 30ms

Repetition rate

kHz operation possible

Ion capacity

10^3 per cycle, 10^6 per second

Bradbury-Nielsen gate

Mechanical design

10µm diameter wires

wire distance 0.5mm

area 3cm^2

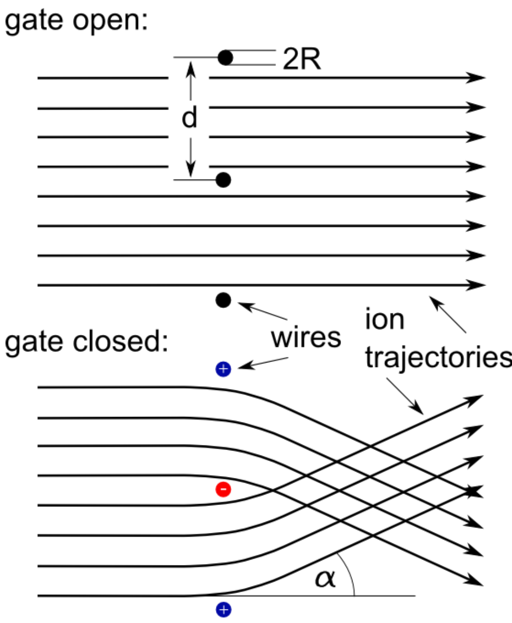
Electrical design

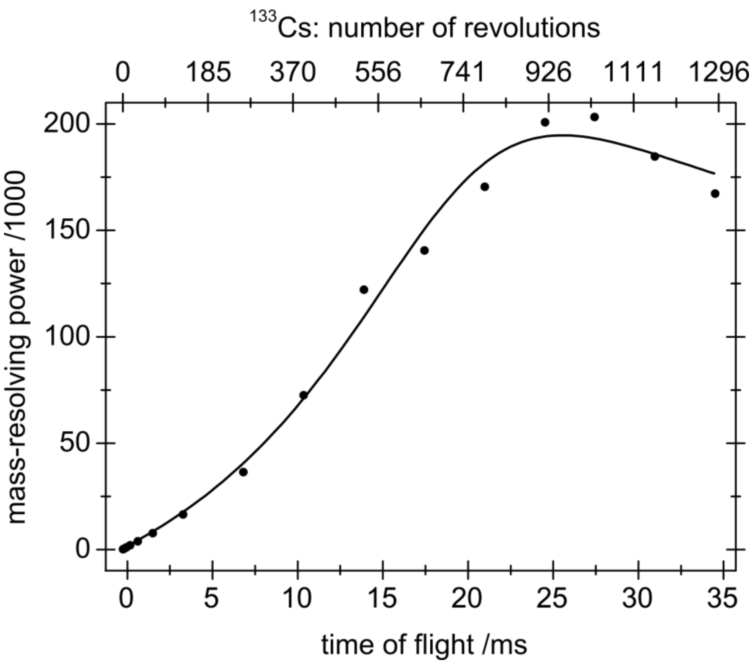
±250V transition in 20ns

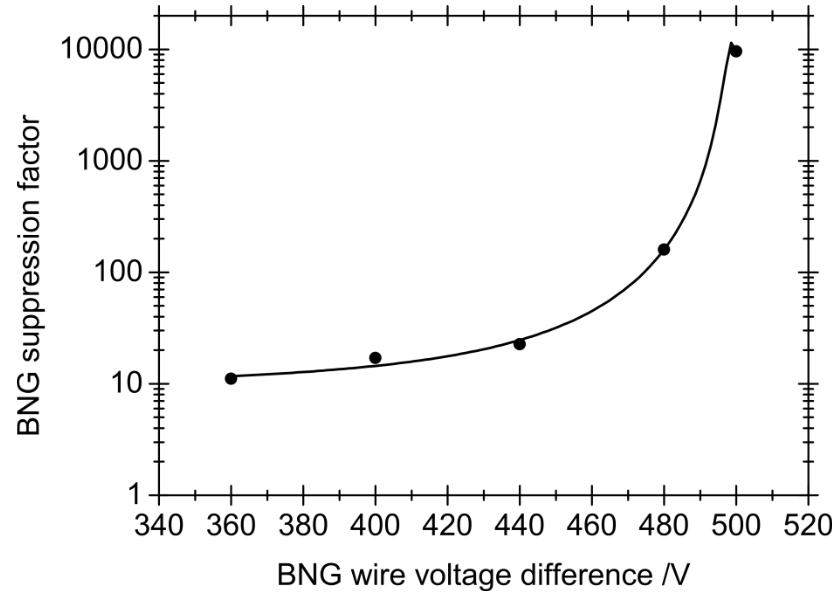
Transmission

open: 95%

closed (±250V): 0.01%







Wolf *et al.*, NIM A 686, 82 (2012)

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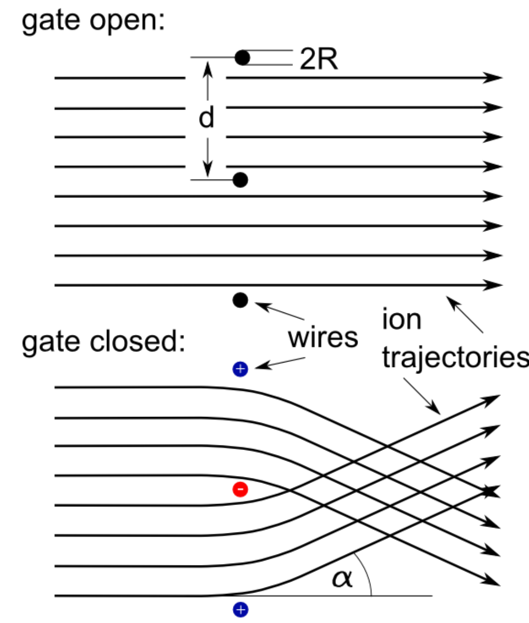
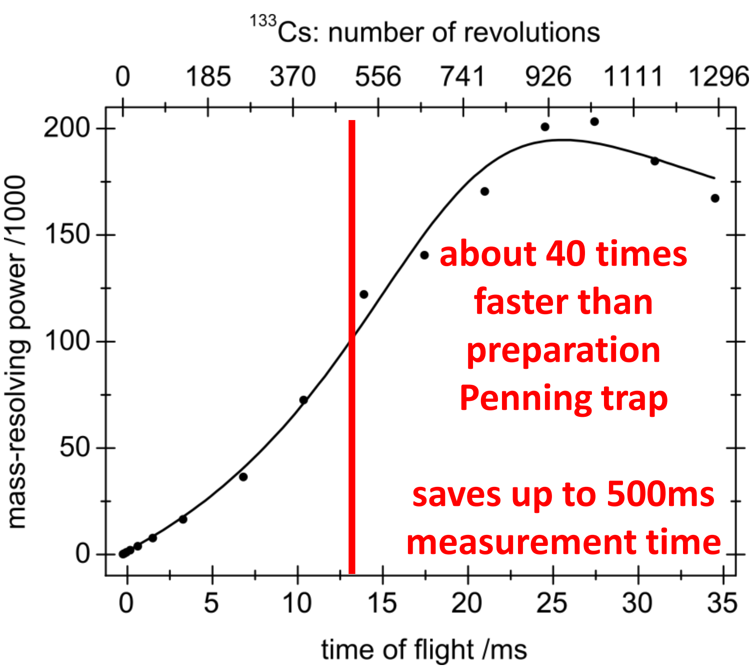
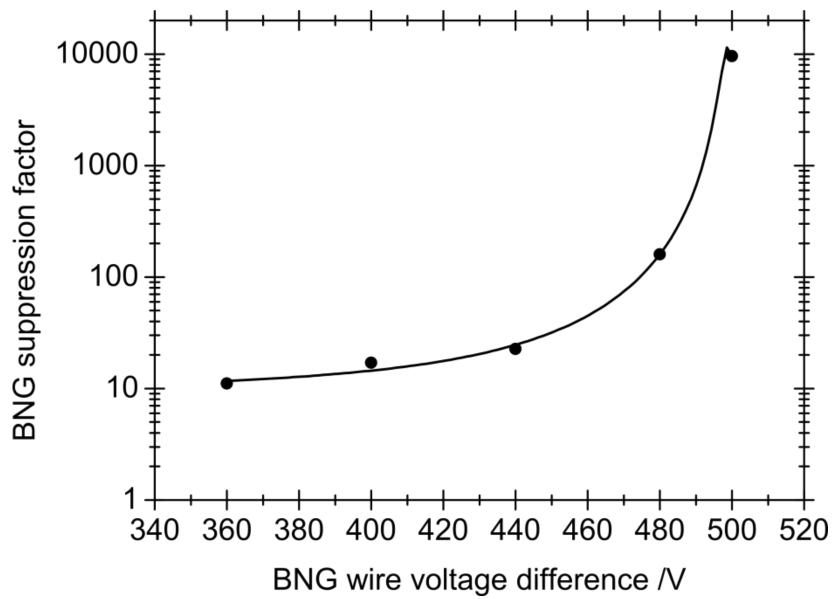






Wolf *et al.*, NIM A 686, 82 (2012)

Coulomb interaction

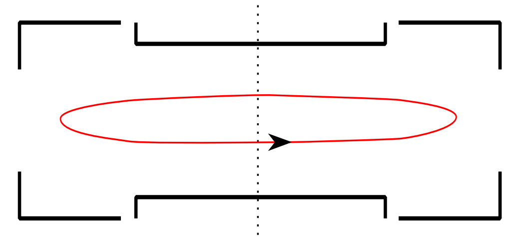
- MR-ToF trajectory calculations with Coulomb interaction for peak coalescence studies[1]
- Using PC graphics card for parallelism, NVIDIA CUDA and SIMBUCA[2]

Recording spectrum in middleplane every revolution

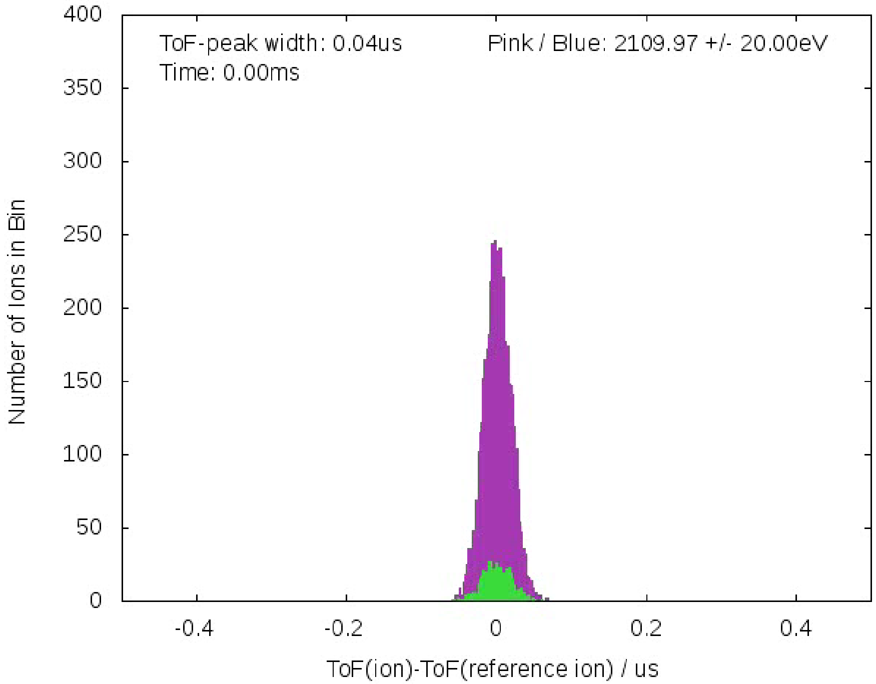
2 species: purple/green=4500/500, $m/\Delta m$=10000

E_{nom}=2110eV, ΔE_{FWHM}=20eV, $\Delta x,y,z_{std}$=1mm

$$\frac{\partial \delta_T}{\partial \delta_E} > 0$$



without interaction



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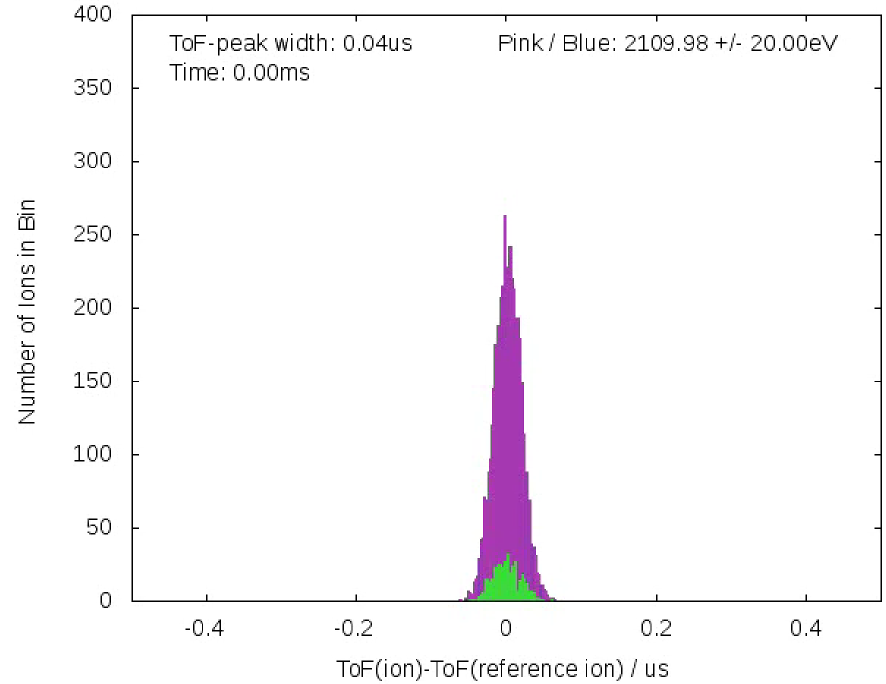

[1]M. Rosenbusch et al., AIP Conf. Proc. 521, 53 (2013)
[2]S. van Gorp et al., NIM A **638,** 192 (2011)

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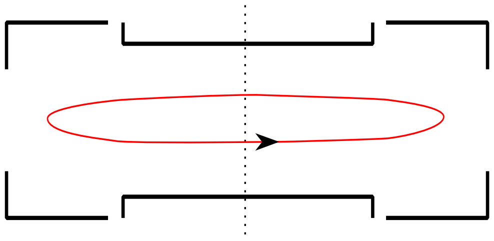

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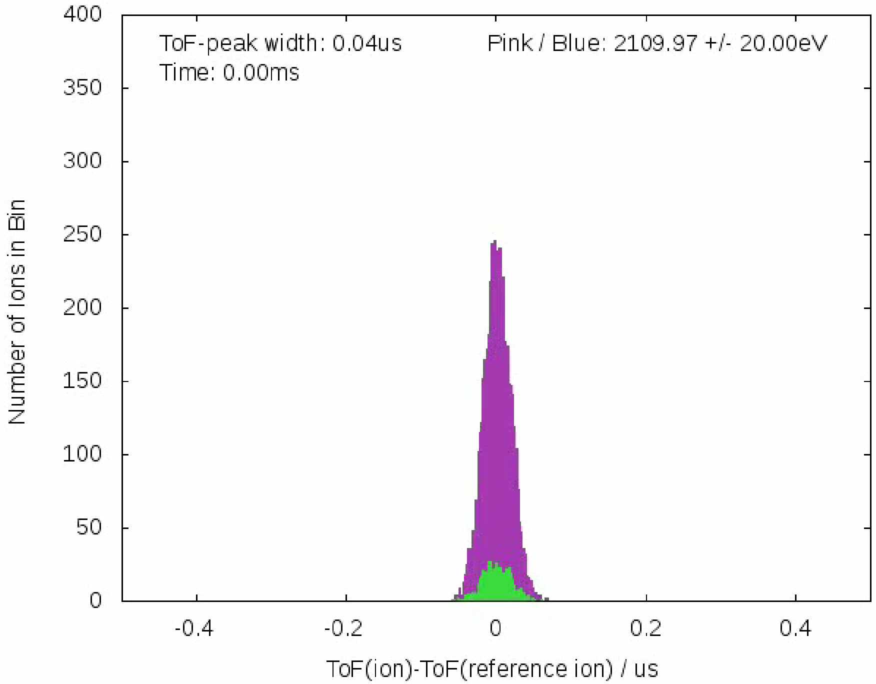

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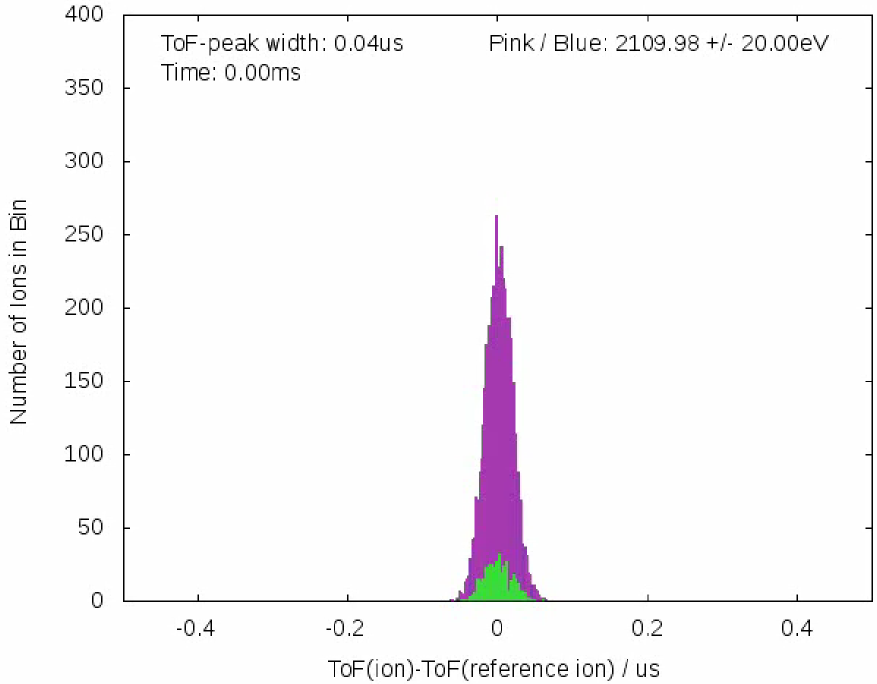

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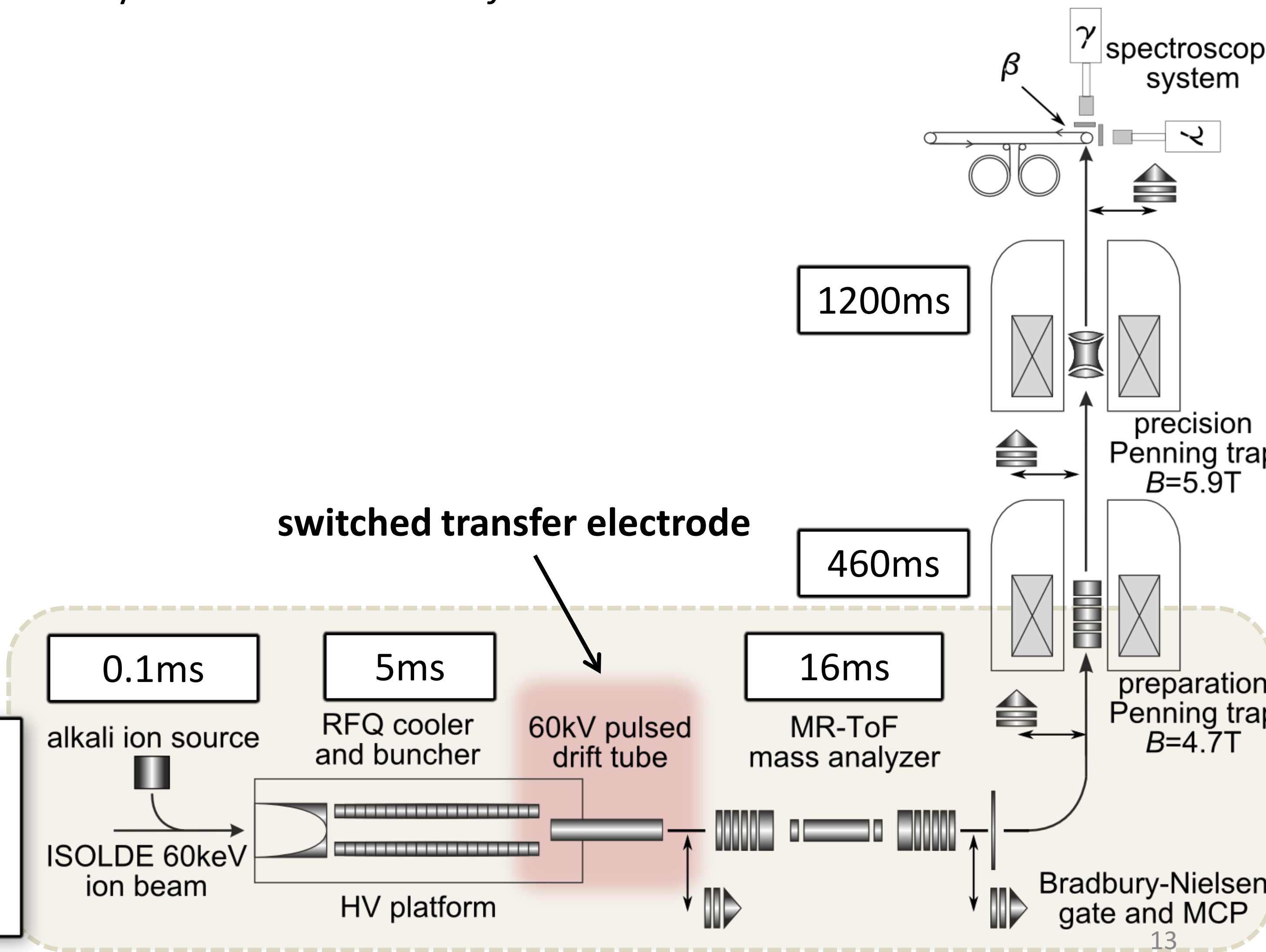
High-frequency 60kV switch

Bottleneck for high ion throughput: **60kV switched transfer electrode**, max. *f*=5Hz

➔high-frequency switch system installed: max. *f*=1kHz at 60kV



^{179}Lu:
3×10^5/s, $T_{1/2}$=4.6h
^{163}Dy^{16}O:
4.5×10^8/s, stable

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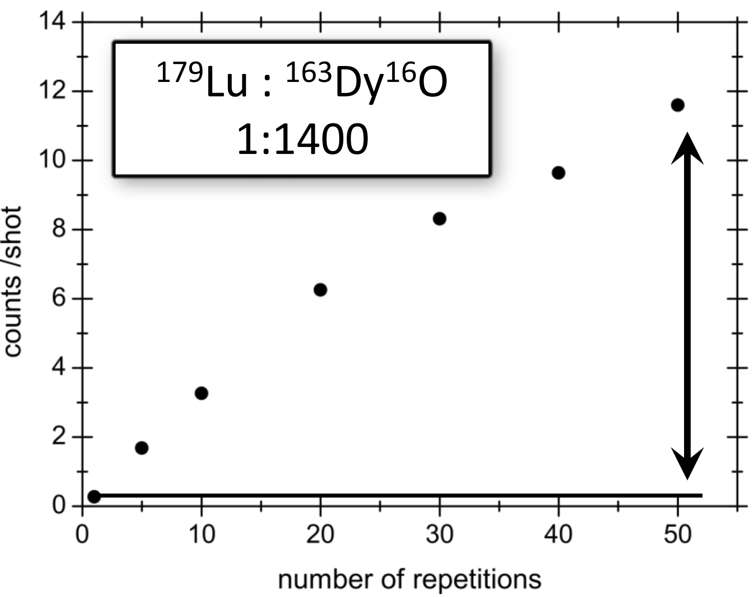
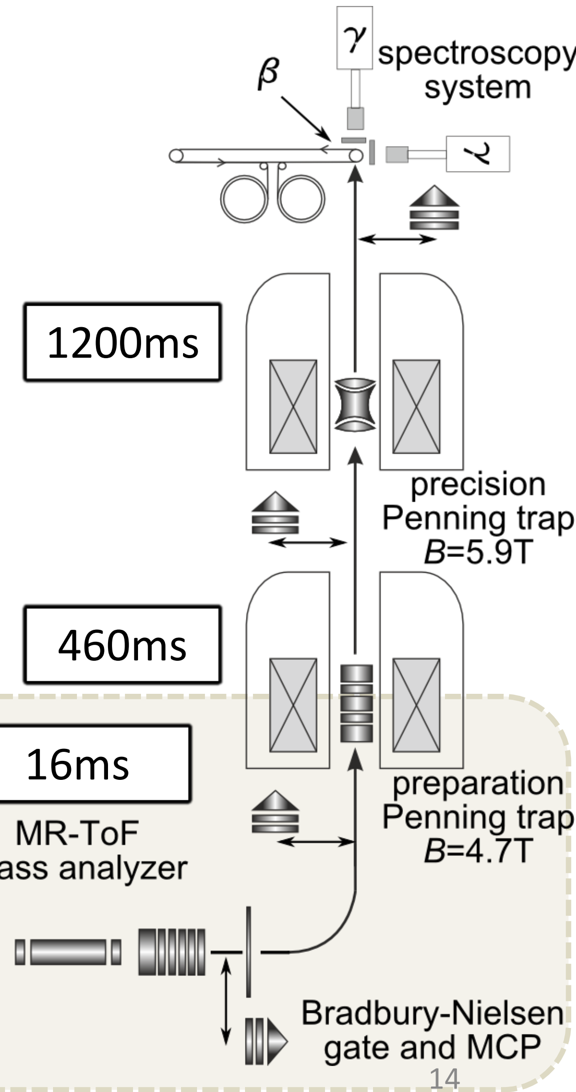


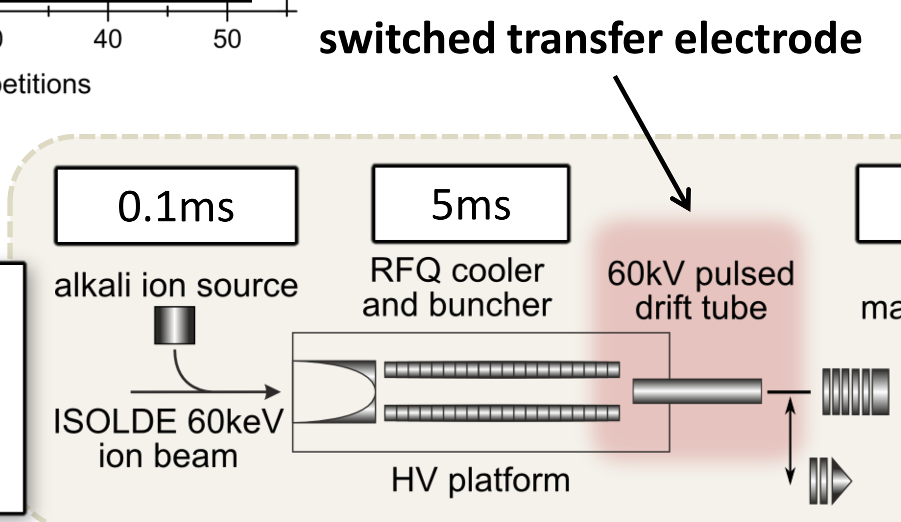
<u>20Hz repetition rate:</u>

- x35 count rate
- x1.6 meas. time
- **x22 faster meas.**

measurement time:

≈1 day ⟶ 1 hour!





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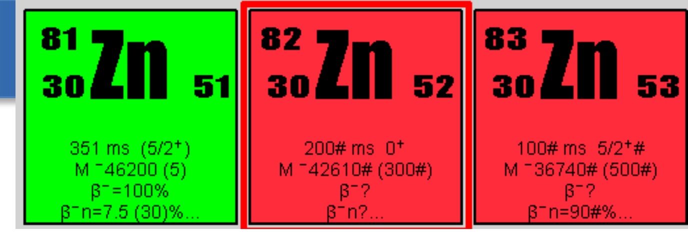
First ^{82}Zn mass measurement

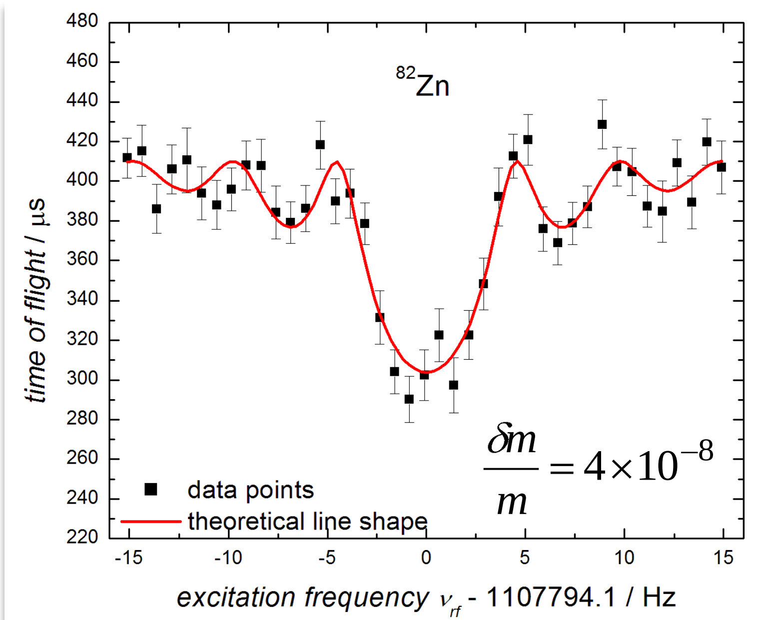


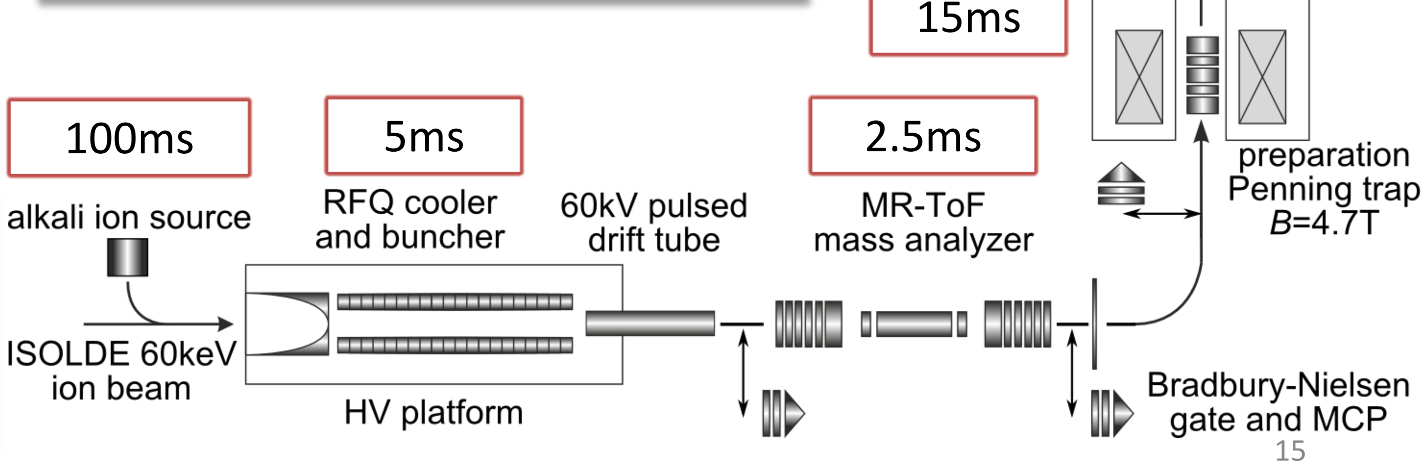
82Zn: most neutron excessive nuclide beyond the *N*=50 shell closure[1]

Preparation Penning trap in a "short cycle":
only buncher and cooler,
high gas pressure,
no mass purification
➔15ms period
➔ <25ms complete preparation

Latest techniques from ISOLDE combined:

- resonant laser ioniz.
- neutron converter
- quartz transfer line

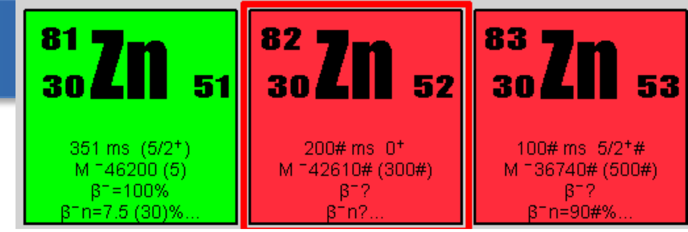




^{82}Zn:
200/s, $T_{1/2}$=228ms[2]
^{82}Rb:
6000/s, $T_{1/2}$=1.3min

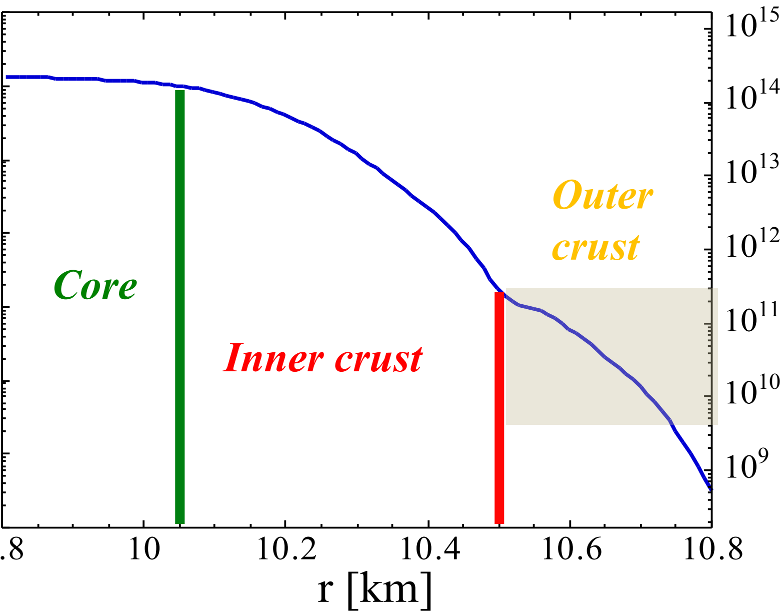
[1]Wolf *et al.*, PRL 110 (2013) 041101 [2]Madurga *et al.*, PRL 109 (2012) 112501

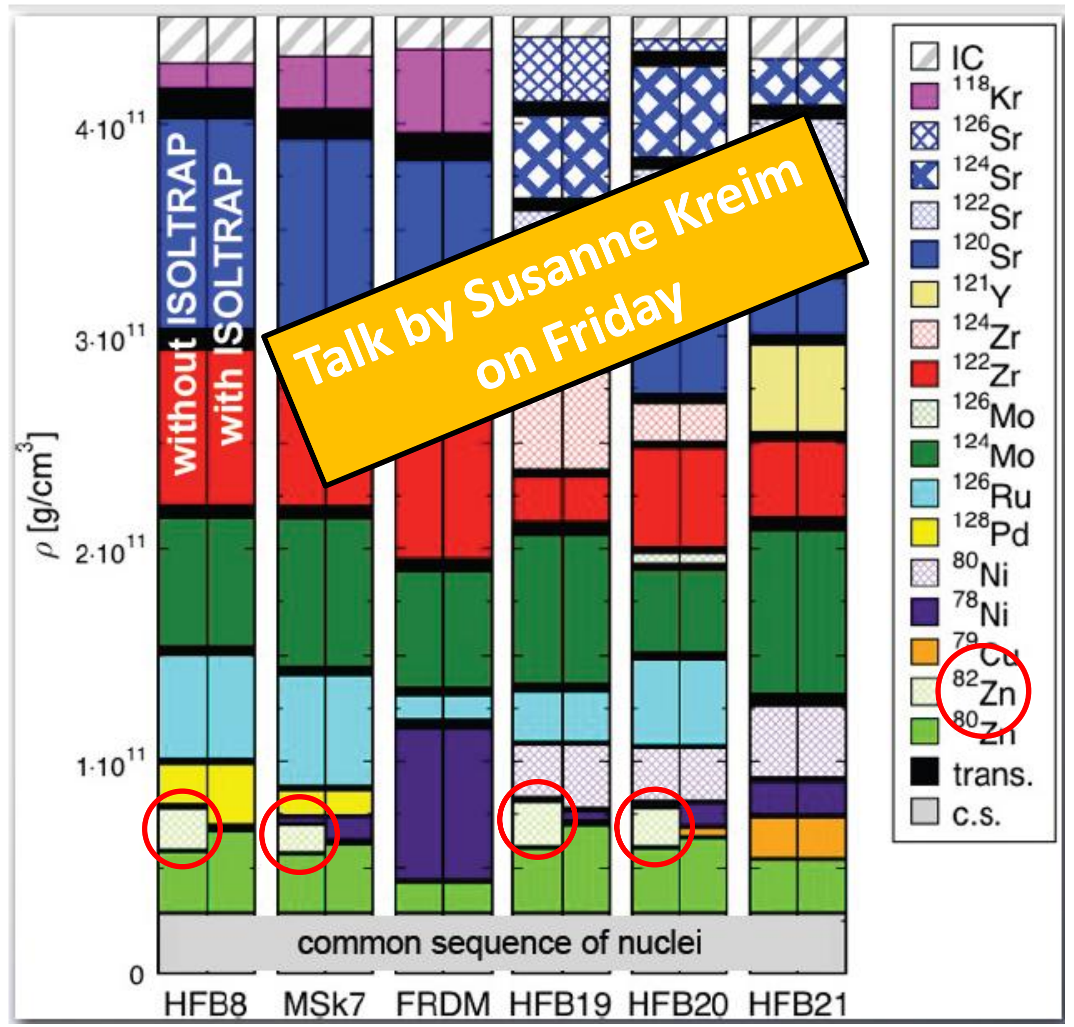
First ^{82}Zn mass measurement



\\ composition of the outer crust of a neutron star

- Outer-crust composition determined by binding energy of n-rich nuclides[1]
  - ➔ precision masses are the most important input parameter
    - *ME*(AME2012) = #-42610(300)keV
    - *ME*(ISOLTRAP) = -42314(3)keV
  - ➔ models to calculate unknown mass
    - *ME*(HFB-19) = #-42960keV
    - *ME*(HFB-21) = #-42700keV



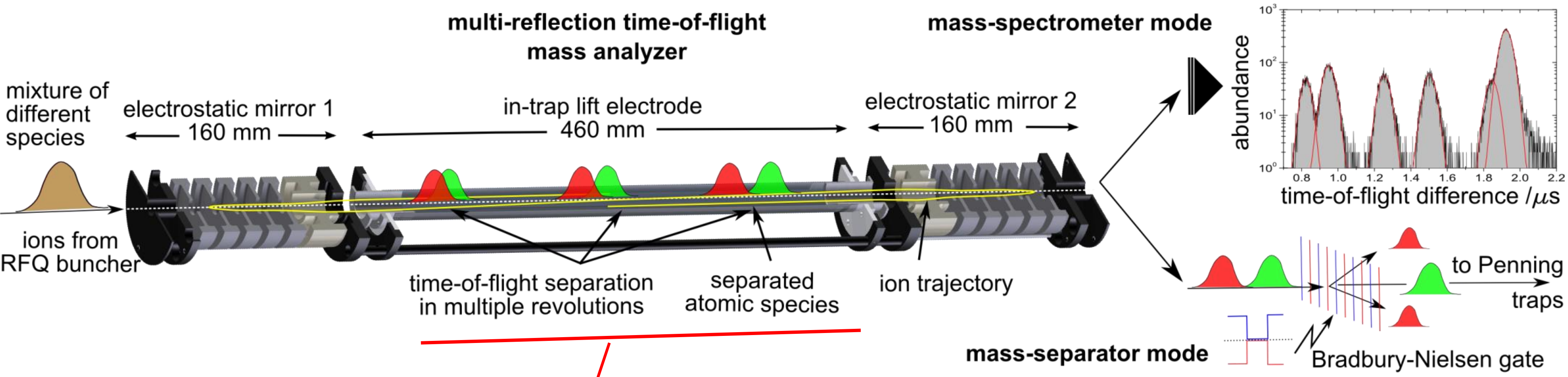


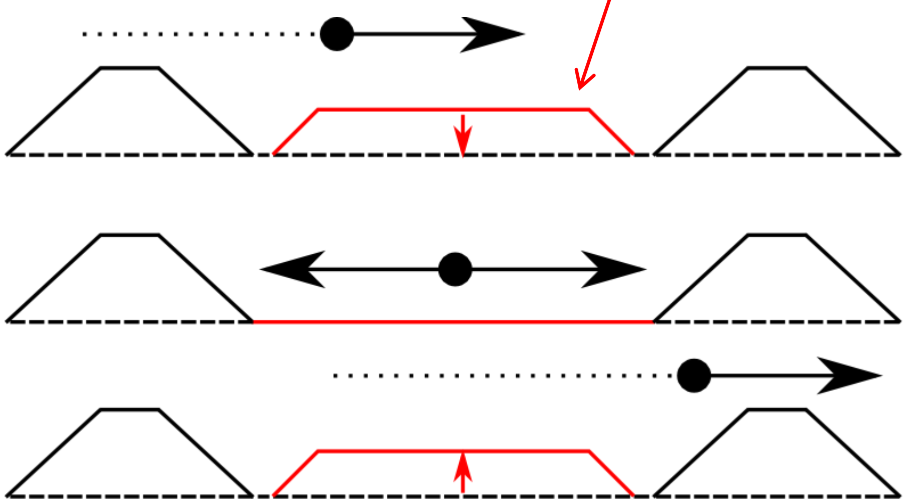
Kreim *et al.*, Nuclear Masses and Neutron Stars, IJMS, in print

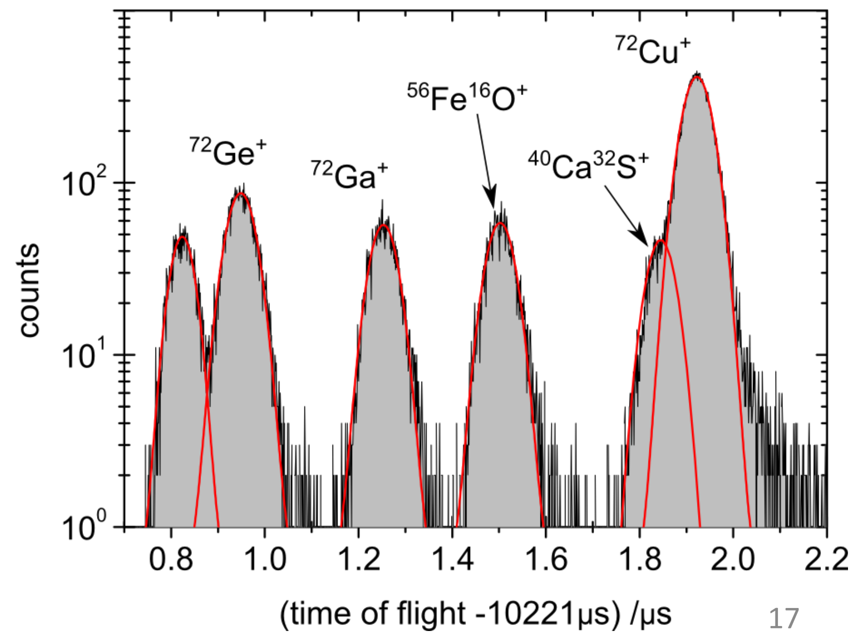
[1]Baym *et al.*, APJ 170, 299 (1971)

MR-ToF mass spectrometer

\\ Principle of Operation







in-trap lift time-of-flight window

Wolf *et al.*, IJMS in print

MR-ToF mass spectrometer: comparison to Penning trap TOF-ICR

Penning trap TOF-ICR:

$$R = \frac{m}{\Delta m} \approx \gamma \cdot \nu_c T_{obs} \qquad \nu_c \propto \frac{q}{m} \rightarrow 10^6$$

MR-ToF-MS:

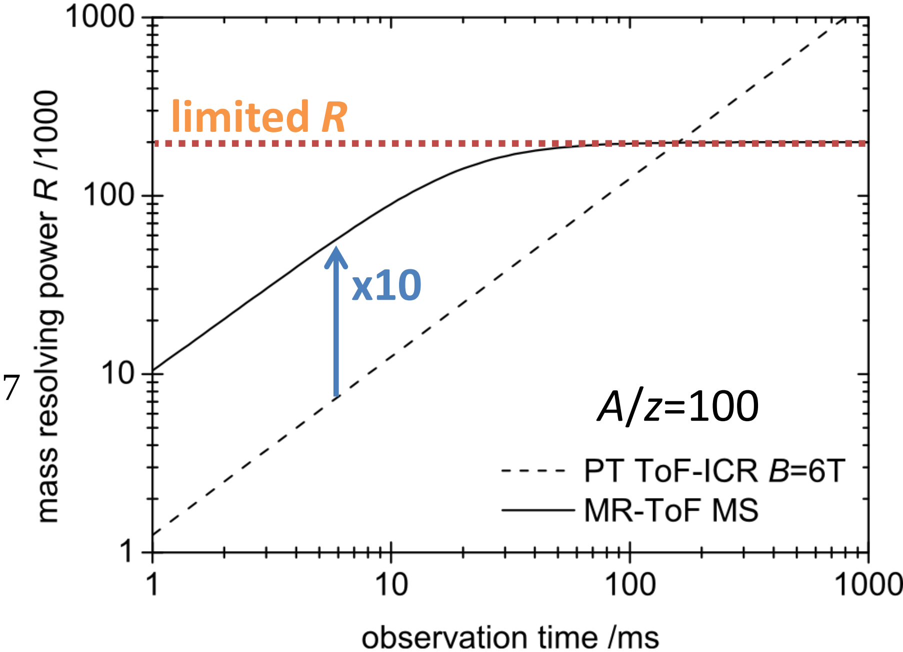
$$R = \frac{m}{\Delta m} = \frac{T_{obs}}{2\Delta t} \qquad \frac{1}{2\Delta t_{th}} \propto \frac{q}{\sqrt{m}} \frac{E_{ex}}{\sqrt{E_{kin}}} \rightarrow 10^7$$

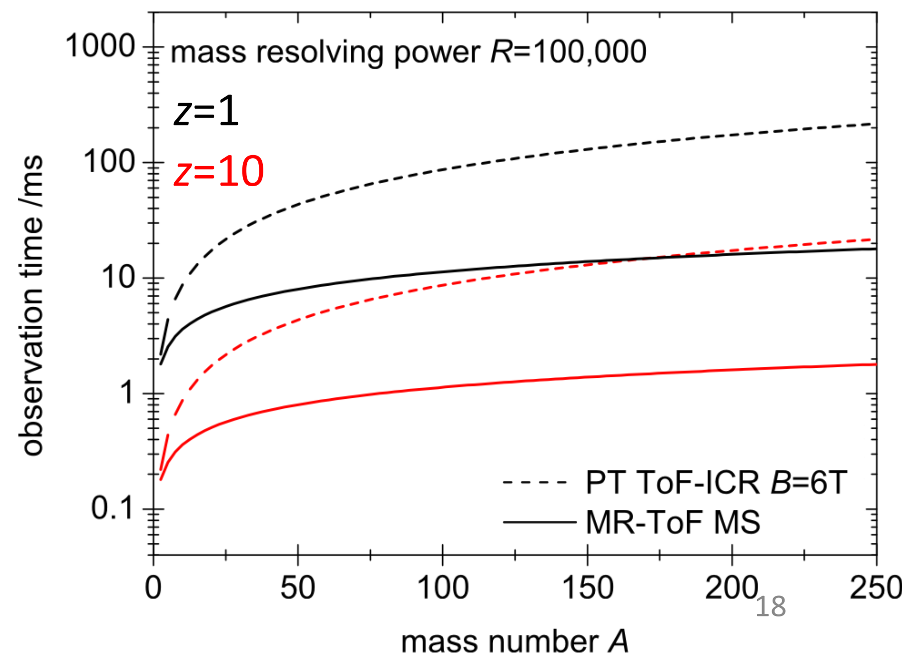
$$= \frac{t_{transfer} + nT}{2\sqrt{\Delta t_{th}^2 + n^2 \Delta T^2}}$$

$$\xrightarrow{n\rightarrow\infty} \frac{T}{2\Delta T}$$

n : # of revolutions
T : revolution ToF
E_{ex} : extraction field strength

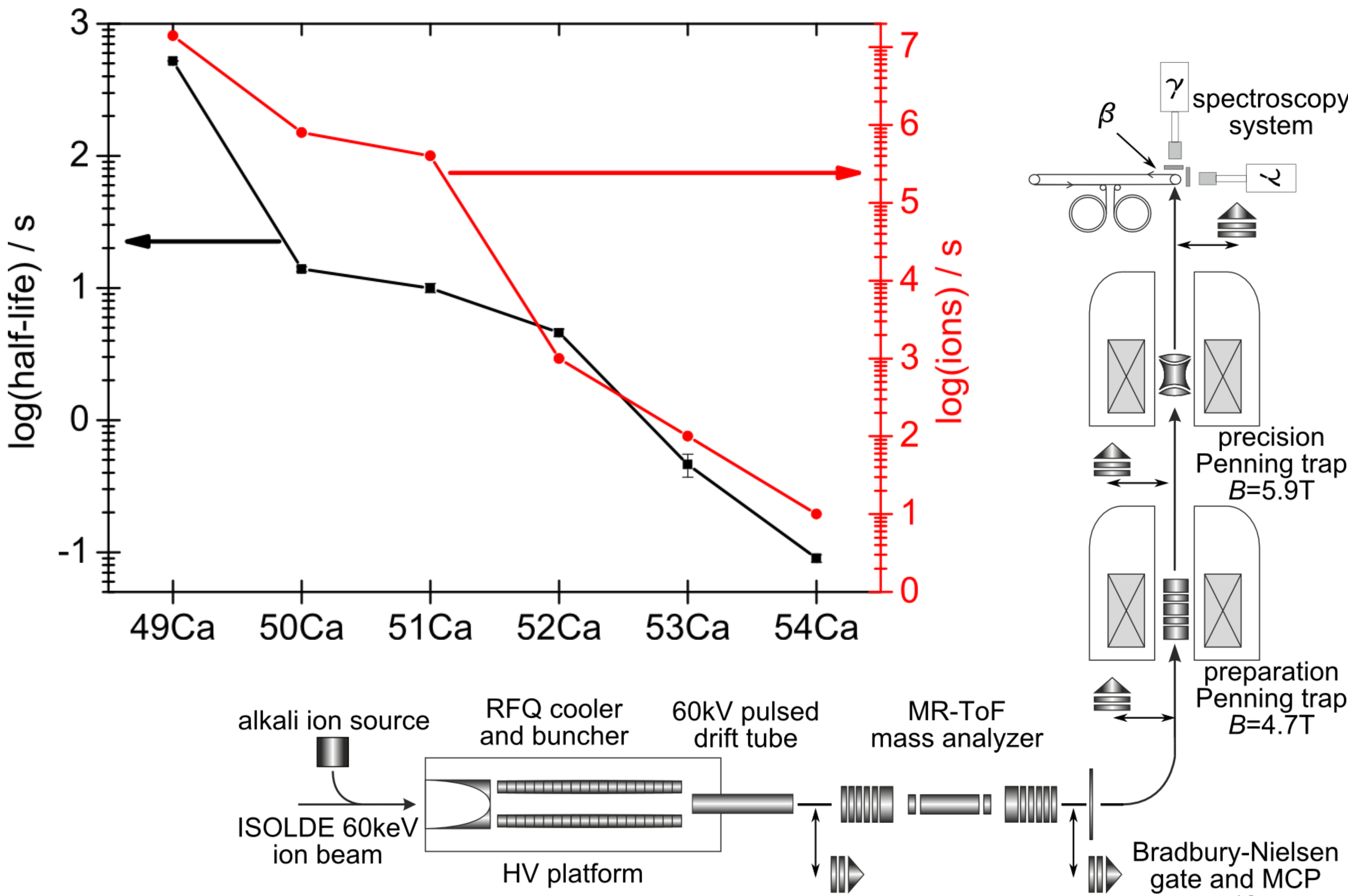
- short observation times (half-lives) below 100ms, MR-ToF-MS beats PT ToF-ICR
- MS-ToF-MS favorable for heavy nuclides
- MR-TOF mass resolving power limited by:
  - ion energy in the source
  - ToF deviations, abberations
  - emittance of the bunch
  - stability of spectrometer parameters





MR-ToF mass spectrometer

\\ n-rich Calcium isotopes: yield and half-life



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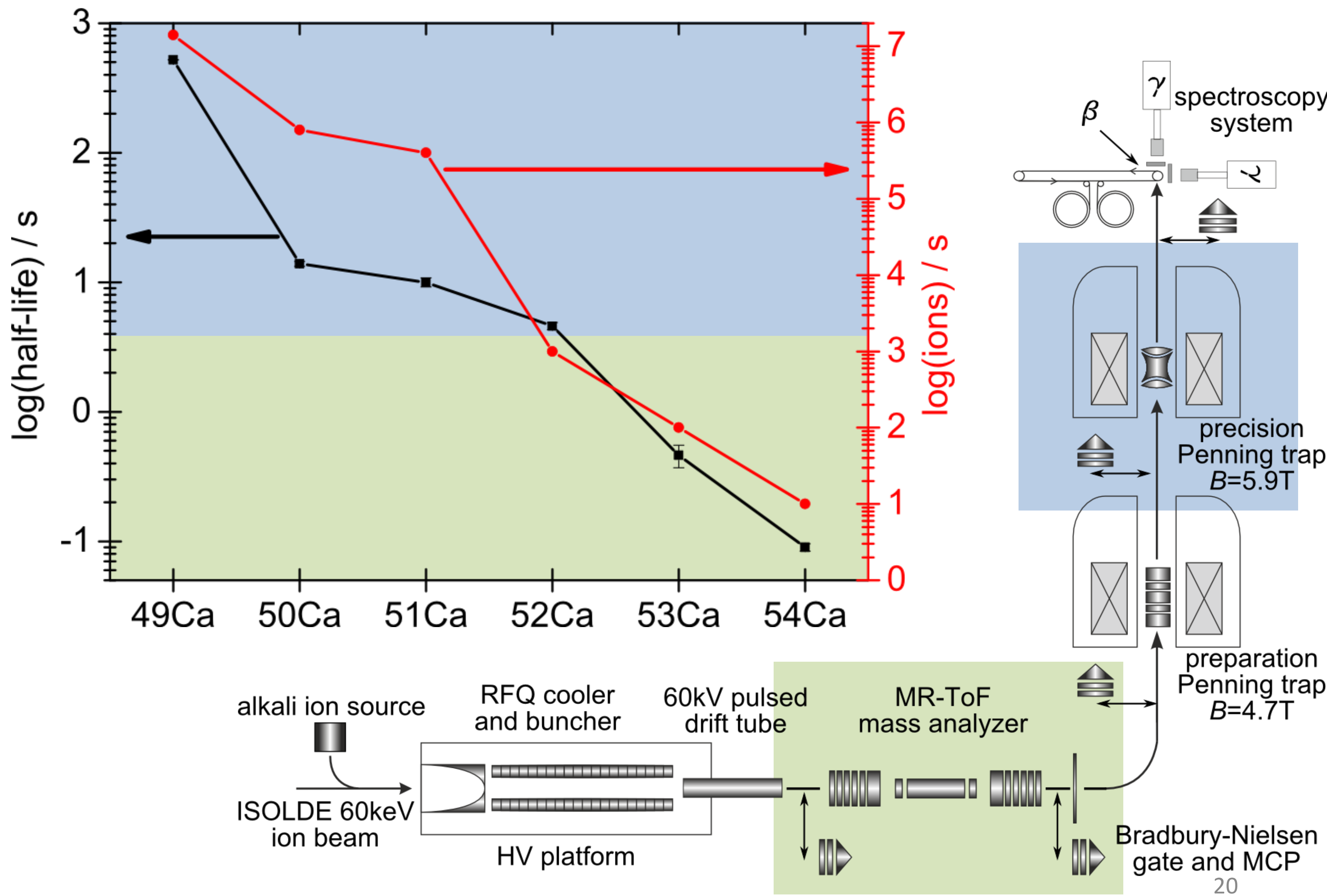
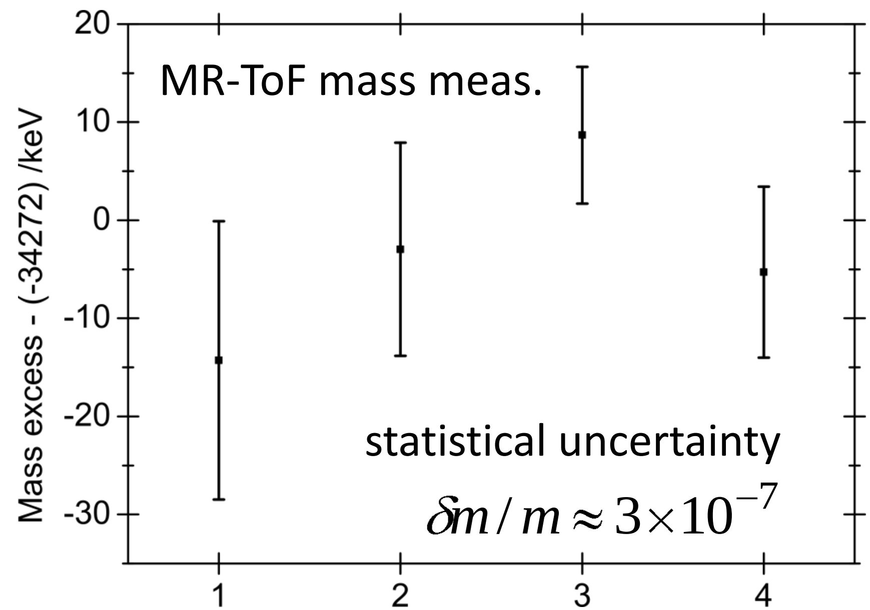
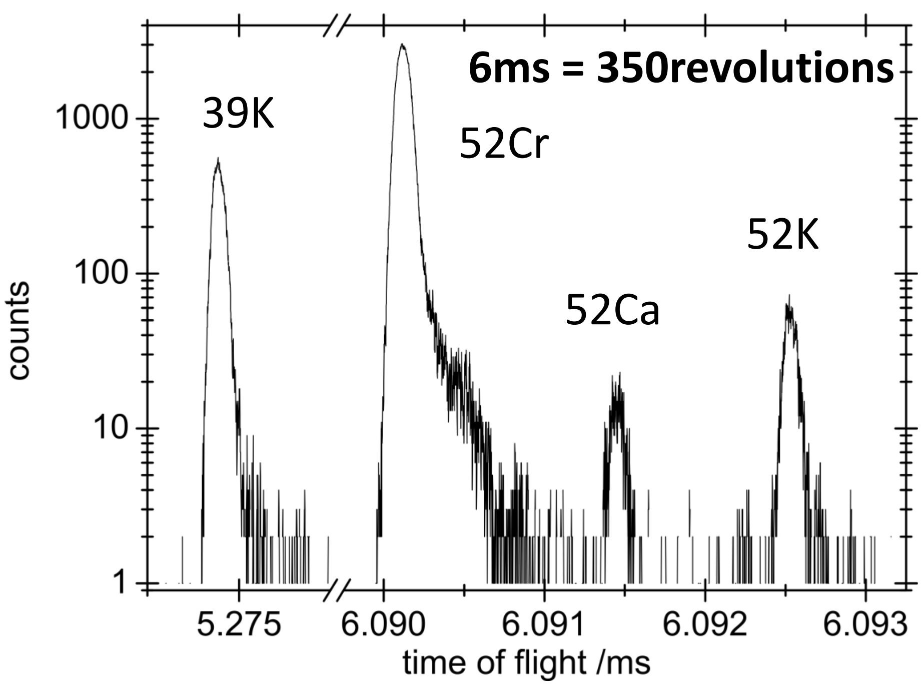


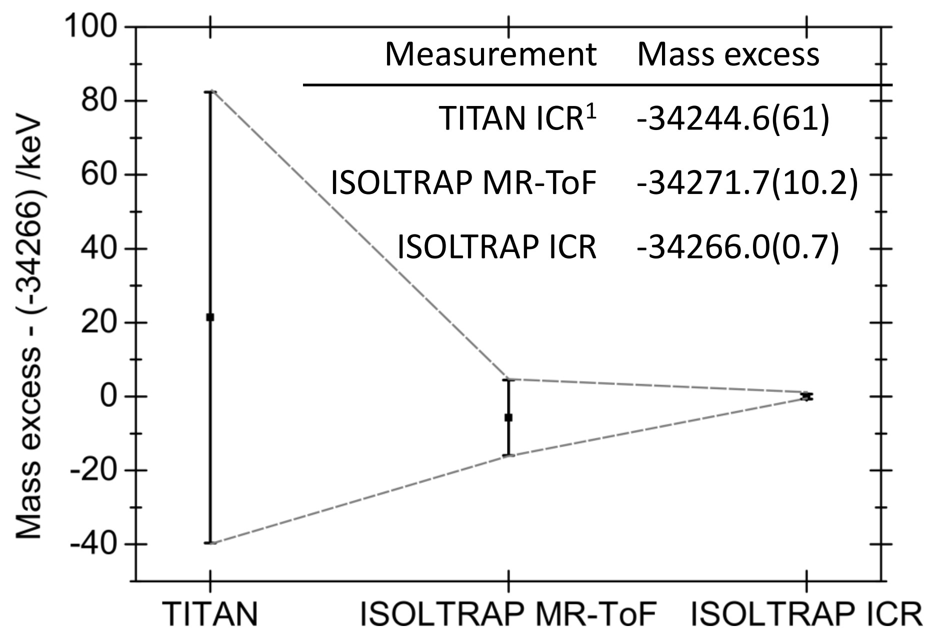
MR-ToF mass spectrometer

\\ n-rich Calcium isotopes: 52Ca

- TITAN measurements of 51,52Ca
- Calculations including 3-body forces from chiral effective field theory
  - Agreement with phenomenological approaches
  - Agreement with TITAN measurements
  - Prediction of Ca masses beyond 52Ca



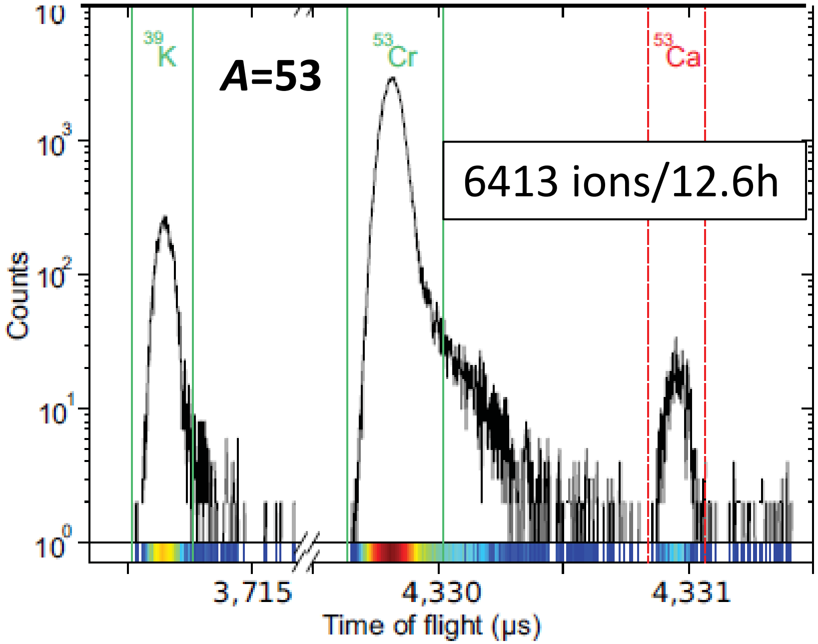


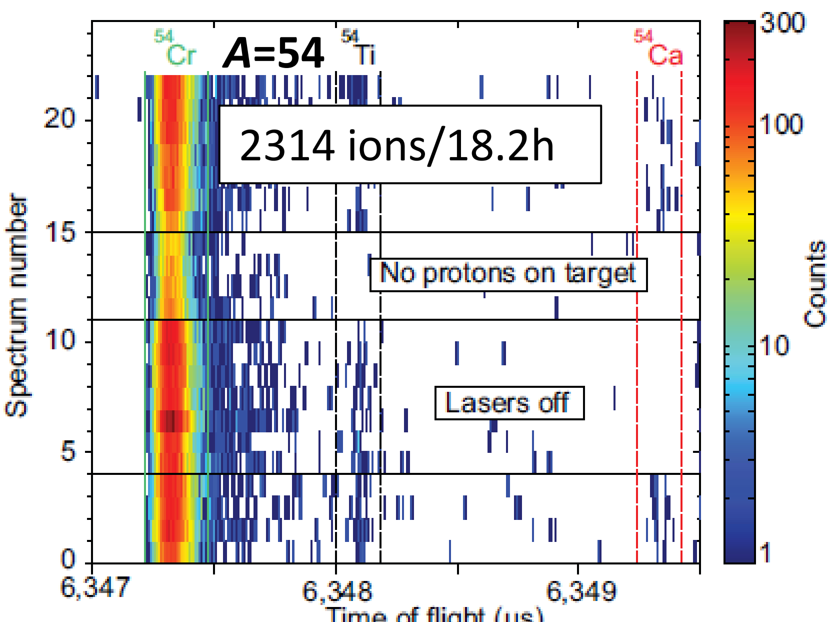


[1]Gallant *et al.*, PRL **109**, 032506 (2012)

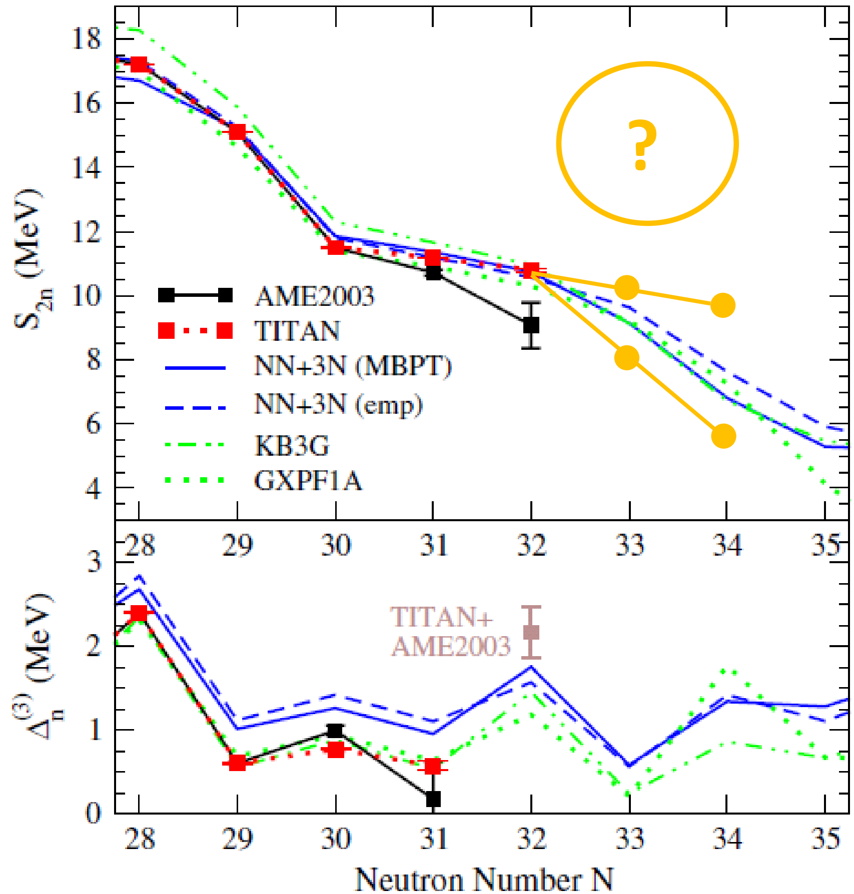
MR-ToF mass spectrometer

\\ n-rich Calcium isotopes: 53Ca and 54Ca





- **Masses of 53Ca and 54Ca** determined for the first time
- Experimental S2n to clarify the question of a new **magic number at *N*=32**

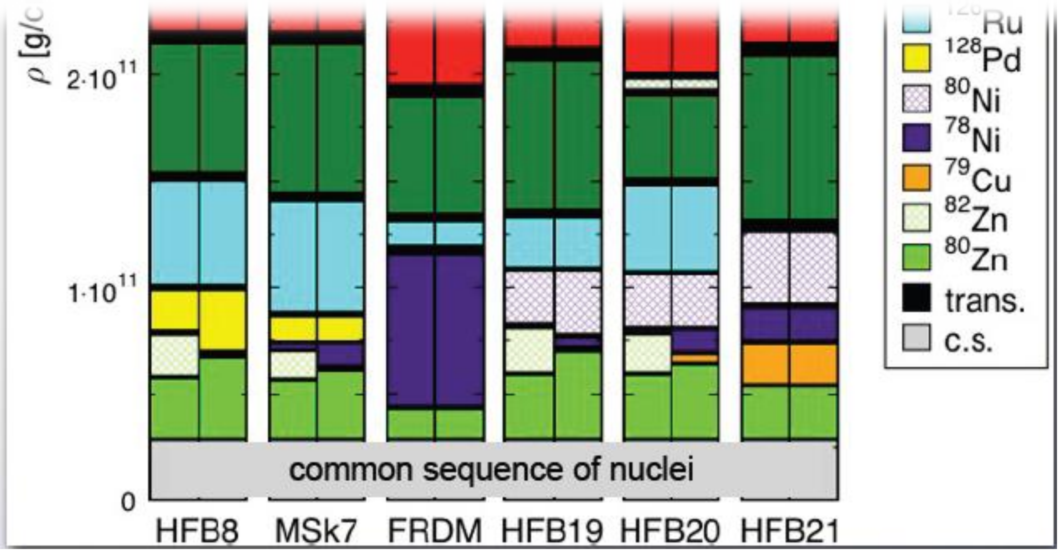


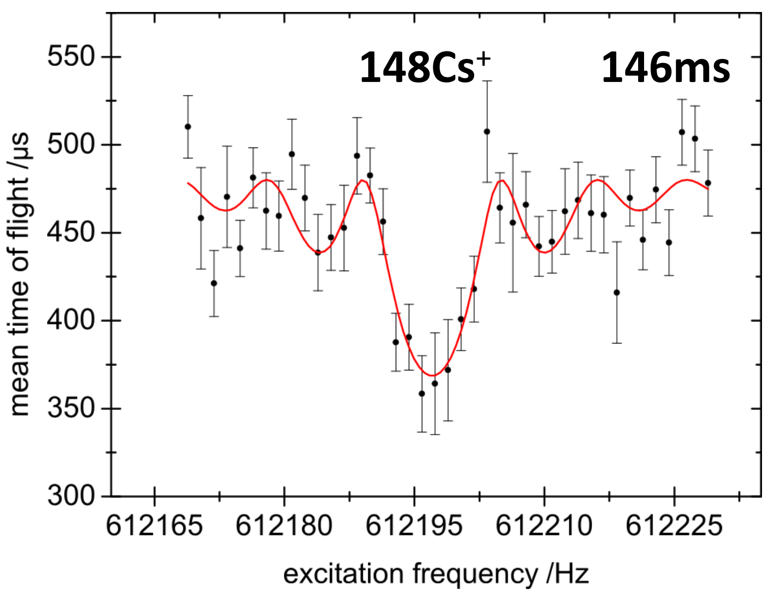
Kreim *et al.*, INTC-P-317, IS 532 (2011)
Gallant *et al.*, Phys. Rev. Lett. **109**, 032506 (2012)
Wienholtz *et al.*, accepted (2013)

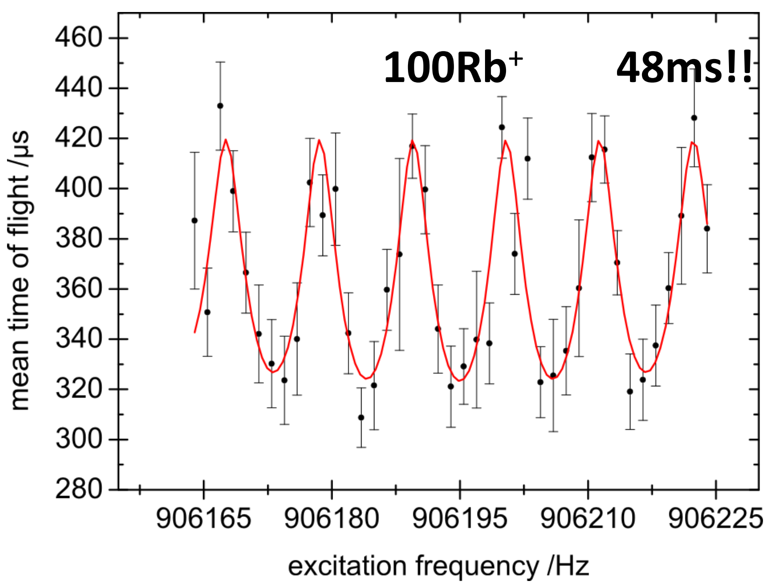
Outlook: Possible future MR-ToF MS applications

\\ Explore *N*=50

- Explore *N*=50 nuclei constituting the outer crust of neutron stars: **79Cu**
→but: beam time in October 2012 failed due to broken neutron converter
- **measured instead:**
  Penning trap: **98-100Rb, 144-148Cs**
  MR-ToF-MS: **149Cs**
  (no isobaric calibrants, evaluation ongoing)







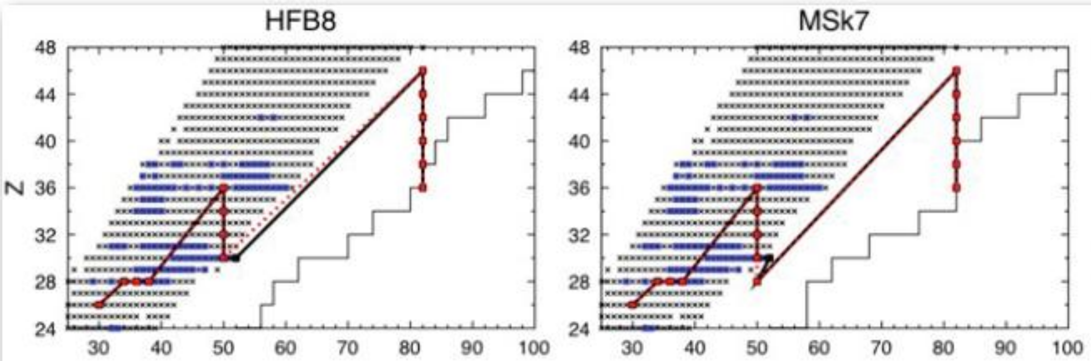
Outlook: Possible future MR-ToF MS applications

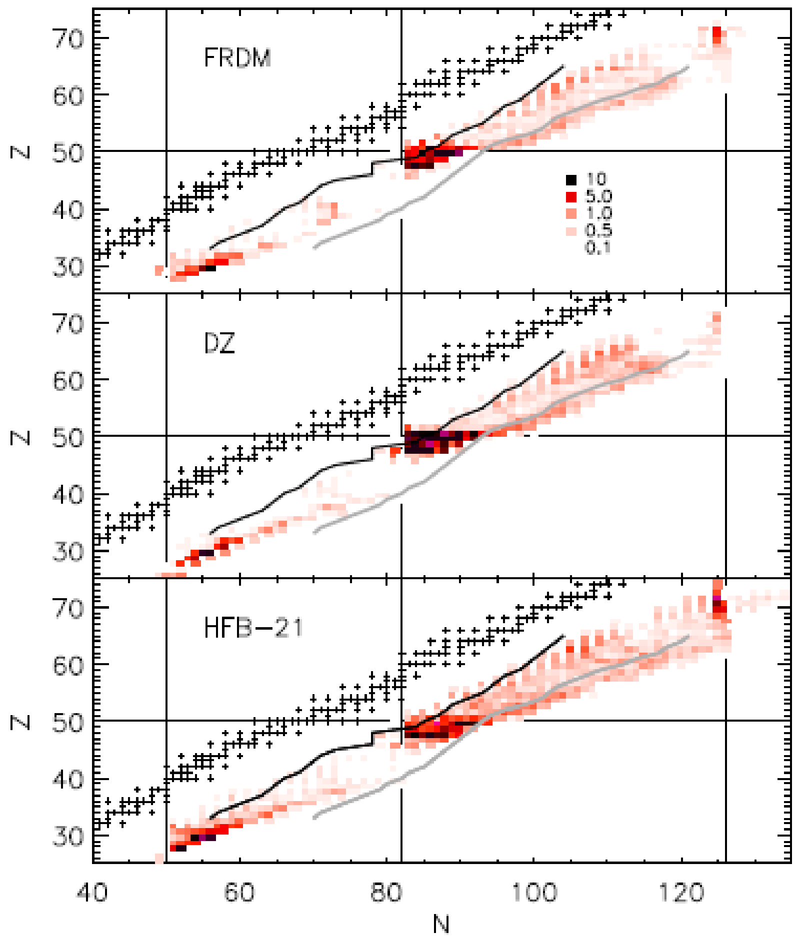
\\ Explore *N*=82

- Explore *N*=82 nuclei constituting the outer crust of neutron stars

- Challenging case: **128Pd** could be provided by upgrades of radioactive-beam facilities

- Sensitivity studies for *r* process provide list of „most wanted nuclei“:
  - **Cadmium: A>130**
  - **Indium: A>132**
  - **Tin: A>136**
  - **Antimony: A>136**

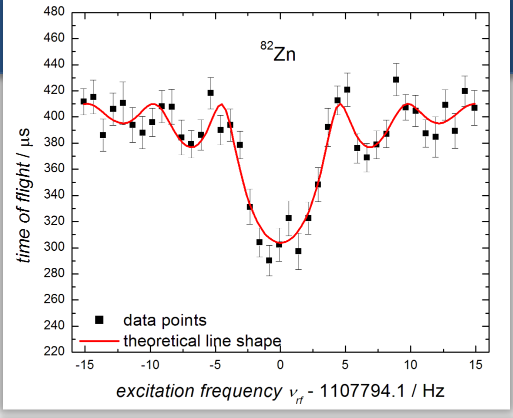


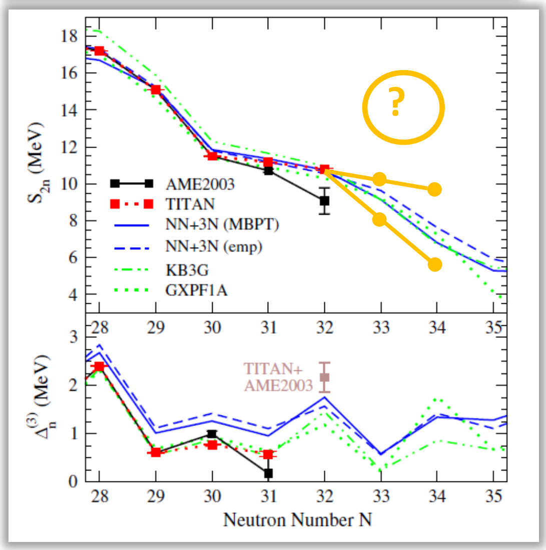


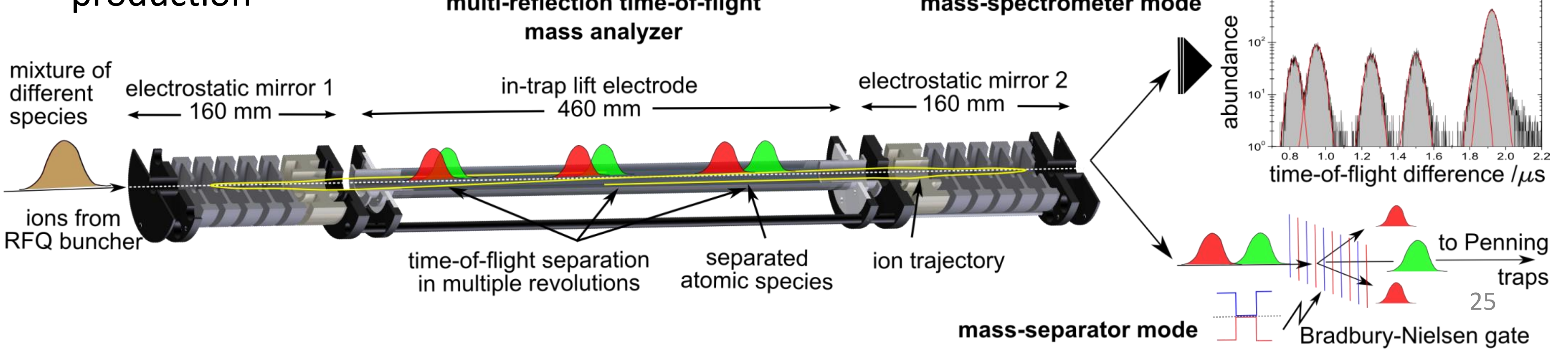
Brett *et al.*, EPJA 48, 184 (2012)

Summary

- MR-ToF mass separator offers fast contamination removal: *R*=200000 after 30ms, suppression ratio of about 10000
- Stacking technique implemented to increase number of separated ions per second
- First Penning trap mass measurement of 82Zn with MR-TOF mass purification
- Application to neutron-star crust
- First MR-ToF MS measurement of a new mass: 53,54Ca
- Precision and fast measurement cycle makes the MR-TOF-MS a promising approach for MS on short-lived isotopes with low production







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