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Cryogenic Stopping Cell and MR-TOF-MS for the LEB of the Super-FRS

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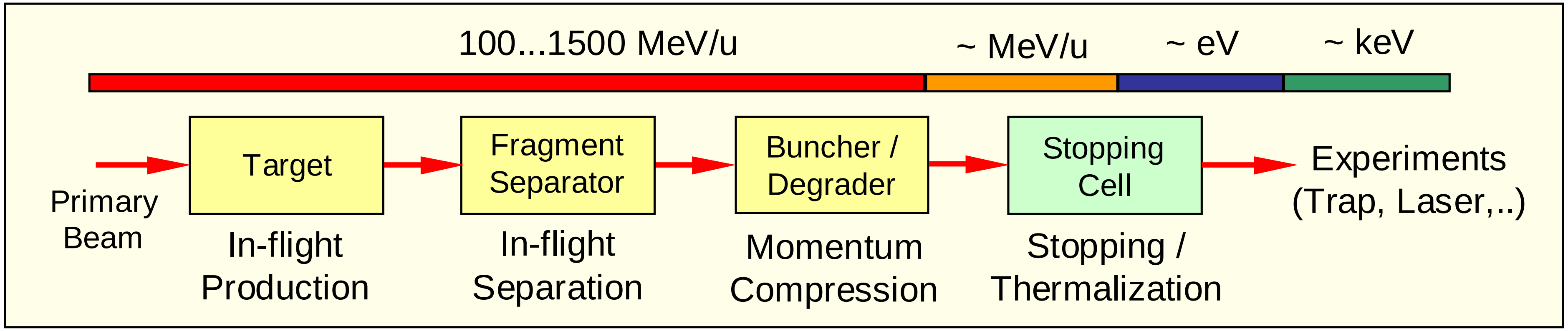
Overview

- Cryogenic Stopping Cell for the Super-FRS at FAIR
- Multiple-Reflection Time-of-Flight Mass Spectrometer
- On-line Commissioning at the FRS Ion Catcher at GSI
- Conclusions and Outlook

Motivation: Low Energy Branch of the Super-FRS

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 spectroscopy

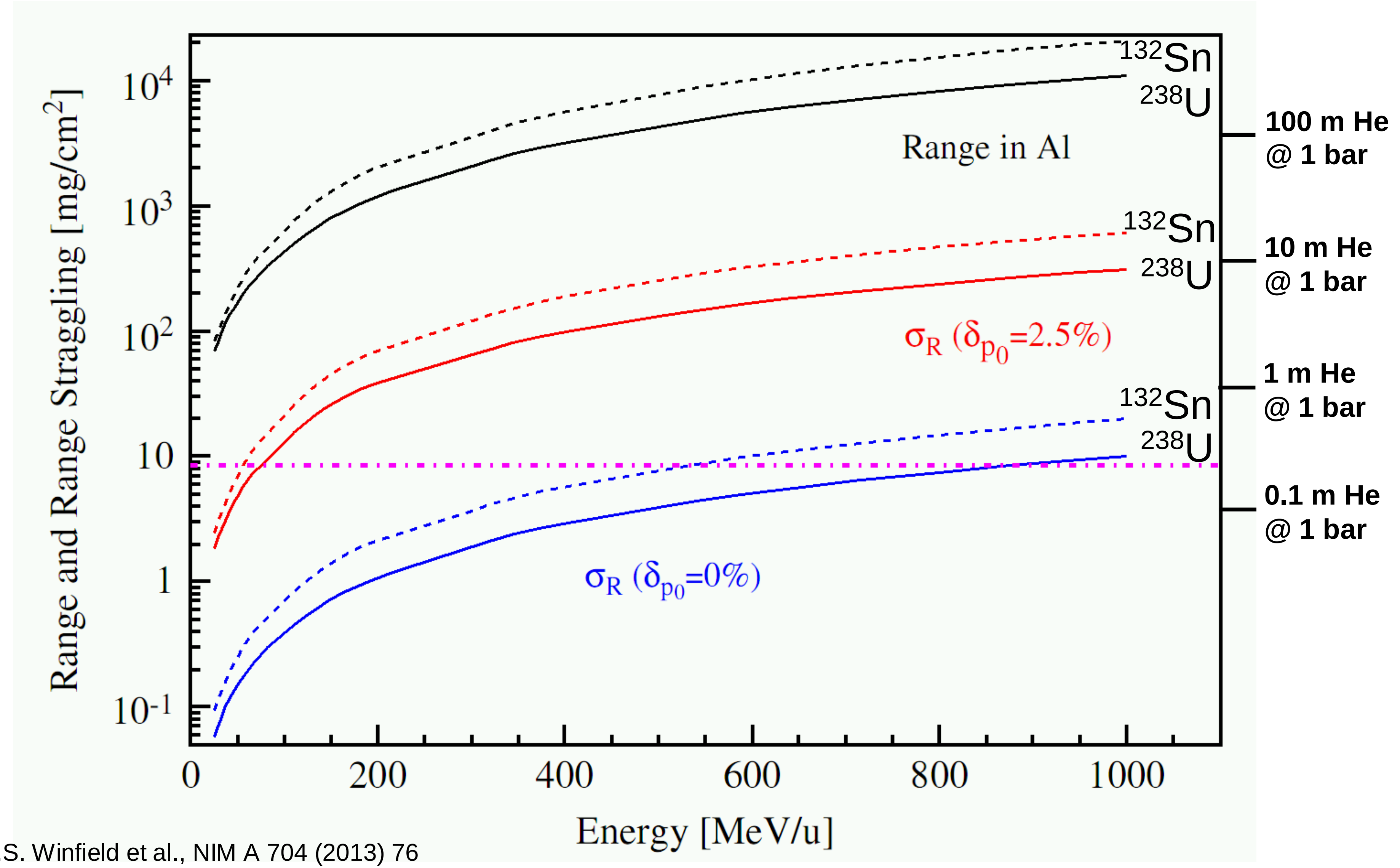
LaSpec (Laser Spectroscopy)

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

Eur. Phys. J. Special Topics 183 (2010) 1

Challenge of Thermalizing Relativistic Ions

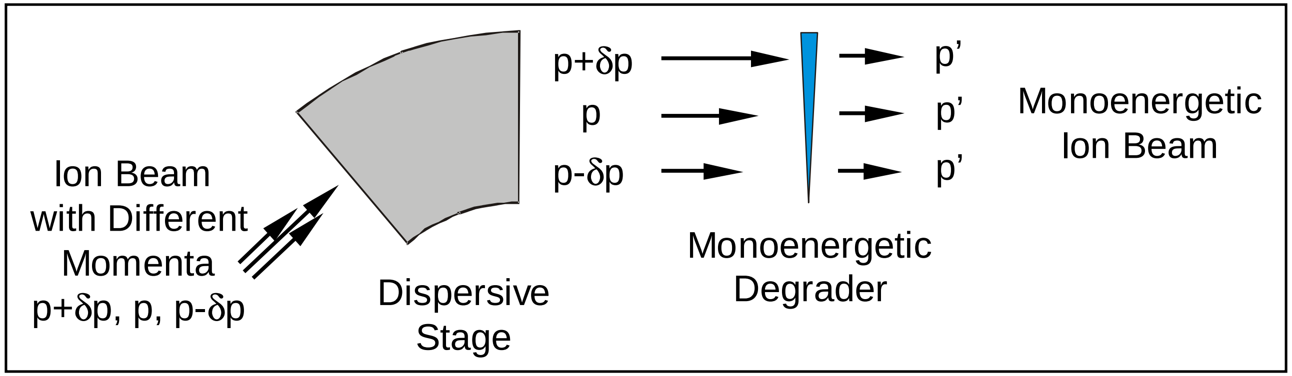
Mean range and range straggling in Al



J.S. Winfield et al., NIM A 704 (2013) 76

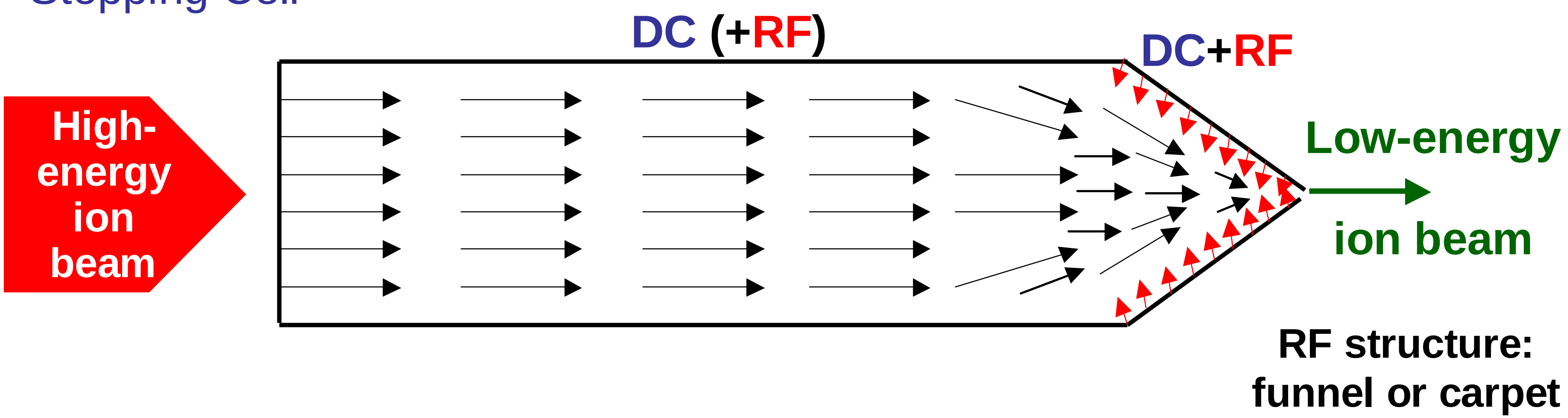
Stopping Cell Principles

Range Bunching



H. Weick et al., NIM B 164 (2000) 168

Stopping Cell



Stopping Cell Design

Cryogenic Operation

Operate He-filled stopping cell at cryogenic temperature (~70 K)

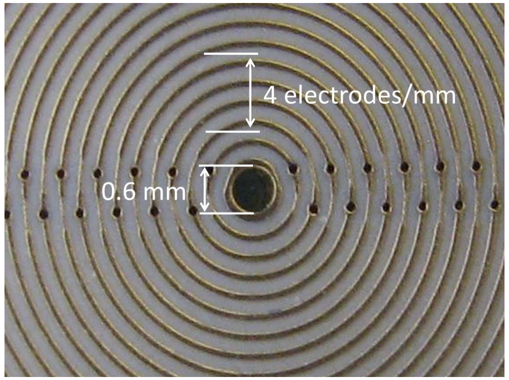
- Ultra-pure helium (freezing-out of contaminants)
  - Ideal for ion survival, 2+ charge state possible
  - No formation of molecules/adducts
- Reduced radial ion diffusion
- Reduced requirements for cleanliness → easier, more flexible construction
- Operational reliability

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

High-density Operation

Use RF structure with small spacing to achieve high RF repelling field (PCB-based RF carpet instead of RF funnel)

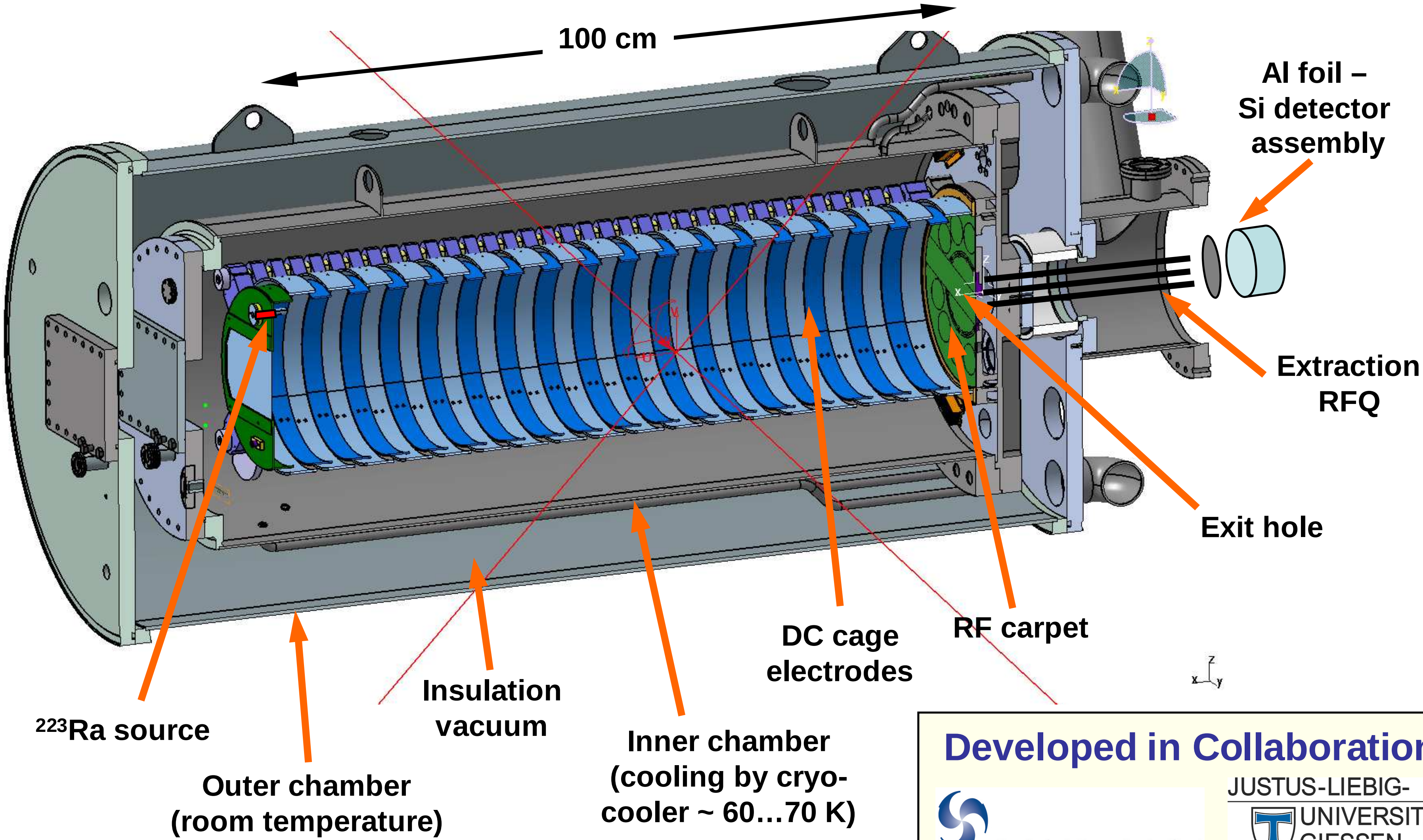
- High stopping gas densities
- Less complex construction than RF funnels



Diameter:	250 mm
Electrode spacing:	0.25 mm

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

Stopping Cell Design



Developed in Collaboration

Kernfysisch Versneller Instituut

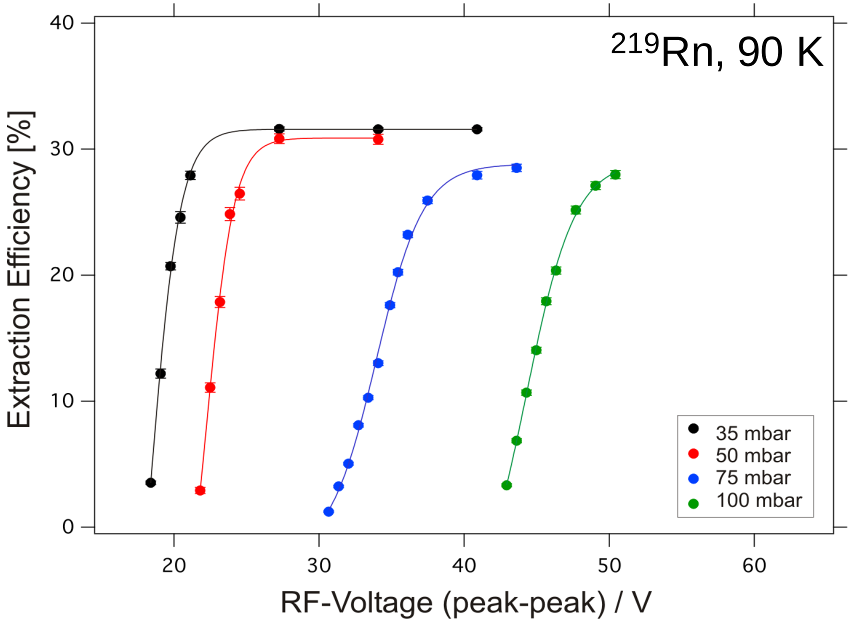
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

university of groningen

GSI

M. Ranjan et al., Europhys. Lett. 96 (2011) 52001
M. P. Reiter, Master Thesis, Justus-Liebig-Universität Gießen (2011)

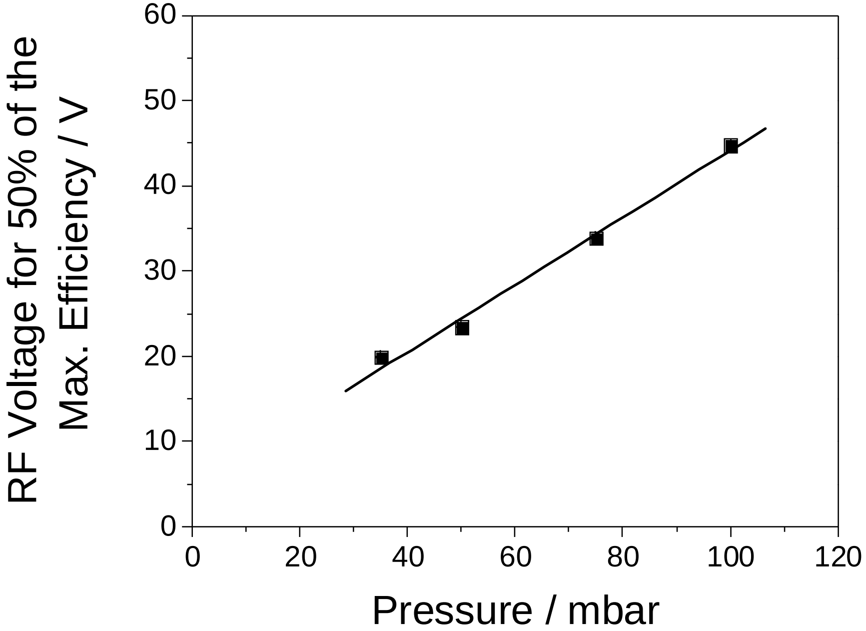
Off-line Performance Study: Efficiency



Maximum survival and extraction efficiency for ^{219}Rn: ~ 30%

Value is close to the assumed efficiency value for stopping the recoils as ions

P. Dendooven et al., NIM A 558 (2006) 580
S. Purushothaman et al, NIM B 266 (2008) 4488
S. Eliseev et al., NIM B 258 (2007) 479



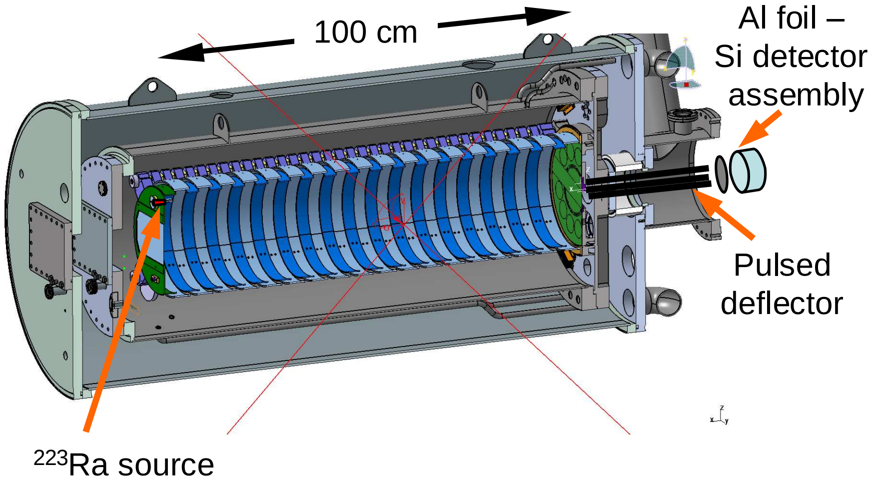
Maximum pressure reached:

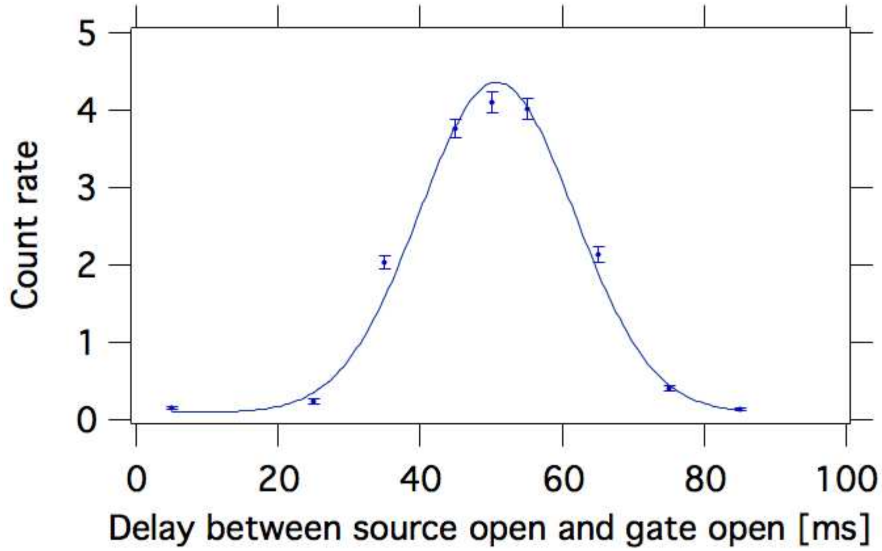
- 100 mbar at 90 K
- 330 mbar room-temperature equivalent
- 5.5 mg/cm^2 (He)

In the future: RF =150 V
→ 1 bar room-temperature equivalent achievable

Off-line Performance Study: Extraction Time

Extraction time measurement with pulsed ^{223}Ra source





Pressure = 50 mbar, temperature = 100 K
DC field = 21 V/cm, distance = 1 m

→ Experiment T_{extr} ~ 50 ms
Theory (K_0=15 cm^2/Vs) T_{extr} ~ 47 ms

Scaled mean extraction time
(extraction from middle of cell)
T_{extr} ~ 25 ms

Challenges for MS at Low-Energy RIB Facilities

Functionalities
- Direct mass measurement
- Ion identification (Discovery of isotopes and isomers; experiment setup: choice of nuclides of interest; optimization of production, separation, detection)
- Mass separation

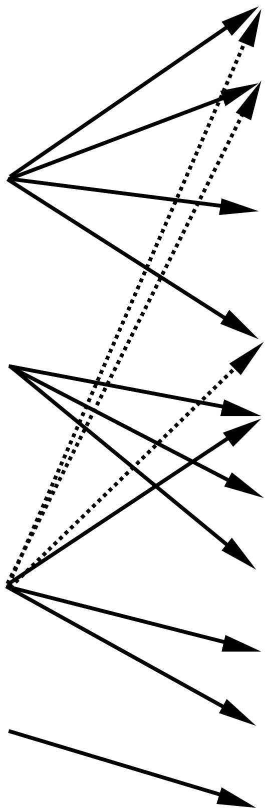
Performance characteristics

Sensitivity
- Low cross-sections (< µbarn)
- Low rates (< 10 / s)

Selectivity
- Nuclei of interest are mixed with abundant contaminants

Accuracy
- Nuclear structure / astrophysics $\delta m/m \sim 10^{-6} \ldots 10^{-7}$

Speed
- Short half-live



High transmission efficiency

Broadband detection
- non-scanning

Universal
- element / decay-independent

Single-ion sensitivity

Resolving power $>10^5$

Dynamic range $>10^4$

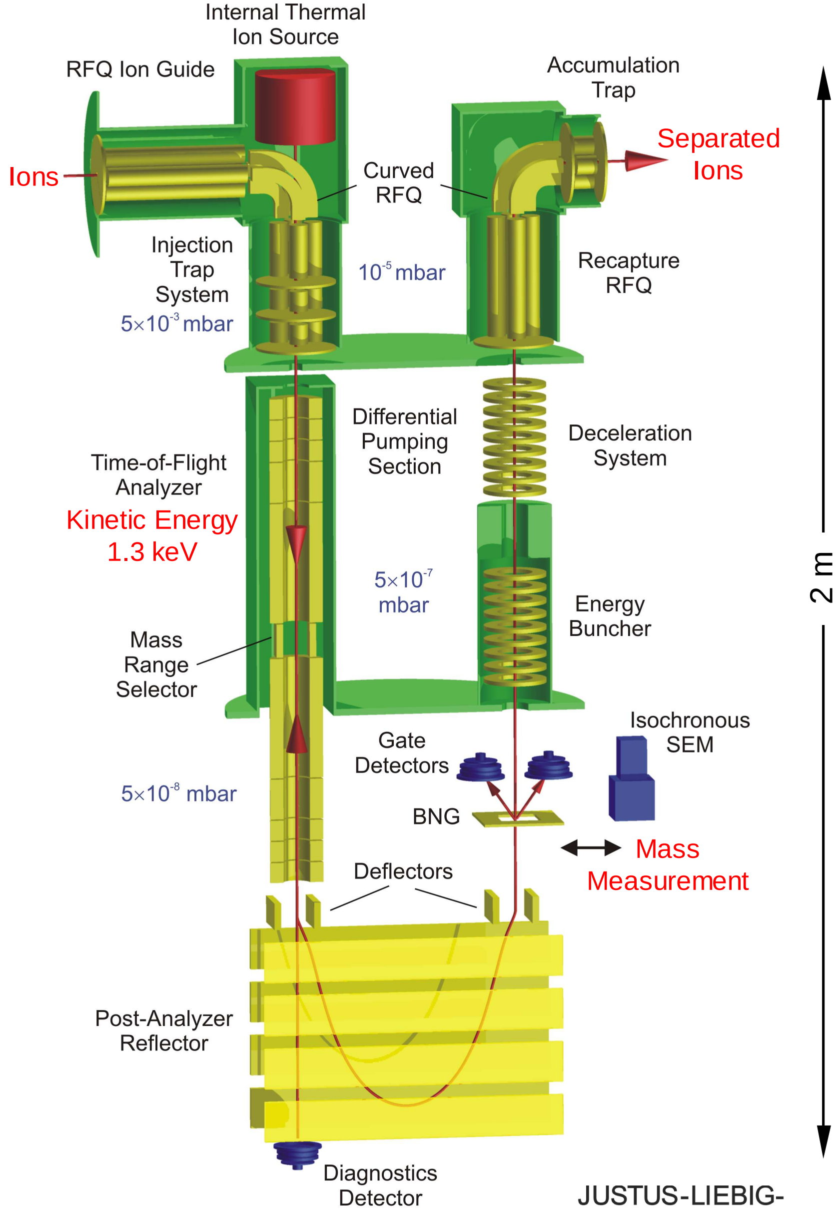
Ion capacity $>10^6$ isobars / s

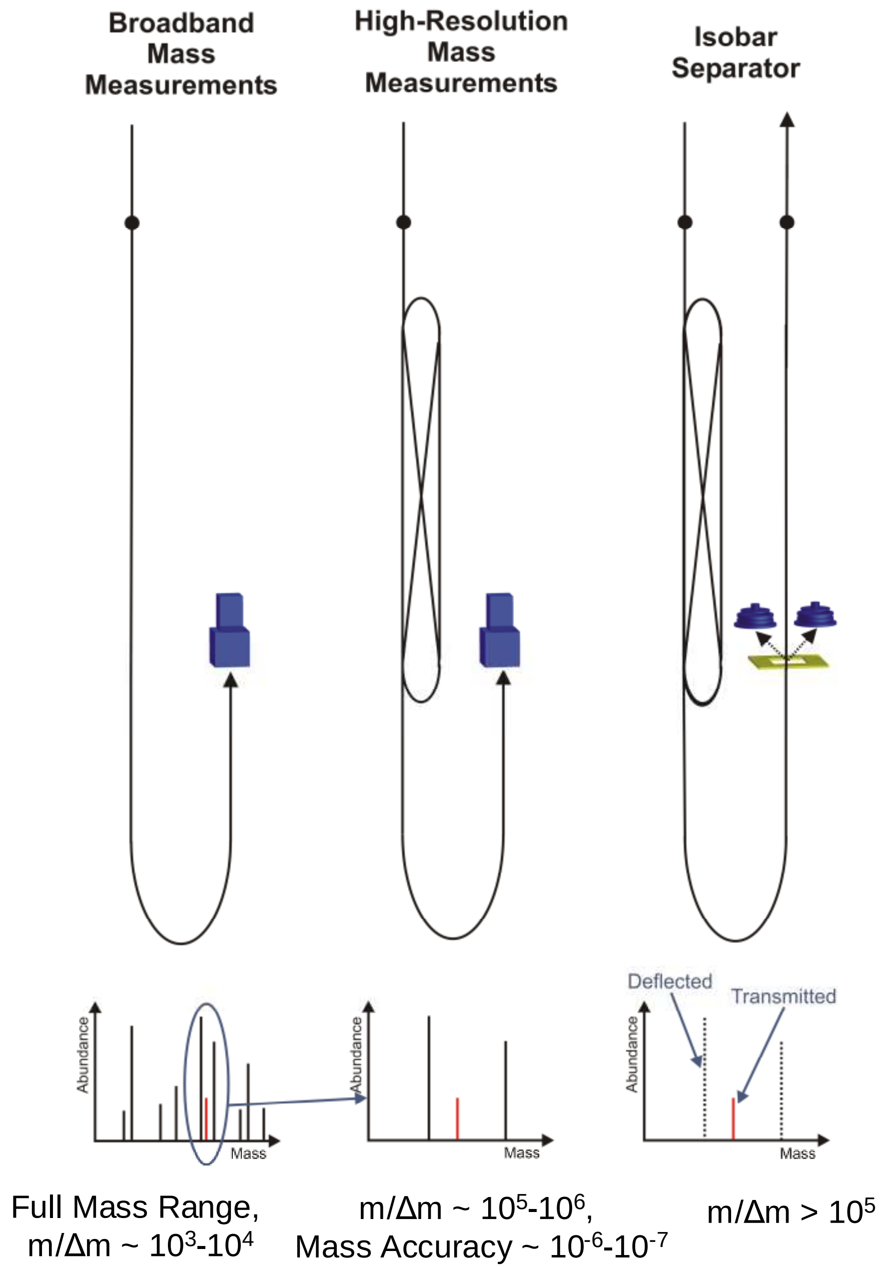
Low systematic errors

Flexible calibration methods

Measurement cycle time ~ ms

Multiple-Reflection Time-of-Flight Mass Spectrometer





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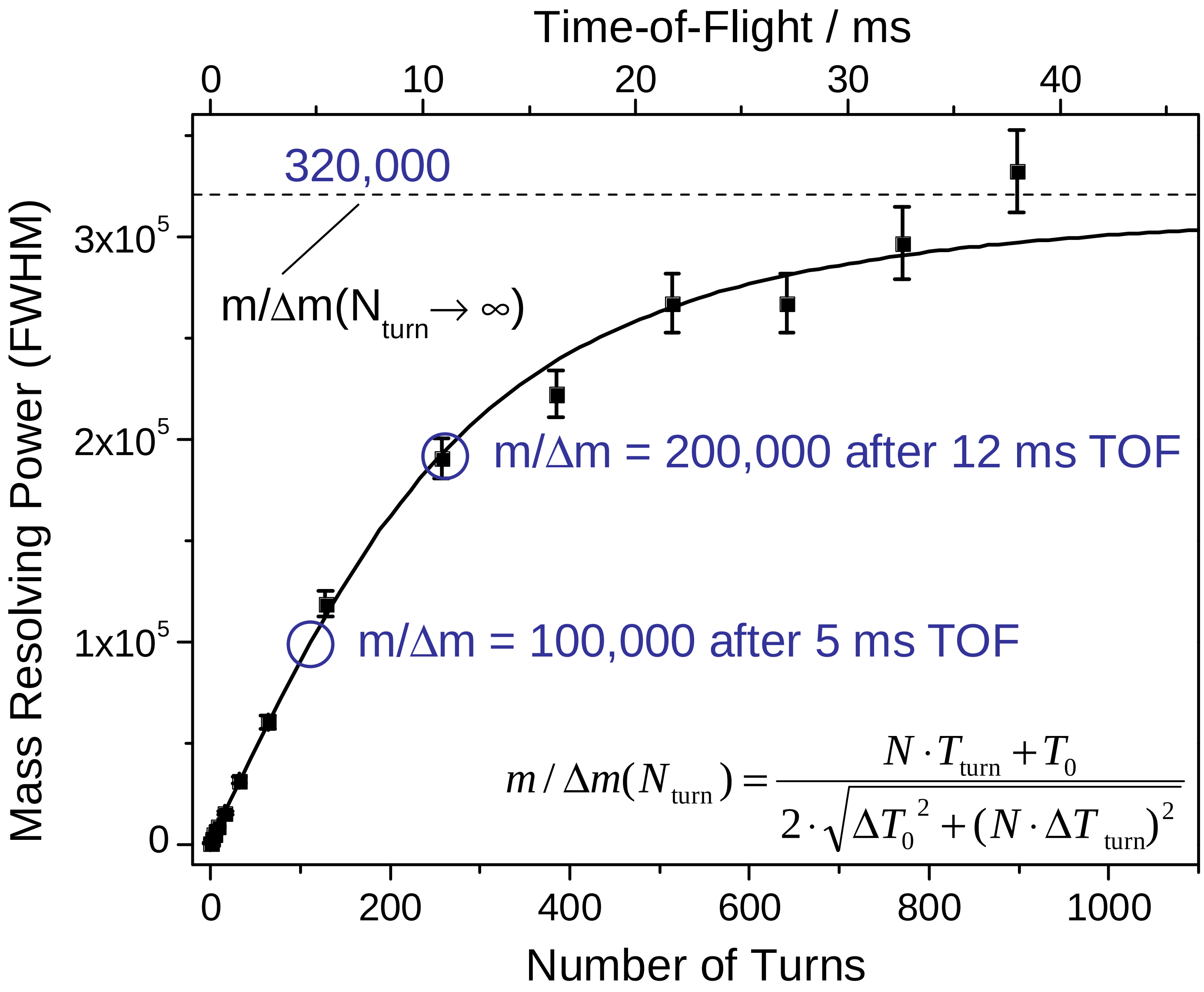
W.R. Plaß et al., NIM B 266 (2008) 4560

MR-TOF-MS: Setup

- Device including electronics mounted in one frame
- Easily transportable
- Variable entrance potential

→ Suitable to be employed at different facilities

MR-TOF-MS: Mass Resolving Power

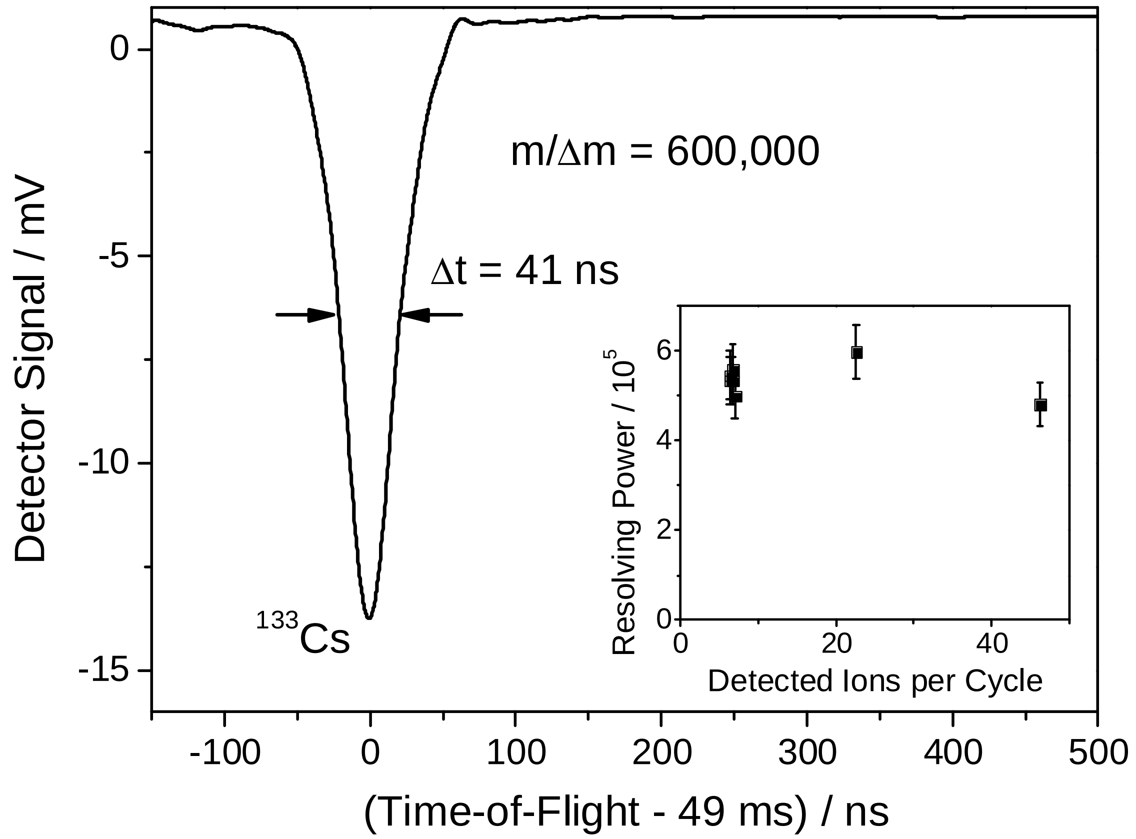


$$m/\Delta m(N_{turn}) = \frac{N \cdot T_{turn} + T_0}{2 \cdot \sqrt{\Delta T_0^{\,2} + (N \cdot \Delta T_{turn})^2}}$$

T. Dickel, PhD Thesis Justus-Liebig-Universität Giessen, 2010

$^{133}Cs^+$, Ion kinetic energy 760 eV

MR-TOF-MS Performance: Pushing the limits



Under optimized conditions: Mass resolving power m/Δm = 600 000!

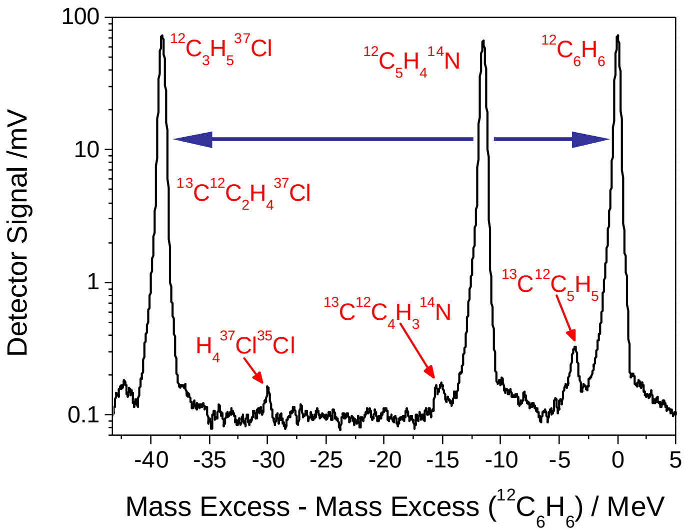
Comparable to 7 Tesla Penning trap (1 s measurement time),
but MR-TOF-MS advantages

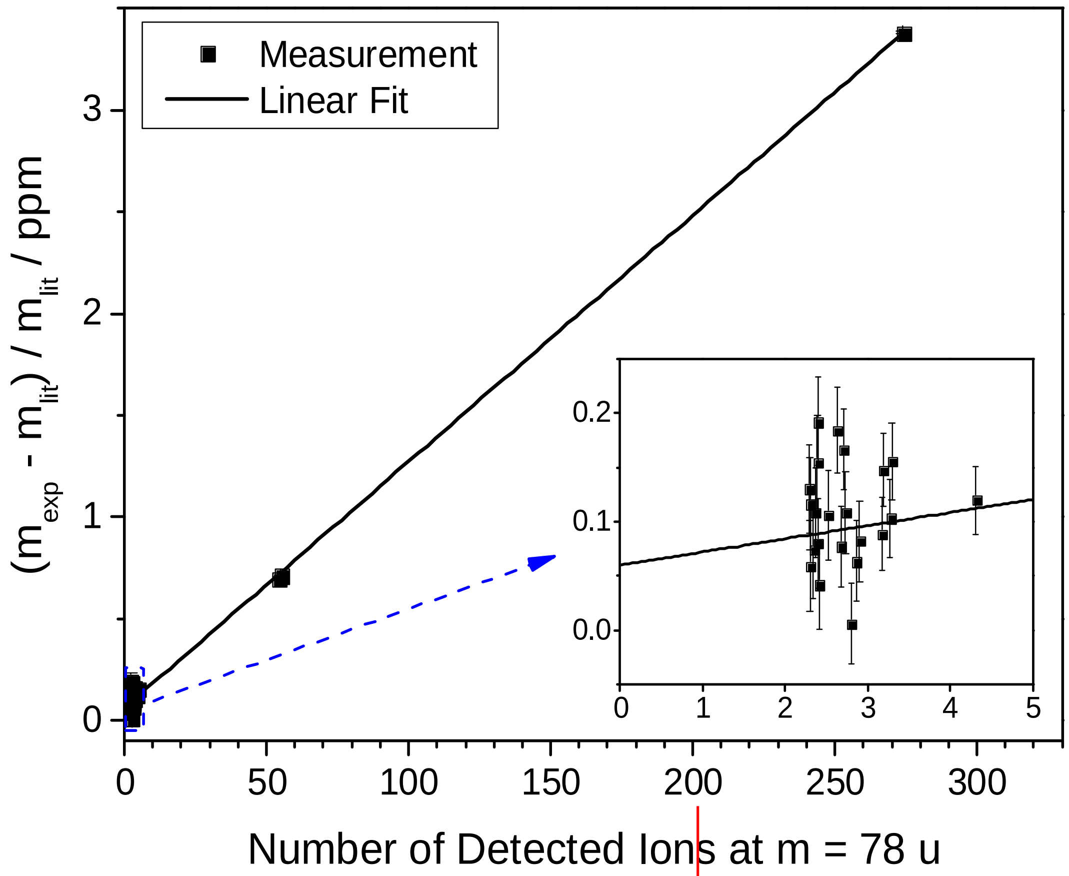
- 1/20 measurement time
- 1/10 detected ions needed

T. Dickel

MR-TOF-MS: Mass Accuracy

Isobar triplet at mass 78 u:
- dichloropropane ($C_3H_6Cl_2$),
- pyridine (C_5H_5N)
- benzene (C_6H_6)





10^4 total ions /cycle

Residual systematic uncertainty
$\delta m/m \sim 10^{-7}$

1 detected ion of m=78 u corresponds to 50 ions in the injection trap

Statistical uncertainty ($m/\Delta m = 6{\cdot}10^5$)
10 ions: $\delta m/m \sim 2{\cdot}10^{-7}$

T. Dickel, PhD Thesis Justus-Liebig-Universität Giessen, 2010

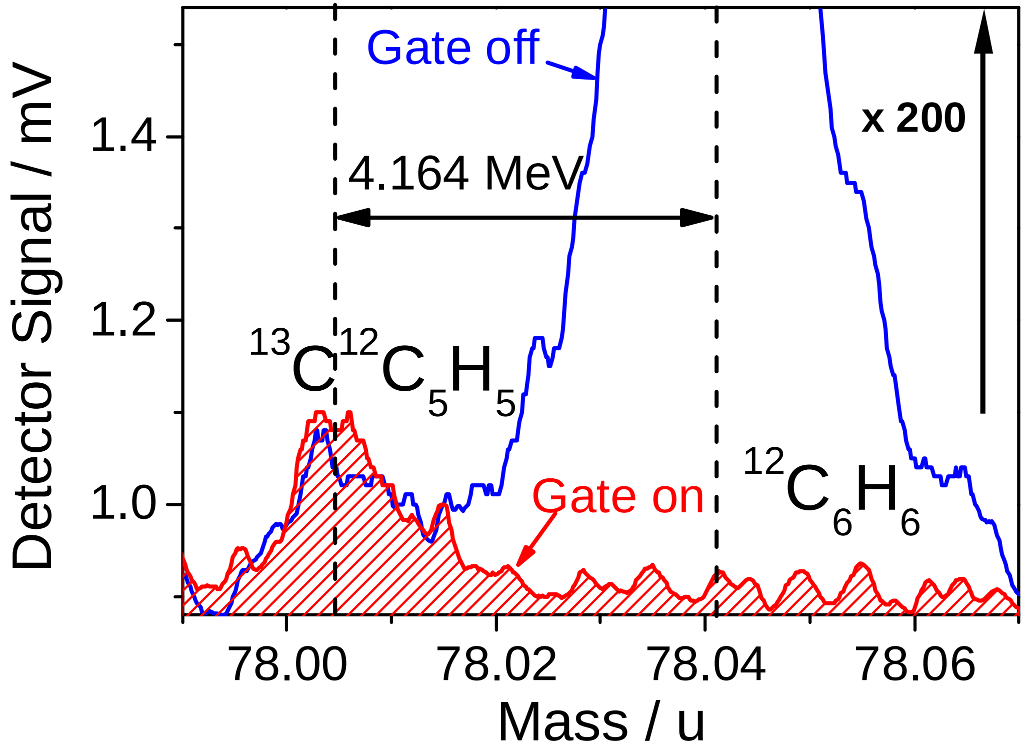
MR-TOF-MS: Isobar Separator

Combination of MR-TOF-MS and Bradbury-Nielsen Gate yields powerful isobar separator

- Proposed in 2005
- First demonstrated in 2006 W.R. Plaß et al., NIM B 266 (2008) 4560

Isobar separation demonstrated for C_6H_6 and $^{13}C^{12}C_5H_5$

- Intensity ratio 200:1
- Δm = 4 mu
- up to 10^4 ions/cycle $\rightarrow 10^6$ ions/s



T. Dickel, PhD Thesis Justus-Liebig-Universität Giessen, 2010

Performance Characteristics of the MR-TOF-MS

Universal mass spectrometer and mass separator
(works for all elements, stable and unstable ions)

Mass Resolving Power	Repetition Rate
600,000	up to 400 Hz

Mass Measurement Accuracy	Transmission efficiency
$\sim 10^{-7}$	up to 70%

Measurement Duration	Ion Capacity
~10 ms	> 10^6 ions / s

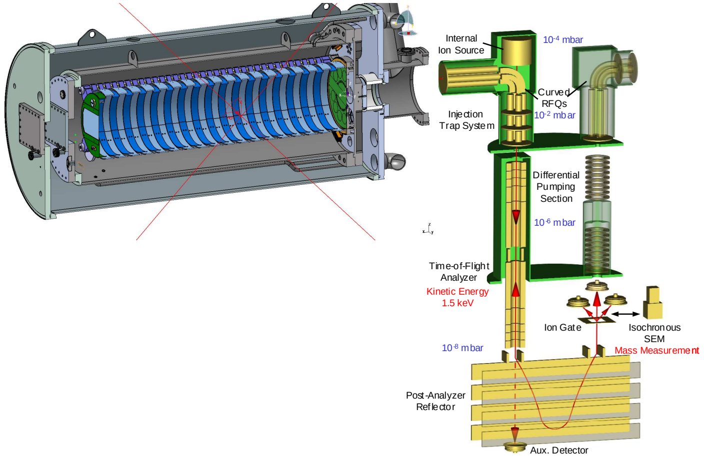
Sensitivity	Dynamic Range
~10 ions	> 10^4

World-wide unique combination of performance characteristics!

Further performance improvements are underway.

FRS Ion Catcher

Fragment separator FRS at GSI is the ideal instrument for testing Super-FRS developments



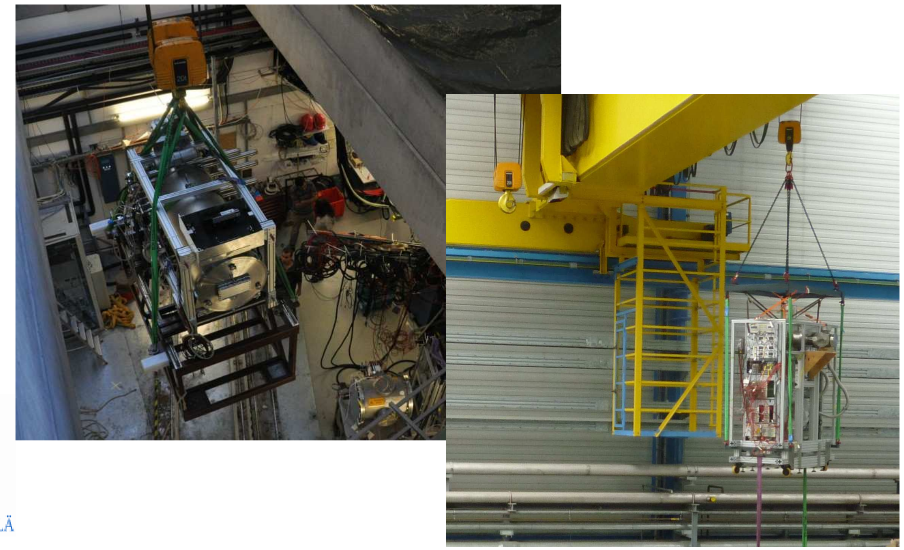
W.R. Plaß et al., GSI Scientific Report 2010 (2011) p. 137

FRS Ion Catcher

- Test facility for the cryogenic stopping cell and the MR-TOF-MS
- Potential for high-precision experiments with stopped projectile and fission fragments
  - Direct mass measurements
  - Mass-selected decay spectroscopy
  - ….

Challenges

- Limited space at the final focal plane
- Setup cannot be installed permanently
- Short setup times
- Limited amount of beam time



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university of groningen
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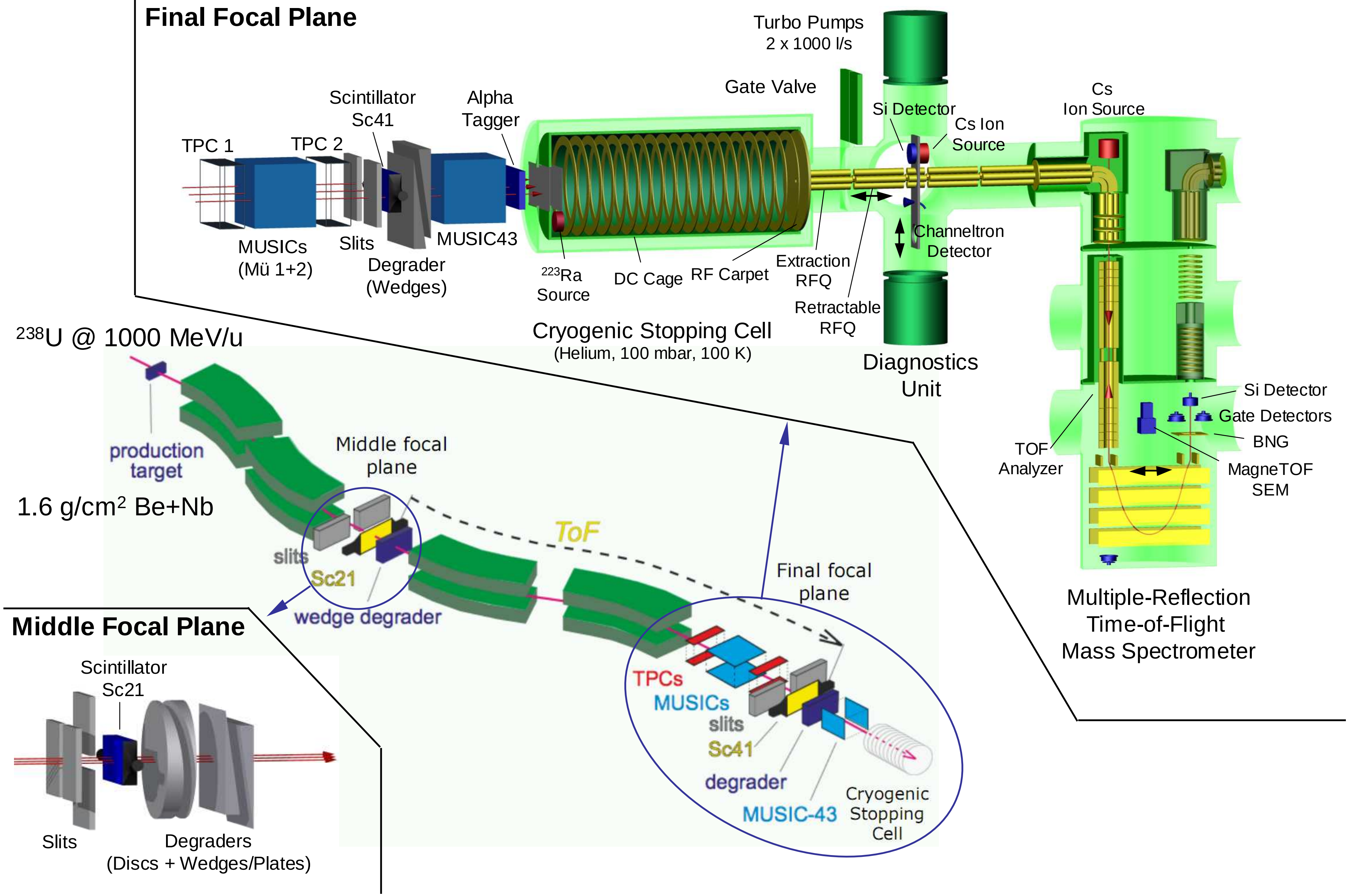
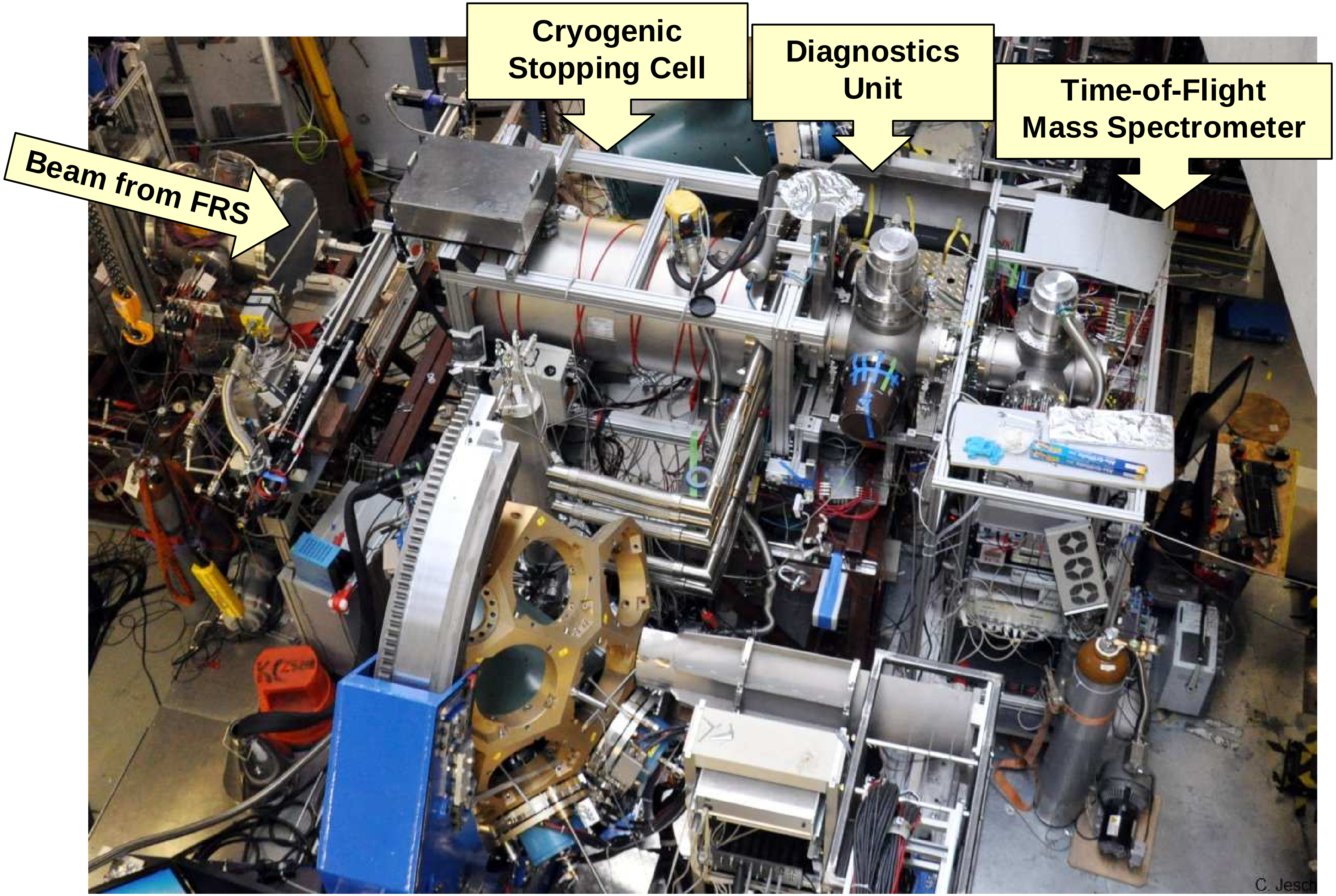
FRS Ion Catcher Experiment in Oct. 2011 / Jul. 2012

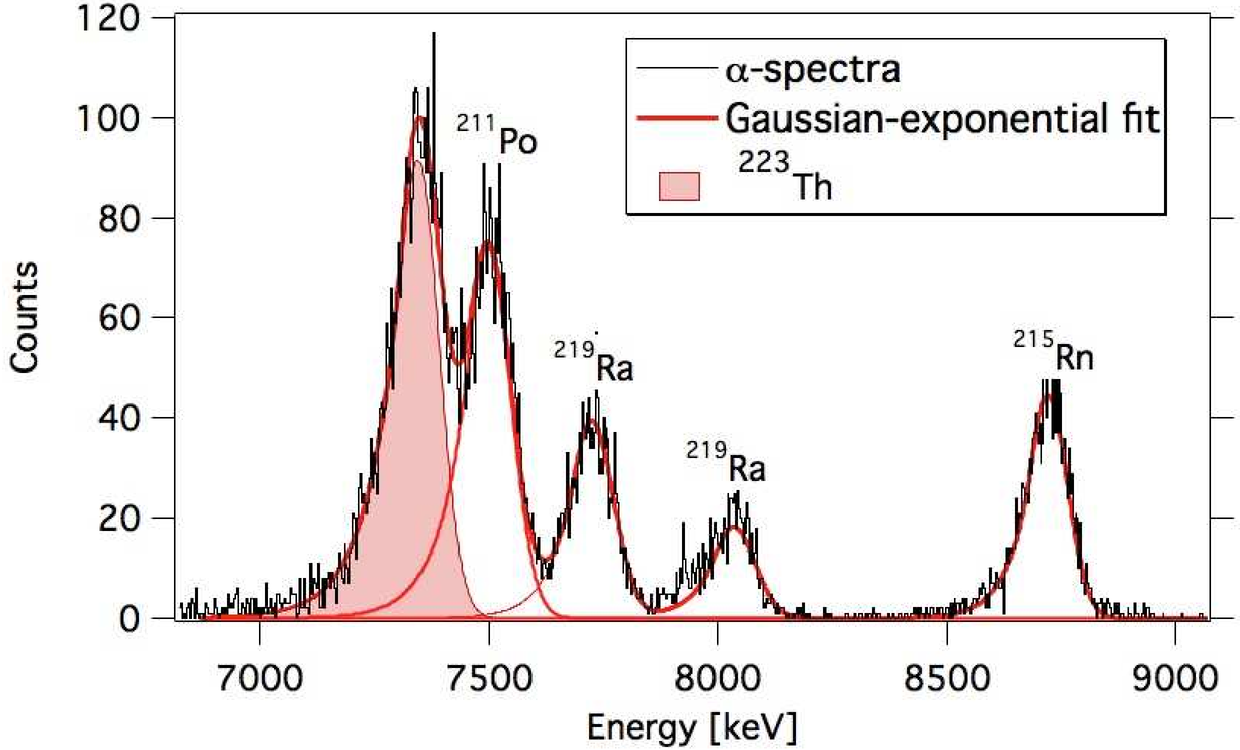


Setup at the FRS Ion Catcher

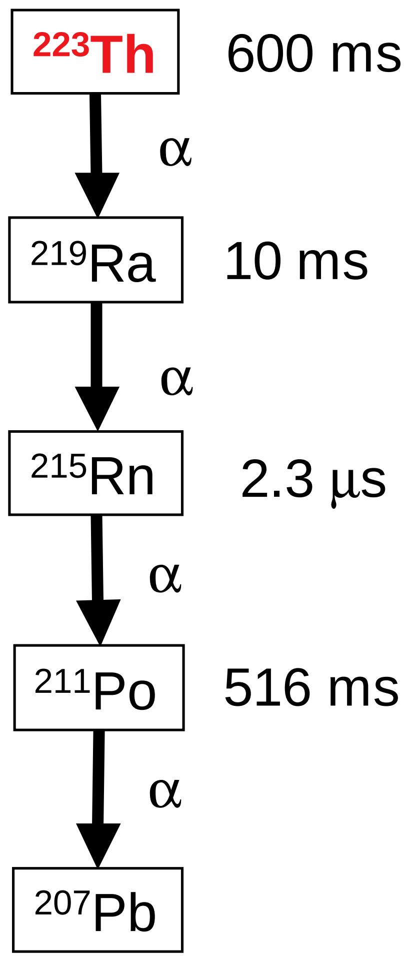


Stopping Cell Performance

Si detector spectrum of extracted projectile fragments



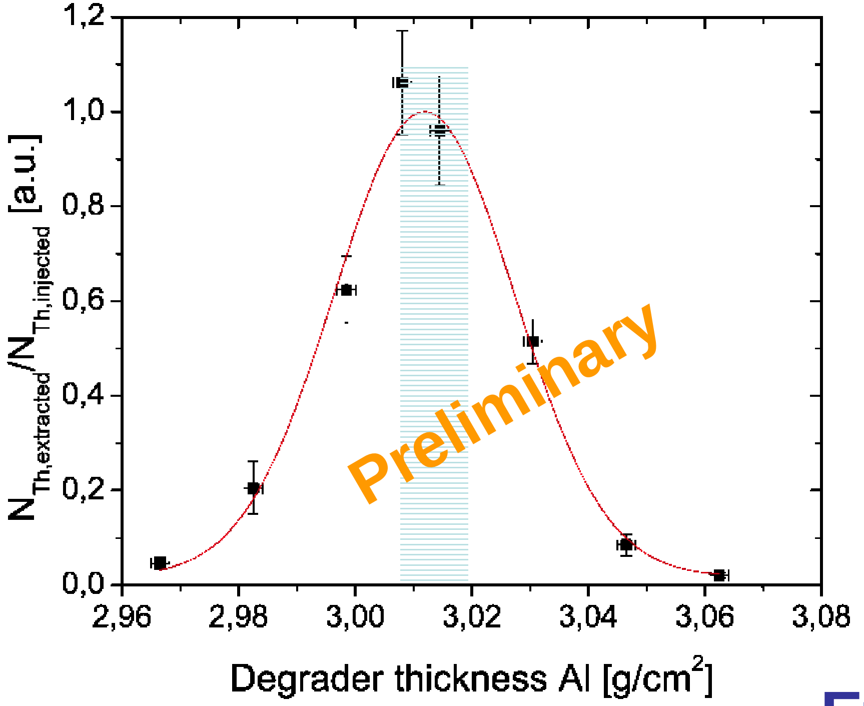
extracted as 2+



First on-line operation of a cryogenic stopping cell for exotic nuclei

Stopping and Extraction Efficiencies

Range distribution of ^{223}Th



- Range distribution:
  σ = 15 mg/cm^2 (Al)
  σ = 7.5 mg/cm^2 (He)
- Stopping cell: 100 mbar, 100 K
  $\rightarrow$ Areal density: 5 mg/cm^2 (He)
  $\rightarrow$ corresponds to ~ 300 mbar at room temperature

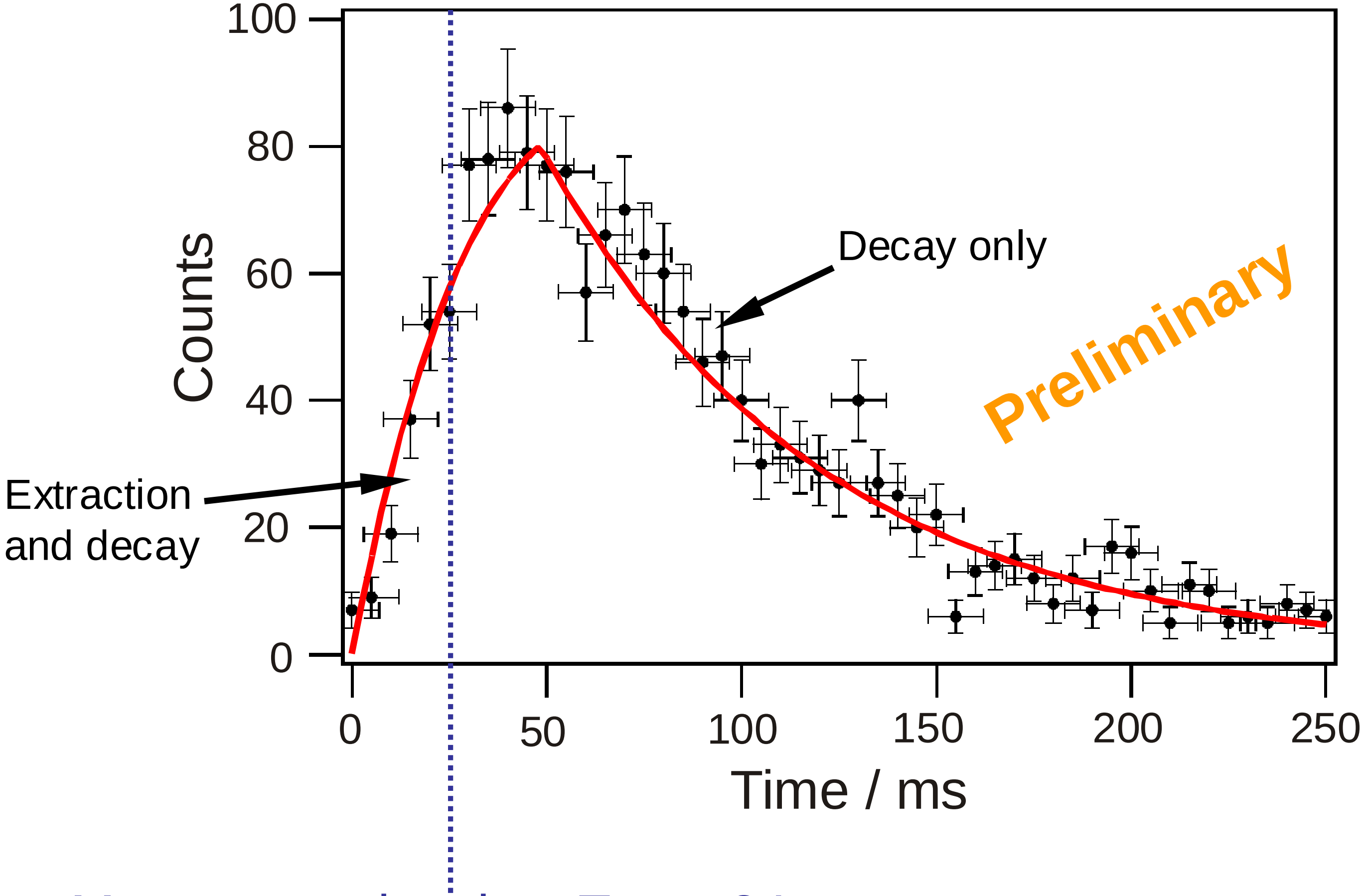
Efficiencies

	^{223}Th
Stopping efficiency	(27 ± 3)%
Survival and extraction efficiency	(43 ± 9)%
Total efficiency	(12 ± 2)%

Preliminary

Extraction Time

Extraction of ^{221}Ac ($T_{1/2}$ = 52 ms)

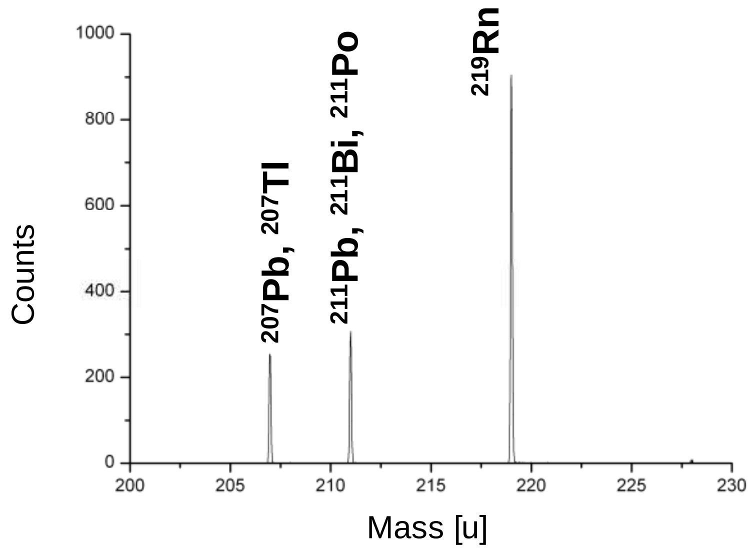


Pressure = 50 mbar,
Temperature = 75 K
DC field = 23 V/cm

Mean extraction time T_{extr} = 24 ms
Theory (K_0=15 cm^2/Vs) T_{extr} = 27 ms

Cleanliness of the Stopping Cell

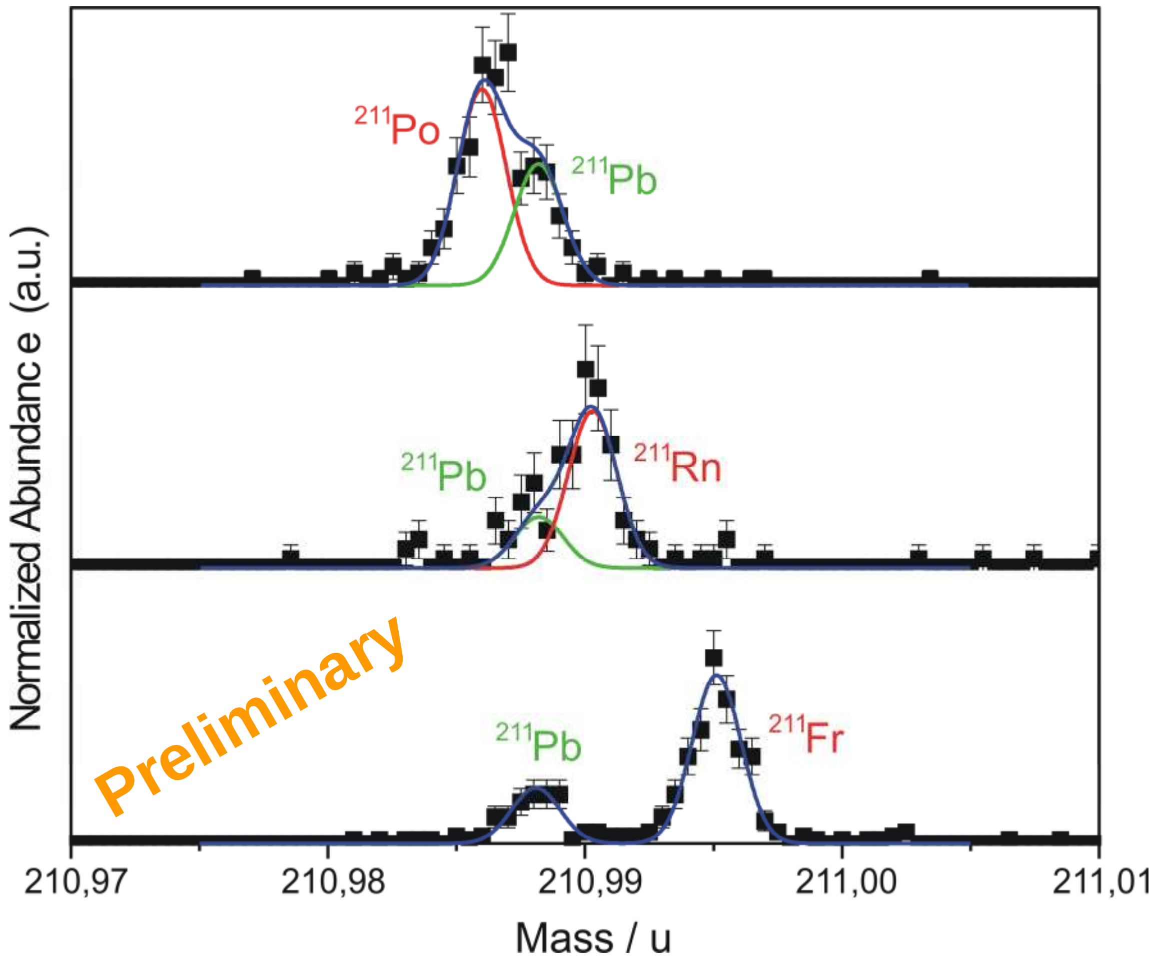
Broadband mass spectrum taken with the MR-TOF-MS



- Molecular contaminants / adduct formation are not a problem for the cryogenic stopping cell
- Broadband mass spectrometry is a necessity for quick and reliable operation of a stopping cell

MR-TOF-MS Mass Measurements

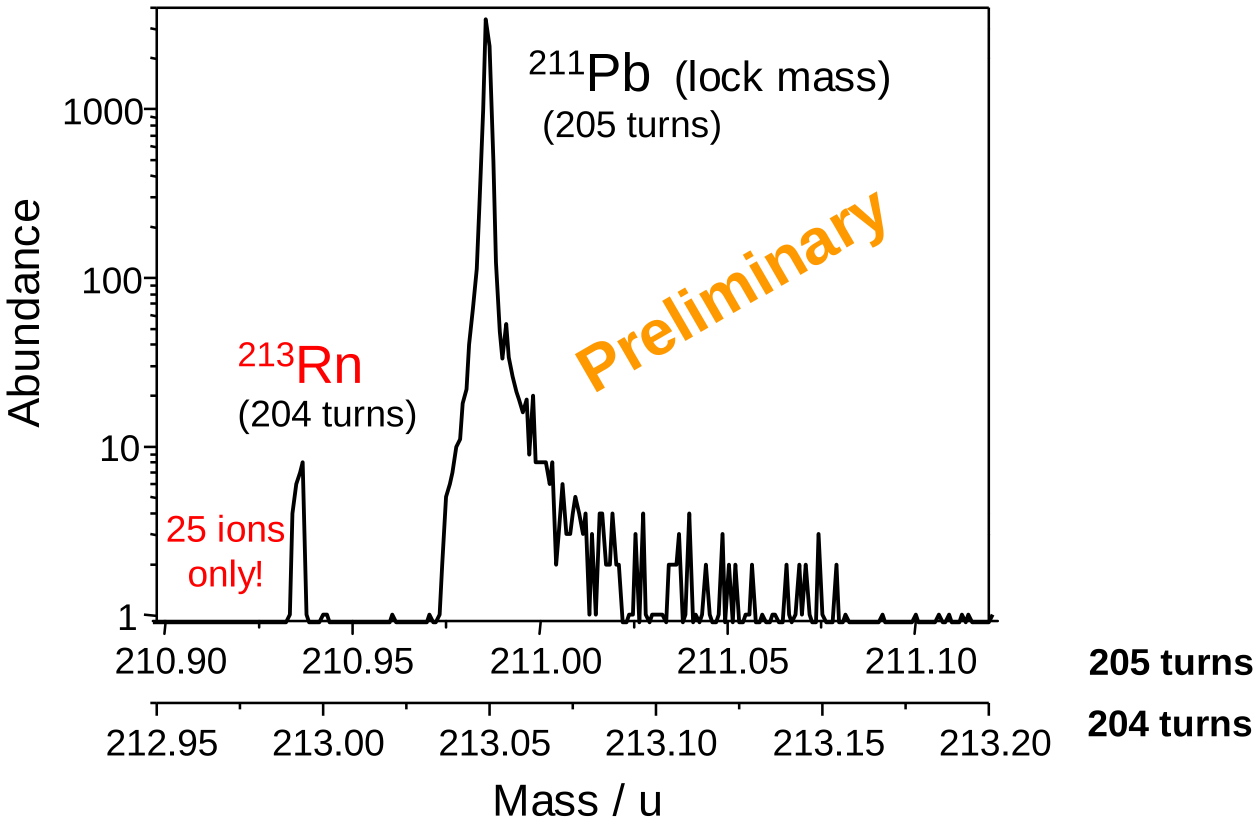
First direct mass measurements of ^{211}Po and ^{211}Rn



First direct mass measurements of projectile fragments with an MR-TOF-MS

MR-TOF-MS Mass Measurements

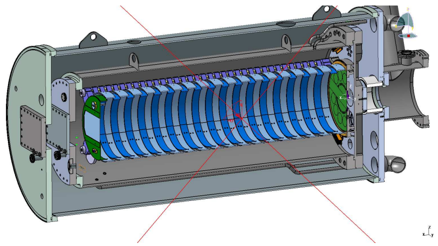
First direct mass measurement of ^{213}Rn ($T_{1/2}$ = 19.5 ms)



Conclusions

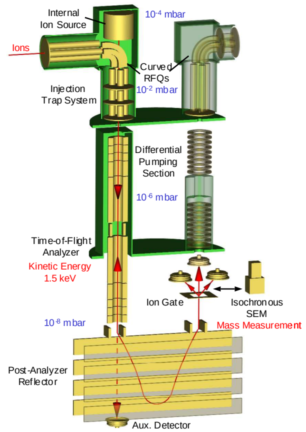
Stopping cell for the Super-FRS and the FRS Ion Catcher

- Cryogenic, high density operation, suitable for exotic nuclei produced at relativistic energies
- Commissioned off-line and on-line
- Preliminary performance values:
  Stopping efficiency ~ 27% (^{223}Th),
  Survival and extraction efficiency ~ 43%
  Extraction time ~ 25 ms



High-performance multiple-reflection time-of-flight mass spectrometer

- Mass resolving power up to 600.000 at 50% transmission
  Mass measurement accuracy down to 10^{-7}
  Cycle time ~ 10 ms
  Single ion sensitivity
- First direct mass measurements of projectile fragments
- High-resolution mass separator
- Diagnostics tool: identification and quantification



Outlook

Cryogenic stopping cell

- Systematic study of the cryogenic stopping cell (e.g. intensity limitations, temperature effects)
- Increase stopping efficiency even further (higher densities)

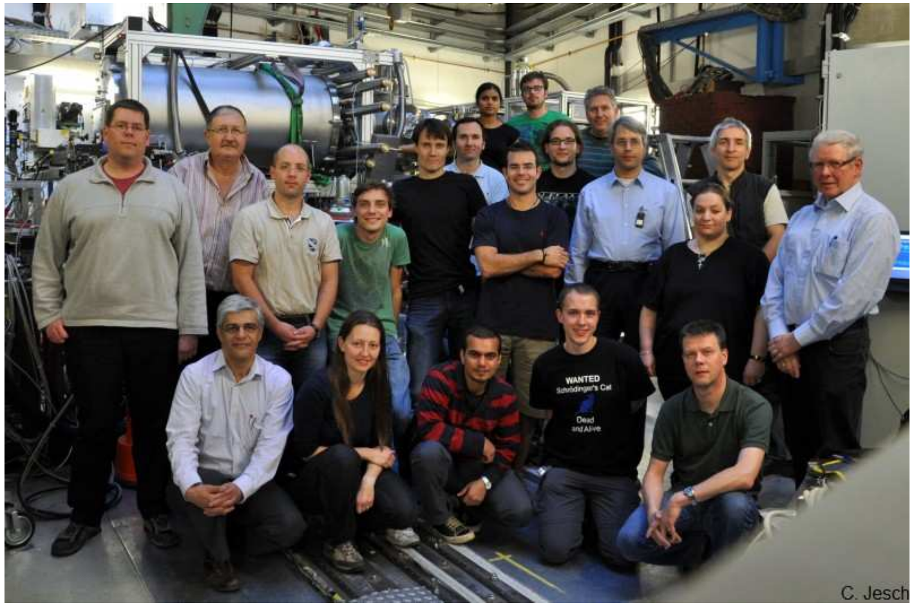
MR-TOF-MS

- Further performance improvements (higher voltages, highly stable HV, cryogenic injection trap, ultra-high-performance analyzer, etc.)
  $\rightarrow$ Resolving power > 10^6 $\rightarrow$ Isomer separator!
- Systematic study of mass measurement accuracy, laser ablation ion source for mass calibration
- Perform mass measurements at the FRS Ion Catcher
- Experiments possible at other facilities (SHIP, TRIUMF, JYFL, ...); applications in analytical mass spectrometry

Acknowledgements

FRS Ion Catcher / S411 Collaboration

F. Amjad[2], S. Ayet[2], T. Dickel[1,2], P. Dendooven[3], M. Diwisch[1], J. Ebert[1], A. Estrade[2], F. Farinon[2], H. Geissel[1,2], F. Greiner[1], E. Haettner[1], C. Jesch[1], N. Kalantar-Nayestanaki[3], R. Knöbel[2], J. Kurcewicz[2], J. Lang[1], I. Moore[4], C. Nociforo[2], M. Petrick[1], M. Pfuetzner[2], W.R. Plaß[1,2], S. Pietri[2], A. Prochazka[2], S. Purushothaman[2], M. Ranjan[3], M.P. Reiter[1], A.-K. Rink[1], S. Rinta-Antila[4], C. Scheidenberger[2], M. Takechi[2], Y. Tanaka[2], H. Weick[2], J.S. Winfield[2], M.I. Yavor[5]



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[4] University of Jyväskylä, Jyväskylä, Finland
[5] Institute for Analytical Instrumentation, RAS, St. Petersburg, Russia

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