Recent Developments and Measurements with the FRS Ion Catcher

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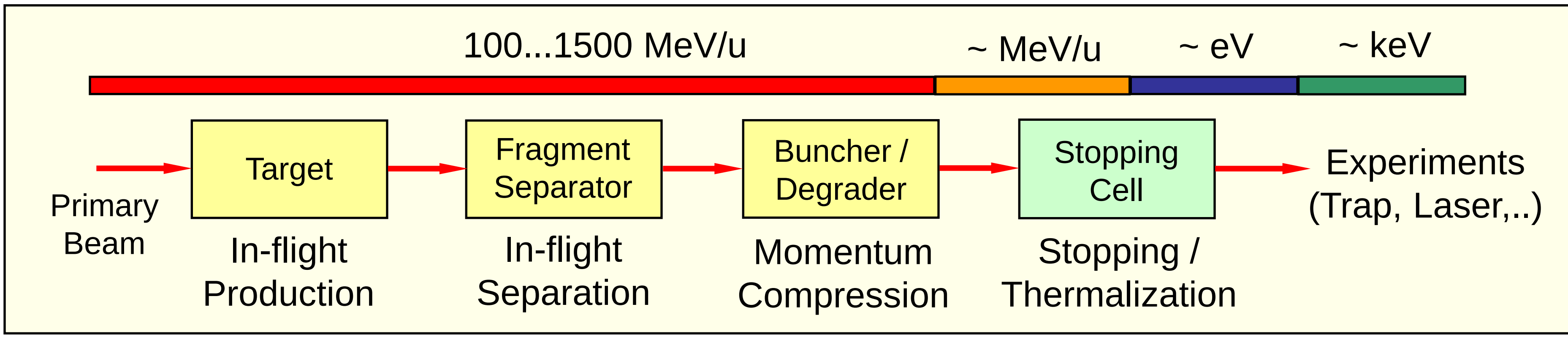
Overview

- The FRS Ion Catcher a test facility for the LEB
- Challenges and Novel Concepts
- Measurements and Results:
    - The FRS Ion Catcher as a auxiliary detection system for the FRS
    - Mass Measurements and Isomers
- The CSC for the LEB
- S4 and FRS Ion Catcher in Phase 0

Low Energy Branch of the Super-FRS at FAIR

LEB: High-precision experiments with in-flight separated exotic nuclei almost at rest, (production by projectile fragmentation / fission)

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



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

- High accuracy mass measurements
- In-trap conversion electron and alpha spectroscopy
- Trap assisted decay spectroscopy

→ Masses, Decay properties

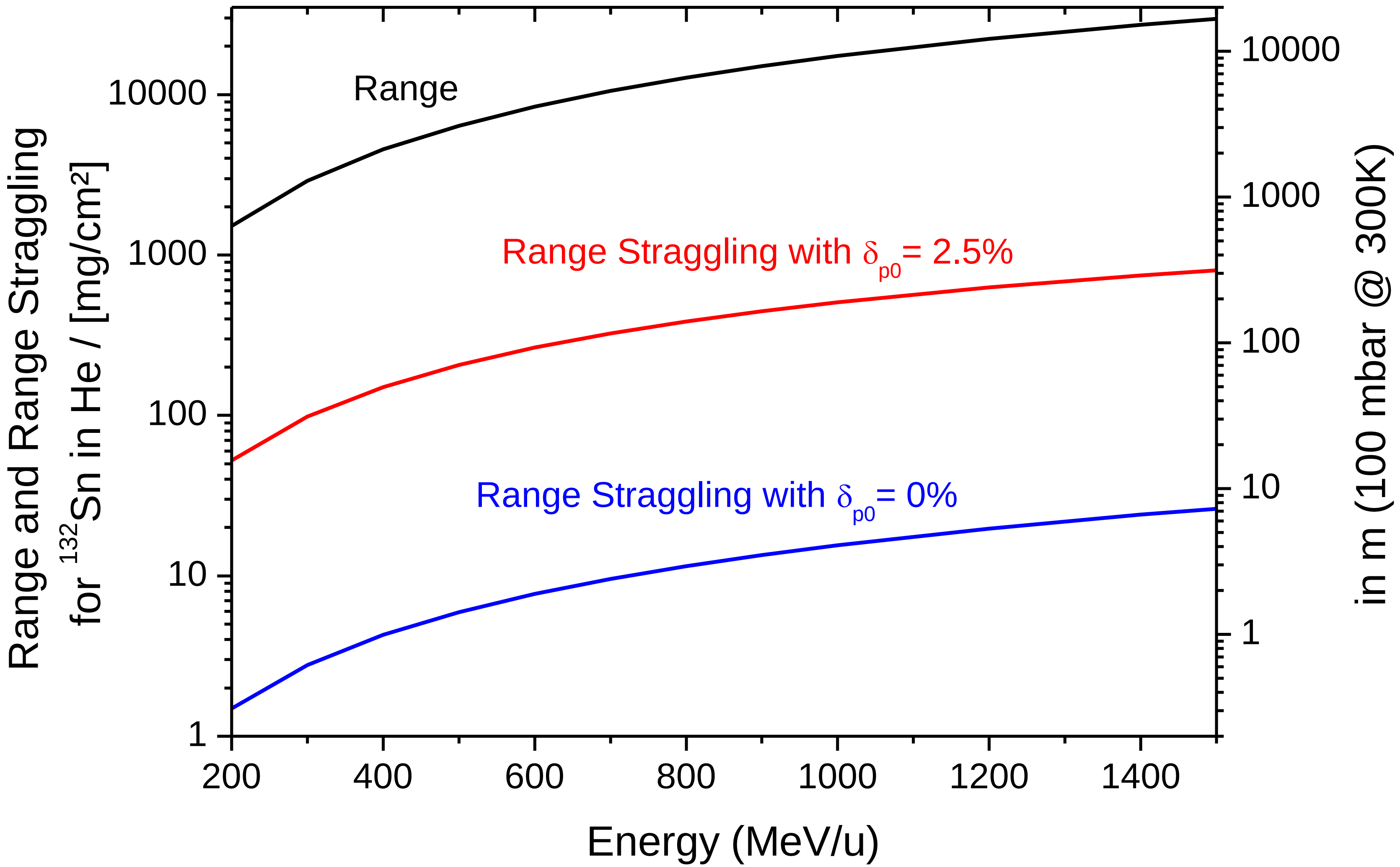
LaSpec (Laser Spectroscopy)

- Collinear laser spectroscopy of ions and atoms
- β-NMR
- Resonance ionization spectroscopy

→ Charge radii, Nuclear moments, Nuclear spin

Challenge of Thermalizing Relativistic Ions

Range straggeling:



Beam size:

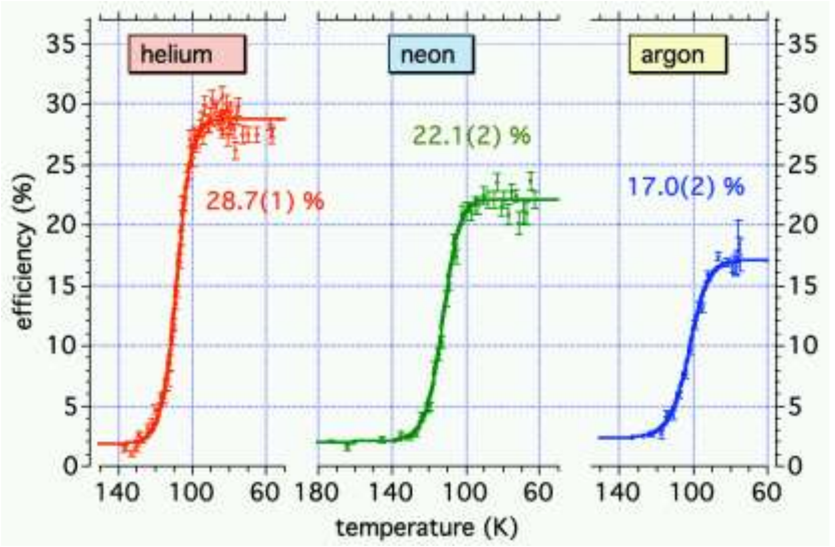
At the LEB of the Super-FRS ~ 200x100mm²

Novel Concepts of the Cryogenic Stopping Cell

Cryogenic temperature

- Gas cell acts as cryogenic pump
- Ultra-pure helium
  (freezing-out of contaminants)
  - Ideal for ion survival
  - No formation of molecules/adducts

P. Dendooven et al., NIM A 558 (2006) 580
S. Purushothaman et al., NIM B 266 (2008) 4488



High stopping gas density and high DC-fileds

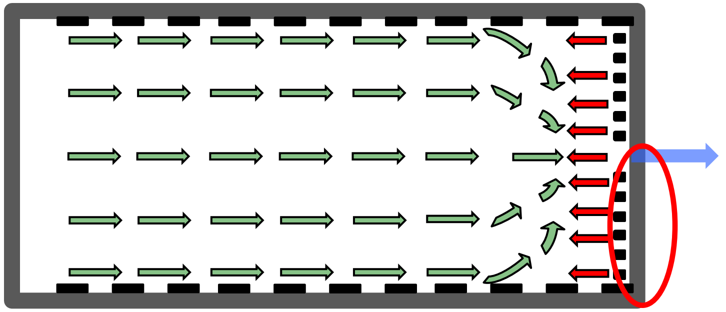
Effective RF field repels ions from electrodes

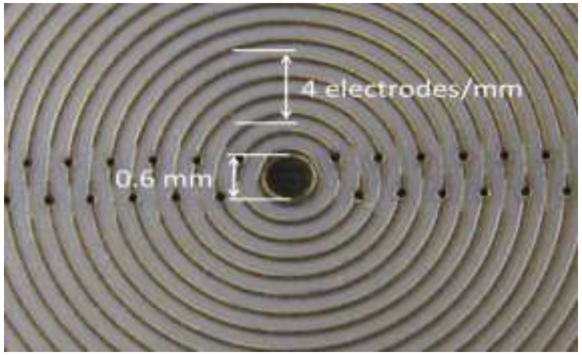
$$E_{eff} \propto K^2 \frac{m}{q} \frac{V_{RF}^2}{r_0^3} \propto \frac{qm}{n^2} \frac{V_{RF}^2}{r_0^3}$$

limited by discharges

reduce structure size!

high gas density → reduction of effctive field





Use RF structure with small spacing (PCB-based RF-carpet) for high RF repelling field

M. Wada et al., NIM B 204 (2003) 570
M. Ranjan et al., Europhys. Lett. 96 (2011) 52001

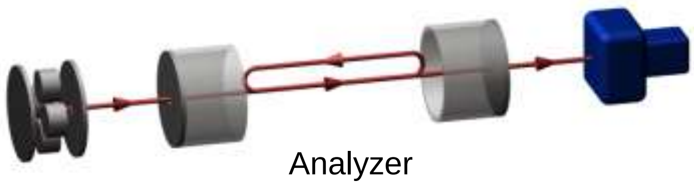
Motivation: TOF Mass Spectrometry in Nuclear Physics

Enables high performance

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

Conventional TOF-MS achieve medium mass resolving power only
→ Solution 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 in nuclear physics

- Direct mass measurements of exotic nuclei

C. Scheidenberger et al., Hyperfine Interact. 132 (2001) 531

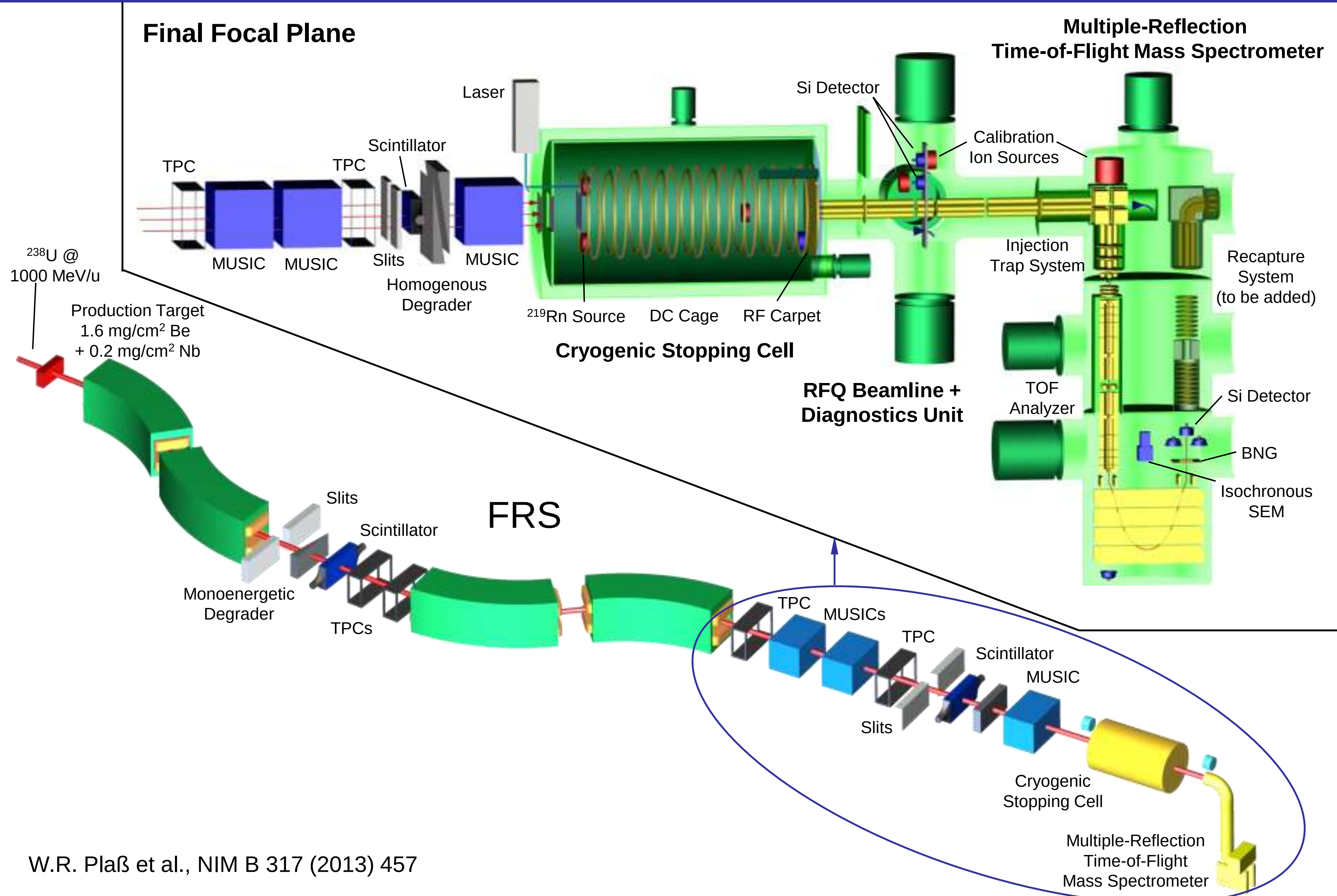
- High-resolution isobar separator

W.R. Plaß et al., NIM B 266 (2008) 4560

- Diagnostics measurements: Monitor production, separation and low-energy beam preparation of exotic nuclei

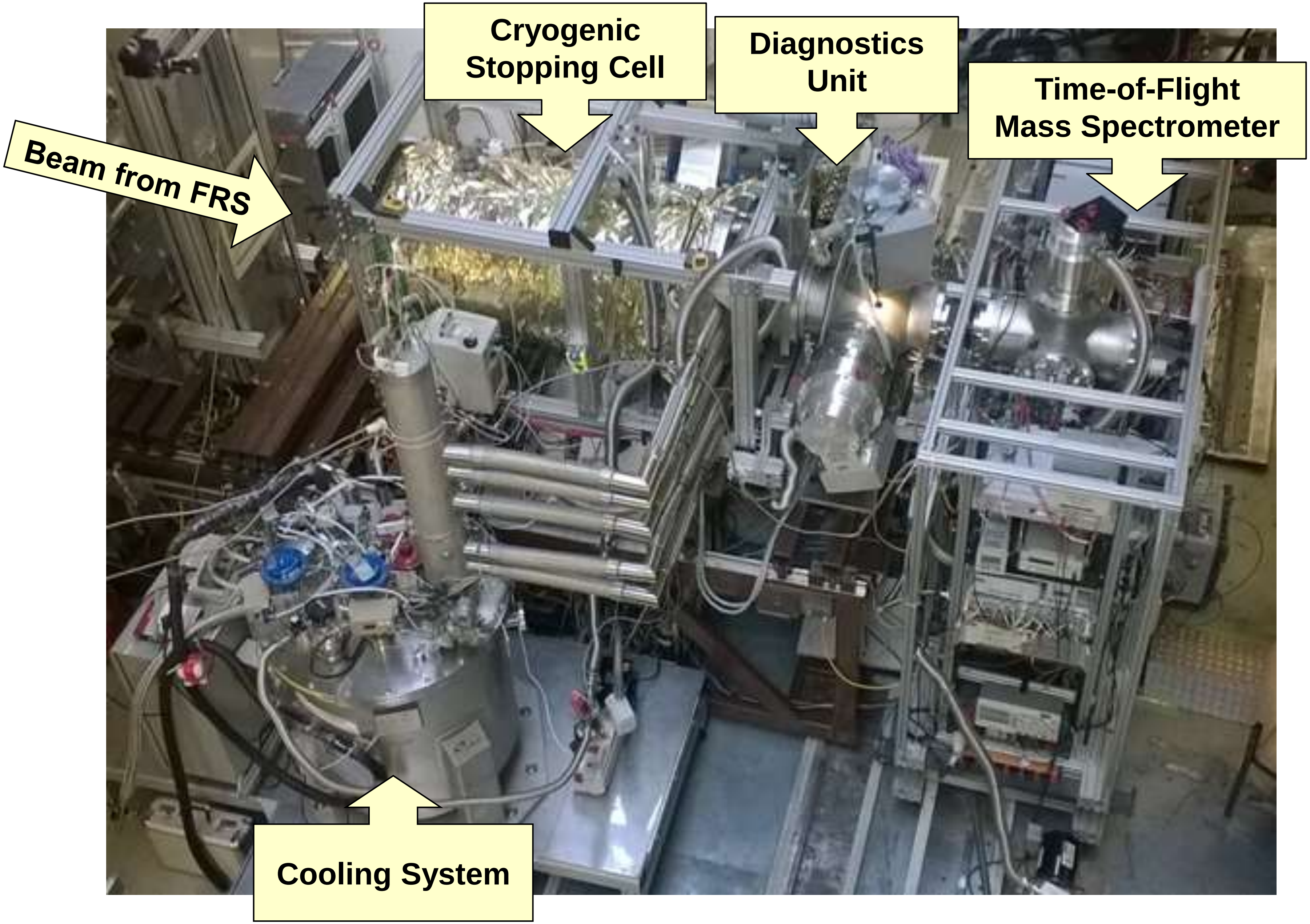
W.R. Plaß et al., NIM B 266 (2008) 4560

FRS Ion Catcher a Test Facility for the LEB



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

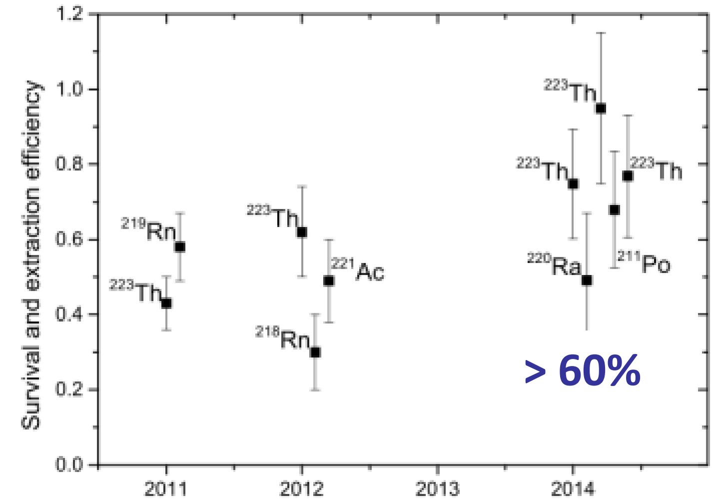
Setup at the FRS Ion Catcher at GSI

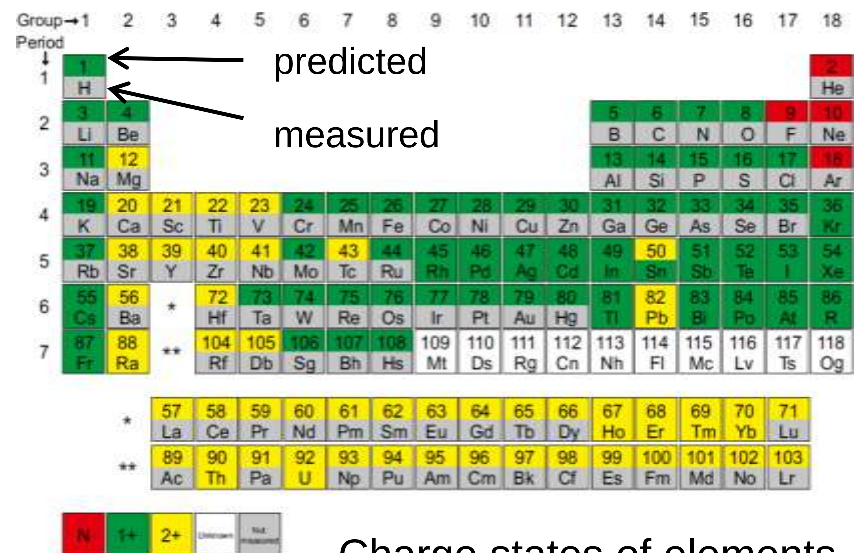


Performance Characteristics: Prototype CSC

For ^{238}U projectile and fission fragments produced at 1000 MeV/u

- Ion survival and extraction efficiencies > 60%
  - Essentially element independent
- Total efficiencies up to ~25 %
  - Unprecedented for relativistic ions
- Extraction times of 25 ms
  - Access to short-lived nuclei
- Charge states defined by ionization potentials of ions and stopping gas





Charge states of elements extracted from the CSC

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

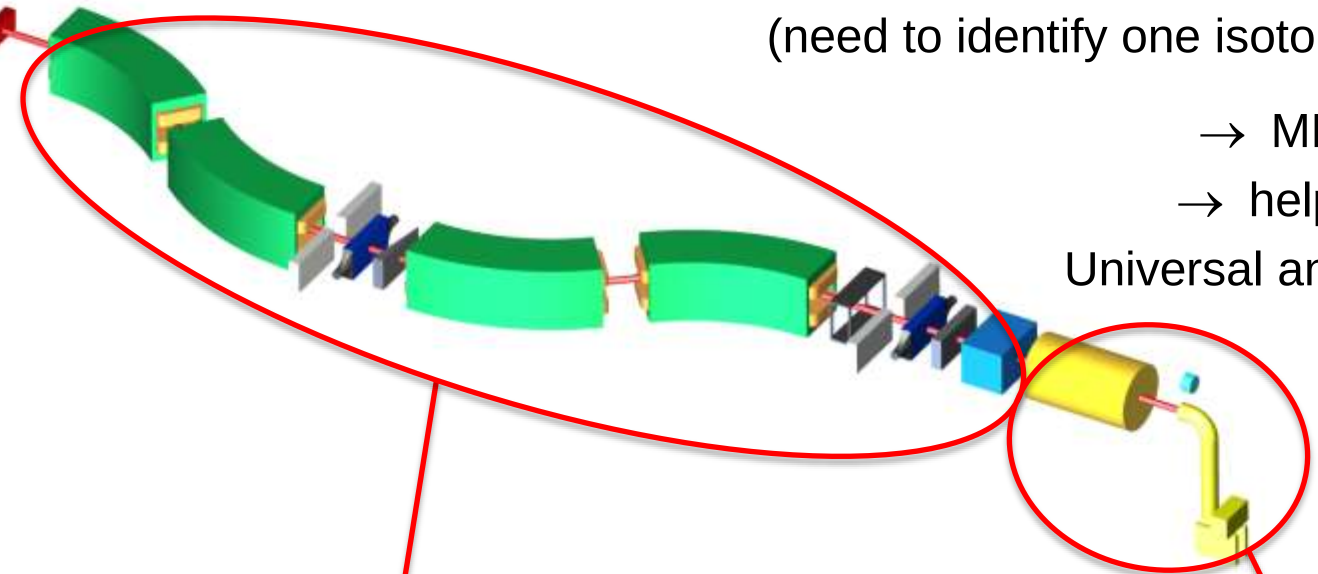
Mass Tagger

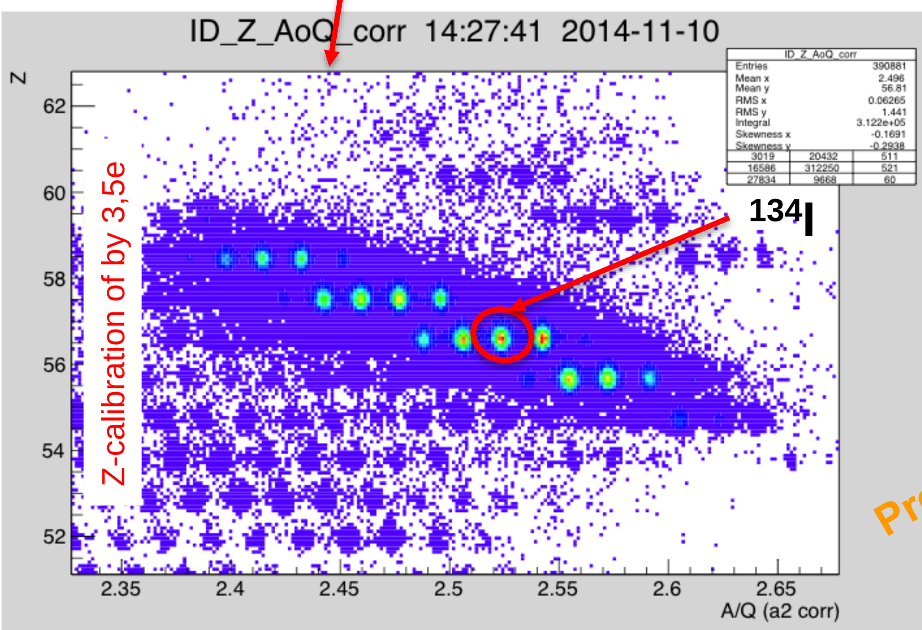
FRS identification may not always be accurate
(need to identify one isotope in the identification plot)

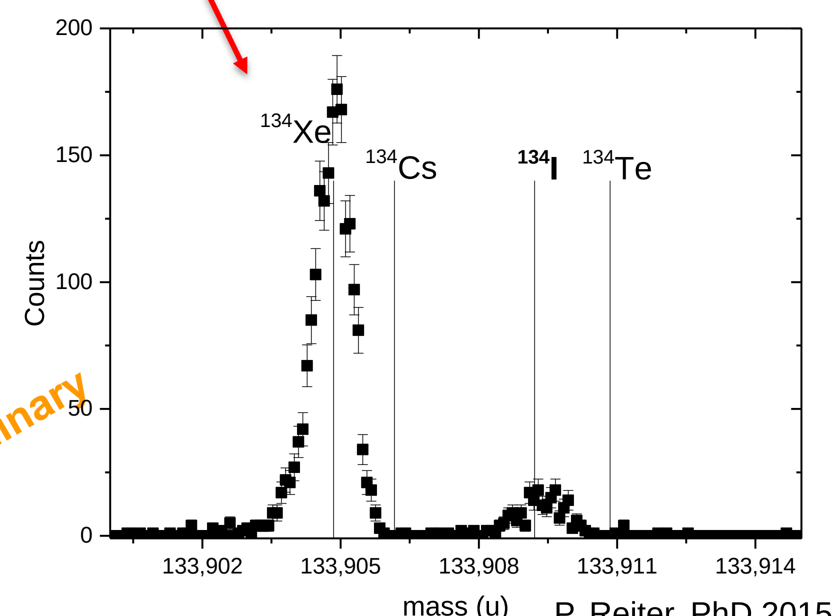
→ MR-TOF-MS as mass tagger

→ helped to correctly identify ^{134}I

Universal and fast technique (~20 min)







P. Reiter, PhD 2015

Particle ID by MS only

Problem:

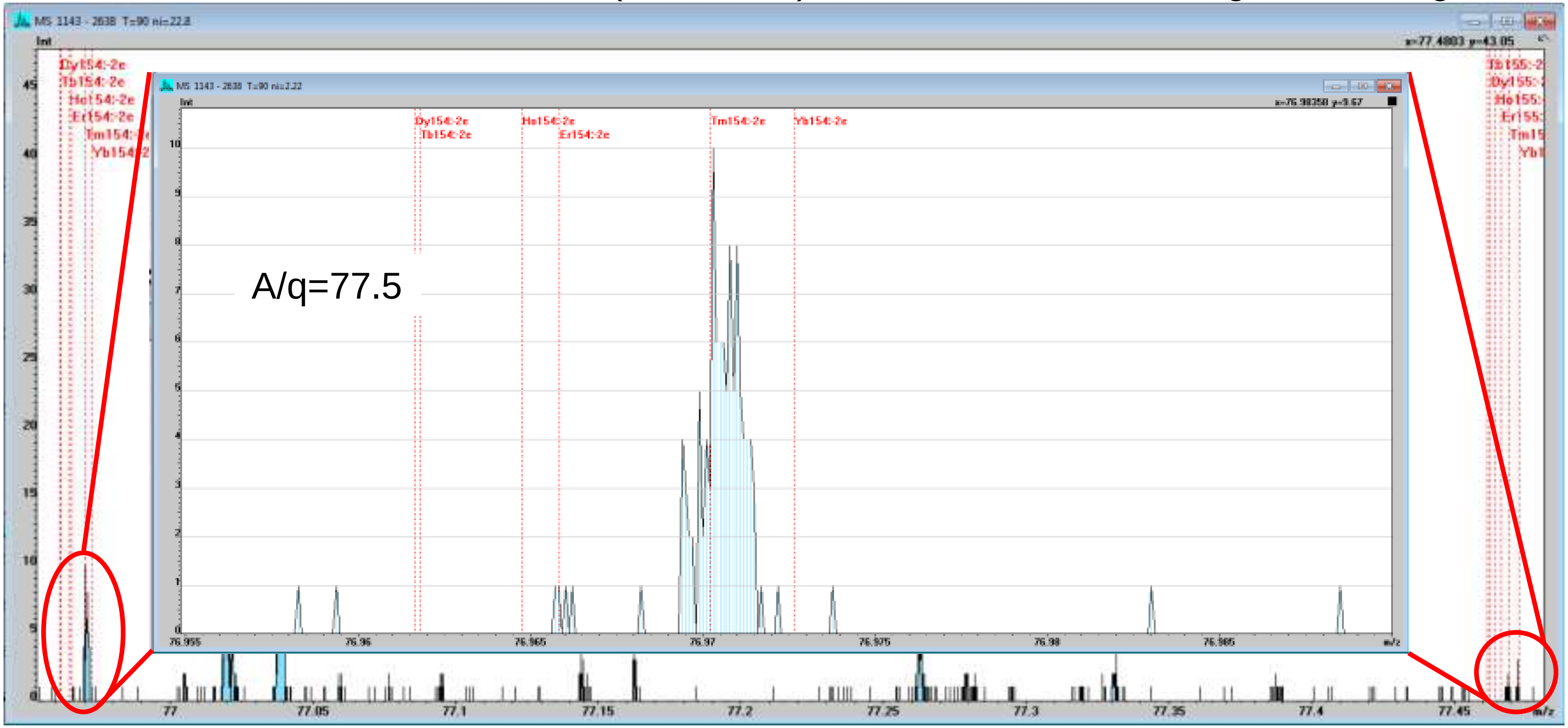
Particle ID at low energies and high Z is challenging

Solution:

ID of thermalized isotopes by broadband and high-resolution MS

→ Fast and universal ID of several isotopes at a time

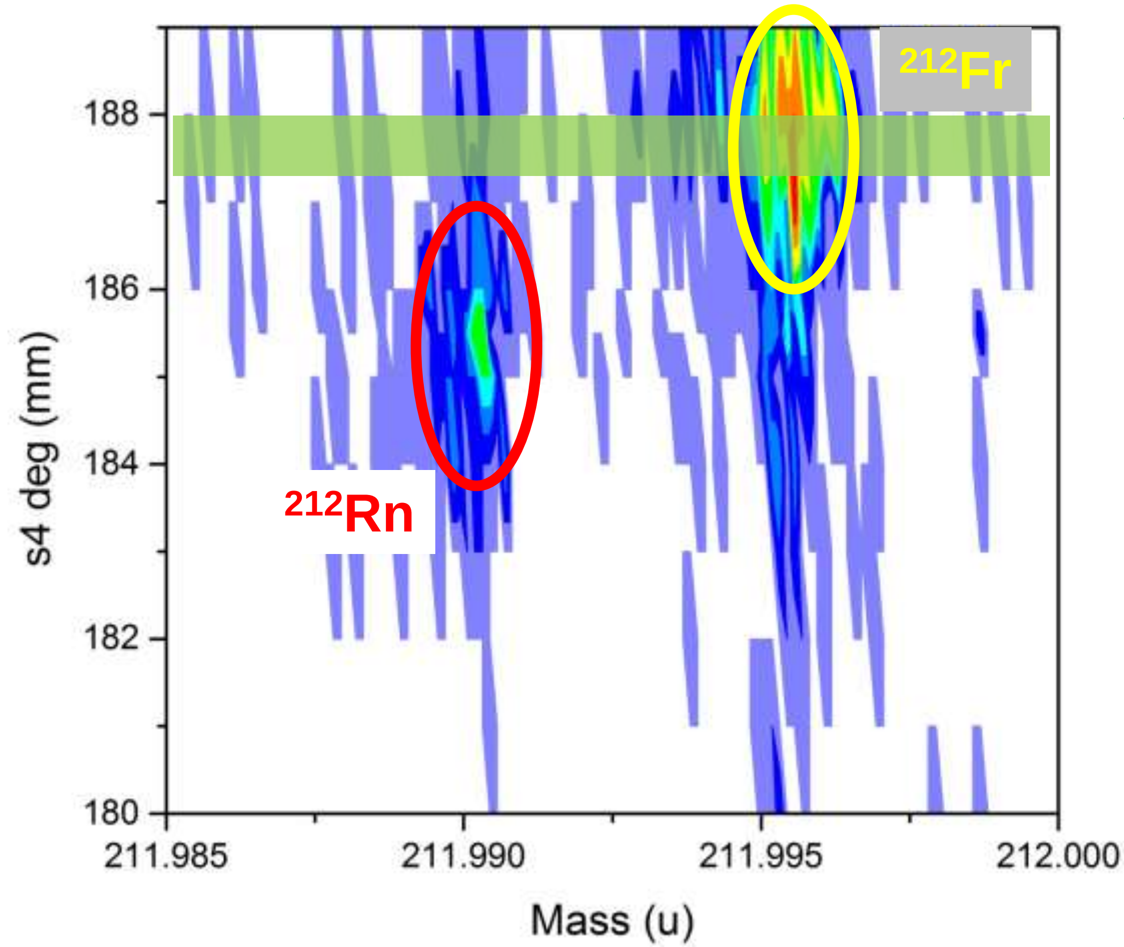
Results from the recent beamtime (June 2016): 300MeV/u ^{238}U on a 0.4g/cm² Be target



C. Hornung et al.

Range Tuning/Range Separation with Stopping Cell

- Range adjustment needs to be done precisely (CSC only ~$5\cdot10^{-4}$ stopping range)
- Can be used as an additional separation step



Areal density CSC

MR-TOF-MS is the ideal/necessary tool to do this

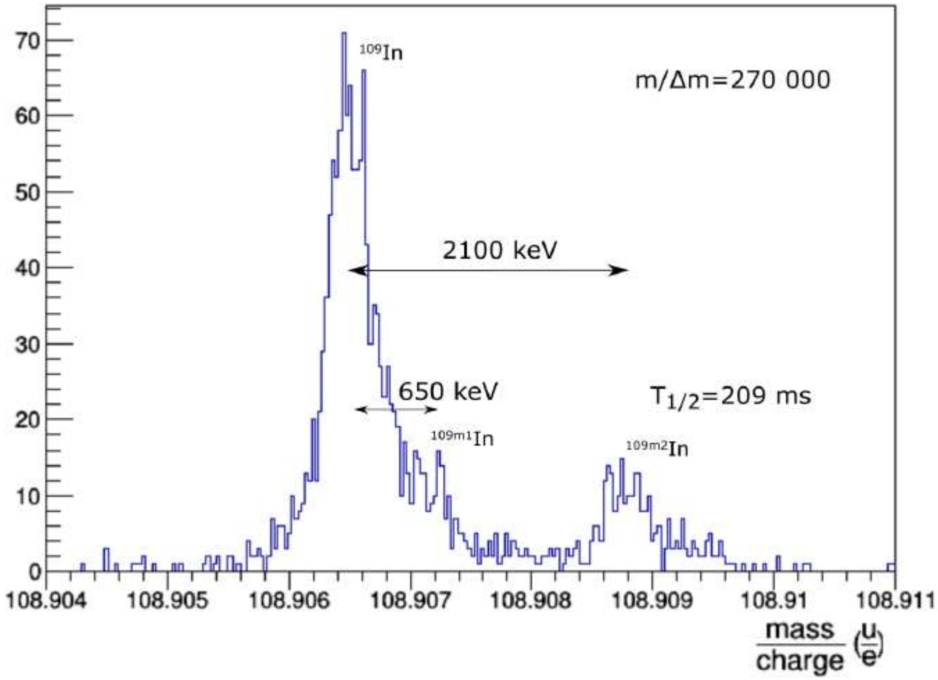
C. Hornung et al.

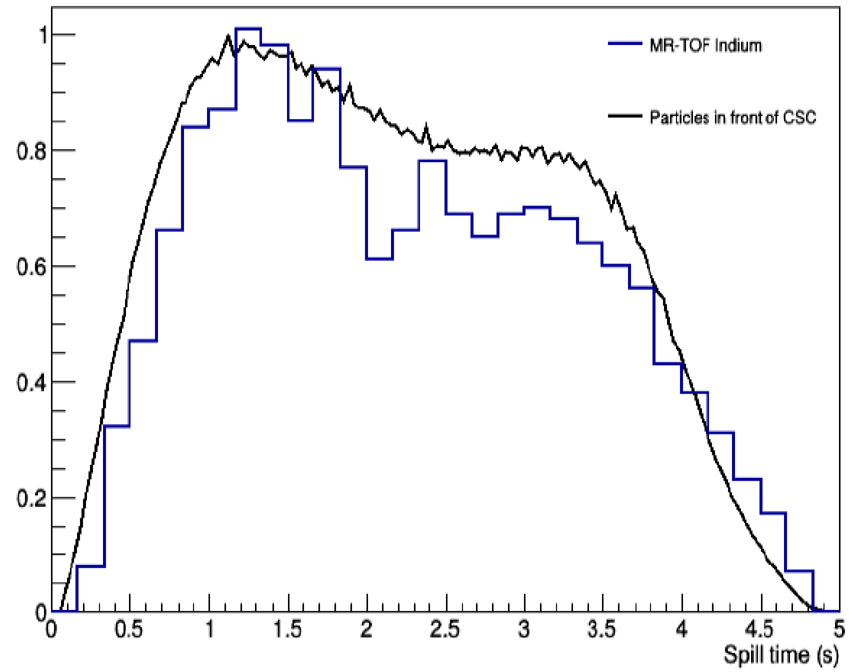
Ion Catcher in the FRS DAQ

Integration of MR-TOF-MS in FRS data acquisition

- ID of long lived isomers
- Measure spill structure and extraction time
- Future:
  - Event-by-event correlation for moderate rates
  - Faster experiment setup ("automated" degrader scan)

Example from beam time 2016: ^{109}In



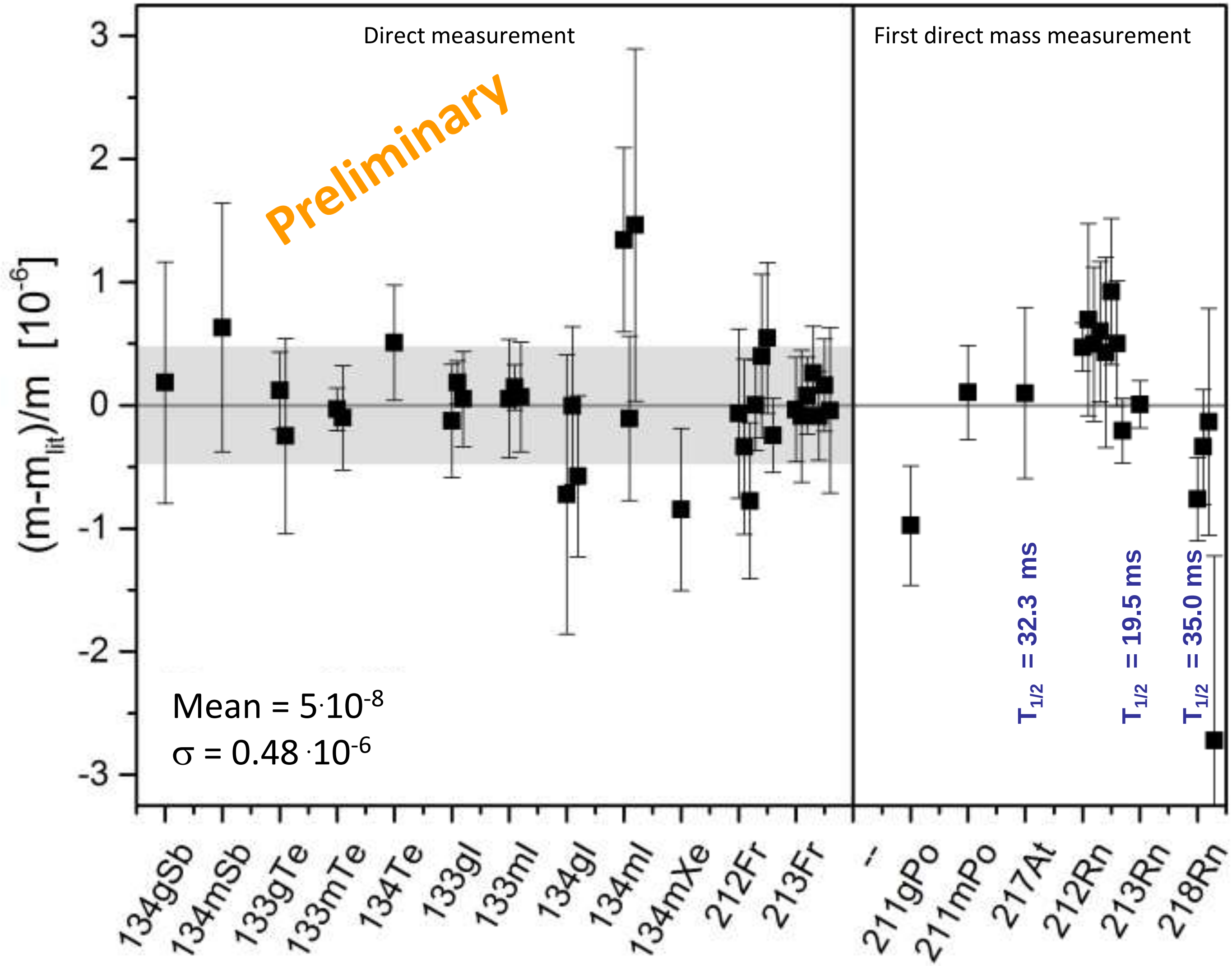


A. Spataru, E. Haettner

Mass Measurements

Mass measurements with an accuracy > $2 \cdot 10^{-7}$

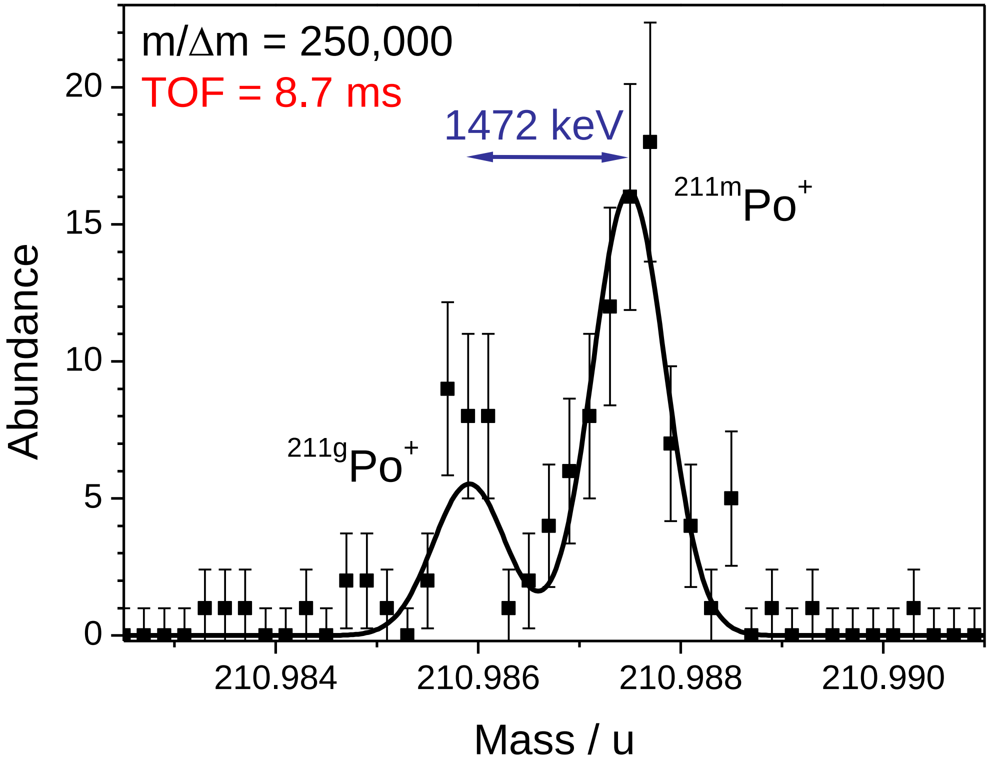
- > 40 short-lived ground states
- 15 isomers

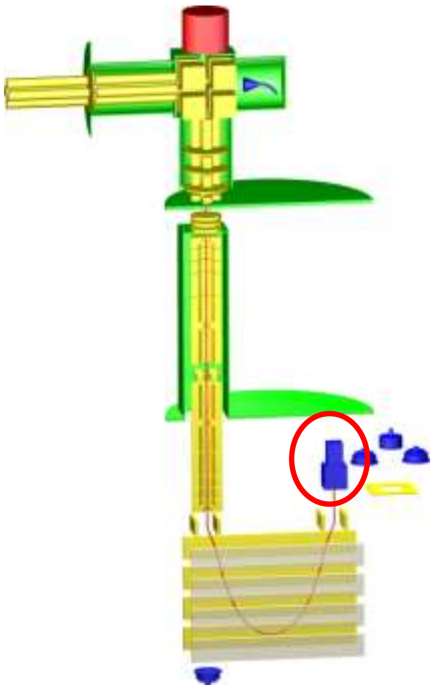


S. Ayet
C. Hornung et al.

Measurement and Separation of Isomers

- Identification of ^{211g}Po and ^{211m}Po by using PID detectors in the FRS, by alpha decay on Si detector and by mass spectrometry
- Measurement of excitation energy:
  (1472 ± 120) keV   Lit.: (1462 ± 5) keV





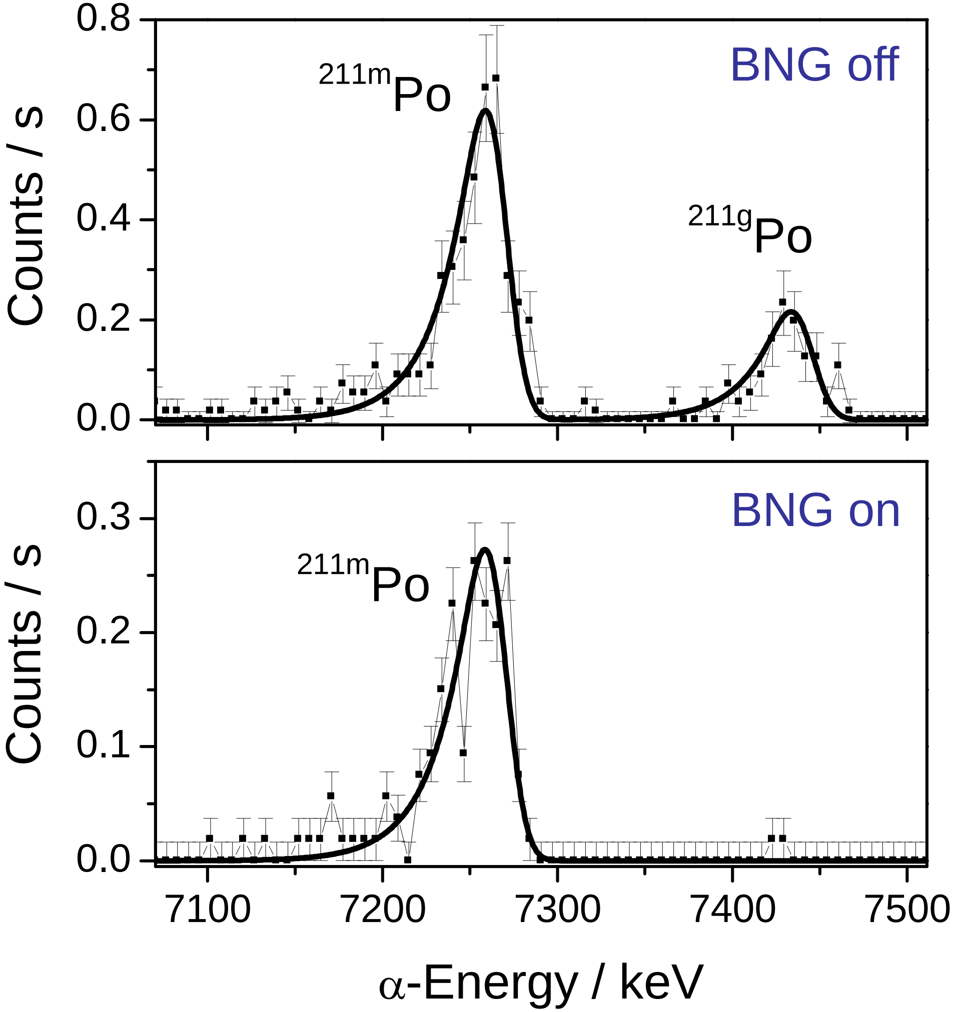
Measurement using the TOF detector

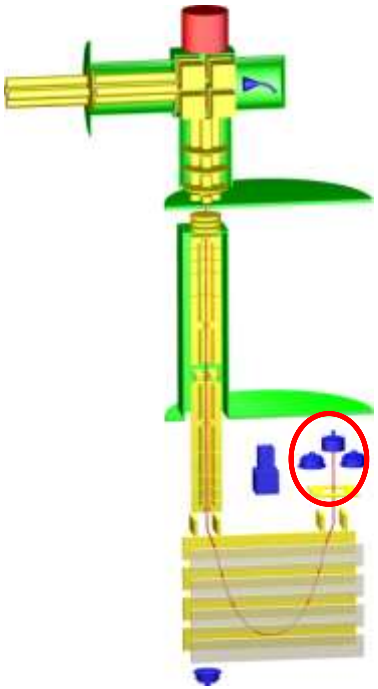
T. Dickel et al., Phys. Lett. B 744 (2015) 137

Measurement and Separation of Isomers

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

Proof-of-principle: production of isomerically clean beams by MR-TOF-MS





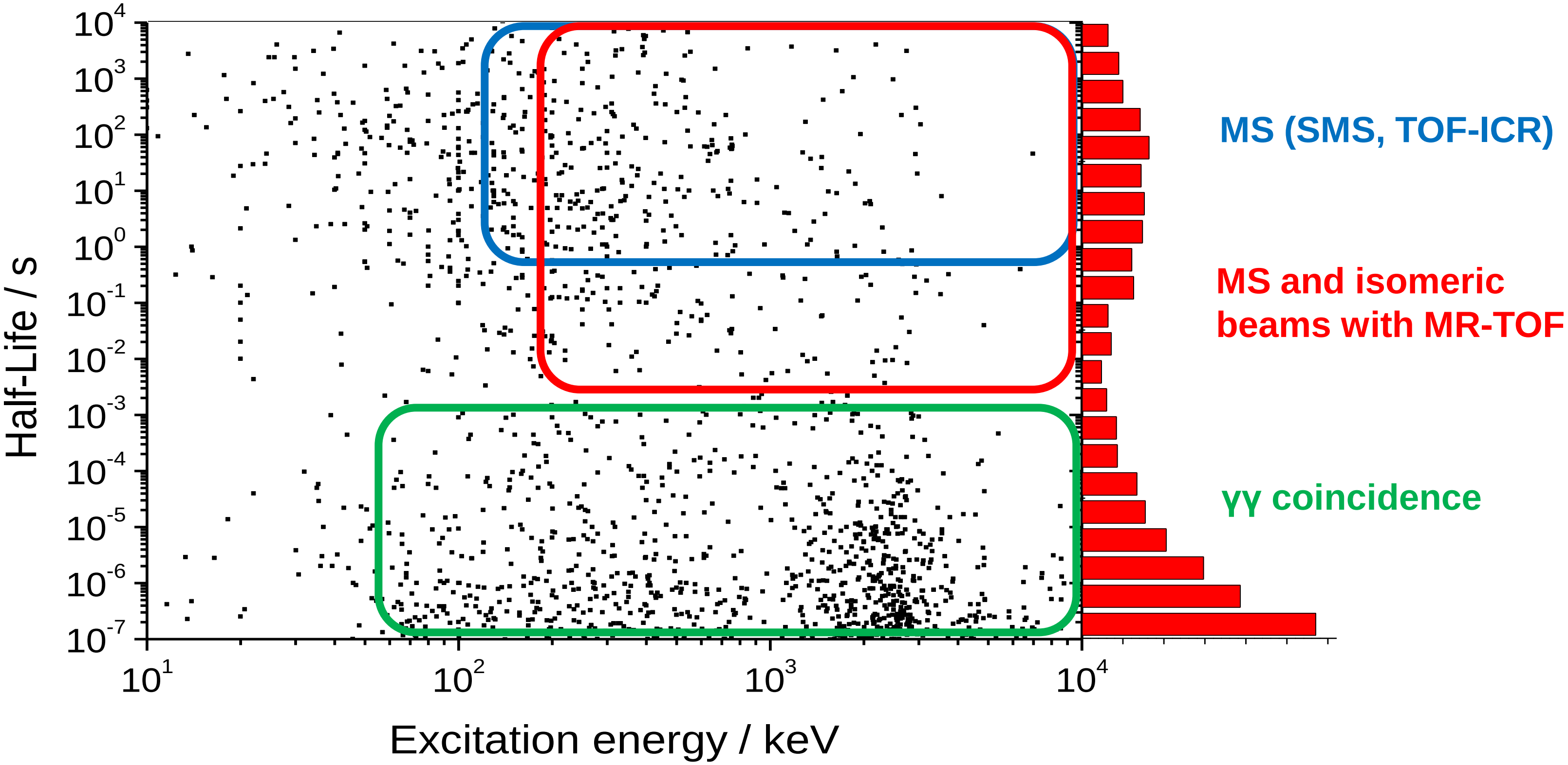
Separation using the Bradbury-Nielsen gate, measurement using the Si detector

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

Isomer Measurement with MR-TOF-MS

Requirements for system for isomere search:

- Fast: ~ms
- Sensitive: Non-Scaning
- High resolving Power: >>10^5
- High Dynamic Range: > 10:1



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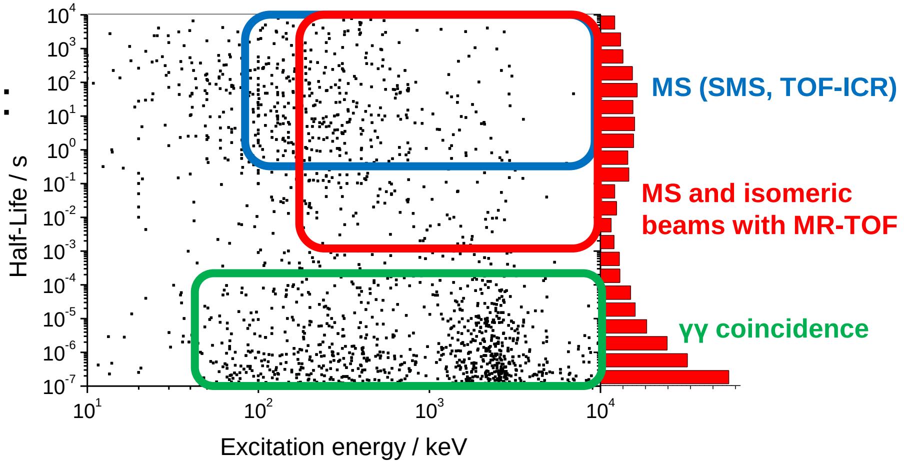
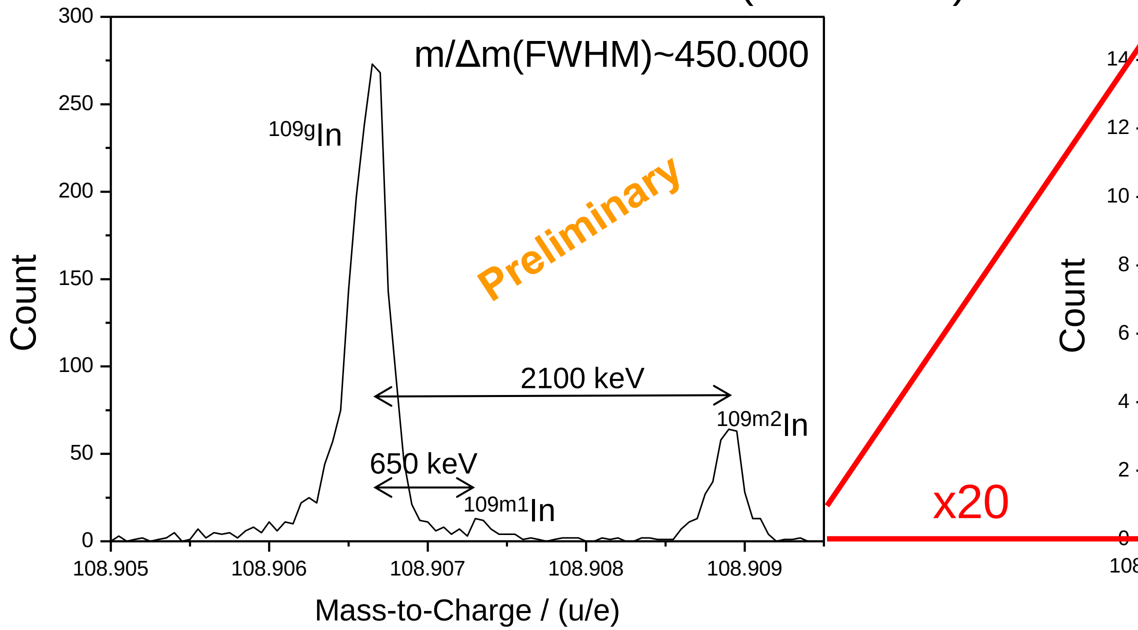
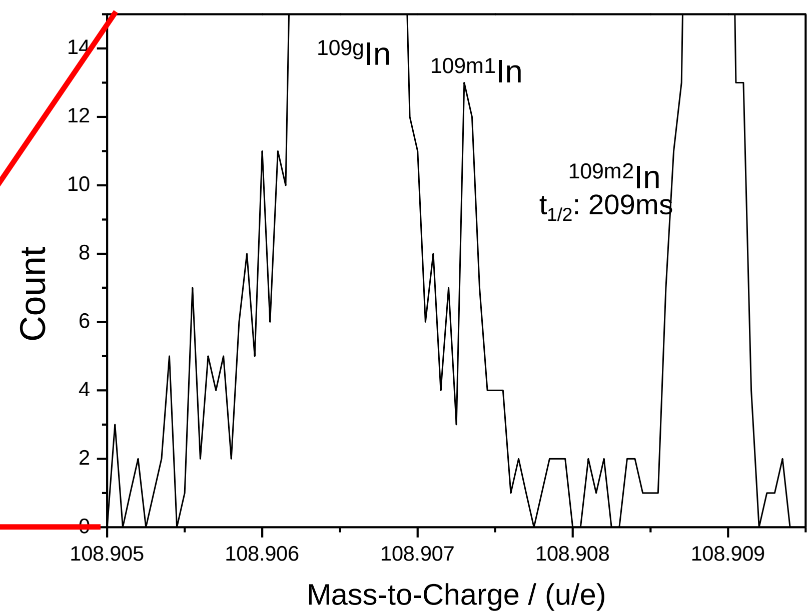


Results from the recent beamtime (June 2016): 600MeV/u ^{124}Xe on a 1.6g/cm² Be target

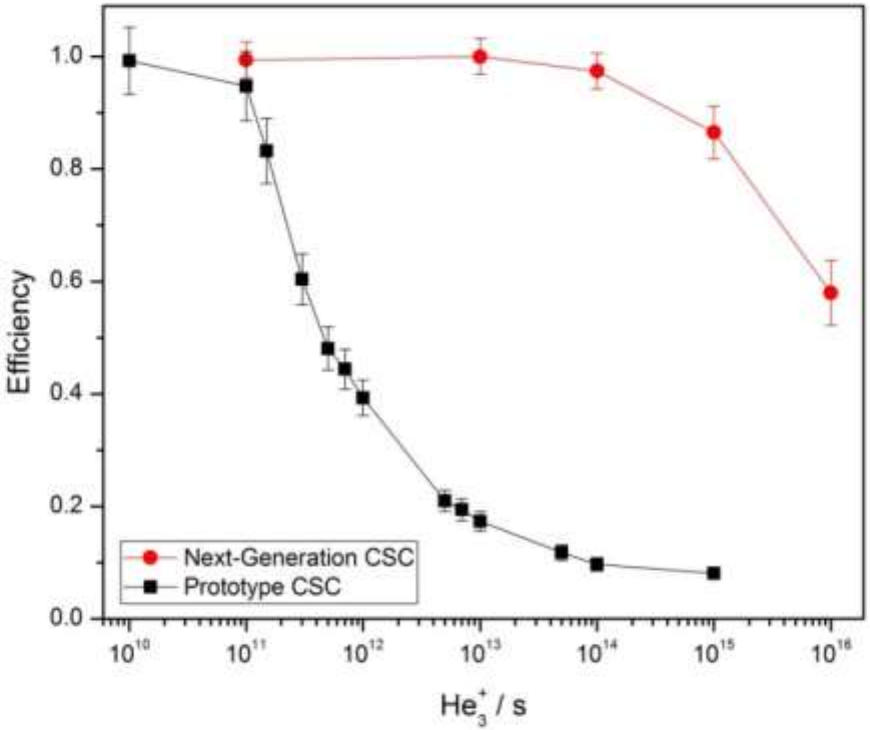


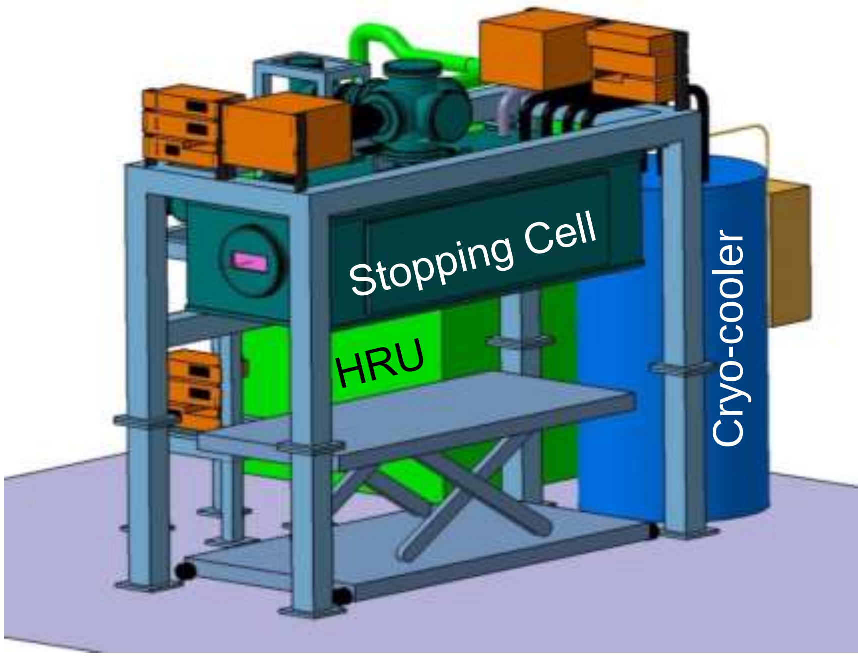


MR-TOF-MS is a powerful tool for the measurement of isomers:
Identification, discover, excitation energies, isomeric ratios and isomeric beams

The LEB CSC

	Prototype CSC	Design Goals LEB CSC
Areal density (He)	6 mg/cm^2	20…40 mg/cm^2
Extraction time	25 ms	5…10 ms
Rate capability	10^4/s	10^7/s

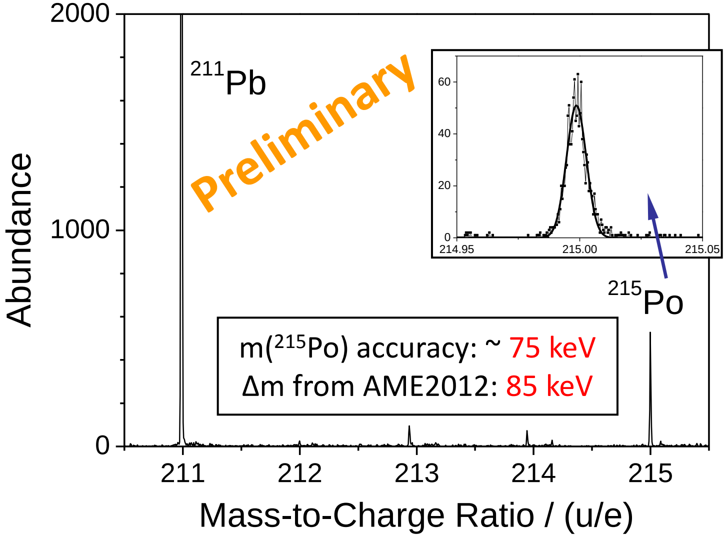


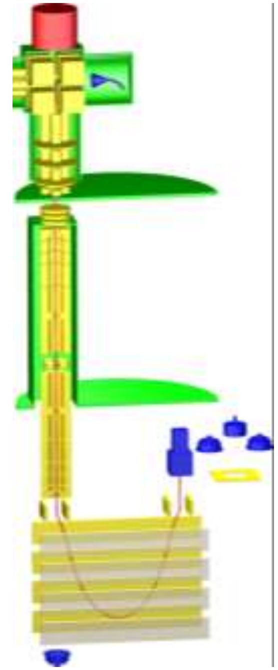


T. Dickel et al., NIMB 376 (2015) 216

Mass and Half-Life Measurements of ms Isotopes

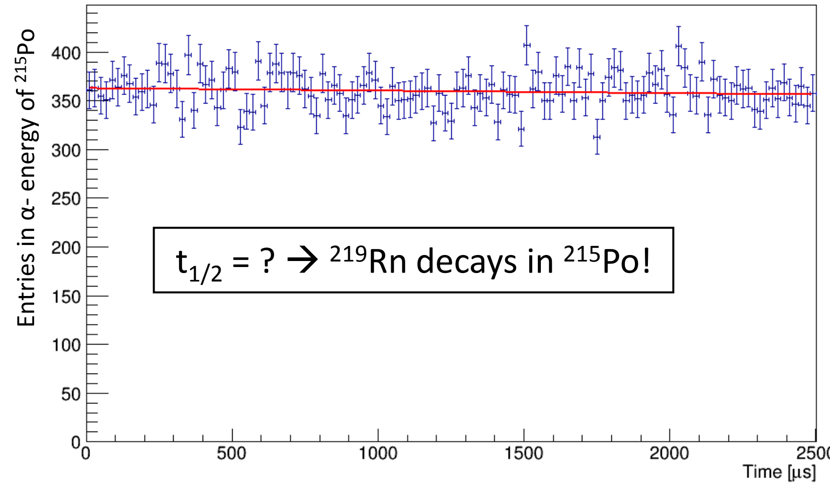
Mass measurement of short lived nuclei



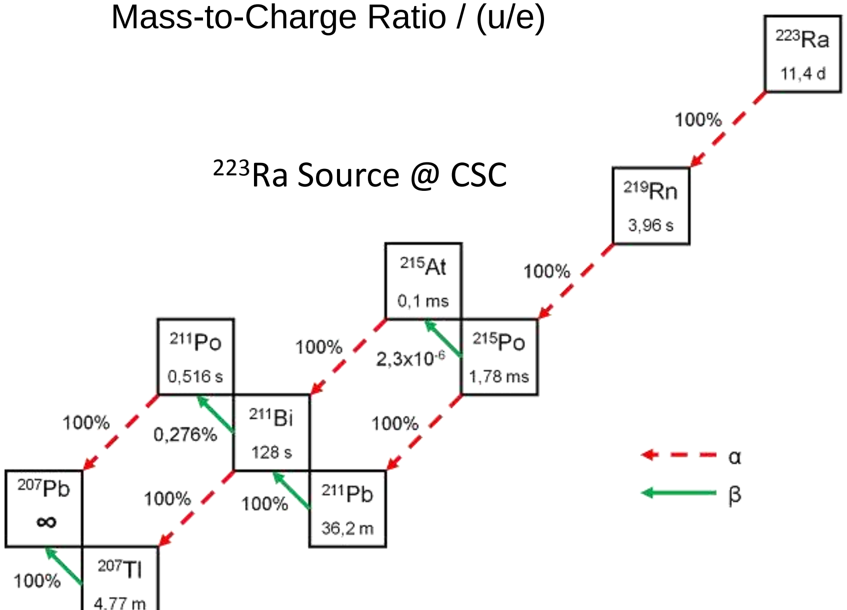


Mass-selected decay spectroscopy

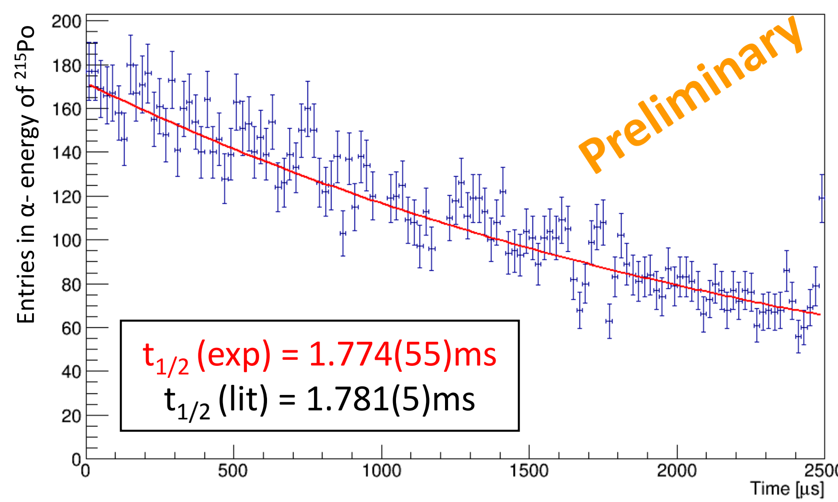
^{219}Rn and ^{215}Po implanted in Si Detector



^{223}Ra Source @ CSC



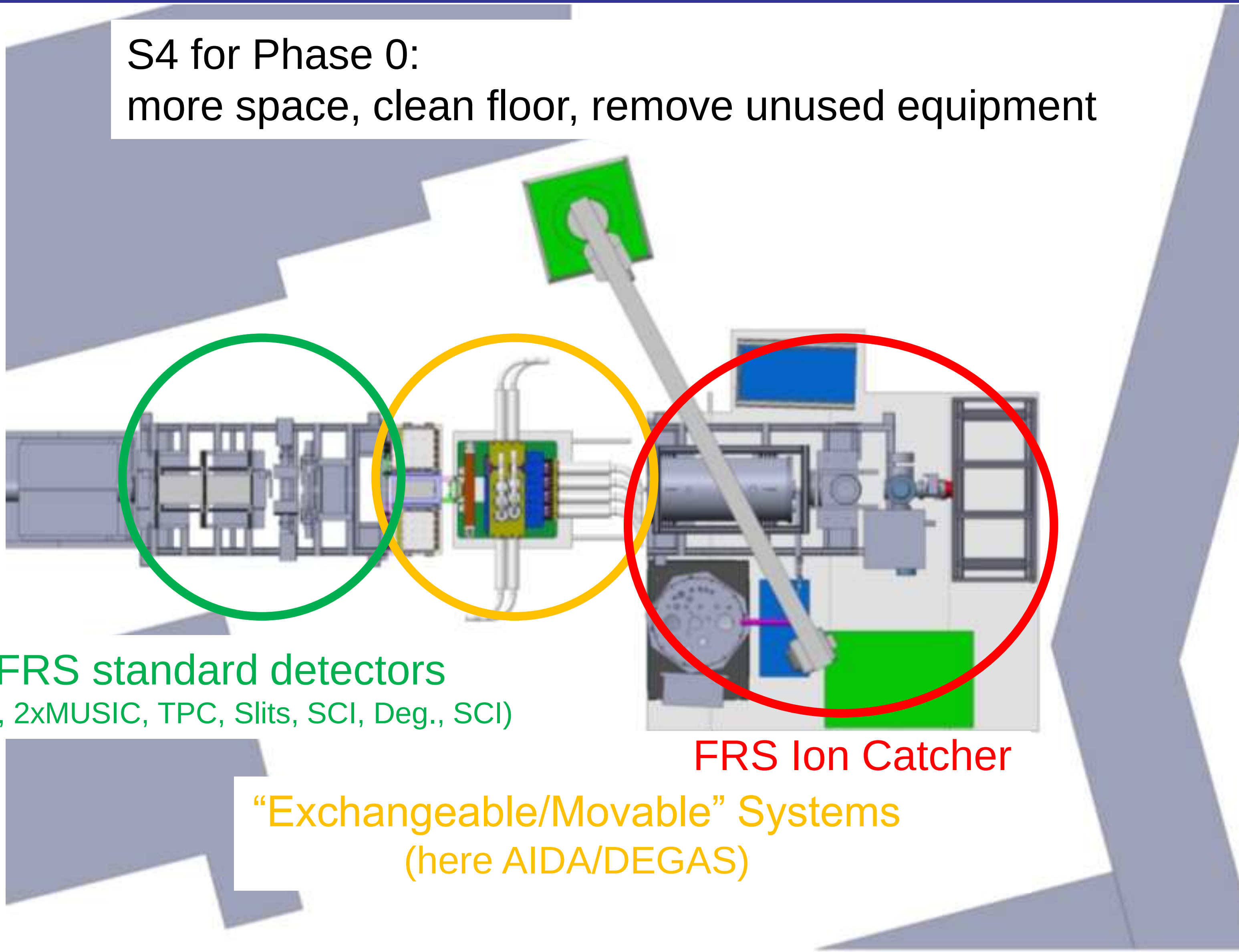
^{215}Po implanted in Si Detector



A.-K. Rink et al.

Final Focus of the FRS: Phase 0

S4 for Phase 0:
more space, clean floor, remove unused equipment



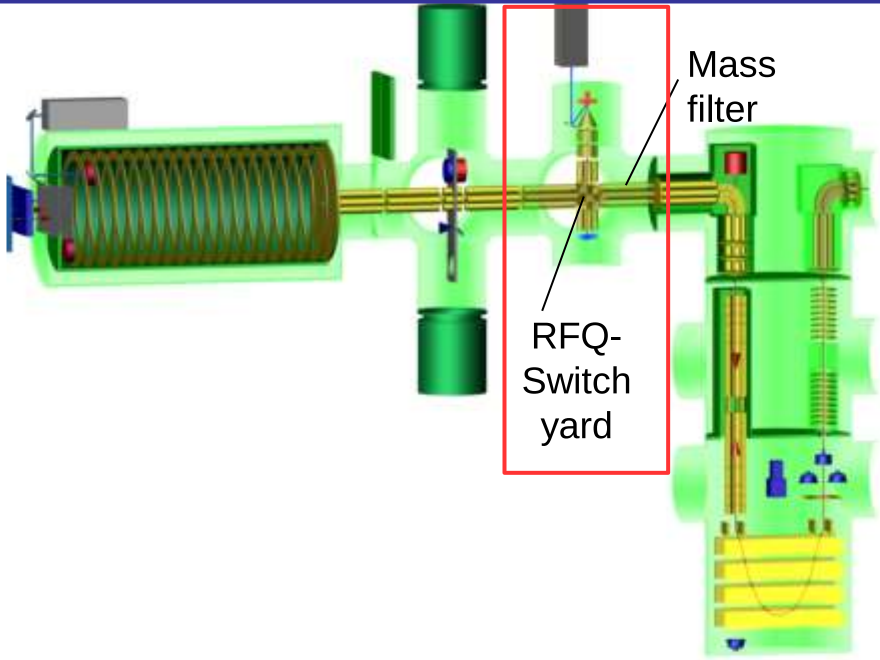
FRS standard detectors
(TPC, 2xMUSIC, TPC, Slits, SCI, Deg., SCI)

FRS Ion Catcher

“Exchangeable/Movable” Systems
(here AIDA/DEGAS)

Technical Improvements

- Improved CSC
- Addition to the RFQ Beamline
- Auxiliary equipment (for LEB)
- Helium Recovery Unit (Finnish In-Kind)



Performance Gain:

- Efficiency
- Higher mass resolving power and accuracy
- Faster extraction: ~15ms
- Control charge states

$$E_{eff} \propto K_0^{\,2} \frac{m}{q} \frac{V_{RF}^2}{r_0^3} \frac{1}{n^2}$$

gain factor in efficiency $\sqrt{3}$

Quality Management	Document type:	Document number: F-DS-SI-11e	Date: 16.05.2017
FAIR @ GSI	Detailed Specification	Template number: Q-FO-QM-0005	Page 1 of 11

Approved by FAIR council
Contract in Preparation

Document Title:	**Pumping System for the CSC of Super-FRS**
Description:	Detailed specifications of the pumping system with helium recovery for the cryogenic stopping cell at the low-energy end of Super-FRS
Division/ Organization:	Super-FRS system design
Field of application:	Project FAIR@GSI

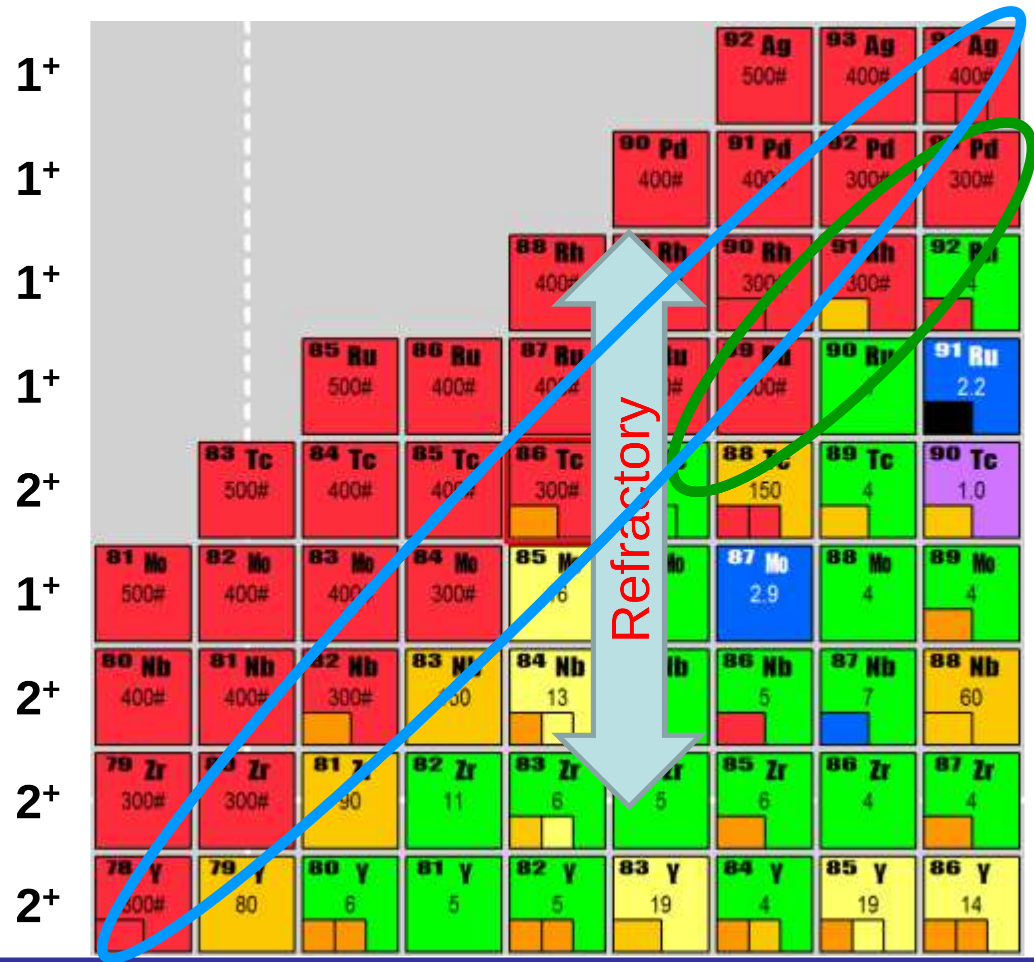
Technical improvements need to be verified with beam

W.R. Plaß et al.

Approved Proposal: Detector Test for the LEB & N=Z

Realistic test under challenging conditions

- Refractory elements
  - In-flight unique; e.g. strong interest from LaSpec for n-rich Zr
- Thermalized ions expected in 1^+ and 2^+ charge states
- “Light” masses compared to previous tests



Physics Goals

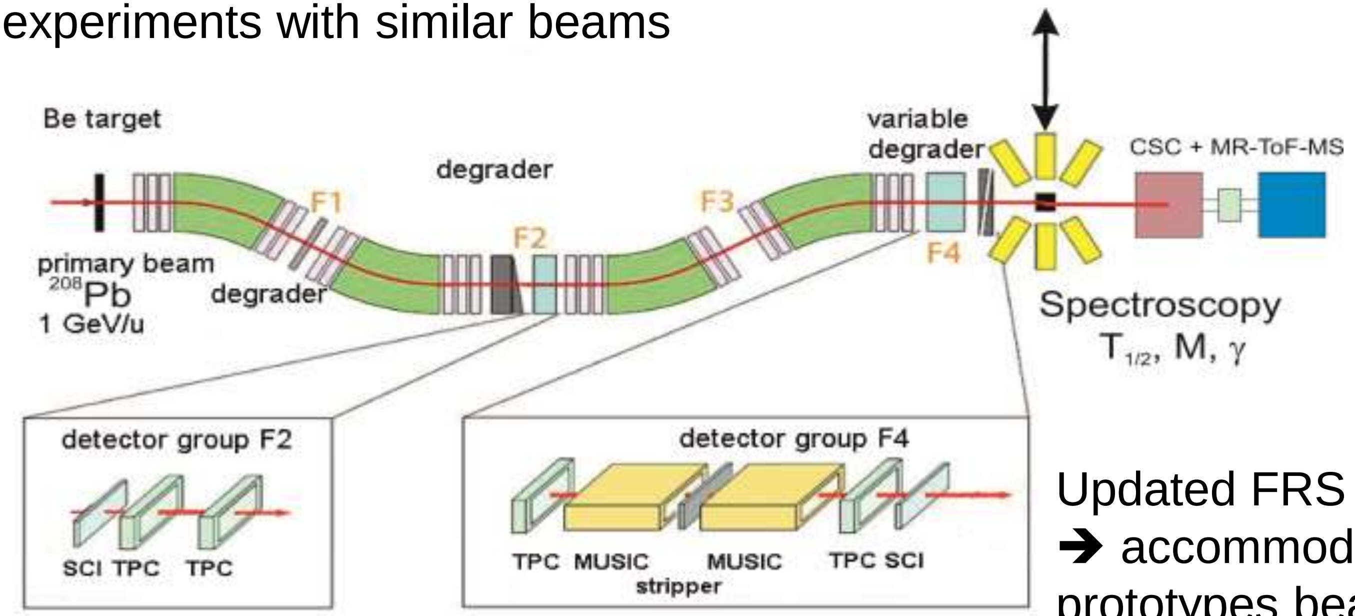
- Resolve inconsistencies in the mass surface (shifts > 1 MeV observed)
  E. Haettner et al., PRL 106 (2011) 122501
- Wigner energy, e.g. ^{80}Zr
  AS Lalleman et al., Hyp. Inter. 132 (2001) 315
- rp-process: ^{78}Y, ^{82}Nb, ^{91}Rh
  H. Schatz, W.J. Ong, ApJ 844 (2017) 139
- New K-Isomers: e.g. ^{80}Zr, ^{82}Zr
  Z.J. Bai et al., Chinese Phys. C 40 (2016) 094102
- High spin isomer in ^{94}Ag (^{93}Pd)
  I Mukha et al., Nature 439 (2006) 298
  A. Kankainen et al., PRL 101, (2008) 142503

W.R. Plaß et al.

Approved Proposal: New Isotope Search

$^{208}Pb+^{9}Be$@ 1 A.GeV at the entrance of the FRS (2.5 g/cm^2 target with Nb backing)

^{208}Pb intensity up to 10^9 per spill (2 second ramping, 0.5 extraction)
➔ assures a duty cycle of 10 to 50 times higher than previous isotope search experiments with similar beams



Updated FRS identification detectors
➔ accommodate Super-FRS prototypes beam diagnostic detectors

At final focal plane:

- FRS Ion Catcher for mass measurements
- AIDA+Fatima for life time measurements

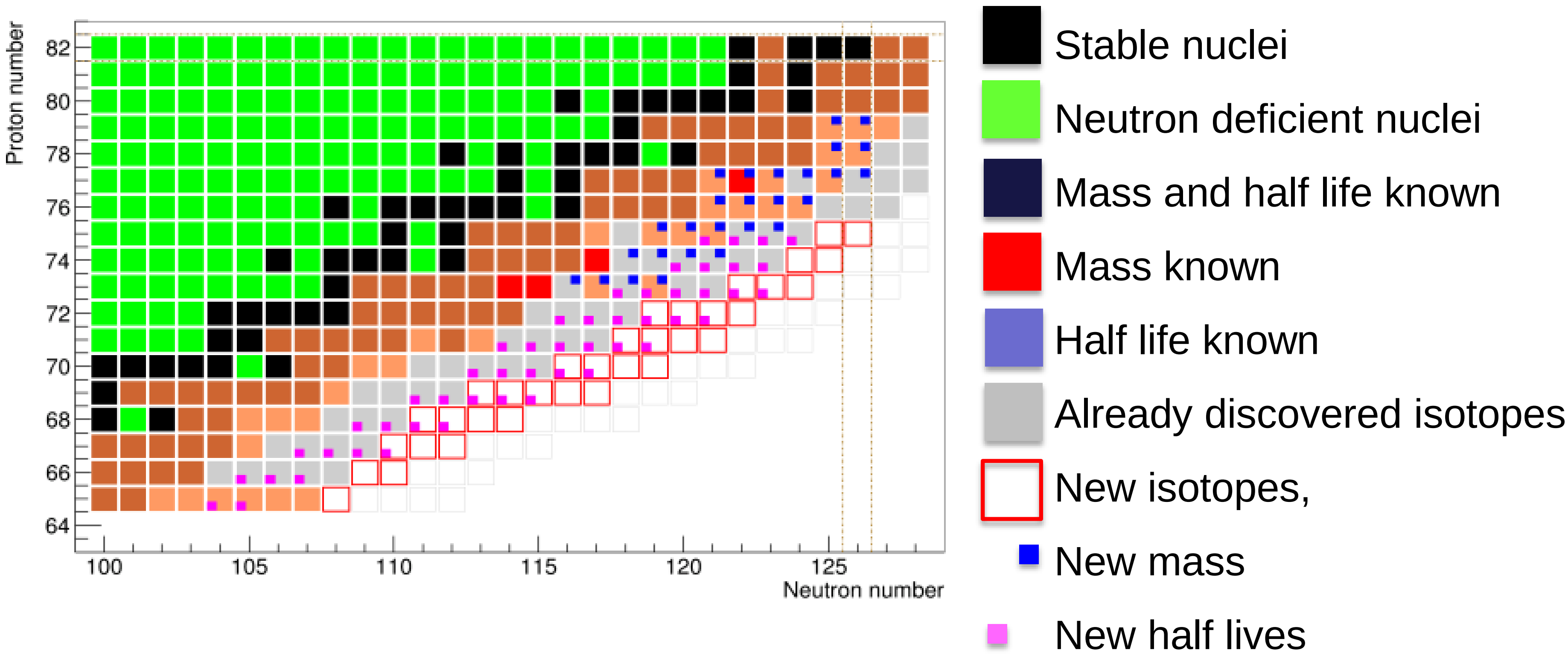
Equipment from Super-FRS Experiment and DESPEC are planned to be used

S. Pietri et al.

Approved Proposal: New Isotope Search

^{208}Pb fragmentation to produce neutron rich isotopes of elements $_{65}Re$ to $_{75}Tb$

- Identification of new neutrons rich isotopes
- Measurement of production cross sections and momentum distribution
- Mass, half-life and decay spectroscopy measurement after implantation

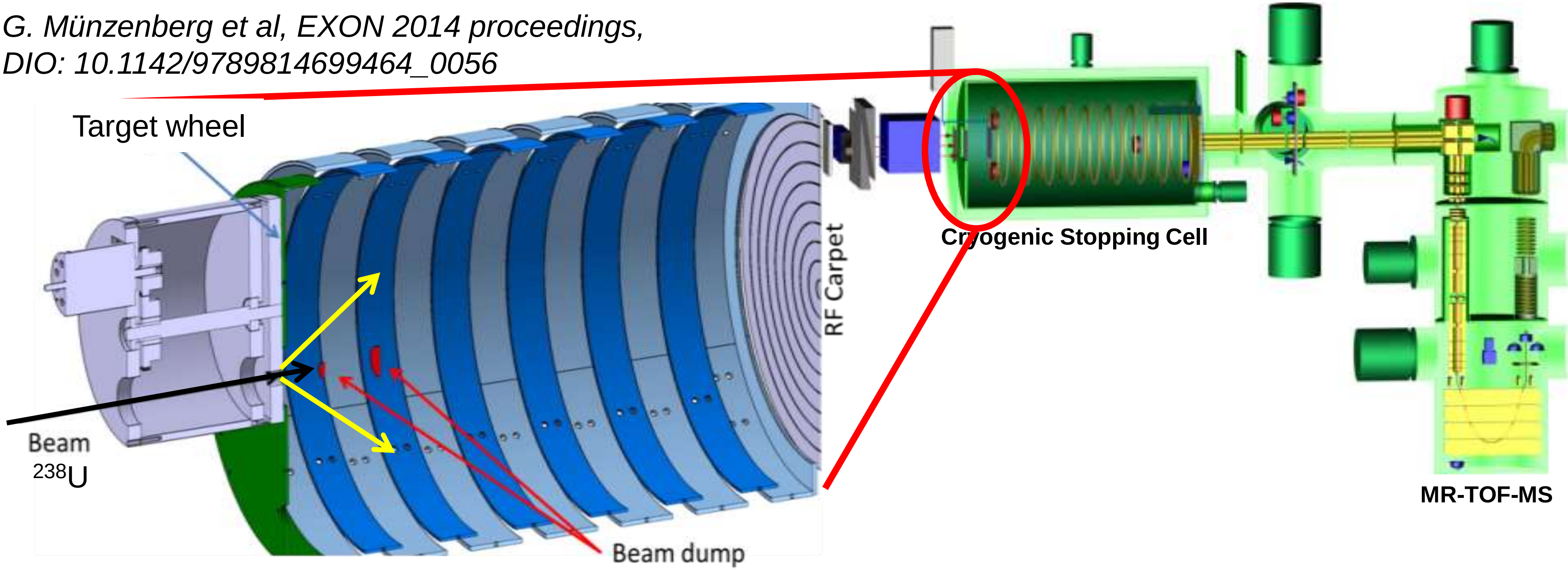


➔ 47 new half lives, 26 new masses and 34 new isotopes

S. Pietri et al.

Proposal: Reaction studies / MNT

G. Münzenberg et al, EXON 2014 proceedings, DIO: 10.1142/9789814699464_0056



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
- Results for ^{238}U on ^{164}Dy & ^{64}Ni:
    - ➢ Cross Sections: >150
    - ➢ New masses: ~25
    - ➢ Discovery of long-lived isomers (G.D. Dracoulis et al., Phys. Scr. T152 (2013) 014015)

Conclusions and Outlook

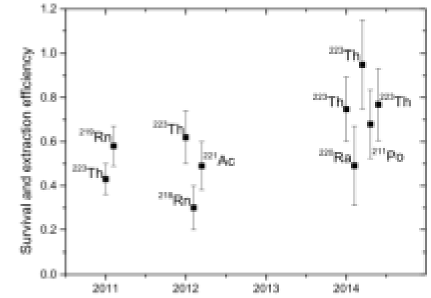
The FRS Ion Catcher

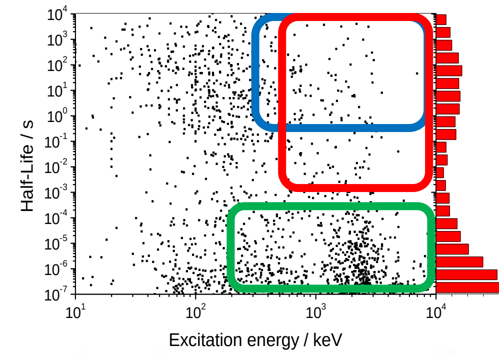
Prototype CSC:
- Cryogenic, high density operation
- Unprecedented efficiencies for relativistic ions
- Access to short life times

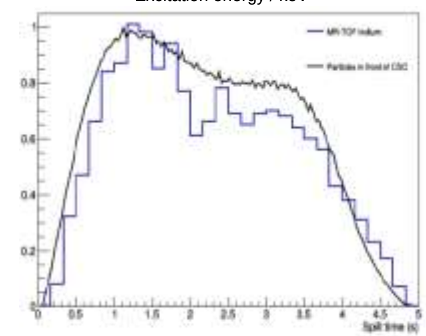
MR-TOF-MS:
- Necessary tool for range tuning
- High-accuracy mass measurements: $2 \cdot 10^{-7}$
- Powerful tool for the measurement of isomers:
  Identification, excitation energies, isomeric ratios
- High-resolution mass separator for isobars and isomers

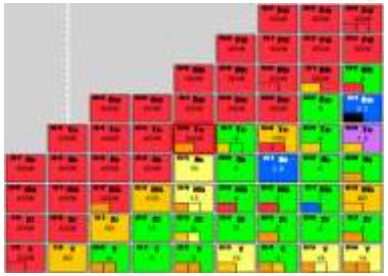
As Auxiliary Detection System for identification and quantification
- Mass tagger
- Particle ID by MS only

FAIR Phase 0 & 1
- Detector Tests and N=Z
- New Isotope search
- MNT reaction studies
- LEB CSC for MATS/LaSpec:
  Higher rates and efficiencies, and shorter extraction times









Acknowledgements

FRS Ion Catcher Collaboration

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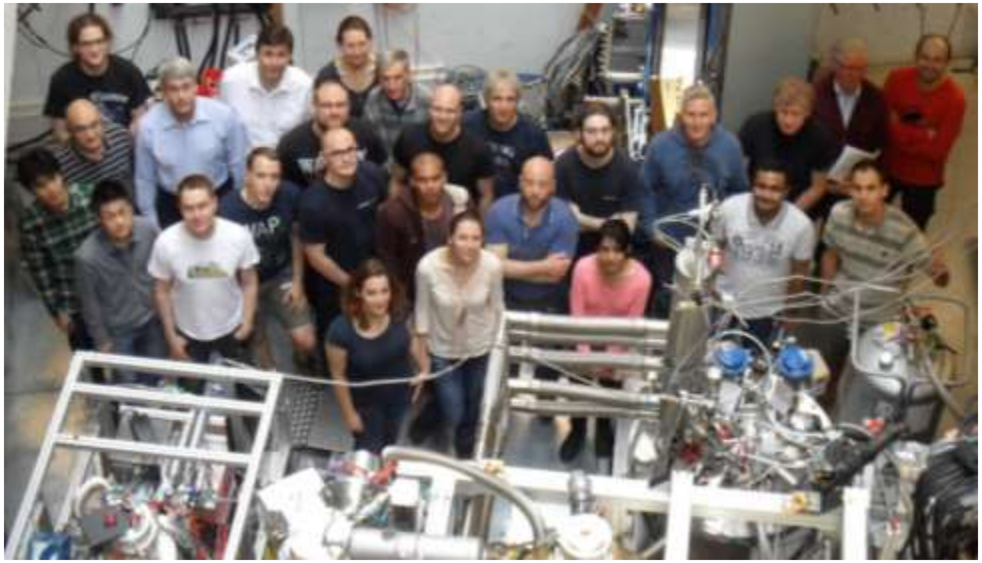

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