Spontaneous fission studies with the FRS Ion Catcher

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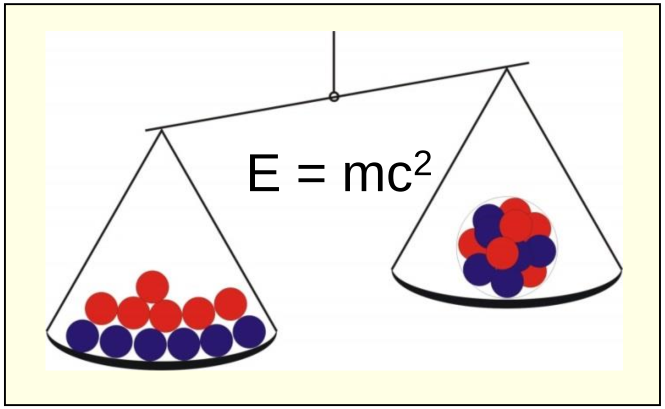
- How to study the properties of exotic nuclei via mass spectrometry
- The FRS Ion Catcher @ GSI
  - Setup
  - Results
- Commissioning / first results from ^{252}Cf
- Outlook
  - Next steps and improvements for the spontaneous fission
  - MNT studies at the FRS and at JYFLTRAP

Mass and Binding Energy

The mass of an atomic nucleus reflects its binding energy and hence its stability and structure



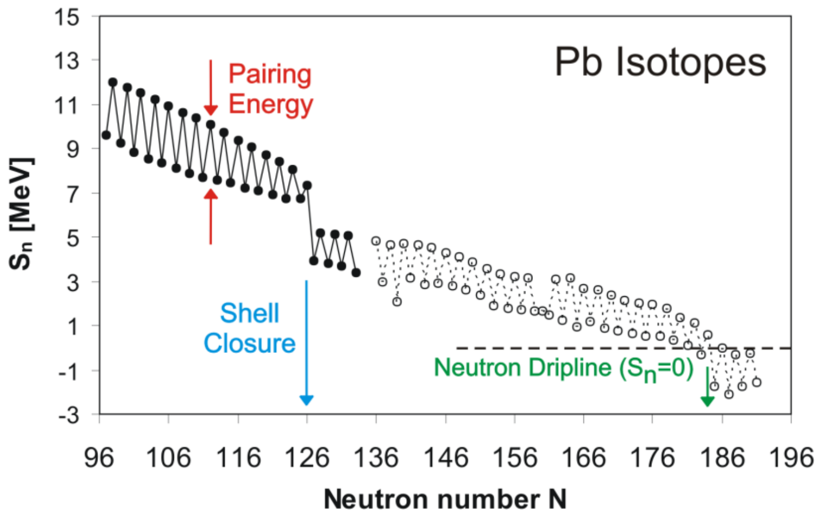
Z Protons (Proton number)

N Neutrons (Neutron number)

A = N + Z (Mass number)

B = Binding energy

Nuclear mass: $M(N, Z) = Z \cdot m_p + N \cdot m_n - B(N, Z)/c^2$



$$S_n = m({}^{A-1}_{Z}X_{N-1}) + m(n) - m({}^{A}_{Z}X_N)$$

Structure & Dynamics of Exotic Nuclei

Precision mass measurements → unambigious identification in A and Z

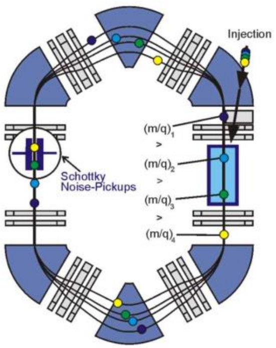
Mass Measurement Techniques for Exotic nuclei

„Standard“ Methods

Storage Rings

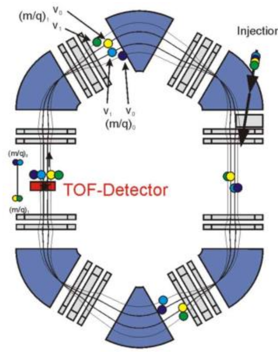
Schottky MS

t_{meas} ~ 10 s
$m/\Delta m = 10^6$
$\delta m/m$ ~ $2 \cdot 10^{-7}$
broadband



Isochronous MS

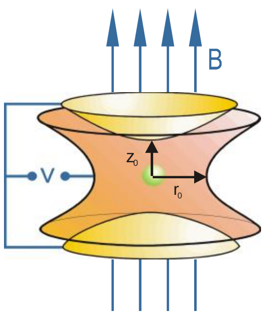
t_{meas} ~ 100 µs
$m/\Delta m = 2 \cdot 10^5$
$\delta m/m$ ~ 10^{-6}
broadband



~500 MeV/u

Penning Trap MS (TOF-ICR-MS)

t_{meas} ~ 1 s
$m/\Delta m = 10^6$-10^7
$\delta m/m < 10^{-7}$
scanning



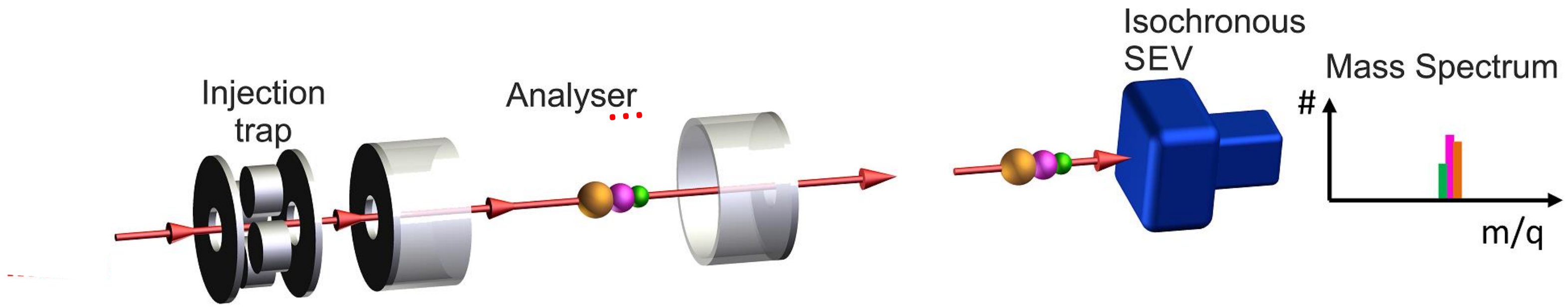
1 eV – 10 keV

No Method is highly accurate, sensitive and fast

TOF Mass Spectrometry for diagnosis and separation

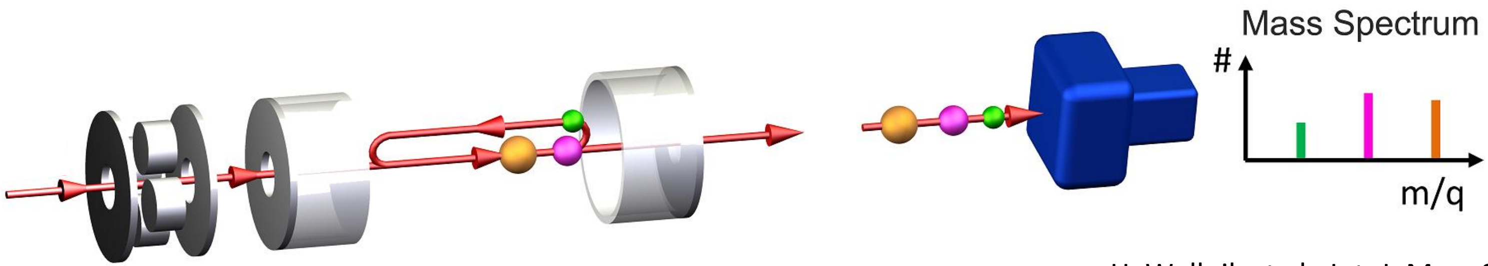
Enables high performance

- Fast → access to very short-lived ions ($T_{1/2}$ ~ ms)
- Sensitive, broadband, non-scanning → efficient, access to rare ions



To achieve high mass resolving power and accuracy:

Multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS)

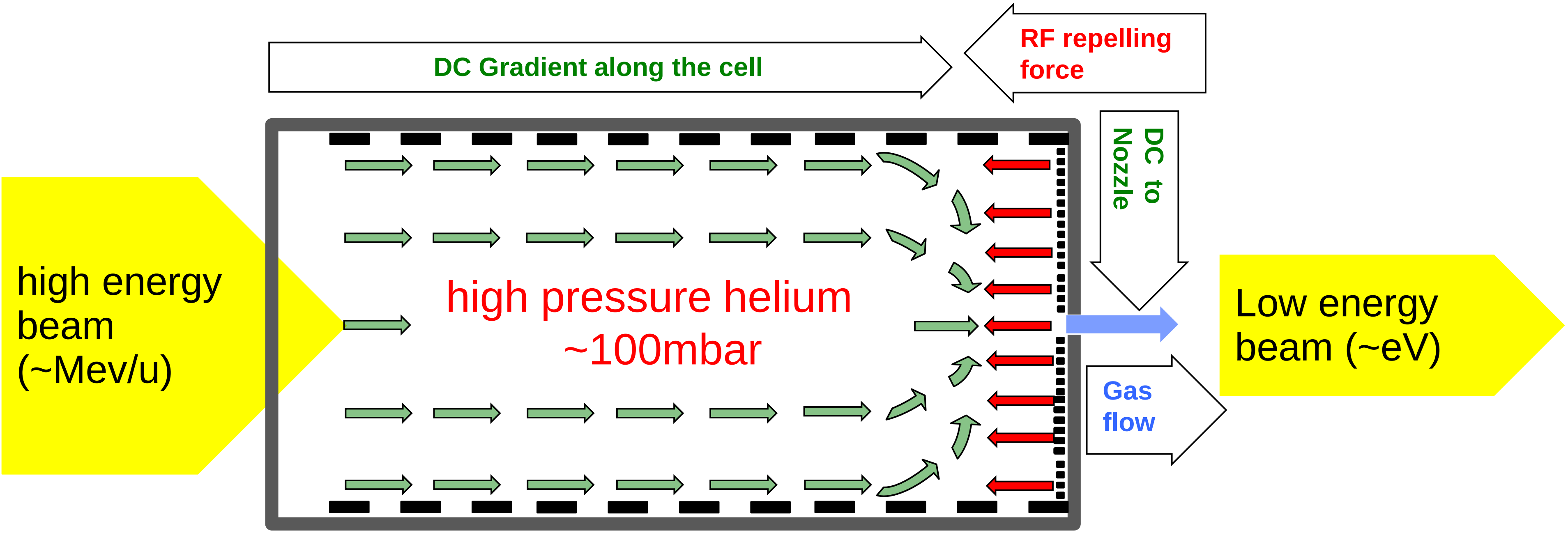


H. Wollnik et al., Int. J. Mass Spectrom. Ion Processes 96 (1990) 267

Applications

- Diagnostics measurements: monitor production, separation and low-energy beam preparation of exotic nuclei — W.R. Plaß et al., Int. J. Mass Spectrom. 394 (2013) 134
- Direct mass measurements of exotic nuclei — C. Scheidenberger et al., Hyperfine Interact. 132 (2001) 531
- High-resolution mass separator — W.R. Plaß et al., NIM B 266 (2008) 4560; T. Dickel et al., Phys. Lett. B 744 (2015) 137

Concept: Cryogenic Stopping Cell (CSC)



IGISOL/Stopping cells:

- **Fast →** access to short-lived exotic nuclides ($T_{1/2}$ ~ ms)
- **Universal →** element-independent
- **Efficient →** highest stopping and extraction efficiency

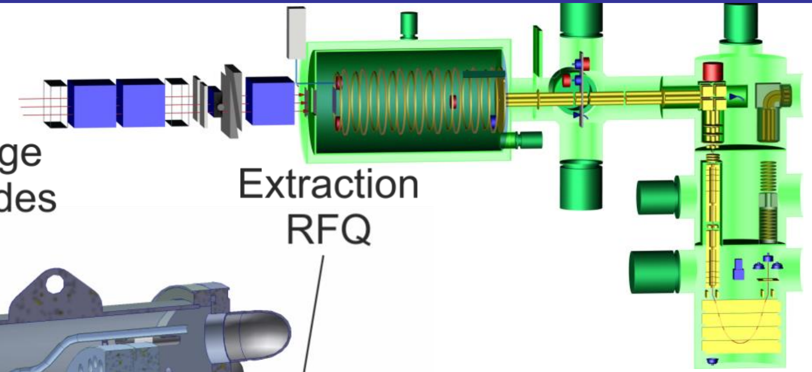
M. Wada NIM B 317 (2013) 450

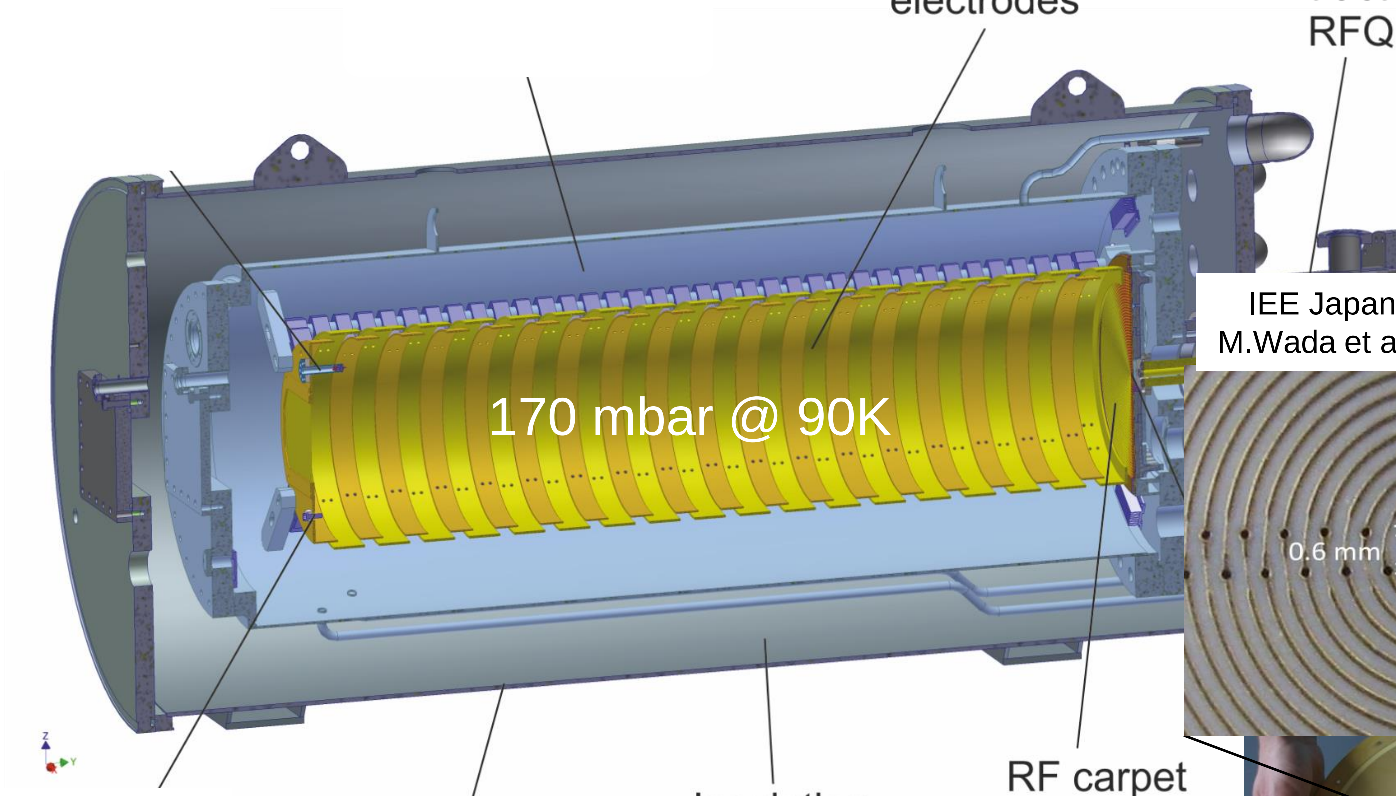
Cryogenic Operation

- **Clean →** ion beams of high cleanliness

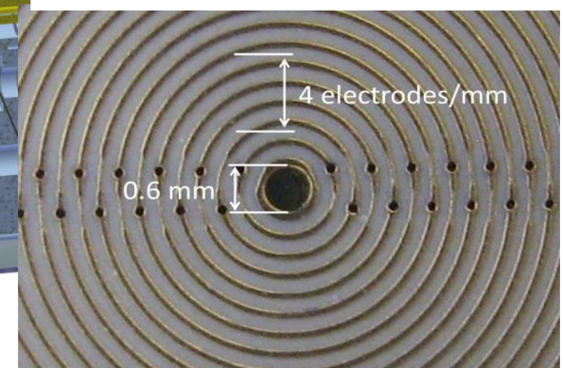
M. Ranjan et al., Europhys. Lett. 96 (2011) 52001
Purushothaman S. et al, EPL 104 (2013) 42001

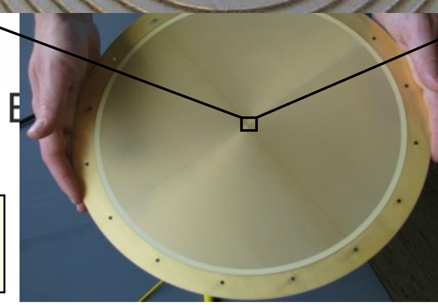
Prototype of the Stopping Cell: Design





IEE Japan, Vol 92B (1972) 9-18
M.Wada et al, NIM B204 (2003) 570

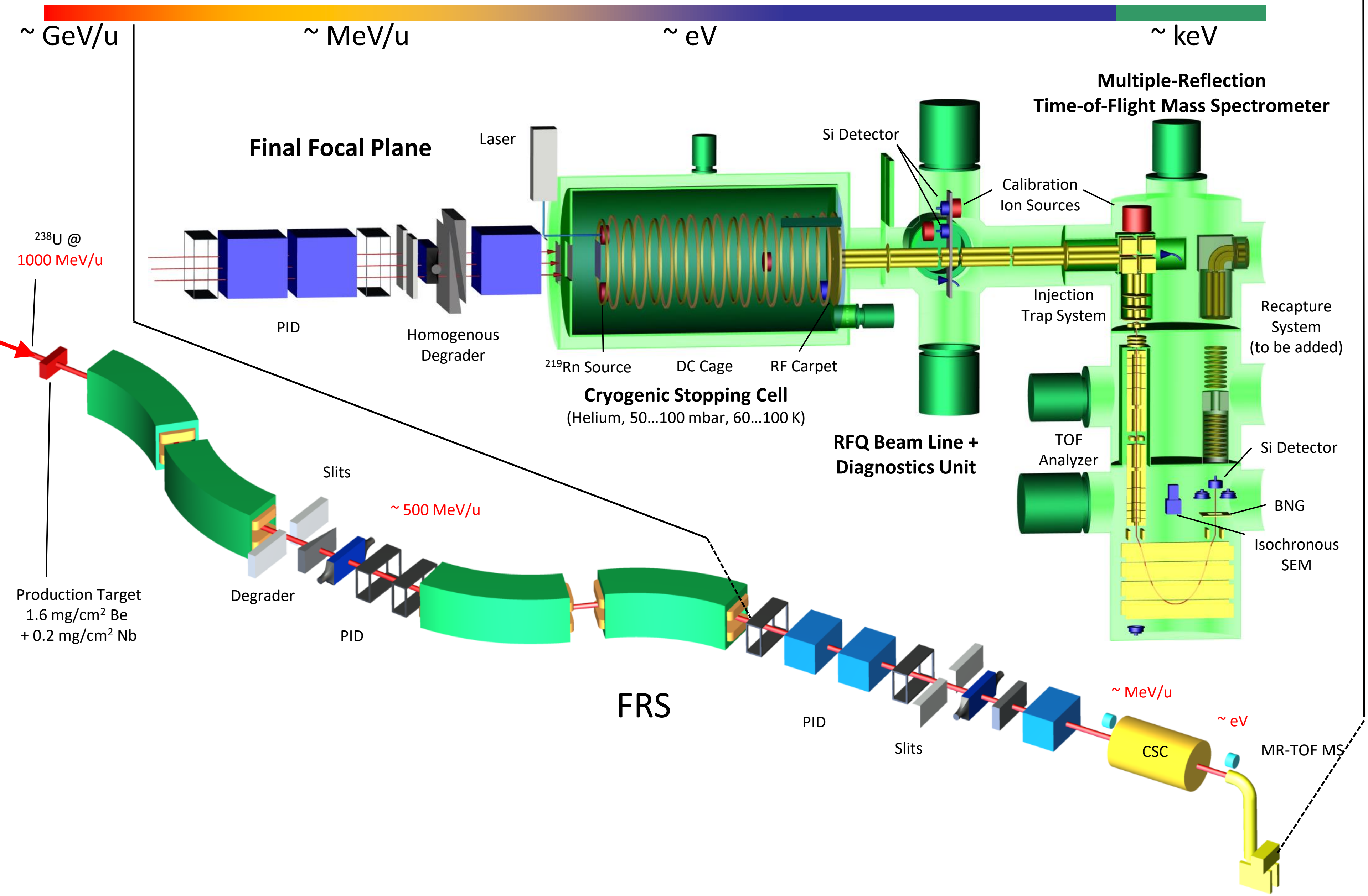




Diameter: 250 mm
Electrode spacing: 0.25 mm

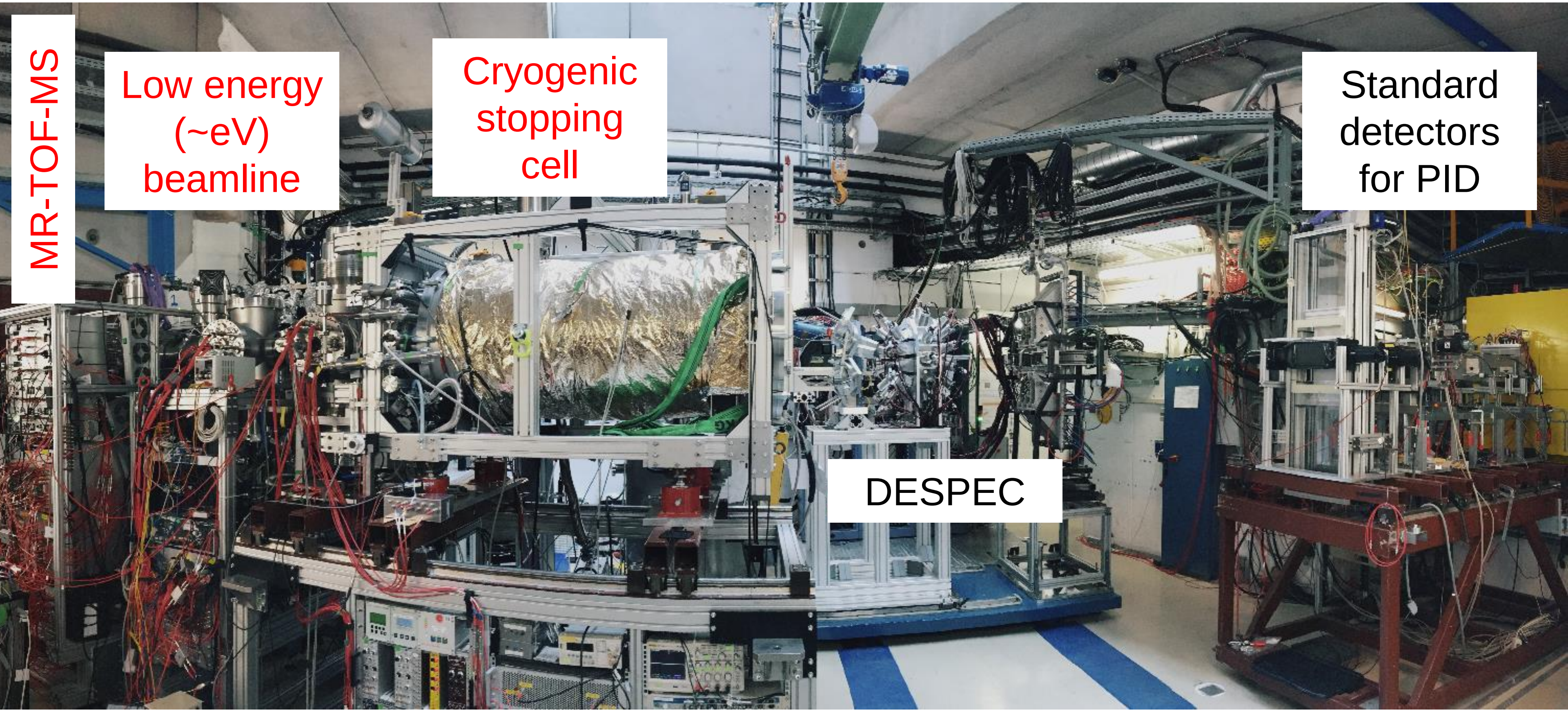
S. Purushothaman et al., EPL 104 (2013) 42001
M. Ranjan et al., NIM A 770 (2015) 87
M.P. Reiter PhD Thesis, JLU Giessen, 2015
M.P. Reiter et al., NIM B 376 (2016) 240
A.K. Rink PhD Thesis, JLU Giessen, 2017

FRS Ion Catcher: Test Facility for the LEB@SuperFRS



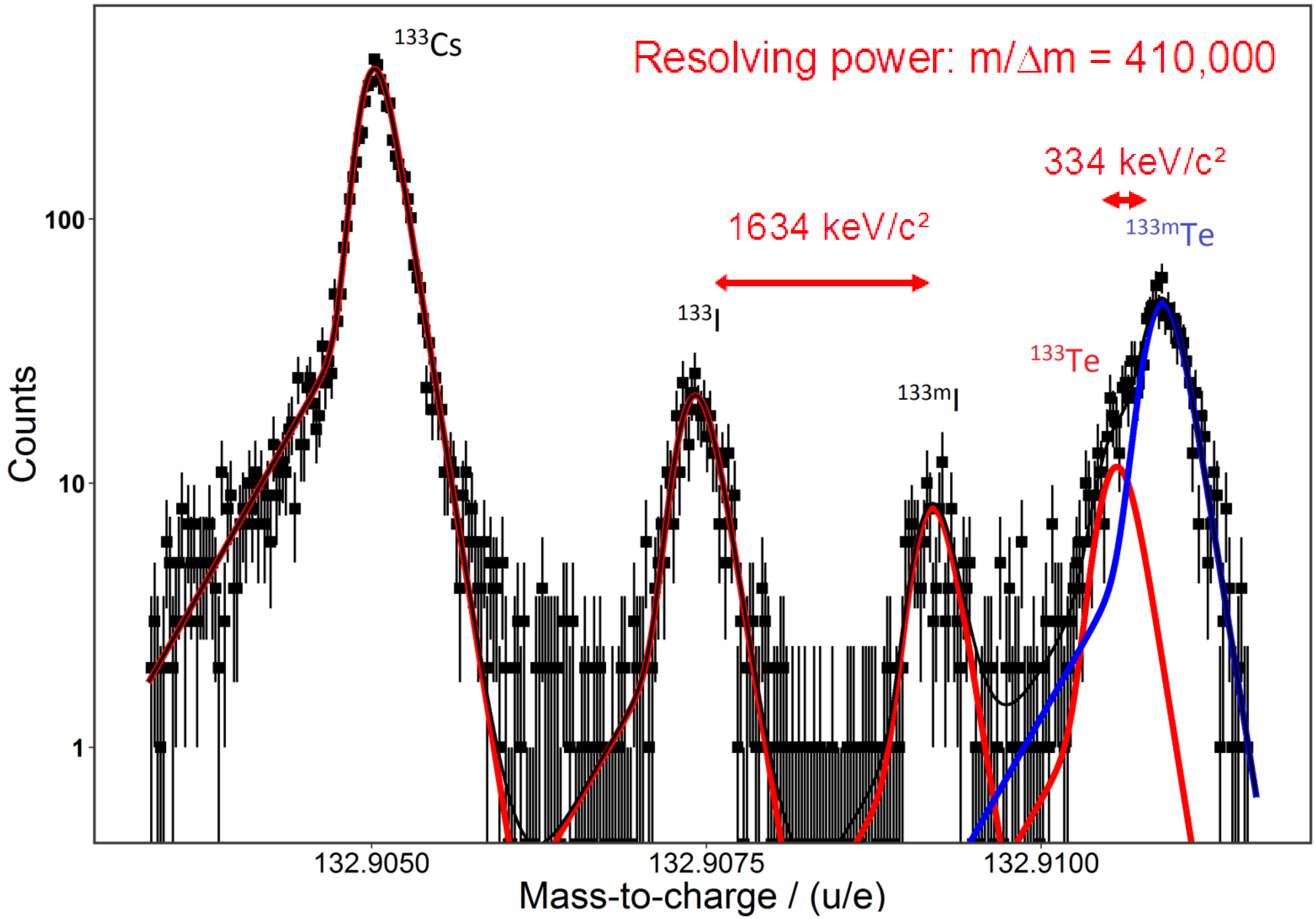
W.R. Plaß et al., NIM B 317 (2013) 457

FRS Ion Catcher



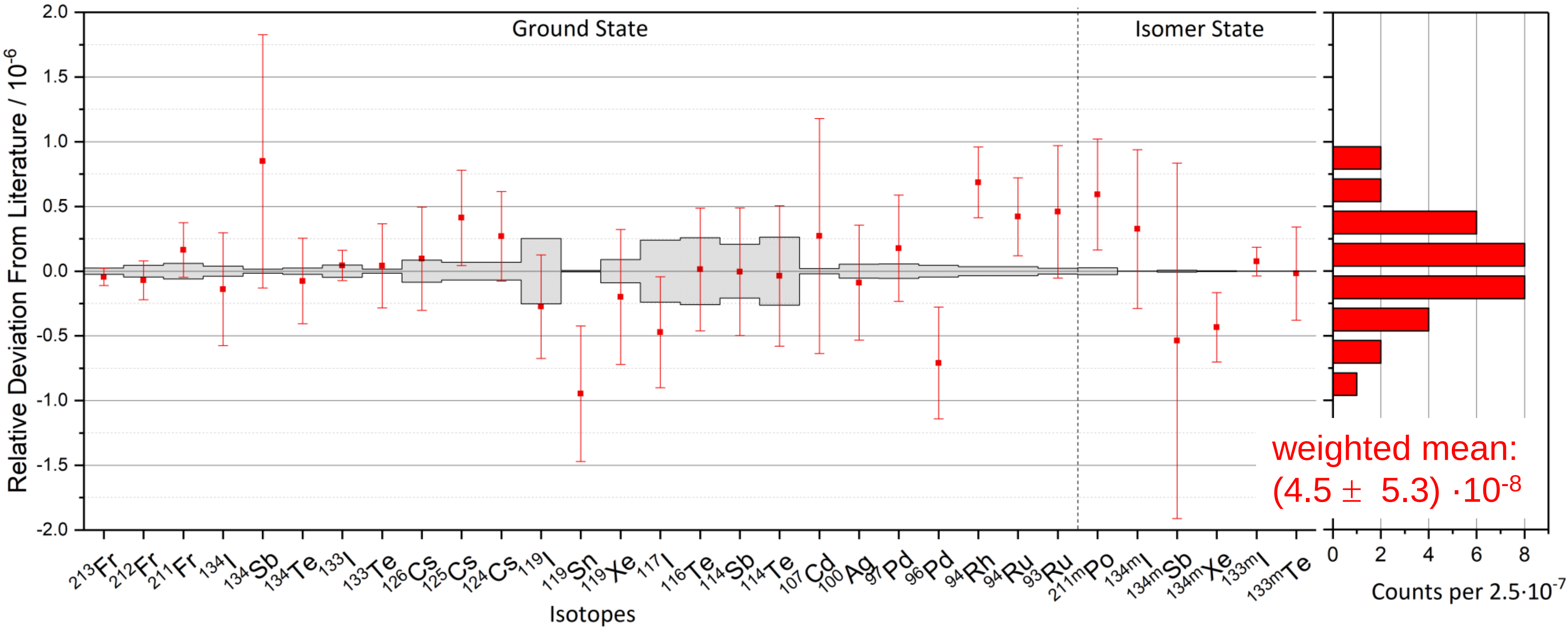
^{238}Uranium Fission Fragments

- Mass measurement of uranium fission products produced at 1000 MeV/u
- MR-TOF-MS will enable efficient search and measurement of new isotopes and isomers



S. Ayet et al., submitted to PRC, arXiv:1901.11278v1

Achieved Accuracy of the Mass Measurement



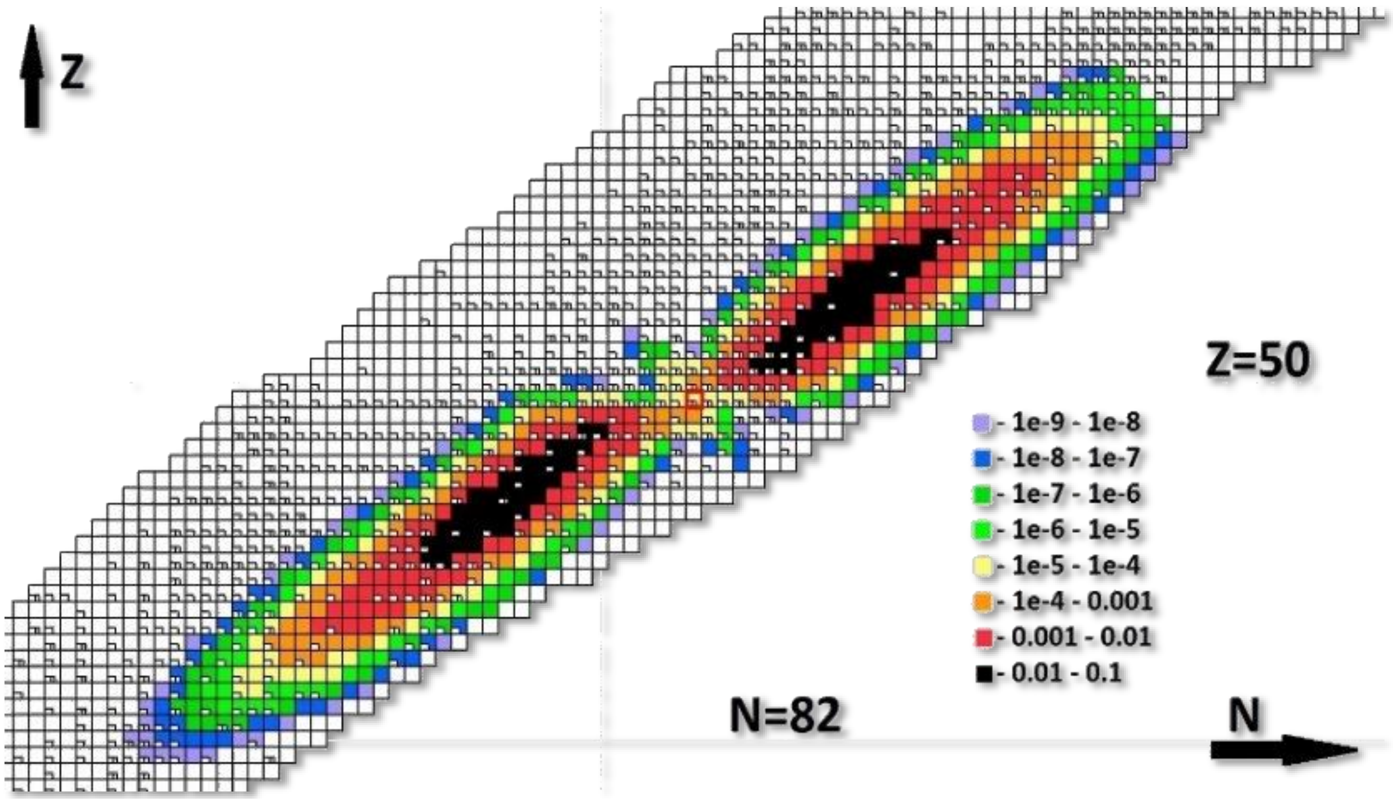
- Data evaluation developed for low statistics and overlapping peaks
- 31 masses of 16 different elements including 6 isomeric states:
    - Relative deviations down to $6 \cdot 10^{-8}$
    - Excitation energies of isomeric states down to 280 keV

S. Ayet et al., submitted to PRC, arXiv:1901.11278v1

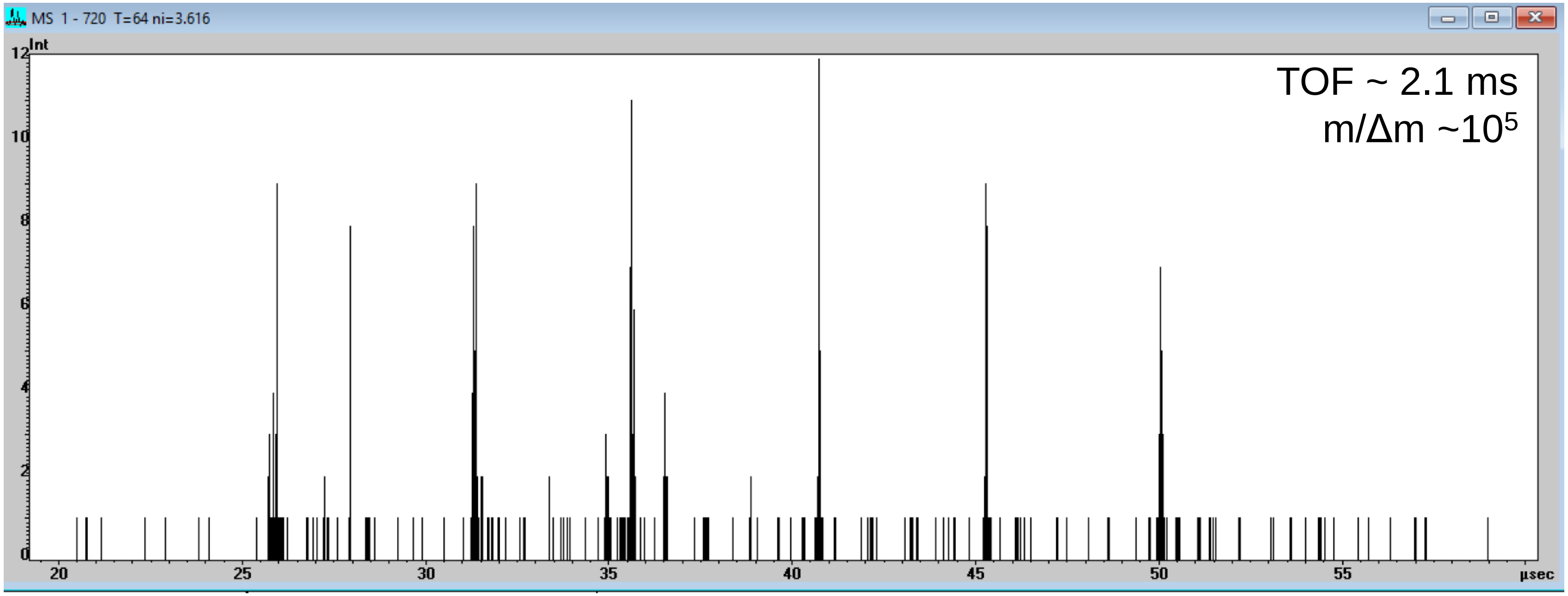
^{252}Cf spontaneous fission source

^{252}Cf spontaneous fission source (37kBq) is mounted in the inner chamber of CSC:

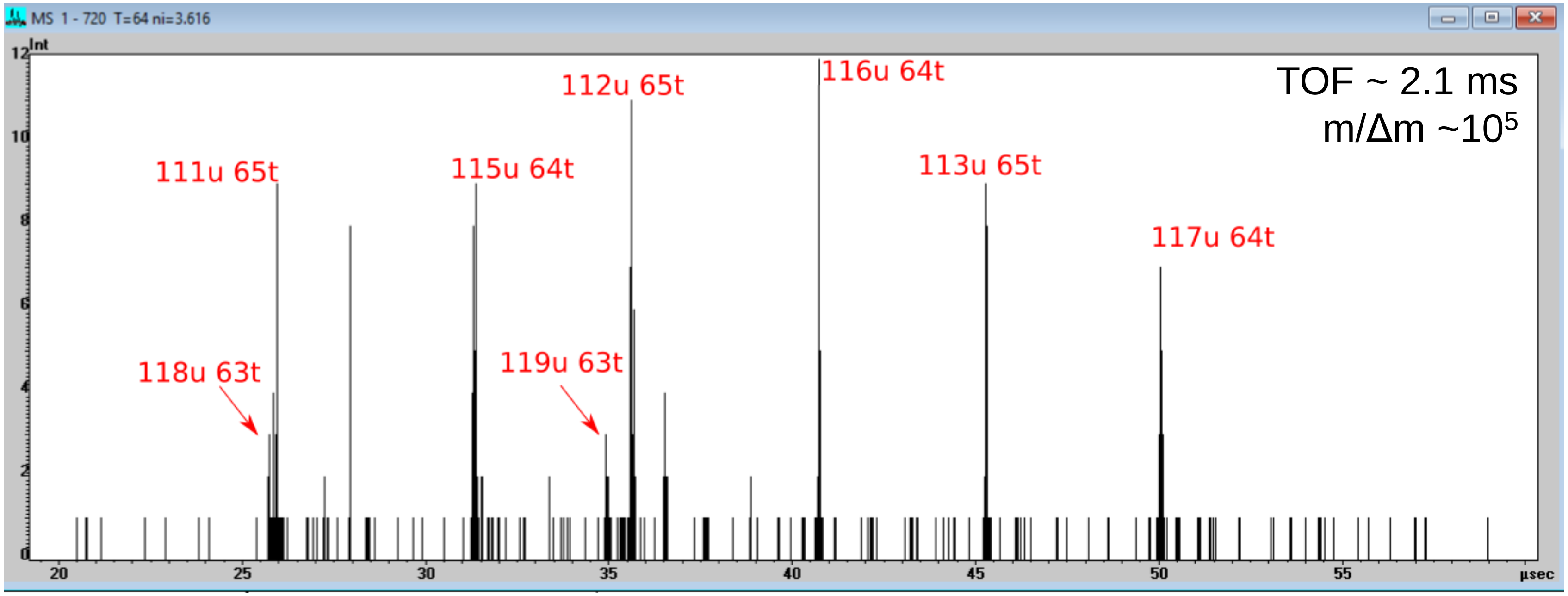
→ systematics of spontaneous fission
  → independent fission yields
  → isomer-to-ground ratios
    in collaboration with Uppsalla University

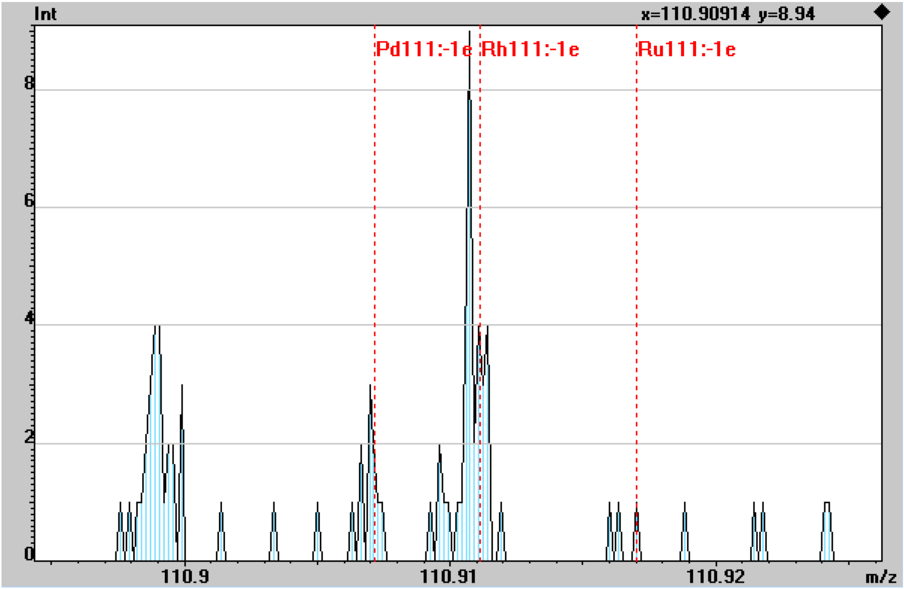


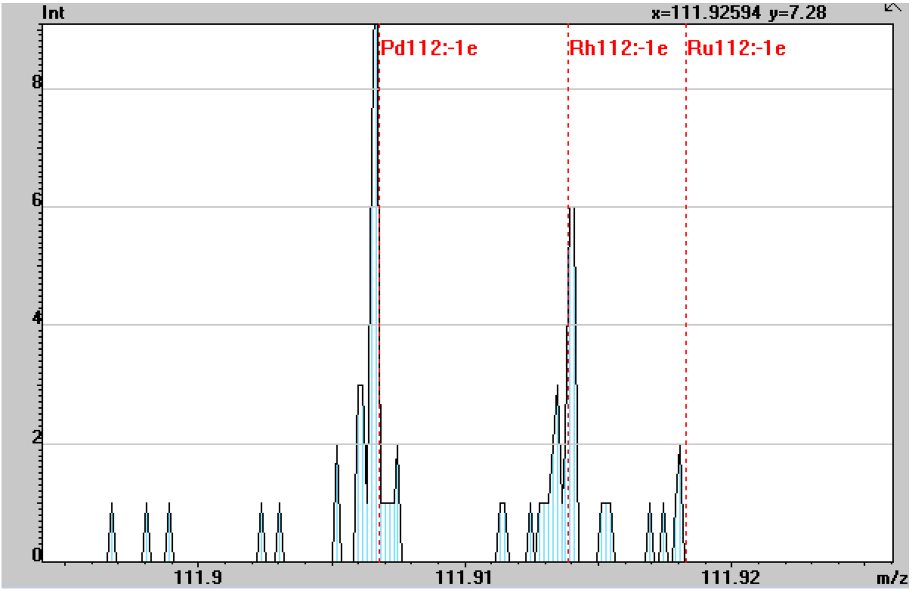
Commissioning of ^{252}Cf source



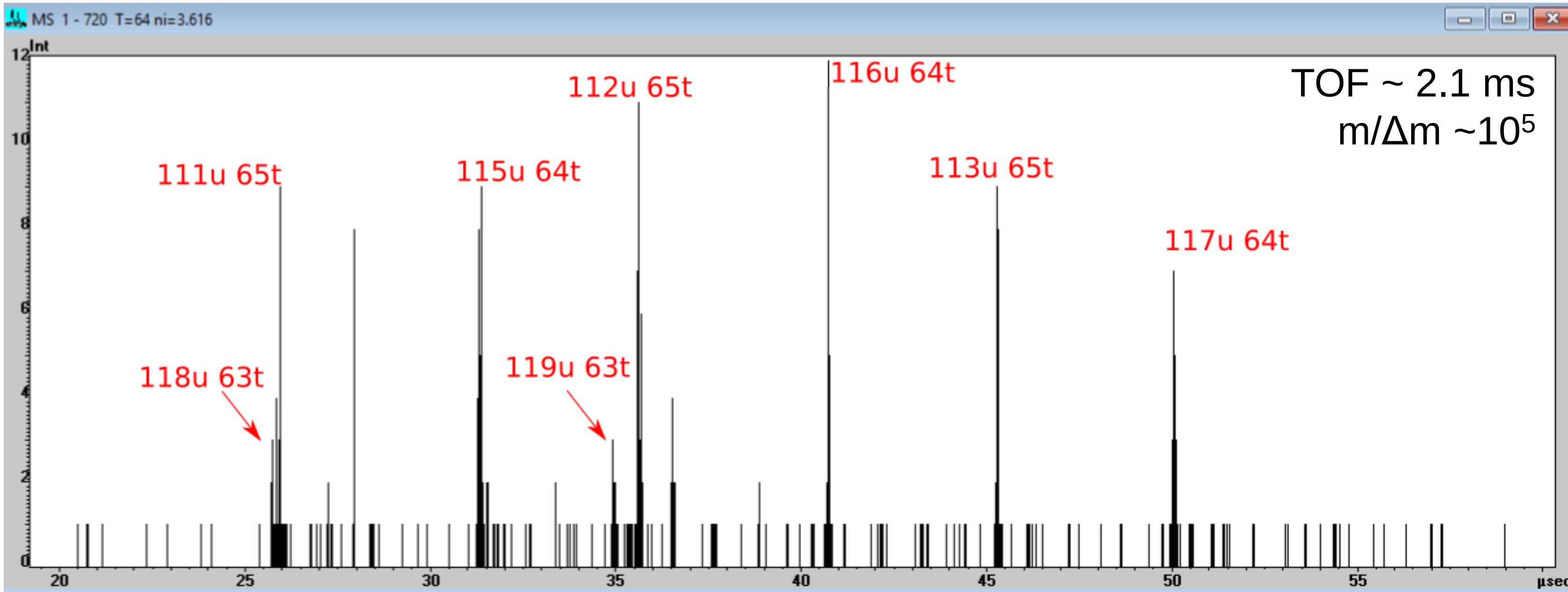
Commissioning of ^{252}Cf source

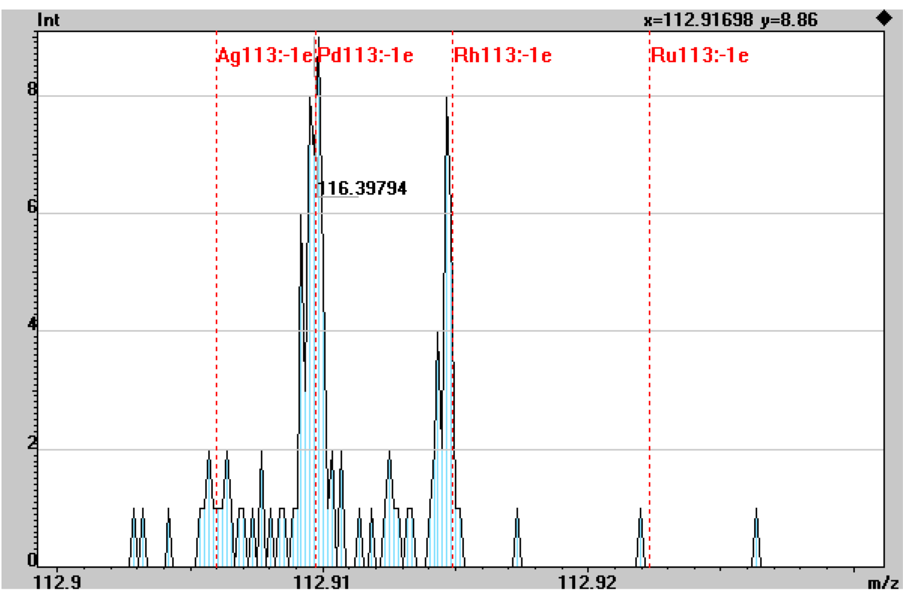


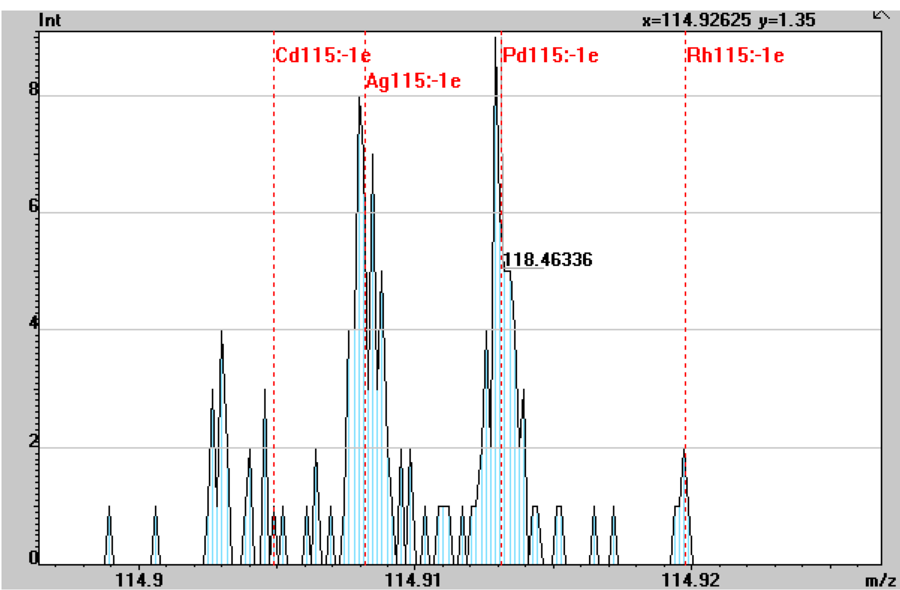




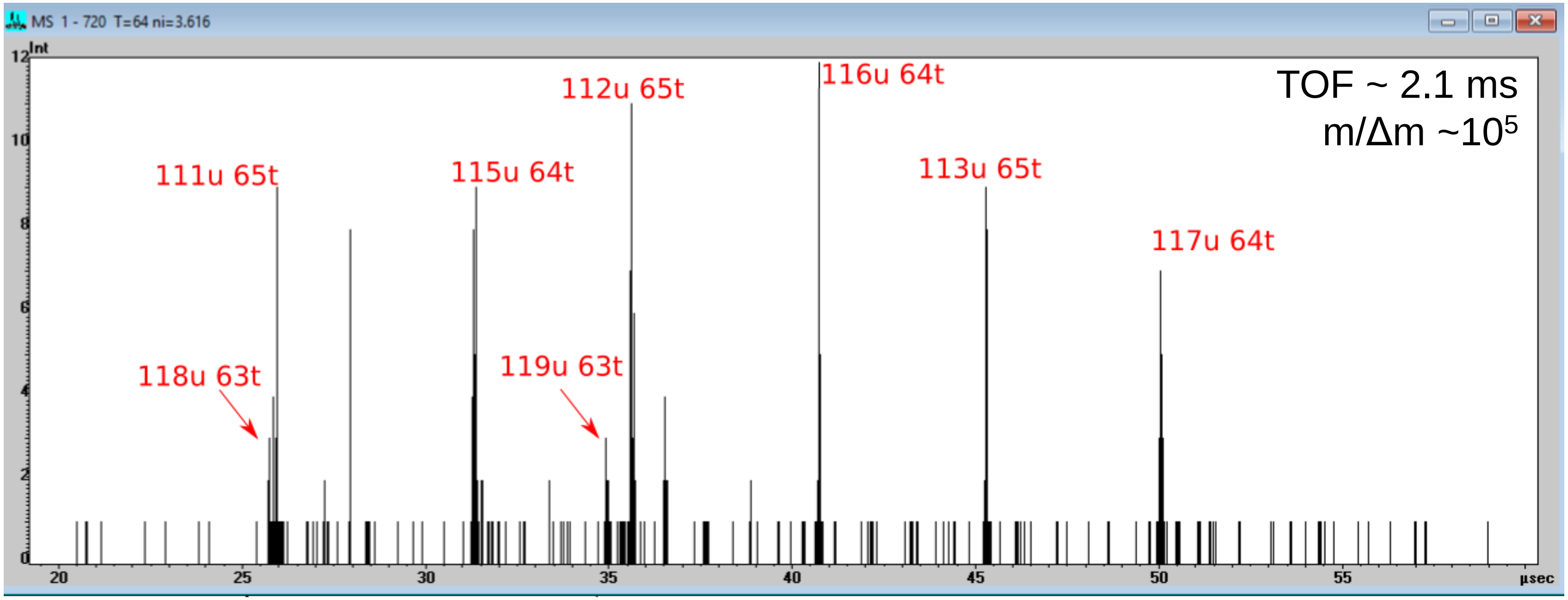
Commissioning of ^{252}Cf source

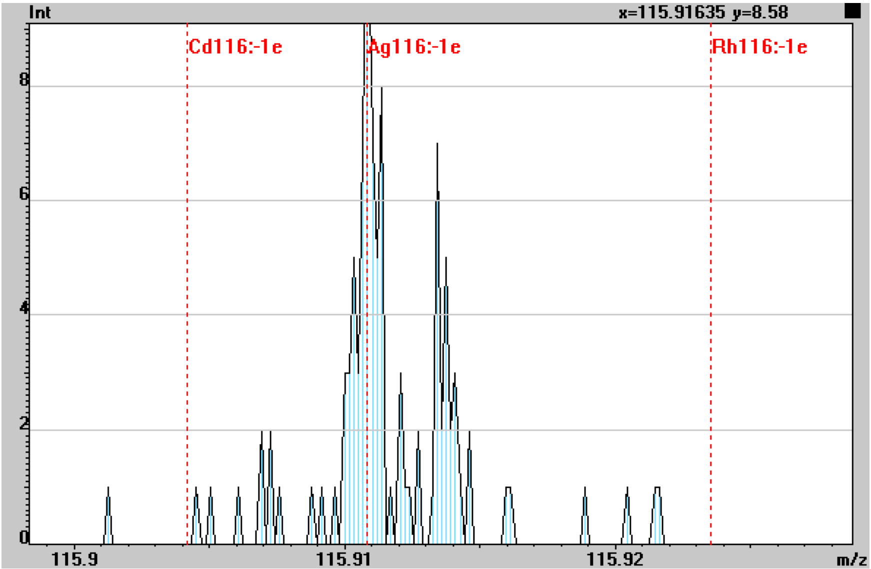


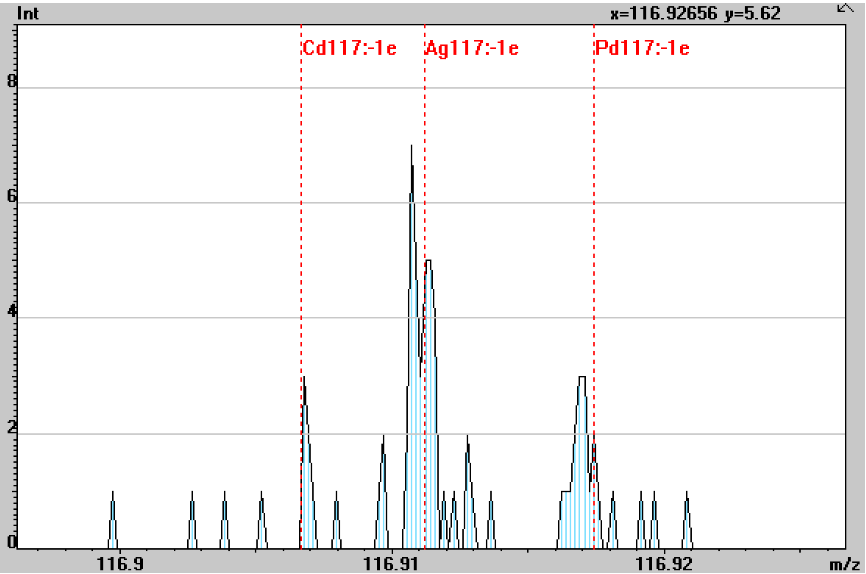




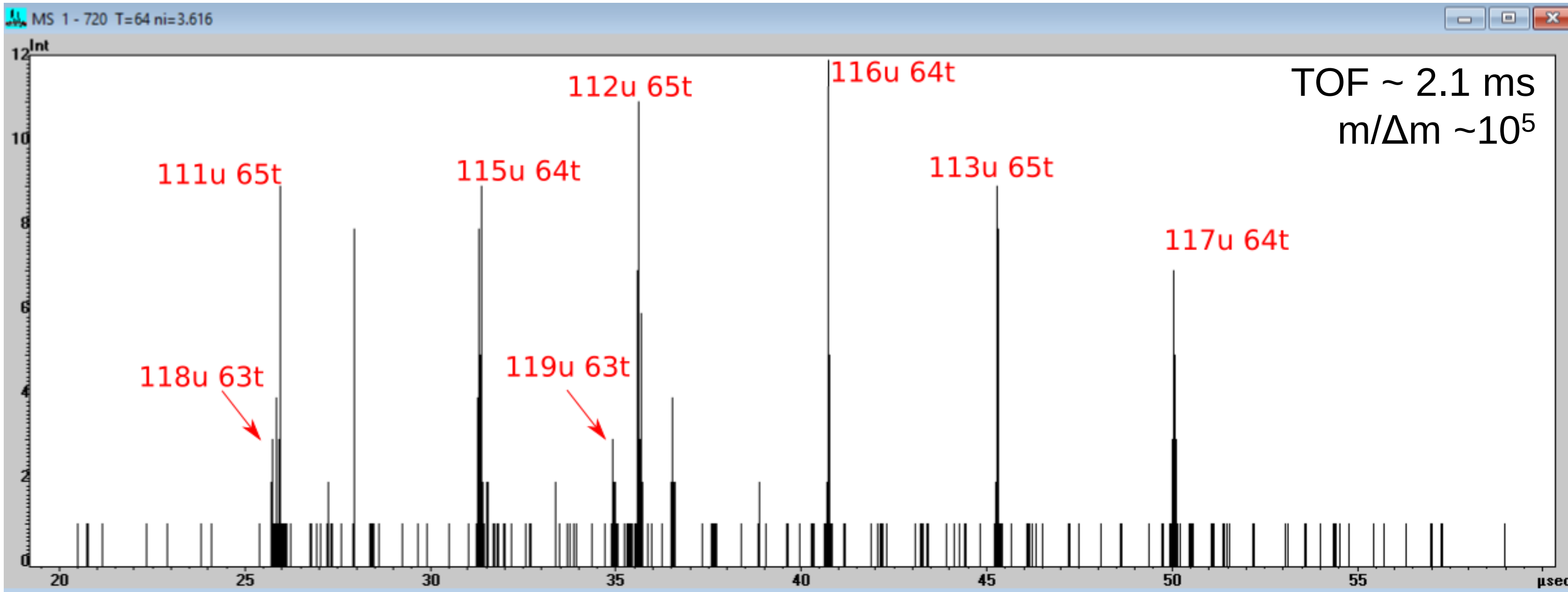
Commissioning of ^{252}Cf source

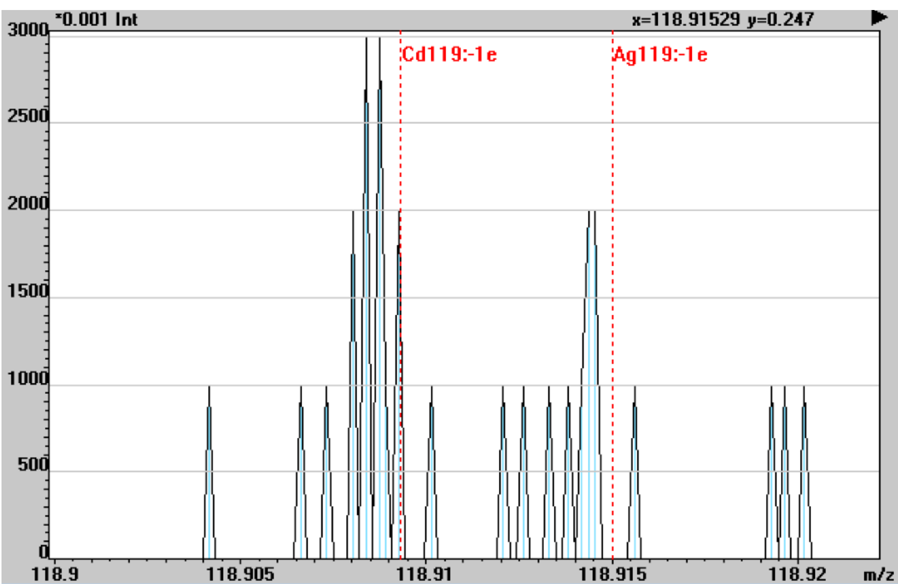






Commissioning of ^{252}Cf source





More than 15 fission fragments identified:

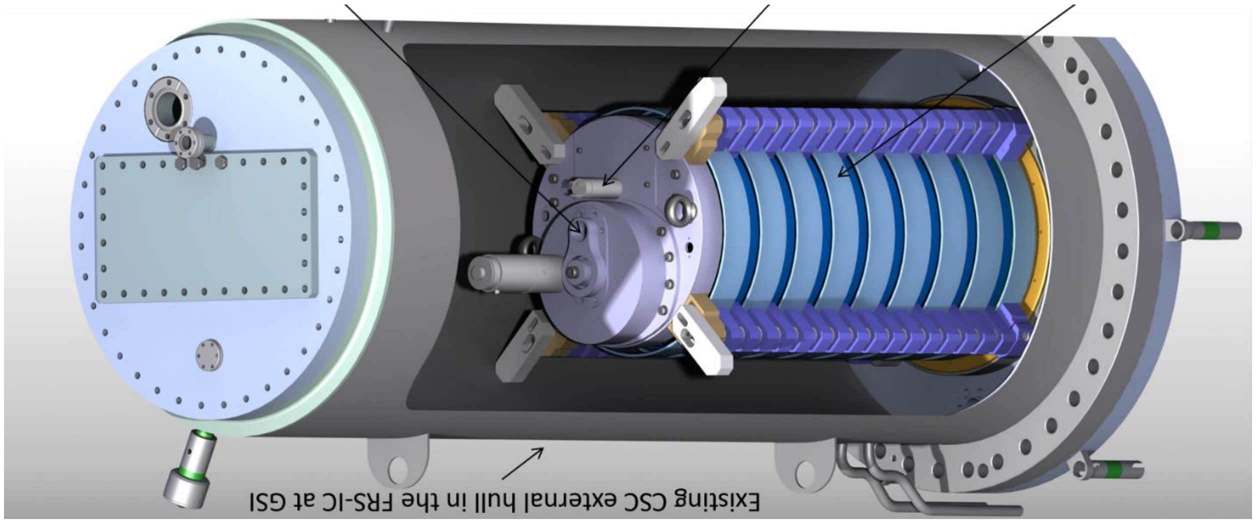
- one hour measurement
- 37kBq

Commissioning of ^{252}Cf source

About 70 fission fragments identified in first run
(about 50 hours, 3 weeks ago)

Next Steps and Improvements

- Upgrade Stopping and Transport Efficiency:
  - gain of an order of magnitude is expected
- Improved electrode structure
  - Factor 4 shorter extraction times
  - up to Factor 2 higher efficiency

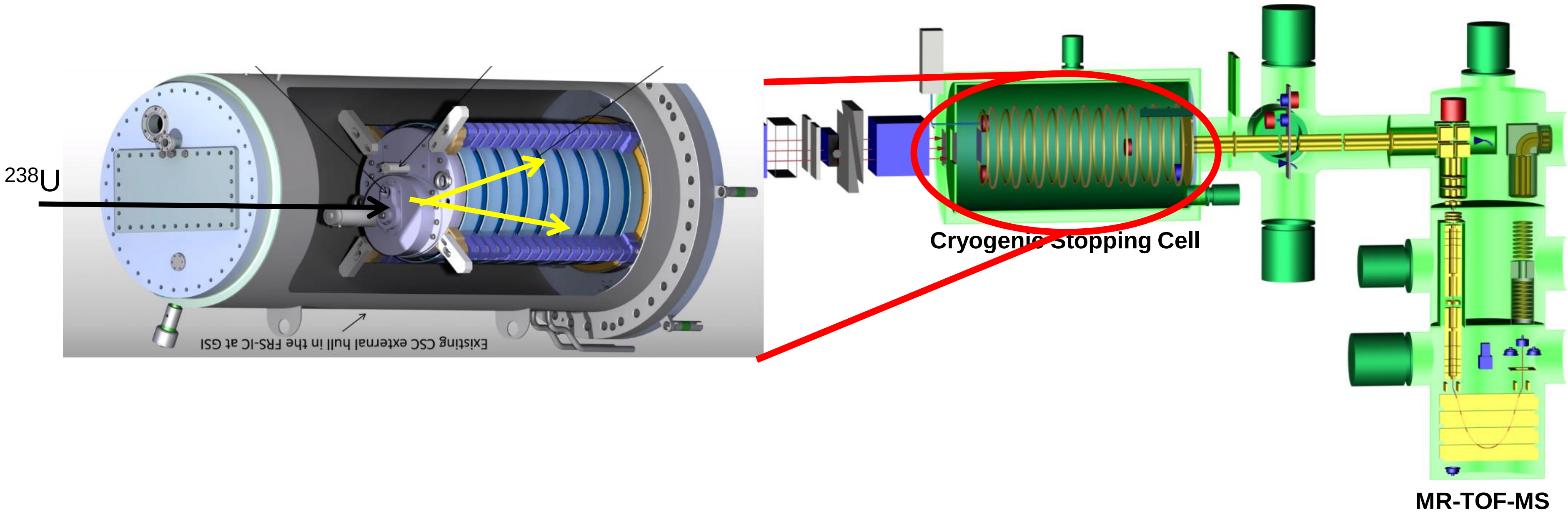


- Stronger source (37kBq → 10MBq)

  → Accessible yields below 10^{-7}

- Study other spontaneous fissioning isotopes: e.g. ^{248}Cm

MNT studies with the FRS-IC



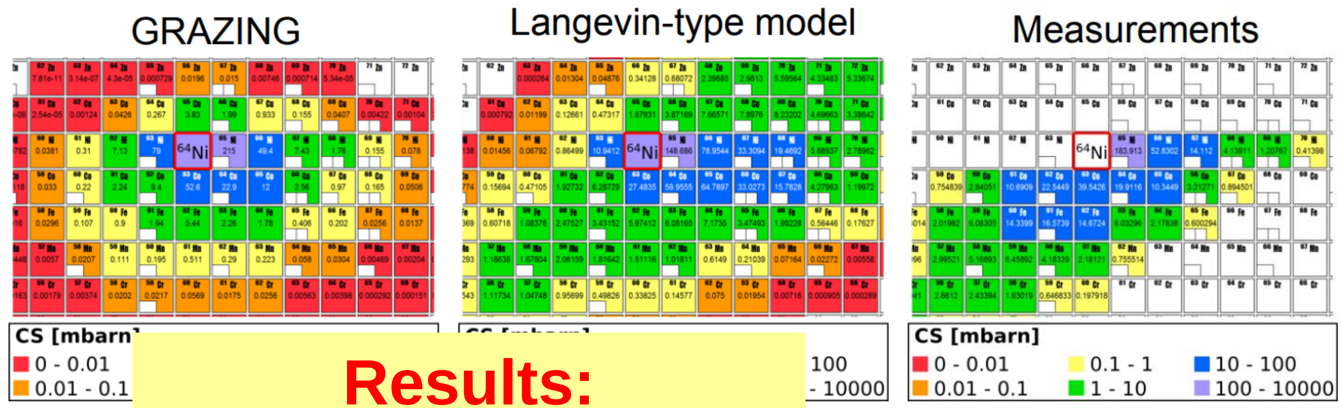
Universal, efficient, sensitive and broadband method:

- Different beams (primary and secondary) from the (Super-)FRS
- CSC: universal, fast, efficient, clean extraction of all reaction products
    - Target (TLF) and projectile-like fragments (PLF) in one experiment
- MR-TOF-MS: Tens of different products measured simultaneously
- „Direct physics results“:
    - ➢ New masses
    - ➢ Discovery of long-lived isomers (G.D. Dracoulis et al., Phys. Scr. T152 (2013) 014015)

MNT studies at the FRS and JYFLTRAP

$^{238}U + ^{64}Ni$

- Benchmark the method
- Validate/discard theoretical models



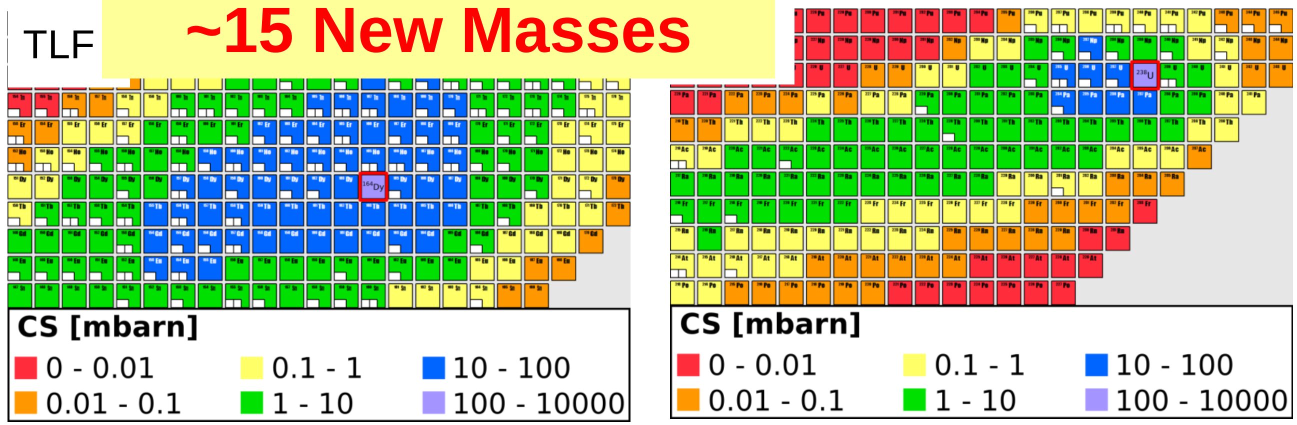
A. Winthe... 57...

L. Corradi, A. M. Stefanini, C. J. Lin, *PRC* **59**, 261–268 (1999).

Results:
~150 Cross Sections
~15 New Masses

$^{238}U + ^{164}Dy$

- r-process rare-earth peak
- n-rich isotopes around ^{238}U



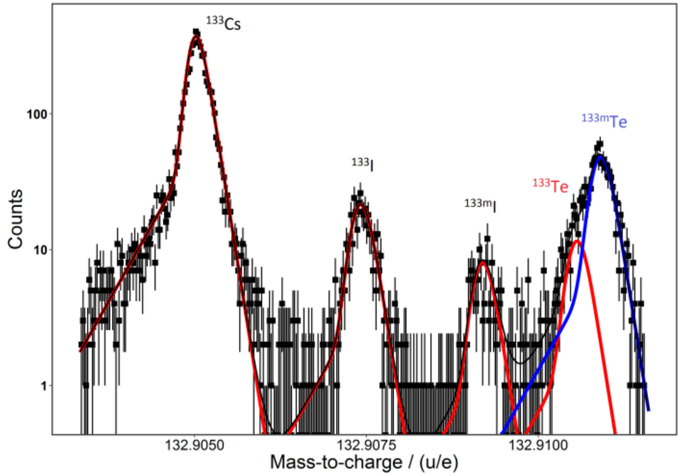
At JYFLTRAP:

^{136}Xe on ^{209}Bi: alpha decaying products

→ Proof-of-concept and study of isomer to ground state ratios

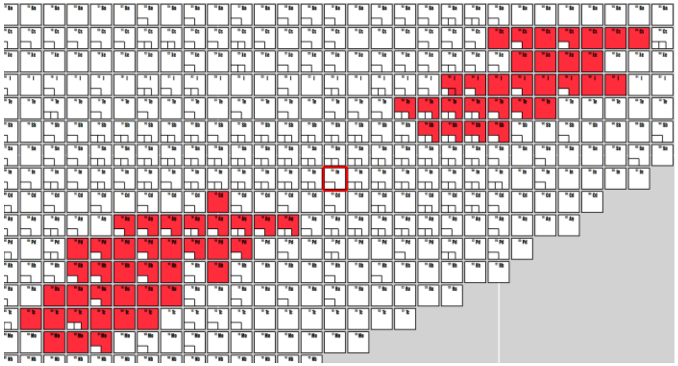
^{136}Xe on ^{198}Pt: half-live measurements of neutron-rich nuclides

Summary and Outlook



The FRS Ion Catcher

- Unique capabilities:
  - Efficient thermalization of fission products
  - Broadband measurements with full ID
  - High mass accuracy, down to $6*10^{-8}$
  - High sensitivity



- Novel way to study spontaneous fission
  - independent fission yields
  - isomer-to-ground state ratios

Outlook:

- Upgrade of system → access to yields below 10^{-7}
- Experiments to study MNT reactions at FRS and at JYFLTRAP
- Experiments in FAIR Phase-0

Acknowledgements

FRS Ion Catcher Collaboration

D. Amanbayev[1], S. Ayet[1,2], B. Soumya[2,9], J. Bergmann[1], P. Constantin[6], T. Dickel[1,2], M. Diwisch[1], J. Ebert[1], A. Finley[7], H. Geissel[1,2], F. Greiner[1], E. Haettner[2], C.Hornung[1], S. Kaur[8], R. Knöbel[2], W.Lippert[1], I. Mardor[10,11], B. Mei[6], I. Miskun[1], I. Moore[3], J.-H. Otto[1], Z. Patyk[4], S. Pietri[2], A. Pikhtelev[8], W.R. Plaß[1,2], I. Pohjalainen[3], A. Prochazka[2], S. Purushothaman[2], C. Rappold[2], M.P. Reiter[1,7], A.-K. Rink[1], C. Scheidenberger[2], M. Takechi[2], Y. Tanaka[2], H. Toernquist[2], H. Weick[2], J.S. Winfield[2], X.Xu[1,2], M.I. Yavor[5]

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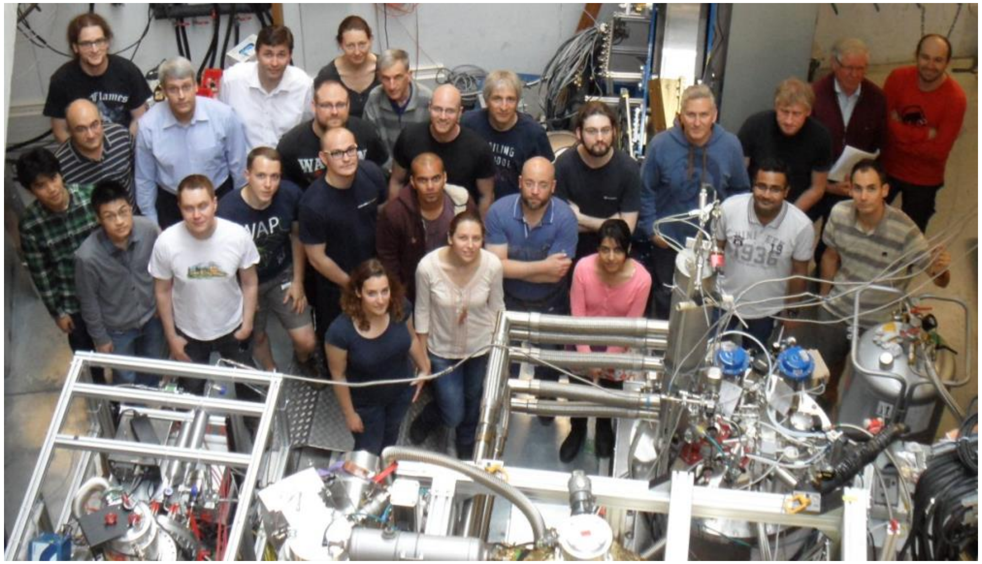

Funding:

BMBF (05P12RGFN8, 05P16RGFN1), **State of Hesse** (HMWK) (LOEWE Center HICforFAIR), **HGS-HIRe**, **JLU Giessen** and **GSI** (JLU-GSI strategic Helmholtz partnership agreement)