JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

EIGENSCHAFTEN UND STRUKTUR KURZLEBIGER KERNE IONAS

Super-FRS EC

GSI

Experiments with thermalized relativistic beams at GSI and FAIR

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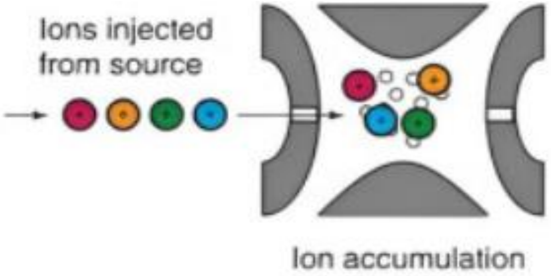
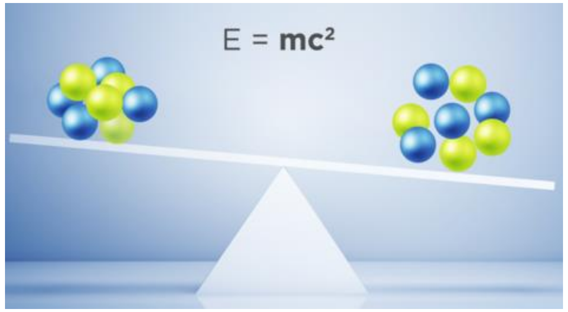
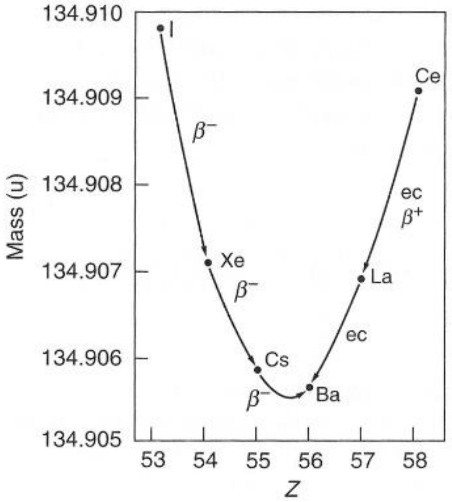
GSI Darmstadt, JLU Gießen

Why thermalizing relativistic beams?

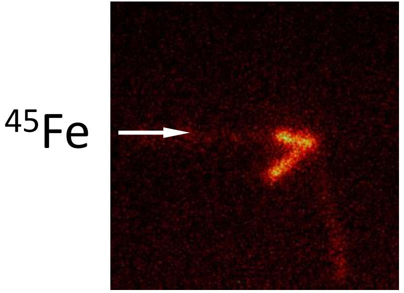


- Long observation times enable
  - Precision studies
  - Spontaneous decay studies
  - Measurement of ground state properties
  - …
- Wide variety of experimental techniques
  - Ion trapping
  - Mass Spectrometry
    - Universal and unambiguous identification by mass
  - Laser spectroscopy
  - Background-free decay spectroscopy
  - Rare decay searches





Two proton radioactivity



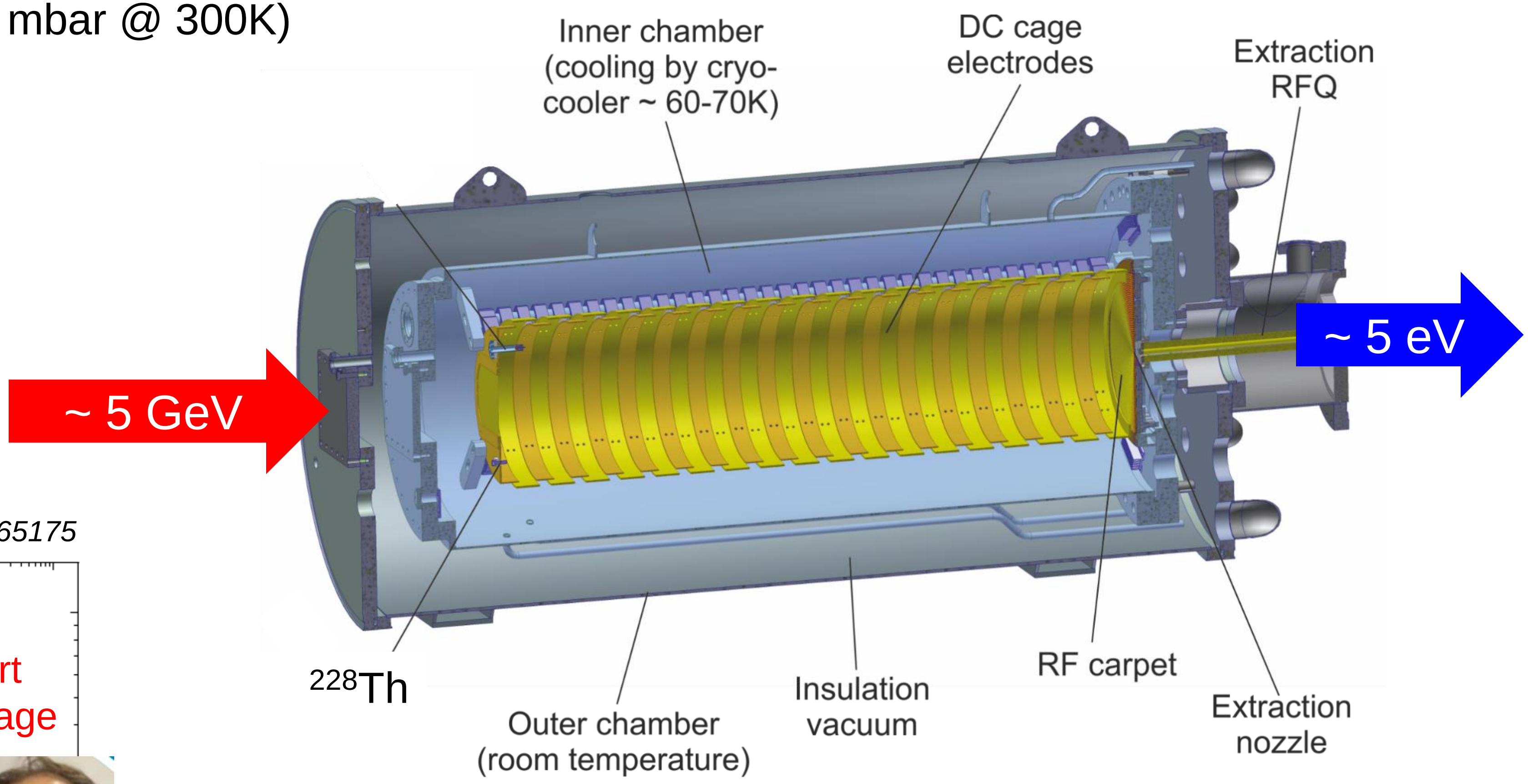
M. Pfützner

Applications

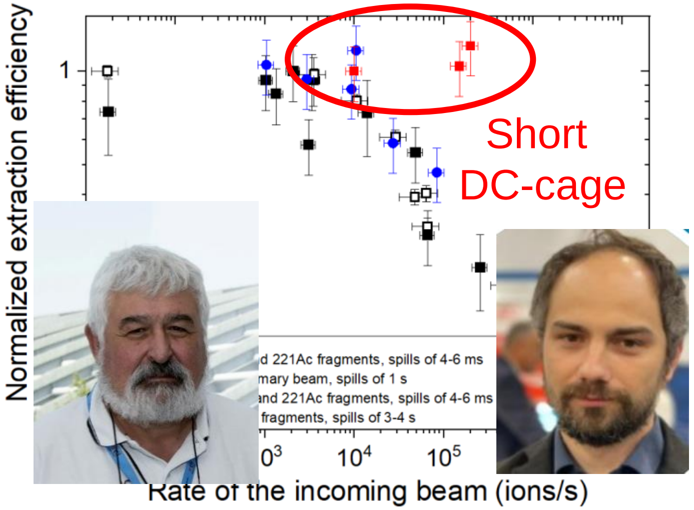
- Radioactive molecules
- Fundamental symmetries and interactions
- …

How we thermalize relativistic beams?

- Large beam size (200x100mm²)
- First cryogenic stopping cell
- Highest density (700 mbar @ 300K)



J.W. Zhao, et al., NIM B 547 (2024), 165175



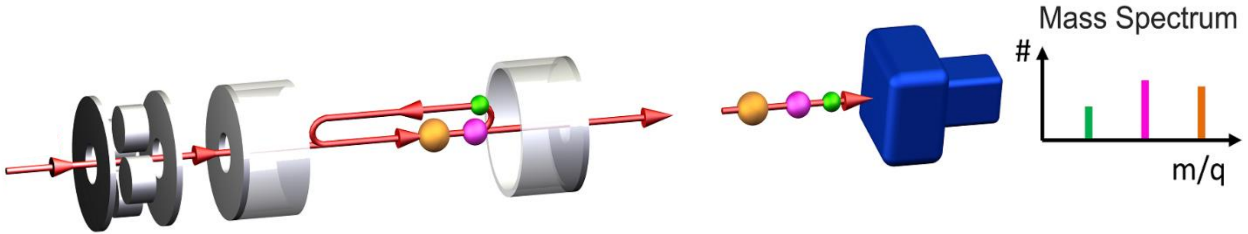
M. Ranjan et al., Europhys. Lett. 96 (2011) 52001
S. Purushothaman et al., EPL 104 (2013) 42001
M. Ranjan et al., NIM A 770 (2015) 87
M.P. Reiter et al., NIM B 376 (2016) 240

Why multiple-reflection time-of-flight mass spectrometry?

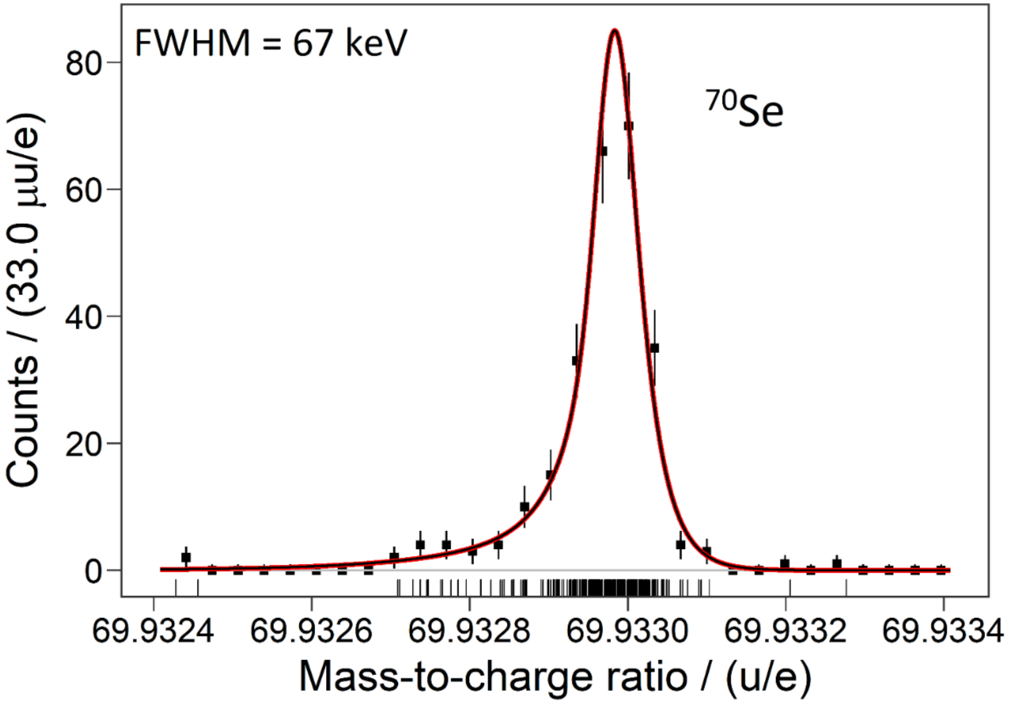
- Higher precision
- Faster measurement
- Higher sensitivity
- Higher rate capability

Enables high performance

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



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



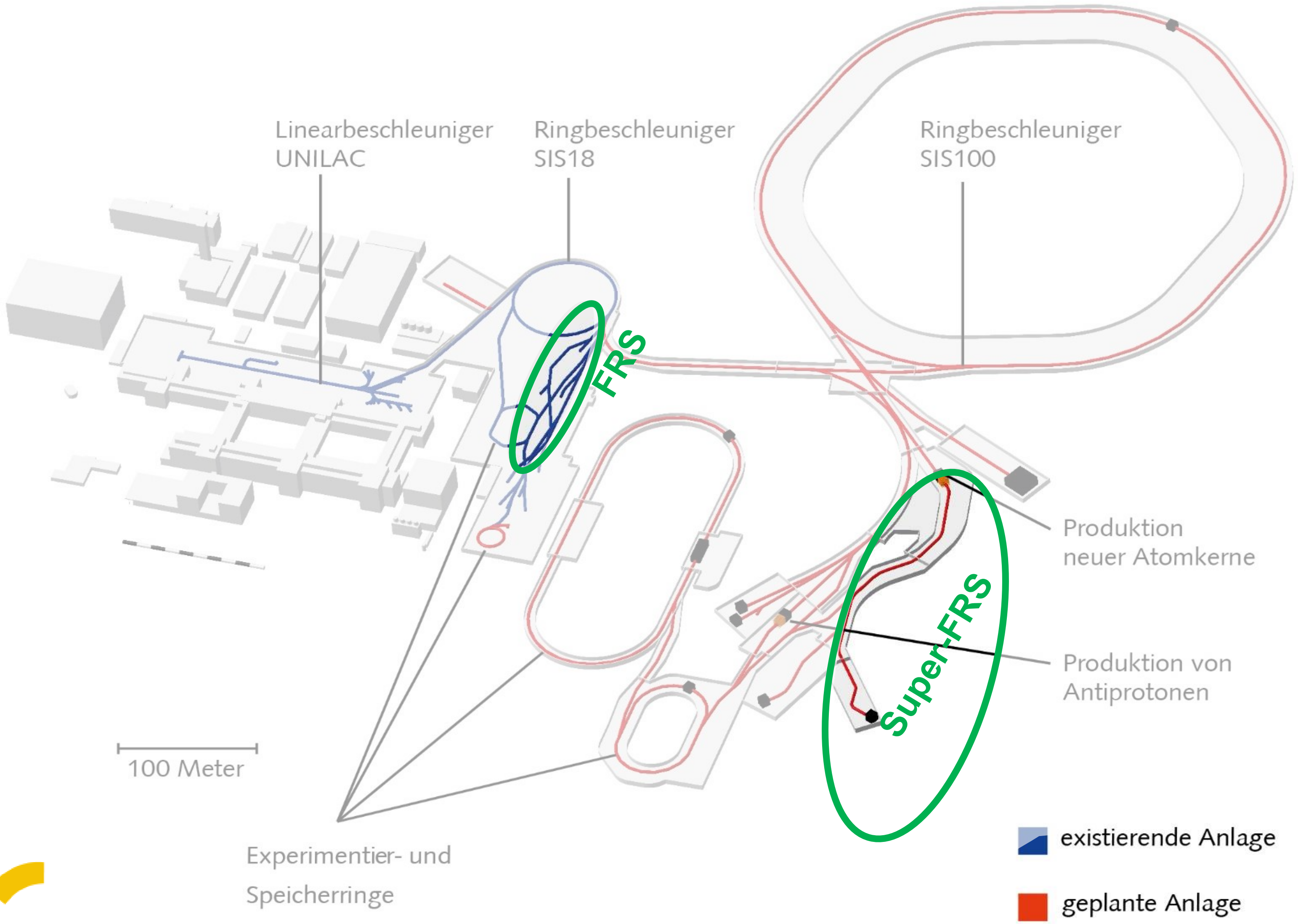
- World record:
  - Mass accuracy down to $1.7 \cdot 10^{-8}$
  - **MRP of 1,000,000 at total TOF of ~23 ms**

^{70}Se:

- 485 events collected
- Mass uncertainty **2.6 keV** ($\delta m/m$ = **4.0×10^{-8}**)

I. Mardor et al., PRC 103, 034319 (2021)

The FRS and Super-FRS Ion Catcher at GSI/FAIR



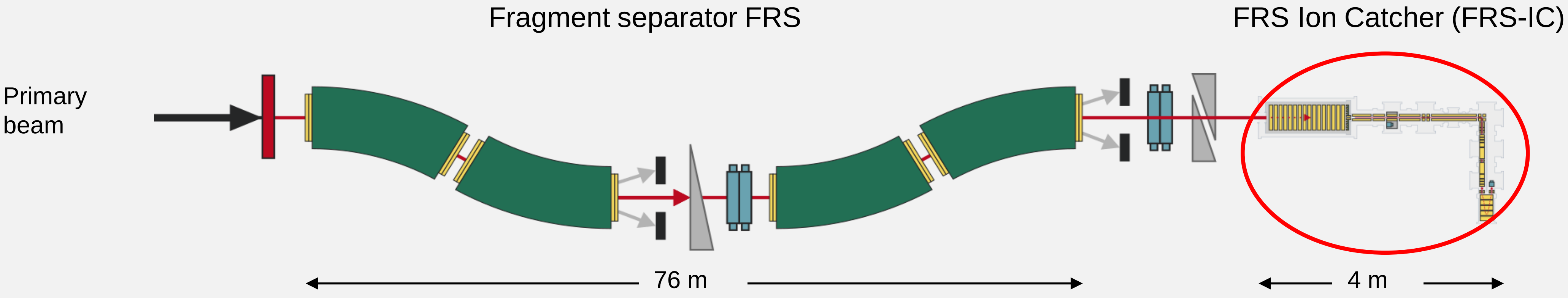
🟦 existierende Anlage

🟥 geplante Anlage

⬛ Experimente

Super-FRS EC

The FRS Ion Catcher at GSI



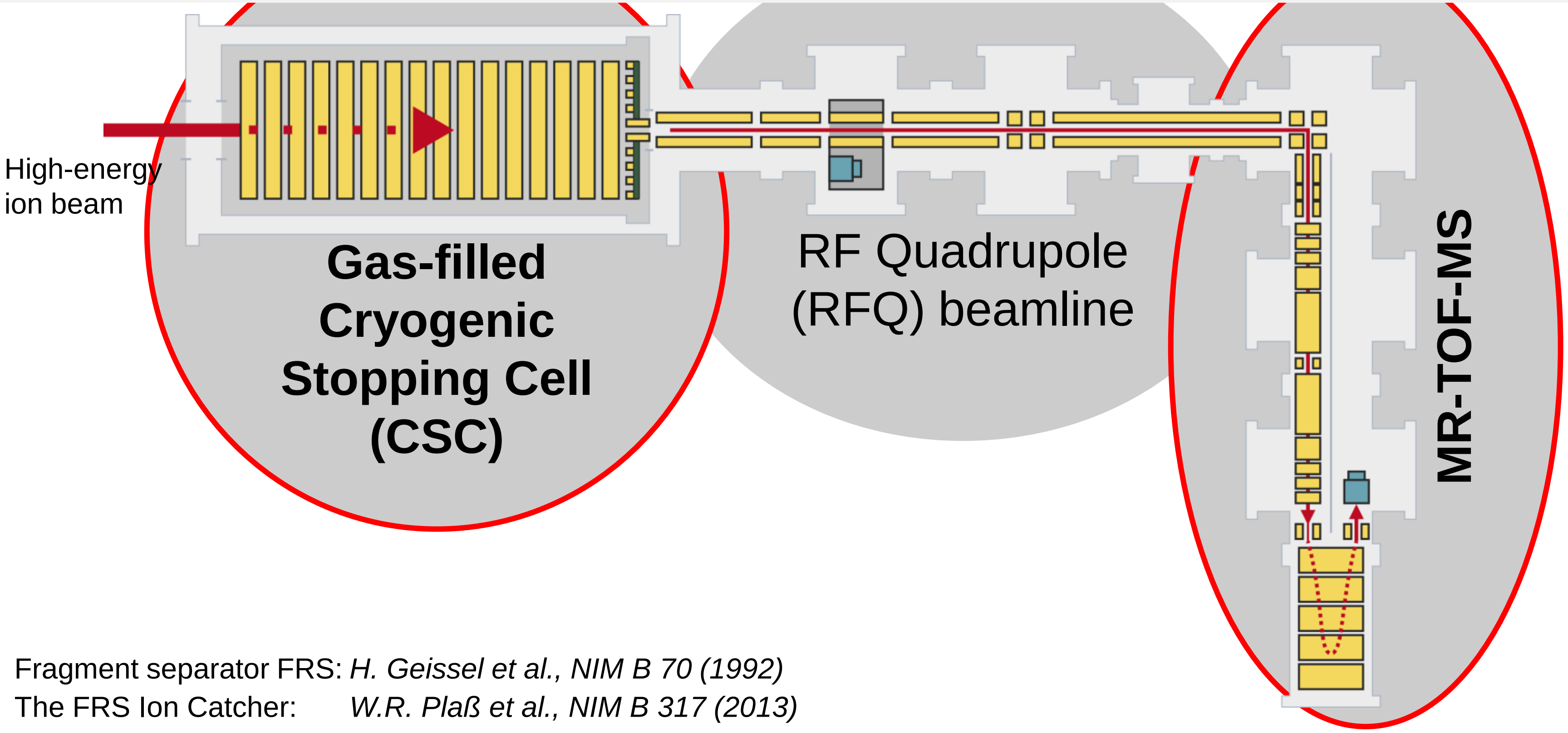
Fragment separator FRS

FRS Ion Catcher (FRS-IC)

Primary beam

76 m

4 m



High-energy ion beam

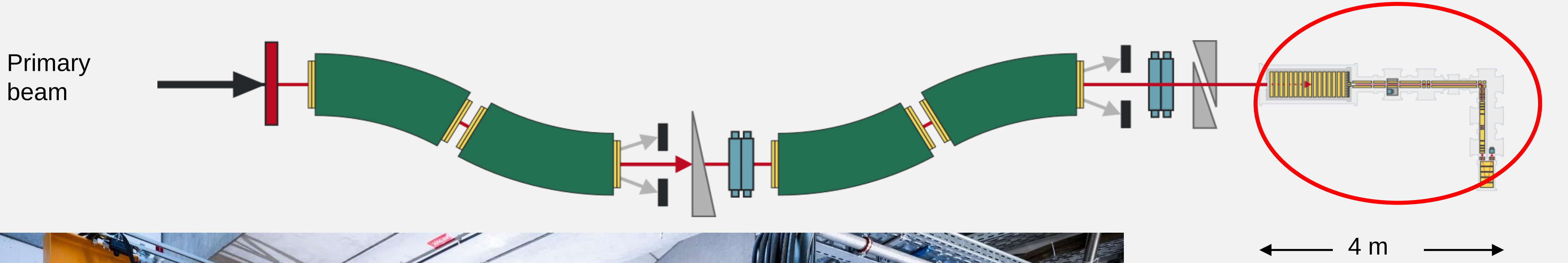
Gas-filled Cryogenic Stopping Cell (CSC)

RF Quadrupole (RFQ) beamline

MR-TOF-MS

Fragment separator FRS: *H. Geissel et al., NIM B 70 (1992)*
The FRS Ion Catcher: *W.R. Plaß et al., NIM B 317 (2013)*

The FRS Ion Catcher at GSI

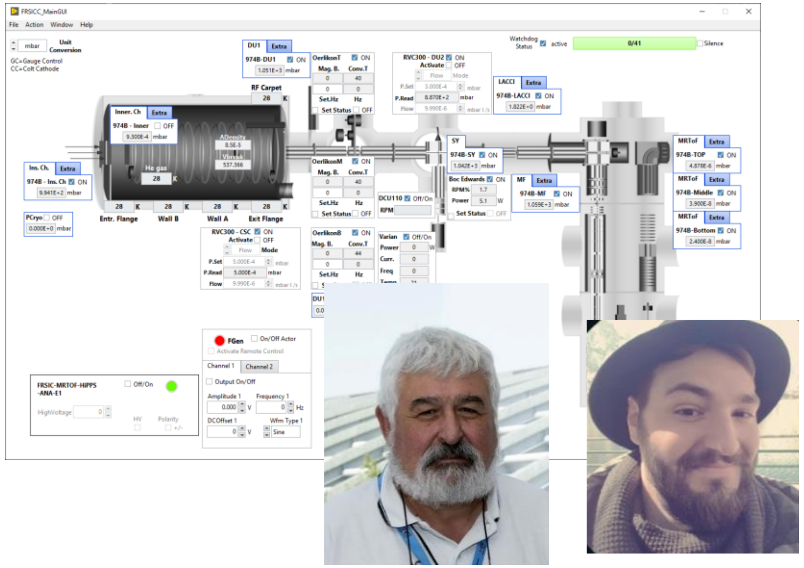

Fragment separator FRS

FRS Ion Catcher (FRS-IC)

Primary beam

4 m

Slow-Control


FRSICC_MainGUI

File Action Window Help

mbar Unit Conversion

GC=Gauge Control
CC=Colt Cathode

DU1 Extra
974B-DU1 ☑ ON
1.051E+3 mbar

OerlikonT ☑ ON
Mag. B. Conv.T
0 40
0 0
Set.Hz Hz
☐ Set Status ☐ OFF

RVC300 - DU2 ☑ ON
Activate ☐ OFF
Flow Mode
P.Set 3.000E-4 mbar
P.Read 8.870E+2 mbar
Flow 9.990E-6 mbar l/s

Watchdog Status ☑ active 0/41 ☐ Silence

LACCI Extra
974B-LACCI ☑ ON
1.822E+0 mbar

RF Carpet 28 K

Inner. Ch Extra
974B - Inner ☐ OFF
9.300E-4 mbar

ADensity 8.5E-5
Vbreak 537.386

He gas 28 K

Ins. Ch. Extra
974B - Ins. Ch ☑ ON
9.941E+2 mbar

PCryo ☐ OFF
0.000E+0 mbar

28 K Entr. Flange
28 K Wall B
28 K Wall A
28 K Exit Flange

OerlikonM ☑ ON
Mag. B. Conv.T
0 40
0 0
Set.Hz Hz
☐ Set Status ☐ OFF

SY
974B-SY ☑ ON
1.042E+3 mbar

Boc Edwards ☑ ON
RPM% 1.7
Power 5.1 W
☐ Set Status ☐ OFF

DCU110 ☑ Off/On
RPM

MF Extra
974B-MF ☑ ON
1.059E+3 mbar

MRToF Extra
974B-TOP ☑ ON
4.878E-6 mbar

MRToF Extra
974B-Middle ☑ ON
3.900E-8 mbar

MRToF Extra
974B-Bottom ☑ ON
2.400E-8 mbar

RVC300 - CSC ☑ ON
Activate ☐ OFF
Flow Mode
P.Set 5.000E-4 mbar
P.Read 5.000E-4 mbar
Flow 9.990E-6 mbar l/s

OerlikonB ☑ ON
Mag. B. Conv.T
0 44
0 0
Set.Hz Hz

Varian ☑ Off/On
Power 0 W
Curr. 0
Freq 0

FGen ☐ On/Off Actor
☐ Activate Remote Control
Channel 1 Channel 2
☐ Output On/Off
Amplitude 1 0.000 V
Frequency 1 0 Hz
DCOffset 1 0 V
Wfm Type 1 Sine

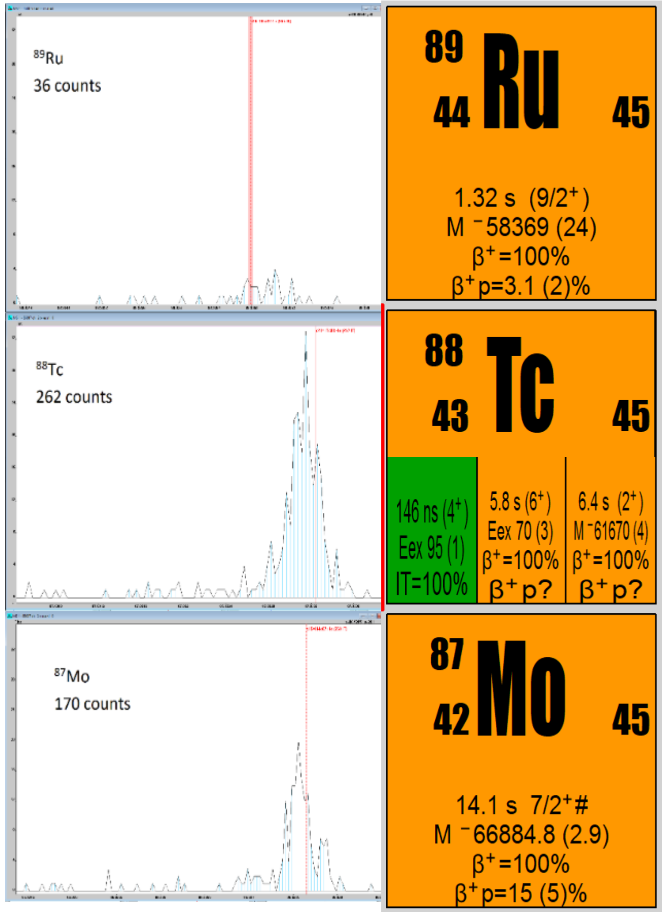
FRSIC-MRTOF-HIPPS-ANA-E1 ☐ Off/On
HighVoltage 0
HV ☐
Polarity ☐ +/-

A. N. State et al., NIMA 1034, 166772 (2022)

FRS and FRS Ion Catcher: Efficient measurement schemes

Energy bunching mode + optimize beam energy

max. stopping efficiency for single isotopes

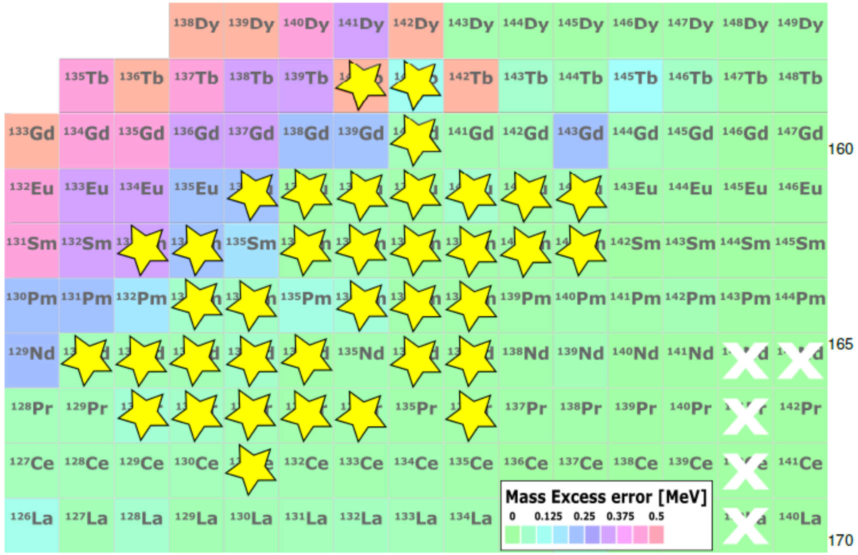


Three isotones in a single setting

Mean Range Bunching (MRB)

Simultaneous stopping of many isotopes

(at slightly reduced efficiency for single isotopes)



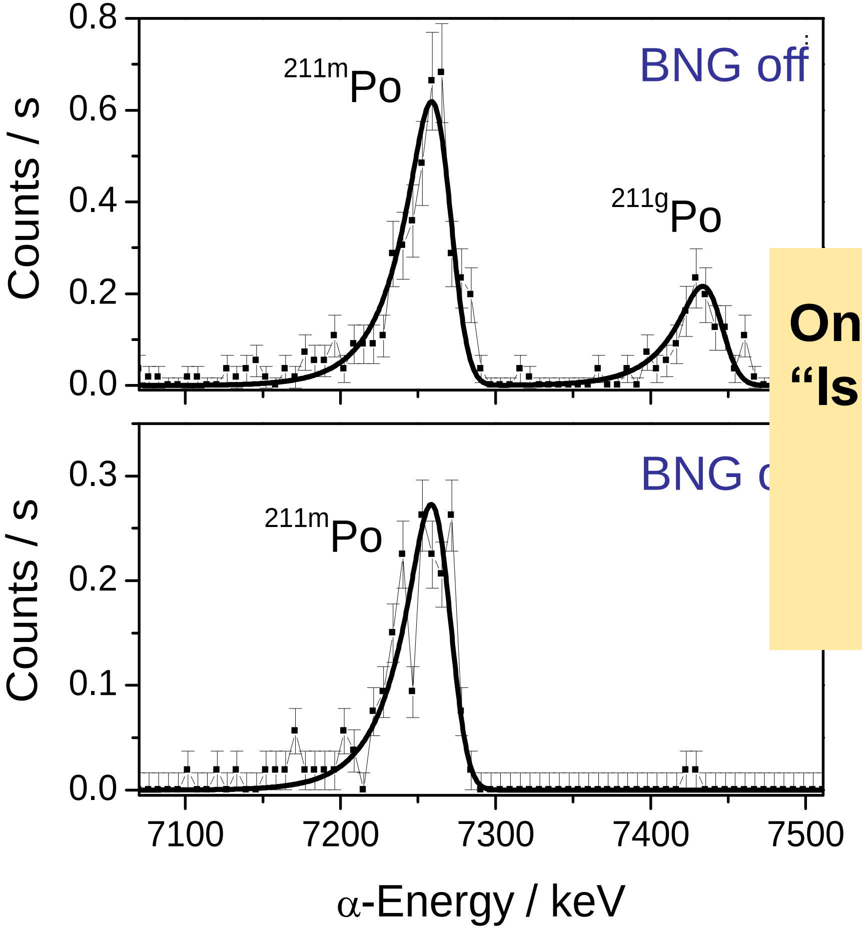
35 nuclides in one(!)
FRS / MR-TOF-MS setting

Broadband mass measurements
→ mapping the mass surface

T. Dickel et al., NIM B 541 (2023) 275-278

Separation of isomers

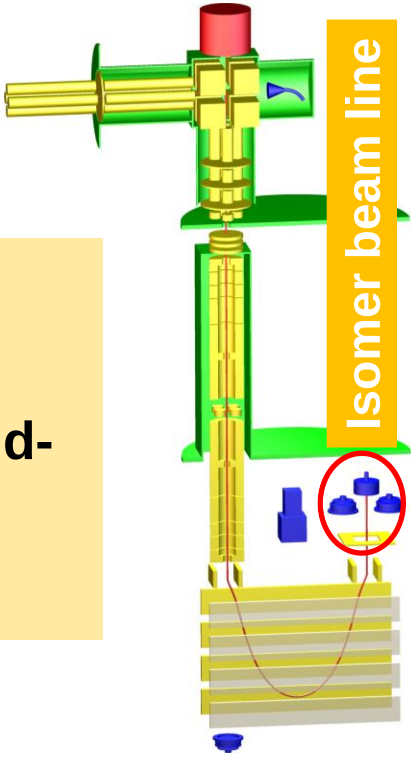
First spatial separation of ground state and isomeric state in an MR-TOF-MS



Ongoing project to implement an “Isomer beam line”:

→ **Enable dedicated, background-free decay spectroscopy of isomeric states**

Ions from the CSC



Separation using the Bradbury-Nielsen gate, measurement using the Si detector

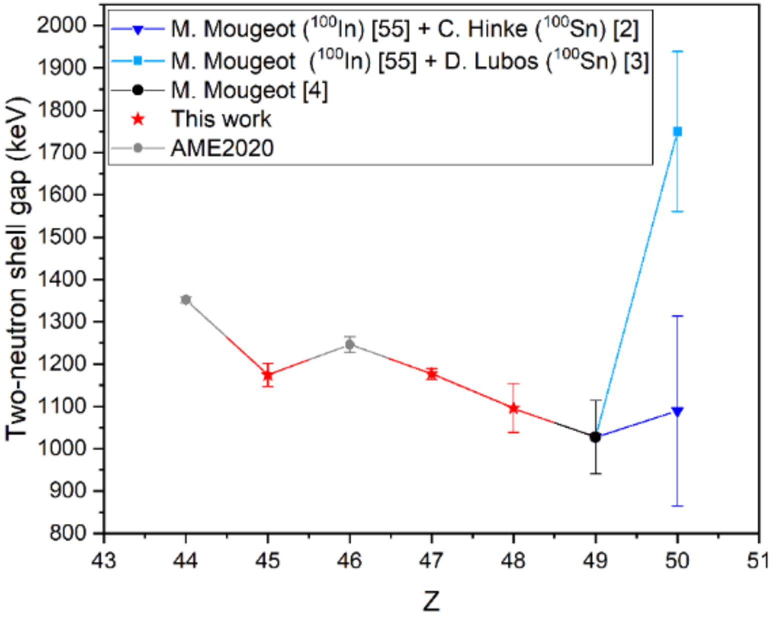
T. Dickel, A. Mollaebrahimi EPJ ST 233 (2024) 1181

T. Dickel et al., Phys. Lett. B 744 (2015) 137

Mass measurements of ^{98}Cd and ^{97}Rh with the FRS Ion Catcher

Shell Gap and Gamov-Teller Strength at *N*=50 and the puzzle of ^{100}Sn mass

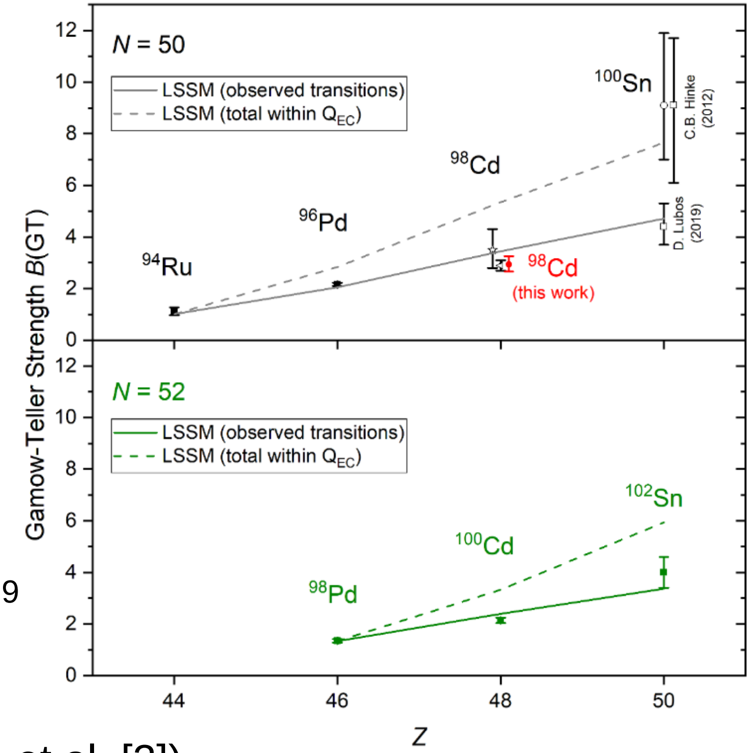
N+2 two-neutron shell gap at N=50



A. Mollaebrahimi *et al*.,
***Phys. Lett. B* 839 (2023) 137833**

[1] C.Hinke *et al*., Nature **486** (2012) 341
[2] D.Lubos *at al*., PRL **122** (2019) 222502
[3] M.Mougeot *et al*., Nature Phys. **17** (2021) 1099

Gamov-Teller Strength at N=50, 52

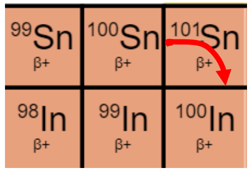


^{100}Sn mass:

New results on discrepancy of **^{100}Sn Q$_{EC}$ values** (Hinke et al. [1] and Lubos et al. [2])

- In recent work Mougeot et al. [3] → value of Hinke et al is favored
- **This work**:
  Evolution of two-neutron shell gap at N=50: Value of Hinke et al. [1] is favored.
  Evolution of Gamov-Teller Strength at N=50: Value of Lubos et al. [2] is favored.

→ **Overall situation unclear, further experiments required**



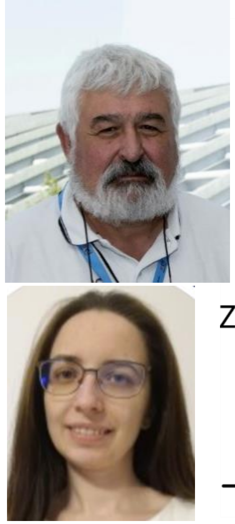
^{252}Cf - Broadband mass and yield measurments

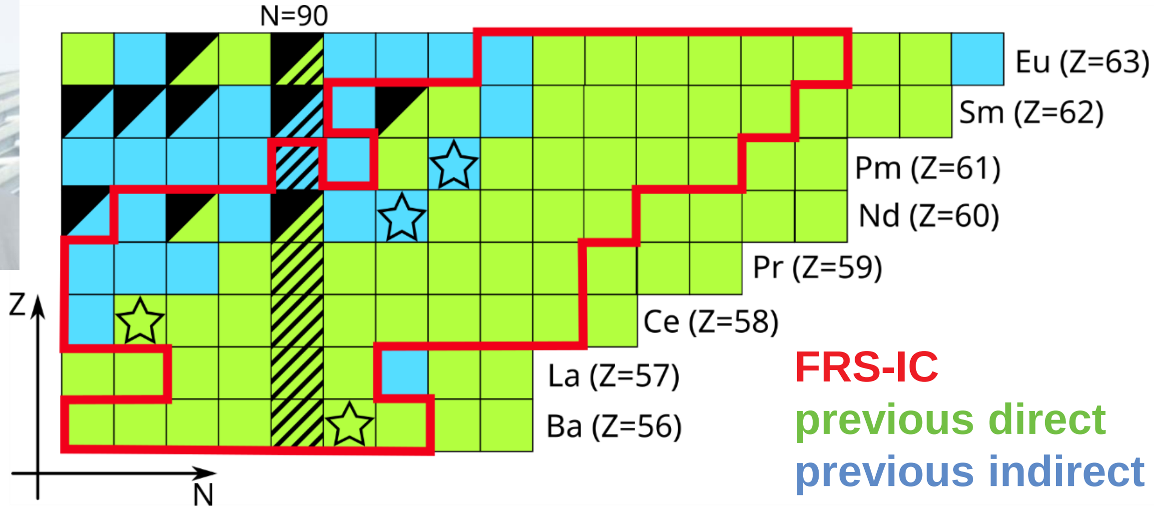
Broadband mass measurements:

Offline experiment with ^{252}Cf (20kBq, < µCu):

- first time simultaneous direct measurement of
  - 64 masses,
  - **50 in a single setting**,
  - 14 first direct
  - 4 improved accuracy

A. Spataru et al., Bulgarian Journal of Physics vol. 48 (2021) 535
A. Spataru et al , Phys. Scr. 99 (2024) 075305



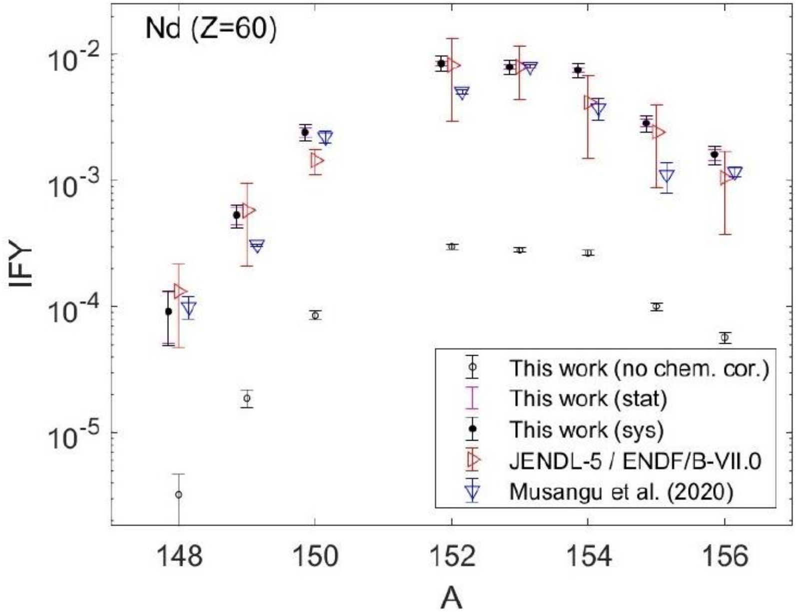


Yield / cross section measurements:

Developed method for IFY measurement
Large chemical efficiency C(Z)

$$\sum IFY(N,Z)_{exp}^{N+Z=A} \cdot C(Z) = frac(FY_{lit}(A)) \cdot FY_{lit}(A)$$

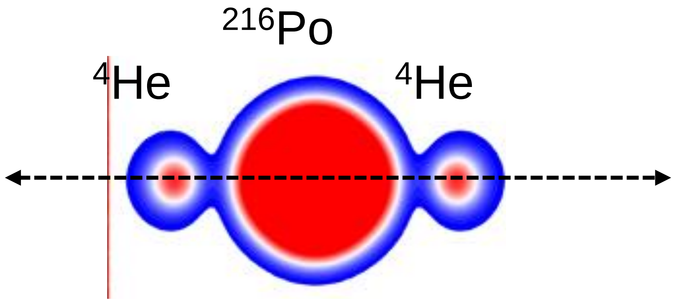
I. Mardor et al., EPJ Web of Conferences 239 (2020)
Y. Waschitz et al., EPJ Web of Conferences 284 (2023)



Search for new radioactive decay modes

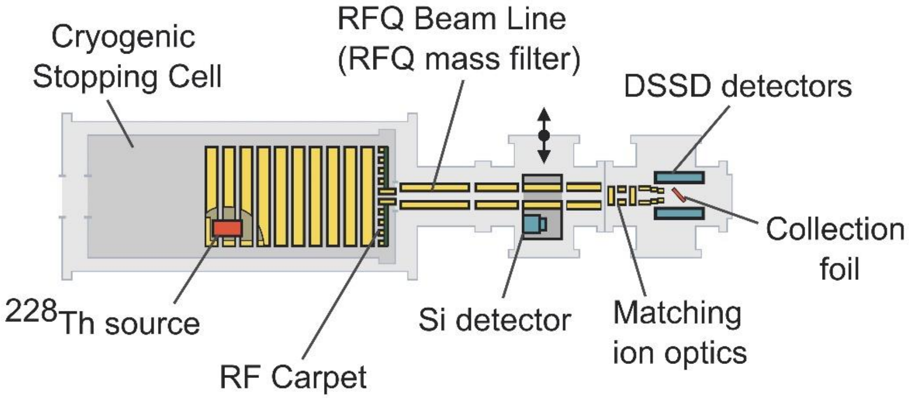
Double α-decay

- Predicted by theory
- Experimentally not observed yet
- Challenge: expected branching ratio ~ 10^{-8}

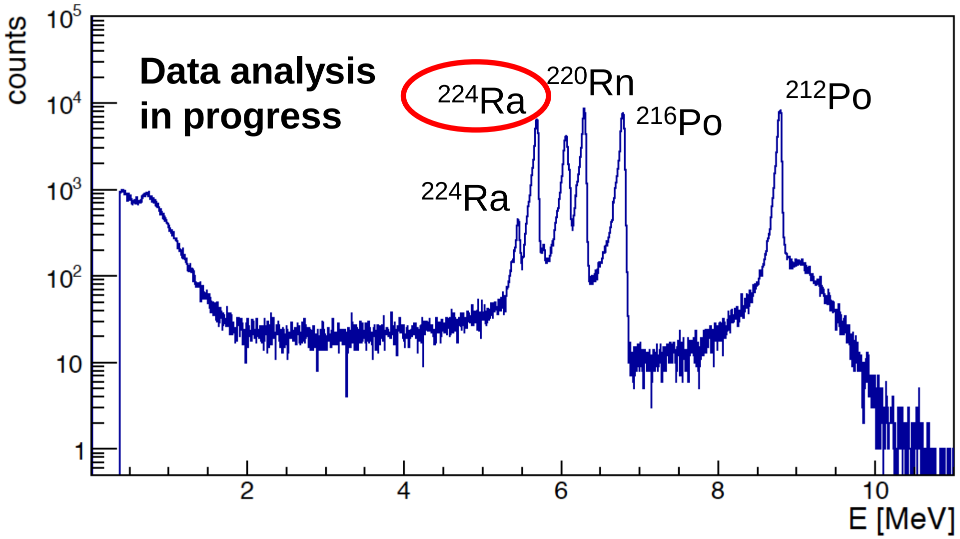


Mercier et al., PRL 127, 012501 (2021)

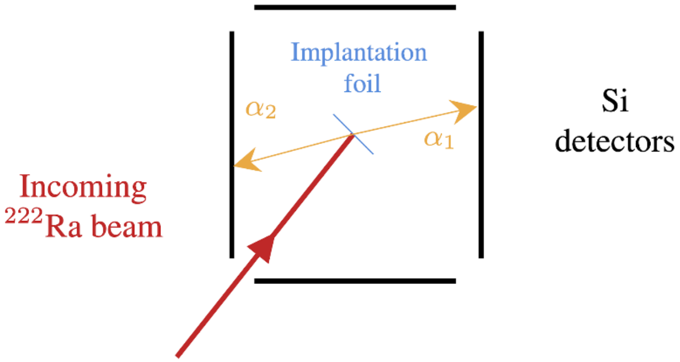
FRS Ion Catcher



4 months of continuous data taking (Feb. – Jul. 2022)



L. Varga et al., NIM A 1063 (2024) 169252



1 week experiment (June 2023)

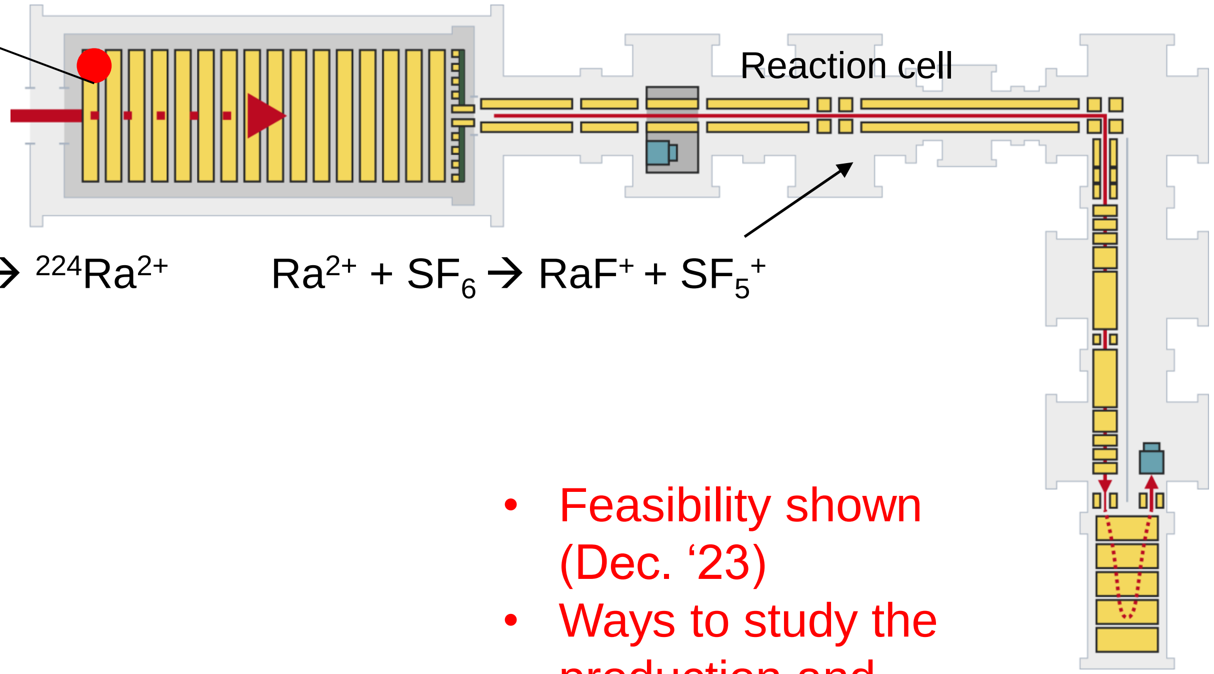
Data analysis in progress

Joined and complementary program focused on “online” isotopes

Radioactive molecules

- Molecules are interesting laboratories to probe fundamental physics, e.g. electric dipole moment of the electron (eEDM)

- Radioactive molecules with heavy and deformed nuclei, like RaF, provide superior sensitivity for eEDM



$^{228}Th \rightarrow {}^{224}Ra^{2+}$

$Ra^{2+} + SF_6 \rightarrow RaF^{+} + SF_5^{+}$

- Feasibility shown (Dec. ‘23)
- Ways to study the production and properties of RM were established
- More to come…

Collaborators

THE UNIVERSITY OF EDINBURGH

M. P. Reiter

Philipps Universität Marburg

R. Berger
(theoretical chemistry)

Future nuclear astrophysics experiments: beta-delayed neutron emission

Challenge: Detect neutrons

Solution: Measure mass change instead

FRS/Super-FRS

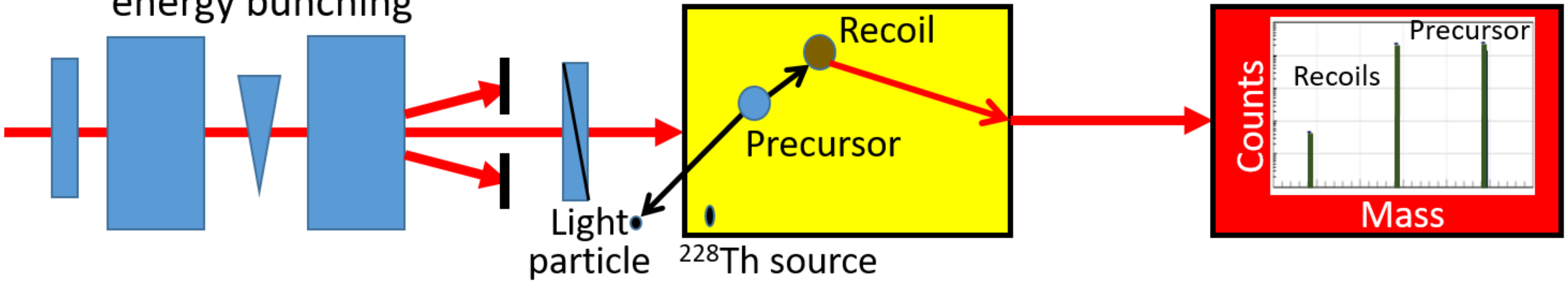
In-flight isotope production and separation, energy bunching

CSC

Required precursors stopped, contained and decay

MR-TOF-MS

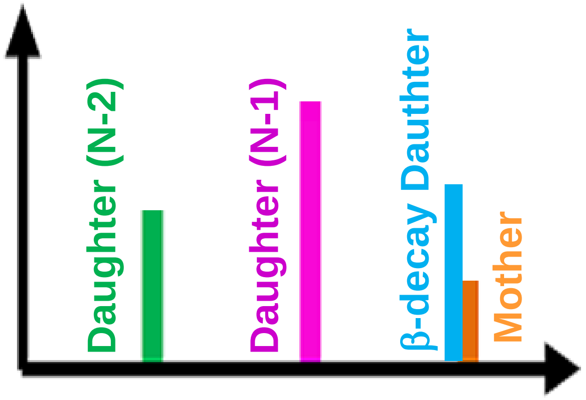
Precursor and recoils identification and counting



Production of exotic nuclei

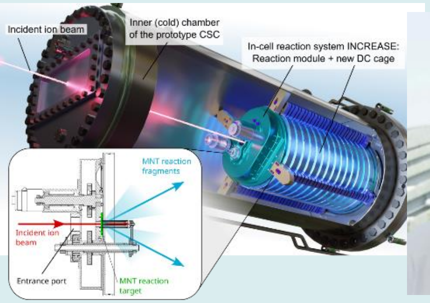
Stopping cell → Ion trap

After containment of ~ $2t_{1/2}$

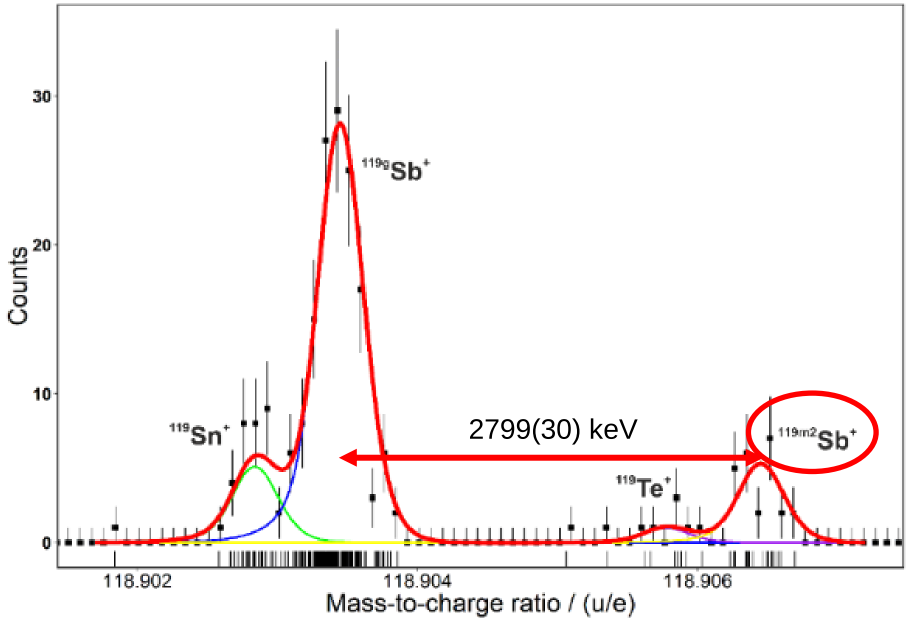


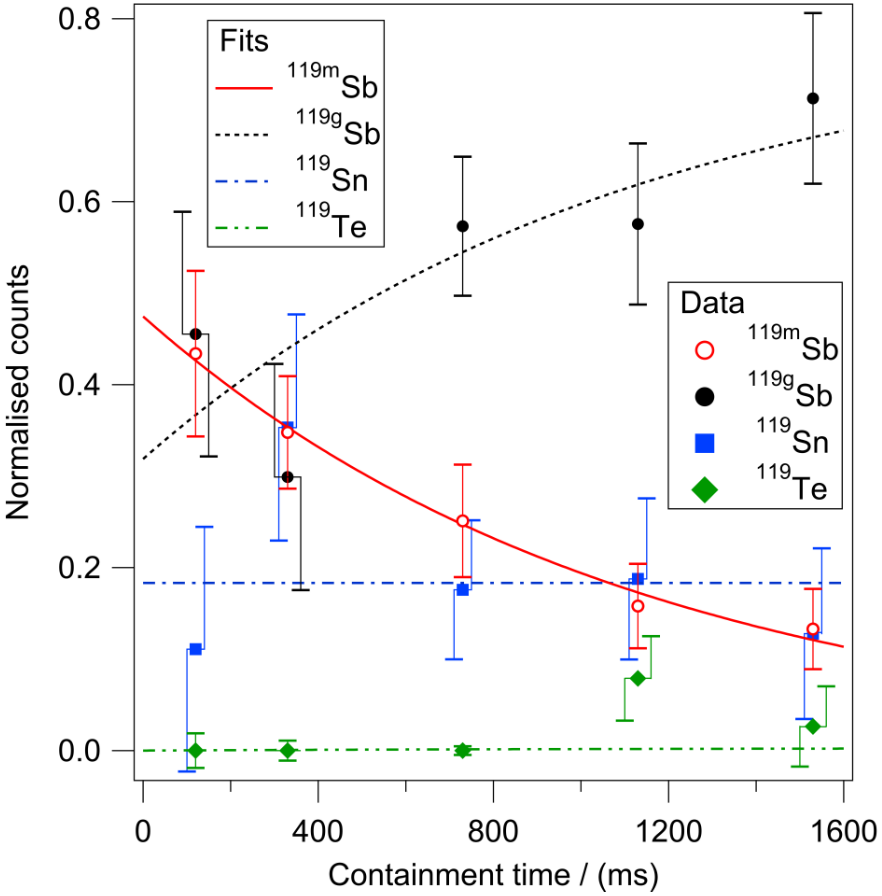
Stopping cell → Active Target

See P. Constantin



Proof-of-concept: Novel method for half-lives and branching ratios (e.g., P_{xn})





Fits based on solution of radioactive decay laws

Measured branching

Isomer Transition	β-	β+
1	0	0

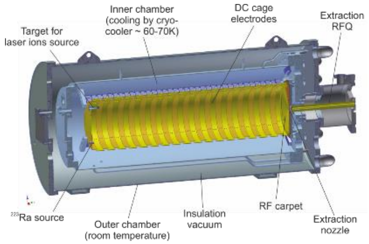
Half-life

Measured value	Literature value
776 ± 181 ms	850 ± 90 ms

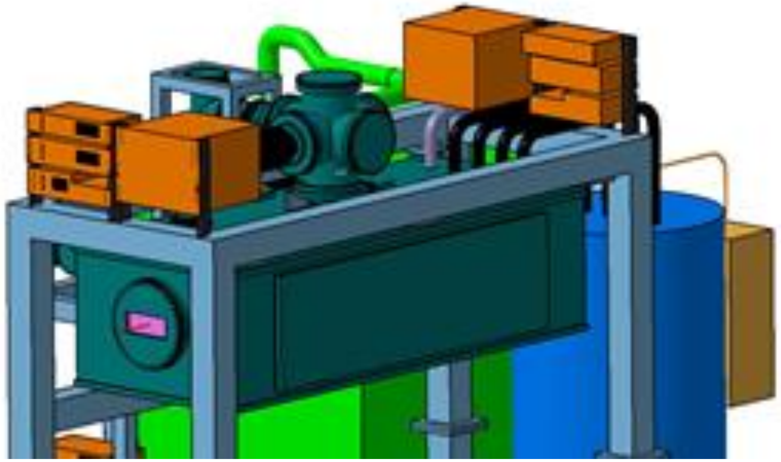
I. Miskun et al., EPJA (2019) 55: 148

Outlook – Evolution from FRS to Super-FRS CSC

From FRS-Ion CSC **to** **Super-FRS Ion CSC**



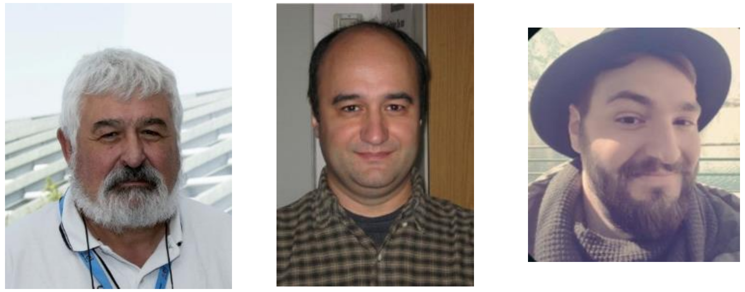
T. Dickel et al., NIM B 317 (2016) 216-220



New scientific opportunities:

- β-delayed neutron emission (one of the first experiments at the Super-FRS)
- MNT reactions with secondary beams
- Mass measurements of more exotic species
- and more…

- More efficient → Higher sensitivity
- Faster → Access to shorter lived nuclei
- Higher rate capability → New class of experiments



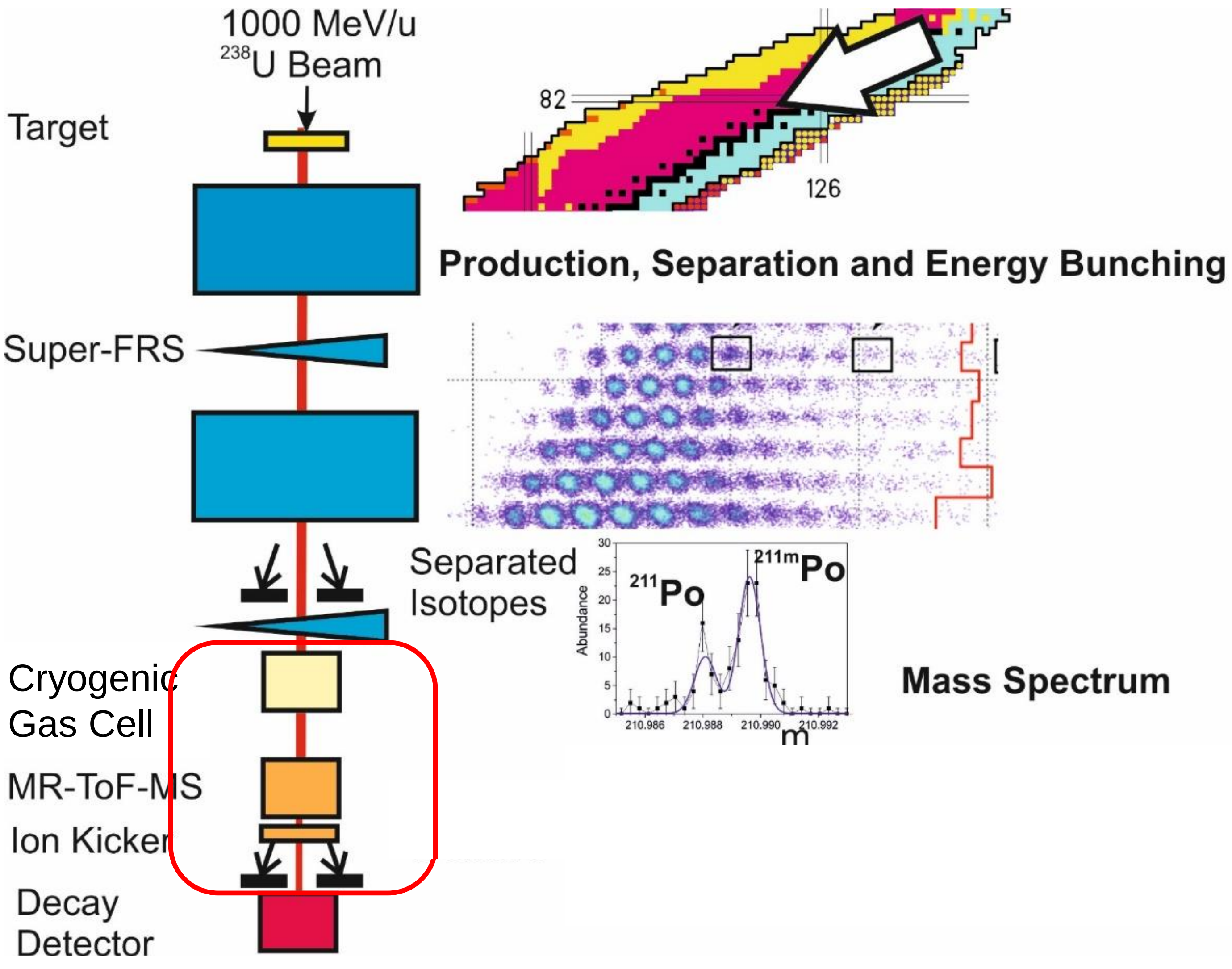
Same technology used in other projects:

- Photofission @ ELI-NP, Romania
- Neutron-induced fission @ Soreq, Israel

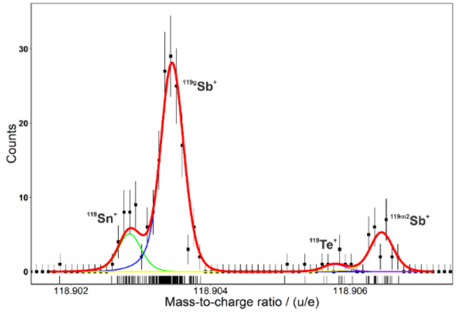
eli nuclear physics

Soreq

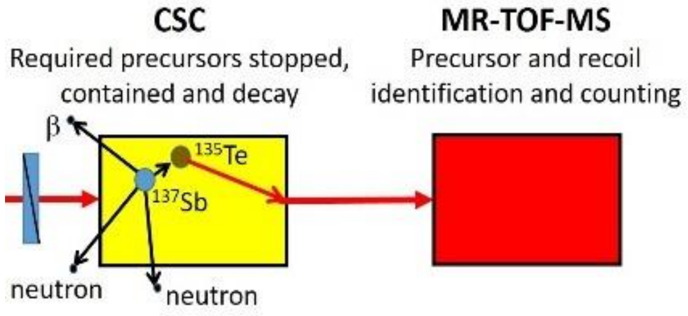
Summary



Direct mass measurements



Measurement of Pn values from beta-delayed neutron emission



Program without relativistic beams

Acknowledgements

Super-FRS Experiment Collaboration

FRS Ion Catcher Collaboration

D. Amanbayev, B. Ashrafkhani, O. Aviv, S. Ayet San Andrés,
J. Äystö, S. Bagchi, D.L. Balabanski, S. Beck, O. Beliuskina,
J. Bergmann, A. Blazhev, Z. Brencic, S. Cannarozzo, O. Charviakova,
P. Constantin, D. Curien, I. Dedes, M. Dehghan, T. Dickel, F. Didierjean,
G. Duchene, J. Dudek, T. Eronen, T. Fowler-Davis, M. Friedman, Z. Gao,
Z. Ge, H. Geissel, S. Glöckner, M. Górska, T. Grahn, F. Greiner, L. Gröf,
M. Gupta, E. Haettner, M. Harakeh, C. Hornung, Y. Ito, A. Jaries,
A. Jokinen, B. Kaizer, N. Kalantar-Nayestanaki, A. Kankainen, D. Kar,
A. Karpov, Y. Kehat, D. Kostyleva, G. Kripkó-Koncz, D. Kumar,
K. Mahajan, I. Mardor, A.A. Mehmandoost-Khajeh-Dad, N. Minkov,
A. Mollaebrahimi, I. Moore, D. Morrissey, I. Mukha, M. Narang, D. Nichita,
Z. Patyk, H. Penttilä, A. Perry, S. Pietri, A. Pikhtelev, W.R. Plaß,
I. Pohjalainen, S. Pomp, R.K. Prajapat, S. Purushothaman, M.P. Reiter,
M. Reponen, S. Rinta-Antila, H. Rösch, A. Rotaru, J. Ruotsalainen,
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N. Tortorelli, E. Vardaci, L. Varga, M. Vencelj, V. Virtanen, M. Wada,
H. Weick, L. Welde, M. Wieser, M. Will, H. Wilsenach, M.I. Yavor,
J. Yu, A. Zadvornaya, J. Zhao

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