

Characteristics and Limitations of Gas Cell Experiments

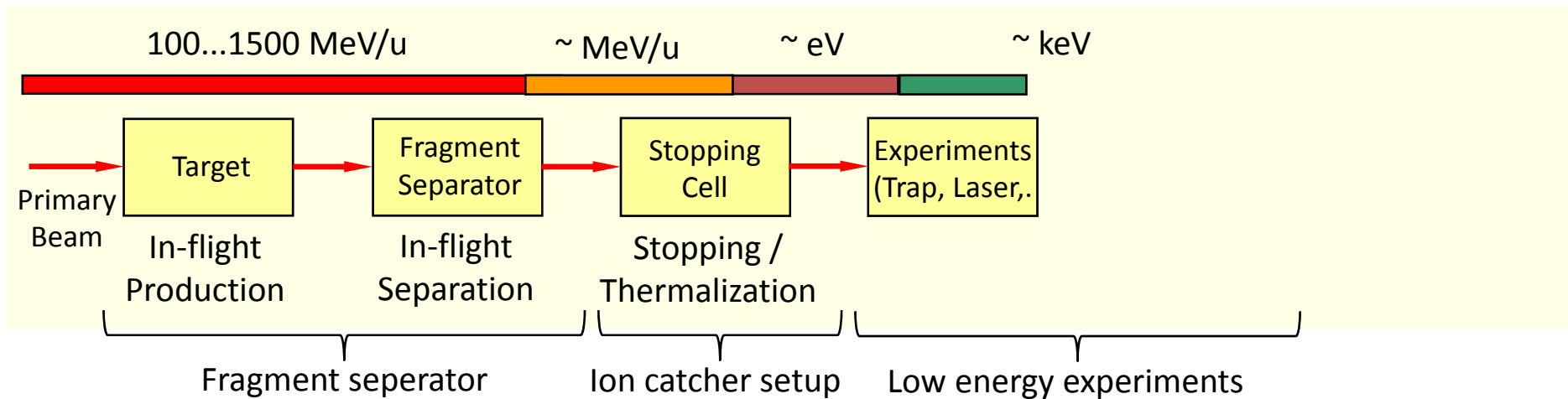


S. Purushothaman
For FRS Ion Catcher collaboration

NUSTAR Annual Meeting 2014



Low energy Experiments at In-flight facilities



Gas Cell Experiments - challenges

Efficient stopping

- Range straggling

➔ Momentum compression

➔ High density operation/Longer stopping length

Beam purity

- Adducts and molecules
- Undesired reaction products from beam

➔ Cleanliness

➔ Mass separator

Efficient extraction

- Decay losses
- Recombination losses
- Space charge/Plasma effects

➔ Fast extraction

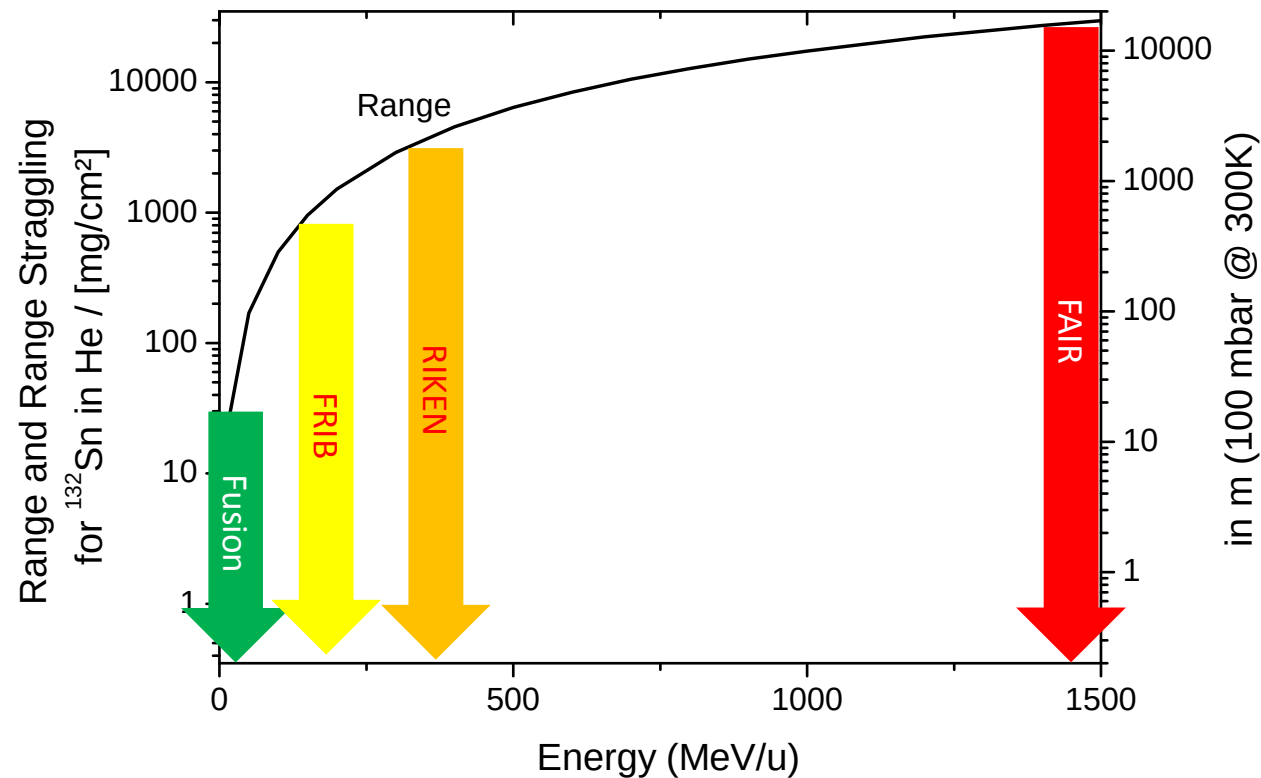
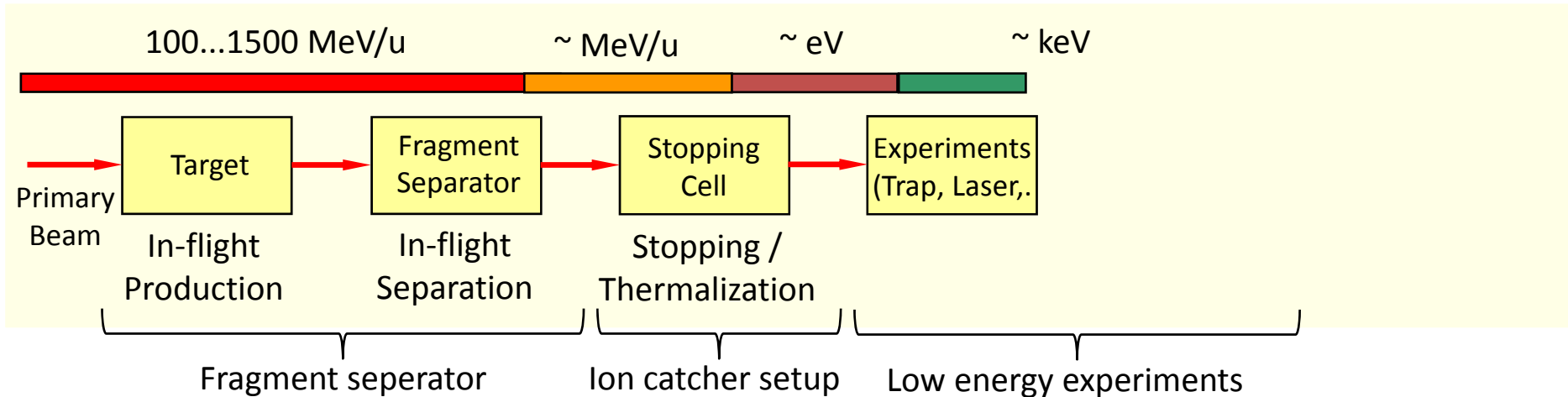
➔ Cleanliness/Fast extraction

➔ High DC fields/Larger stopping volume

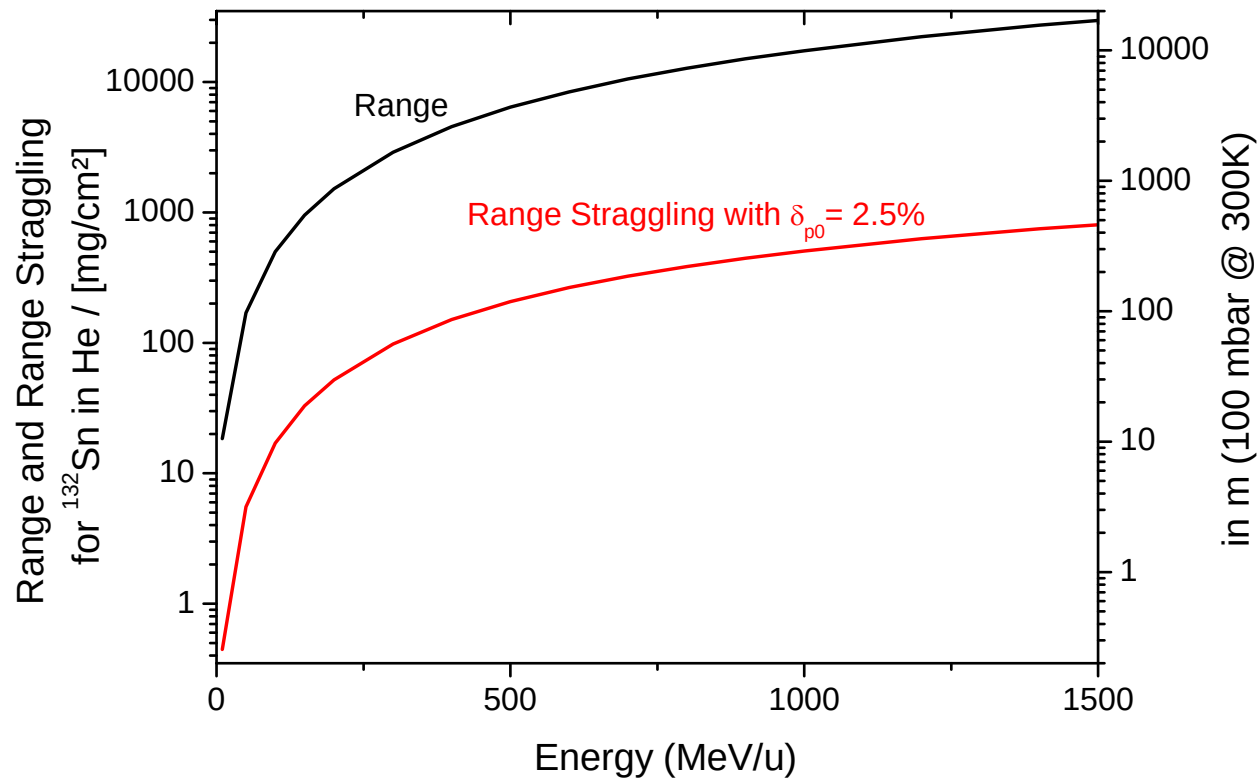
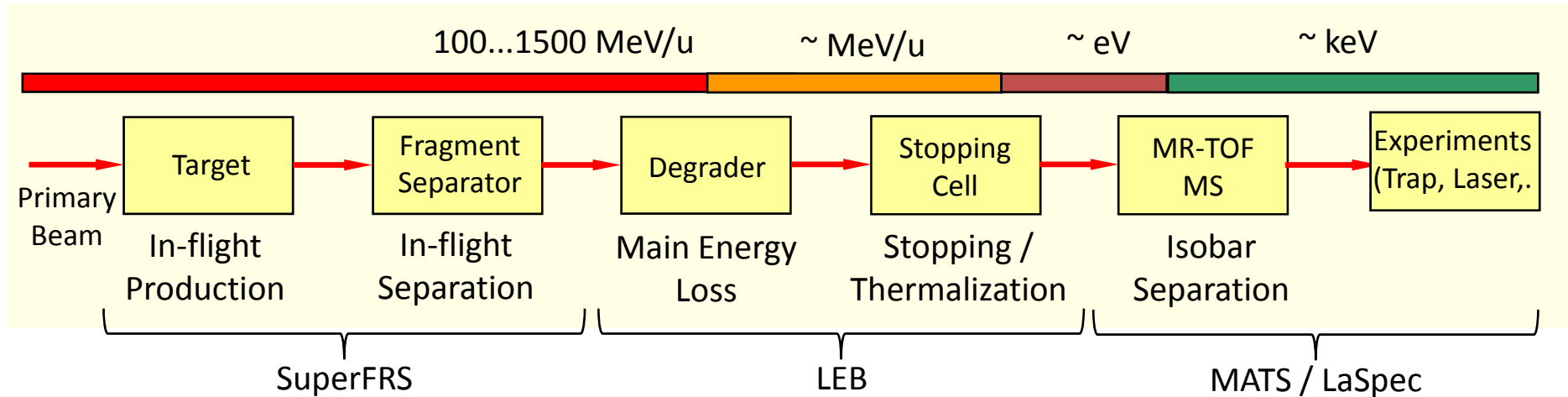
Efficient stopping

Range & range straggling

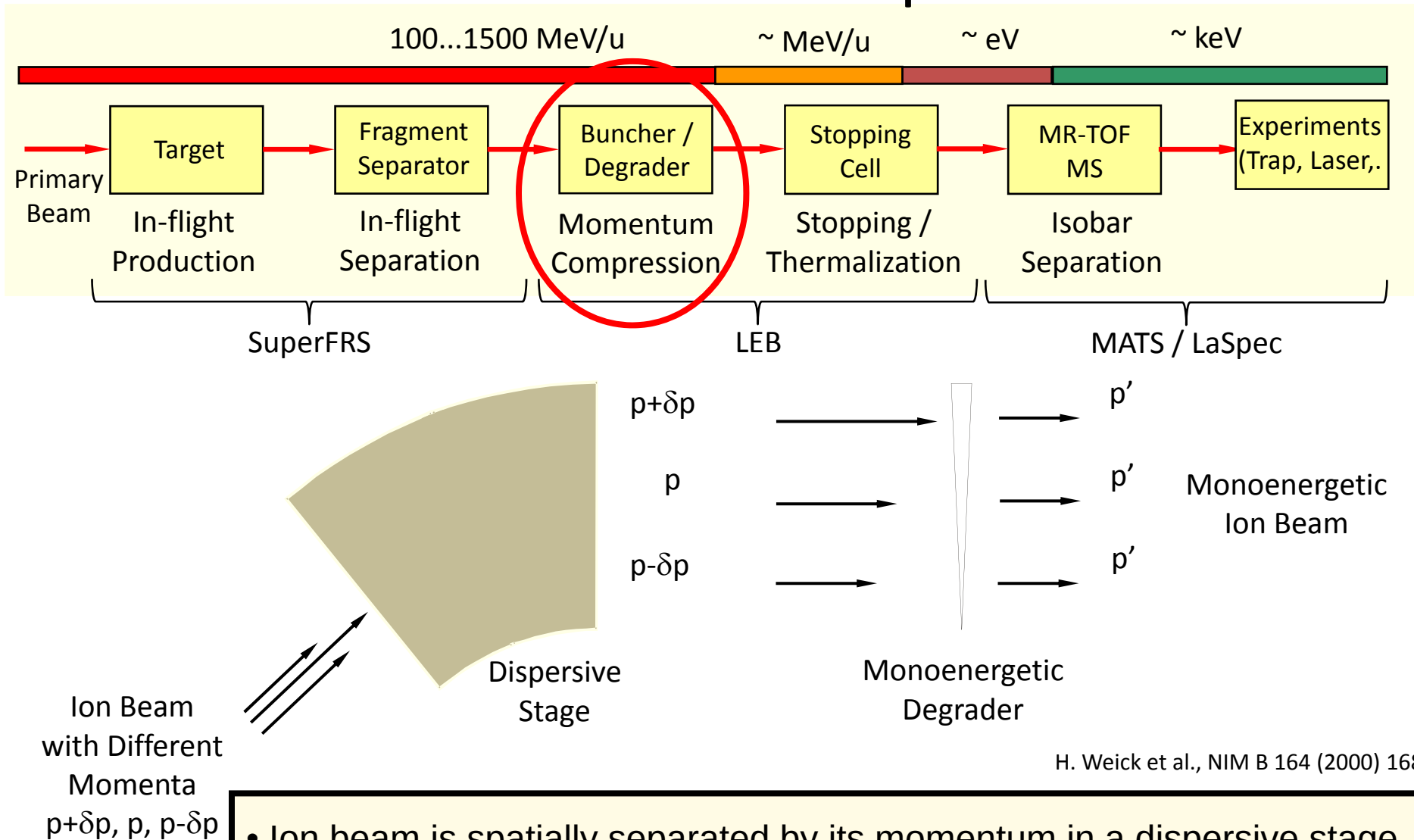
Low energy Experiments at In-flight facilities



Low Energy Branch (LEB) of Super FRS at FAIR



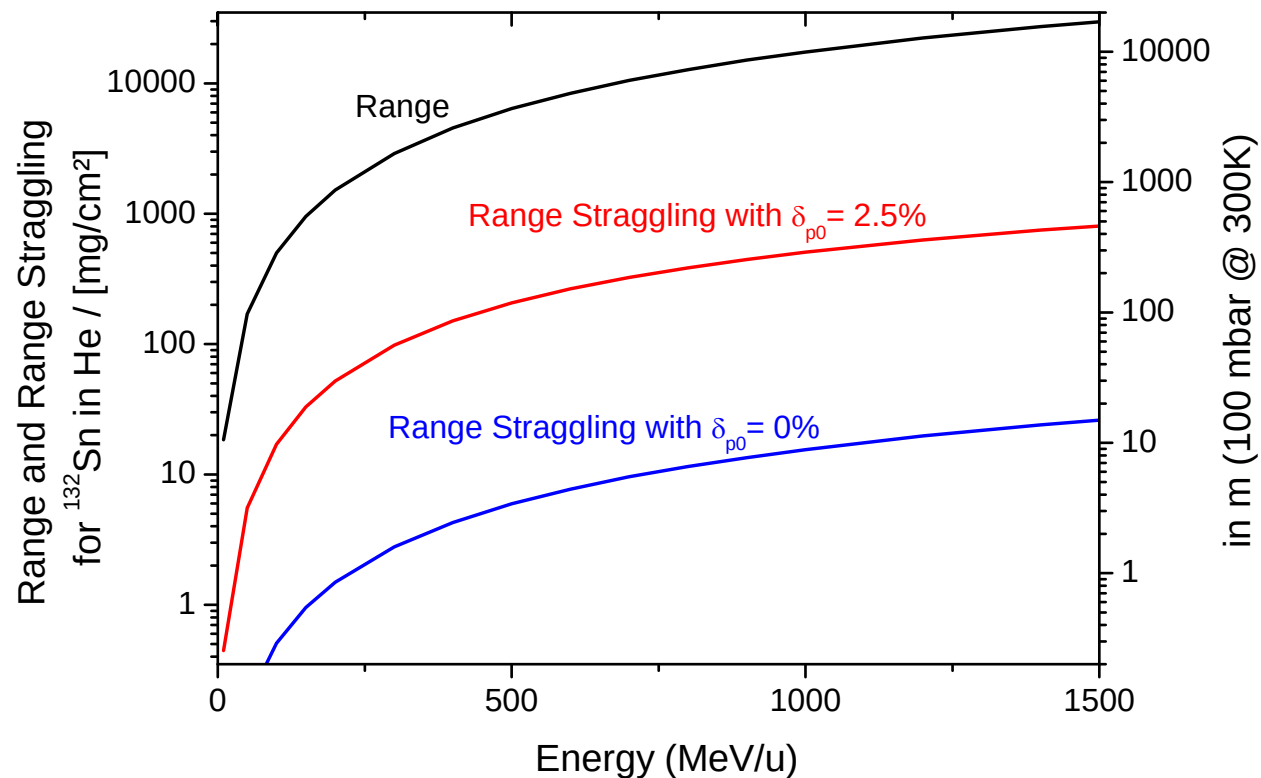
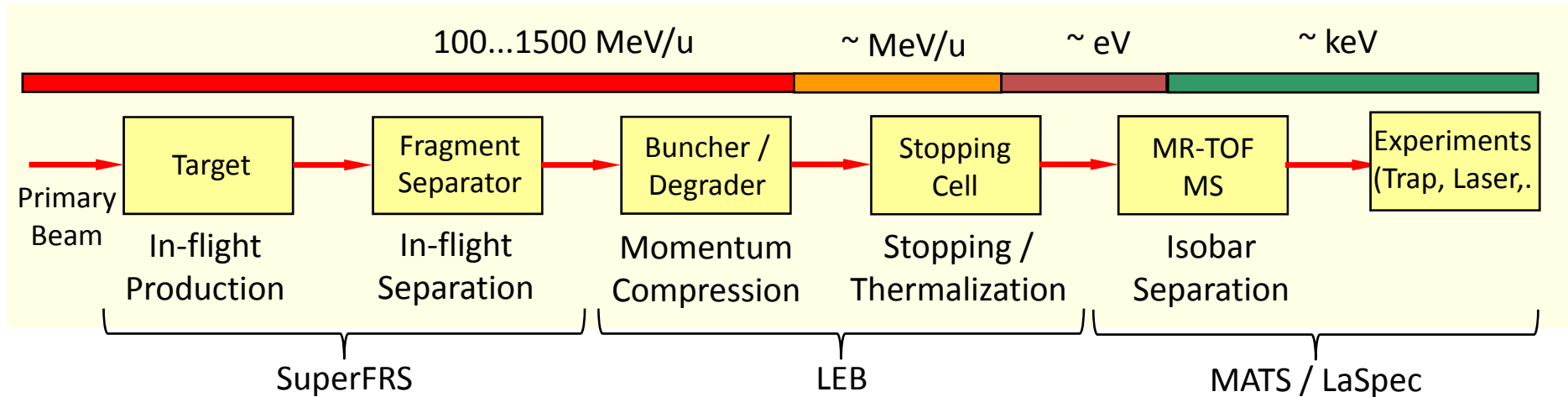
LEB: Momentum Compression



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

- Ion beam is spatially separated by its momentum in a dispersive stage
- Monoenergetic degrader reduces momentum spread
- Allows stopping in realistic amount of material

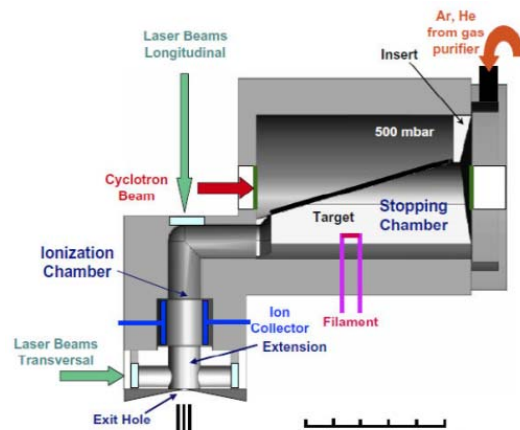
LEB: Momentum Compression



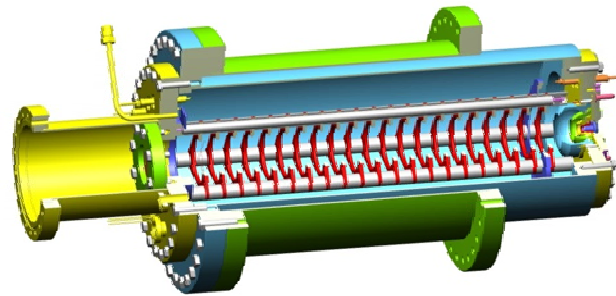
Gas cell

Beam thermalization in noble gas and extraction

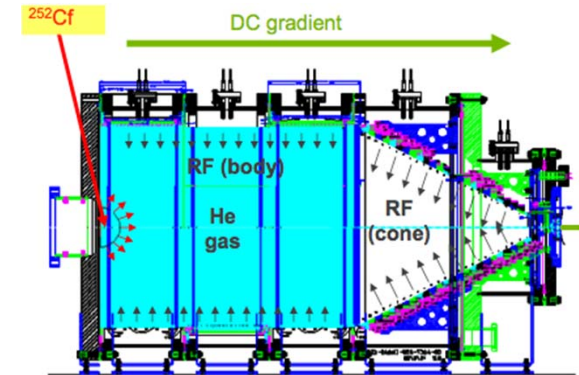
Gas cell-Different concepts



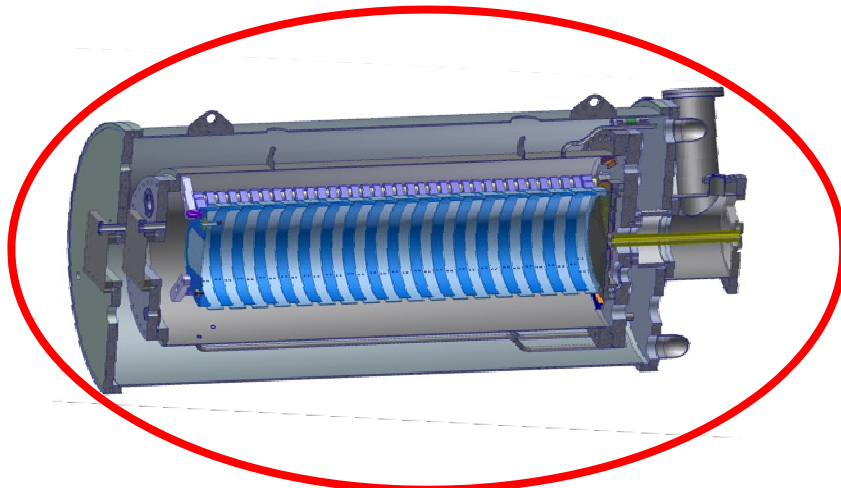
Gas flow only gas cell - IGISOL/LISOL
(KUL, JYFL)



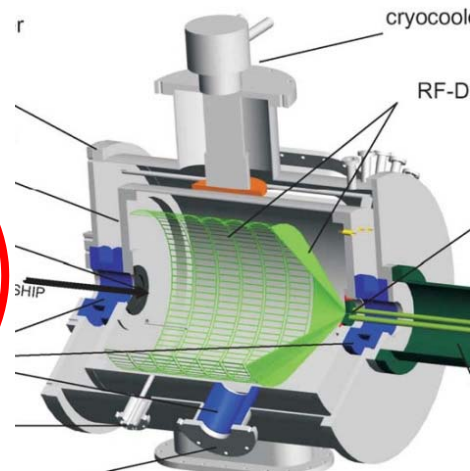
DC only stopping cell
(MSU)



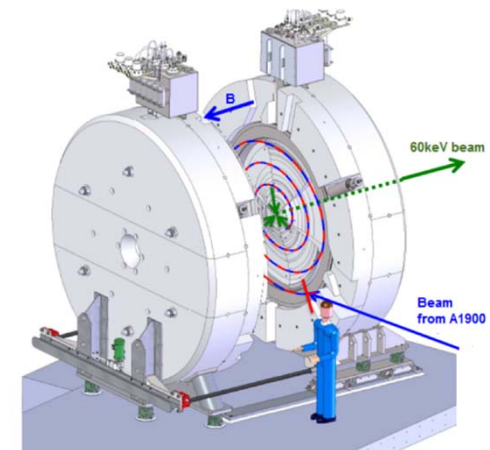
Full RF+DC Body
(ANL)



DC body and RF Carpet
(GSI (FRS), RIKEN)

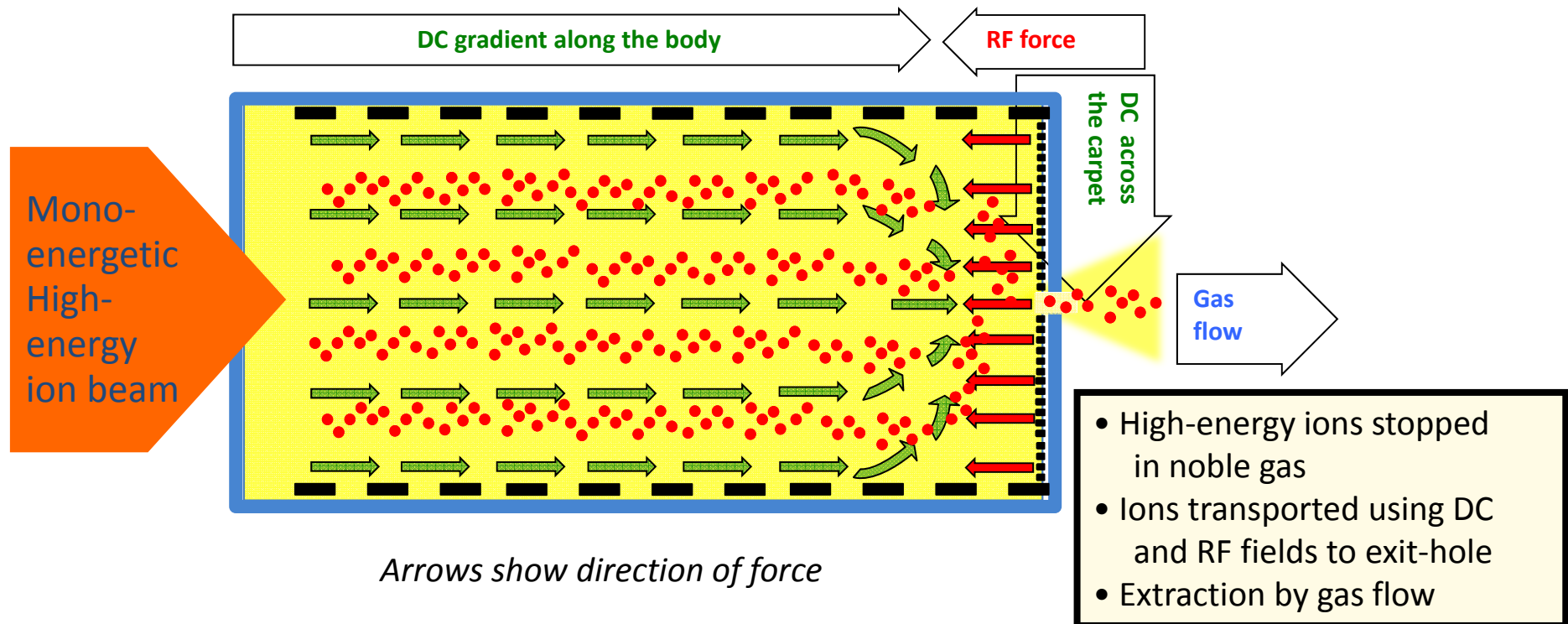
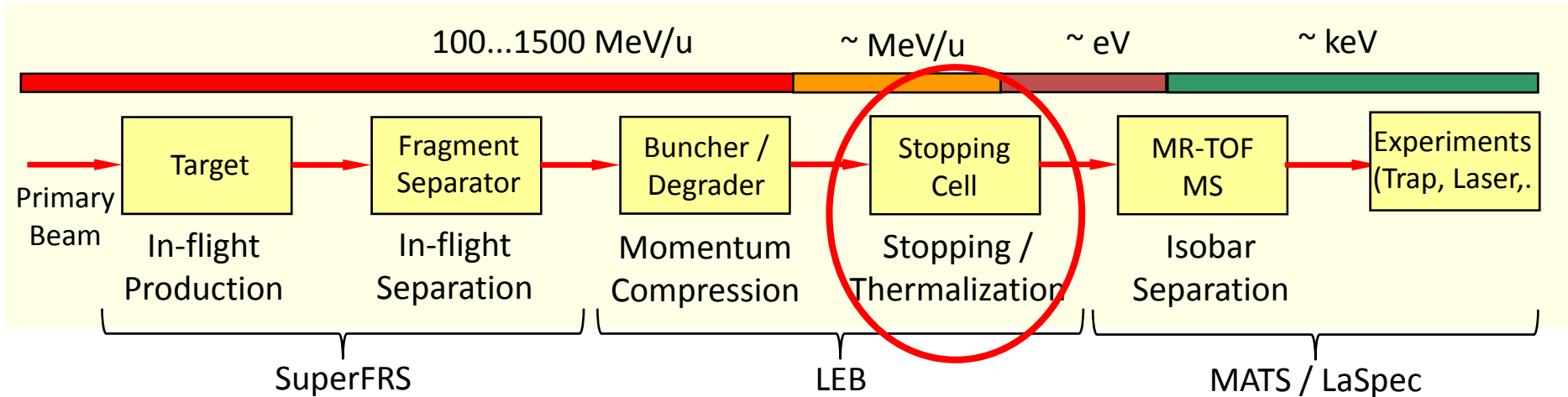


DC body and RF Funnel
(GSI (SHIPTRAP), ANL, MSU, MLL)



Cyclotron gas stopping cell
(MSU)

LEB: Stopping and Thermalization



Novel Concept: High Density Stopping Cell

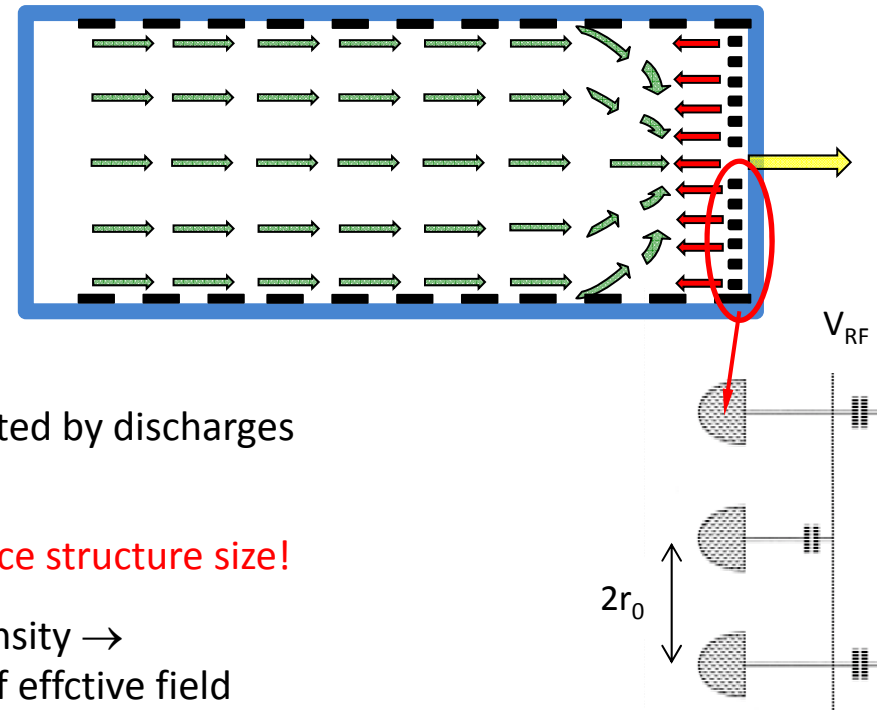
Large axial DC field → fast extraction

$$v_z = KE_z^{\text{DC}}$$

Effective RF field repels ions from electrodes

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

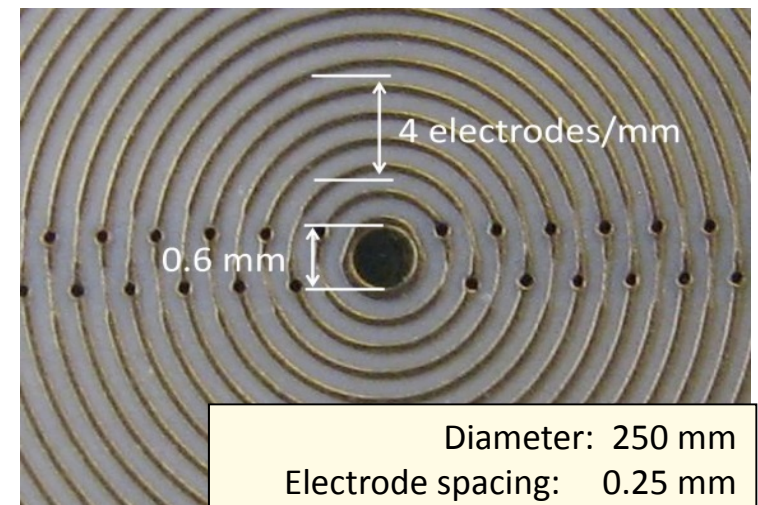
← limited by discharges
 ← **reduce structure size!**
 ← high gas density → reduction of effective field



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

(4 electrodes/mm compared to 1 electrode/mm)

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



Beam purity

Adducts and molecules

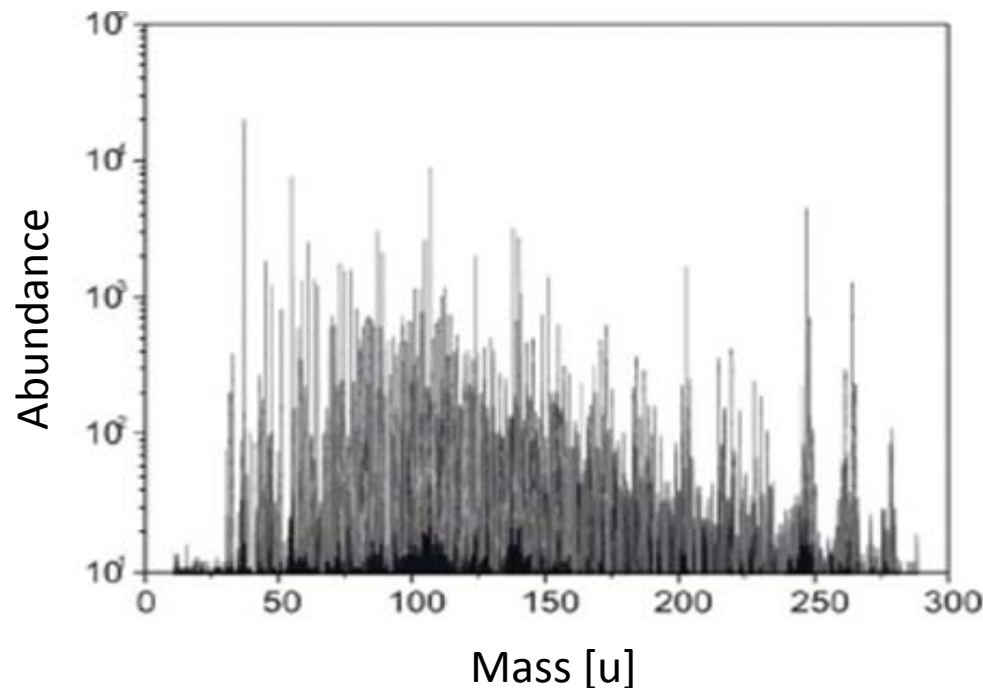
Undesired reaction products from beam

What's coming out from the Gas Cell?

Everything !!!

that is ionized and transported by the RF repelling structure

FRS ion catcher gas cell - First Prototyp 2005
Online with Beam

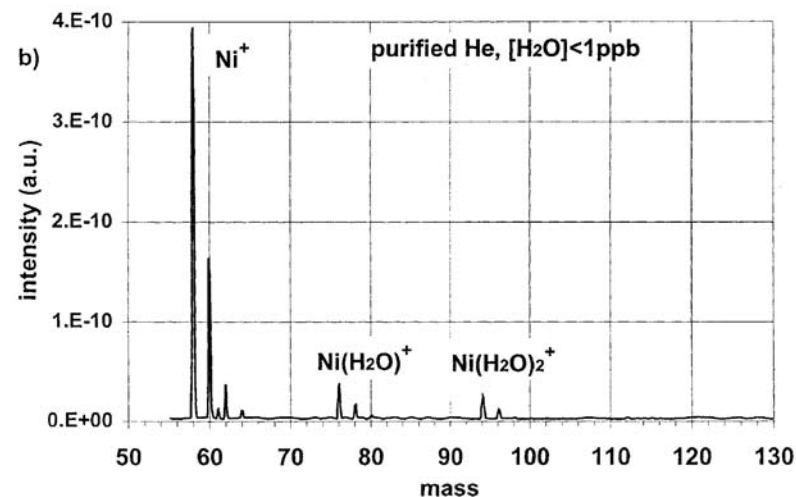
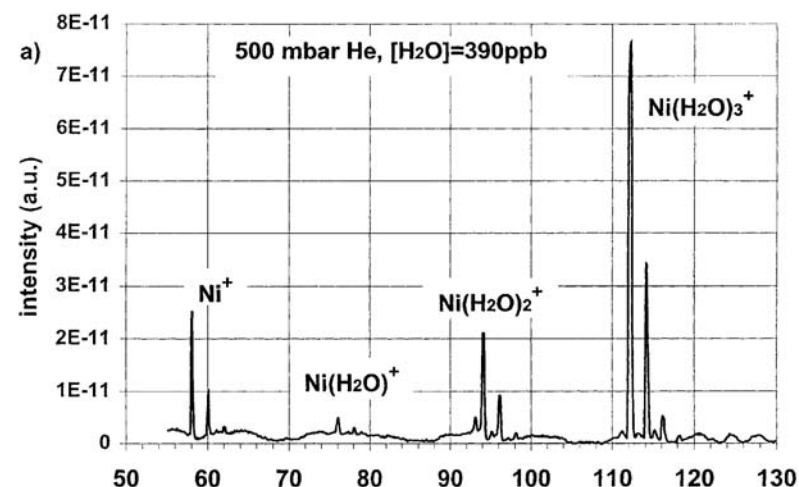
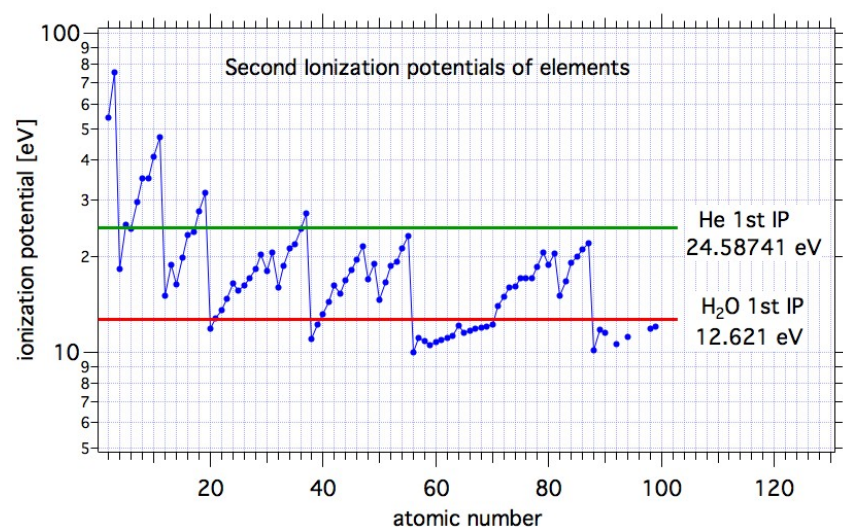
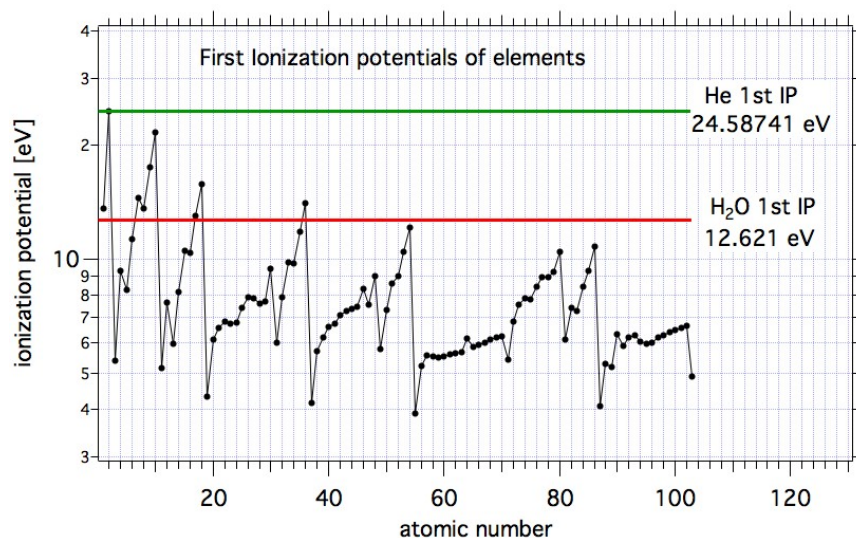


Ortho-TOF spectra

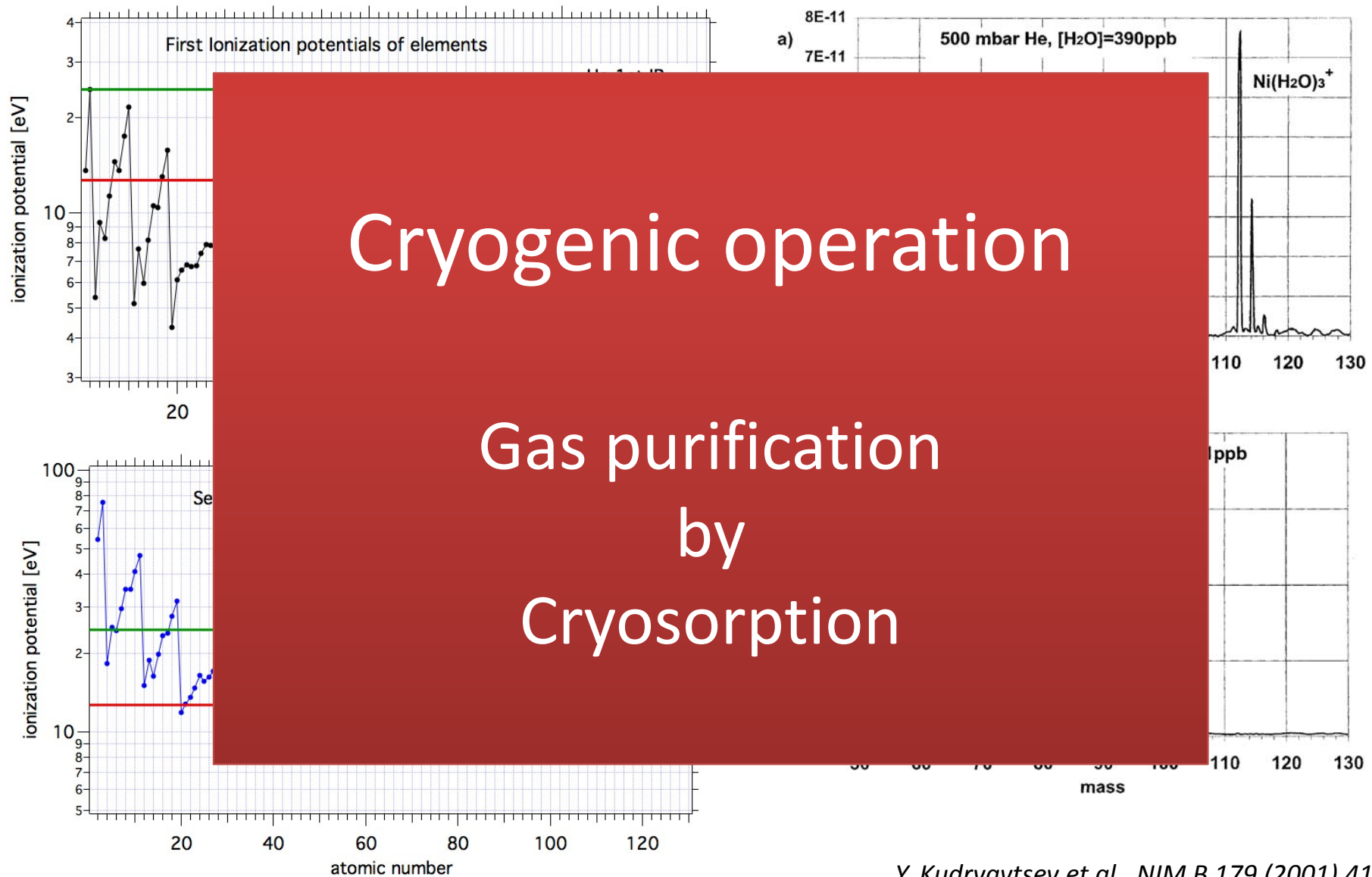
Examples

- Undesired reaction products (from beam) -
- Adducts, impurity atomic/molecular ions From buffer gas/Stopping cell

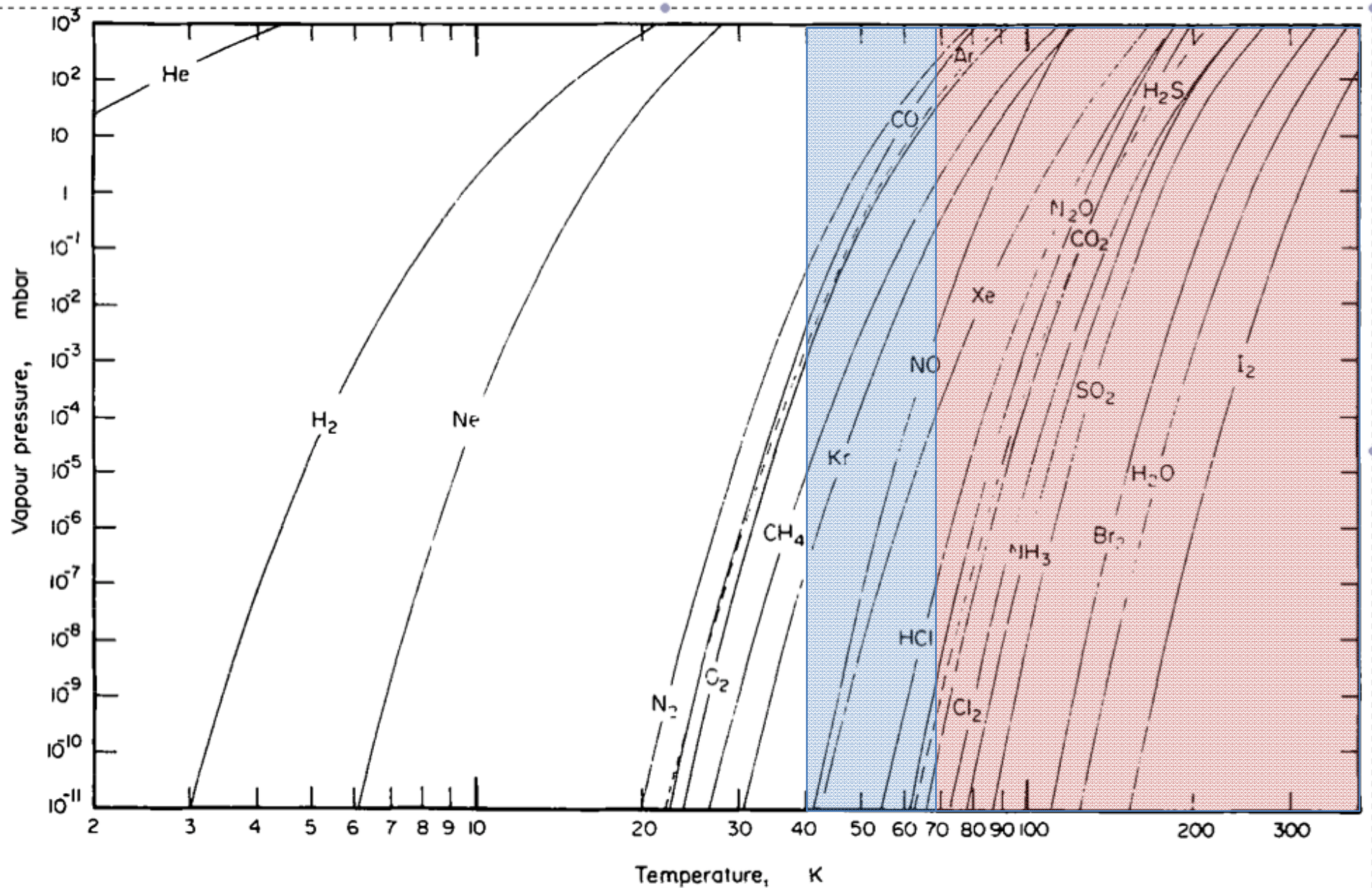
What's coming out from the Gas Cell?



Solution



Partial pressure vs. Temperature



Efficient extraction

Decay losses

Recombination losses

Space charge/Plasma effects

Efficient extraction - Space charge issues

Parallel plate capacitor approximation

$$\frac{\partial \rho}{\partial t} + K_+ E \frac{\partial \rho}{\partial x} + \frac{K_+}{\varepsilon} \rho^2 = J$$

Continuity equation
&
Maxwell's equation

stationary state solution

$$E(x) = f(J, V, x)$$

$$\rho(x) = g(J, V, x)$$

$$\text{Dimensionless variable } \alpha = \frac{L^2}{V} \sqrt{\frac{J}{K_+ \varepsilon}}$$

$$E(x) = f(\alpha, x)$$

$$\rho(x) = g(\alpha, x)$$

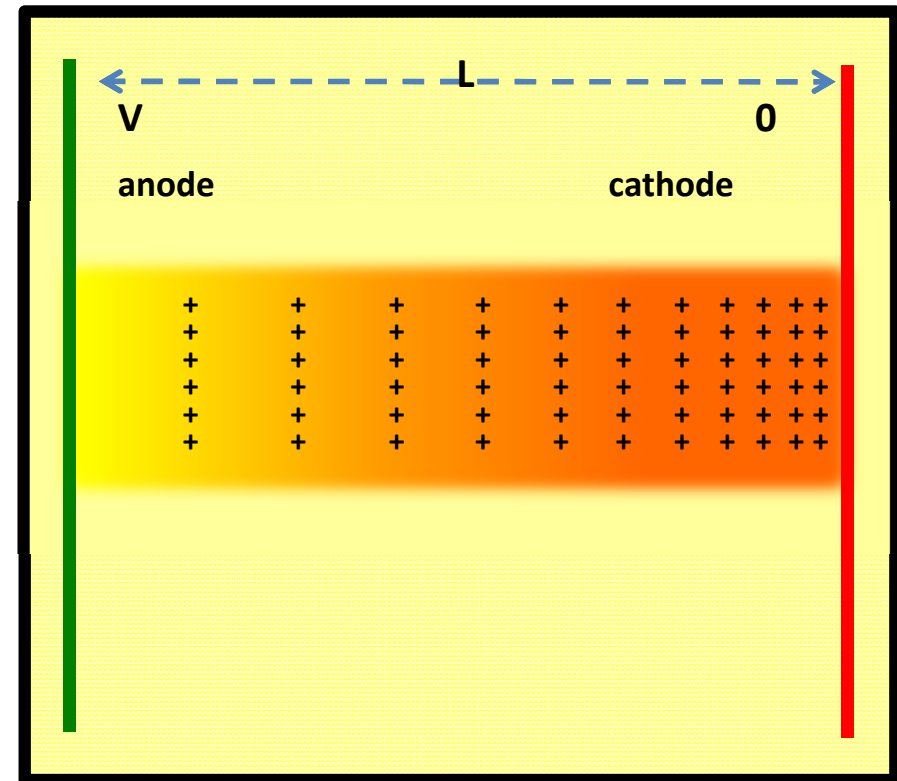
J = Volume rate of charge creation

L = Anode cathode separation

V = Potential difference between anode and cathode

K_+ = Mobility of buffer gas ions

ε = dielectric constant of the medium

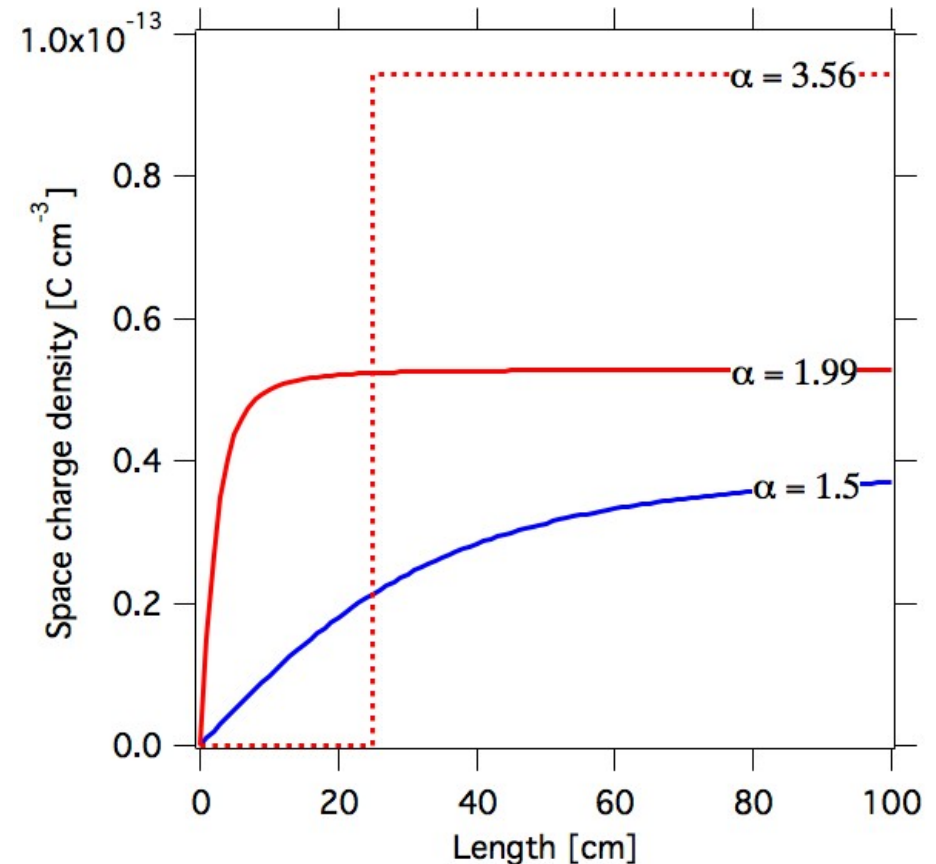
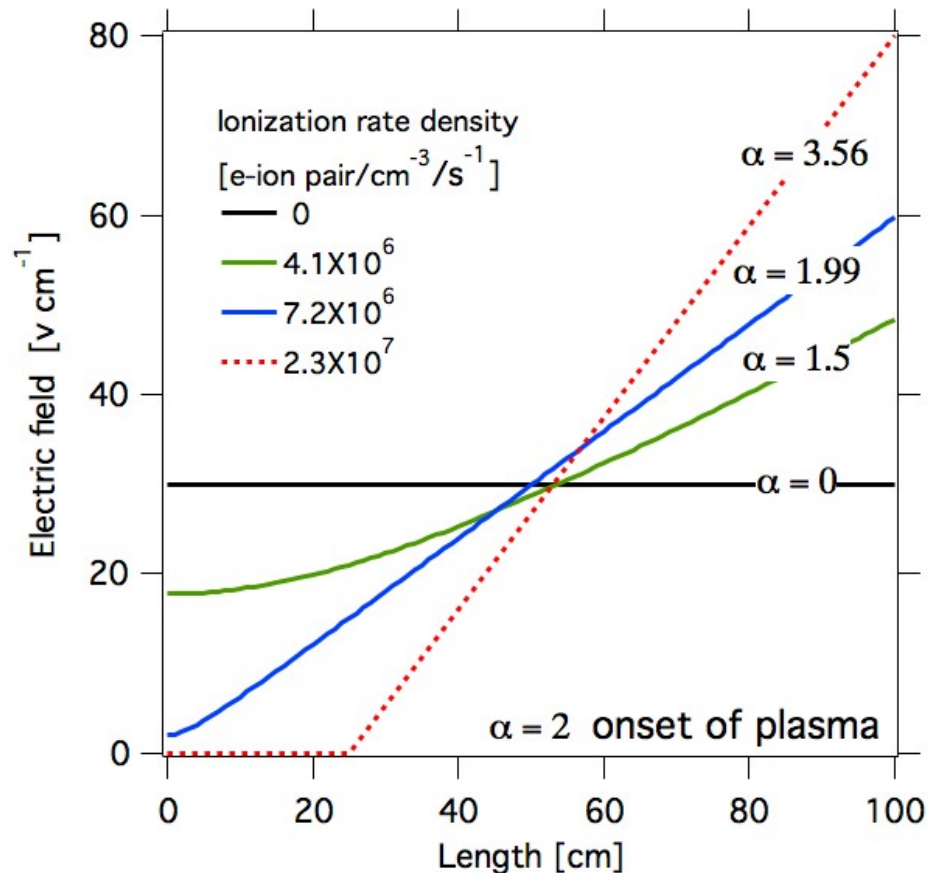


Treatment fails if $\alpha > 2$
And plasma effect starts

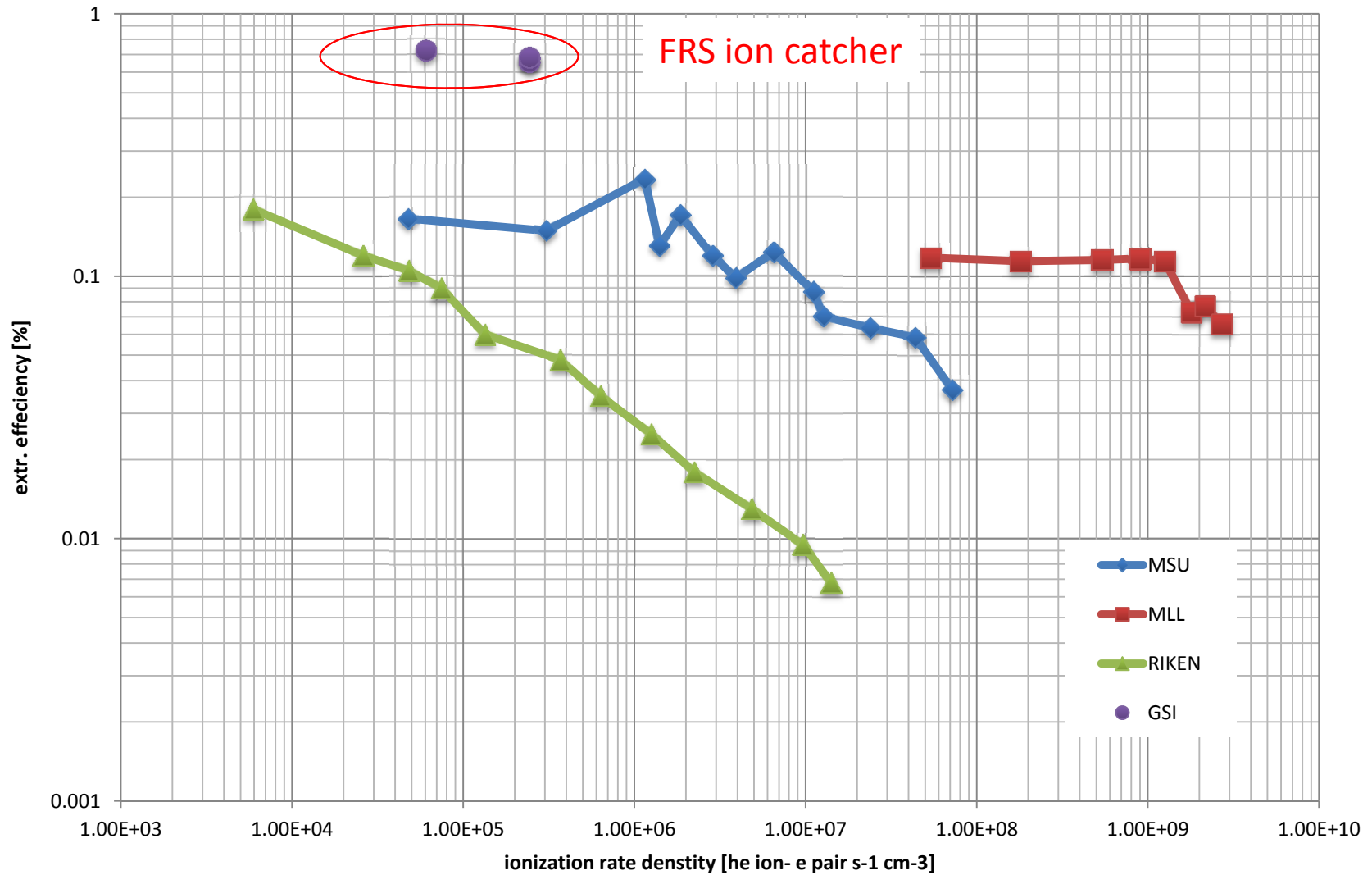
Space charge and plasma effects

2.5 MeV/u ^{238}U ions, thermalized in a 100 mbar helium gas 70 K.
30 V/cm is applied across the length, 8 cm beam diameter

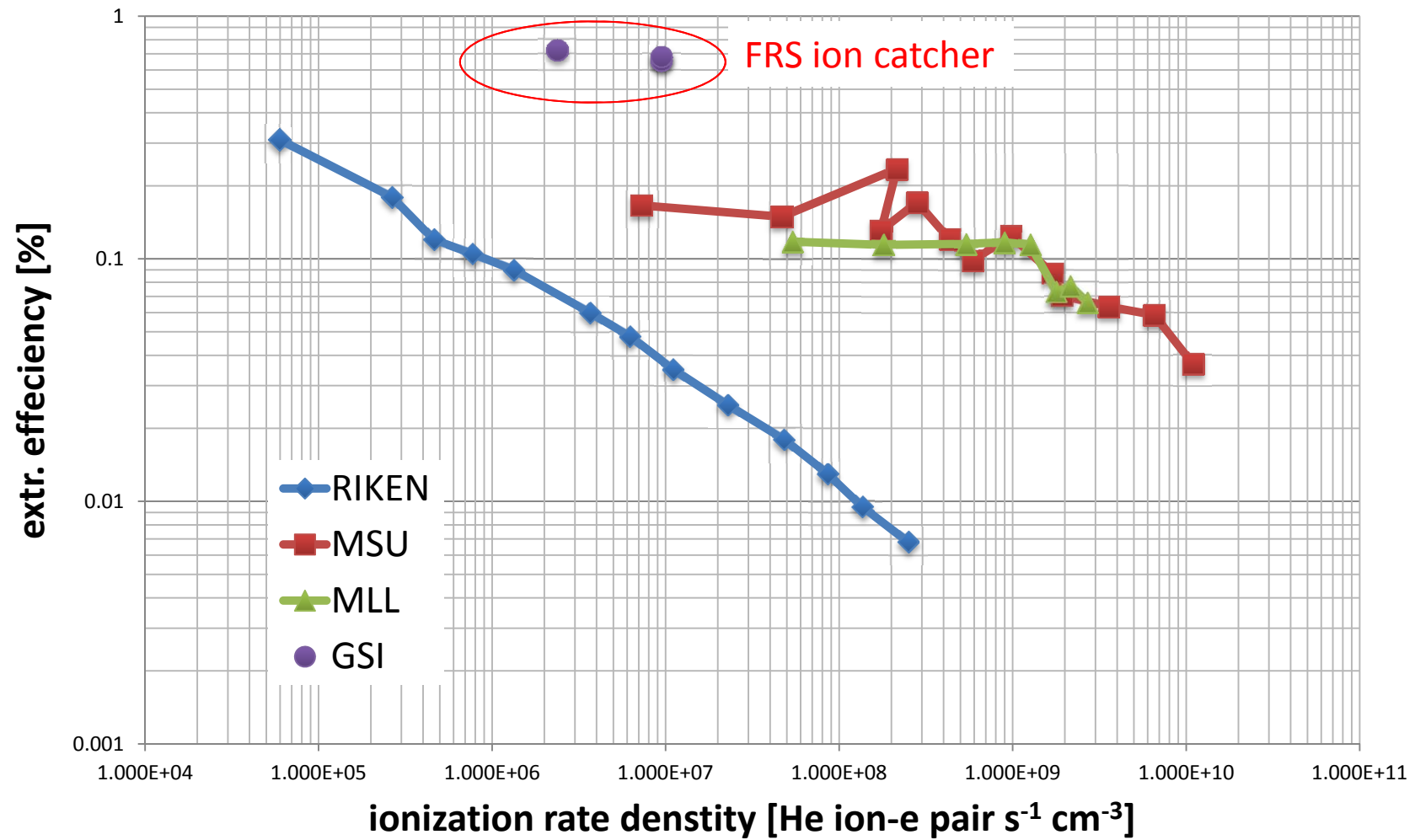
Parallel plate capacitor approximation



Gas cell performance

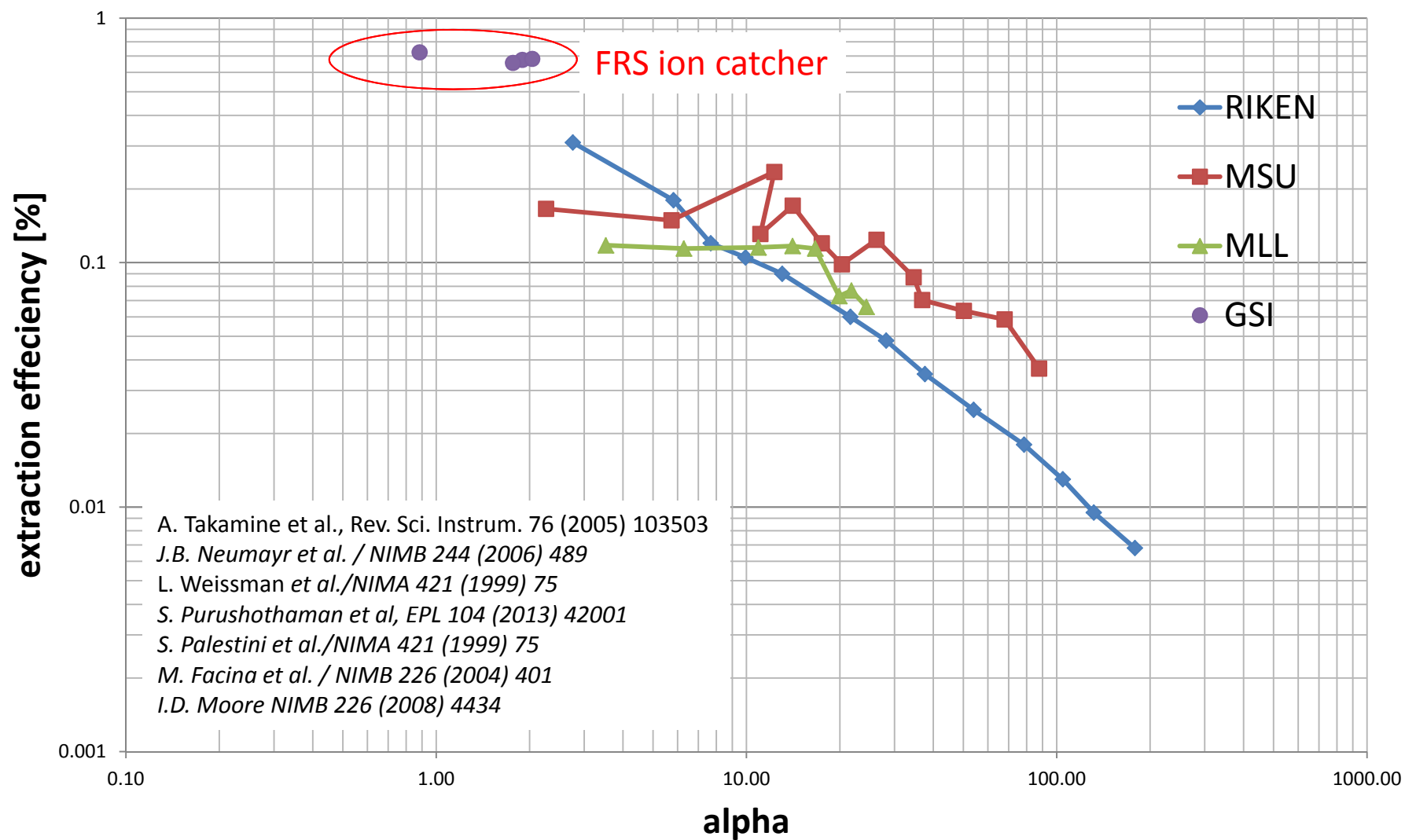


Gas cell performance



Beam volume for ionization rate density

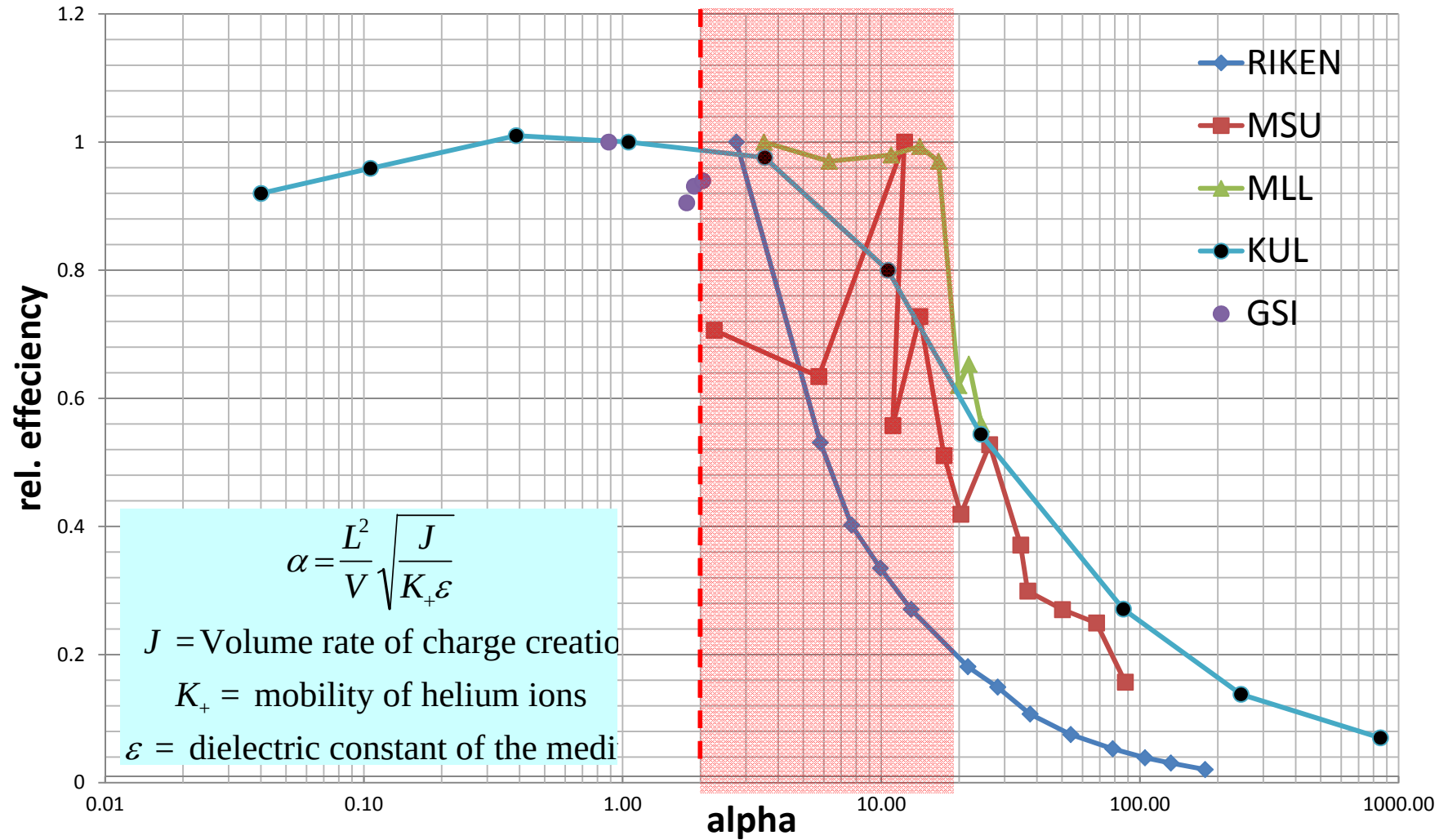
Gas cell performance



Beam volume for ionization rate density

Gas cell performance

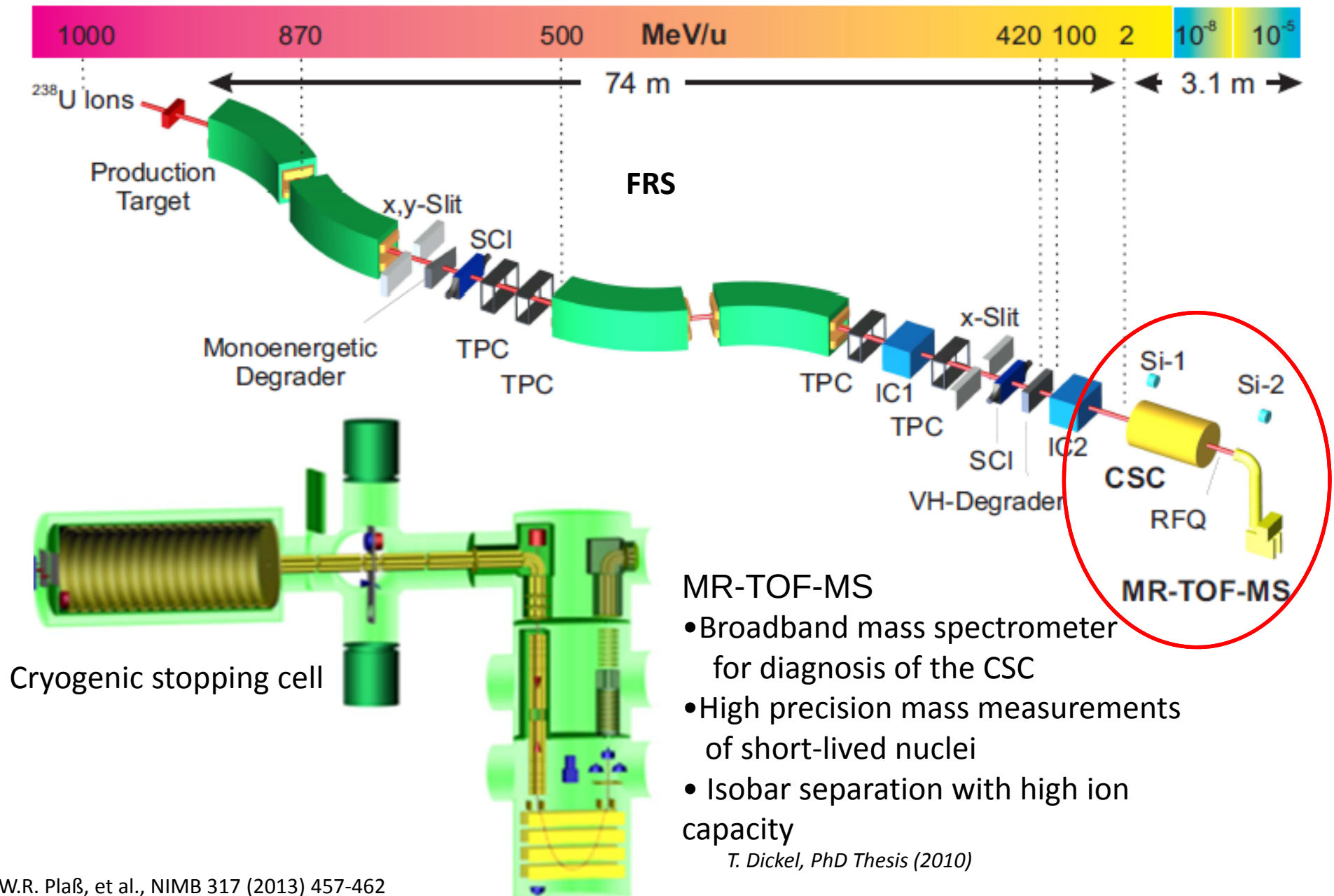
$\alpha=2$ (Theoretical onset of plasma effect)



FRS Ion Catcher setup

Test bench for LEB of Super FRS @ FAIR
Online in October 2011 and July 2012

FRS ion catcher setup (a test bench for LEB at FAIR)



1000 870 500 MeV/u 420 100 2 10^{-8} 10^{-5}

^{238}U Ions

74 m

3.1 m

Production Target

x,y-Slit

SCI

Monoenergetic Degradator

TPC

TPC

FRS

TPC

IC1

TPC

IC2

x-Slit

SCI

VH-Degradator

CSC

RFQ

MR-TOF MS

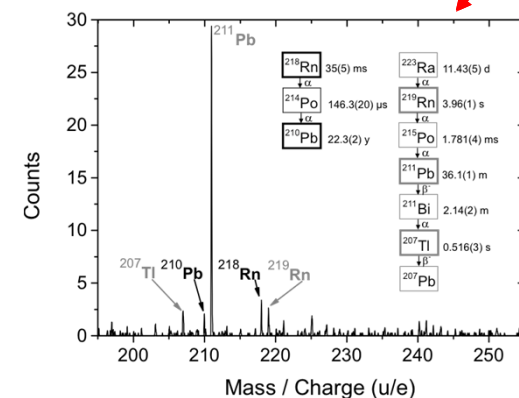
Si-1

Si-2

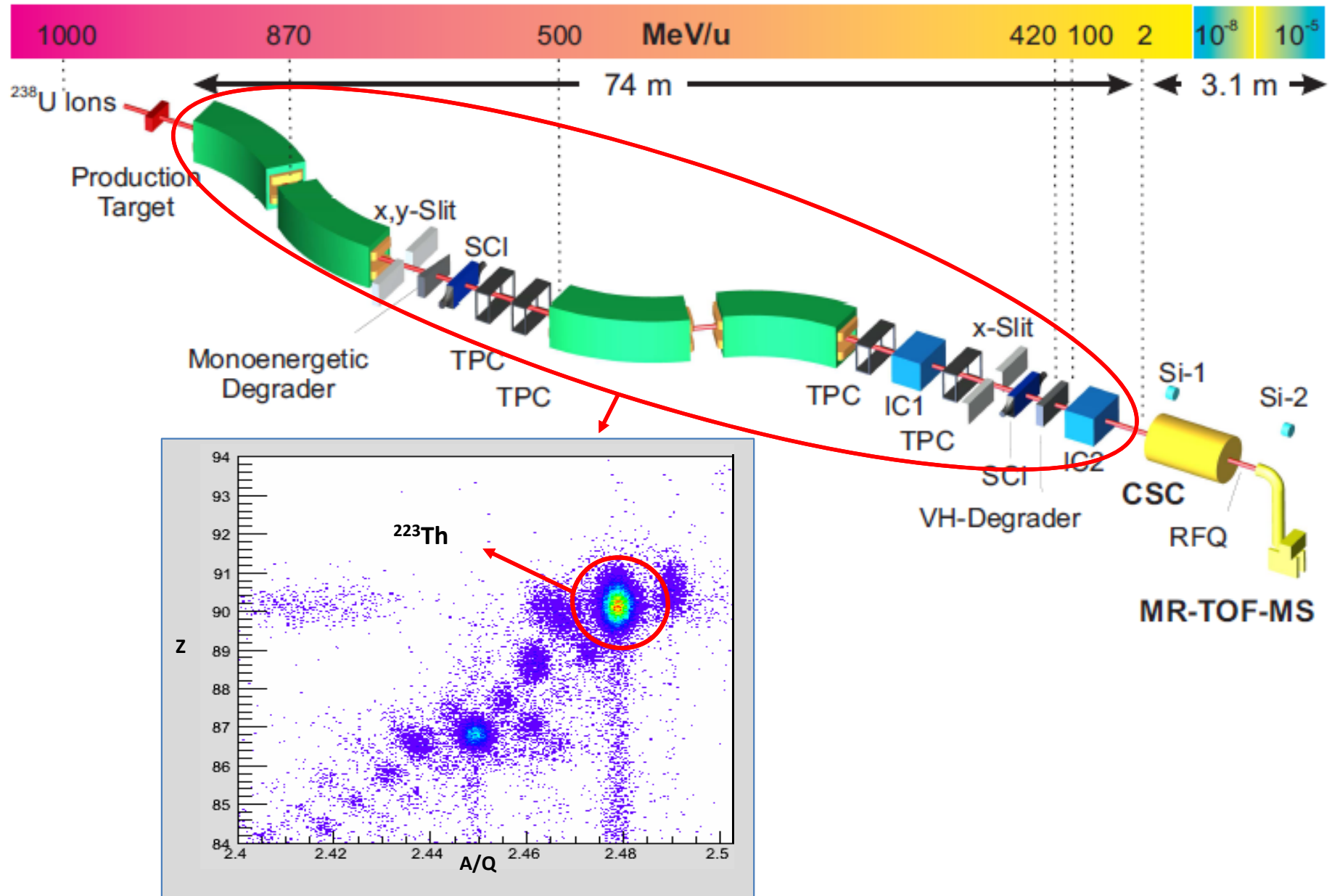
^{223}Th

^{223}Th extracted as $2+$

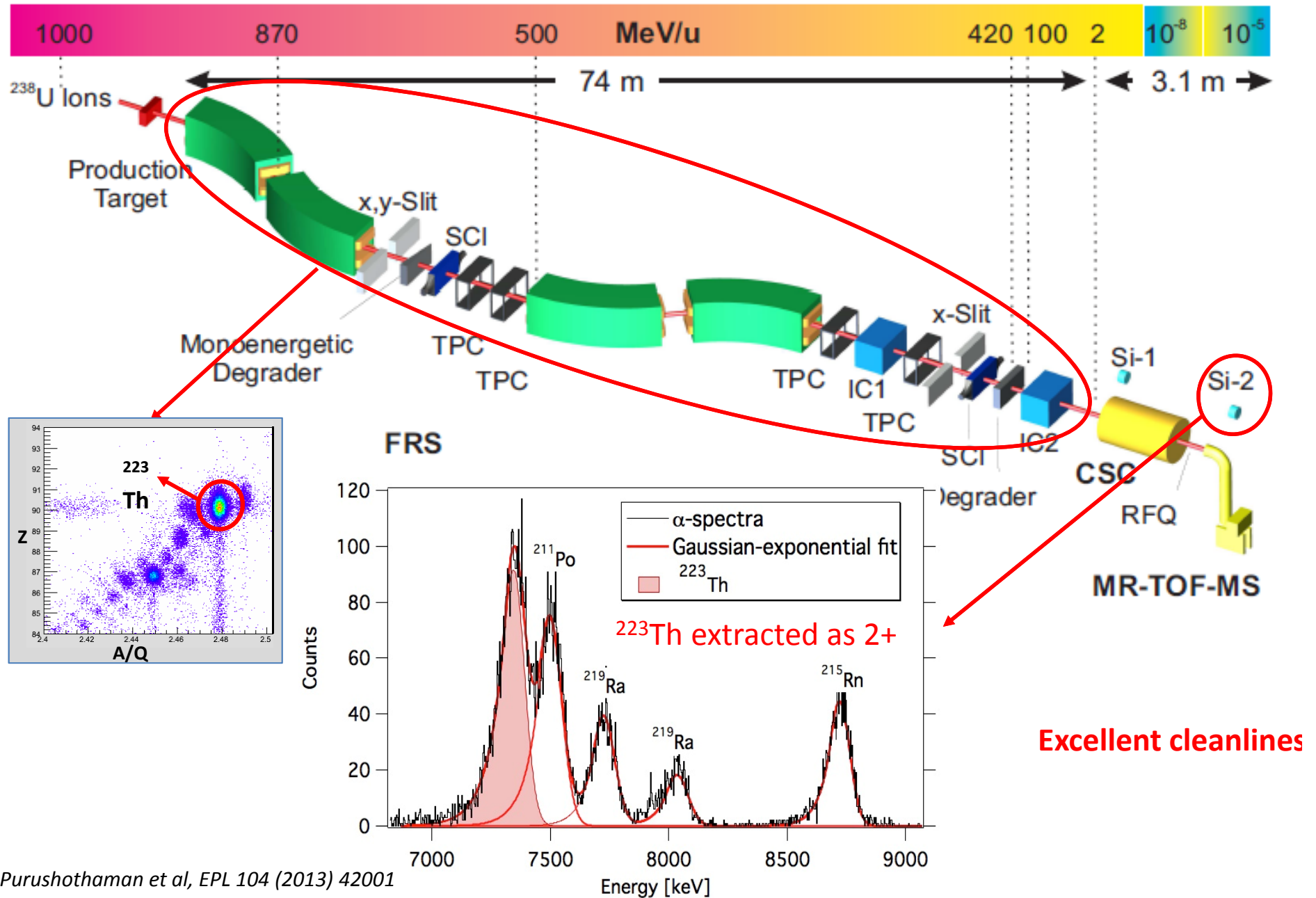
α -spectra



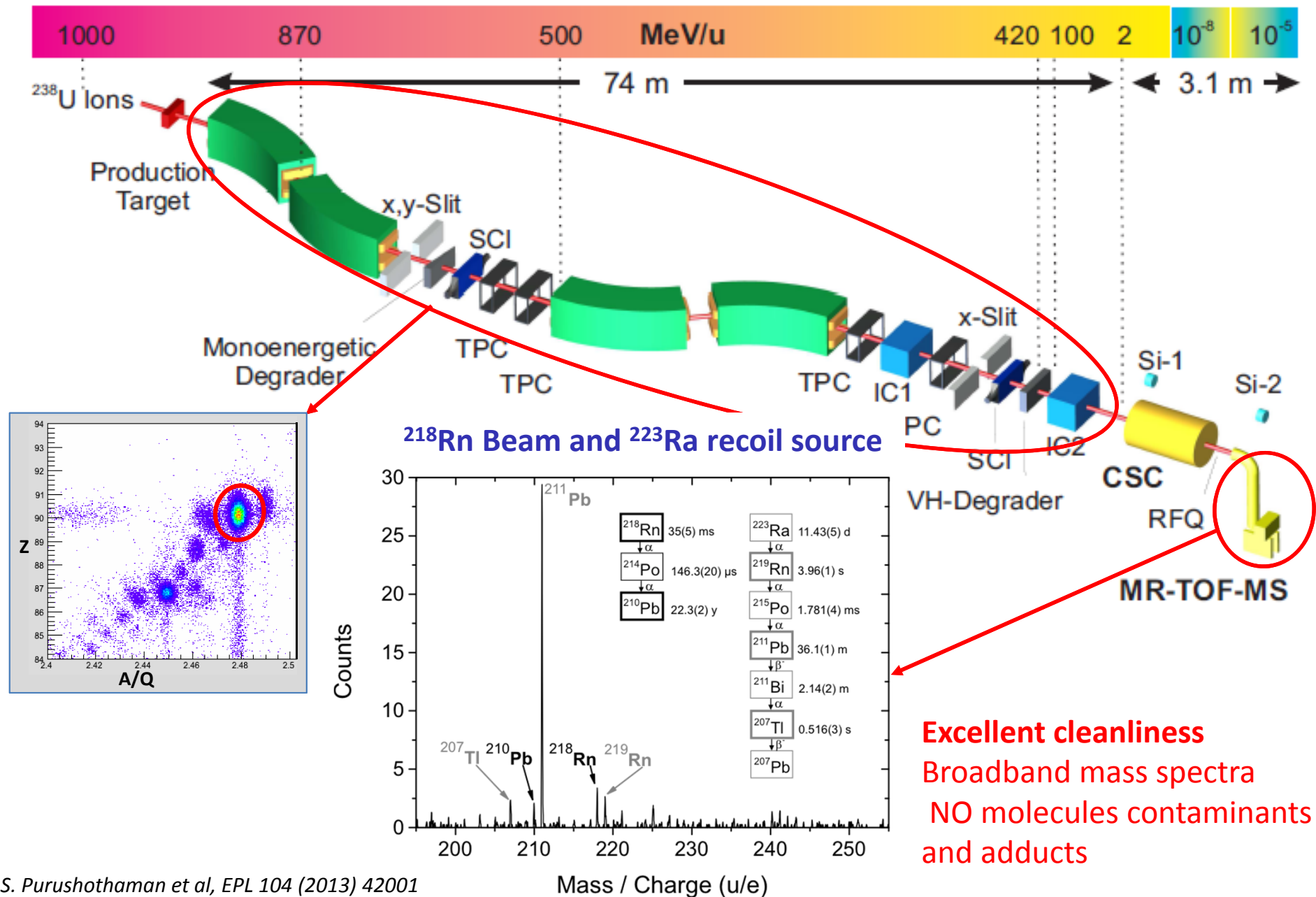
FRS ion catcher setup (a test bench for LEB at FAIR)



FRS ion catcher setup (a test bench for LEB at FAIR)

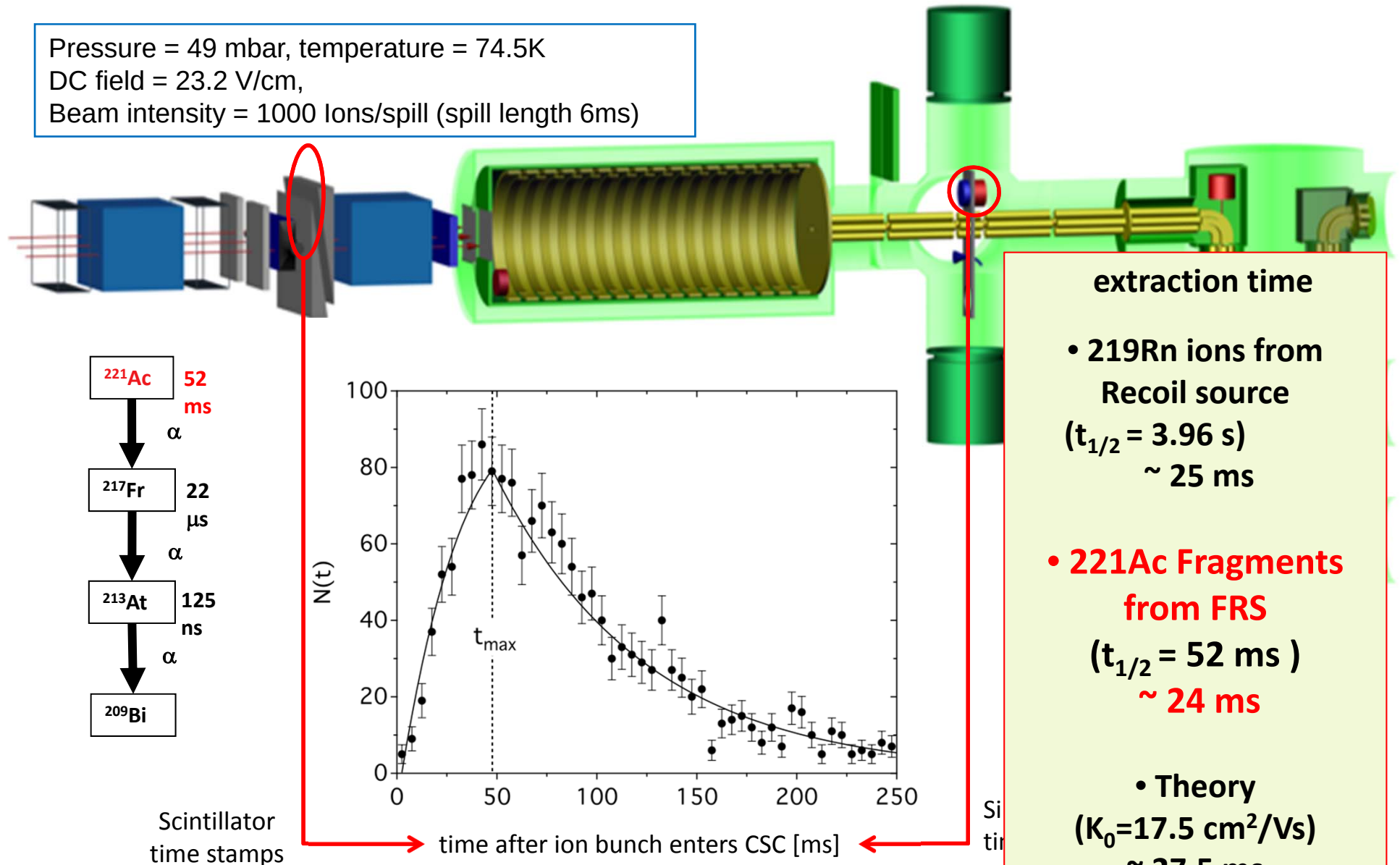


FRS ion catcher setup (a test bench for LEB at FAIR)



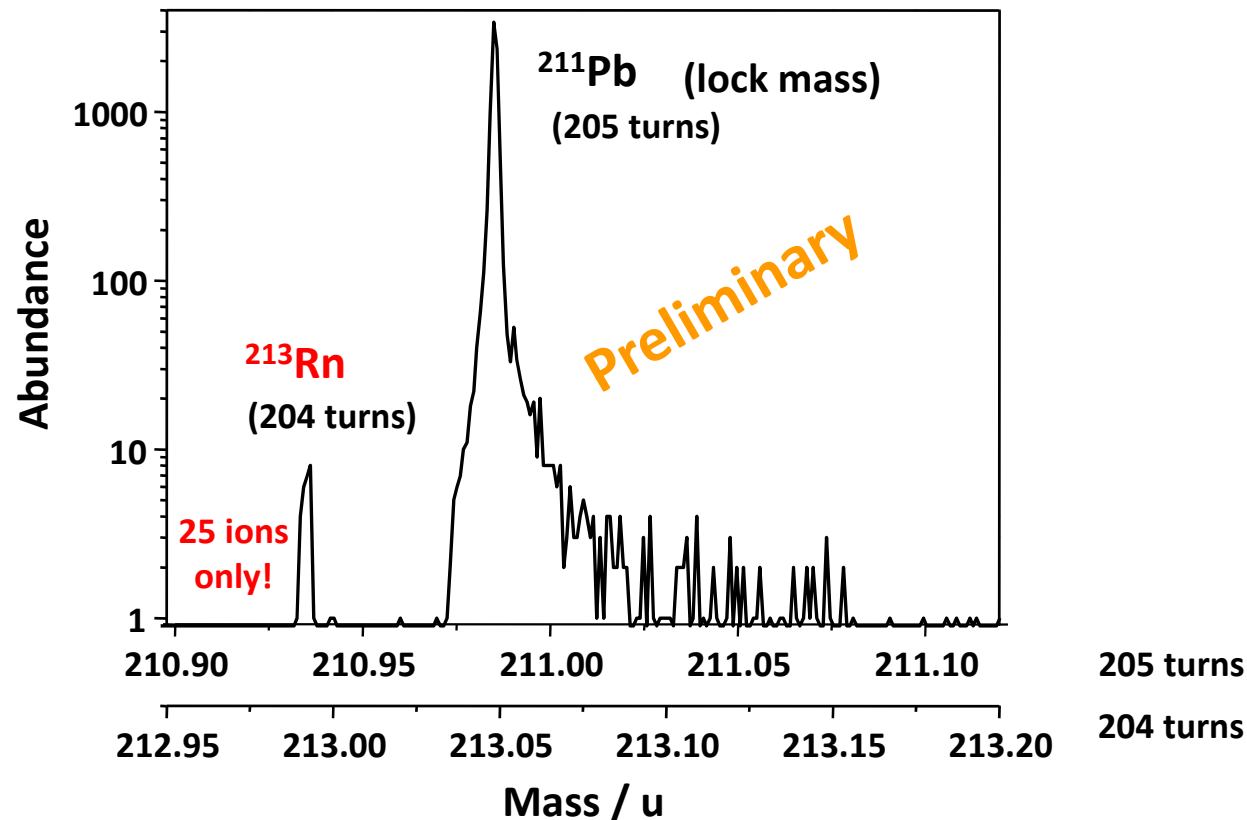
FRS Ion Catcher Results: Extraction time measurement

Pressure = 49 mbar, temperature = 74.5K
 DC field = 23.2 V/cm,
 Beam intensity = 1000 Ions/spill (spill length 6ms)



FRS Ion Catcher Results: Mass Measurements

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



Calibrating with different turns

- measure not only different isobars at the same time
- measure all isobars of neighboring mass numbers

FRS Ion Catcher Results

- Total efficiency: of up to 14.5%

Novel concepts (RF Carpet/high density and cryogenic operation)

High efficiency stopping cell

- Stopping efficiency: up to 27%

Areal Density: 4.9 mg/cm²

Almost 2 times higher gas density compared to other stopping cells using an RF structure

- Ion survival and extraction efficiency : up to 62%

Element independent

Compares favorably with other stopping cells

- Extraction time of about 25 ms

Agrees with offline measurements and theory

- ²²³Th extracted as 2+, no formation of adducts, clean mass spectrum

Excellent cleanliness

- Mass measurements of projectile fragments and identification of exotic nuclei with MR-TOF-MS

eg. ²¹³Rn (half-life: 19.5ms)

Future plans

For 2014 beam time

- Operation at higher gas density
- High intensity operation, space charge and plasma limitations
- Temperature effects on cleanliness
- Test with fission fragments (large emittance, low mass)

TDR for third generation stopping cell for LEB at FAIR

Acknowledgements

F. Amjad², S. Ayet², T. Dickel^{1,2}, P. Dendooven³, M. Diwisch¹, J. Ebert¹, A. Estrade², F. Farinon², H. Geissel^{1,2}, F. Greiner¹, E. Haettner¹, C. Jesch¹, N. Kalantar-Nayestanaki³, R. Knoebel², J. Kurcewicz², J. Lang¹, I. Moore⁴, C. Nociforo², M. Petrick¹, M. Pfuetzner², W.R. Plaß^{1,2}, S. Pietri², A. Prochazka², S. Purushothaman², M. Ranjan³, M.P. Reiter¹, A.-K. Rink¹, S. Rinta-Antila⁴, C. Scheidenberger², M. Takechi², Y. Tanaka², H. Weick², J.S. Winfield², M.I. Yavor⁵

¹ II. Physikalisches Institut, Justus-Liebig-Universität Gießen, Gießen, Germany

² GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

³ KVI, University of Groningen, The Netherlands

⁴ University of Jyväskylä, Jyväskylä, Finland

⁵ Institute for Analytical Instrumentation, RAS, St. Petersburg, Russia



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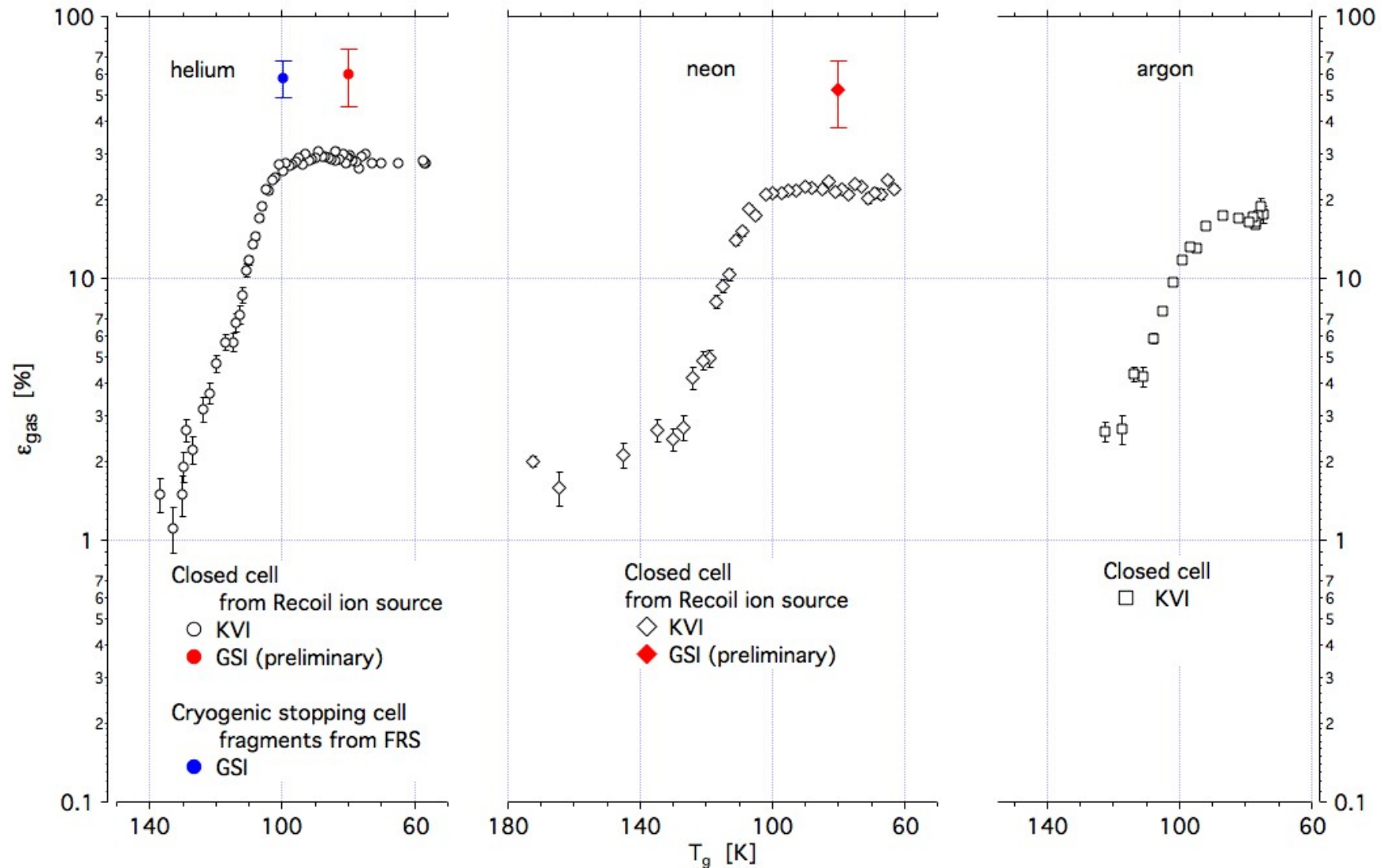
State of Hesse (LOEWE Center HIC for FAIR)

JLU and GSI (JLU-GSI strategic Helmholtz partnership agreement)

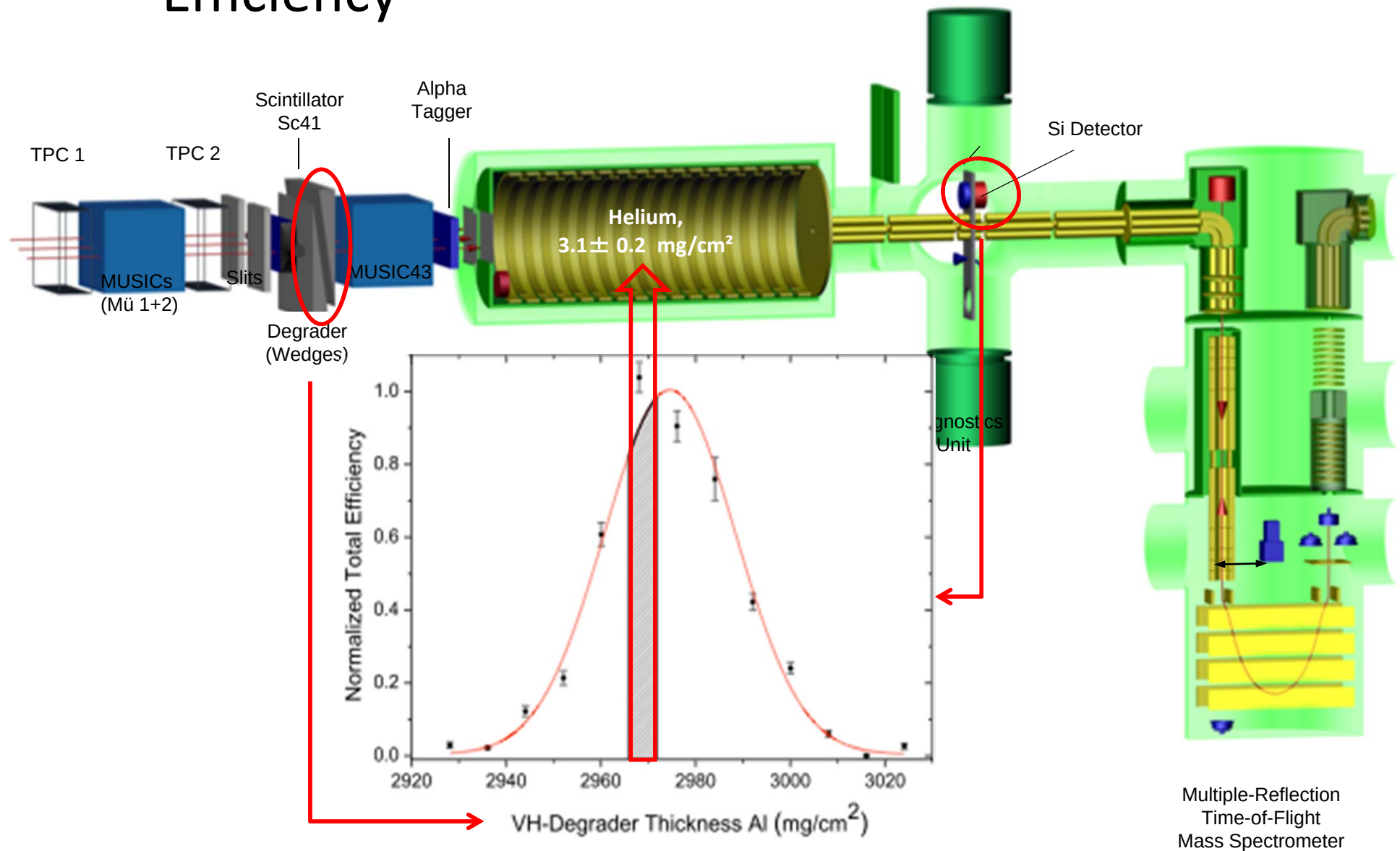


C. Jesch

Ion survival efficiency of energetic ^{219}Rn ions in Helium



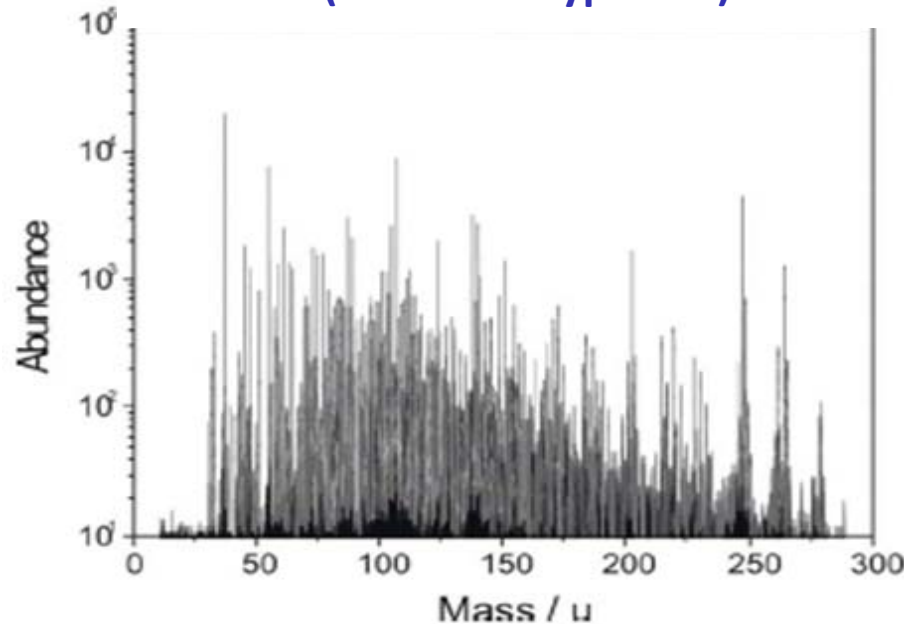
FRS Ion Catcher Results: Stopping Efficiency



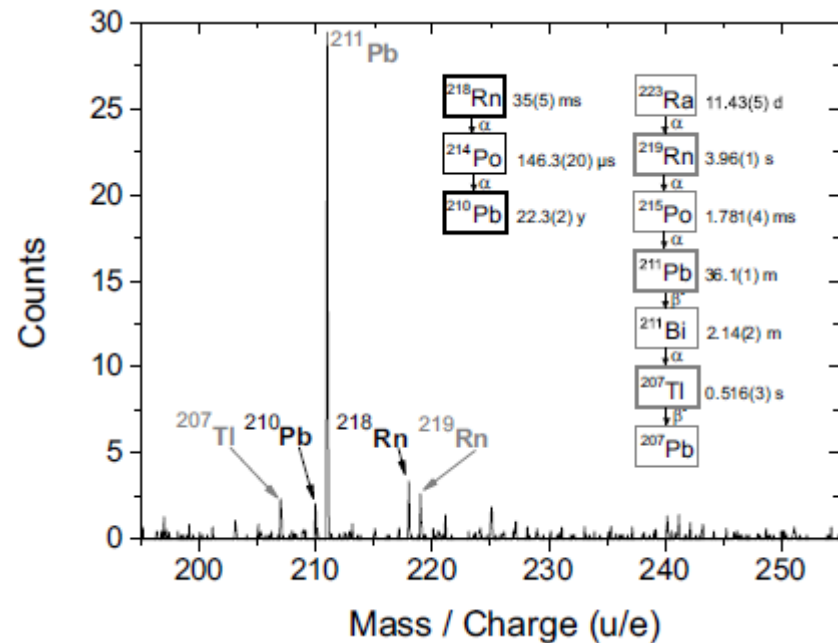
FRS Ion Catcher Results: Cleanliness of the CSC

MR-TOF-MS (Broadband Measurement)

Online with Beam
(First Prototyp 2005)



Online with ^{218}Rn Beam
and ^{223}Ra recoil source



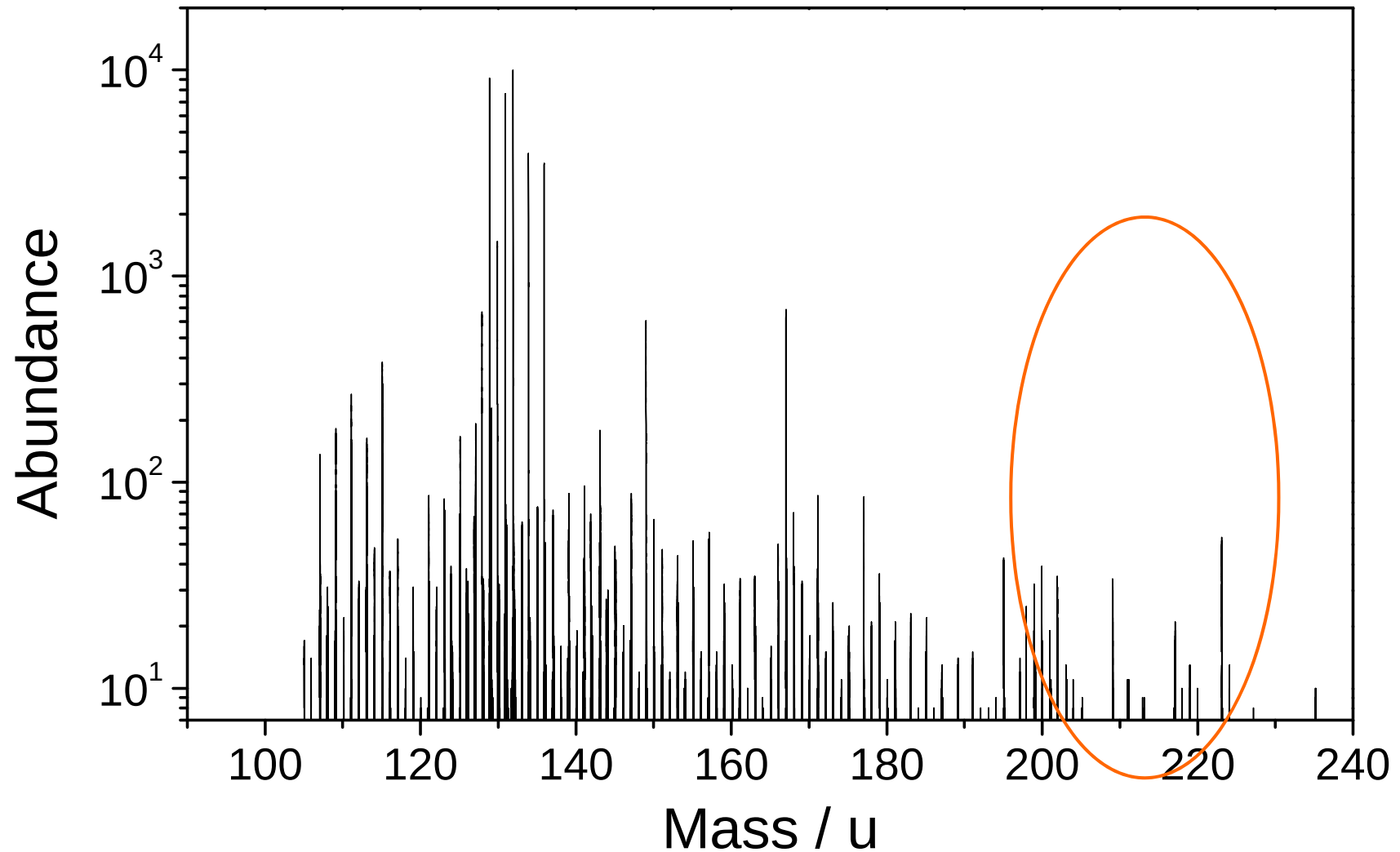
- Broadband mass spectrometry is a necessity for quick and reliable operation of a stopping cell
- Molecular contaminants / adduct formation are not a problem for the cryogenic stopping cell

Many orders of magnitude cleaner compared to
2005 GSI experiment (First prototype)

Example

Off-line test at SHIPTRAP

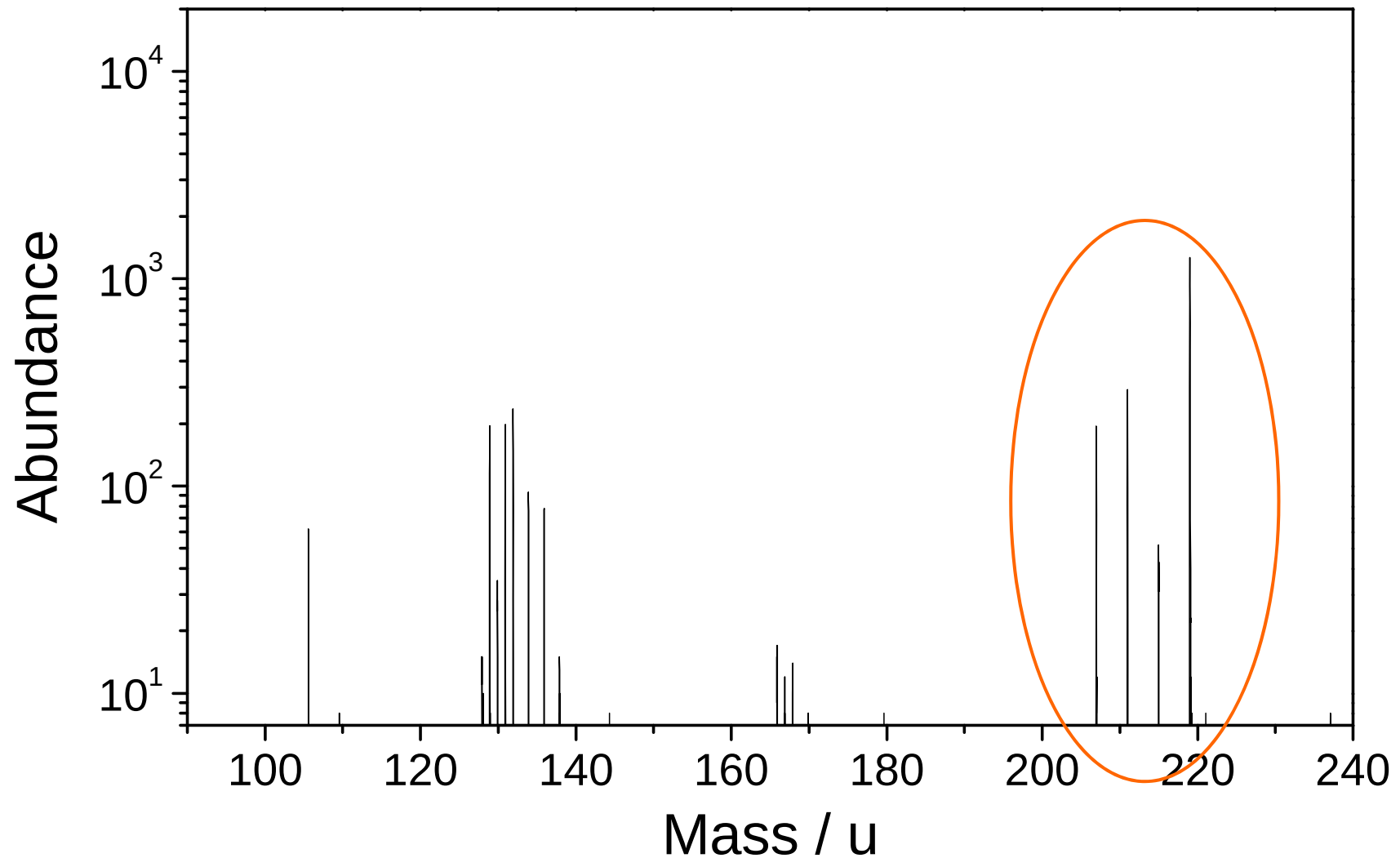
Mass spectrum of extracted ions before bake-out



Example

Off-line test at SHIPTRAP

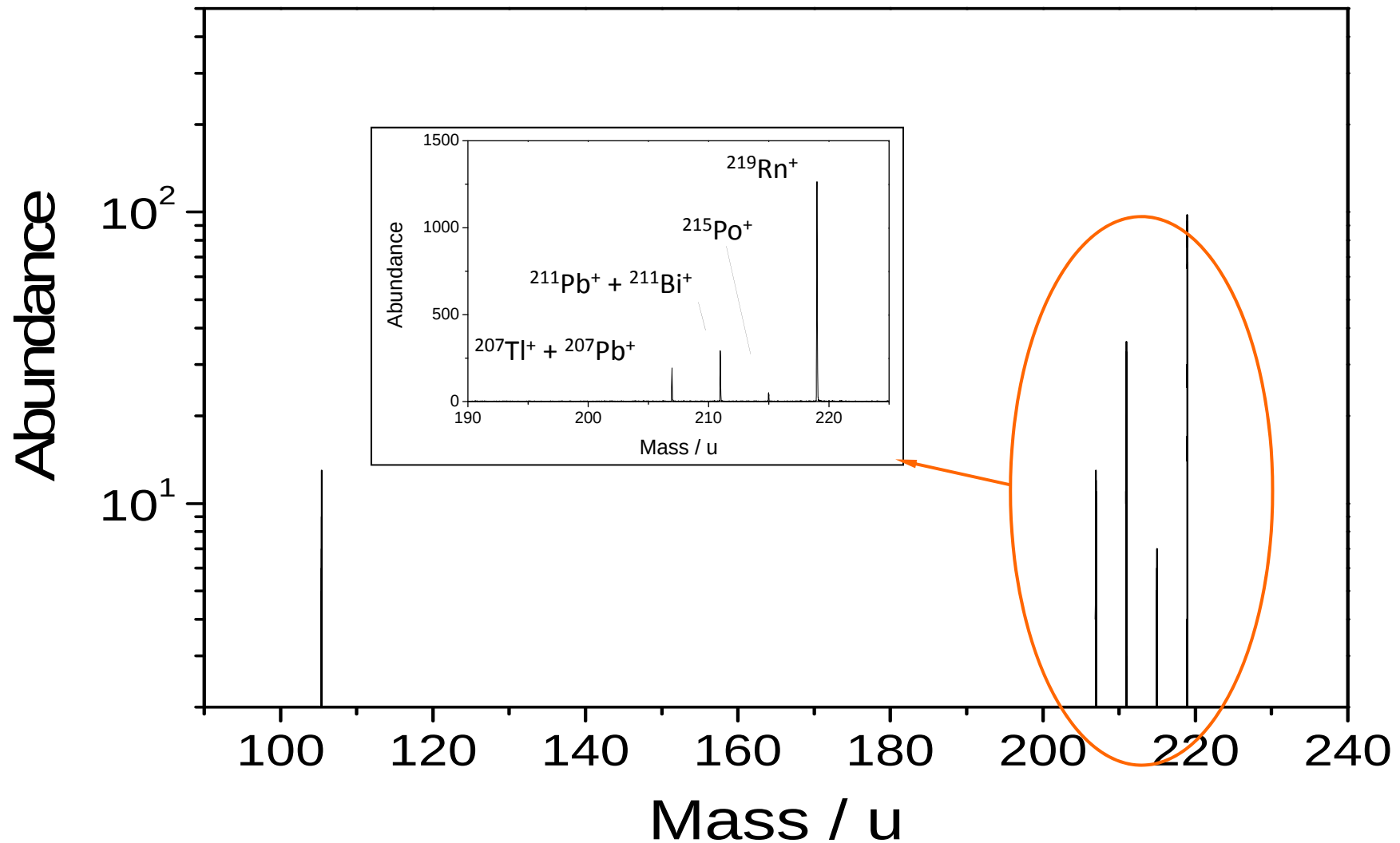
Mass spectrum of extracted ions **after** bake-out



Example

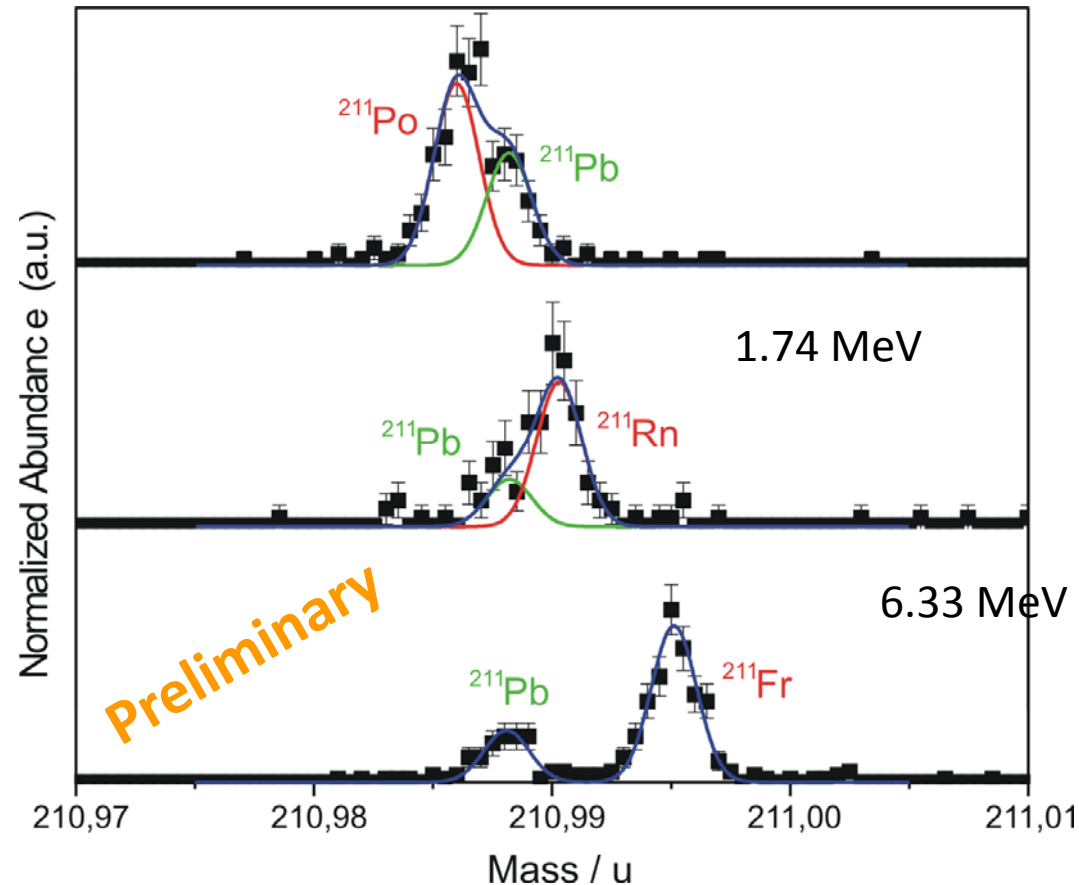
Off-line test at SHIPTRAP

Mass spectrum of extracted ions after bake-out **with cold trap** at gas inlet



FRS Ion Catcher Results: Mass Measurements

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

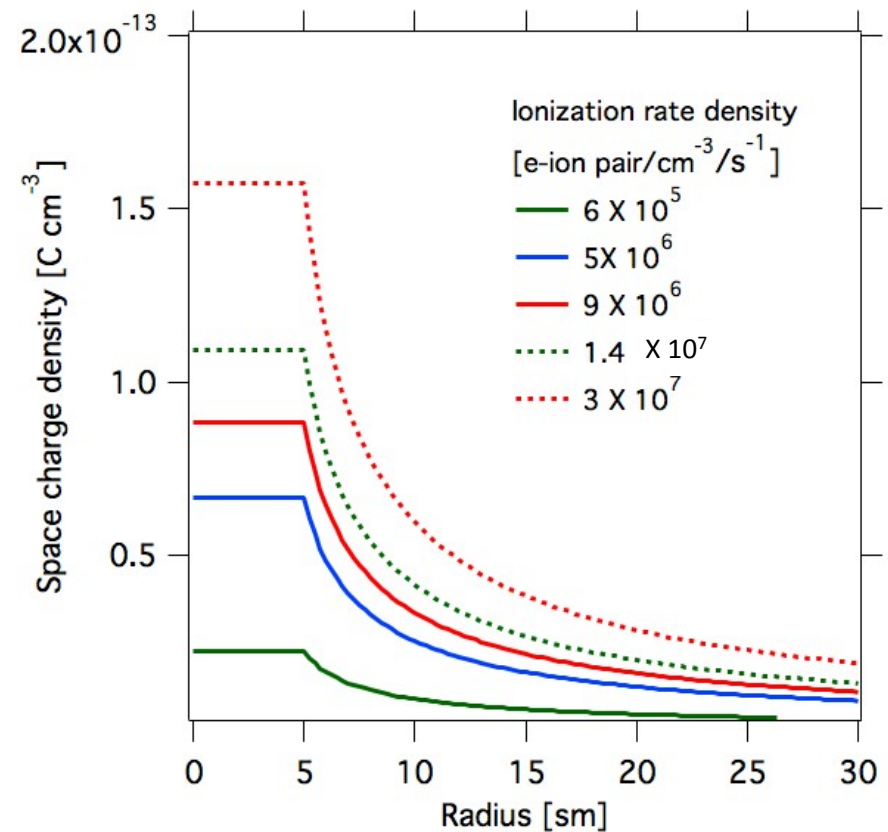
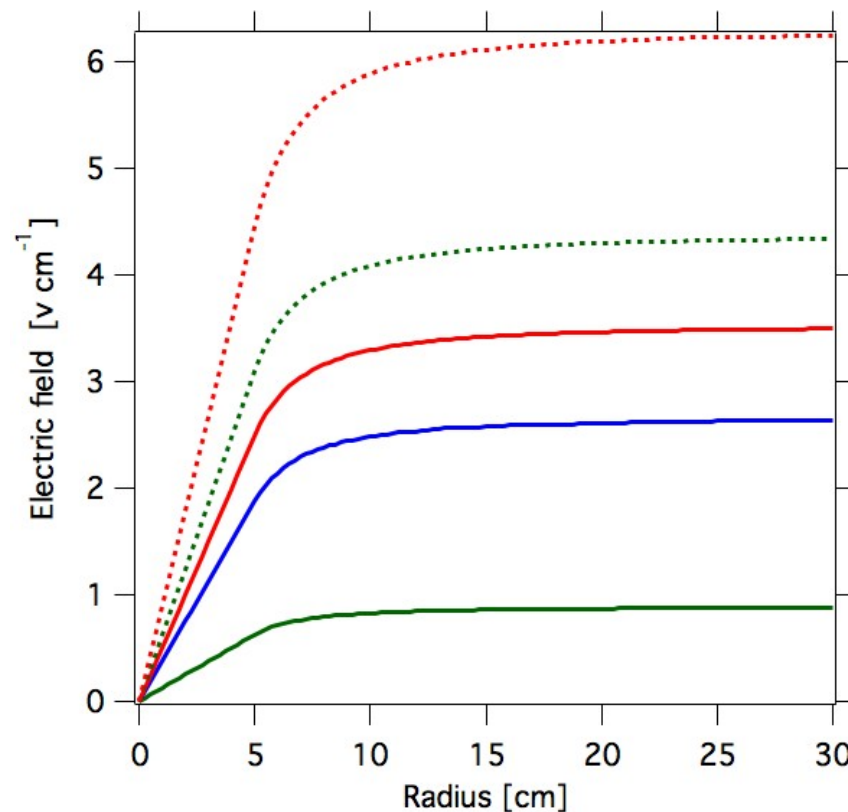


First direct mass measurements of
projectile fragments with an MR-TOF-MS

Radial space charge effect

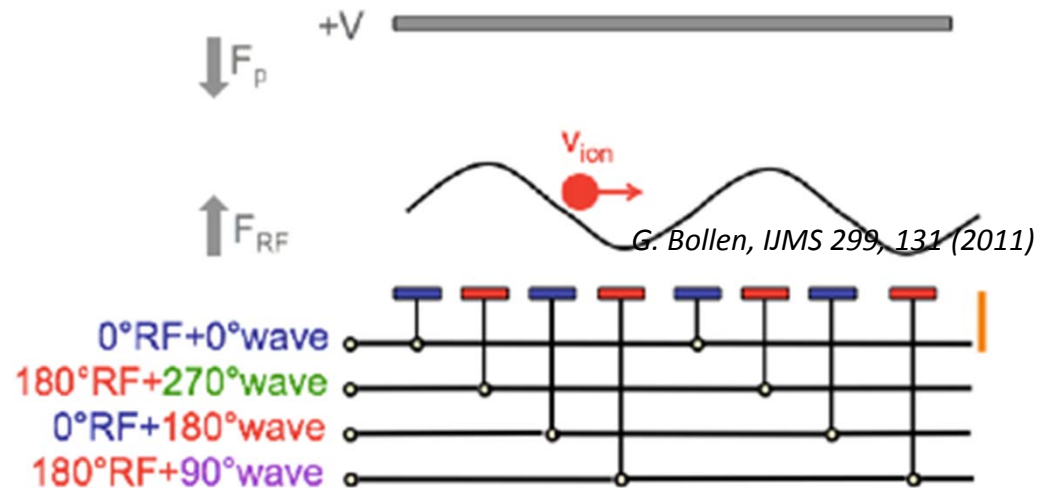
2.5 MeV/u ^{238}U ions, thermalized in a 220 mbar helium gas 80 K.
No electric field applied along the gas cell.

Stationary state solution obtained using Continuity equation and Poisson's equation in cylindrical coordinates (A. Takamine et al., Rev. Sci. Instrum. 76 (2005) 103503)

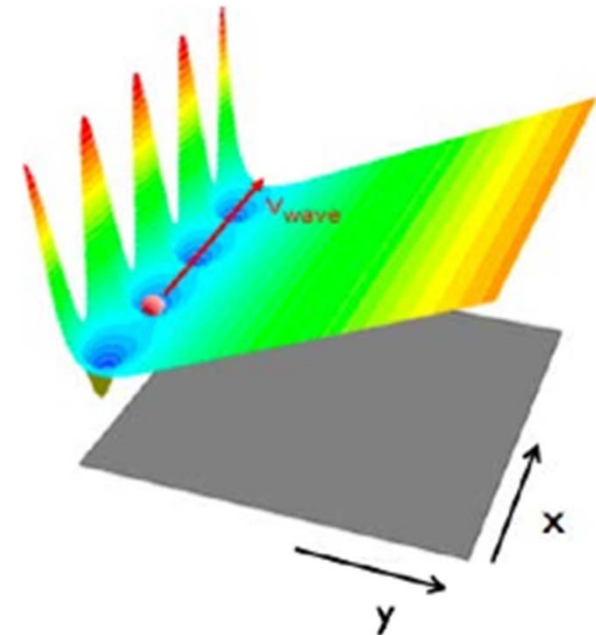


Travelling wave RF carpet

Potential gradient replaced by a travelling wave

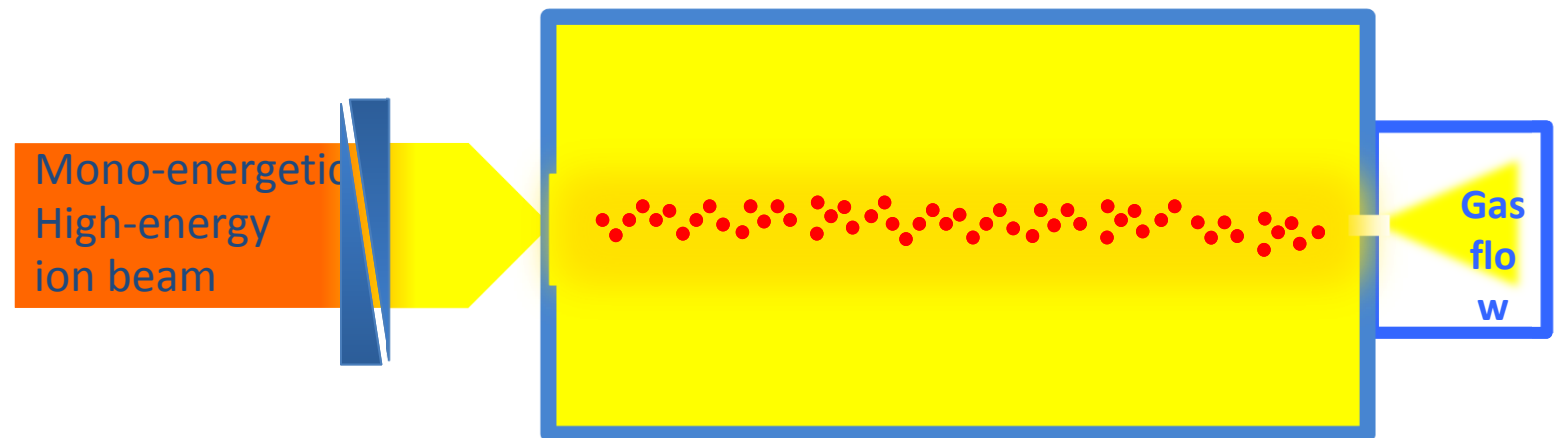


Snapshot of the pseudo-potential with traveling wave



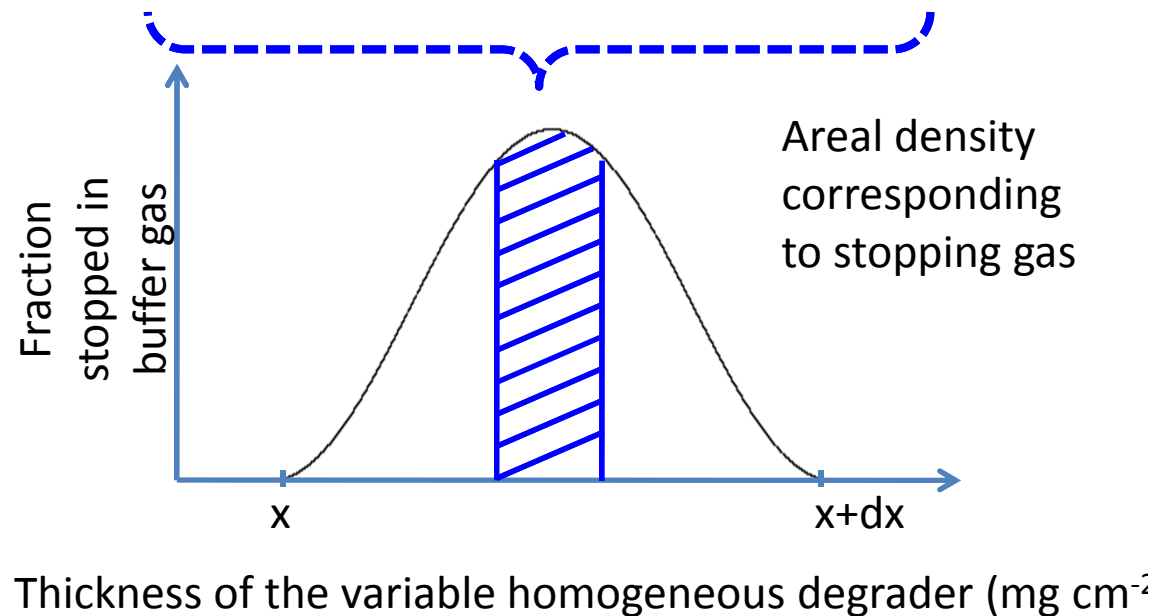
- Transport using travelling wave
- Simpler circuitry
- No high-voltage involved, ion speed not discharge-limited
→ can extract shorter-lived isotopes

Efficient stopping – High density operation



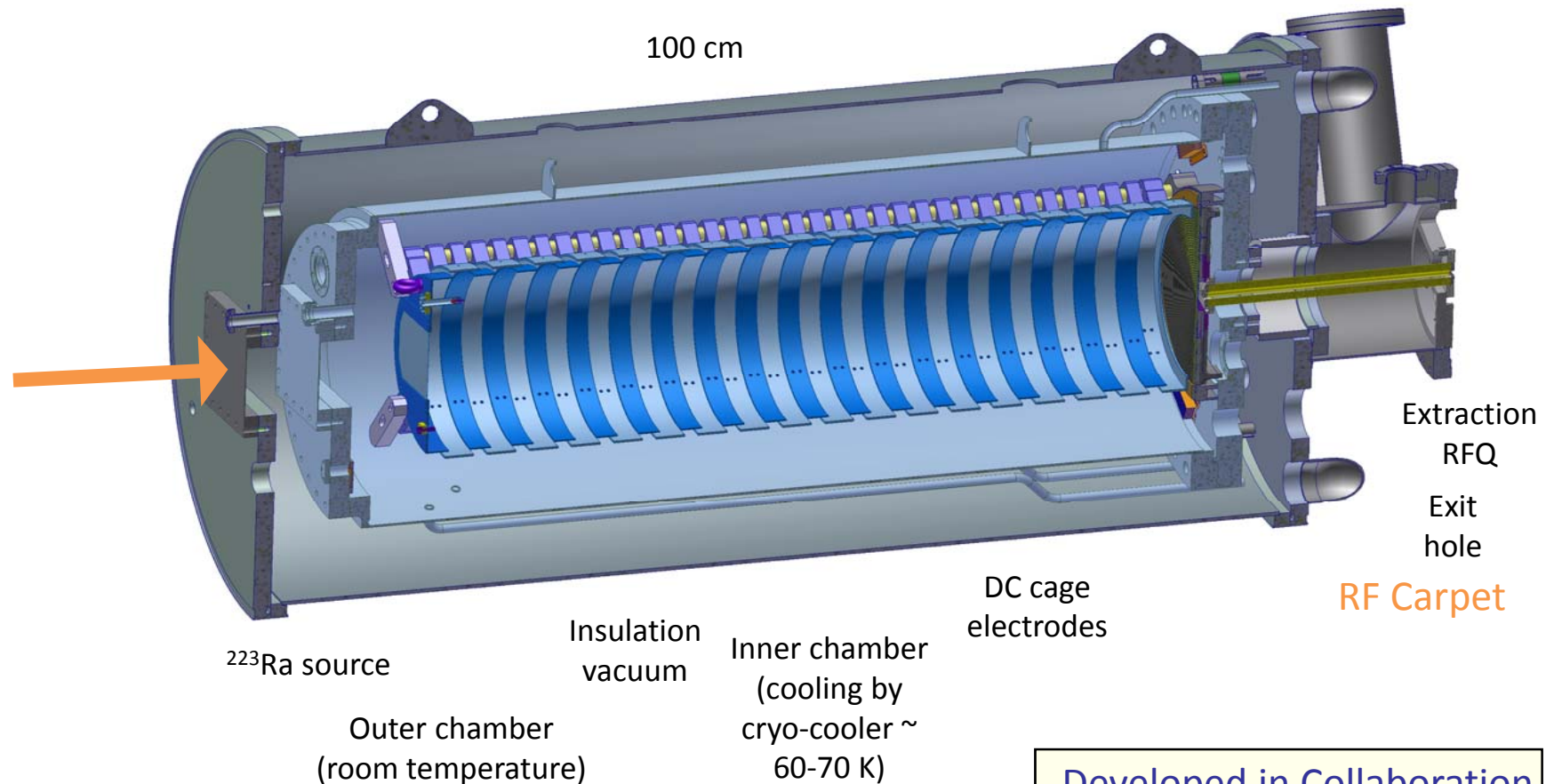
Problem with gas flow assisted extraction (IGISOL)

- Long extraction time/small volume
- Low Efficiency (recombination losses)
- ✓ Use Laser ionization to solve the problem (LISOL)



J. Äystö, Nuclear Physics A 693 (2001) 477
. Kudryavtsev et al., NIM B 179 (2001) 412

Cryogenic stopping cell design



M. Ranjan et al., *Europhys. Lett.* 96 (2011) 52001

M. P. Reiter, *Master Thesis, Justus-Liebig-Universität Gießen* (2011)

On-line Performance Study: Efficiencies

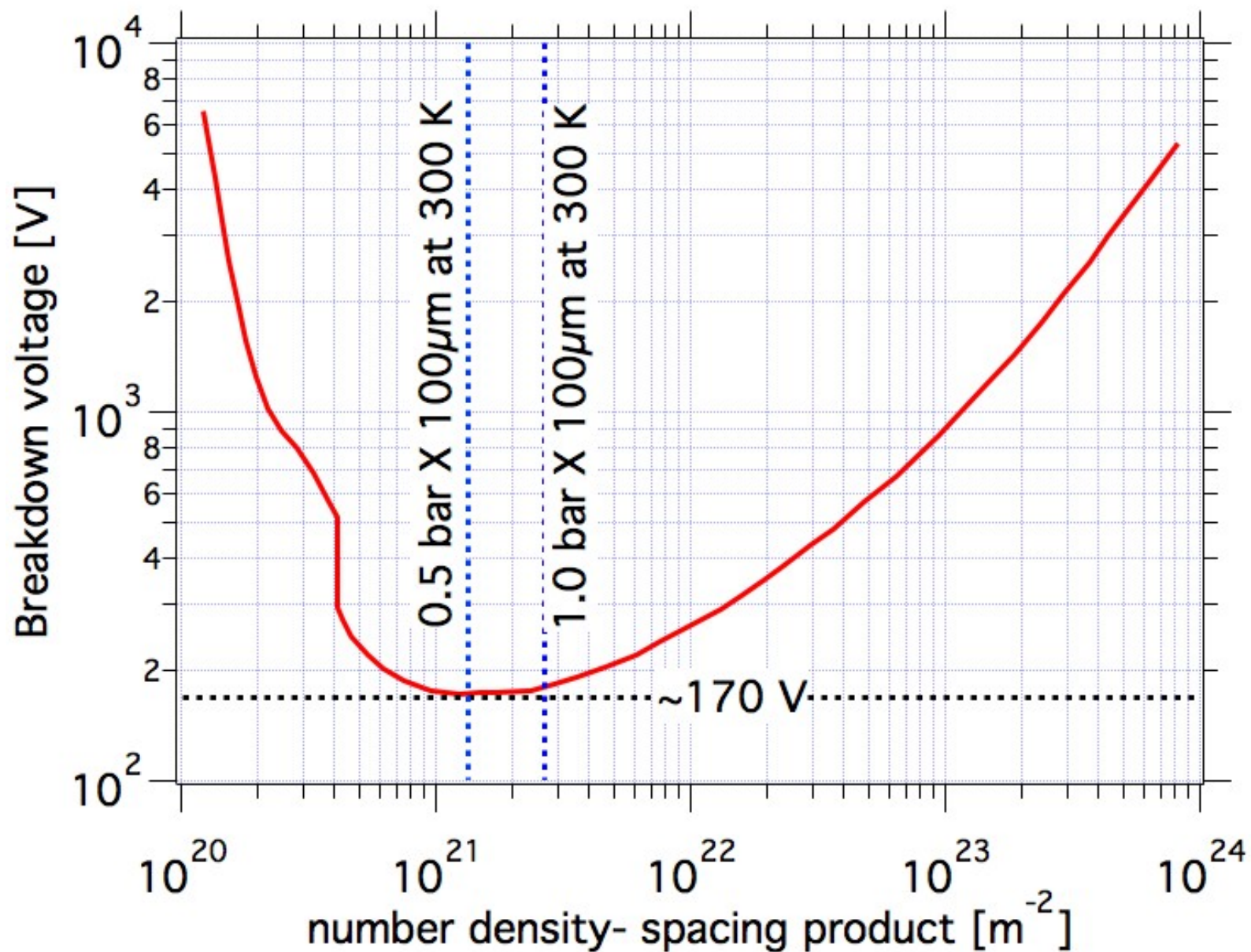
	Areal Density (mg/cm ²)	²²³ Th	²²¹ Ac	²¹⁹ Rn
Stopping efficiency	4.9 ± 0.3	(27 ± 2.4)%		(25 ± 2.4)%
	3.1 ± 0.2	(15.9 ± 1.8)%	(15.7 ± 1.8)%	
Total efficiency	4.9 ± 0.3	(11.6 ± 1.6)%		(14.5 ± 2.0)%
	3.1 ± 0.2	(9.9 ± 1.5)%	(7.7 ± 1.6)% *	
Survival and extraction efficiency	4.9 ± 0.3	(43 ± 7)%		(58 ± 9)%
	3.1 ± 0.2	(62 ± 12)%	(49 ± 11)%	

* Corrected for decay losses

- Intensity : few hundreds up to 2000 ions/s
→ up to 10⁷ He-ion-electrons/cm³/s

Almost 2 times higher gas density compared to other stopping cells using an RF structure

Helium Paschen curve



Efficient extraction – High ion survival

High ion survival → High purity helium

Source of Impurities

→ Residual gas

→ Impurities in the helium gas

→ Degassing of surfaces inside the cell

Ultra-high vacuum technology

→ Possible but complicated

limited choice of materials

cryogenic operation

Ultra-pure helium

→ Ideal for ion survival

→ 2+ charge state possible

→ No formation of molecules/adducts

Improves differential pumping

Reduced diffusion

Reduced requirements for cleanliness

→ easier, more flexible construction