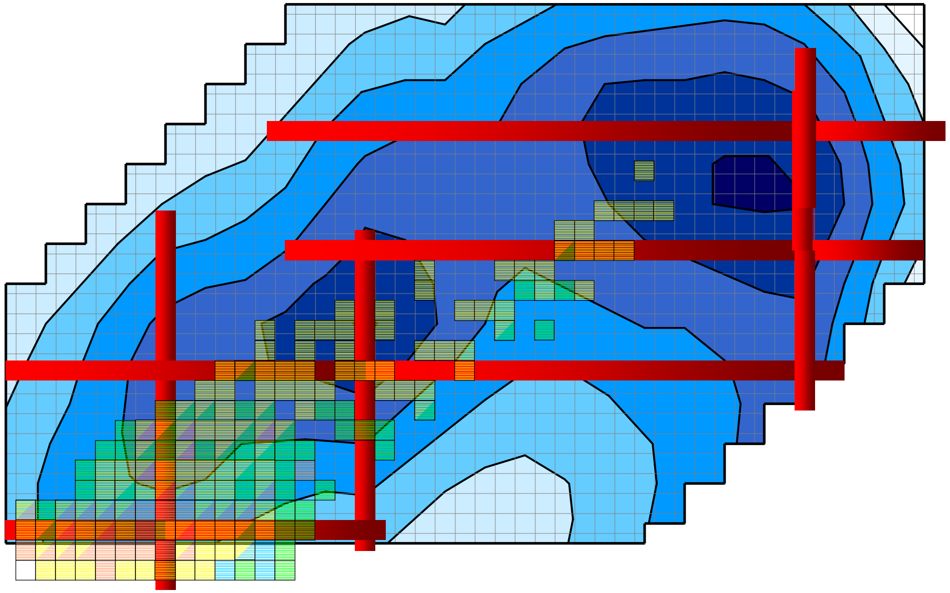
Workshop on Rare Atoms Ann Arbor 2009

Perspectives for Penning Trap Mass Measurements of Super Heavy Elements



- Introduction to Super Heavy Elements
- Production of SHE
- Mass determination of SHE
- Direct mass measurements for Z > 100 with SHIPTRAP
- Extending the reach towards SHE
- Conclusions

Michael Block

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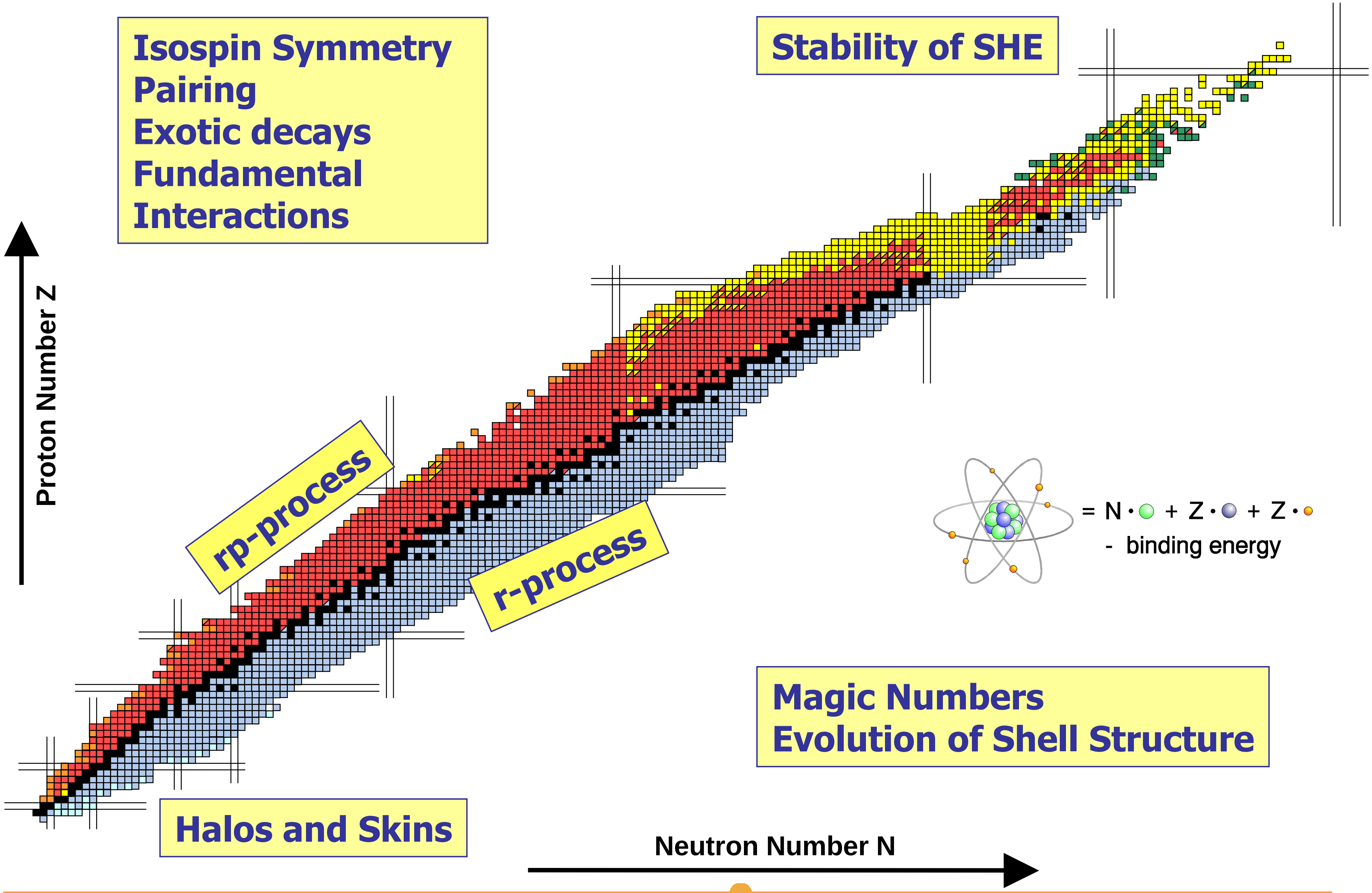
Mass Measurements for Nuclear Physics



Isospin Symmetry
Pairing
Exotic decays
Fundamental
Interactions

Stability of SHE

rp-process

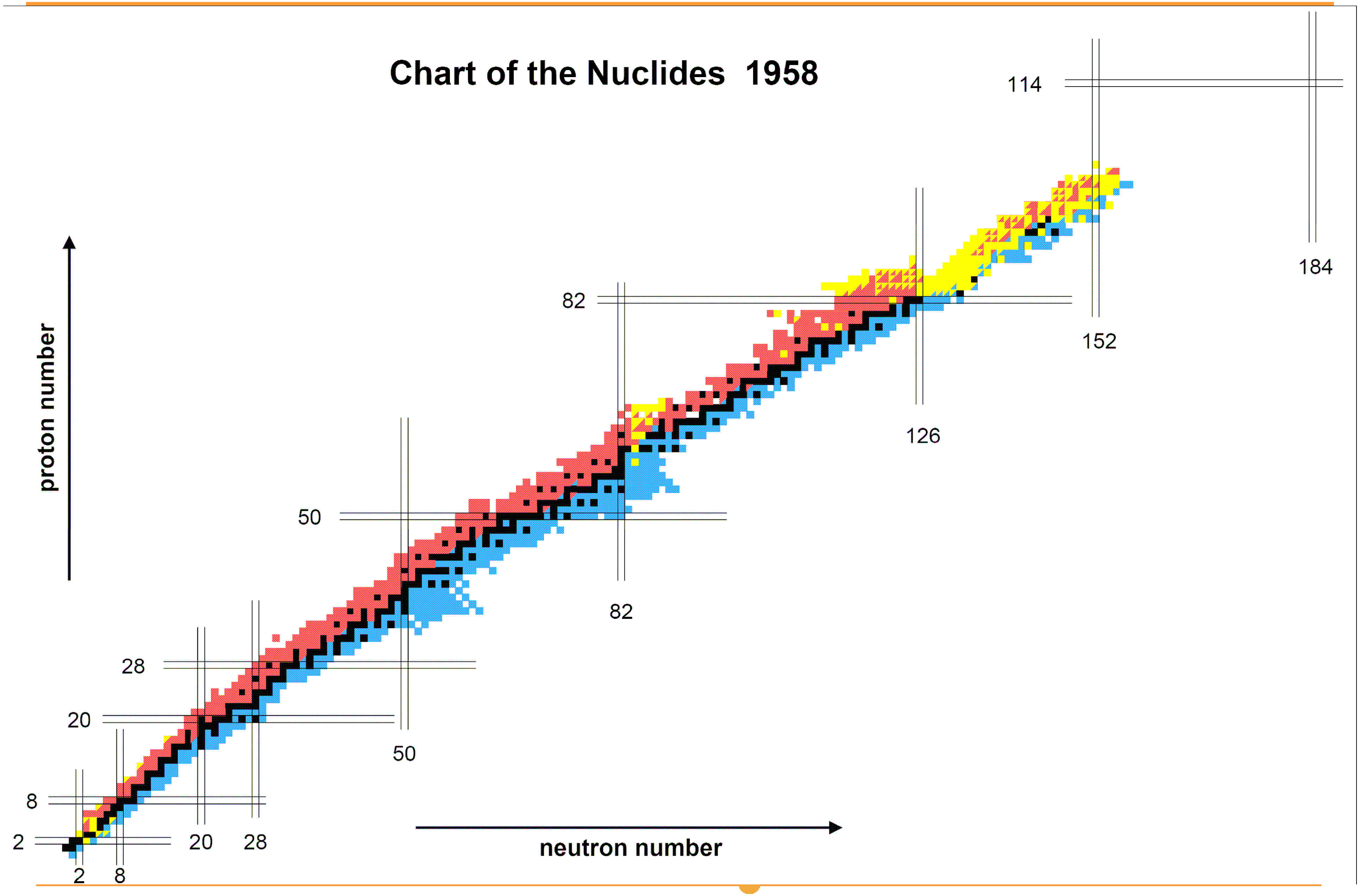
r-process

= N · 🟢 + Z · 🔵 + Z · 🟠
- binding energy

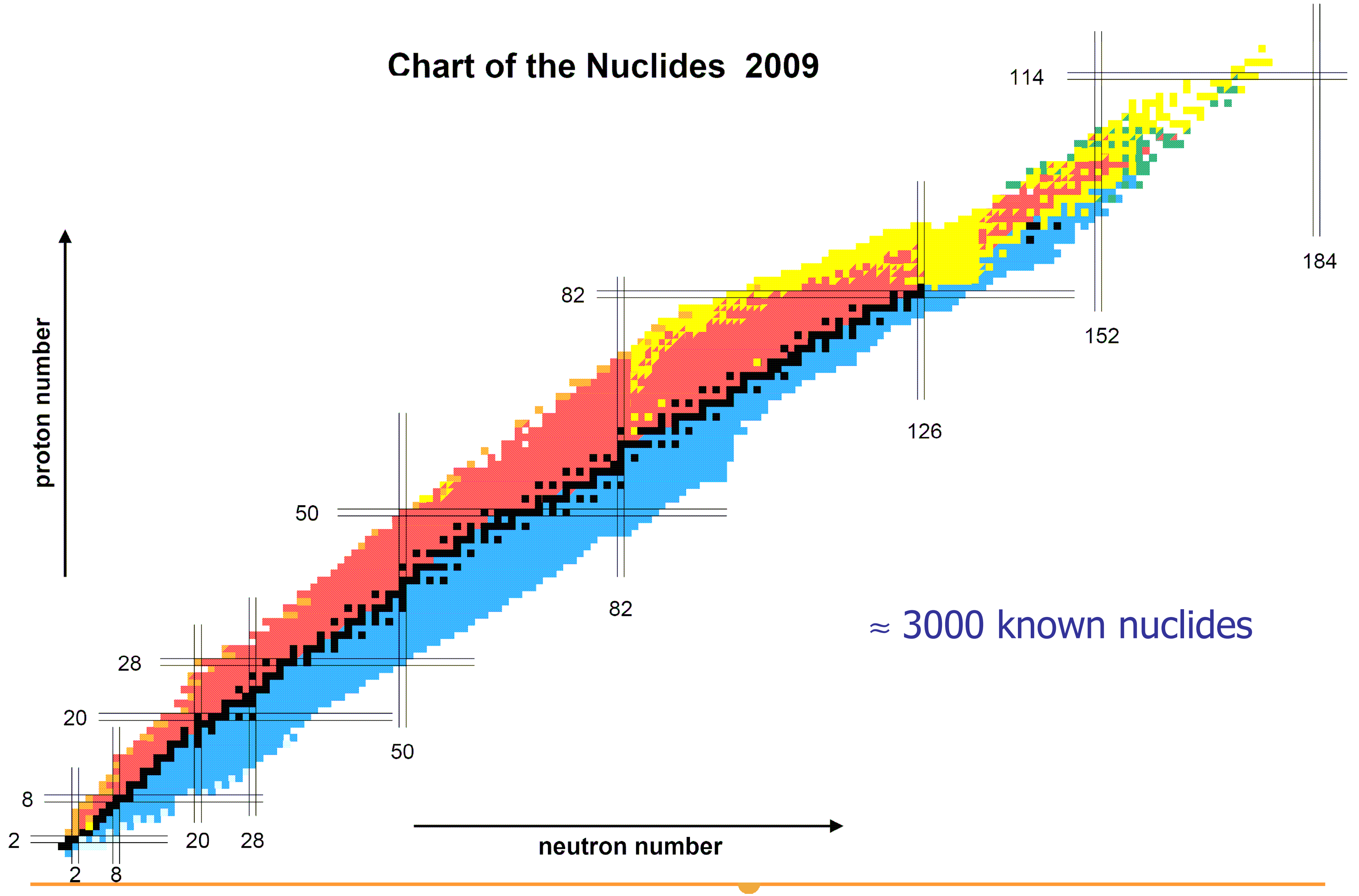
Magic Numbers
Evolution of Shell Structure

Halos and Skins

Extending the Nuclear Chart at RIB Facilities

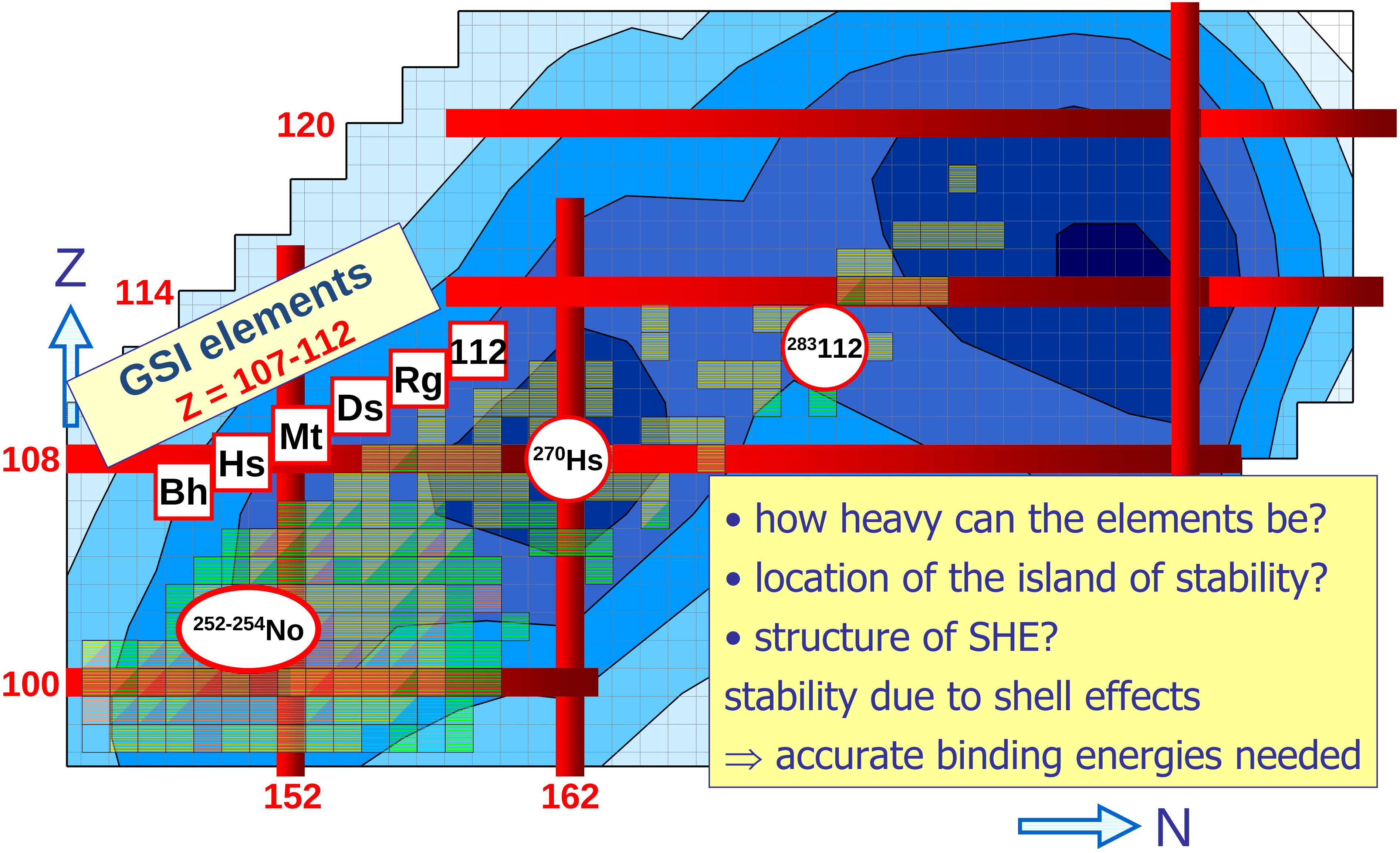


Extending the Nuclear Chart at RIB Facilities



≈ 3000 known nuclides

Super Heavy Elements



- how heavy can the elements be?
- location of the island of stability?
- structure of SHE?

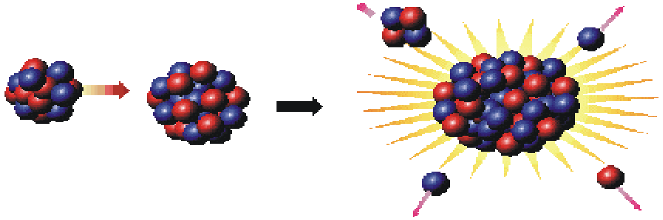
stability due to shell effects

⇒ accurate binding energies needed

Production of SHE

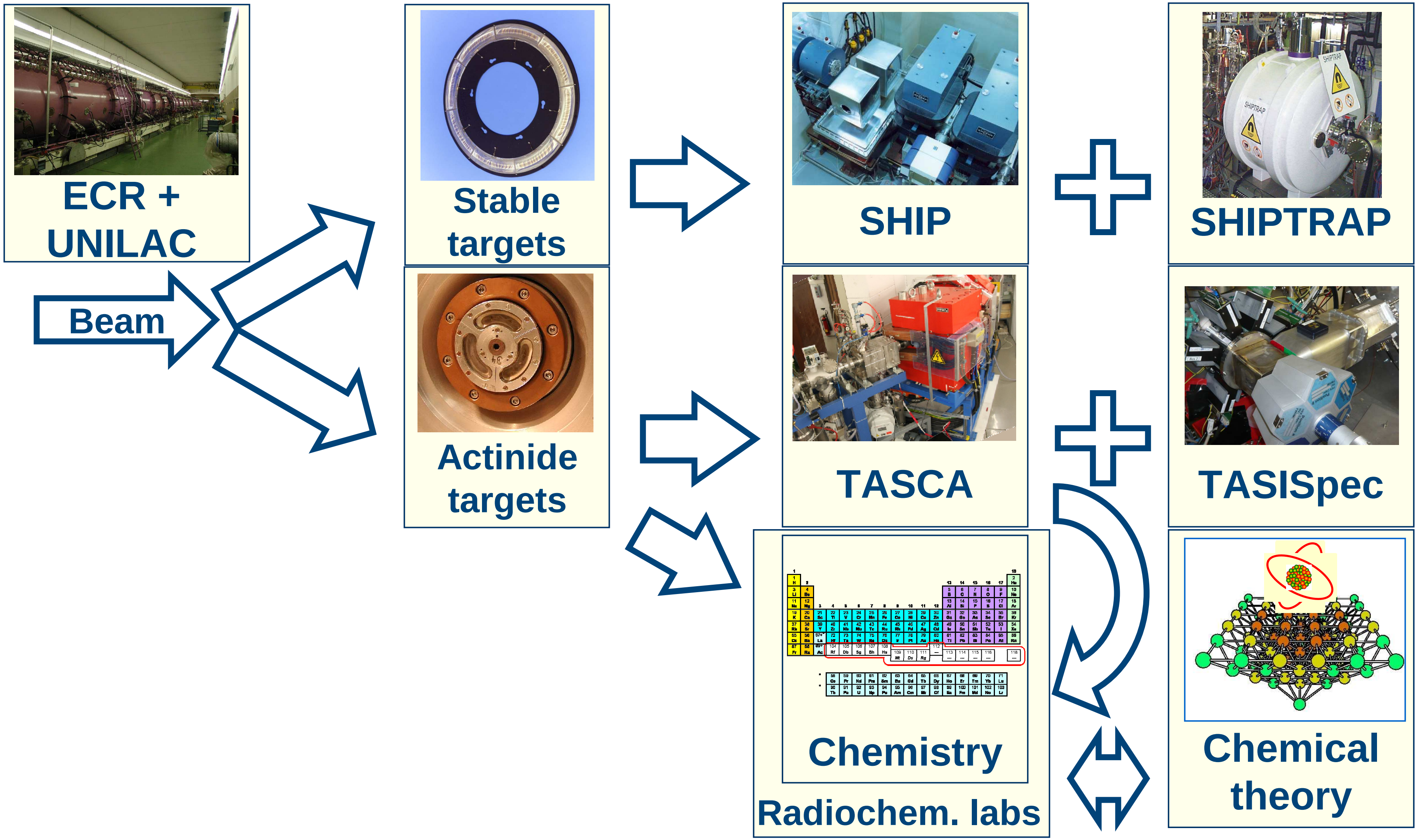
Exclusive access to nuclides with Z > 100 by fusion-evaporation reactions

- “cold” fusion: heavy ions on Pb and Bi targets
- “hot” fusion: ^{48}Ca induced reactions on Actinide targets



- Heavy-ion accelerator to provide high-intensity stable beams at coulomb barrier energies
- thin targets ≈ 0.5 mg/cm^2
- Recoil separator to separate evaporation residues from primary beam in flight

GSI: Unique Combination for SHE Studies



ECR + UNILAC

Beam

Stable targets

Actinide targets

SHIP

TASCA

Chemistry

Radiochem. labs

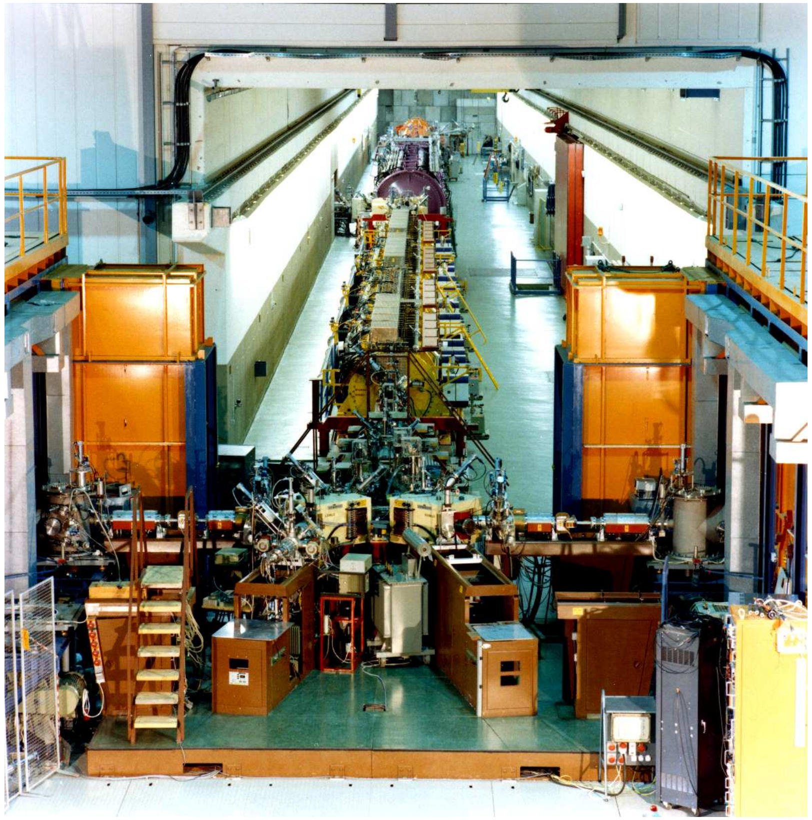
SHIPTRAP

TASISpec

Chemical theory

Courtesy of Ch. E. Duellmann

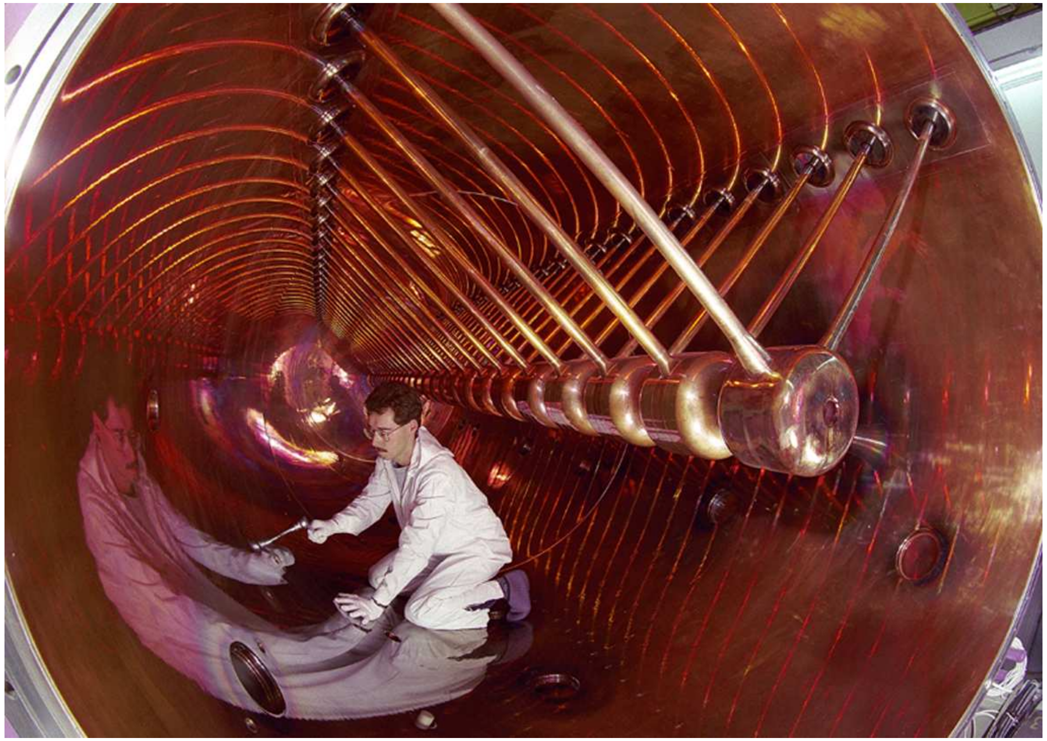
The UNIversal Linear ACcelerator – UNILAC



≈ 12 MeV/u for all elements

Beam intensity (on target) 0.5 - 4 μA_p

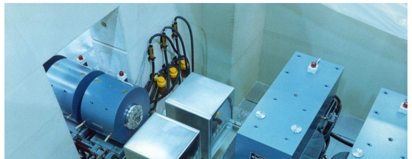
(25% duty cycle)

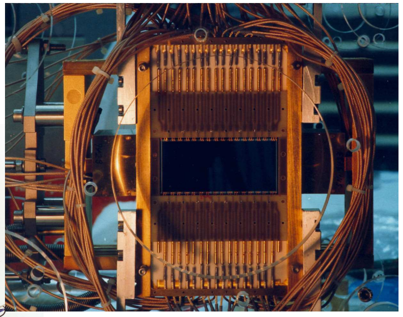


The Recoil Separator SHIP

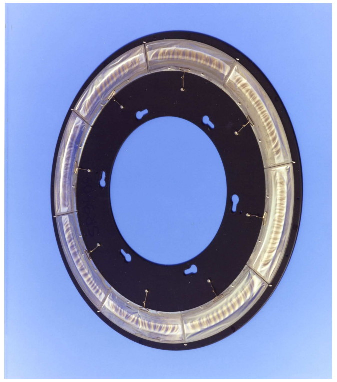
SHIP:

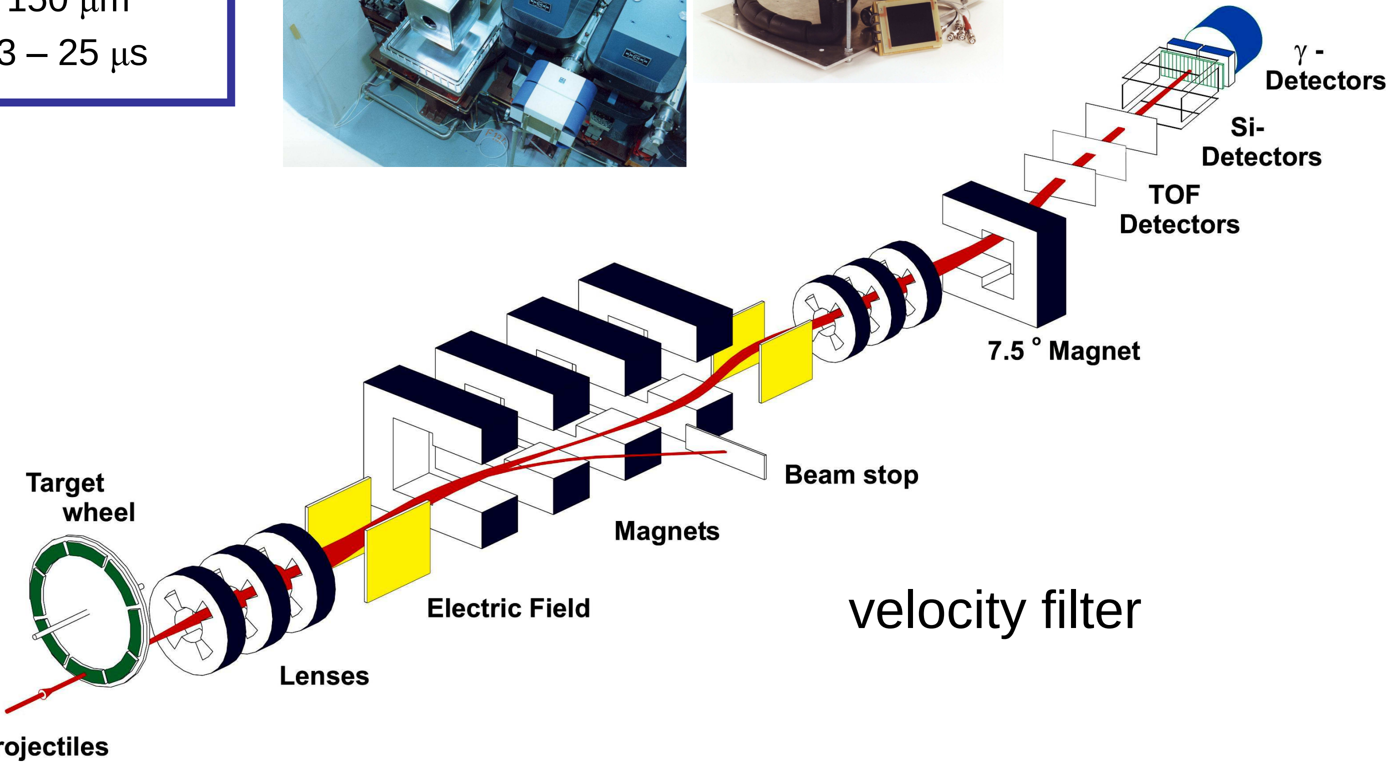
Separation time:	1 – 2 µs
Transmission:	20 – 50 %
Background:	10 – 50 Hz
Det. E. resolution:	18 – 25 keV
Det. Pos. resolution:	150 µm
Dead time:	3 – 25 µs





0.1-1 MeV/u





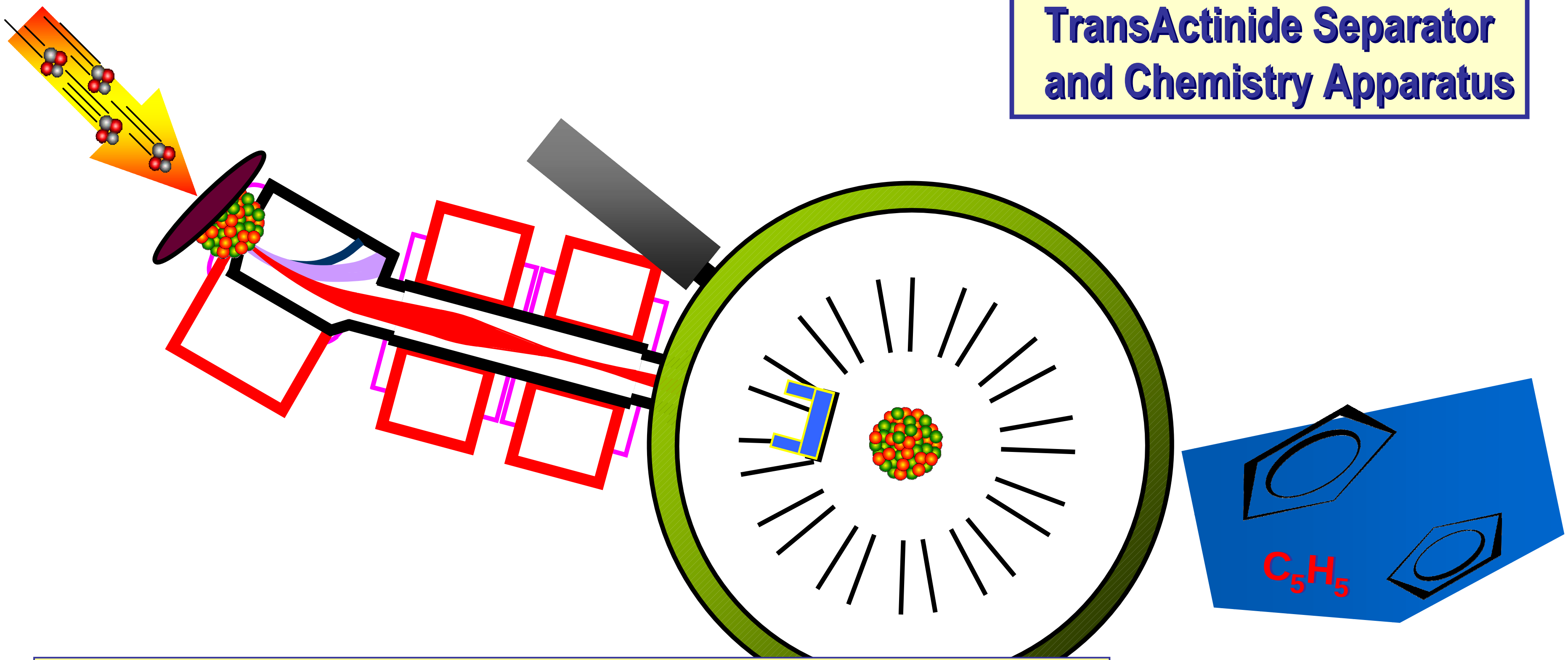
velocity filter

≈ 5 MeV/u

TASCA - a Gas-filled Separator for Chemistry and Physics

TASCA

TransActinide Separator and Chemistry Apparatus

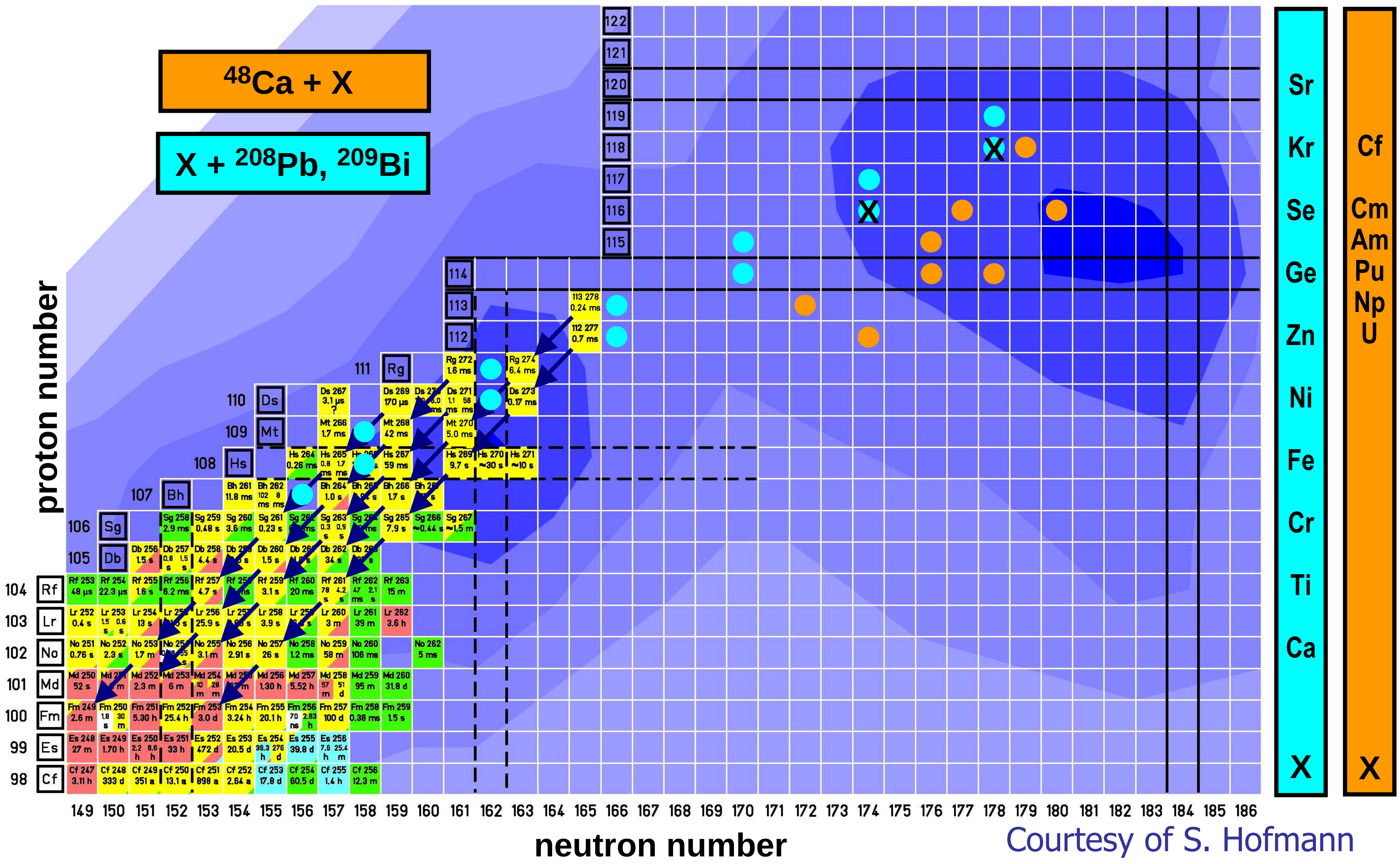


- **Chemical investigations of the transactinide elements: one-atom-at-a-time chemistry**
- **Nuclear structure investigations**
- **Hot-fusion nuclear reaction studies**

Courtesy of Ch. E. Duellmann

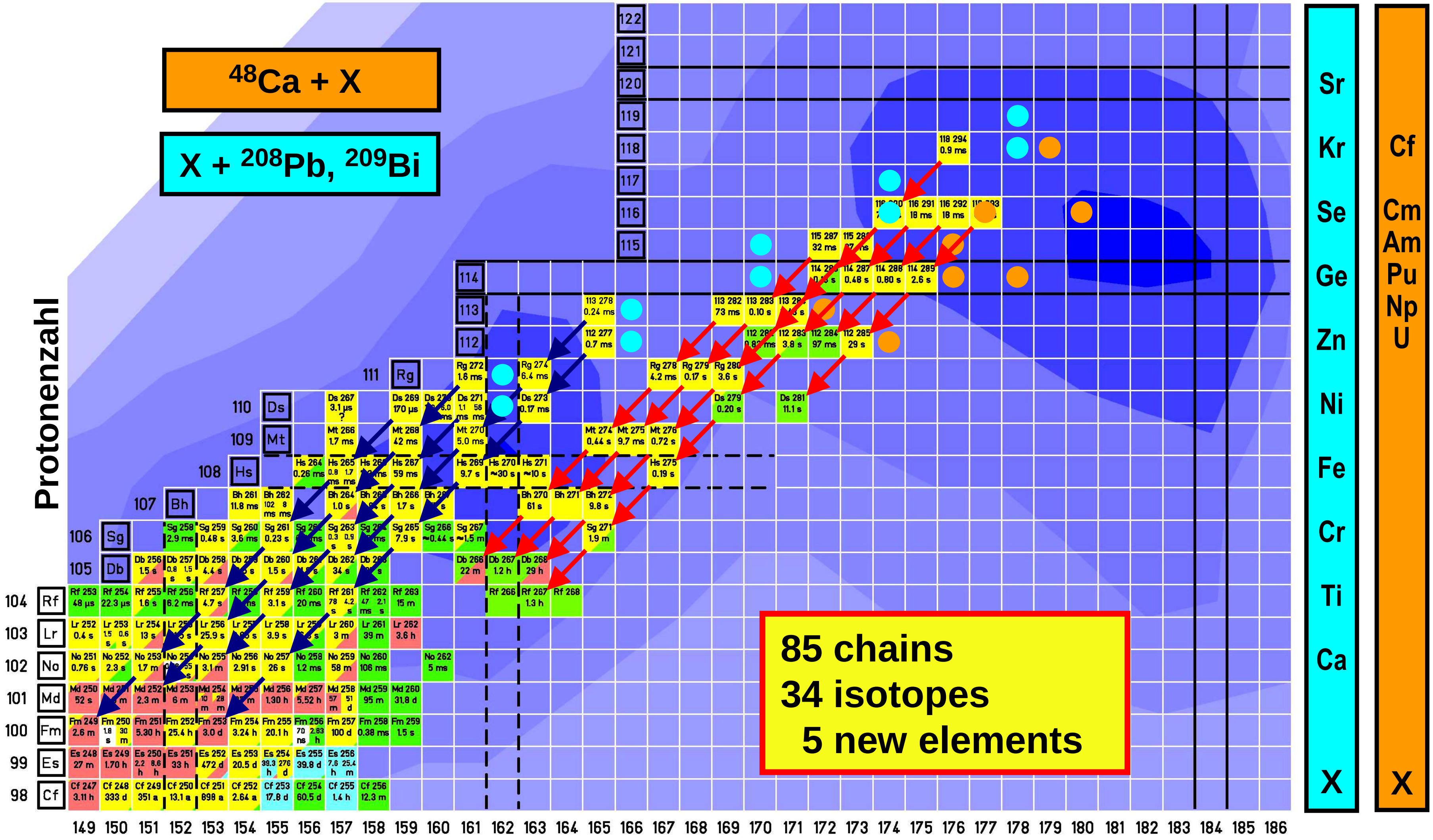
TASCA Gas-filled Separator

GSI: Elements 107 – 112



Courtesy of S. Hofmann

Results at FLNR Dubna



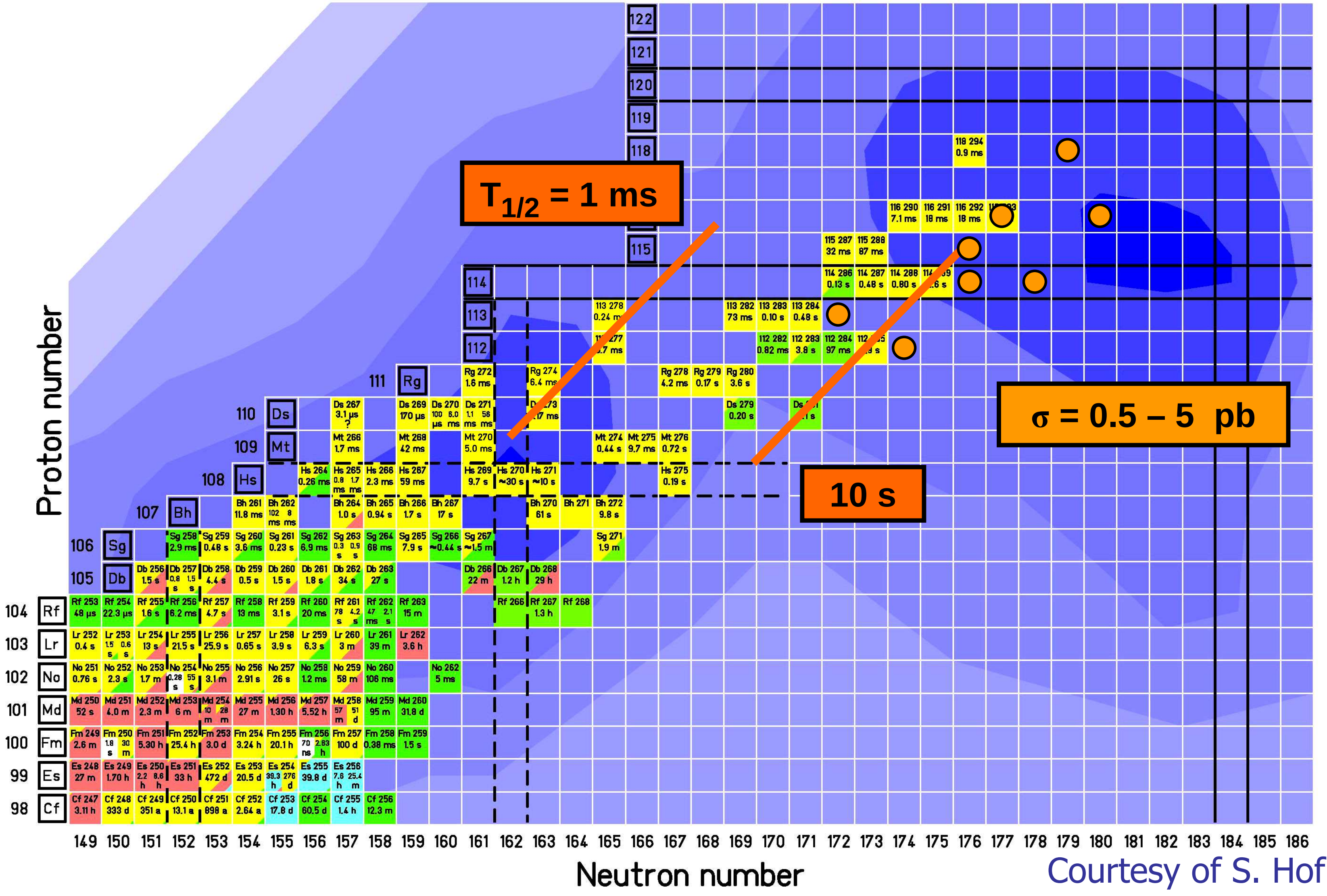
^{48}Ca + X

X + ^{208}Pb, ^{209}Bi

85 chains
34 isotopes
5 new elements

Courtesy of S. Hofmann

Key Results: growing $T_{1/2}$ and constant σ



$T_{1/2}$ = 1 ms

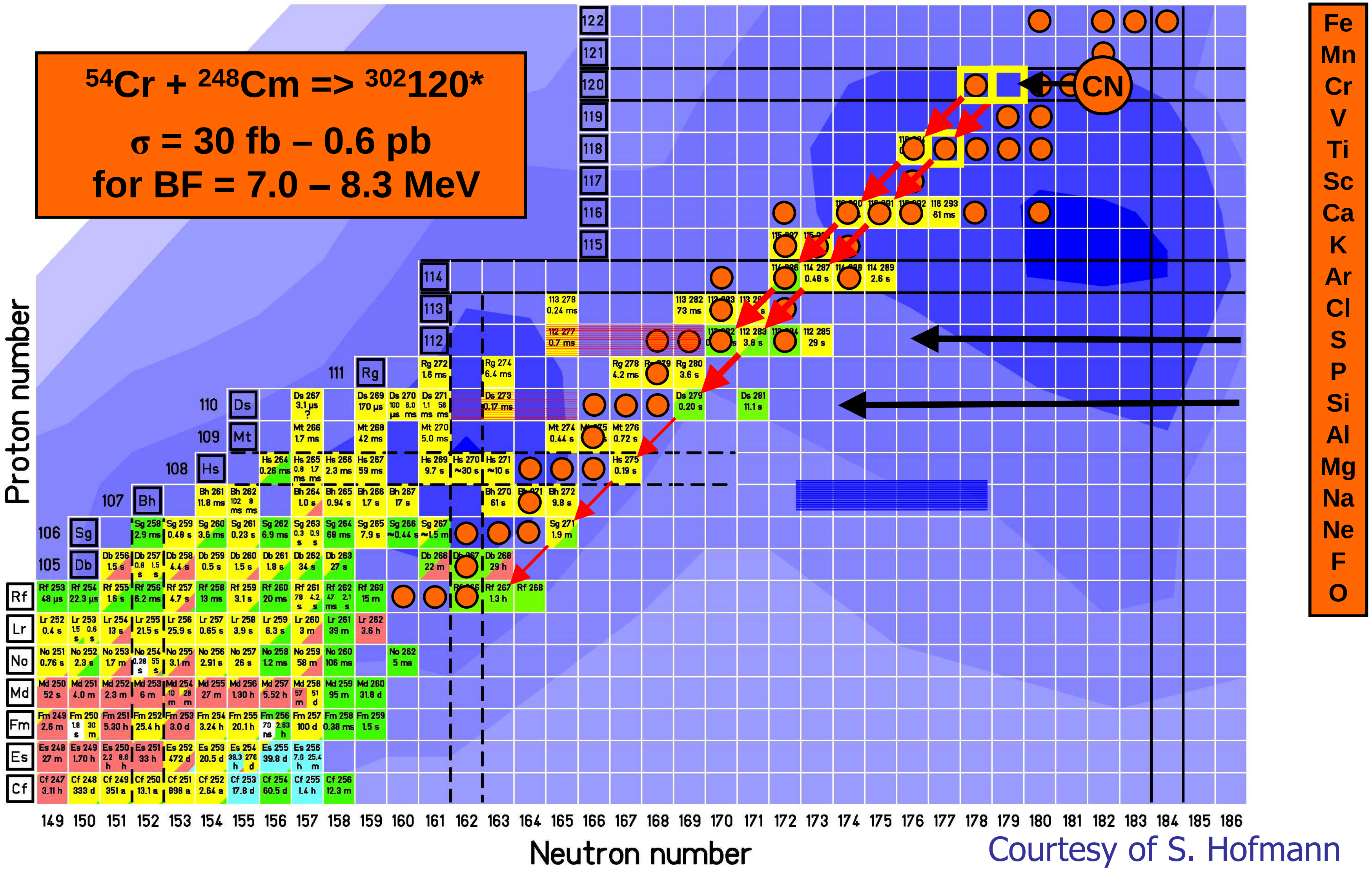
10 s

σ = 0.5 – 5 pb

Courtesy of S. Hofmann

Producing New Isotopes and Elements

Experiments with ^{248}Cm targets



^{54}Cr + ^{248}Cm => ^{302}120*

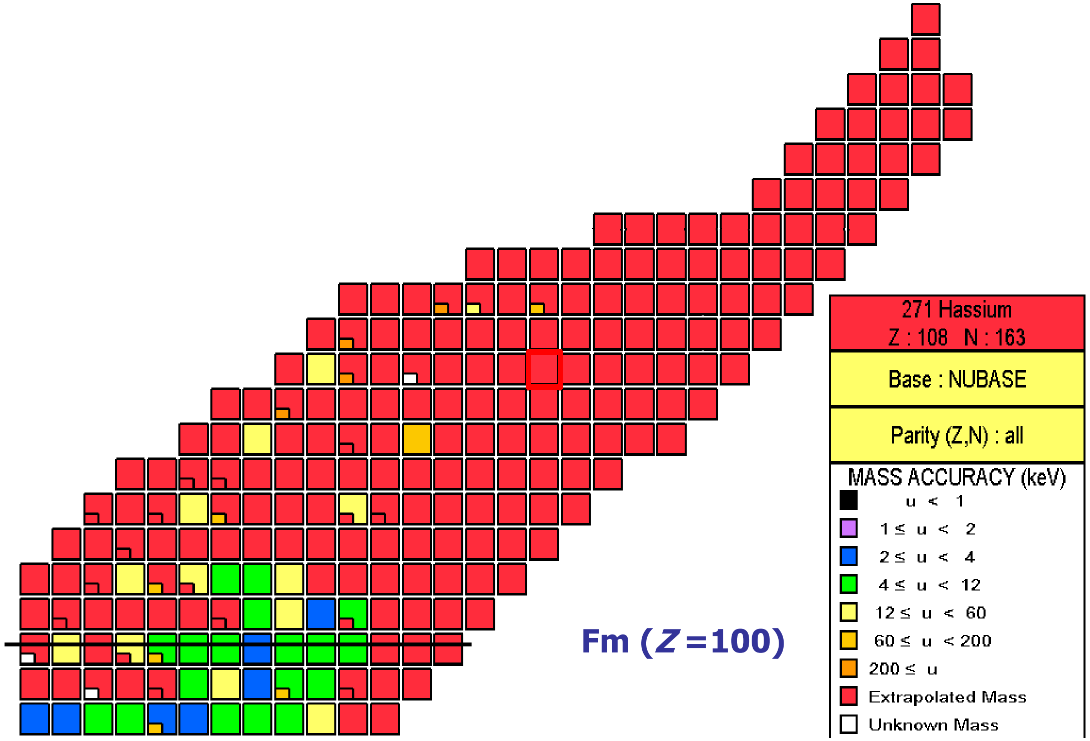
σ = 30 fb – 0.6 pb

for BF = 7.0 – 8.3 MeV

Courtesy of S. Hofmann

Knowledge of Masses for Z > 100

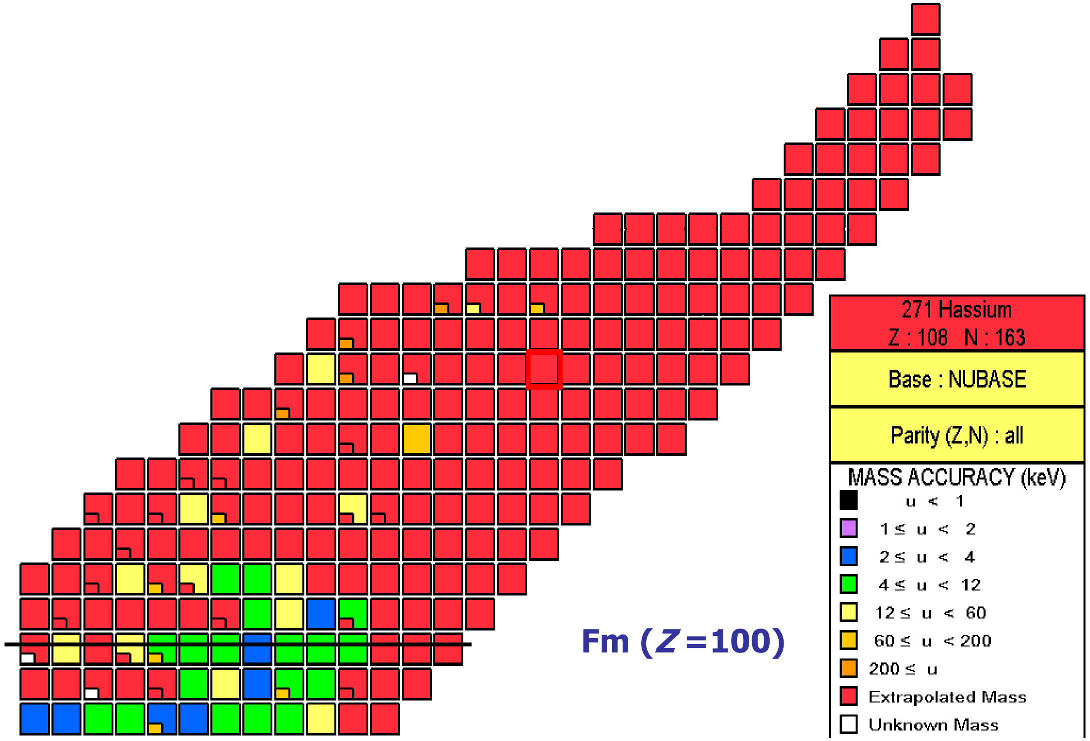
AME 2003



- no direct mass measurements for $Z>92$
- some masses indirectly determined from Q_α values
- many masses extrapolated from systematic trends

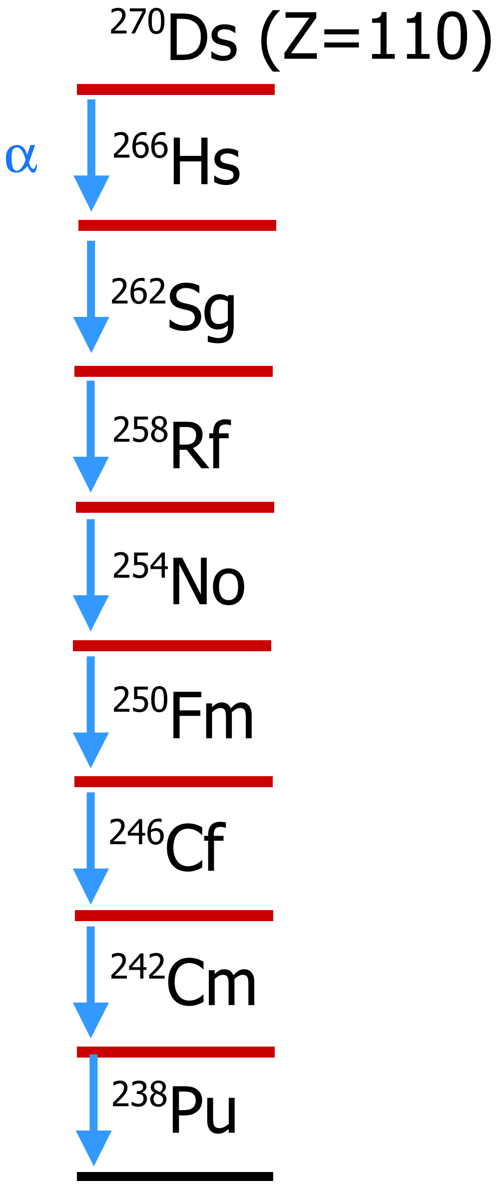
Impact of Masses for Z > 100

AME 2003



- binding energy determines existence of SHE
- studies of the shell structure evolution N = 152, 162
- pin down endpoints of decay chains (Rf, Sg)
- studies of long-lived isomeric states

Mass Determination using Decay-links



^{270}Ds (Z=110)

α

^{266}Hs

^{262}Sg

^{258}Rf

^{254}No

^{250}Fm

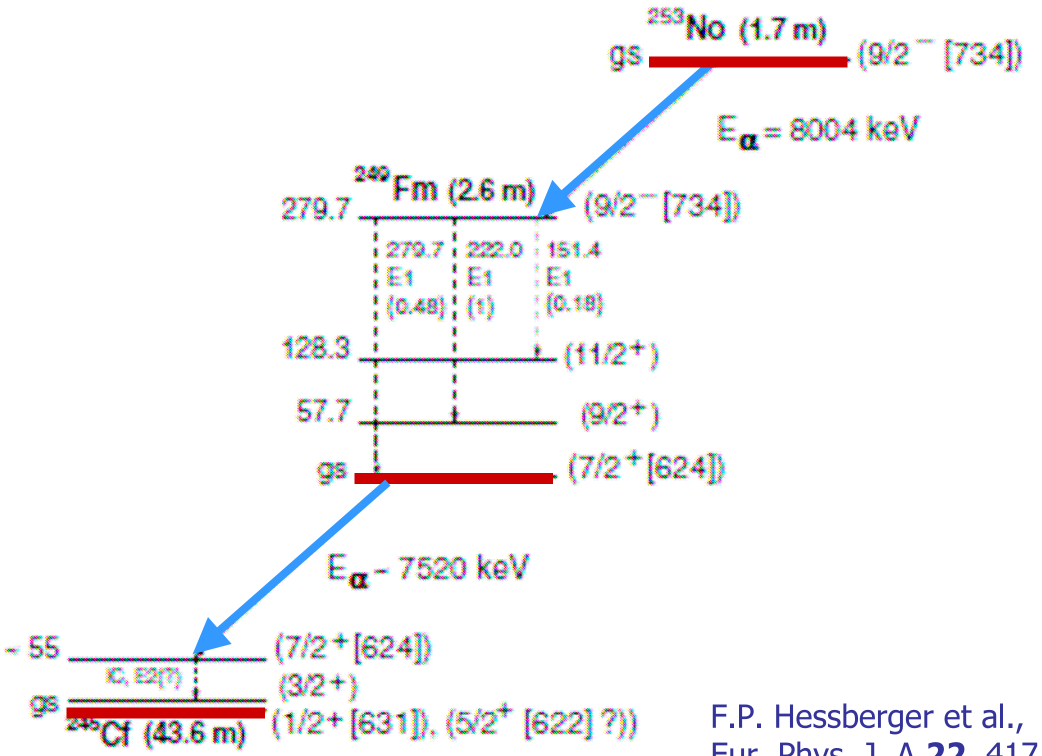
^{246}Cf

^{242}Cm

^{238}Pu

Difficulties:

- "incomplete" α-chains
- decays not between ground states
- uncertainties accumulate



F.P. Hessberger et al.,
Eur. Phys. J. A **22**, 417 (2004)

Direct Mass Measurements above *Z* = 100

Typical production rates at present facilities:

- 1 atom/s @ Z=102 ($\sigma \approx \mu$b)
- 1 atom/week @ Z=112 ($\sigma \approx$ pb)

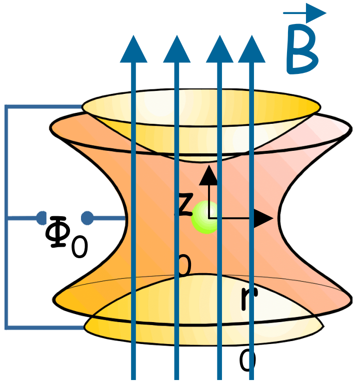
Present reach of Penning Traps for RIBs

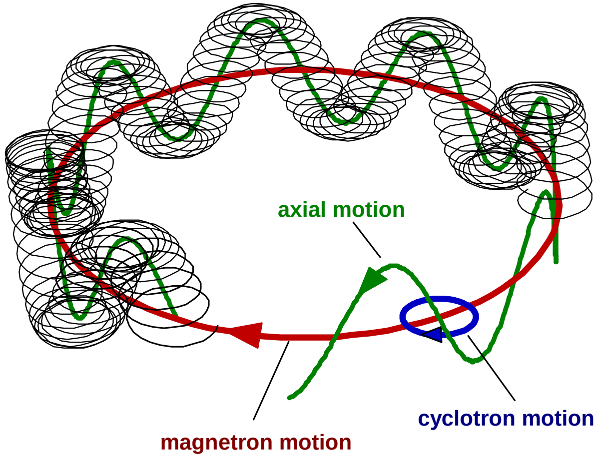
• Half-life	> 10 ms
• Rate of trapped ions	> 0.01 / s

Requirements:

- energy matching of reaction products to trap's energy scale
- high efficiency to deal with very low production rates
- high cleanliness for low background
- stable and reliable operation over extended time

Penning Trap Basics in Brief





Axial motion:

harmonic oscillation in E-field

$$\omega_z = \sqrt{\frac{qV_0}{md^2}}$$

Magnetron motion:

E x B drift

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

Reduced cyclotron motion:

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

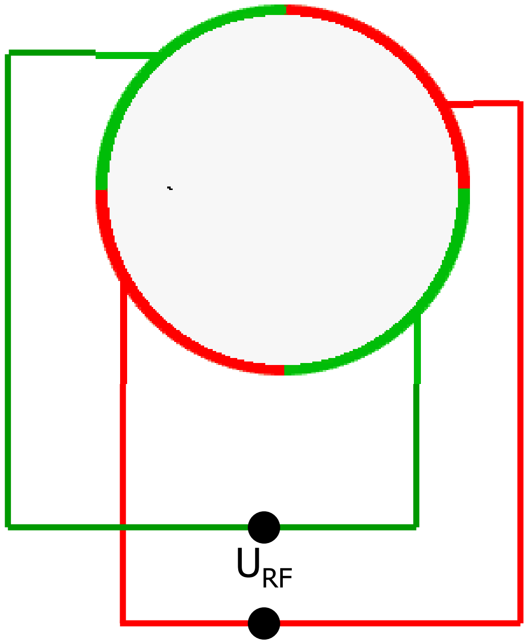
in an ideal trap: $\boxed{\omega_c = \omega_+ + \omega_- = \frac{q}{m} B}$

invariance theorem: $\boxed{\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2}$

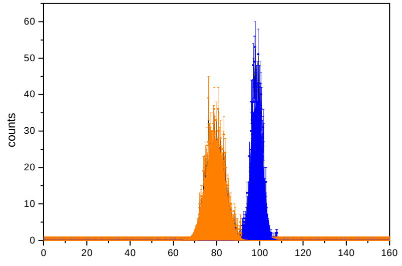
L. S. Brown and G. Gabrielse, Rev. Mod. Phys. 58 (1986) 233
G. Gabrielse, IJMS 279, (2009) 107

Cyclotron frequency measurement

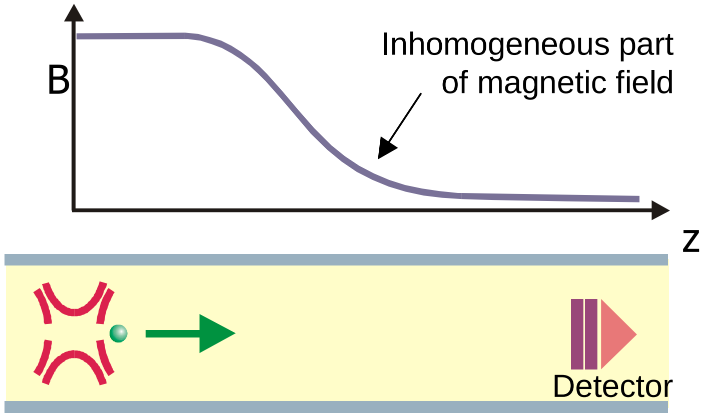
Step1: Excite radial motion



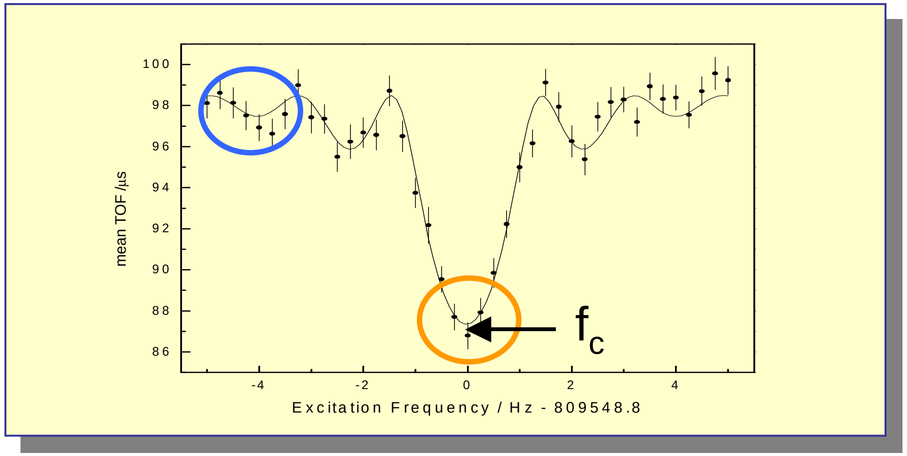
E_- ~1meV ⇔ E_+ ~ 1eV



Step 2: Convert E_{rad} into $E_{axial,}$ measure TOF



Record TOF as function of excit. frequency ⇒ Resonance



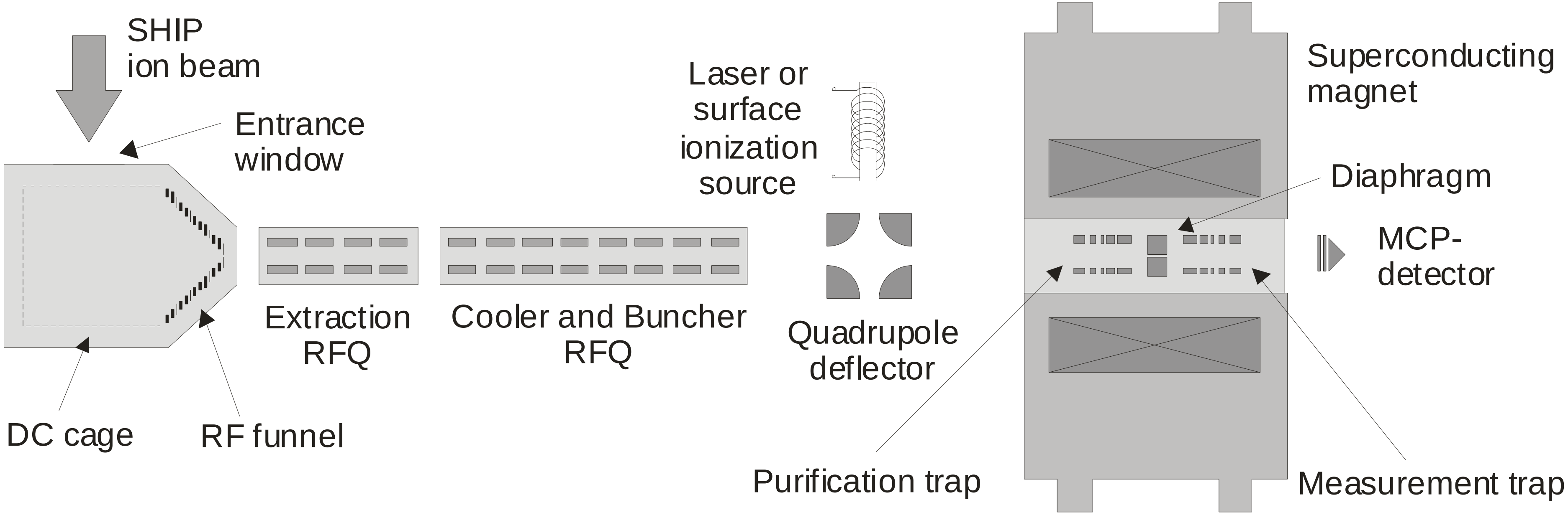
M. König et al., Int. J. of Mass Spectr. and Ion Proc. 142 (1995) 95

G. Bollen et al. J. Appl. Phys. 68 (1990) 4355; G. Gabrielse, Phys. Rev. Lett 102, (2009) 172501;

SHIPTRAP Setup

0.1-1 MeV/u → **≈ 1 eV**

Gas Cell Buncher Transfer Penning Traps



SHIP ion beam

Entrance window

DC cage

RF funnel

Extraction RFQ

Cooler and Buncher RFQ

Laser or surface ionization source

Quadrupole deflector

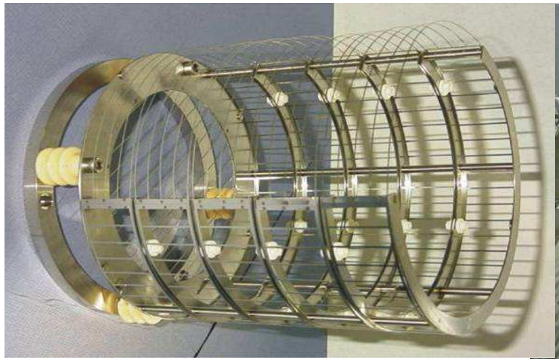
Purification trap

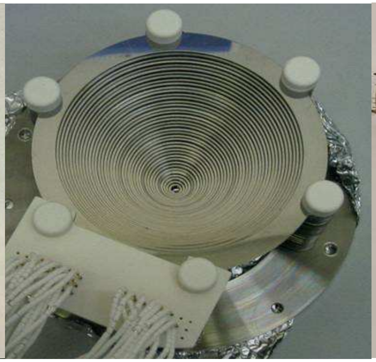
Superconducting magnet

Diaphragm

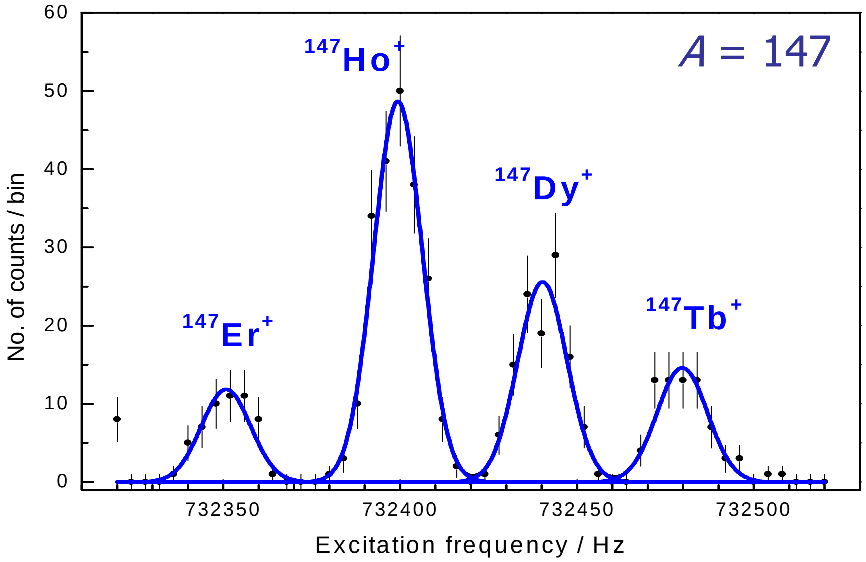
MCP-detector

Measurement trap





SHIPTRAP Performance

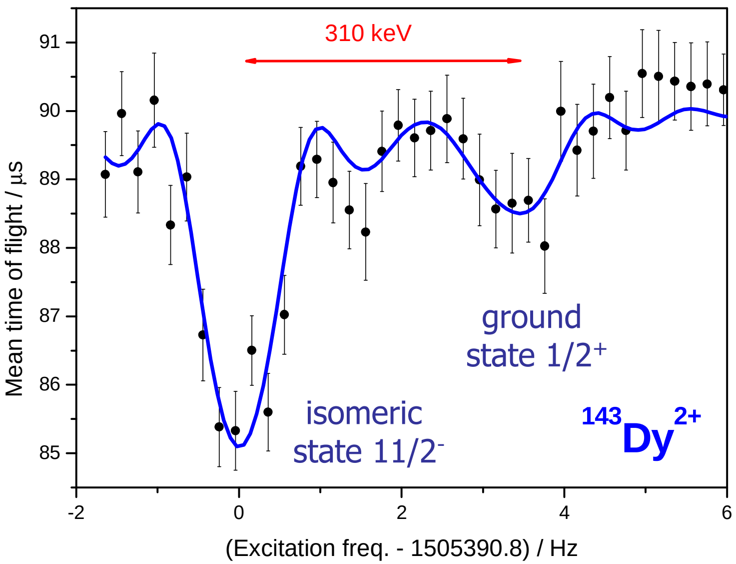


Mass resolving power of

m/δm ≈ 100,000

in purification trap:

⇒ separation of isobars



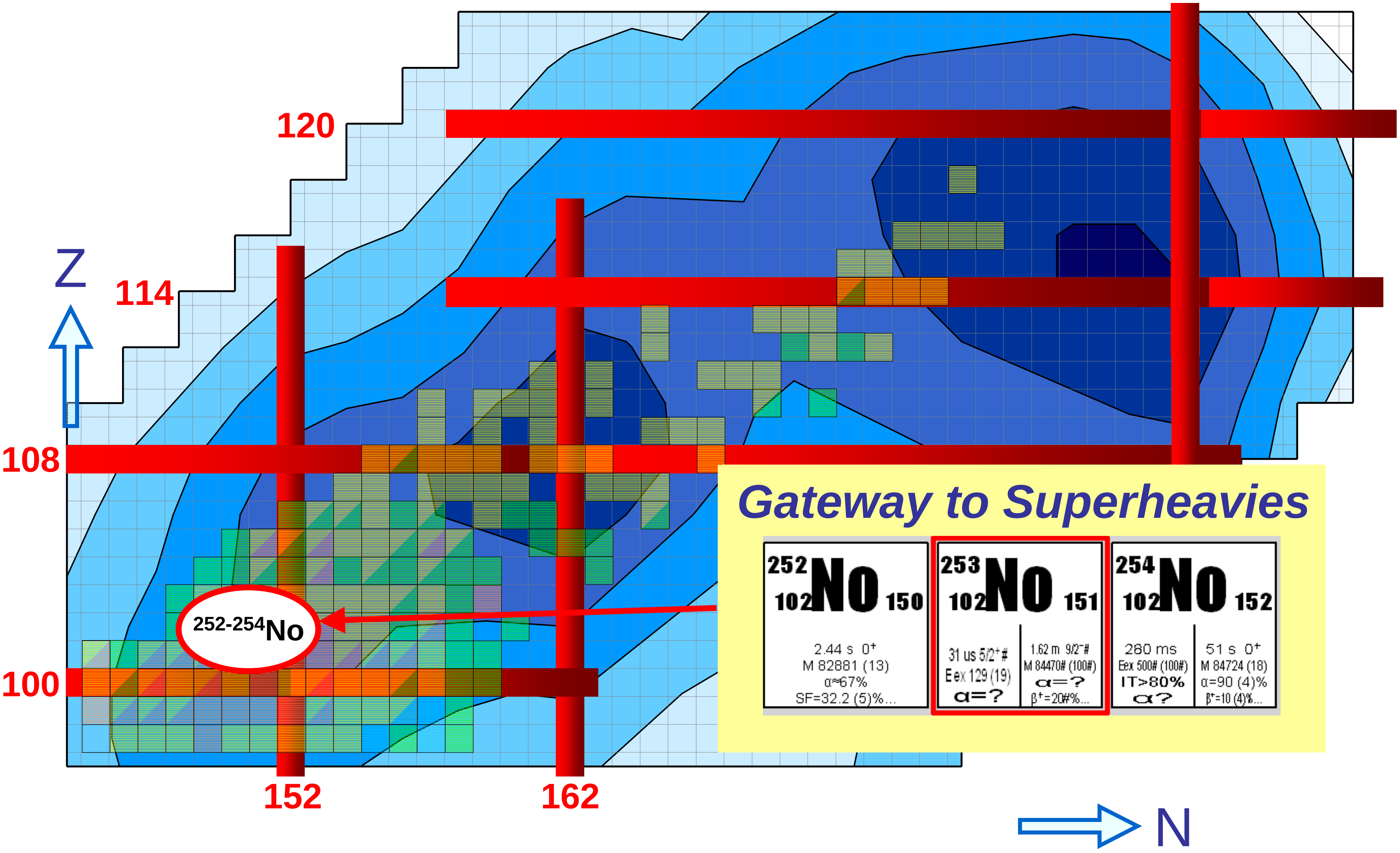
Mass resolving power of

m/δm ≈ 1,000,000

in measurement trap:

⇒ separation of isomers

Direct Mass Measurements of $^{252-254}$No



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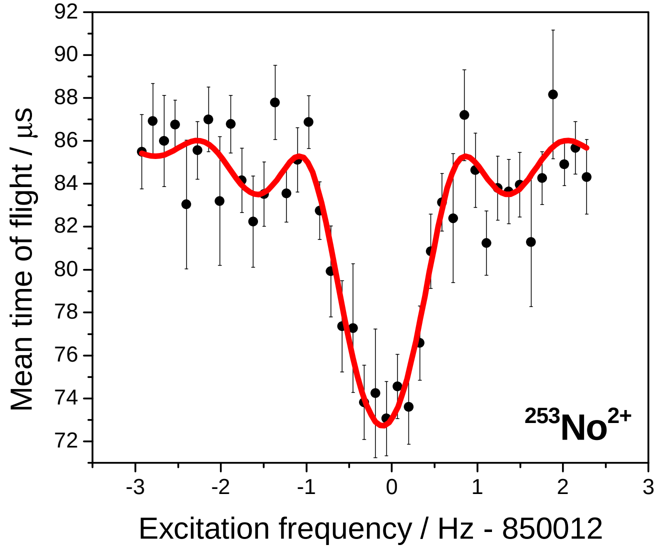
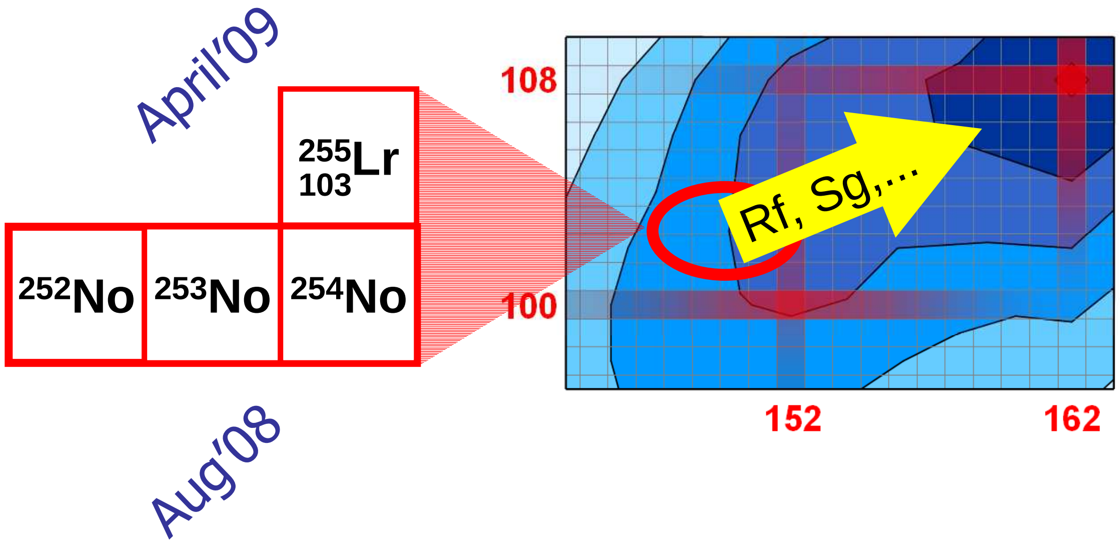
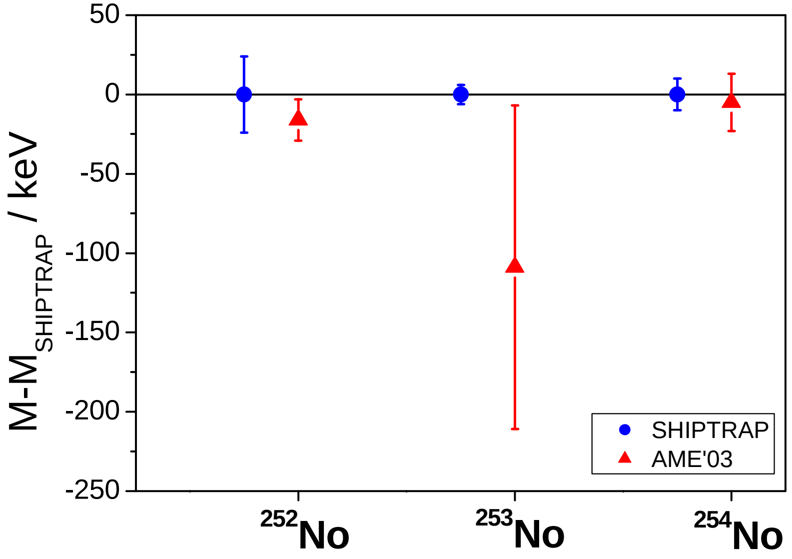
Entering the Gateway to the SHE





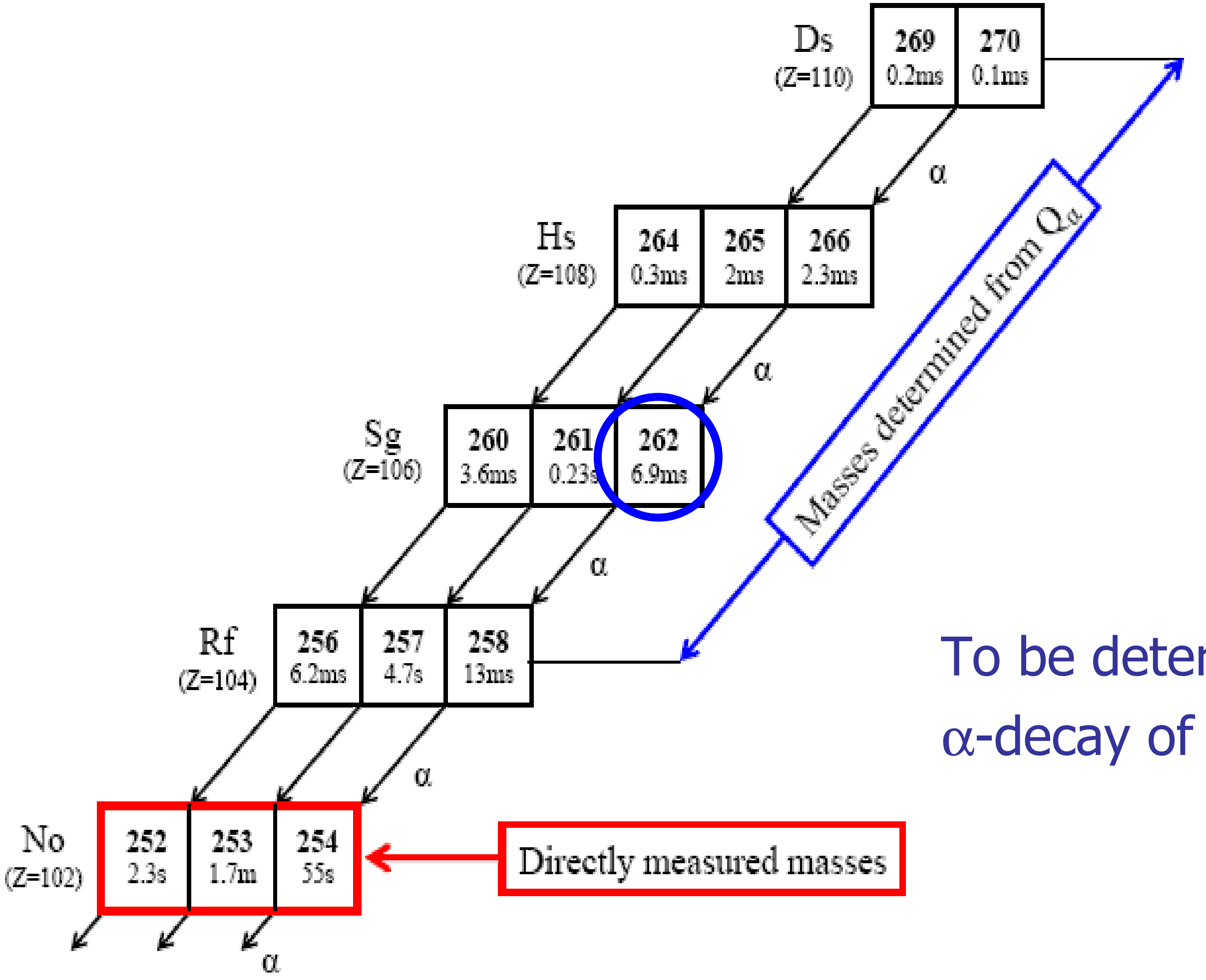
- rate of incoming particles for ^{255}Lr only 0.3 ions/s



- **First direct mass measurements in the region *Z* > 100**
- **^{255}Lr nuclide with lowest rate ever measured in a Penning trap**

Mass determination of SHE

- Combine new, directly measured masses and α-decay spectroscopy
- Determine the masses of short-lived higher-Z nuclides



To be determined:

α-decay of ^{262}Sg (15%)

The Route to SHE

- **improve production rates**
  - increase primary beam intensities
    - improved ECR sources (28 GHz)
    - optimized cw accelerator for stable beams
    - target developments (compounds, cooling)
- **access to more neutron-rich nuclides**
  - hot-fusion reactions with actinide targets
- **higher sensitivity and efficiency**
  - detection system with single-ion sensitivity
  - next generation gas stoppers

Higher Intensities at GSI

New 28-GHz EZR Source:

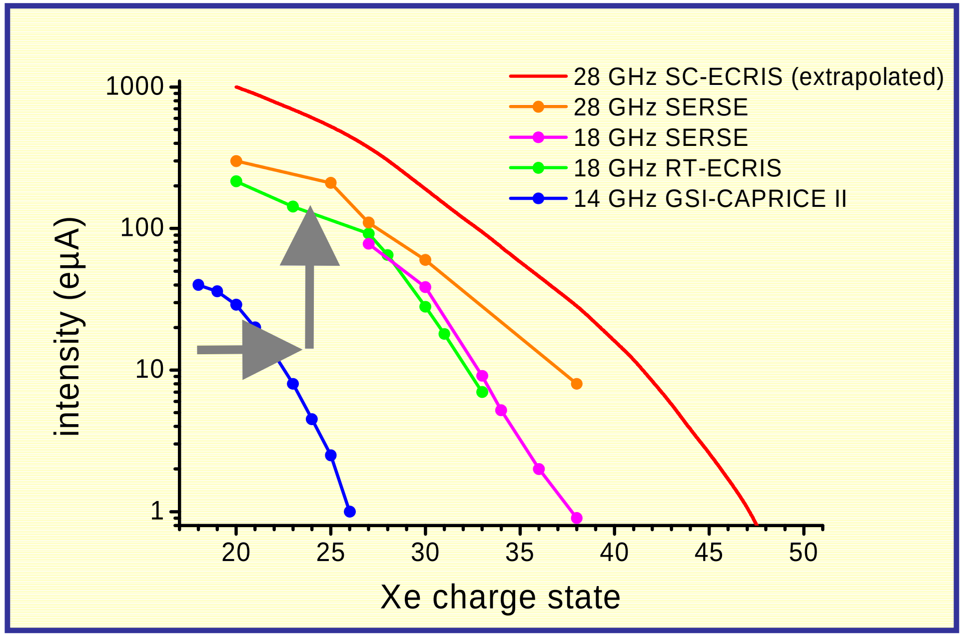
- Higher charge state
- Higher intensity

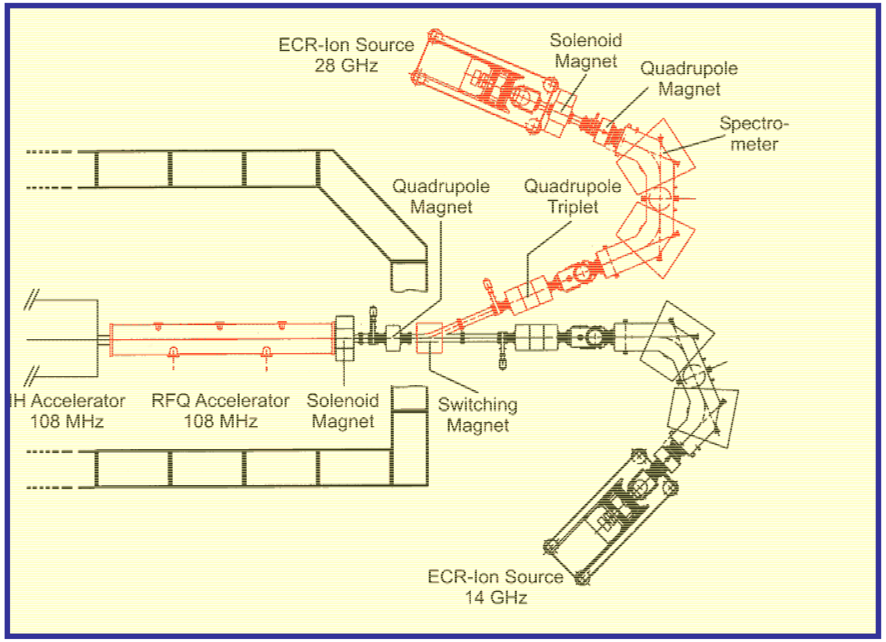
Factor: 2 – 5

New RFQ Injector:

- Duty factor 25 % => 50 %
- Higher injection energy
- Higher acceptance

Factor: ≥ 2

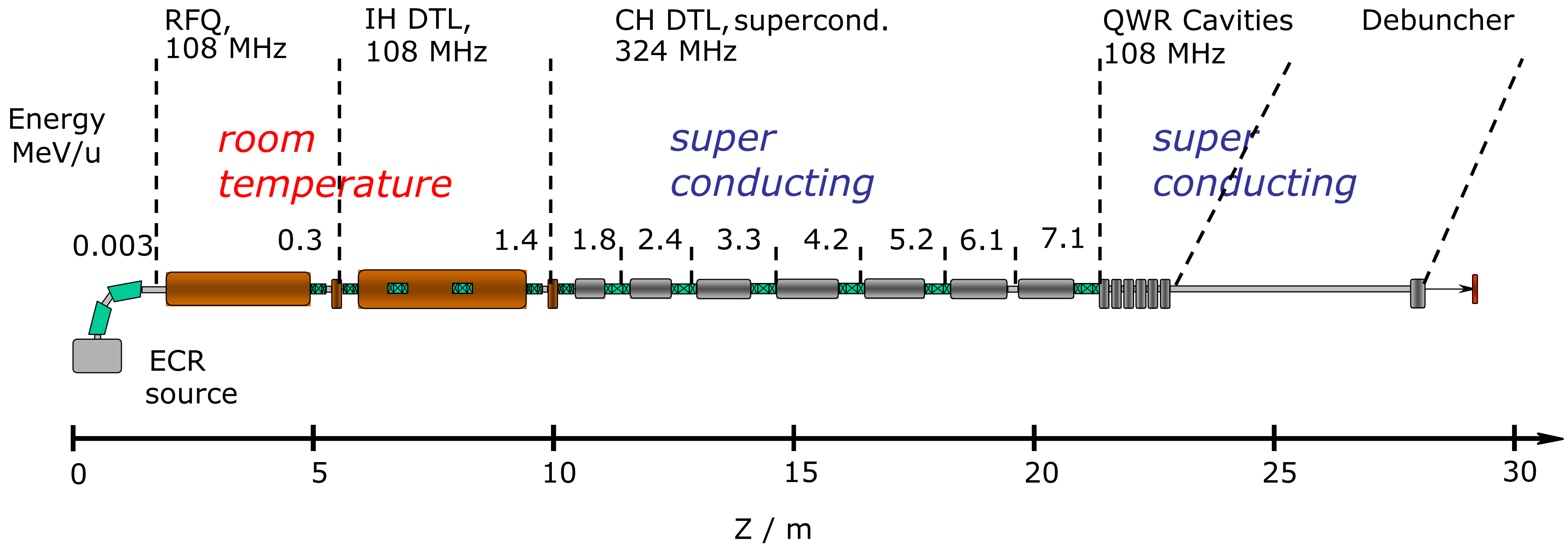




U. Ratzinger, K. Tinschert et al.

Optimized Accelerator for SHE Production

Superconducting continuous wave accelerator:



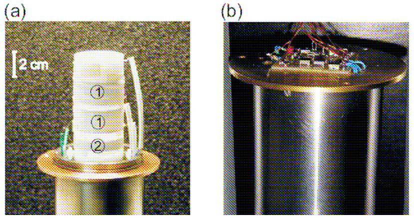
Design specifications

- DC beam
- $1 < A/q < 7$
- E_{beam}: 4-7.5 MeV/u
- $\Delta E_{beam} < \pm 3$keV/u

U. Ratzinger et al., Frankfurt University
W. Barth, L. Dahl et al., GSI

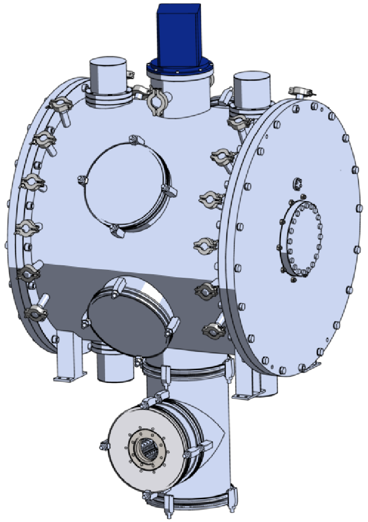
The Route to SHE

increase sensitivity and efficiency



- (non-destructive) detection system with single-ion sensitivity

→ mass measurement with one ion only



- next generation gas stoppers:
  - cryogenic for highest cleanliness
  - RF carpet extraction systems

Coupling of TASCA and SHIPTRAP

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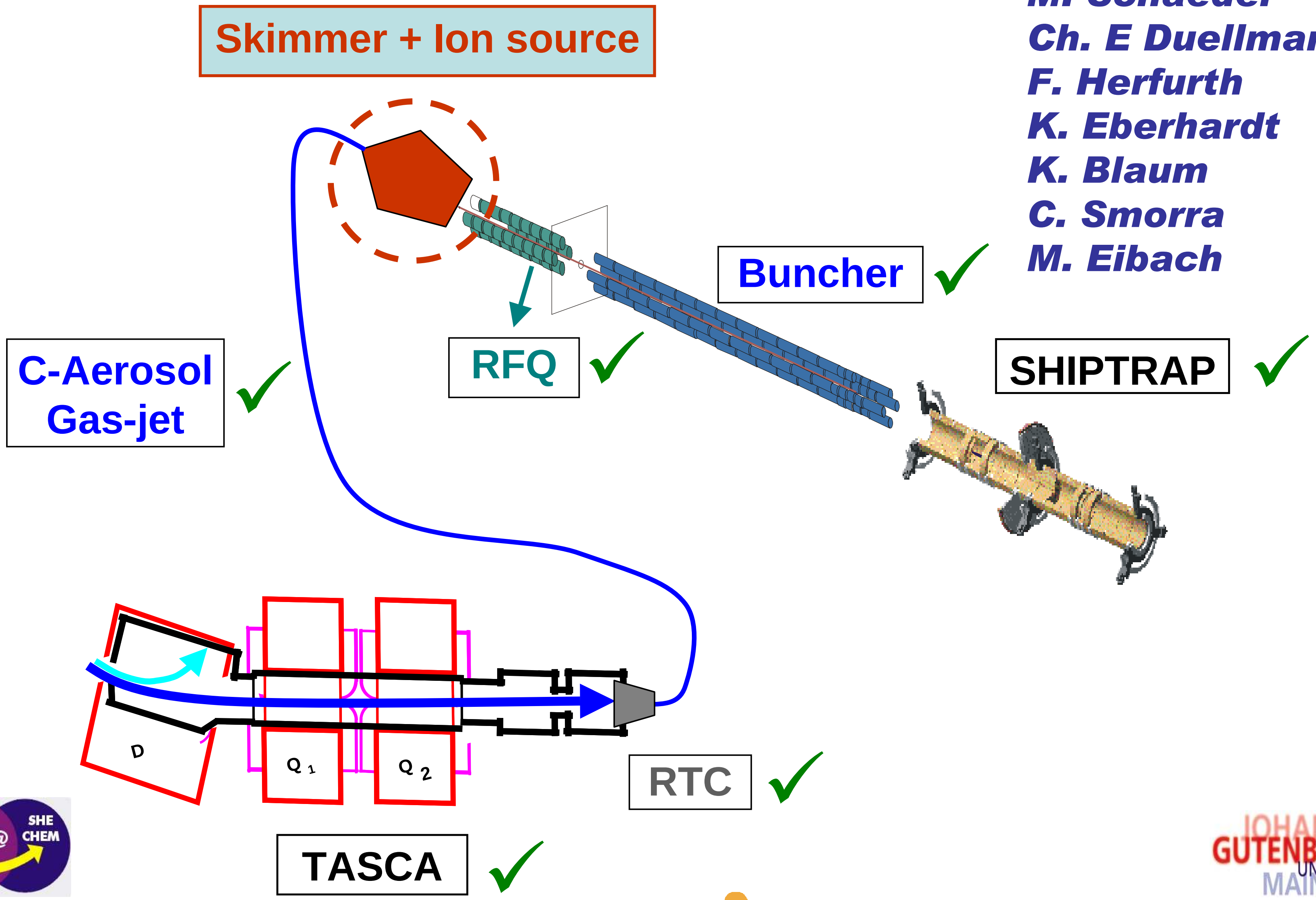
F. Herfurth
K. Eberhardt
K. Blaum
C. Smorra
M. Eibach



Conclusions

- Direct mass measurements for No, Lr region have been performed
- High-precision mass measurements of stopped rare isotopes with production rates of about 0.1 per second are possible today
- Opened the door for novel experiments with stopped heavy elements
- Technical developments and new techniques will pave the way to heavier elements

Thank you for your attention !

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THANKS TO

The SHIPTRAP, TRIGA-TRAP, and TASCA Collaborations

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G. Vorobjev, C. Weber, K. Eberhardt, Ch.E. Duellmann, and M. Schädel