II. Physikalisches Institut

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

IONAS

GSI

HELMHOLTZ GEMEINSCHAFT

Operation and Results of MR-TOF-MS at GSI and TRIUMF

Samuel Ayet San Andrés for the FRS Ion Catcher and the TITAN Collaborations

- Motivation
- FRS Ion Catcher at GSI
- TITAN at TRIUMF
- Summary and Outlook

MASSES OF EXOTIC NUCLEI: NUCLEAR STRUCTURE AND NUCLEOSYNTHESIS

Exotic Nuclei

Exotic Nuclei

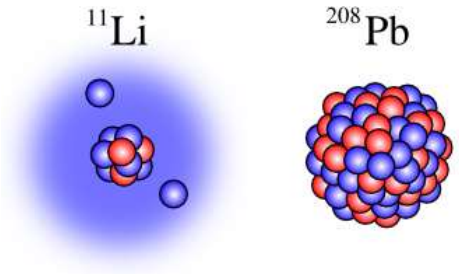
- Nuclei with unusual proton-neutron number ratio
- Short-lived, to be found in the stars or in the laboratory
- Unexpected, novel properties

Supernova 1994D in NGC 4526

GSI / FAIR Darmstadt

Examples:

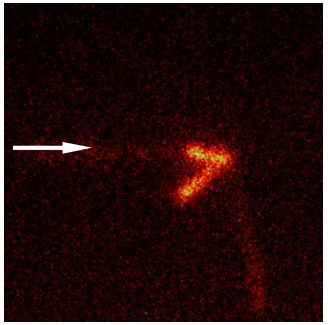
Halo nuclei



www.triumf.ca/sites/default/files/images/Halo_Nucleus.png

Two proton decay

^{45}Fe



M. Pfützner

Experimental Challenges:

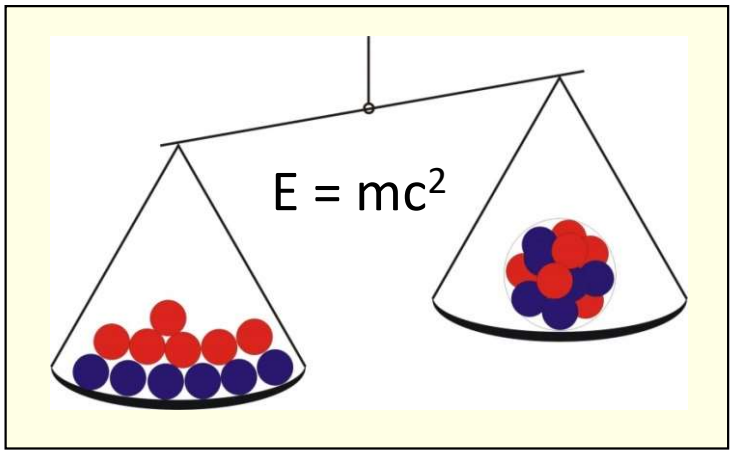
- Small production cross section

  (~ pbarn-μbarn)
- Short half-lives (~ ms)

  ➔ need for fast and efficient experimental methods

Mass and Binding Energy

Mass → Binding Energy → Stability and Structure



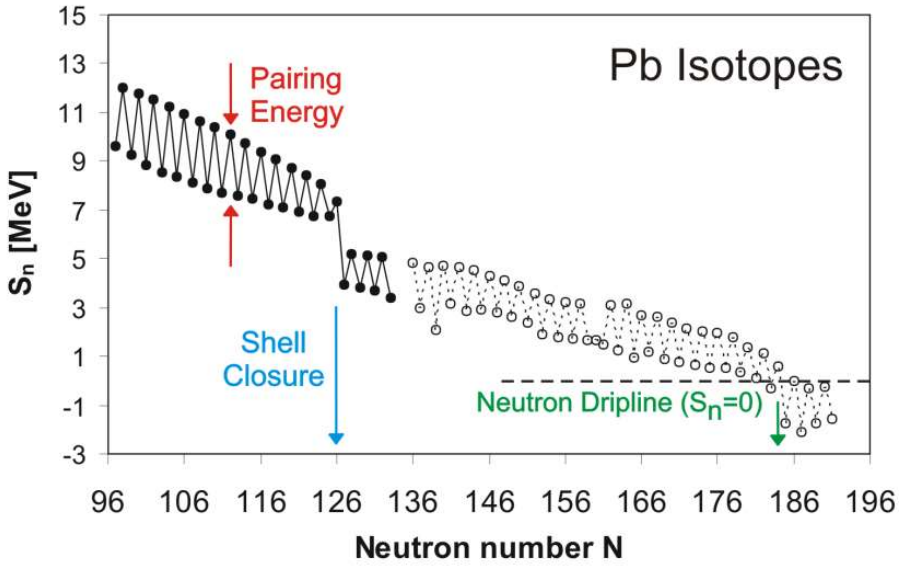
Z Protons (Proton number)

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

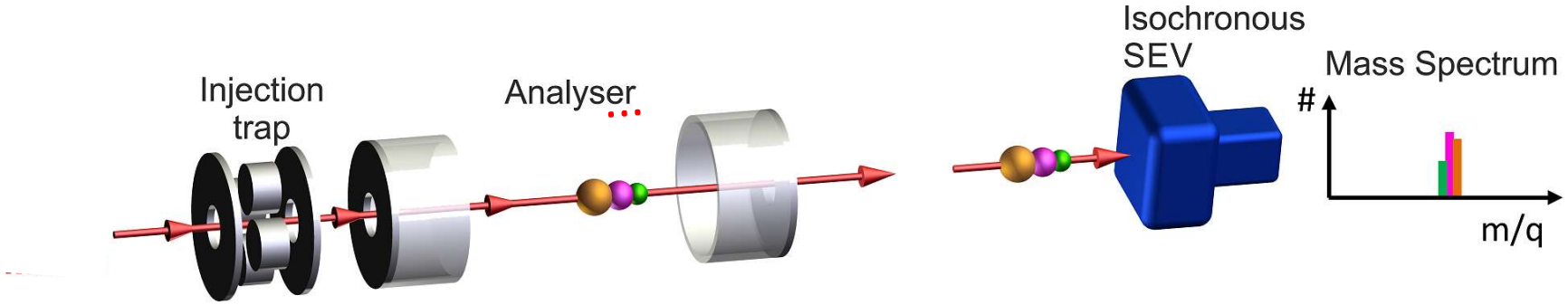
(MULTIPLE-REFLECTION) TIME-OF-FLIGHT SPECTROMETRY

(MR) TOF Mass Spectrometry

Enables high performance

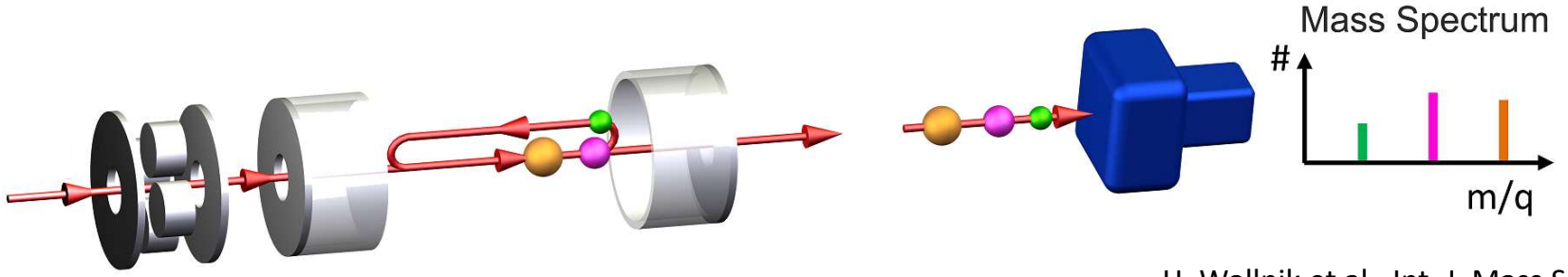
$$E = \frac{1}{2}mv^2 = qeU \Rightarrow \frac{m}{q} \propto t^2$$

- 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)

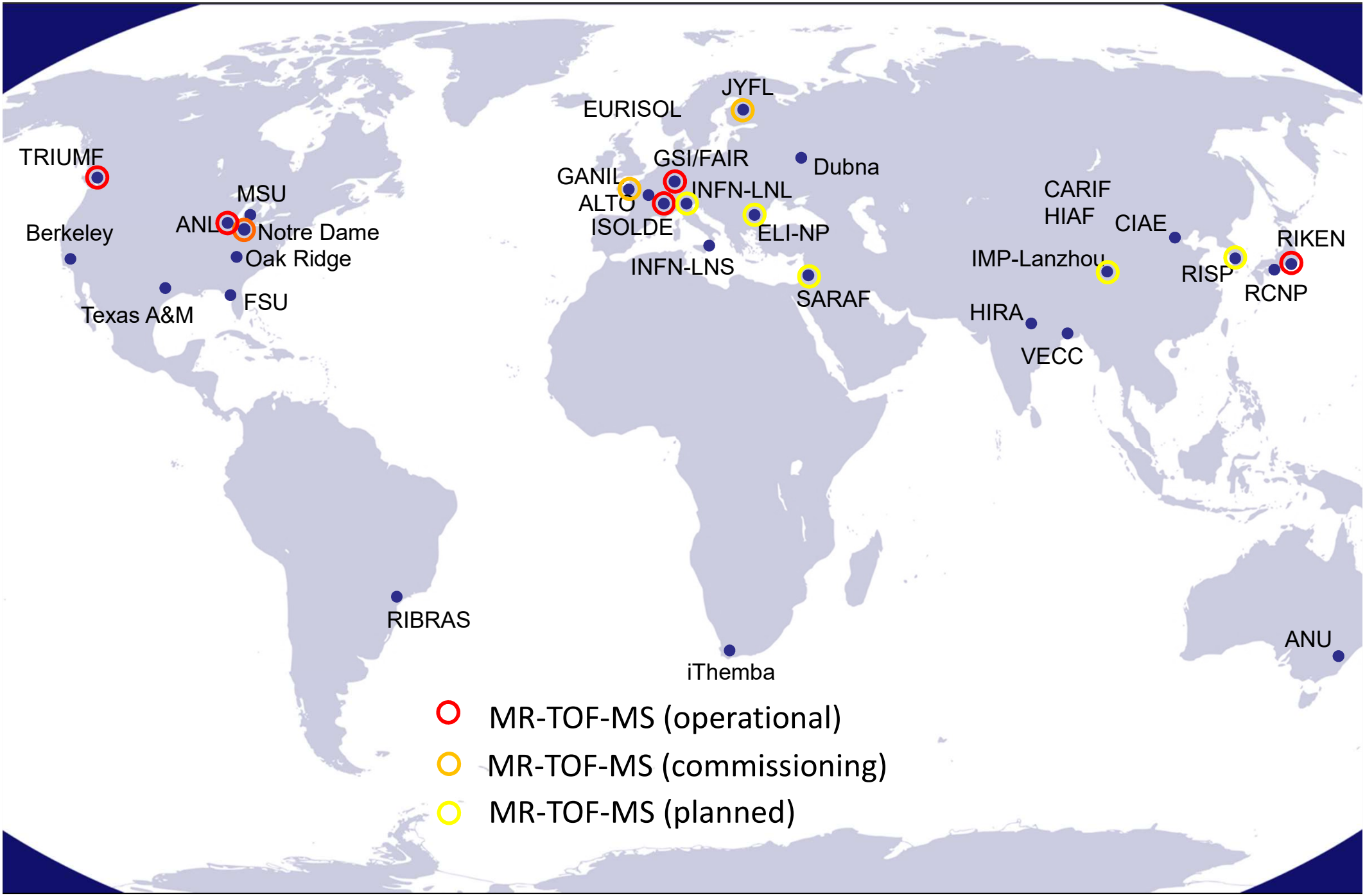


H. Wollnik et al., Int. J. Mass Spectrom. Ion Processes 96 (1990) 267

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

MR-TOF-MS in RIB Facilities



MR-TOF-MS in RIB Facilities

MR-TOF-MS Isobar separator for the TITAN facility (TRIUMF)

MR-TOF-MS at FRS Ion Catcher (GSI)

TRIUMF
Berkeley
Texas A&
RIBRAS
EURISOL
JYFL
GSI/FAIR
GANIL
INFN-LNL
ALTO
ISOLDE
ELI-NP
INFN-LNS
SAR
iThemba
RISP
RIKEN
RCNP
ANU

MR-TOF-MS (operational)

MR-TOF-MS (commissioning)

MR-TOF-MS (planned)

Genealogy of MR-TOF-MS built @ JLU Giessen

MR-TOF-MS at FRS Ion Catcher (GSI)

T. Dickel et al., NIM A 777 (2015) 172

MR-TOF-MS Isobar separator for the TITAN facility (TRIUMF)

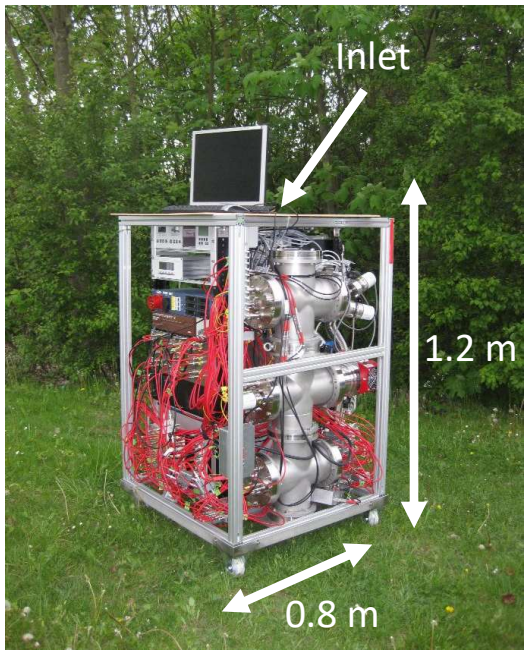
C. Jesch et al., Hyperfine Interact. 235 (2015) 97

Development platform:

- retrapping
- software
- electronics
- …

Ion-optical identical scaled down versions

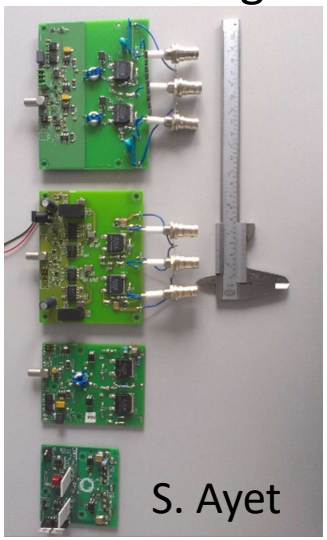
Mobile MR-TOF-MS for analytical mass spectrometry (JLU)



Dickel et al. NIM B 317 (2013)

Examples of Technical Developments

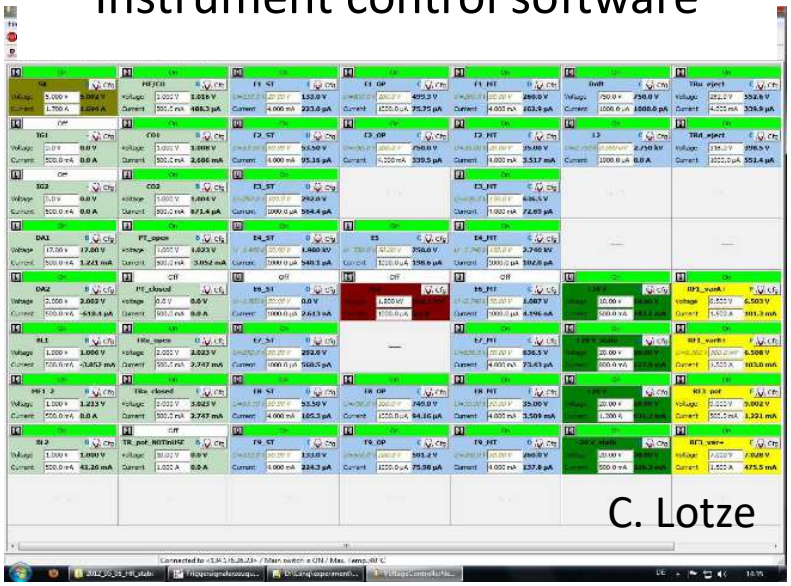
Fast high voltage switching



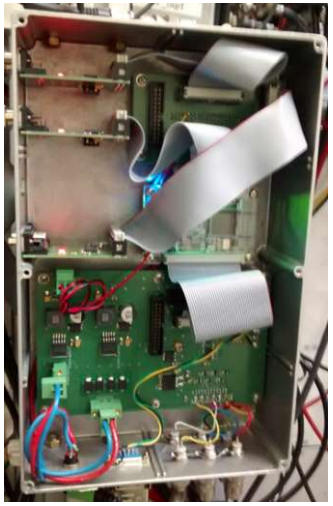
Voltage stabilization

S. Ayet

Instrument control software

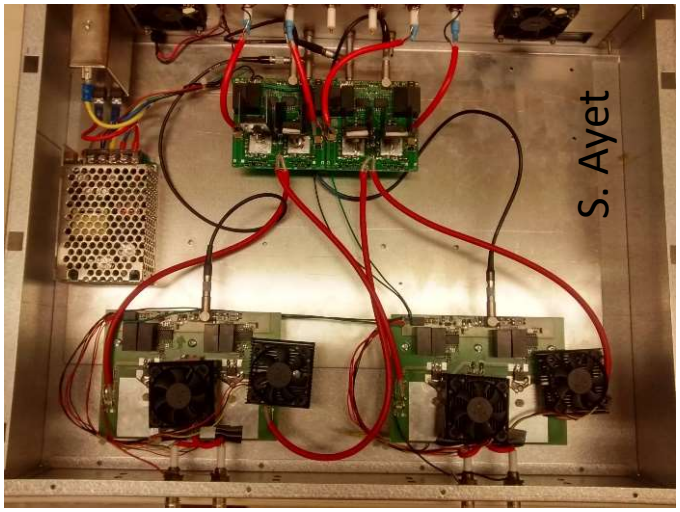


FPGA-based timing control

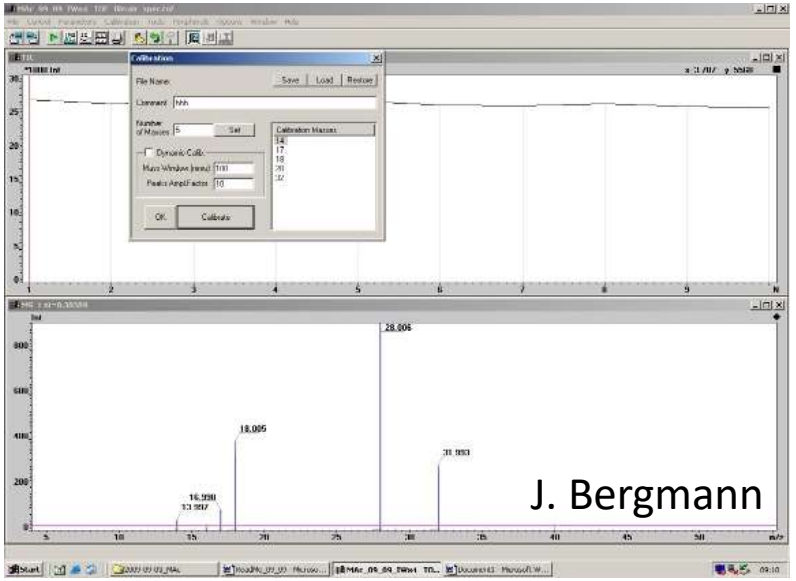


C. Jesch

Square Wave RF generation

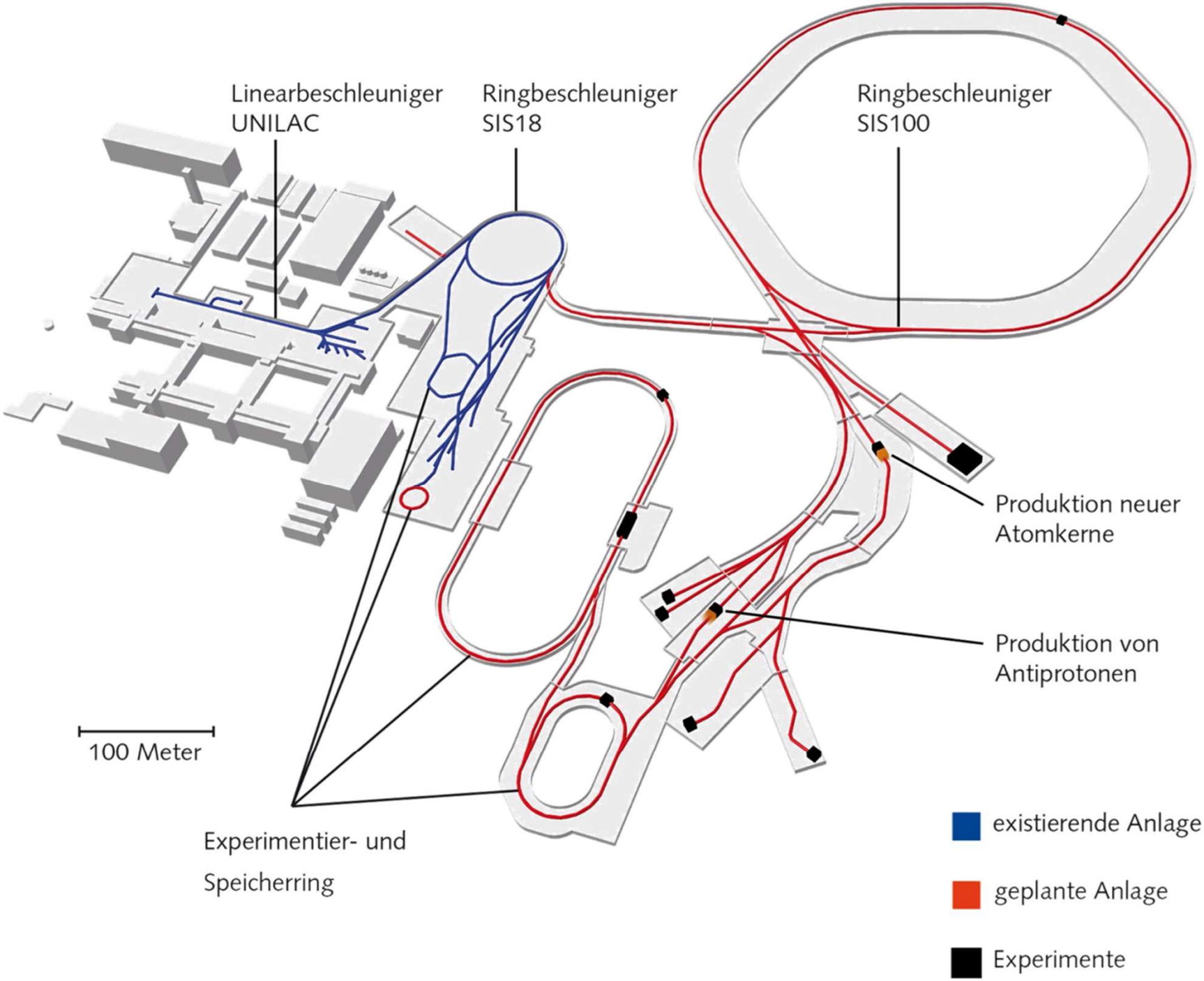


Data acquisition software

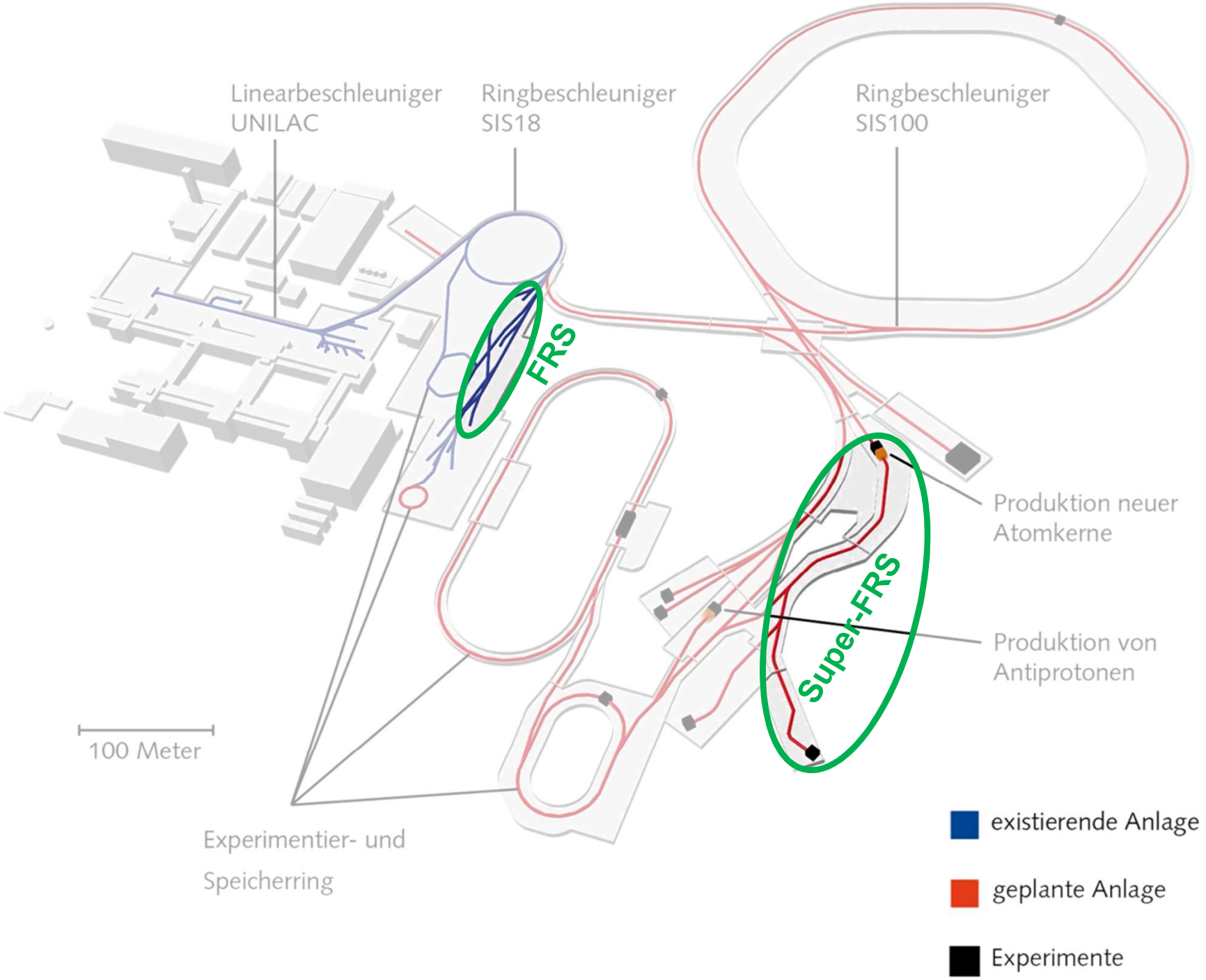


FRS ION CATCHER @ GSI

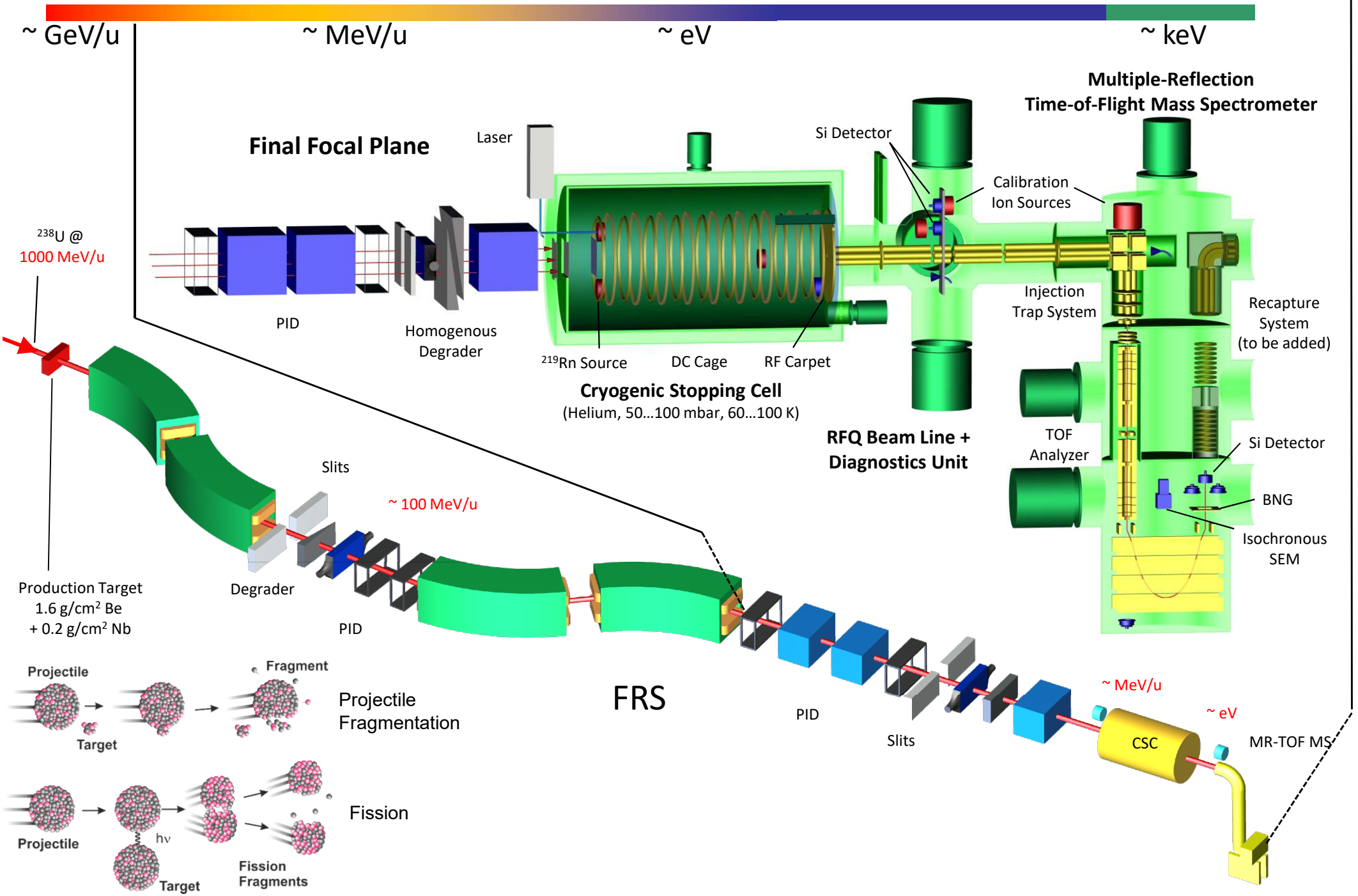
The FRS Ion Catcher at GSI/FAIR



The FRS Ion Catcher at GSI/FAIR

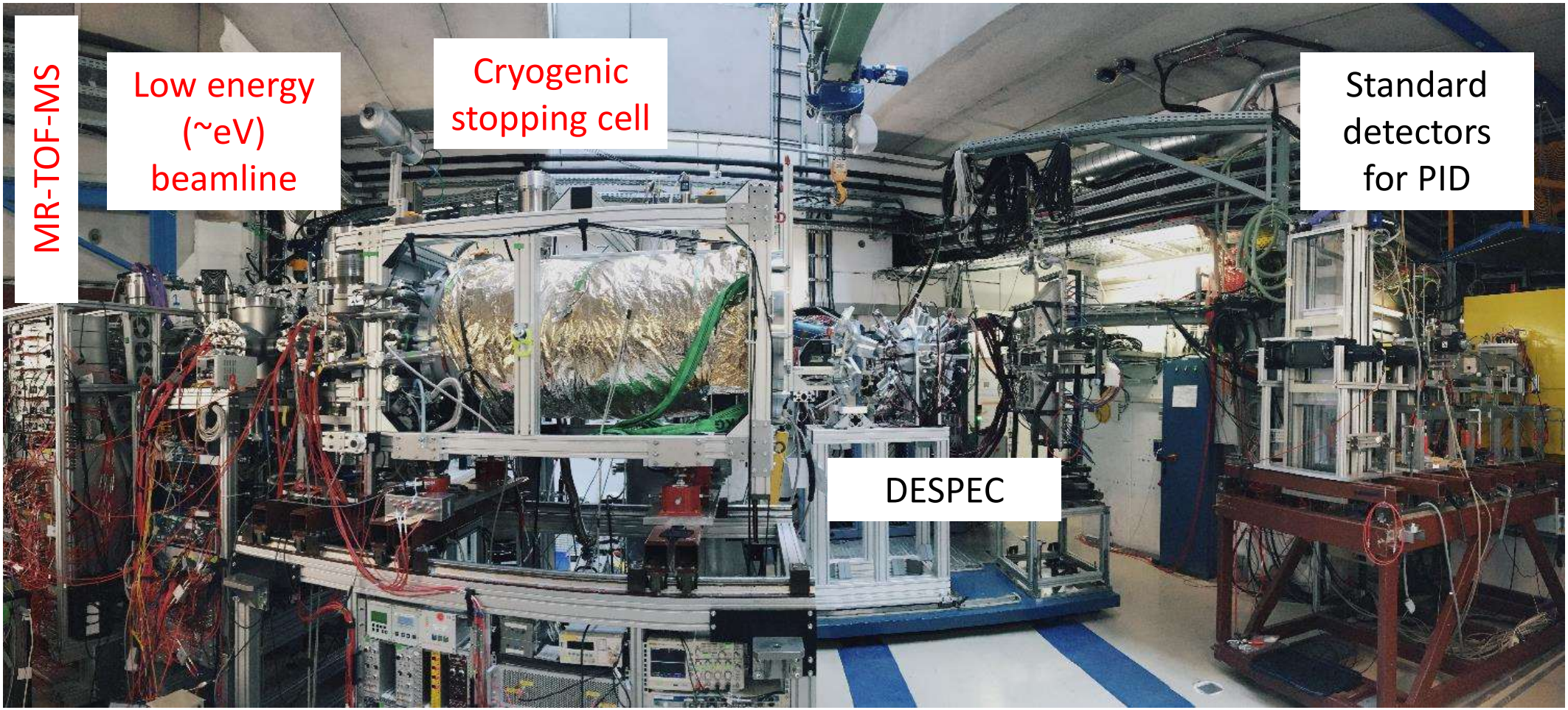


FRS Ion Catcher: Test Facility for the LEB@SuperFRS



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

FRS Ion Catcher



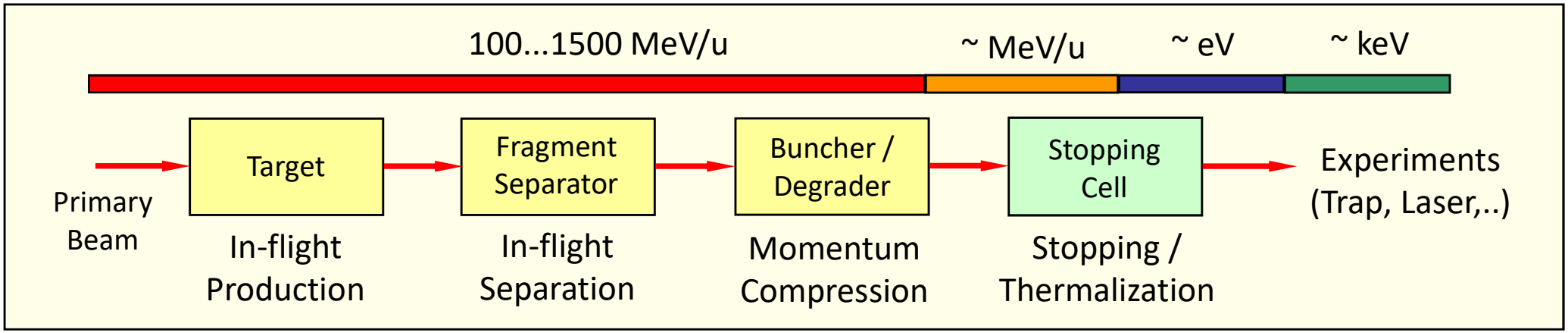
W.R. Plaß et al., NIM B 266 (2008) 4560
W.R. Plaß et al., Int. J. Mass Spectrom. 394 (2013) 134
T. Dickel et al., NIM A 777 (2015) 172
S. Purushothaman et al., IJMS 421 (2017) 245

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
F. Greiner et al., NIMB in press

Low Energy RIB @ Super-FRS/FRS

High-precision experiments with in-flight separated exotic nuclei almost at rest

- universal and fast production
- high selectivity
- cooled exotic nuclei



@FRS & LEB:

Super-FRS Experiment Collaboration

(Mass Tagging for PID, New Isotope search, Reaction Studies,…)

J. Äystö et al., NIMB **376** (2016) 111

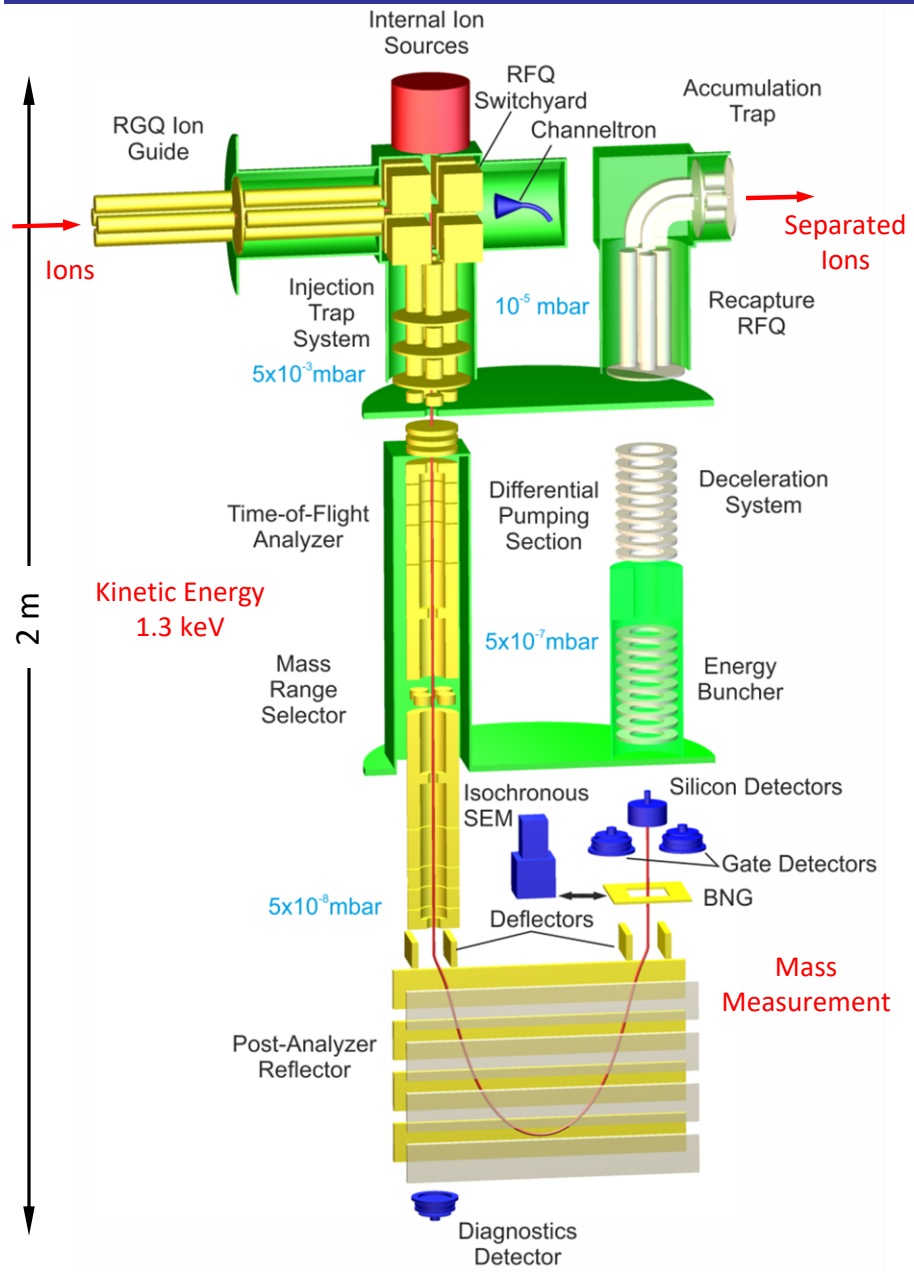
@LEB:

MATS (Precision Measurements of very short-lived nuclei using an Advanced Trapping System for highly charged ions)

LaSpec (Laser Spectroscopy)

D. Rodriguez, et a., EPJ 183 (2010) 1

MR-TOF-MS for the FRS-IC and MATS



Mass Measurement Accuracy

~10^{-7}

Isobar separator with high ion capacity

>10^6 ions/s

Transmission efficiency

up to 70%

Sensitivity

~10 ions

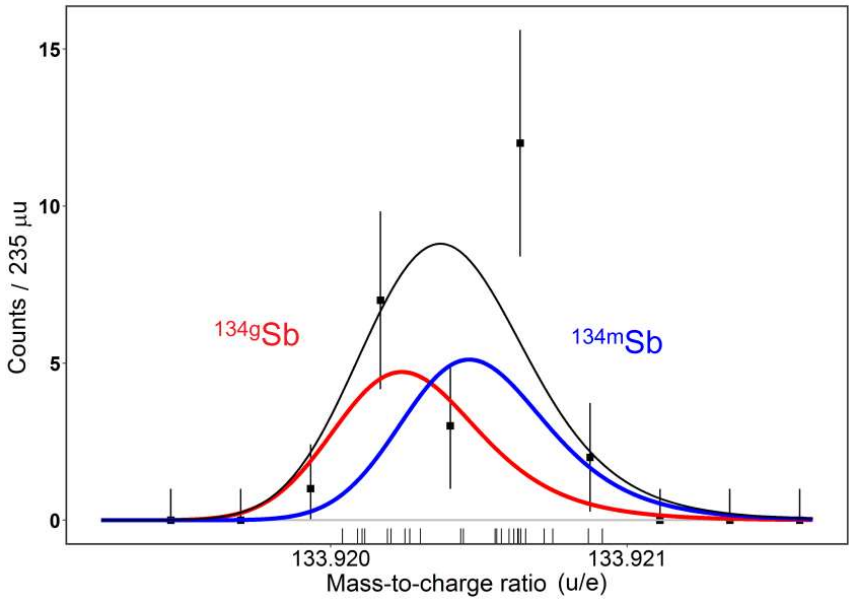
World-wide unique combination of performance characteristics!

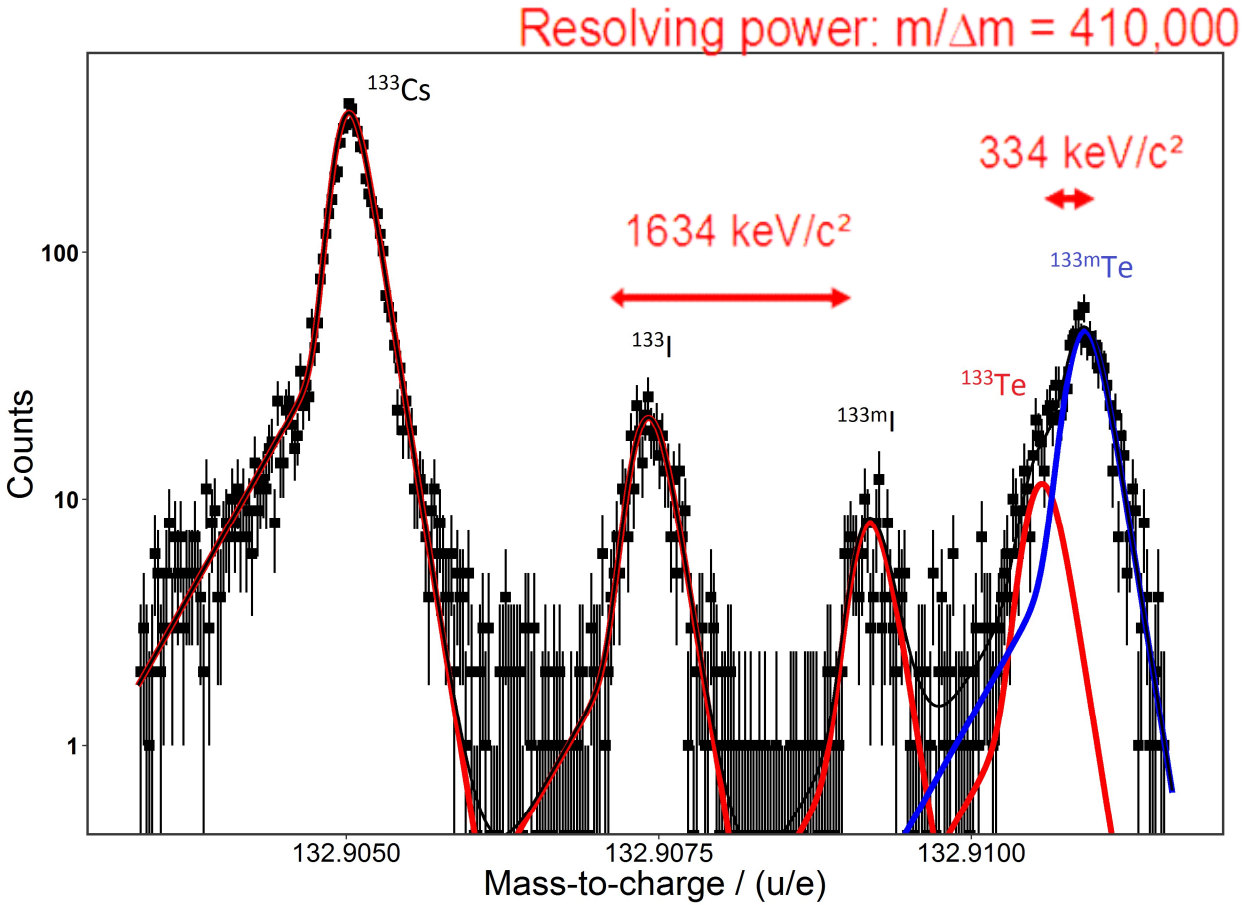
W.R. Plaß et al., NIM B 266 (2008) 4560
W.R. Plaß et al., Int. J. Mass Spectrom. 394 (2013) 134
T. Dickel et al., NIM A 777 (2015) 172
T. Dickel et al., Phys. Lett. B 744 (2015) 137

Data-Analysis Procedure

Data-analysis procedure optimzed for sensitivity and accuracy:

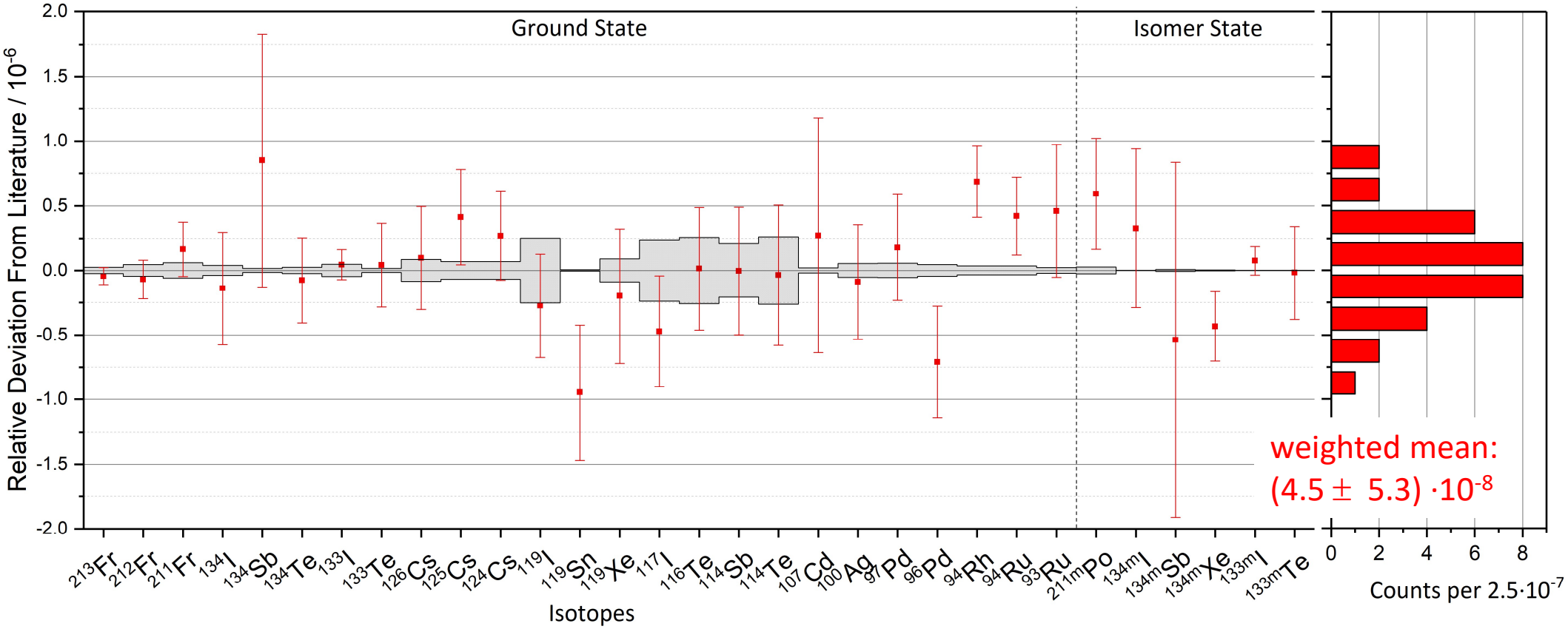
- dedicated fit function S. Purushothaman et al, IJMS, 421, 245 (2017)
- weighted MLE fitting
- quantification of more than 10 error contributions





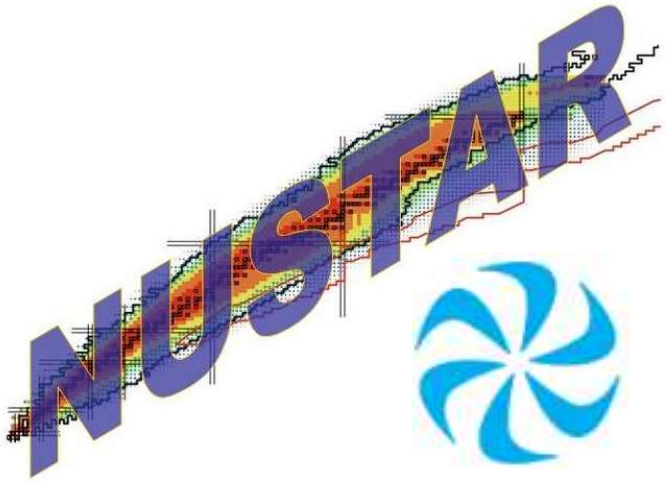
S. Ayet et al PRC 99, 064313 (*2019*)

Mass Accuracy Study



- 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 PRC 99, 064313 (*2019*)



TITAN MR-TOF-MS, THE NUSTAR-TRIUMF SINERGY

TITAN at TRIUMF

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MR-TOF-MS:

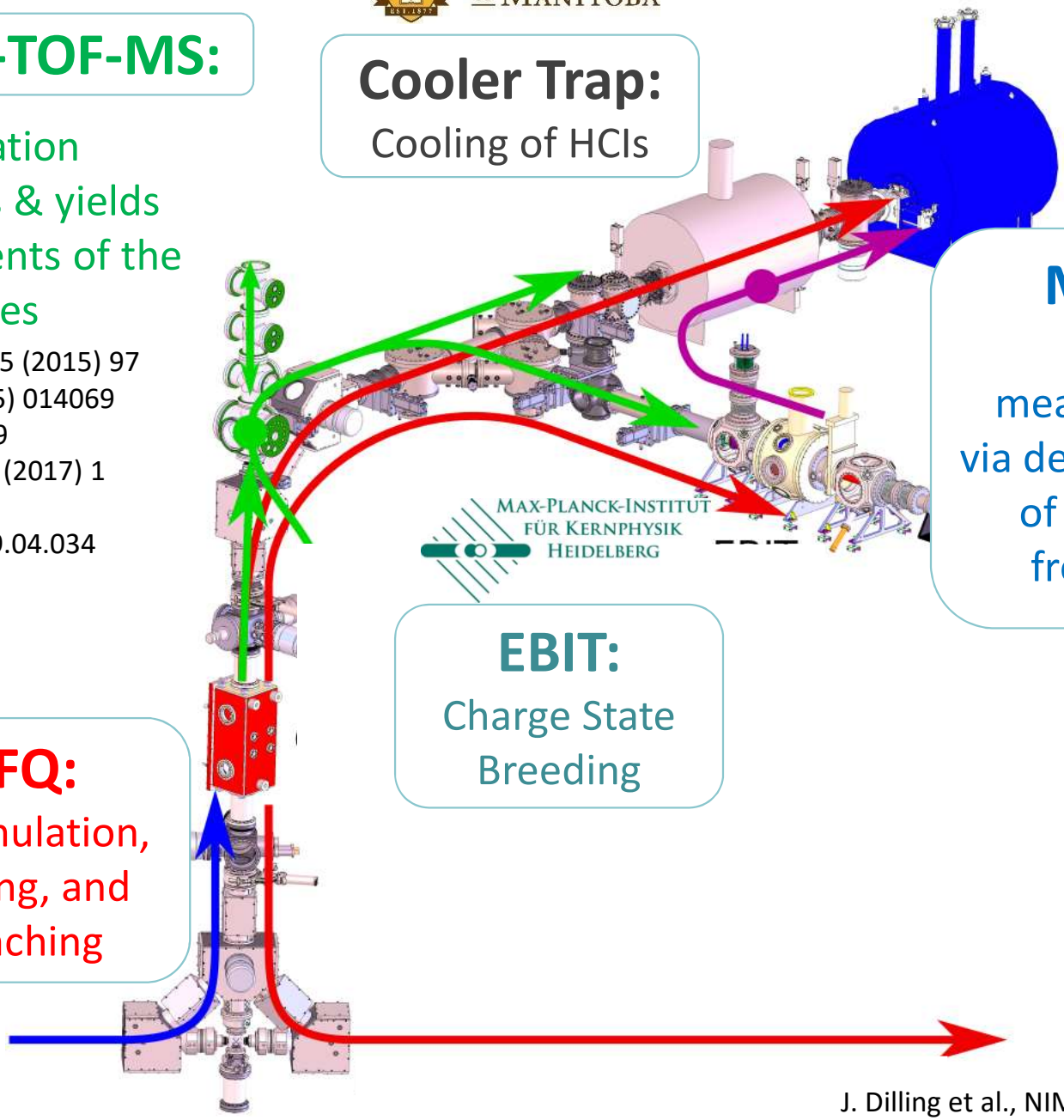
- RIB beam purification
- beam diagnostics & yields
- mass measurements of the most exotic species

C. Jesch et al., Hyperfine Interact. 235 (2015) 97
W. Plass et al., Phys. Scr. T 166 (2015) 014069
T. Dickel et al., JASMS 28 (2017) 1079
T. Dickel et al., Int. J. Mass Spec. 412 (2017) 1
M. P. Reiter et al., NIMB In Press
https://doi.org/10.1016/j.nimb.2019.04.034

UNIVERSITY OF MANITOBA

Cooler Trap:

Cooling of HCIs



MPET:

mass measurement via determination of cyclotron frequency

EBIT:

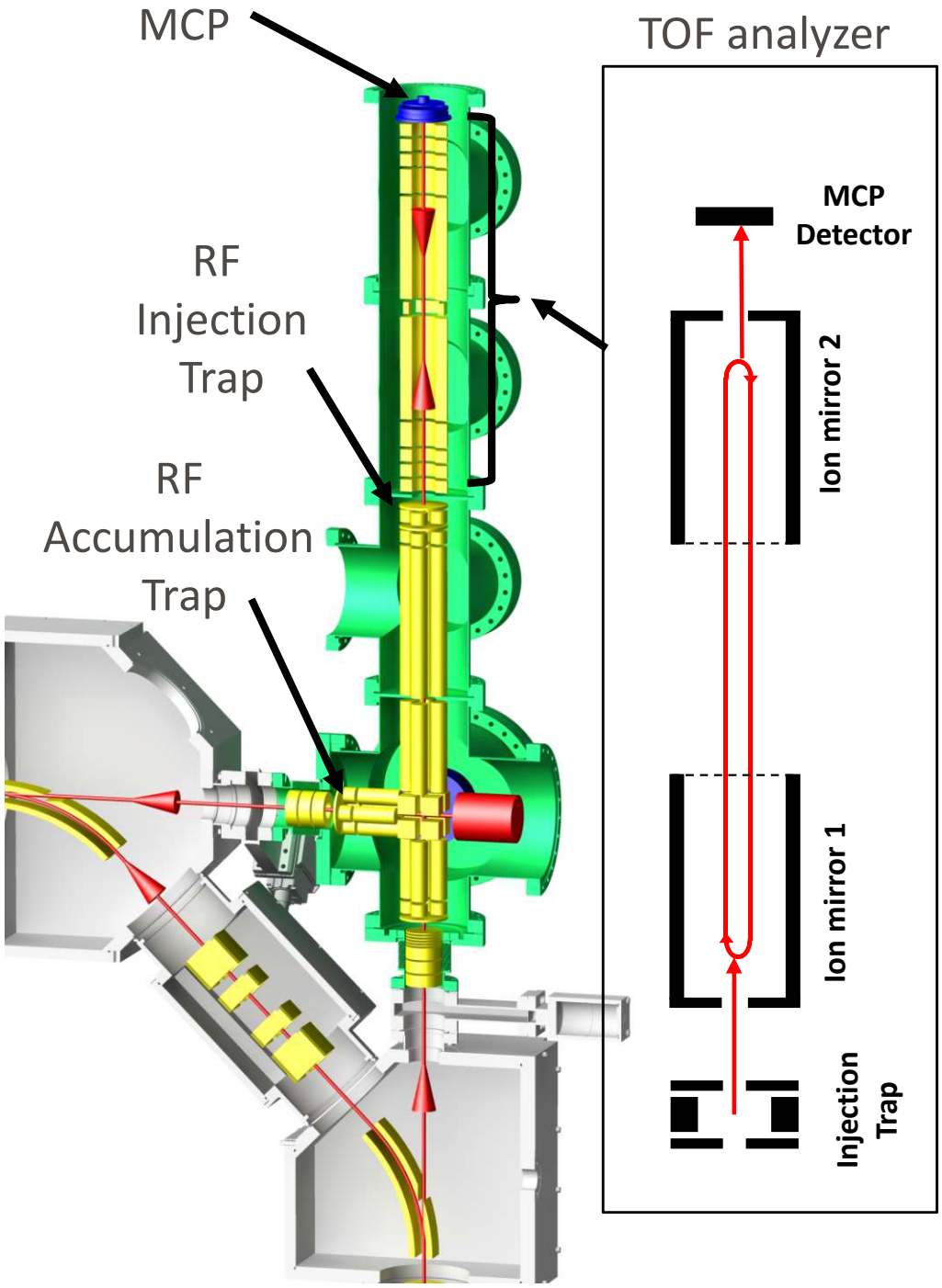
Charge State Breeding

RFQ:

Accumulation, cooling, and bunching

J. Dilling et al., NIMB 204 (2003) 492

MR-TOF-MS



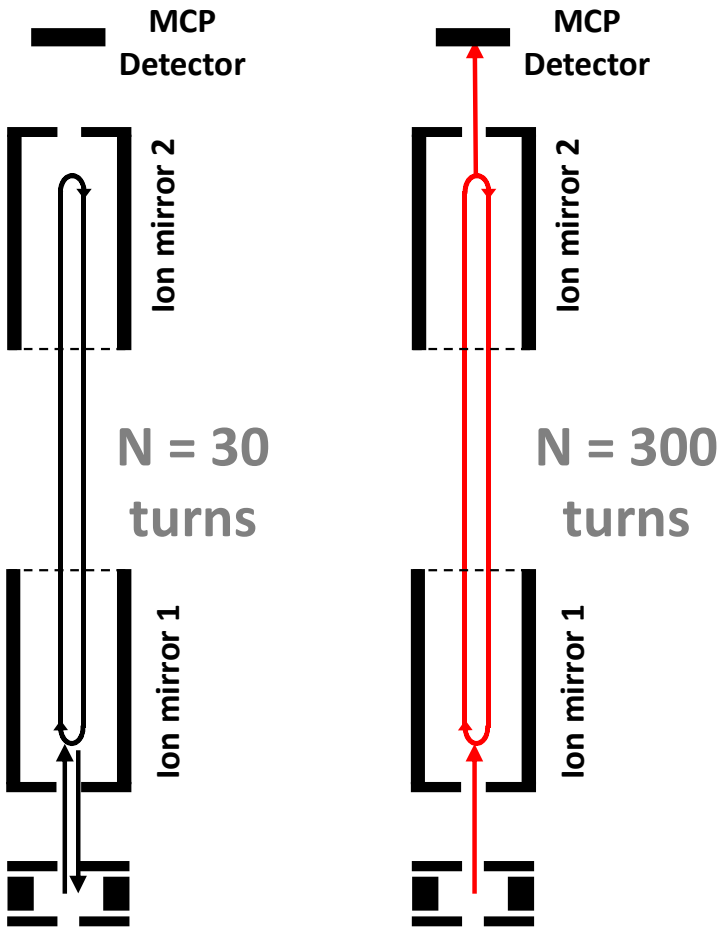
Characteristics

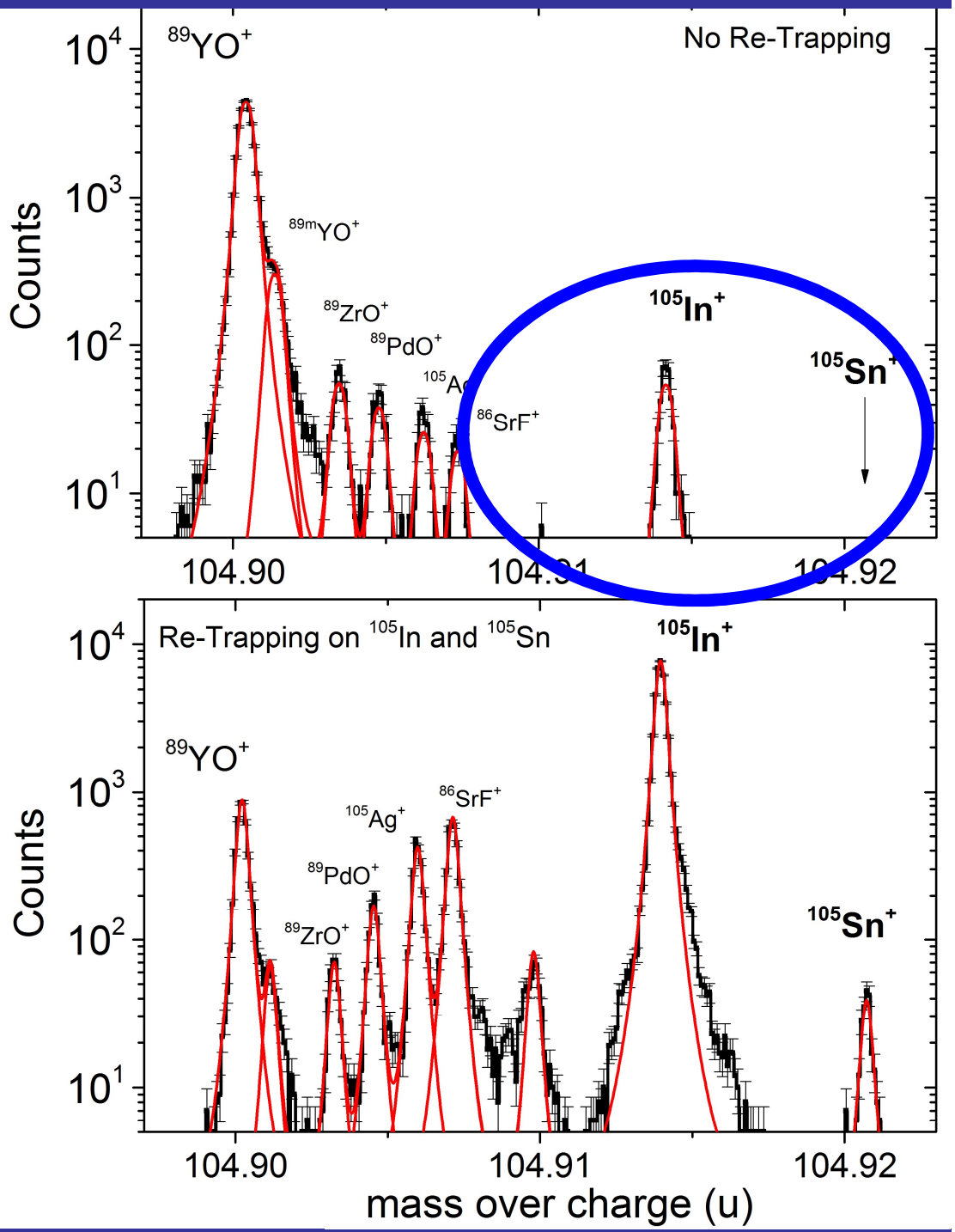
- Resolving power up to 200k
  - Good for highly contaminated beams
- Precision ~ $3 \cdot 10^{-7}$
  - Good for nuclear astrophysics
- High sensitivity (low rates)
- High background capabilities

T. Dickel et al., J. ASMS 28 (2017) 1079
T. Dickel et al., Int. J. Mass Spec. 412 (2017) 1-7
C. Jesch et al., Hyperfine Interact. 235 (2015) 97
M. Yavor et al., Int. J. Mass Spec. 381 (2015) 1-9

Mass-Selective Re-Trapping

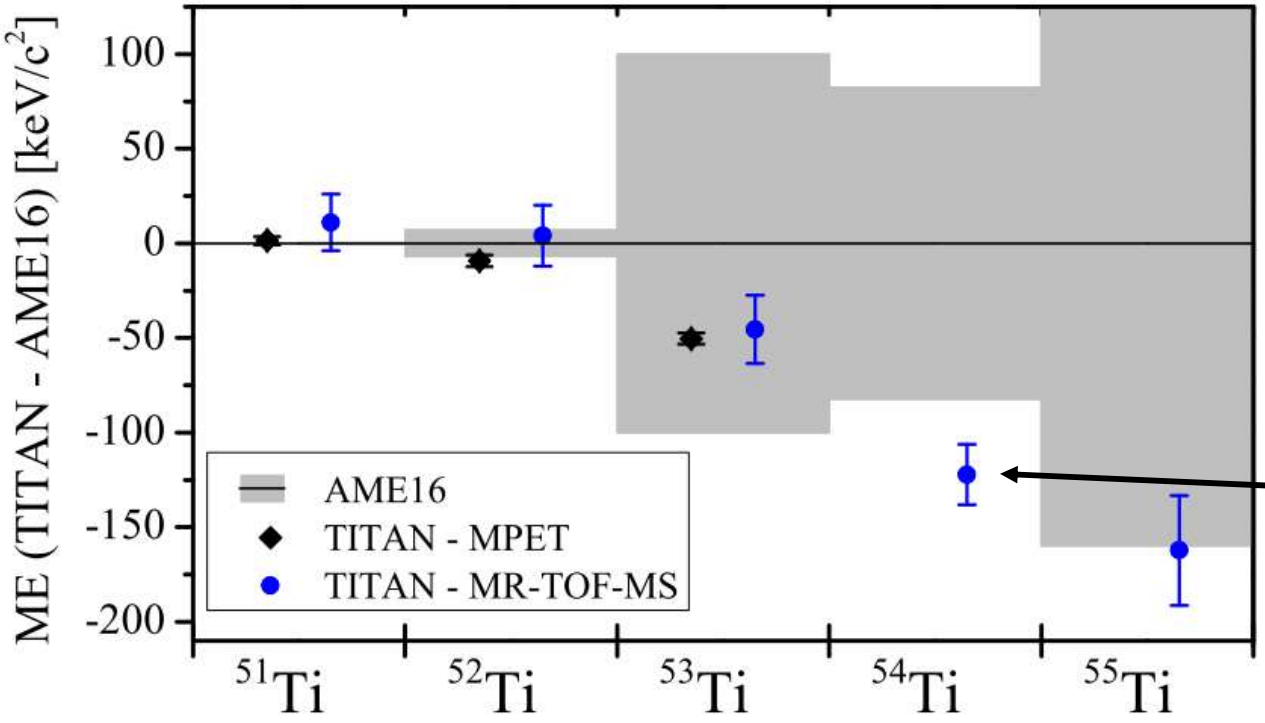
- Online Isobar separation
  - e.g. ^{105}Sn
    (Yield ~ 1pps,
    background ~ 10^6pps)



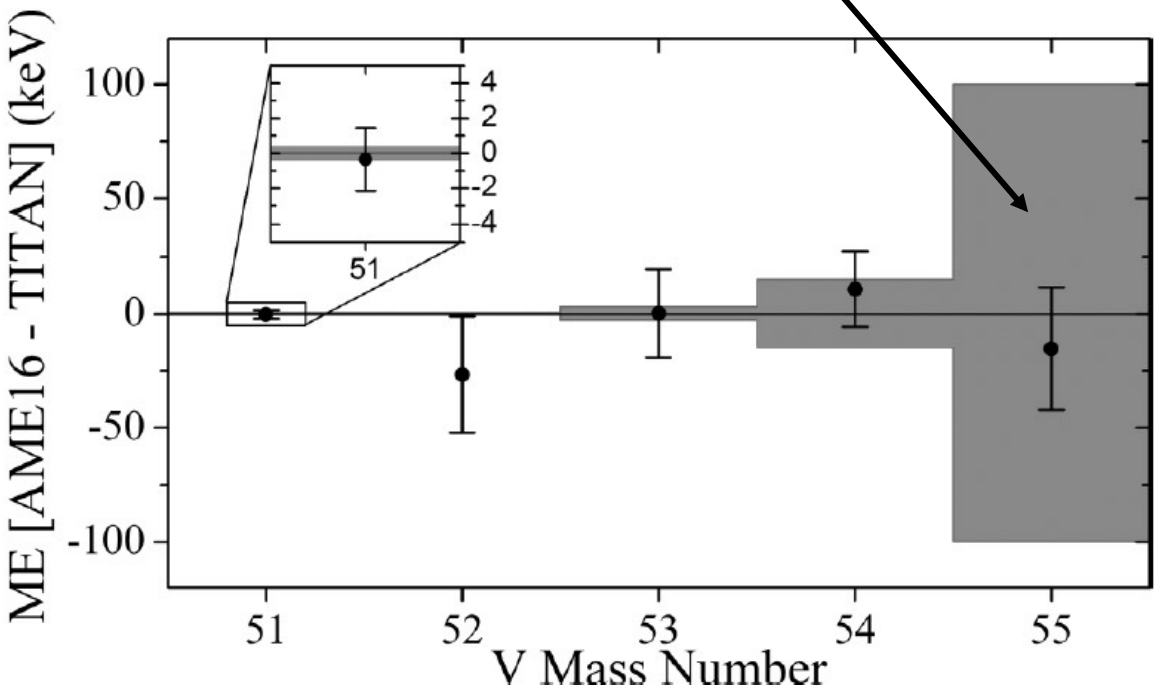


Mass Measurements neutron-rich Ti an V

E. Leistenschneider et al., PRL 120 (2018) 062503



N = 32



Mass accuracy: $3 \cdot 10^{-7}$

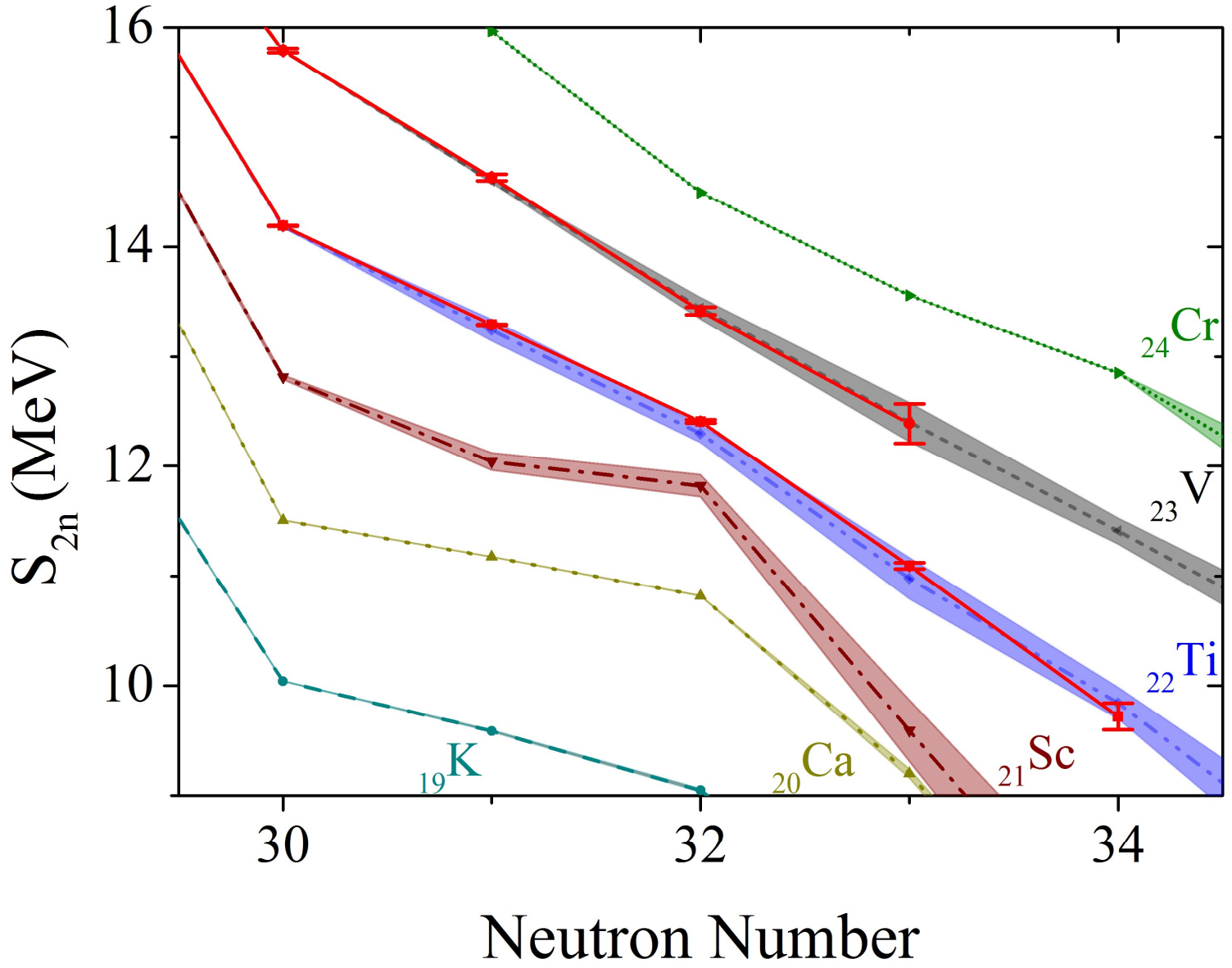
M.P. Reiter et al., PRC 98 (2018) 024310

S_{2n} at the N = 32 shell closure

E. Leistenschneider et al., PRL 120 (2018) 062503

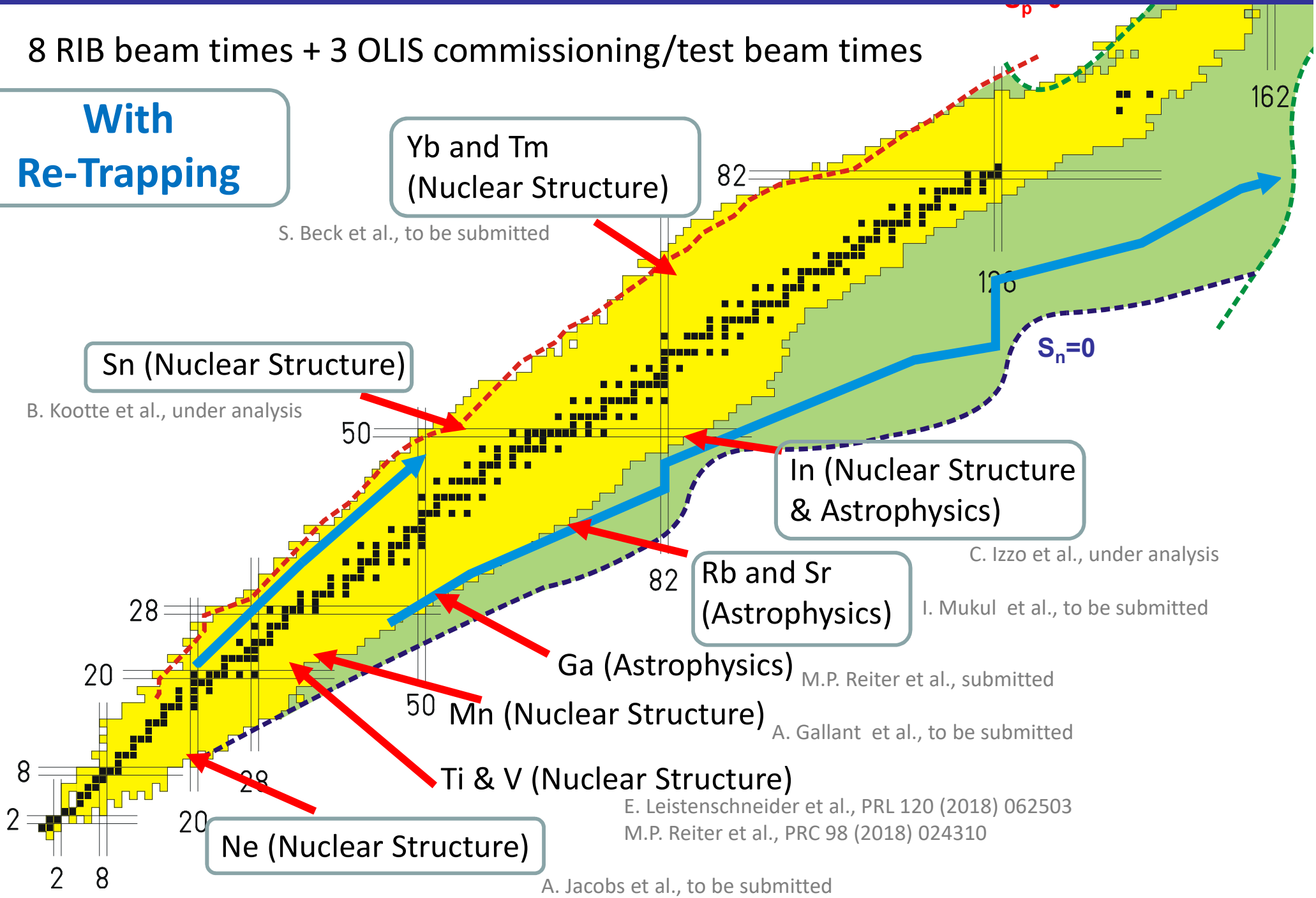
Shell Signature for N = 32

– Resolved with new high precision measurements



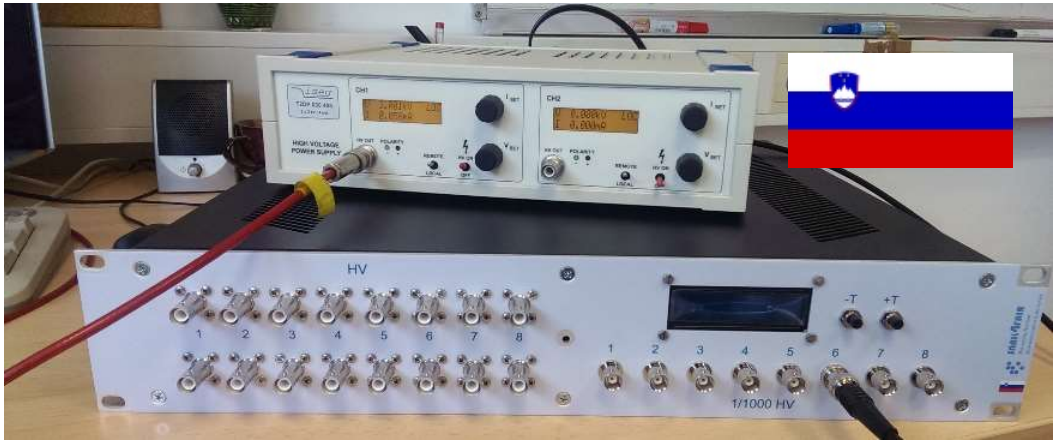
Mass Measurements TITAN's MR-TOF-MS

- 8 RIB beam times + 3 OLIS commissioning/test beam times



Future Plans: Technical Improvements

- Hardware upgrades:
  - temperature stabilized Power supplies.
  - temperature stabilized voltage divider for analyzer voltages.
- Software upgrades:
  - Automated Tuning



- Deliver isobaric clean beams to EBIT and MPET

- Keep Synergy:

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TRIUMF

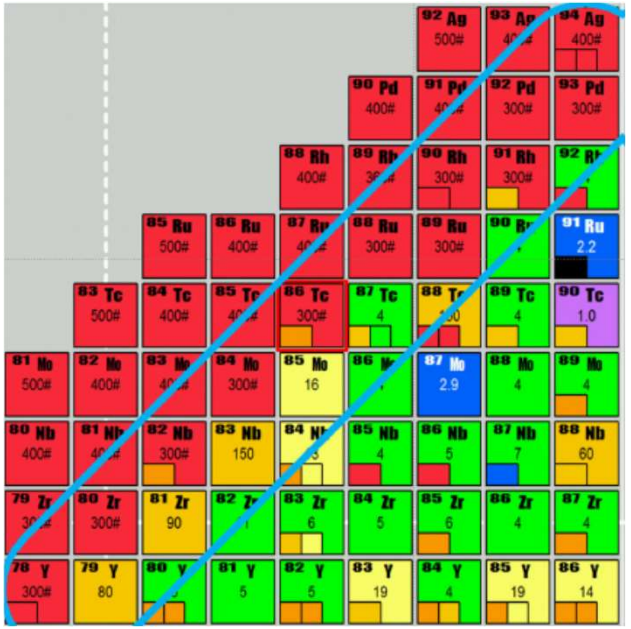
Open Position
PhD/PostDoc @ TRIUMF

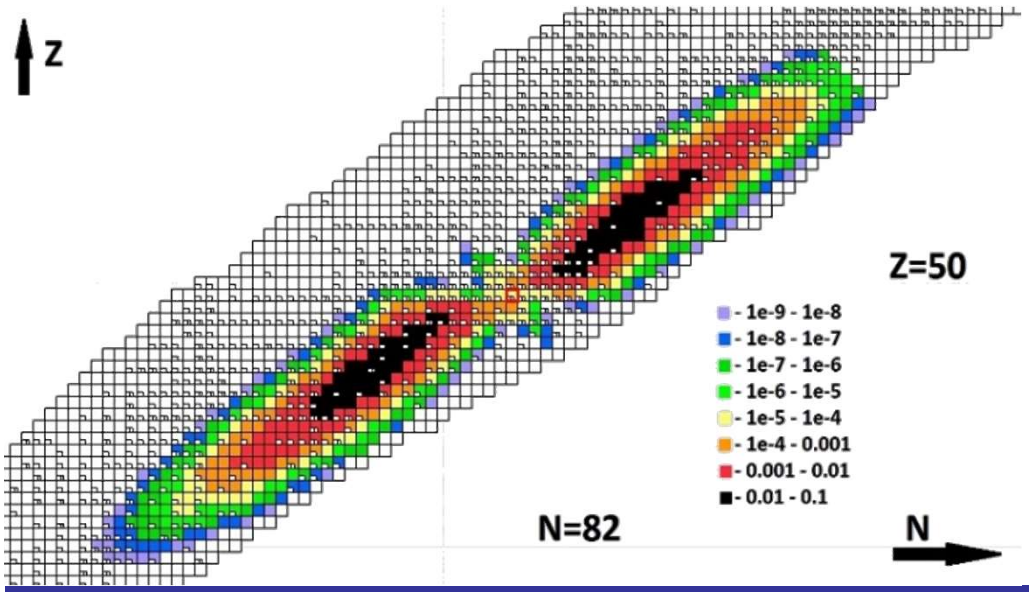
The **research group of Prof. Scheidenberger, II. Institute of Physics, Faculty of Mathematics and Informatics, Physics, Geography** at the **Justus-Liebig-University Gießen** offers within the project "*Mass measurements of exotic nuclei with TITAN at TRIUMF (Vancouver, Canada)*" a part-time position (66%) for a

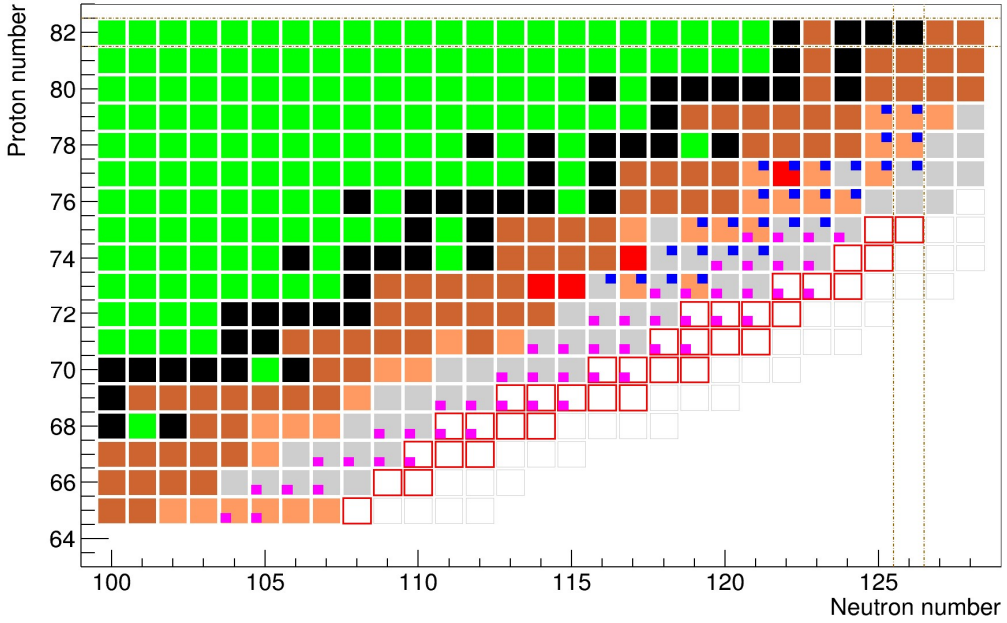
http://www.inst.uni-giessen.de/stellenmarkt/pdf/stelle0012249.pdf

Future Plans: FAIR phase-0 and SFS

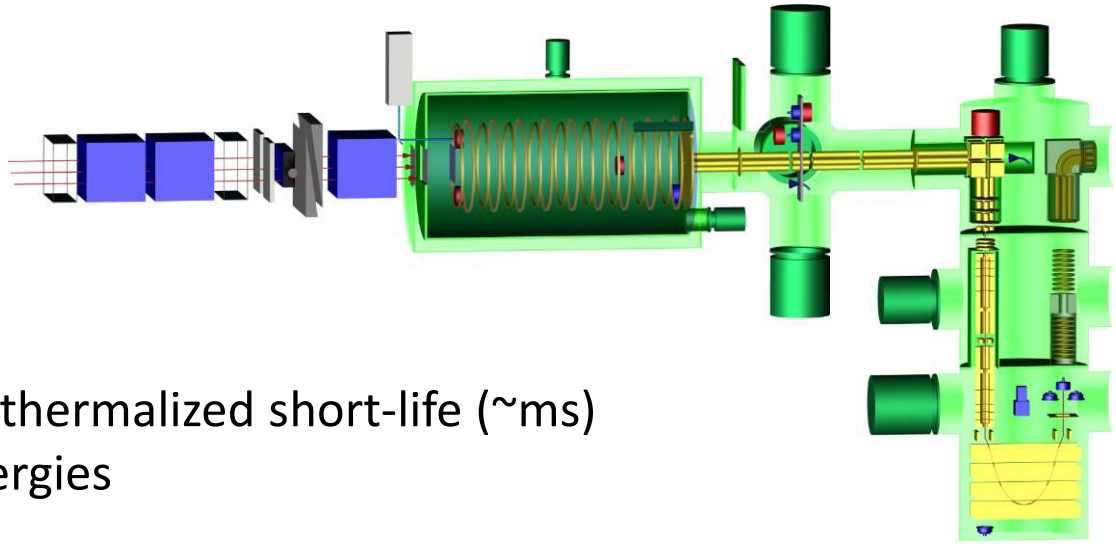
- FAIR phase-0: W.R. Plaß et al. Hyperfine Interact (2019) 240: 73
  - N=Z
  - New Isotope Search
  - MNT
  - pxn I. Miskun et al. Eur. Phys. J. A (2019) 55: 148
- Spontaneous Fission Source: I. Mardor et al. ND2019 Proceedings
  - systematics of spontaneous fission
  - independent fission yields
  - isomer-to-ground ratios (Uppsalla University)







Summary

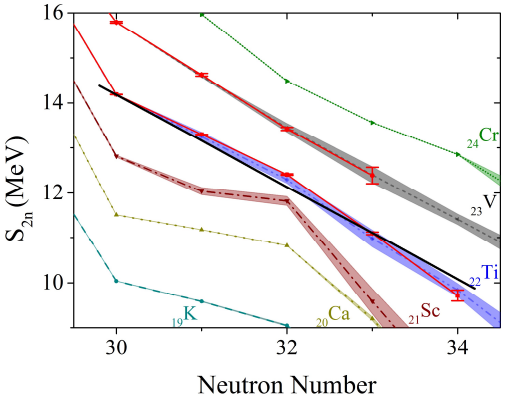


The FRS Ion Catcher

- Unprecedented efficiencies for thermalized short-life (~ms) ions produced at relativistic energies
- MRP > 10^6
- High-accuracy mass measurements: $6 \cdot 10^{-8}$
- Powerful tool for the measurement of isomers: Identification, separation, excitation energies, isomeric ratios

TITAN MR-TOF-MS

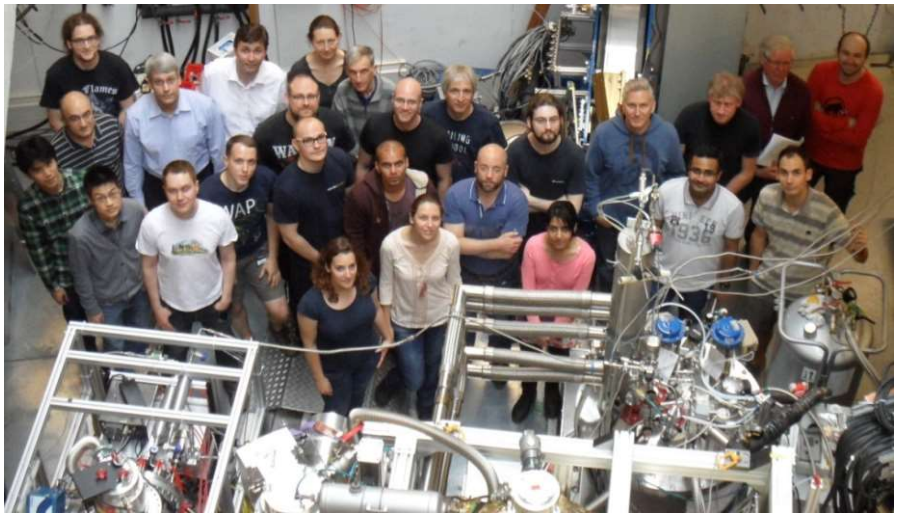
- Mass Selective Retrapping for isobar cleaning
- Neutron shell @ N=32
- Other interesting mass landscape visited by the MR-TOF-MS:
  - Nuclear Structure
  - Astrophysics



Acknowledgements

IONAS Group at JLU Gießen

FRS Ion Catcher Collaboration



TITAN Collaboration

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

Federal Ministry of Education and Research

HESSEN Hessisches Ministerium für Wissenschaft und Kunst

LOEWE – Landes-Offensive zur Entwicklung Wissenschaftlich-ökonomischer Exzellenz

HELMHOLTZ GEMEINSCHAFT

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research