

# FAIR Ion Catcher

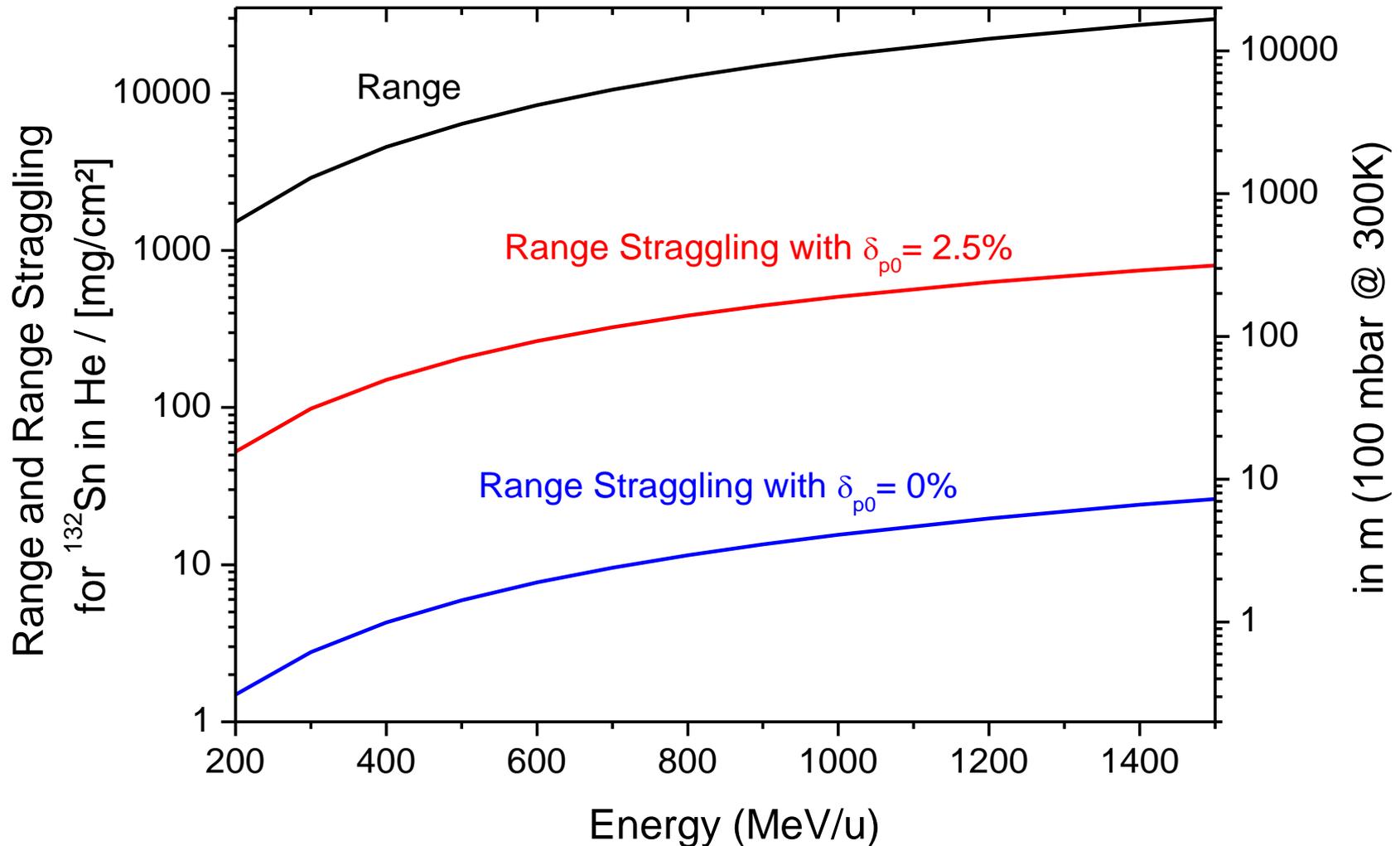
Timo Dickel

GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt  
II. Physikalisches Institut, Justus-Liebig-Universität Gießen, Germany

- Challenges and concepts for the Ion Catcher @ FAIR
- FRS Ion Catcher:
  - PID by mass measurements
  - Gas Degradar
  - Measurements with isomers
- Next generation CSC for FAIR

# Challenge of Thermalizing Relativistic Ions

Range straggeling:



Beam size:

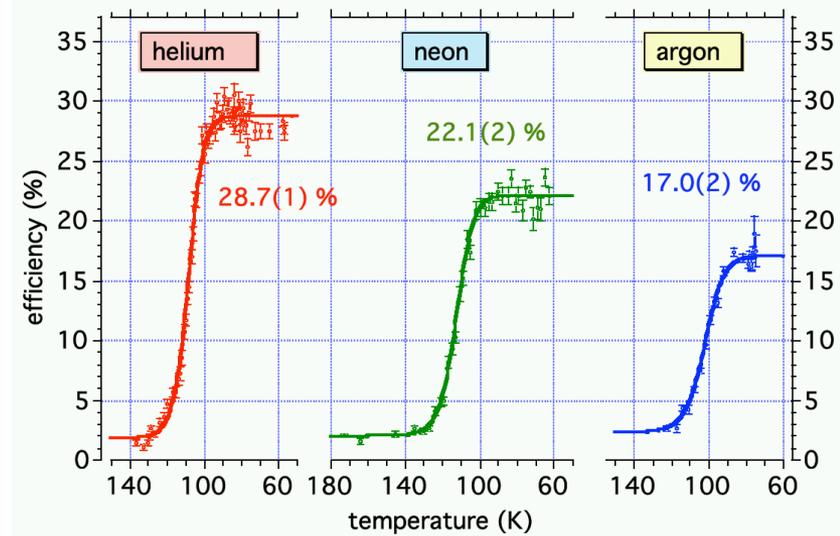
At the LEB of the Super-FRS ~ 200x100mm<sup>2</sup>

# 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

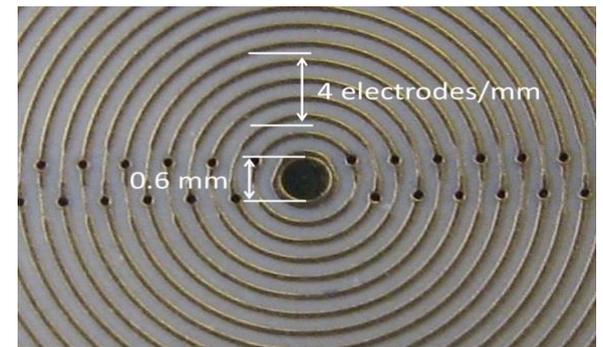
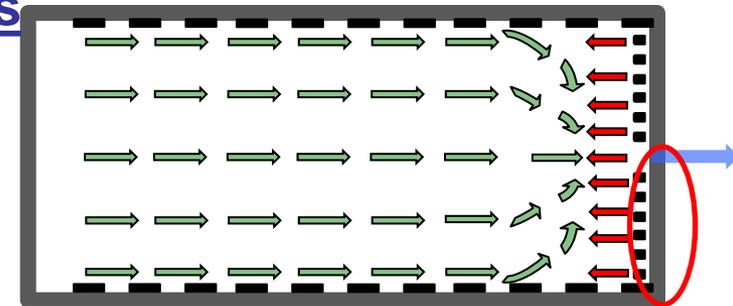
Effective RF field repels ions from electrodes

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

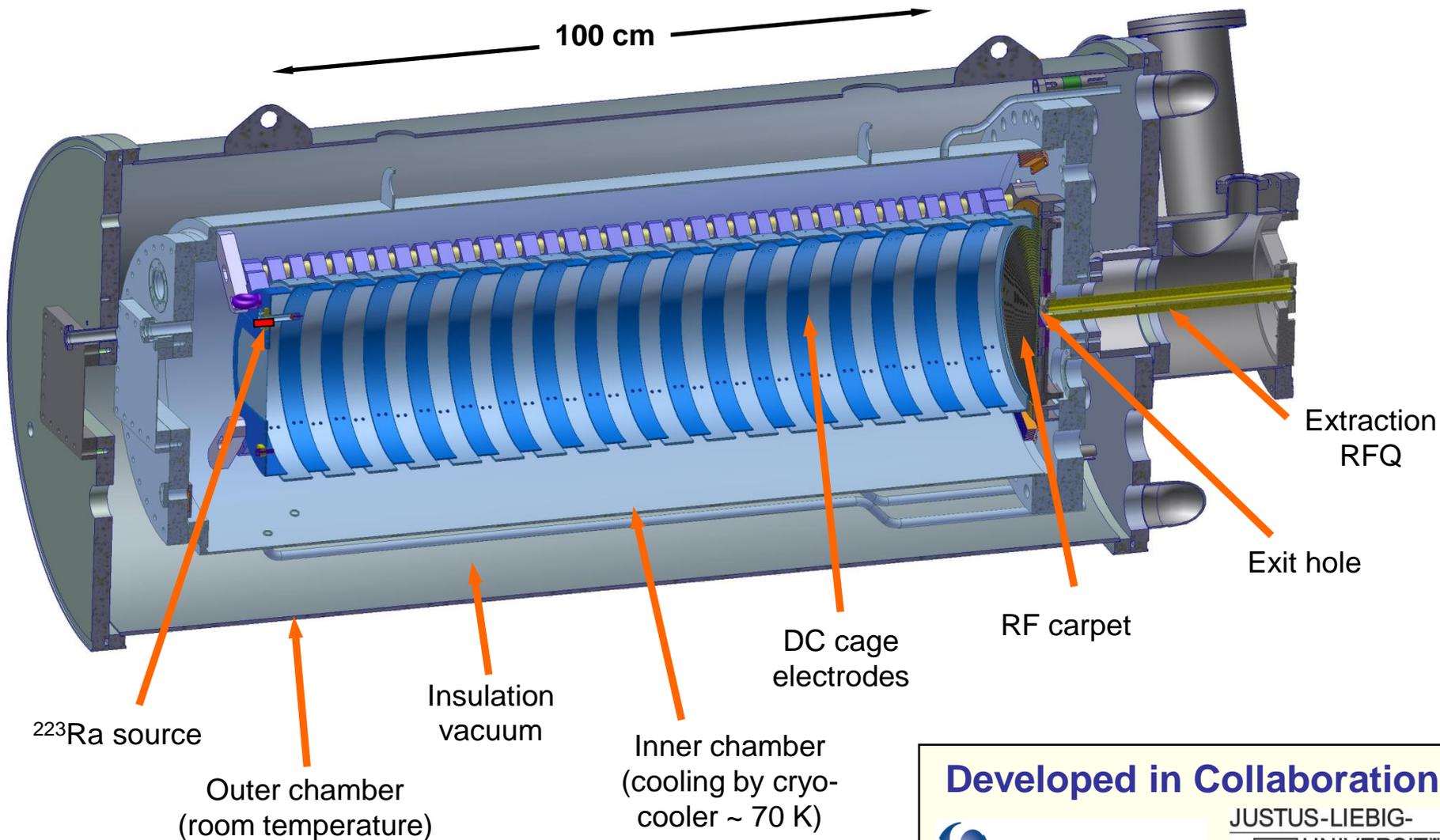
← limited by discharges  
 ← **reduce structure size!**  
 ← high gas density → reduction of effective field

**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



# Prototype of the Stopping Cell for the LEB



Developed in Collaboration



Kernfysisch Versneller Instituut



university of  
 groningen

JUSTUS-LIEBIG-



UNIVERSITÄT  
 GIESSEN



- M. Ranjan et al., Europhys. Lett. 96 (2011) 52001.
- W.R. Plaß et al., Nucl. Instrum. Methods B 317 (2013) 457.
- M. Ranjan et al., Nucl. Instrum. Methods A 770 (2015) 87.

# Why TOF Mass Spectrometry in Nuclear Physics?

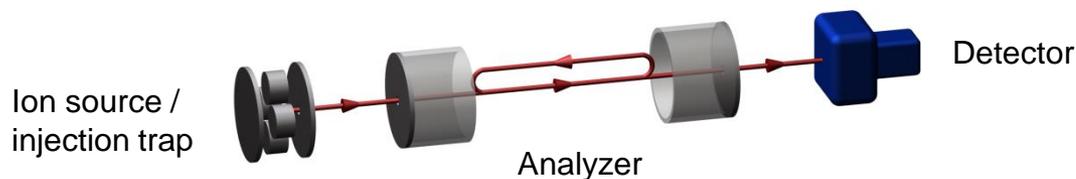
## Enables high performance

- Fast → access to very short-lived ions ( $T_{1/2} \sim \text{ms}$ )
- Sensitive, broadband, non-scanning → efficient, access to rare ions
- Mass resolving power and accuracy almost mass-independent

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)

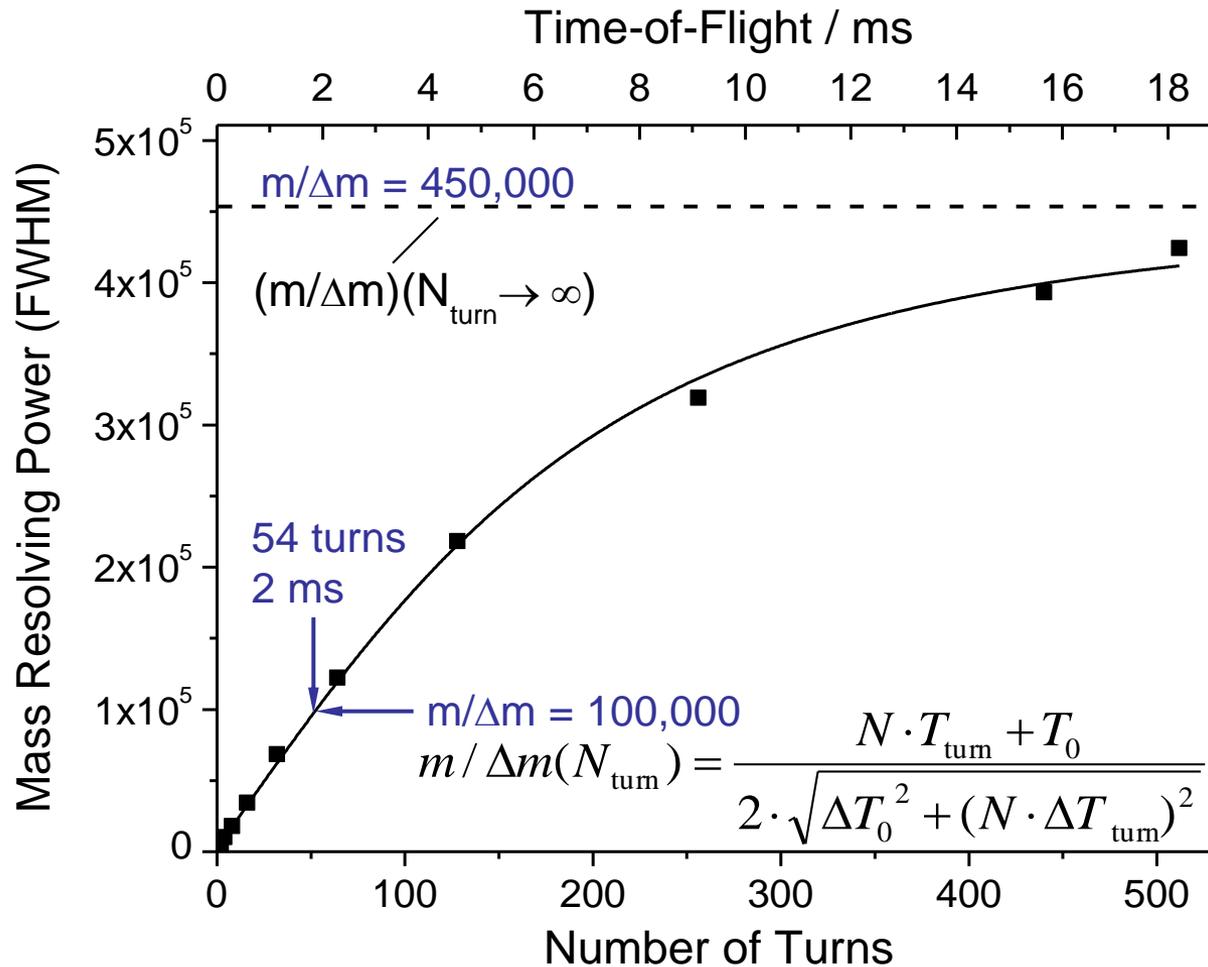


H. Wollnik et al., Int. J. Mass Spectrom. Ion Processes 96 (1990) 267

## 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., Int. J. Mass Spectrom. 394 (2013) 134

# MR-TOF-MS: Mass Resolving Power



Mass Measurement Accuracy

$\sim 10^{-7}$

Transmission efficiency

up to 70%

Sensitivity

$\sim 10$  ions

Isobar separator with high ion capacity

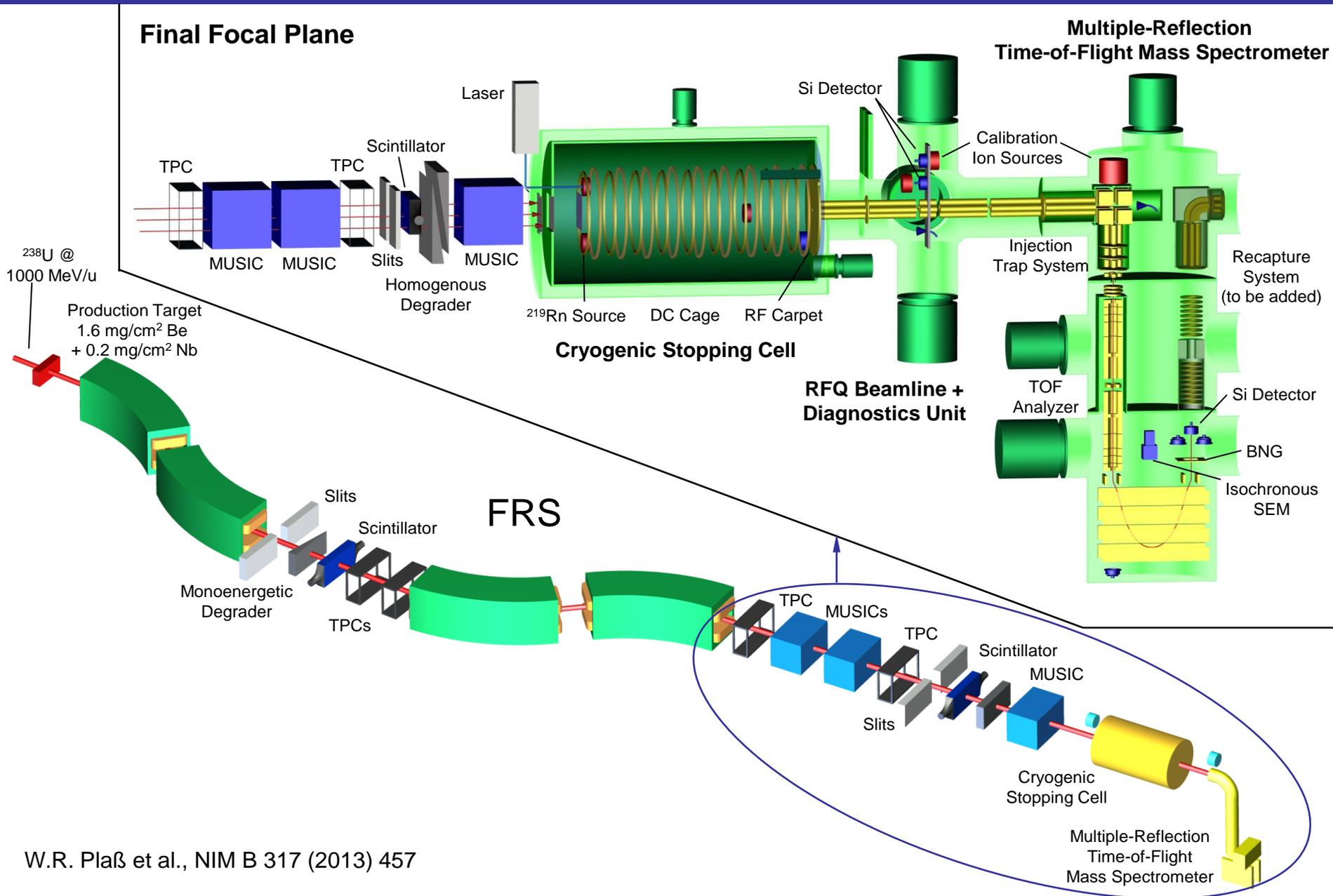
$>10^6$  ions/s

**World-wide unique combination of performance characteristics!**

$^{133}\text{Cs}^+$ , Ion kinetic energy 1.3 keV

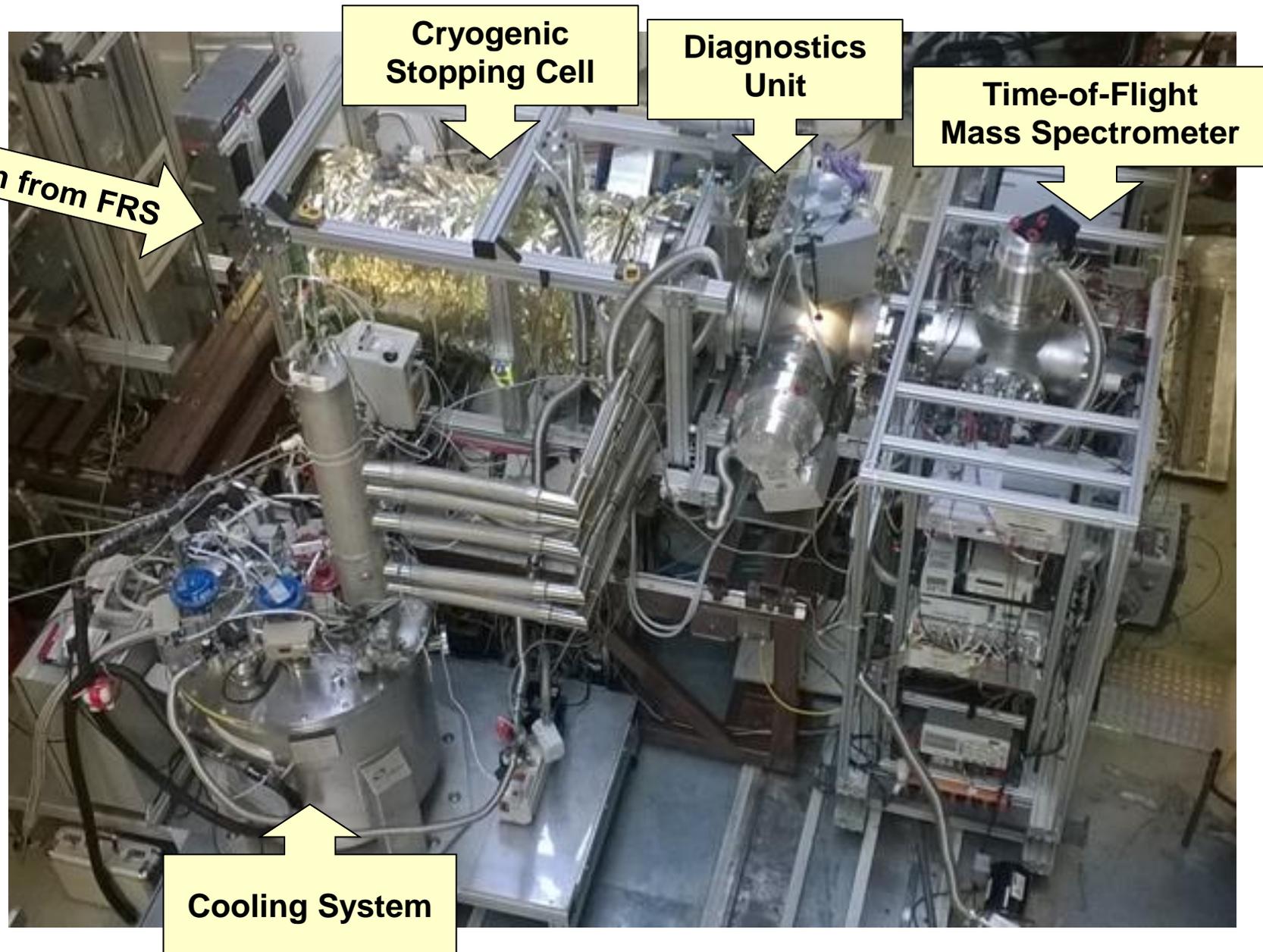
W.R. Plaß et al., Phys. Scr. T166 (2015) 014069  
T. Dickel et al., NIM A 777 (2015) 172 - 188

# FRS Ion Catcher at GSI



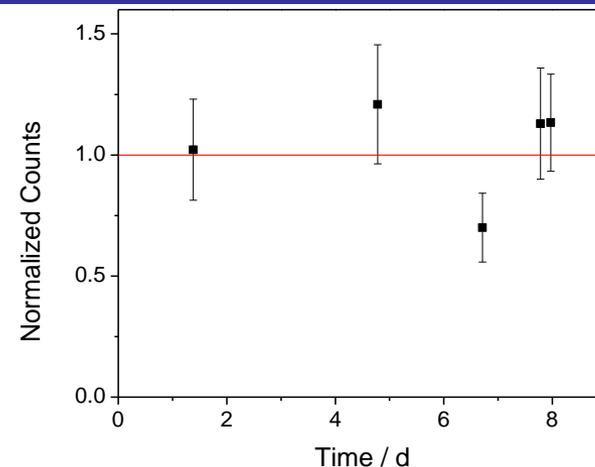
W.R. Plaß et al., NIM B 317 (2013) 457

# Setup at the FRS Ion Catcher at GSI

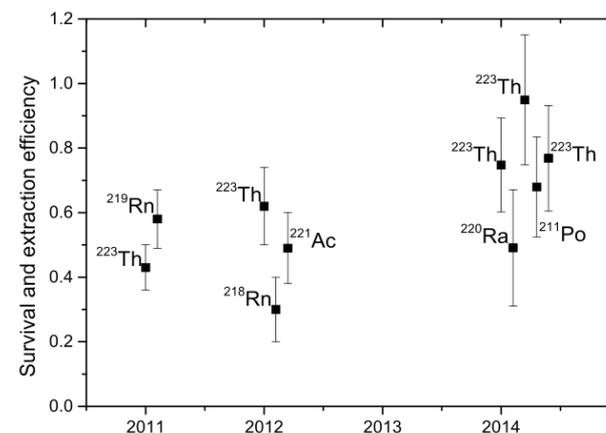


# Characterization of the CSC

- **Stability of operation:**  
Stable over one week beam time
- **Improved bake-out + New carpet**  
→ better cleanliness  
→ Higher ion survival and extraction efficiency (eg.  $^{223}\text{Th}$ )



- **Higher differential pumping**  
→ Higher areal density → Higher stopping efficiency  
2012: 3.1 mg / cm<sup>2</sup>  
2014: 6.3 mg / cm<sup>2</sup>



→ Improved total efficiency up to 30%

- **Extraction time:** 25 ms

P. Reiter, PhD 2015

Purushothaman S. et al, EPL 104 (2013) 42001

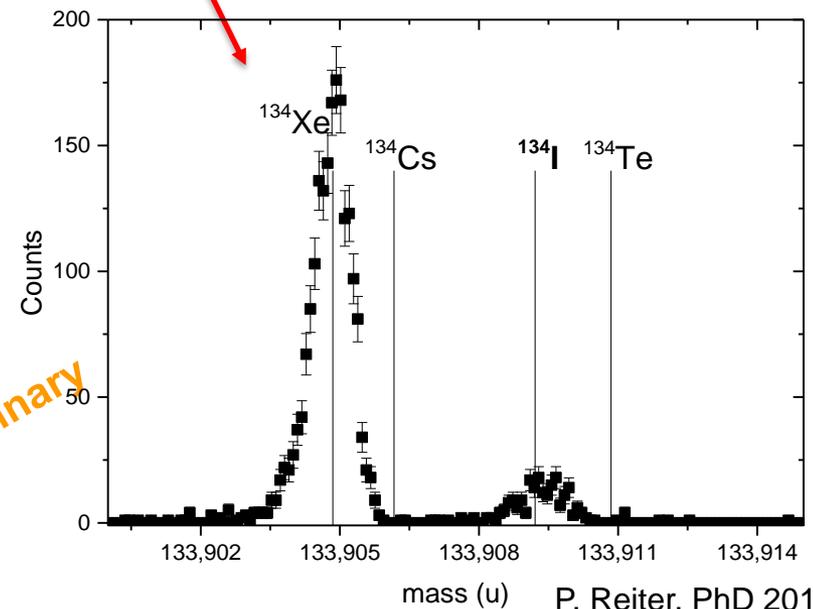
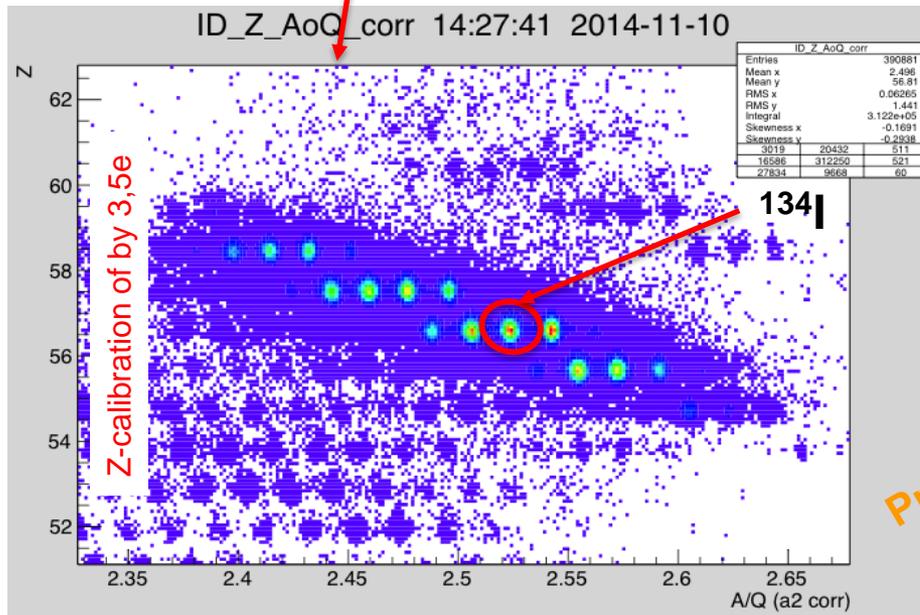
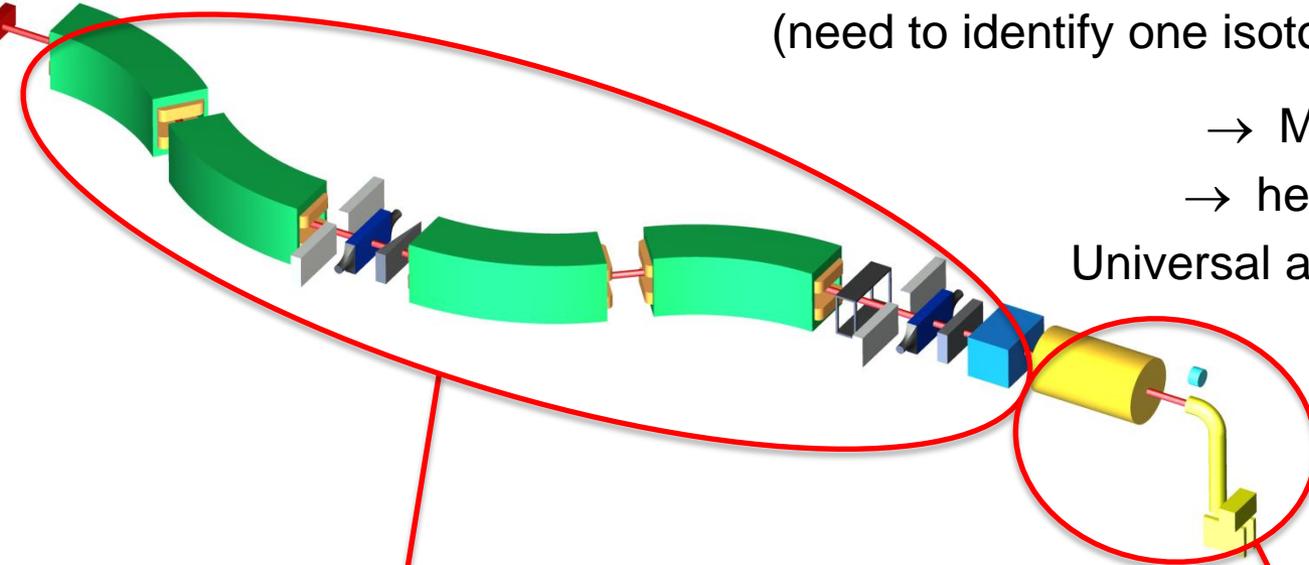
# CSC + MR-TOF-MS as Mass Tagger

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  $^{134}\text{I}$

Universal and fast technique (~20 min)



# Particle ID by MS only

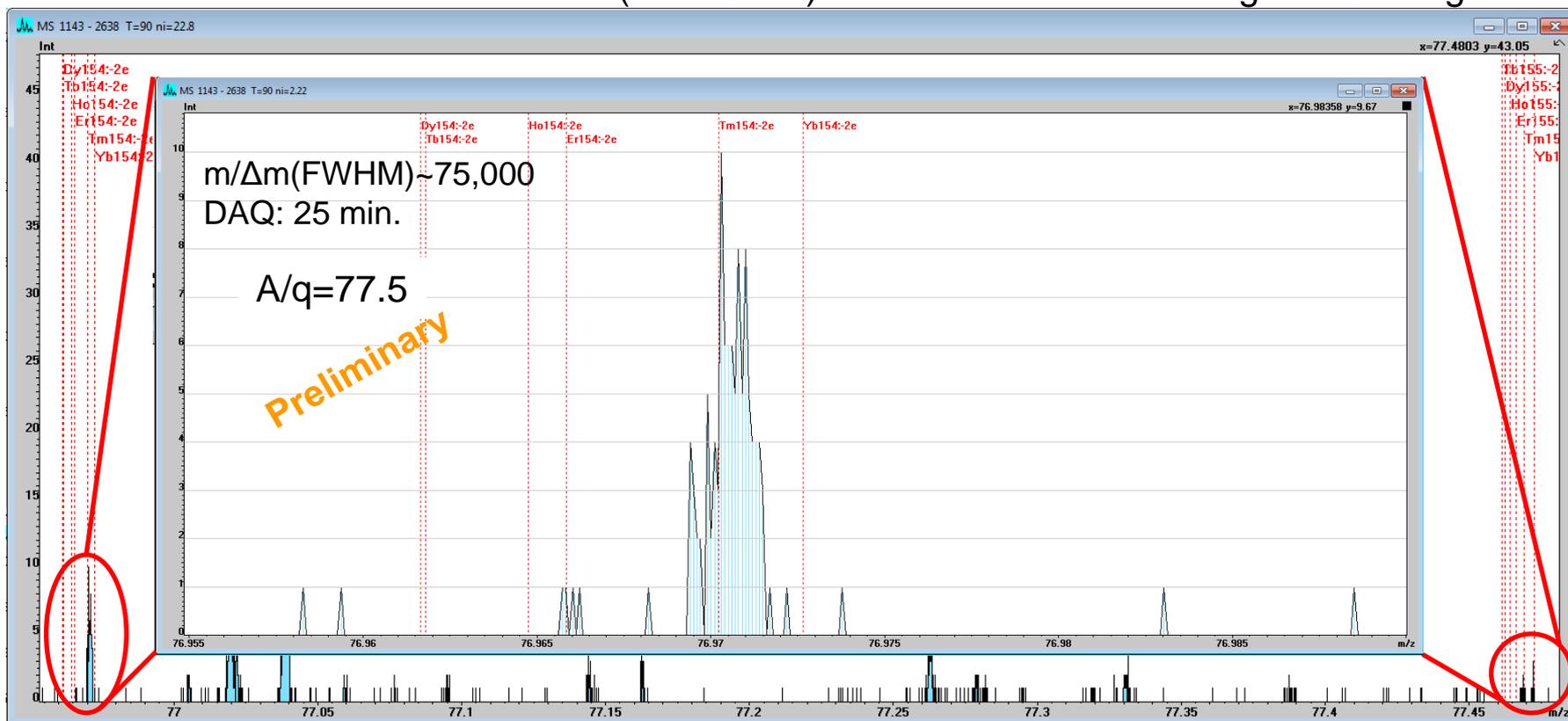
Problem:

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  $^{238}\text{U}$  on a 0.4g/cm<sup>2</sup> Be target



Particle ID for Z=70 @ 300MeV/u primary beam

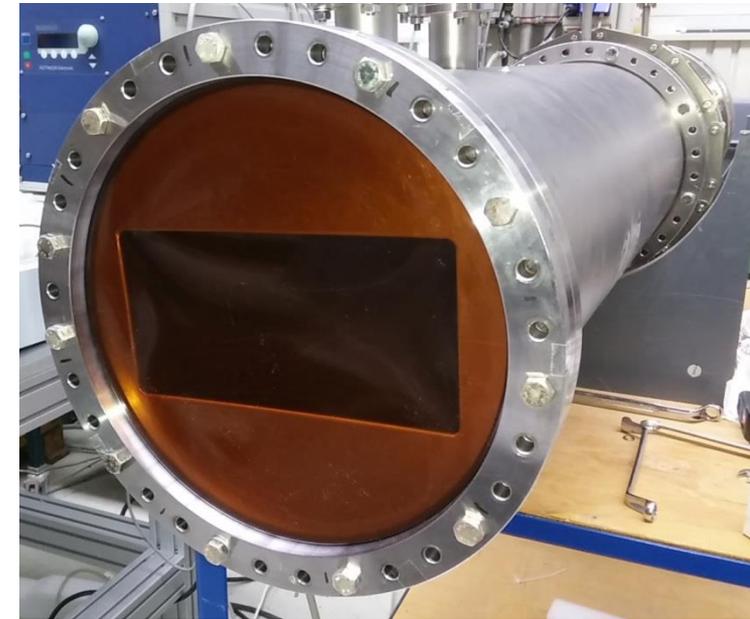
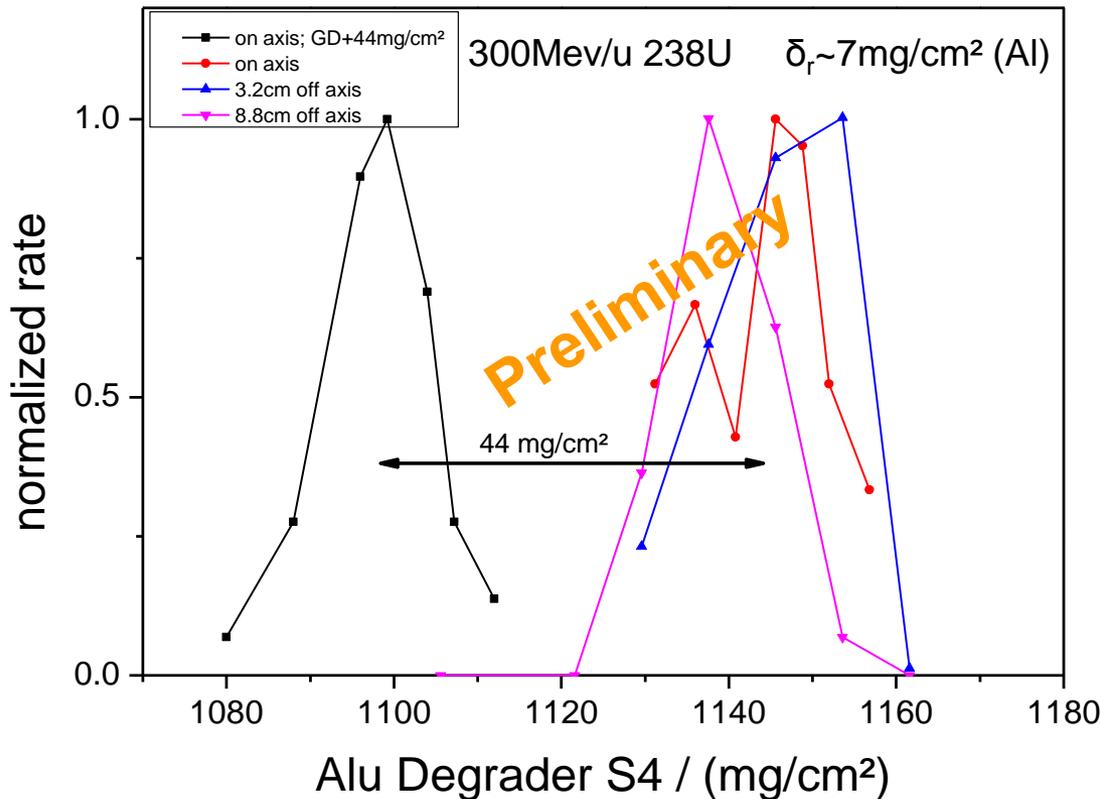
E. Haettner et al.

# Gas Degradar

At the LEB very homogenous, large and thin degraders are necessary

Novel degrader concept:

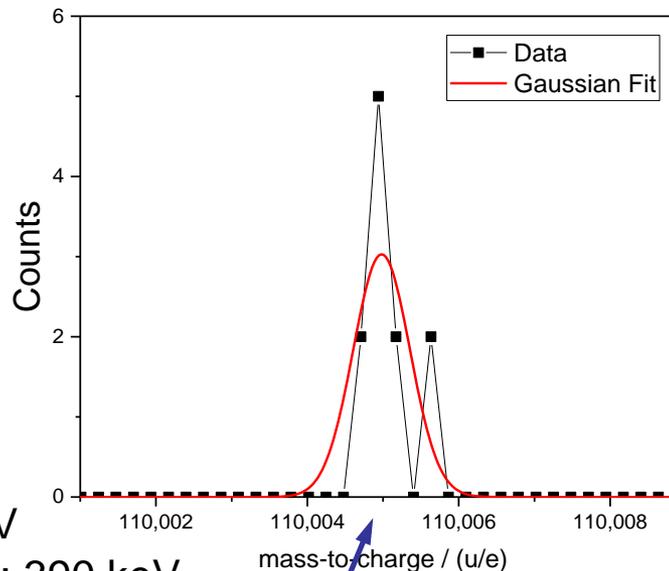
- vacuum chamber (1.5m length) with pressure between 0 and 0.9 bar
- Thin Kapton windows, carbon coated
- corresponding to a areal density of  $\sim(40 - 200)$  mg/cm<sup>2</sup>
- replace 1.5 m air (180 mg/cm<sup>2</sup>)



S. Purushothaman et al.

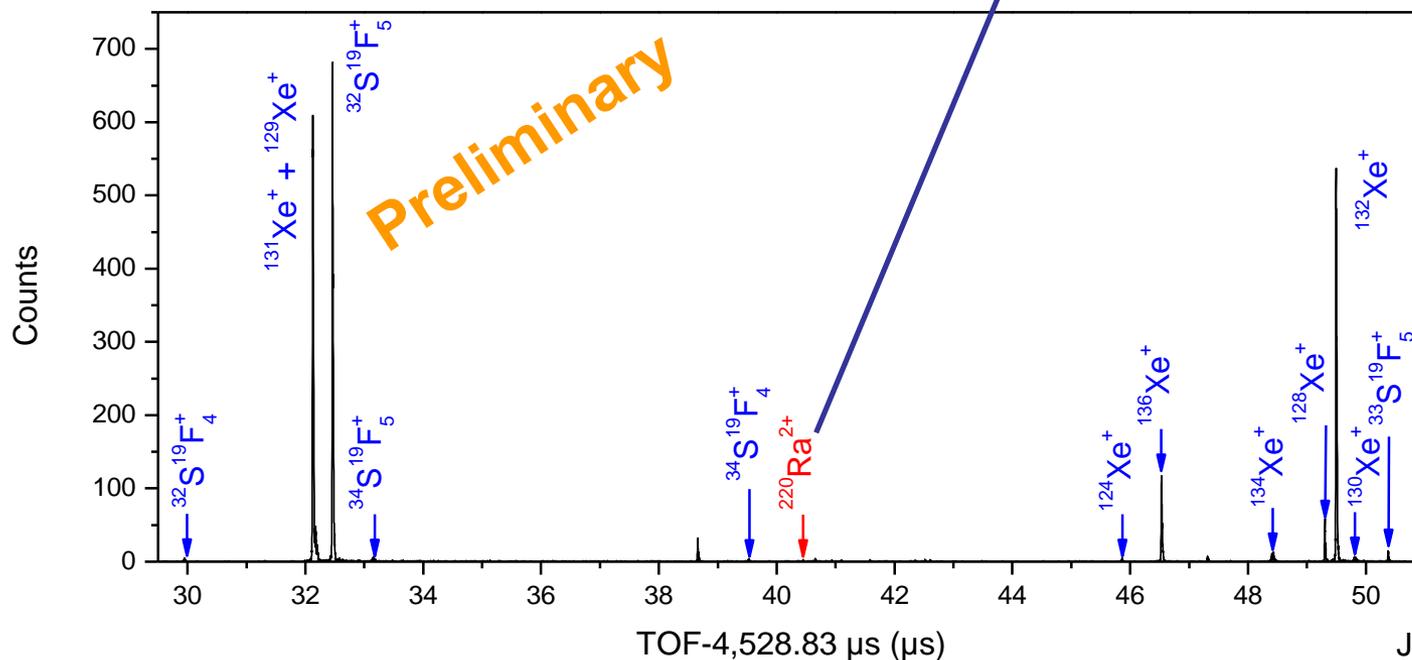
# Mass Measurement: Uranium Projectile Fragments

- Mass window of  $\sim 30$  u
- Mass resolving power  $\sim 140,000$
- Doubly charged
- Shortest half-life
- Highest sensitivity



**$^{220}\text{Ra}^{2+}$**   
**Half-life: 17.9 ms**  
**11 ions**

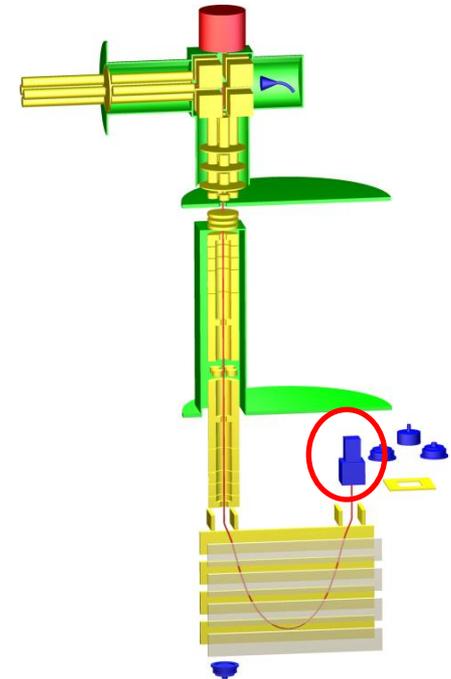
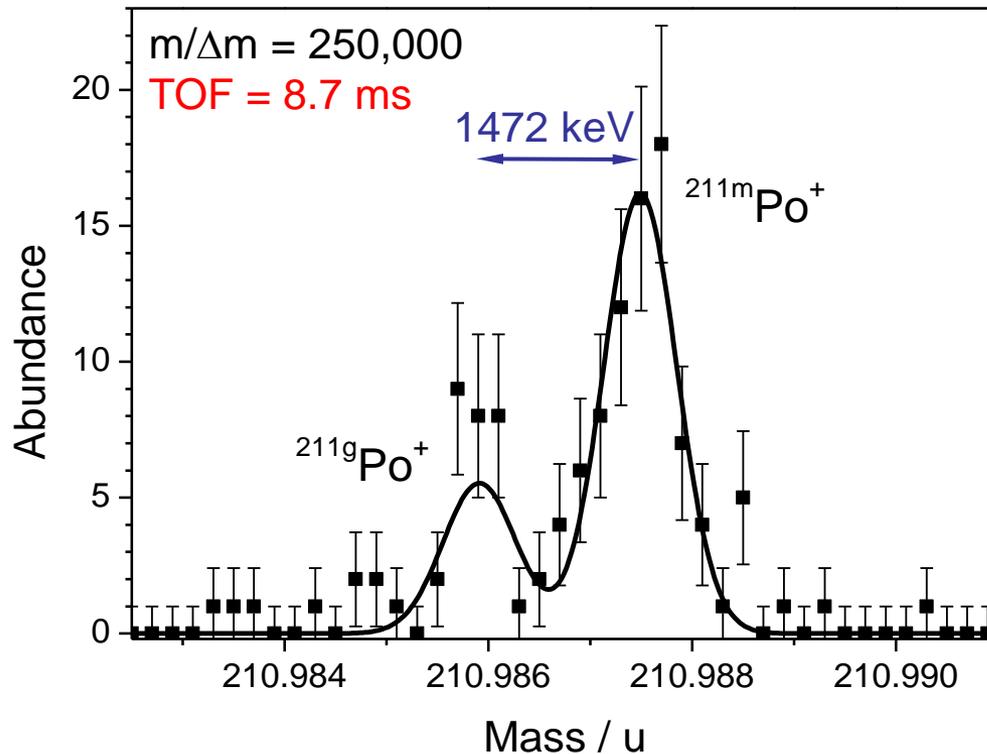
Mass accuracy:  $\sim 250$  keV  
Deviation from AME2012: 390 keV



J. Ebert, PhD 2016

# Measurement and Separation of Isomers

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

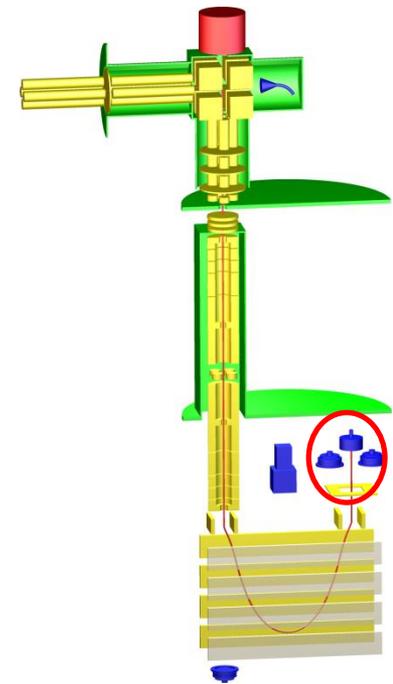
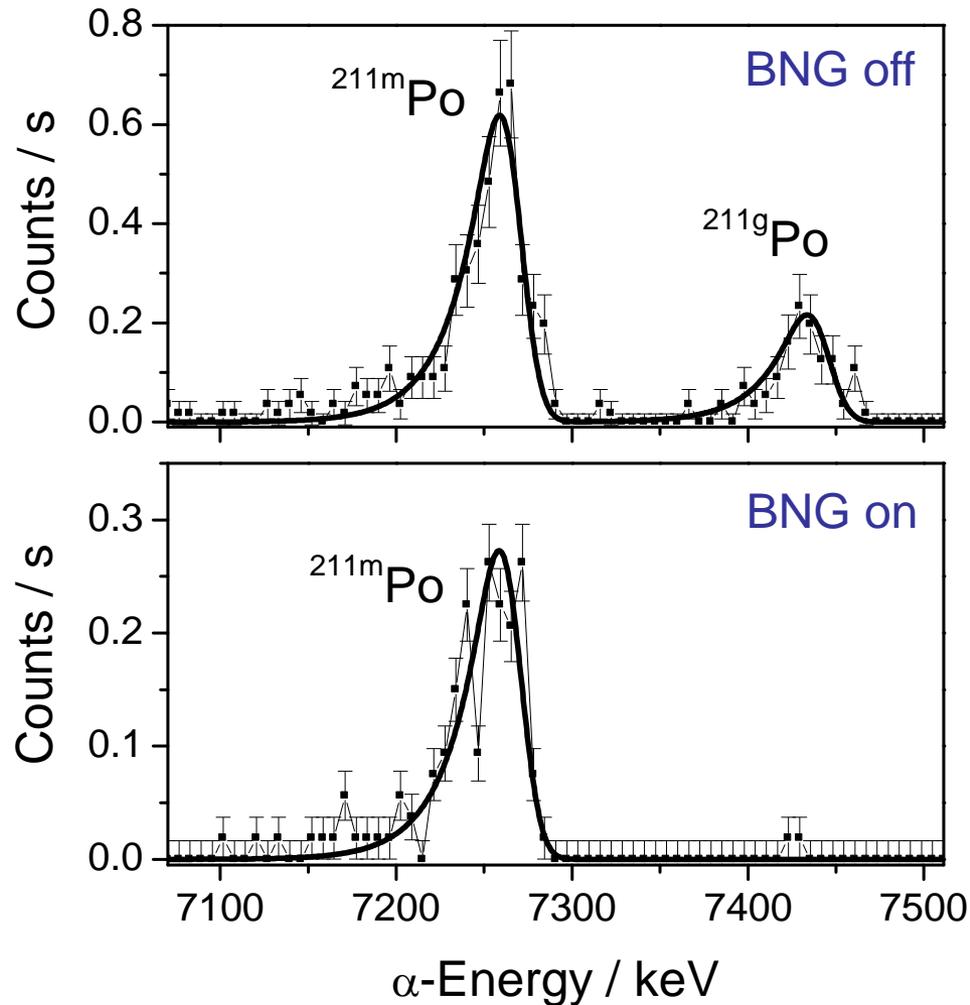


Measurement using the TOF detector

# 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



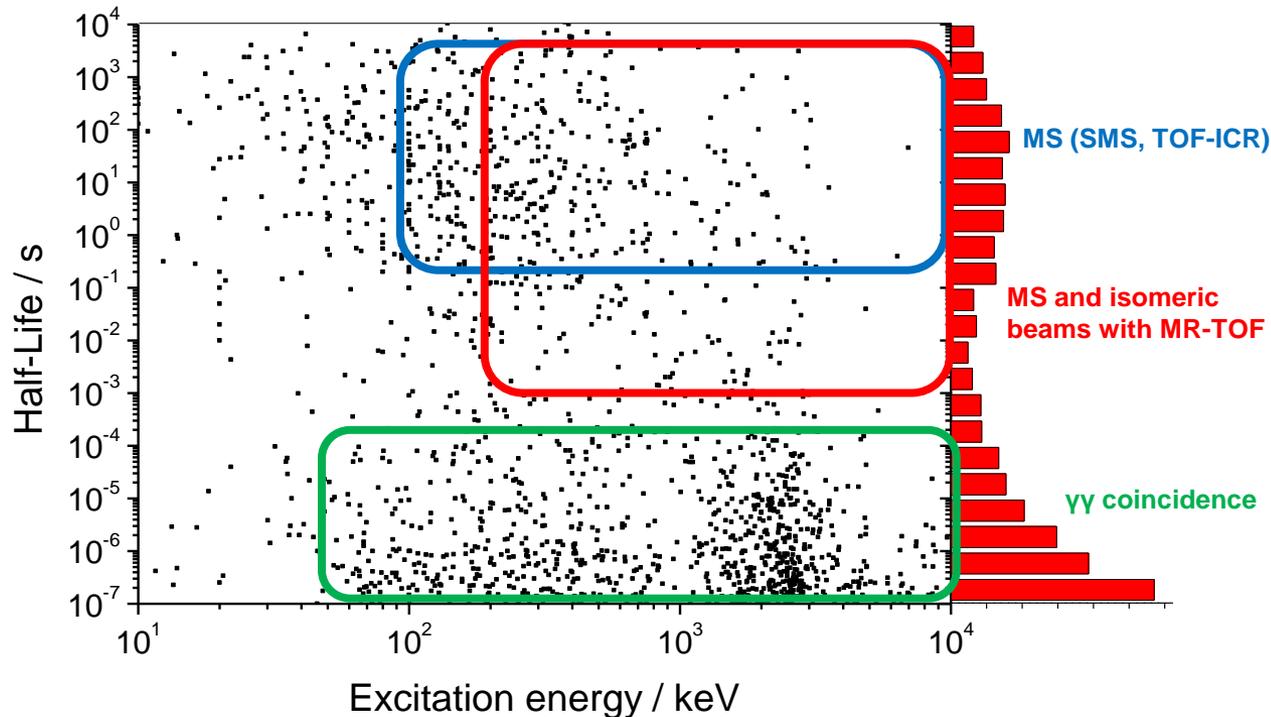
Separation using the Bradbury-Nielsen gate, measurement using the Si detector

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

# Isomer Measurement with MR-TOF-MS

Requirements for system for isomere search:

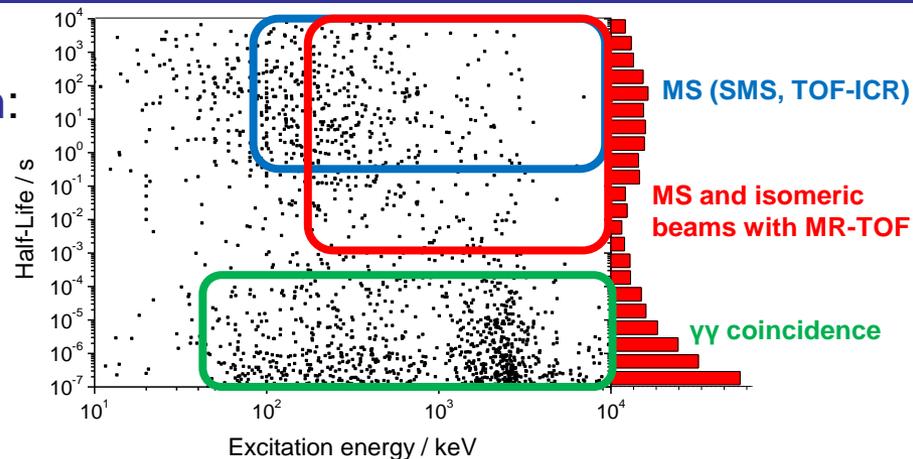
- Fast:  $\sim$ ms
- Sensitive: Non-Scanning
- High resolving Power:  $\gg 10^5$
- High Dynamic Range:  $> 10:1$



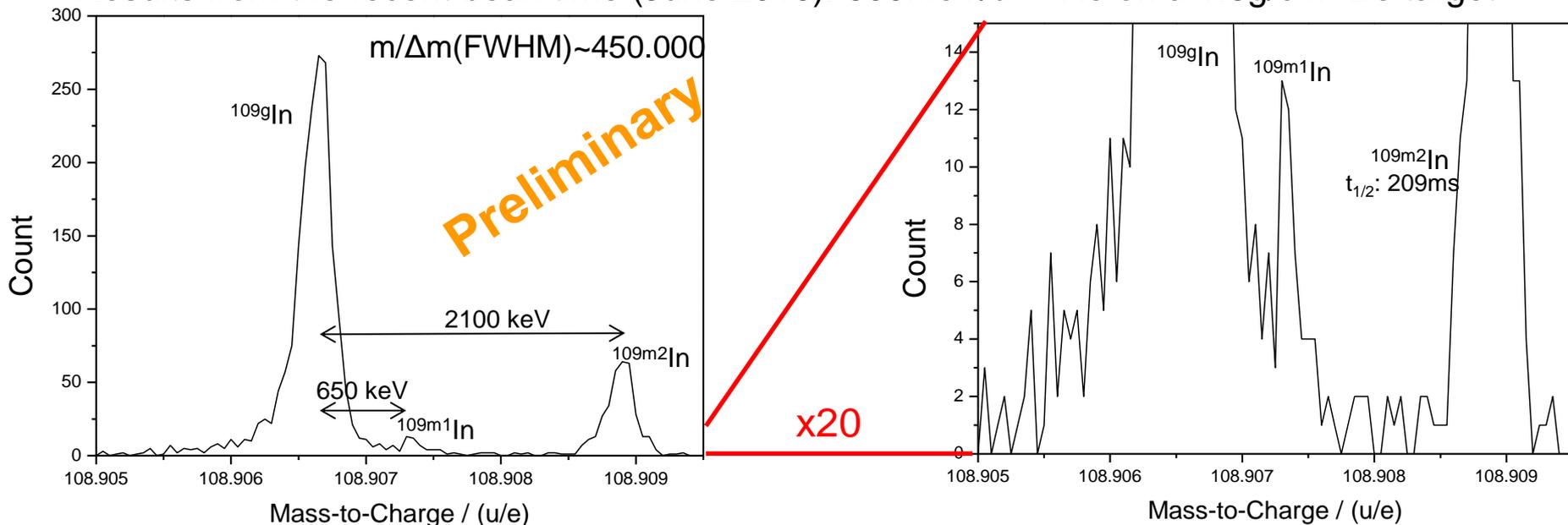
# Isomer Measurement with MR-TOF-MS

Requirements for system for isomere search:

- Fast: ~ms
- Sensitive: Non-Scanning
- High resolving Power:  $\gg 10^5$
- High Dynamic Range:  $> 10:1$



Results from the recent beamtime (June 2016): 600MeV/u  $^{124}\text{Xe}$  on a 1.6g/cm<sup>2</sup> Be target

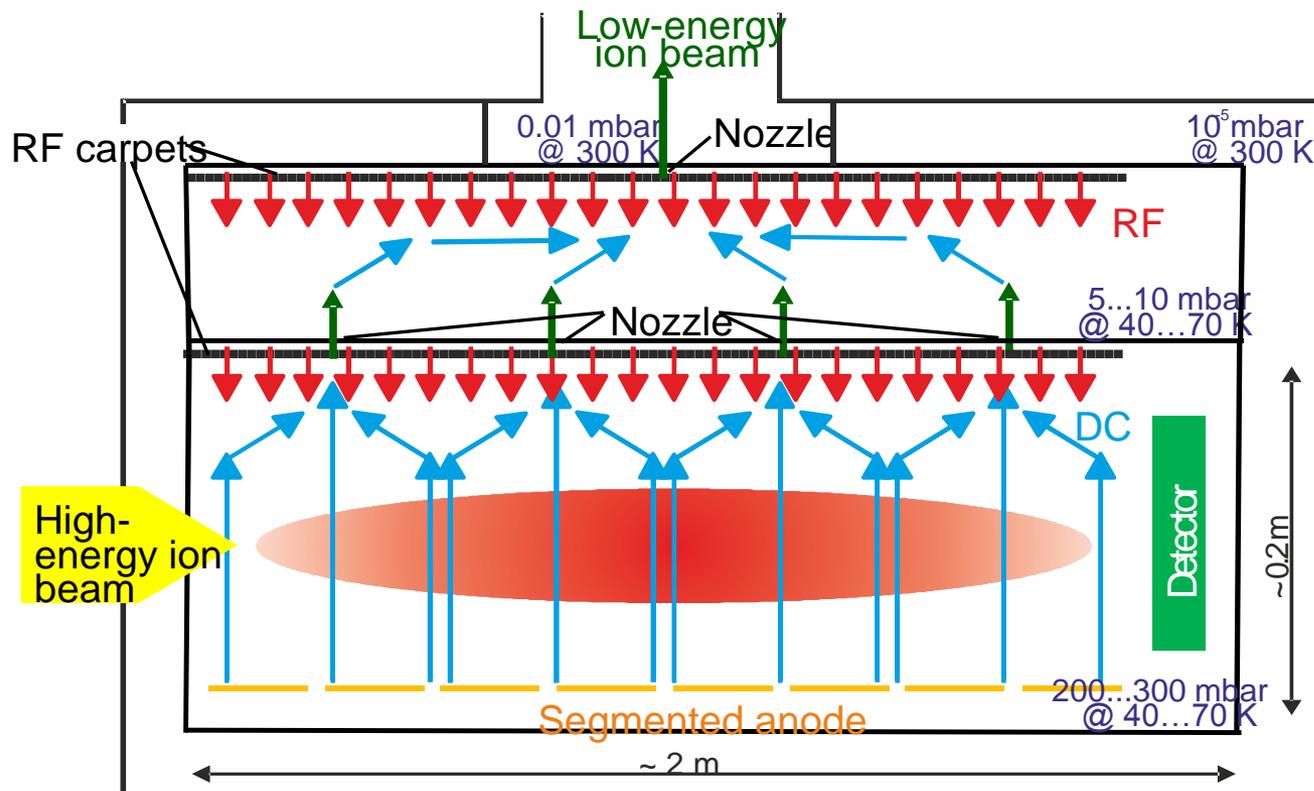


MR-TOF-MS is a powerful tool for the measurement of isomers:

Identification, discover, excitation energies, isomeric ratios and isomeric beams

# The FAIR Ion Catcher

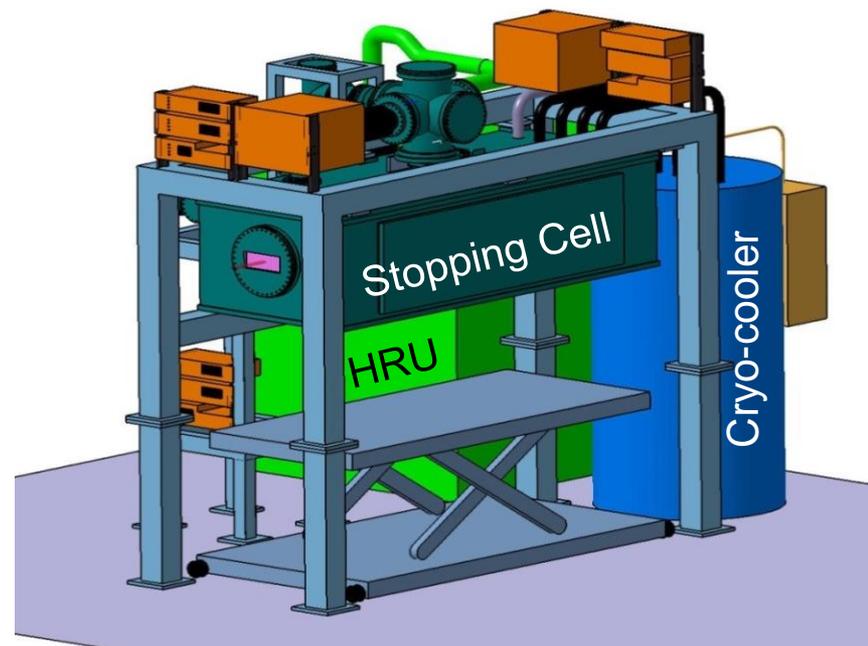
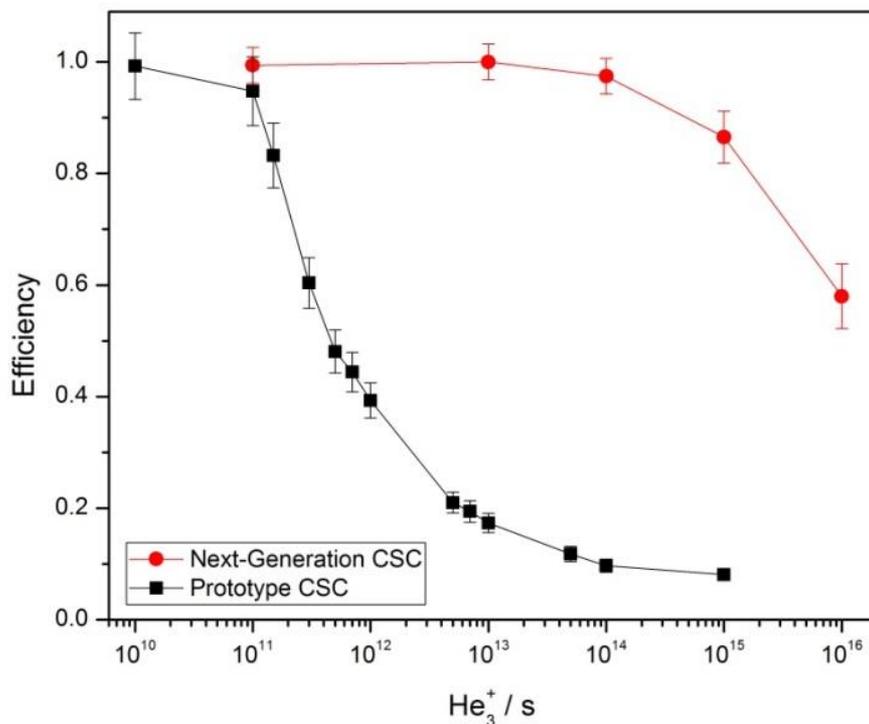
	Prototype CSC	Design Goals FAIR CSC
Areal density (He)	6 mg/cm <sup>2</sup>	20...40 mg/cm <sup>2</sup>
Extraction time	25 ms	5...10 ms
Rate capability	10 <sup>4</sup> /s	10 <sup>7</sup> /s



- Higher density
- Longer stopping volume
- Shorter Extraction path
- Higher Field strength

# The FAIR Ion Catcher

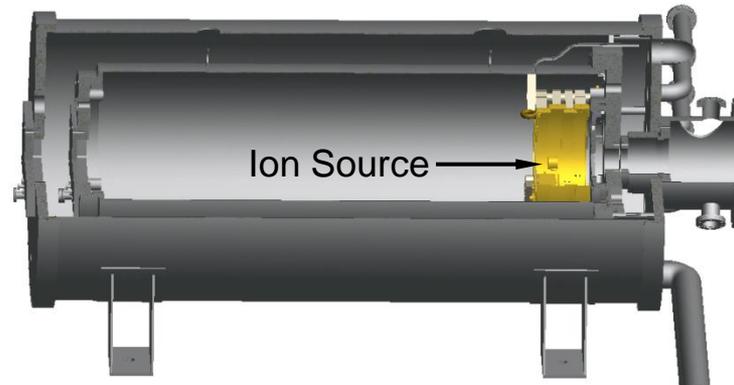
	Prototype CSC	Design Goals FAIR CSC
Areal density (He)	6 mg/cm <sup>2</sup>	20...40 mg/cm <sup>2</sup>
Extraction time	25 ms	5...10 ms
Rate capability	10 <sup>4</sup> /s	10 <sup>7</sup> /s



# Test of the novel concepts of the FAIR CSC

	Prototype CSC	Design Goals FAIR CSC
Density (He)	$\sim 50 \mu\text{g}/\text{cm}^3$ : limited by differential pumping	$\sim 150 \mu\text{g}/\text{cm}^3$ : limited by repelling field of RF carpet
Extraction time	dominated by movement in the DC cage	dominated by movement along the RF carpet and at the nozzle
DC fields	$\sim 10\text{V}/\text{cm}$ : Voltage-limited by discharge	$\sim 100\text{V}/\text{cm}$ : limited by repelling field of RF carpet?

- Test with Neon as stopping gas
  - Density limited by repelling field of RF carpet
- Tests with shorter DC electrode cage
  - higher field strengths and extraction times dominated by RF carpet

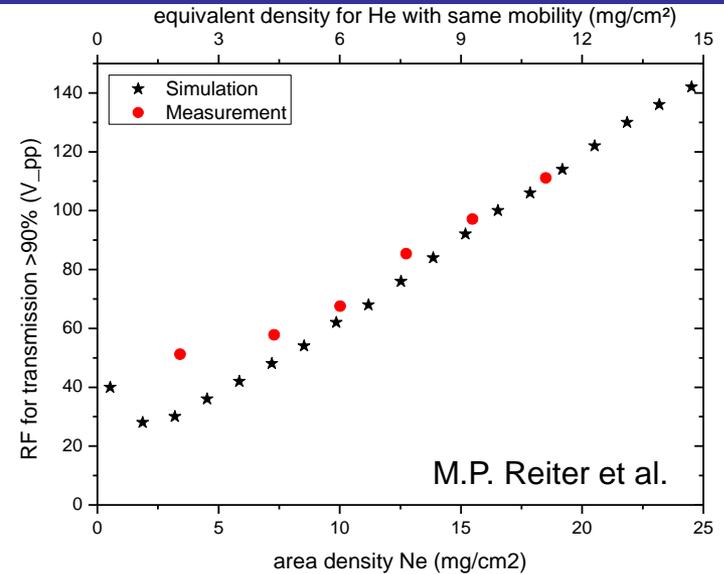


# Test Measurements for the next CSC

Test with Neon as stopping gas

RF Carpet is working at  $150 \mu\text{g}/\text{cm}^3$  He

→  $\sim 30 \text{mg}/\text{cm}^2$  will be possible for FAIR CSC

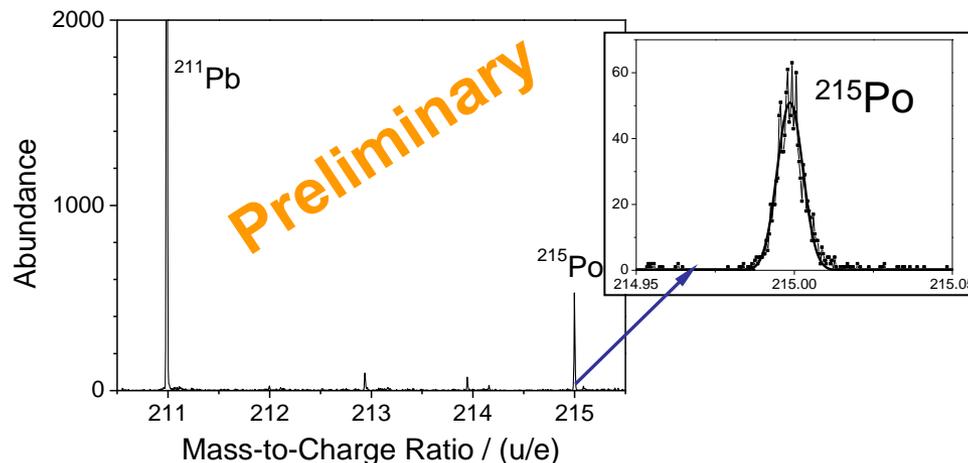


Measurement of  $^{215}\text{Po}$  ( $T_{1/2} = 1.781 \text{ ms}$ ) with MR-TOF-MS at 400 Hz

Mass measurement

Mass accuracy:  $\sim 150 \text{ keV}$

Deviation from AME2012:  $30 \text{ keV}$

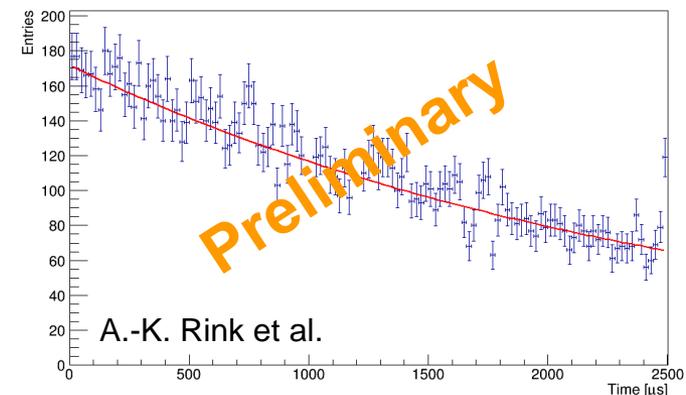


Mass-selected decay spectroscopy

Half-life measurement:

$(1,770 \pm 54) \mu\text{s}$

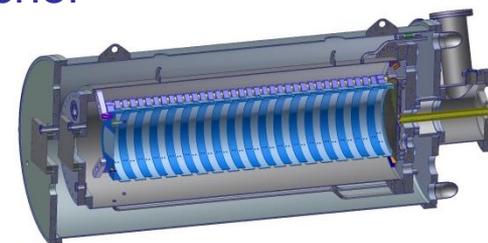
Decay slope  $\geq 15\sigma$



# Conclusions and Outlook

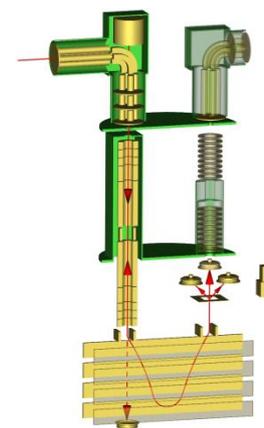
## (Prototype) Stopping cell for the Super-FRS and the FRS Ion Catcher

- Cryogenic, high density operation, suitable for exotic nuclei produced at relativistic energies
- Unprecedented efficiencies for relativistic ions
- Access to short life times (extraction time  $\sim 25$  ms)



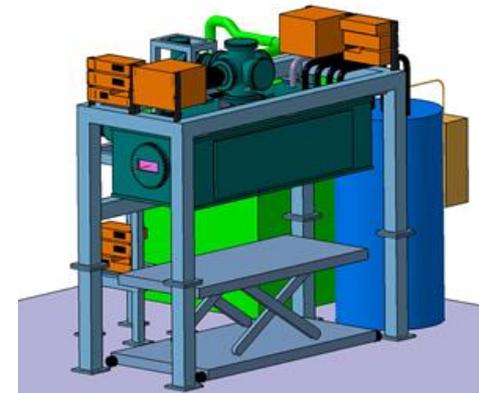
## High-performance multiple-reflection time-of-flight mass spectrometer

- High-accuracy mass measurements at  $m/\Delta m$  up to  $\sim 450,000$
- Powerful tool for the measurement of isomers: Identification, excitation energies, isomeric ratios
- High-resolution mass separator for isobars and isomers
- Diagnostics tool: identification and quantification
  - Mass tagger
  - Particle ID by MS only



## Developments and tests for the FAIR CSC

- Gas degrader
- Higher areal densities (tests with Neon)
- Shorter extraction times (mass and half-life meas. of  $^{215}\text{Po}$ )
- Higher rate capabilities



# Acknowledgements

## FRS Ion Catcher / S411 Collaboration

F. Amjad<sup>2</sup>, S. Ayet<sup>2</sup>, B. Soumya<sup>2</sup>, J. Bergmann<sup>1</sup>, P. Constantin<sup>7</sup>,  
P. Dendooven<sup>3</sup>, T. Dickel<sup>1,2</sup>, M. Diwisch<sup>1</sup>, J. Ebert<sup>1</sup>, A. Estrade<sup>2</sup>, F. Farinon<sup>2</sup>,  
A. Finley<sup>8</sup>, H. Geissel<sup>1,2</sup>, F. Greiner<sup>1</sup>, E. Haettner<sup>2</sup>, F. Heiße<sup>2</sup>, C. Hornung<sup>1</sup>,  
C. Jesch<sup>1</sup>, N. Kalantar-Nayestanaki<sup>3</sup>, R. Knoebel<sup>2</sup>, J. Kurcewicz<sup>2</sup>, J. Lang<sup>1</sup>,  
W. Lippert<sup>1</sup>, I. Mardor<sup>9</sup>, B. Mei<sup>7</sup>, I. Miskun<sup>2</sup>, I. Moore<sup>4</sup>, I. Mukha<sup>2</sup>,  
C. Nociforo<sup>2</sup>, J.H. Otto<sup>1</sup>, M. Petrick<sup>1</sup>, M. Pfuetzner<sup>2</sup>, S. Pietri<sup>2</sup>, A. Pikhtev<sup>5</sup>,  
W.R. Plaß<sup>1,2</sup>, I. Pohjalainen<sup>4</sup>, A. Prochazka<sup>2</sup>, S. Purushothaman<sup>2</sup>,  
M. Ranjan<sup>3</sup>, C. Rappold<sup>2</sup>, M.P. Reiter<sup>1</sup>, A.-K. Rink<sup>1</sup>, S. Rinta-Antila<sup>4</sup>,  
C. Scheidenberger<sup>2</sup>, M. Takechi<sup>2</sup>, Y. Tanaka<sup>2</sup>, H. Weick<sup>2</sup>, J.S. Winfield<sup>2</sup>,  
X.Xu<sup>1,2</sup>, M.I. Yavor<sup>6</sup>

<sup>1</sup> II. Physikalisches Institut, Justus-Liebig-Universität Gießen, Gießen, Germany

<sup>2</sup> GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

<sup>3</sup> KVI-CART, University of Groningen, The Netherlands

<sup>4</sup> University of Jyväskylä, Jyväskylä, Finland

<sup>5</sup> Institute for Energy Problems of Chemical Physics, RAS, Chernogolovka, Russia

<sup>6</sup> Institute for Analytical Instrumentation, RAS, St. Petersburg, Russia

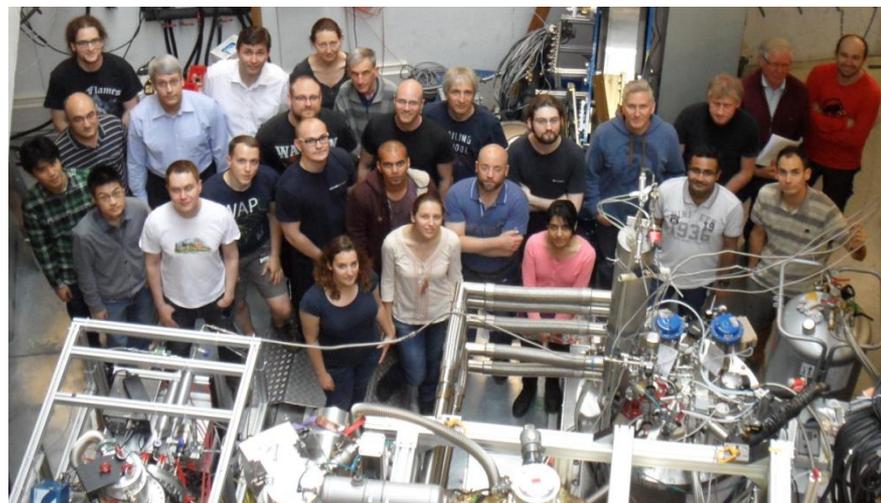
<sup>7</sup> ELI-NP, Bucharest, Romania

<sup>8</sup> TRIUMF, Vancouver, Canada

<sup>9</sup> Soreq NRC, Yavne, Israel

## IONAS Group at JLU Gießen

S. Ayet, J. Bergmann, A. Buers, U. Czok, T. Dickel, M. Diwisch, J.  
Ebert, H. Geissel, F. Greiner, E. Haettner, C. Hornung, C. Jesch, R.  
Knöbel, J. Lang, W. Lippert, A. Pikhtev, W.R. Plaß, M.P. Reiter, A.-  
K. Rink, C. Scheidenberger, M. Yavor



### Funding:

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

