S3 Workshop 2017

Future Perspectives for Mass Measurements of the Heaviest Elements

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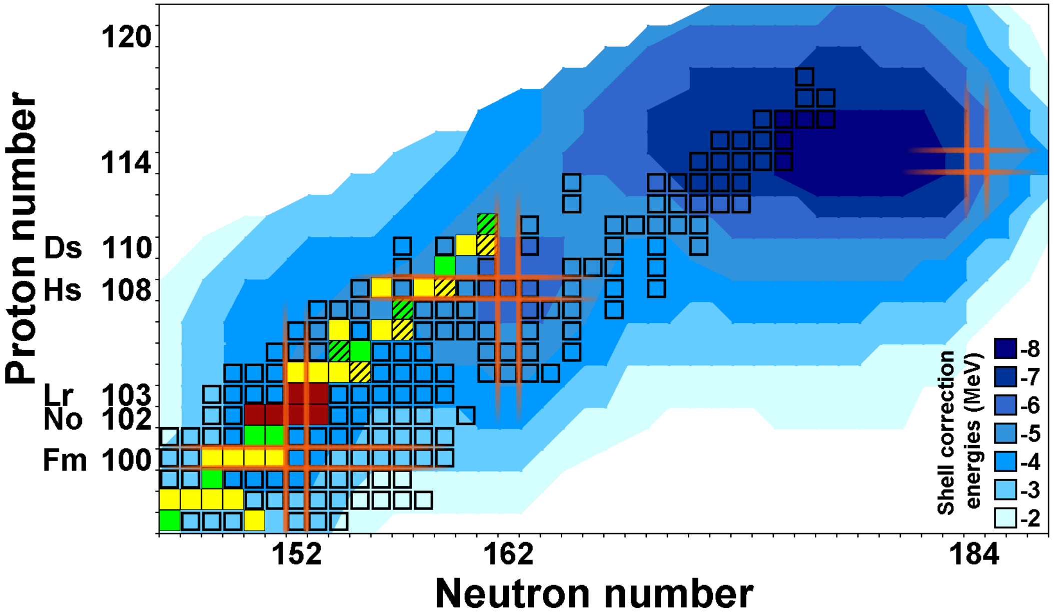
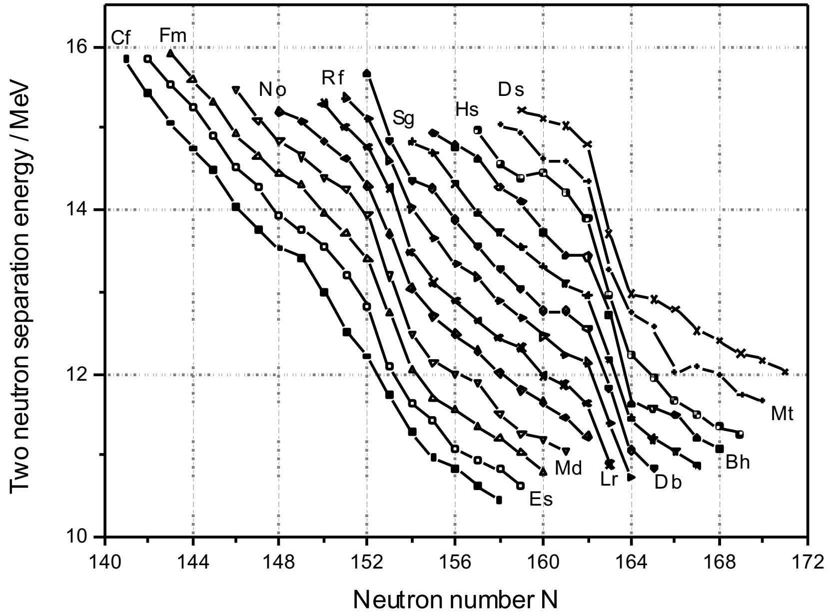
Importance of Masses for Z > 100



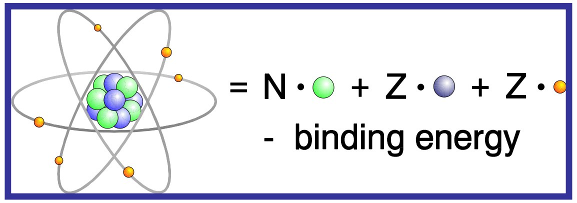


high-precision mass measurements provide

- accurate absolute binding energies to map nuclear shell effects
- anchor points to pin down decay chains

➡ Studies the nuclear structure evolution

➡ Benchmark theoretical nuclear models



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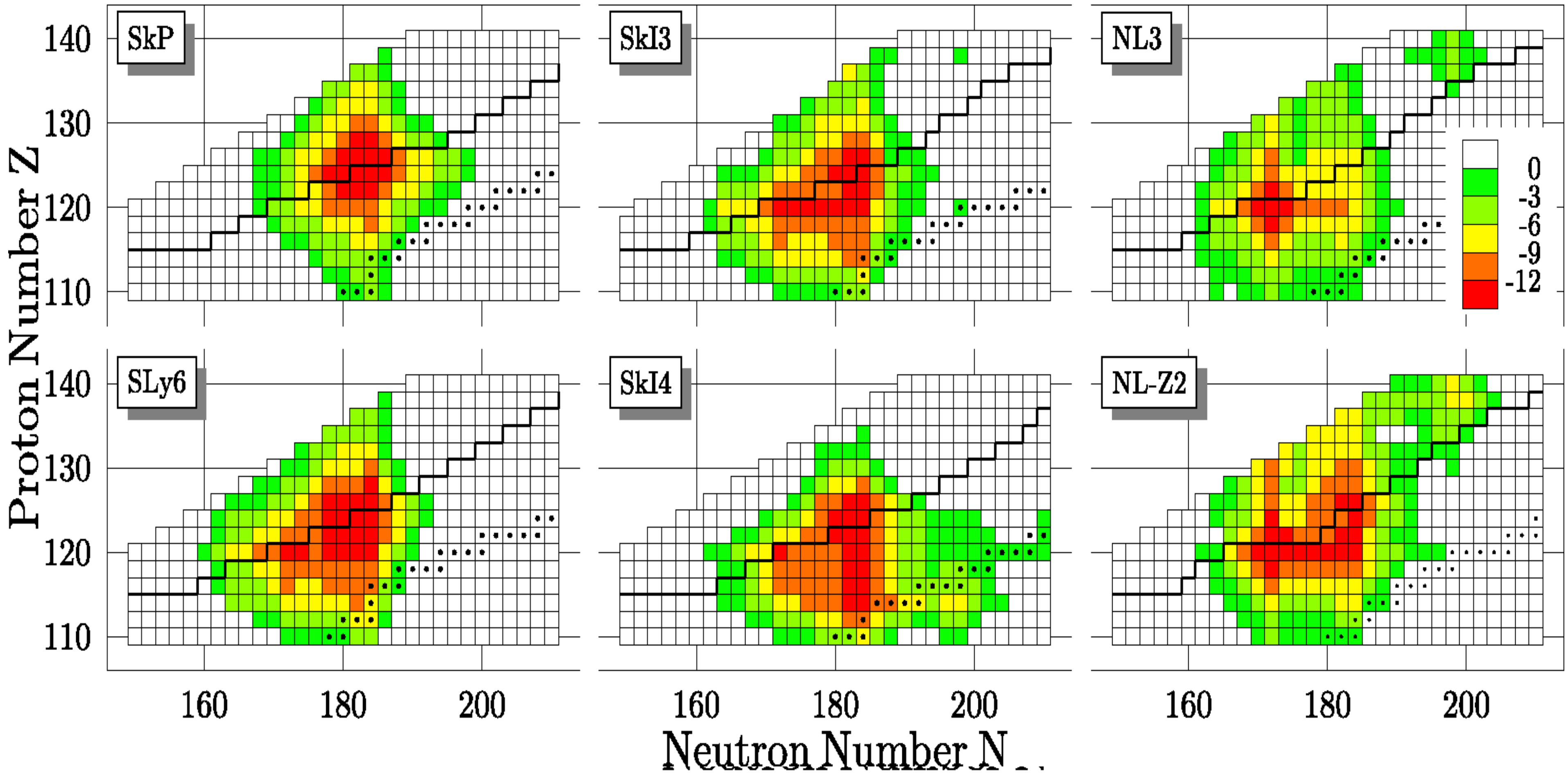
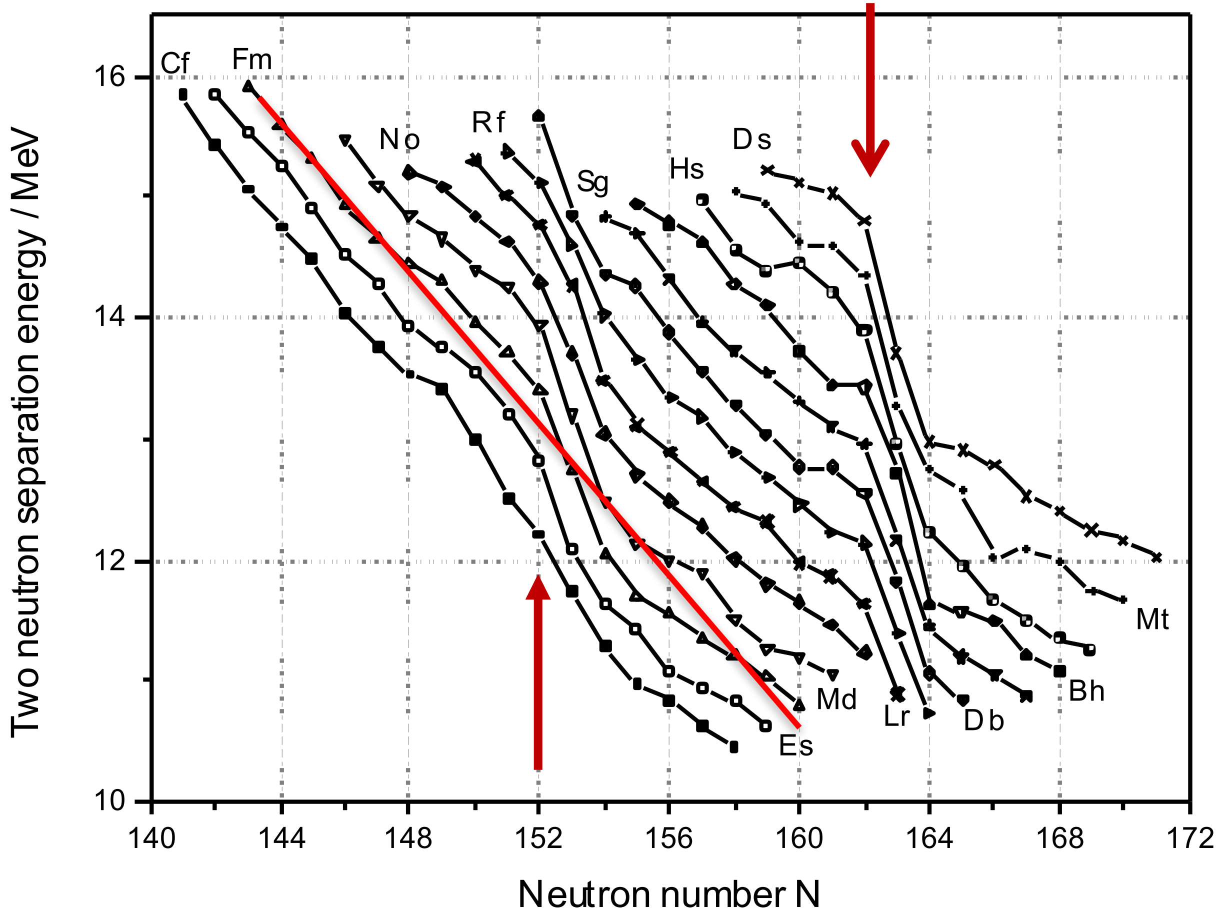
Nuclear Shells: Magic Numbers in SHE?



M. Bender et al., Phys. Lett. B 515 (2001) 42

Nuclear Structure Indicators from Masses

two-neutron separation energy $S_{2n}(N,Z) = M(N,Z) - M(N-2,Z) + 2\,m_n$



indication for shell closure at $N = 152$ & $N = 162$

Data from Atomic Mass Evaluation 2012:
M. Wang et al., CPC(HEP & NP), 2012, 36(12): 1603–2014

Nuclear Structure Indicators from Masses

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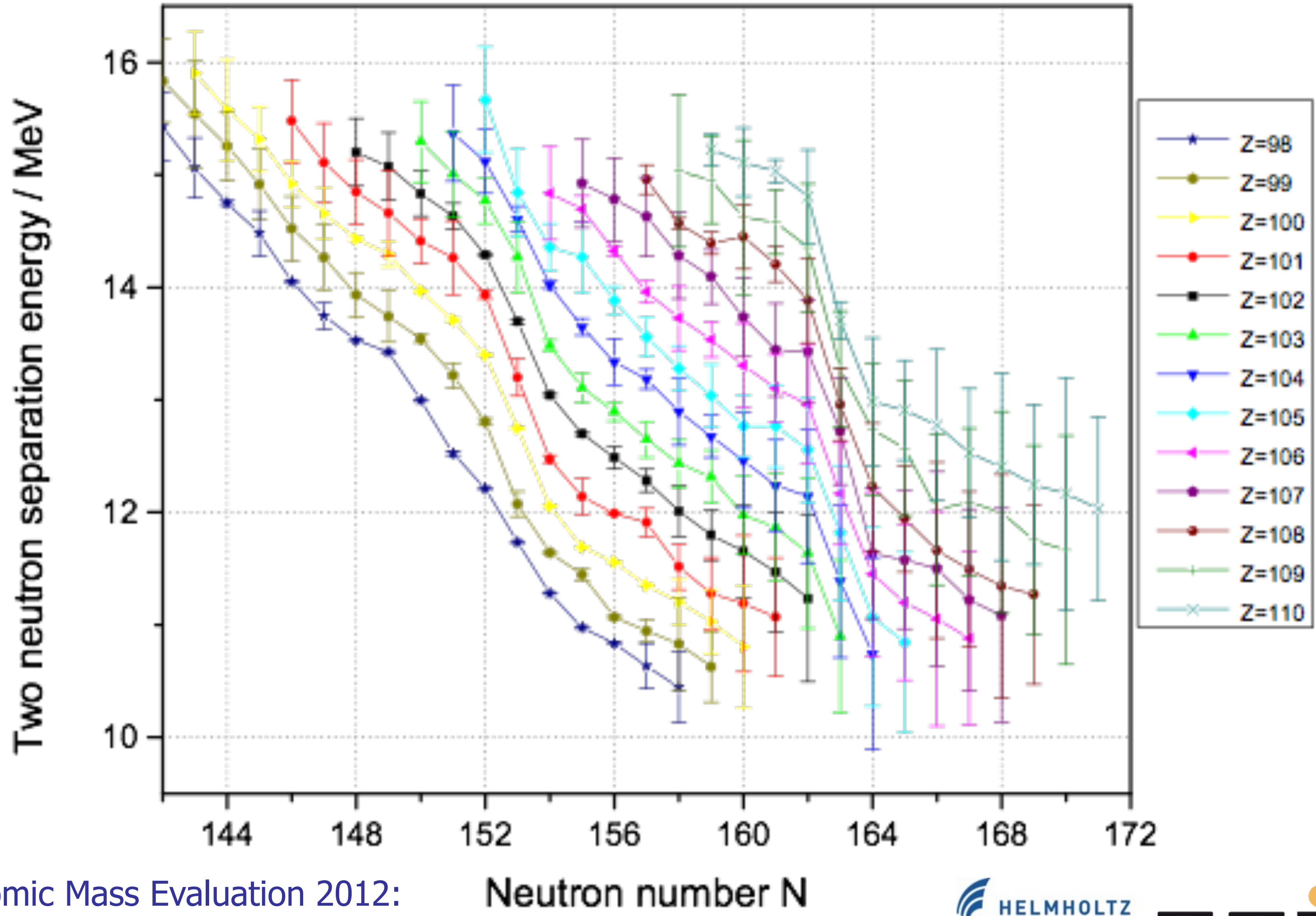
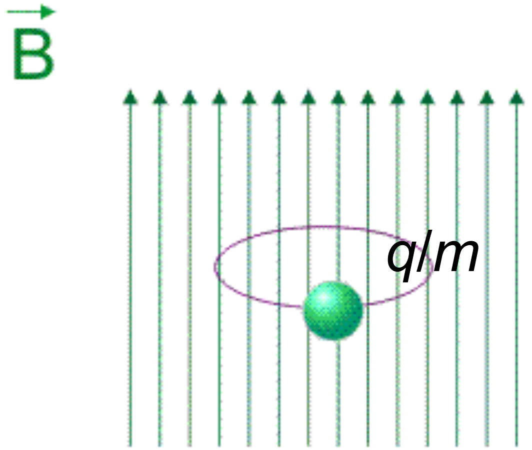
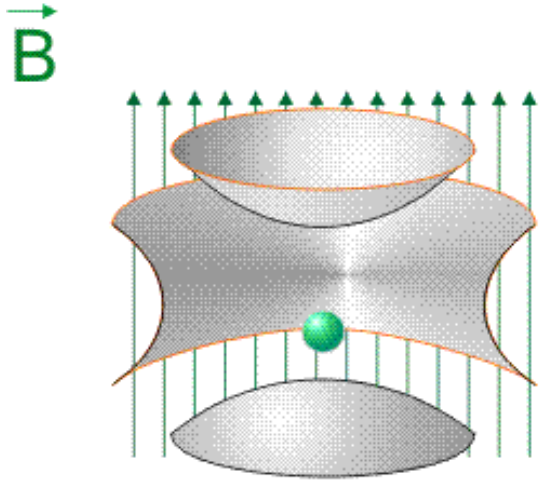


Data from Atomic Mass Evaluation 2012:
M. Wang et al., CPC(HEP & NP), 2012, 36(12): 1603–2014

Principle of Penning Traps

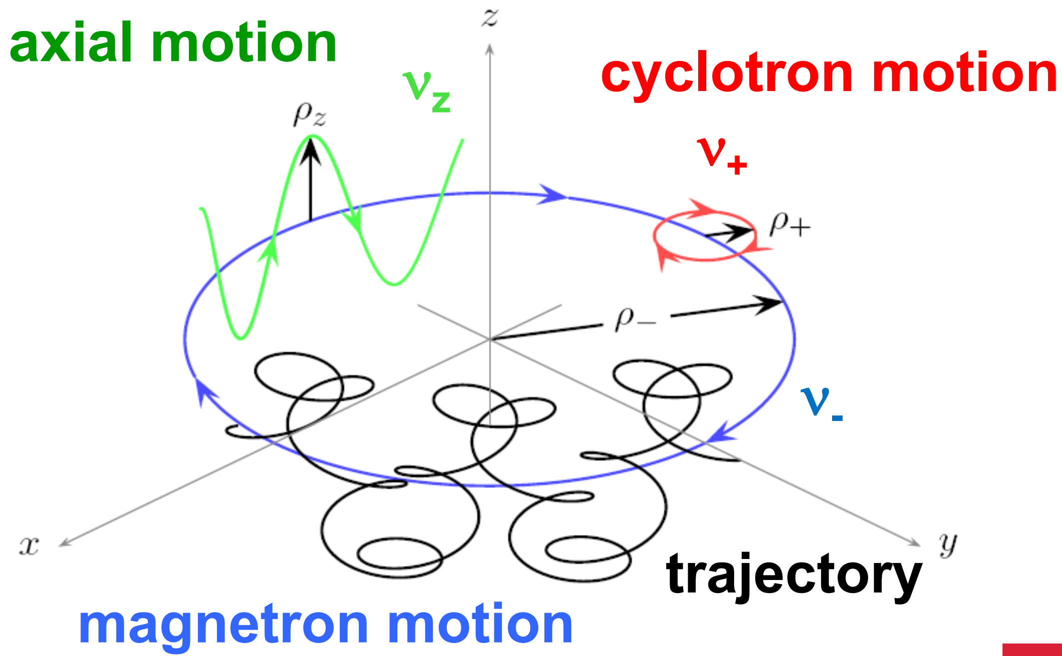
PENNING trap





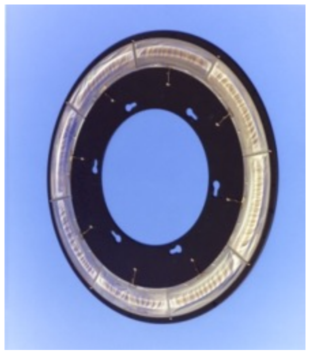
- Strong homogeneous magnetic field
- Weak electric 3D quadrupolar field

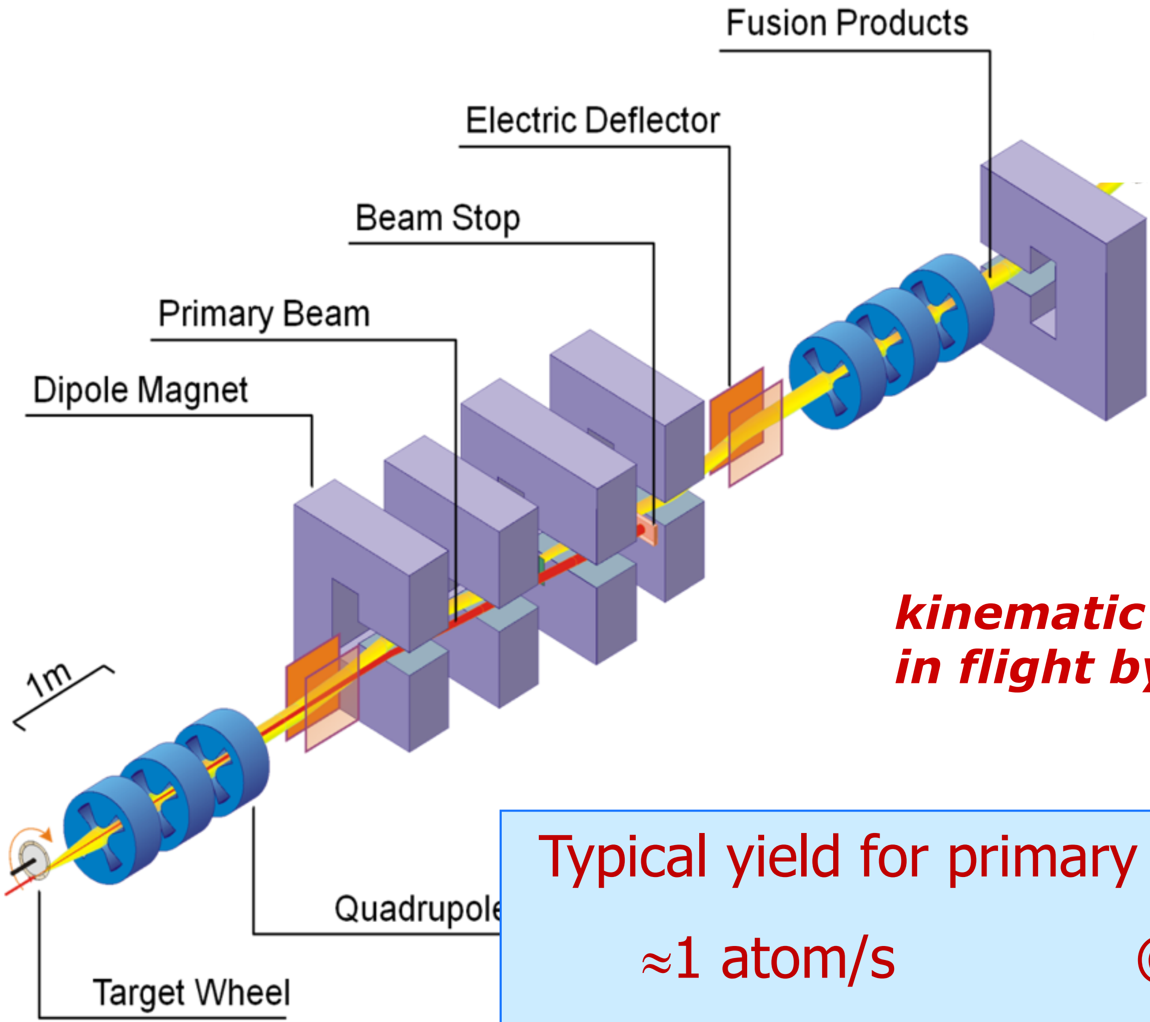
Cyclotron frequency: $$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$



L. S. Brown and G. Gabrielse, Rev. Mod. Phys. 58 (1986) 233
G. Gabrielse, Int. J. Mass Spectr. 279, (2009) 107

Synthesis and Separation by SHIP





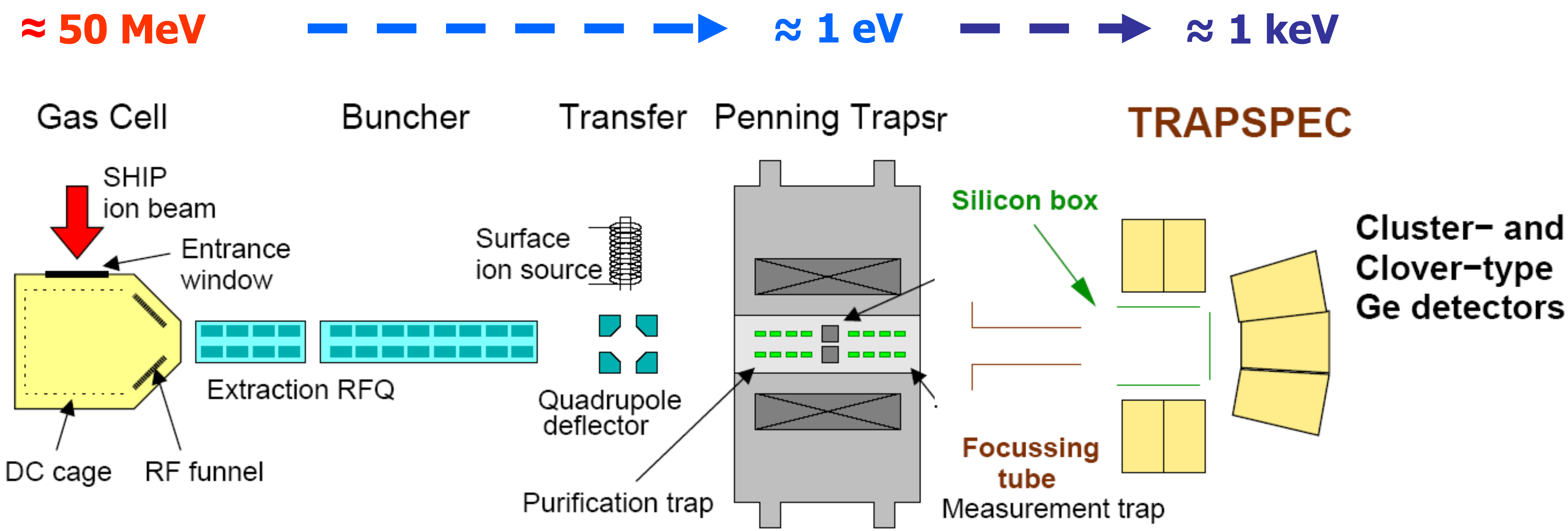
kinematic separation
in flight by velocity filter

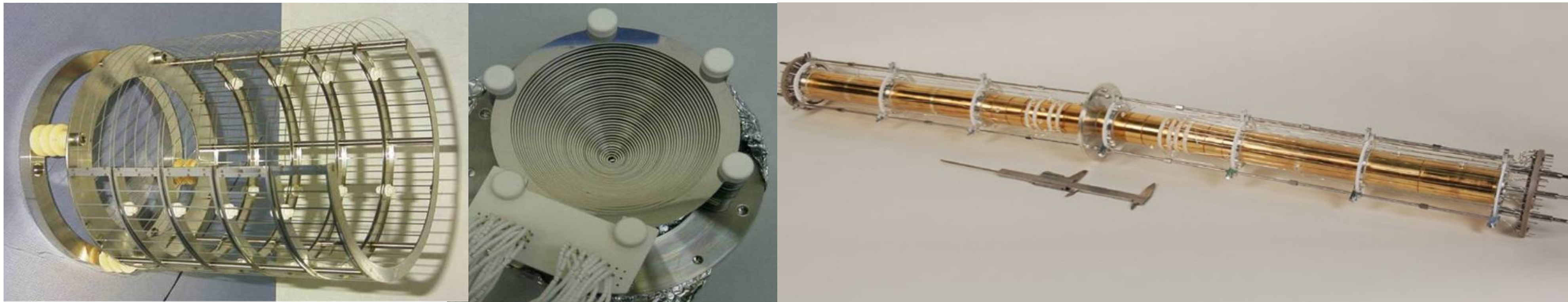
Typical yield for primary beam ≈ 6 x 10^{12} / s

≈1 atom/s @ Z ≈ 102 ($\sigma \approx 1\ \mu b$)

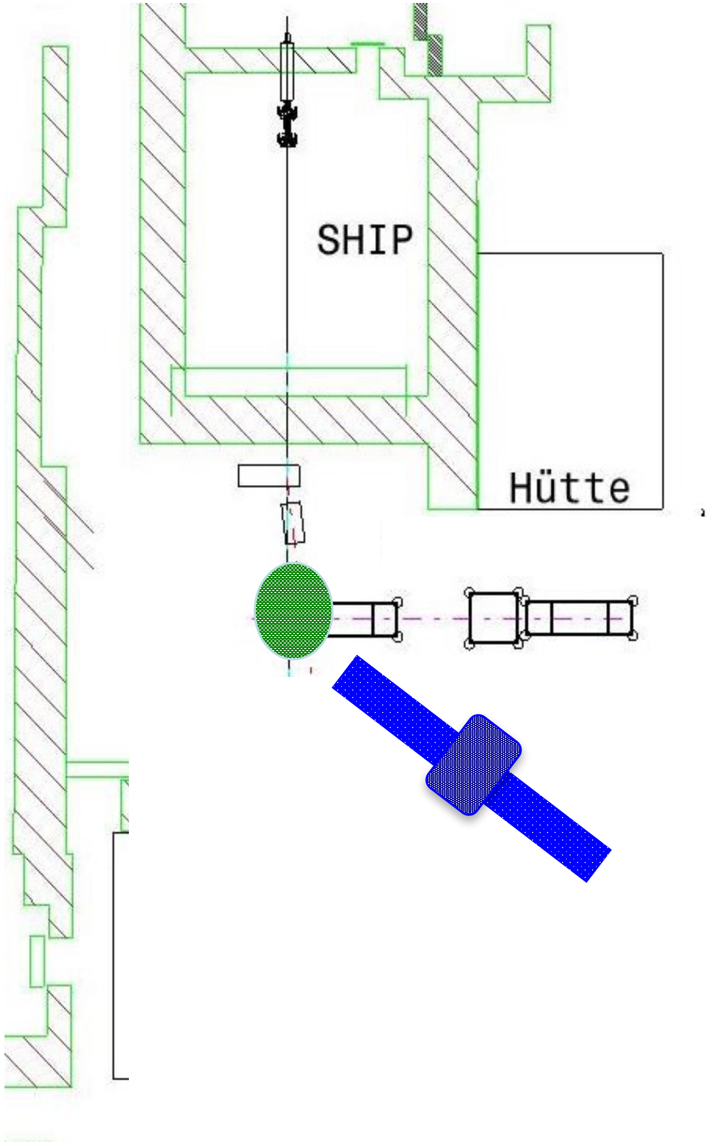
≈1 atom/week @ Z= 112 ($\sigma \approx 1$ pb)

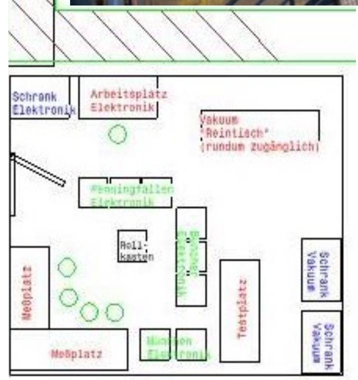
SHIPTRAP Setup

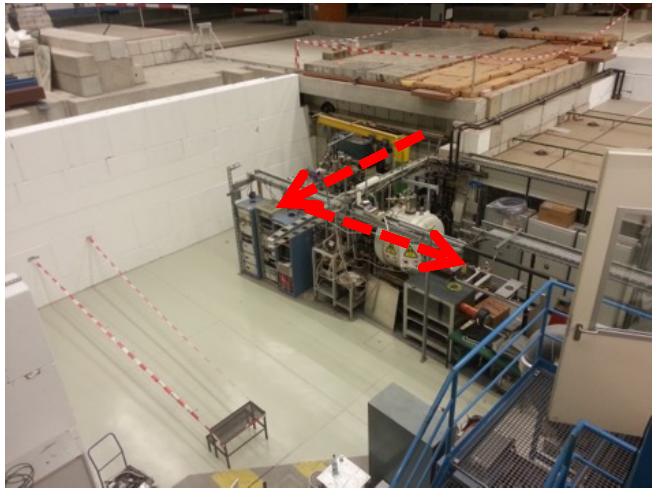


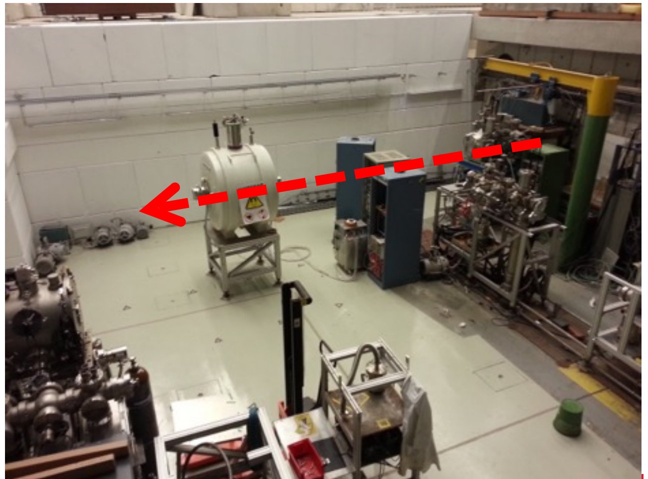


2016: Setup relocation









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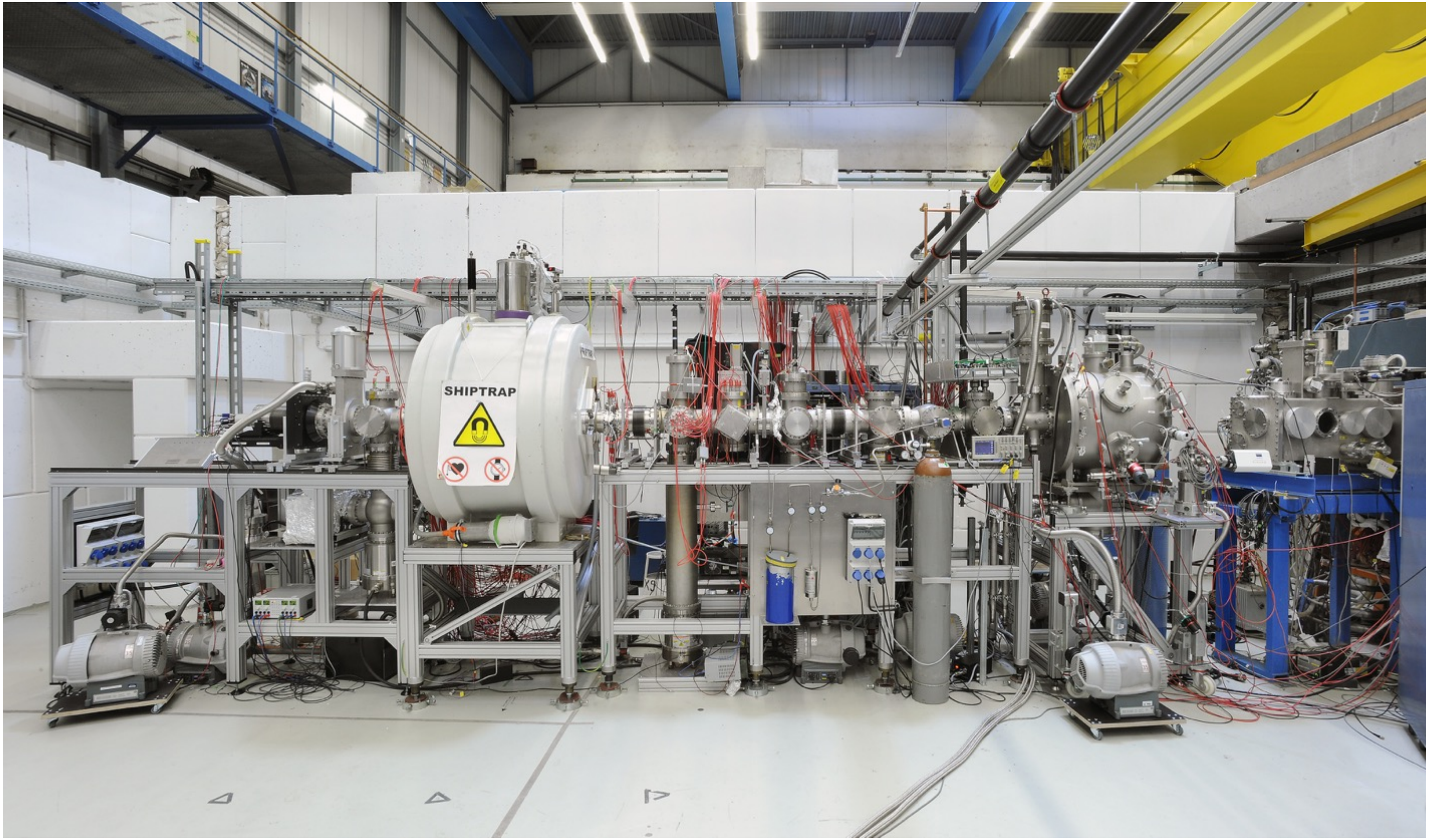
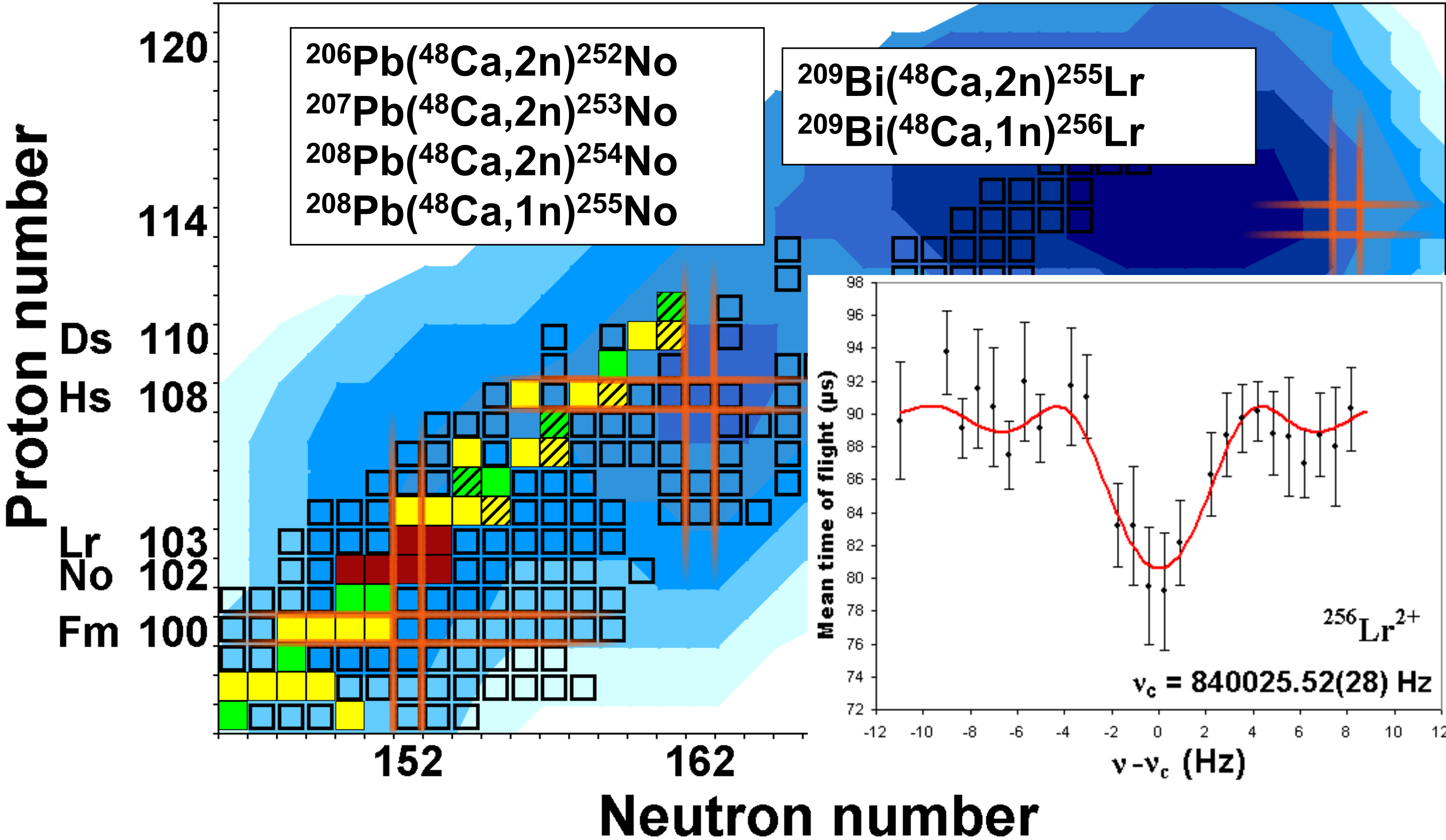
SHIPTRAP Setup

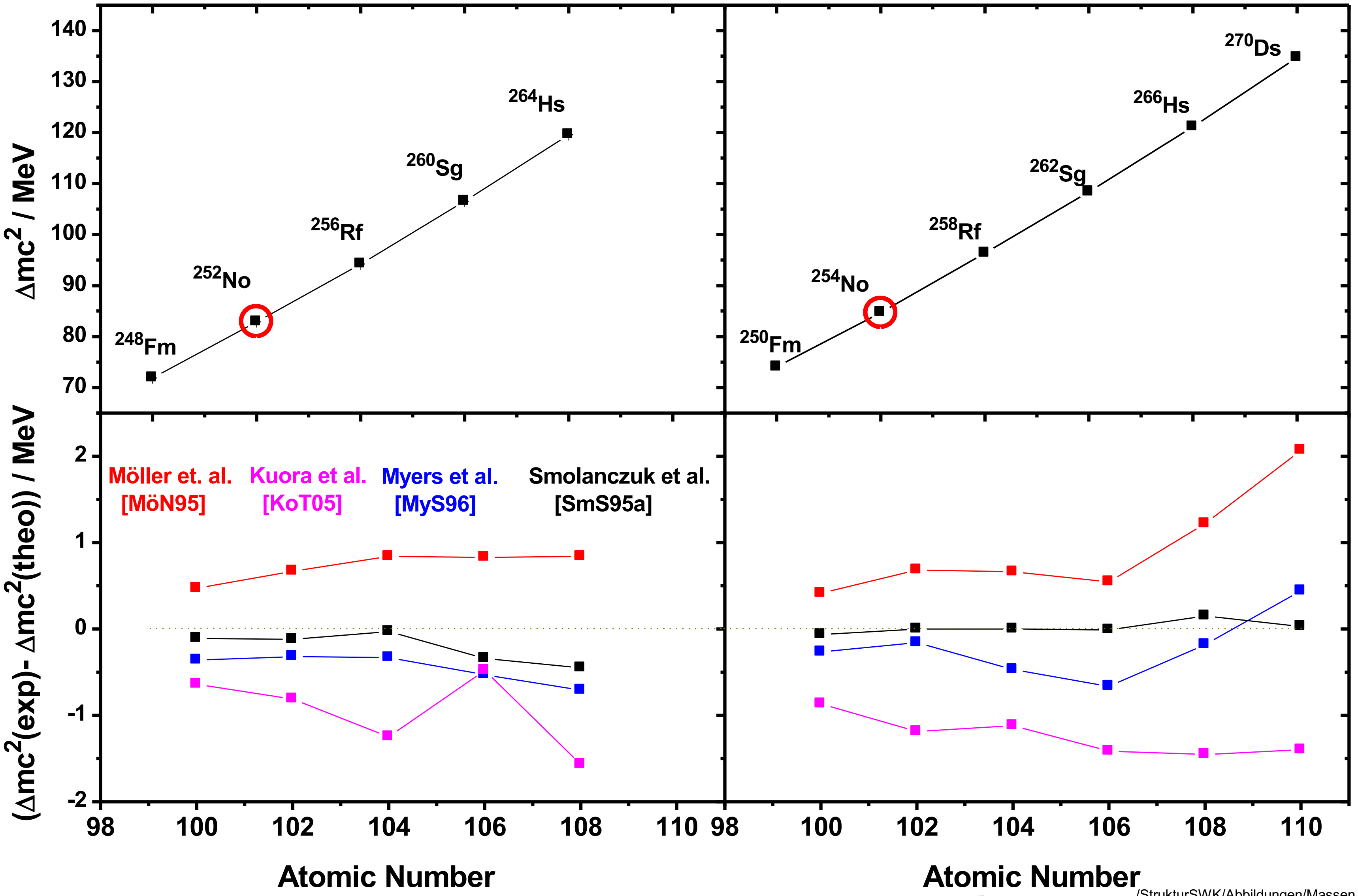


Direct mass measurements with SHIPTRAP



M. Block et al., Nature 463, 785 (2010), M. Dworschak et al., Phys. Rev. C 81, 064312 (2010)
E. Minaya Ramirez et al., Science 337, 1183 (2012)

Masses of even-even $N-Z = 48$ and $N-Z = 50$ Nuclei



/StrukturSWK/Abbildungen/Massen, F.P. Heßberger, 3.9.2013

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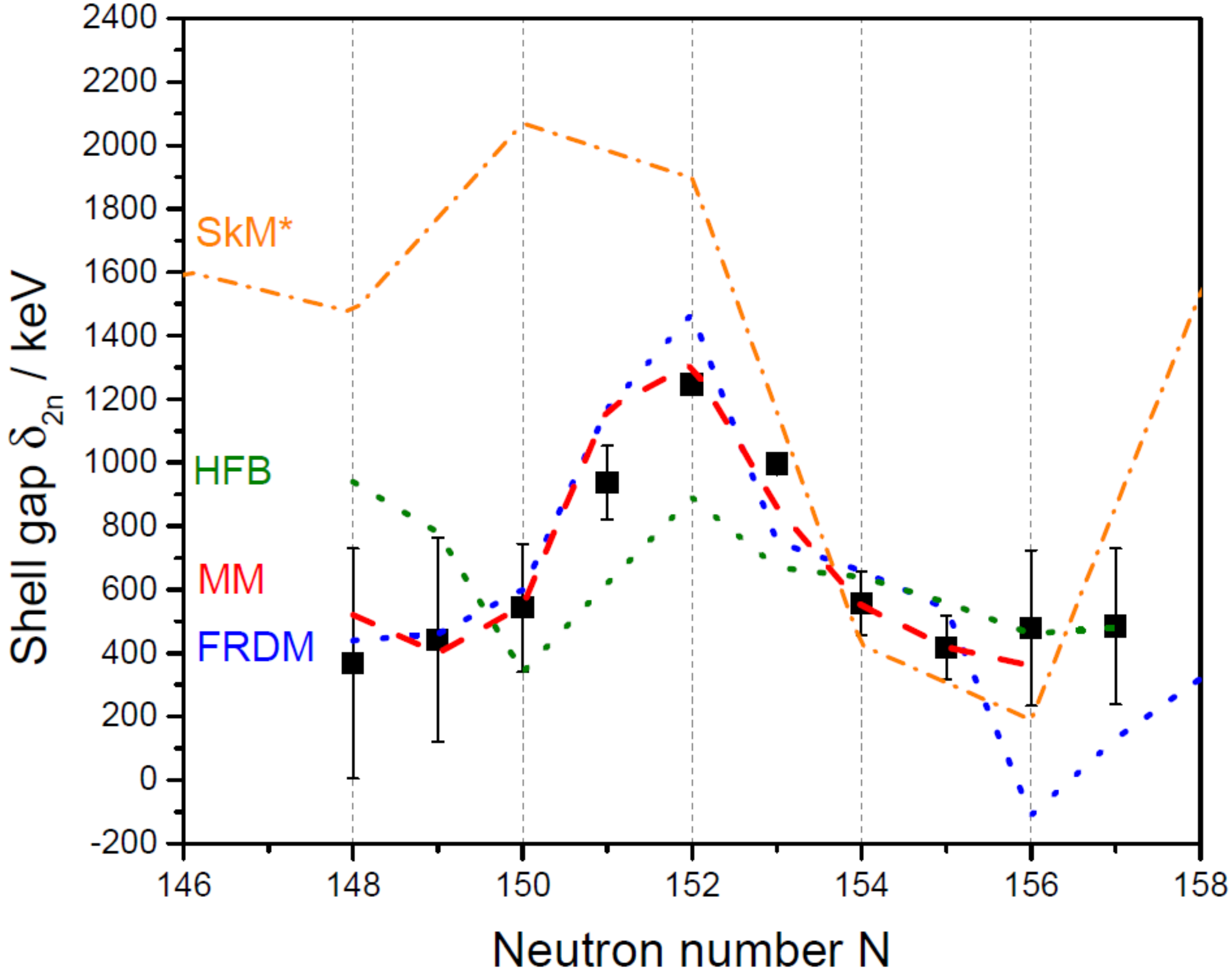
courtesy F. P. Hessberger

Probing the Strength of Shell Effects

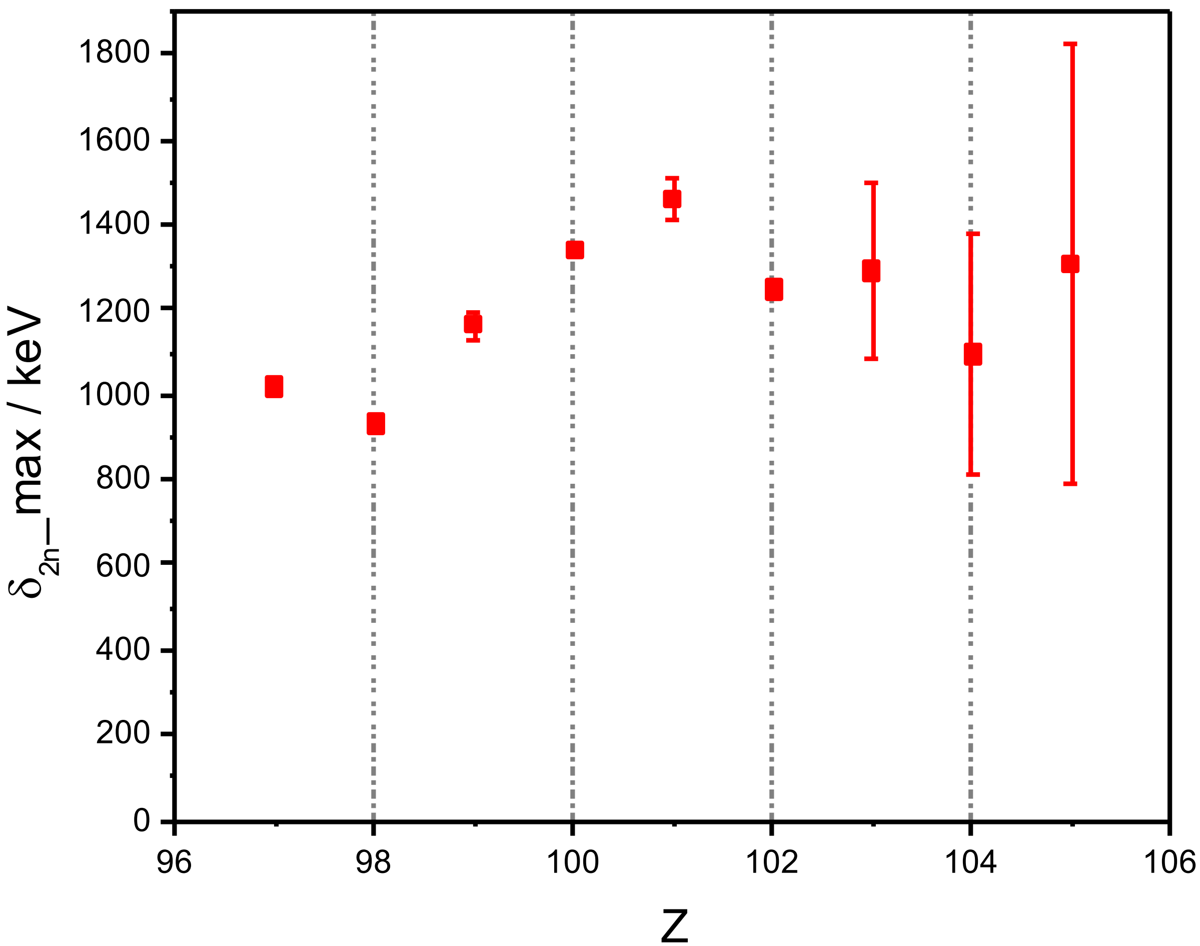
$\delta_{2n}(N,Z) = 2B(N,Z) - B(N\text{-}2,Z) - B(N\text{+}2,Z)$



Science 337 (2012) 1207

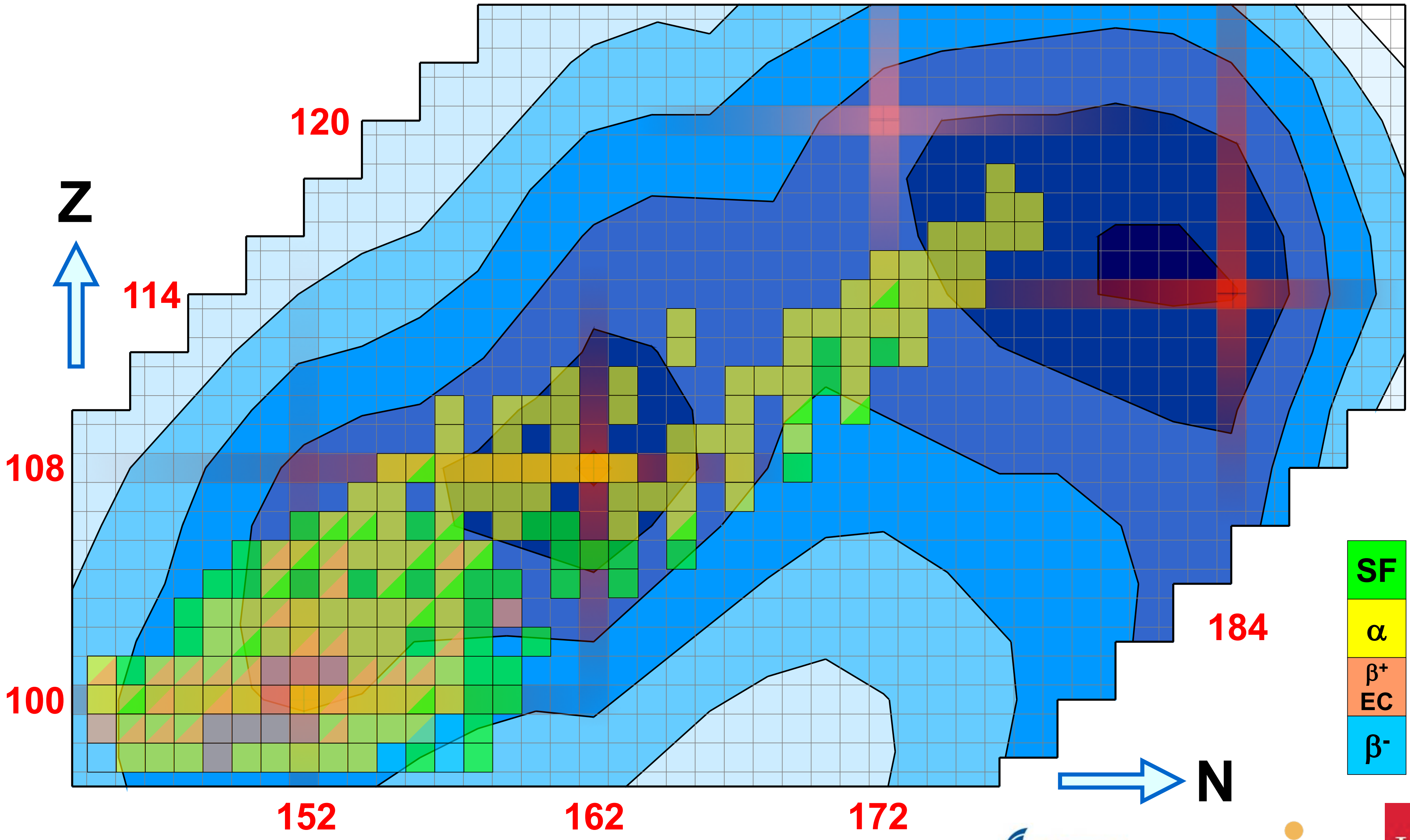
Probing the Strength of Shell Effects

Evolution of *N* = 152 shell closure



M.B. Nucl. Phys. A 944 (2016)
Data taken from Atomic Mass Evaluation (AME) 2012: M. Wang et al.

Superheavy Element Research – Current Status



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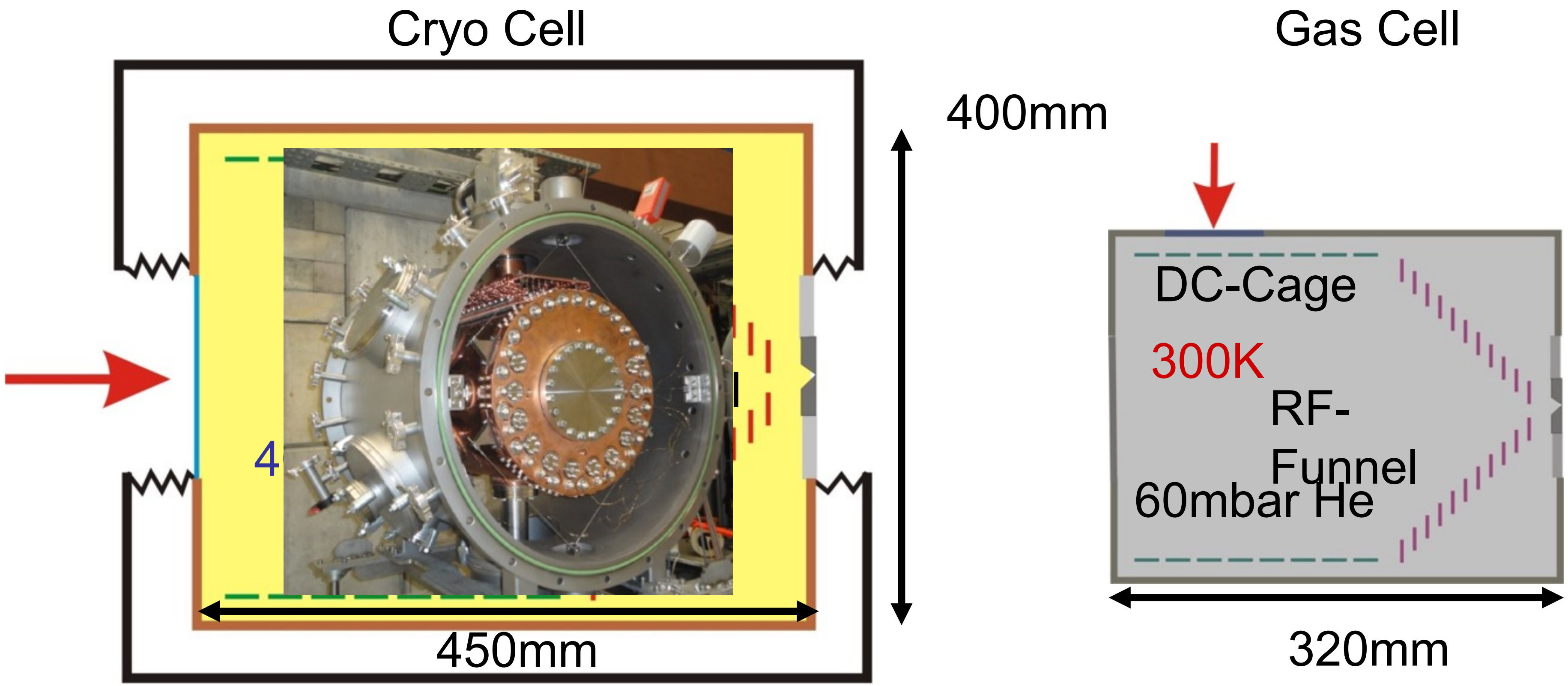
Nuclides of interest

Nuclide	Half-life	N	Cross section
Fm-250	30 min	150	750-1000 nb
Fm-251	5.3 h	151	750-1000 nb
Fm-252	25.39 h	152	750-1000 nb
Lr-255m	2.53 s	152	200 nb
Lr-256	27 s	153	60 nb
Rf-257	4.7 s	153	15 nb
Rf-260	21 s	156	1.5 nb
Rf-261	1.9s	157	1.8 nb
Db-258	4.2 s	153	4.4 nb
Sg-259	0.32 s	153	1 nb
Sg-261	0.23 s	155	

Possible future measurements

- **Most exotic measurement so far: Lr-256 (60nb)**
- Measure isomeric states in Lr-255 (200nb)
- Measure mass of Rf-257 (15nb)
- measure masses of No-251 and improve masses of other nuclides such as No-255, Lr-255, Lr-256
- Measure masses of Sg-26x (Cr-54+Pb)
- Measure masses of Fm-250,251,252 (O-16/18+U-238) (1ub)
- No-257 (C-13 + Cm-248)
- Rf-261 (Ne-22 + Pu-244)

Cryogenic Gas Cell



Advantages compared to 1st generation gas cell:

- Larger stopping volume and Coaxial injection of reaction products
- Higher cleanliness due to cryogenic operation
- Larger gas density at a lower absolute pressure

C. Droese et al. NIM B 338, 126 (2014)

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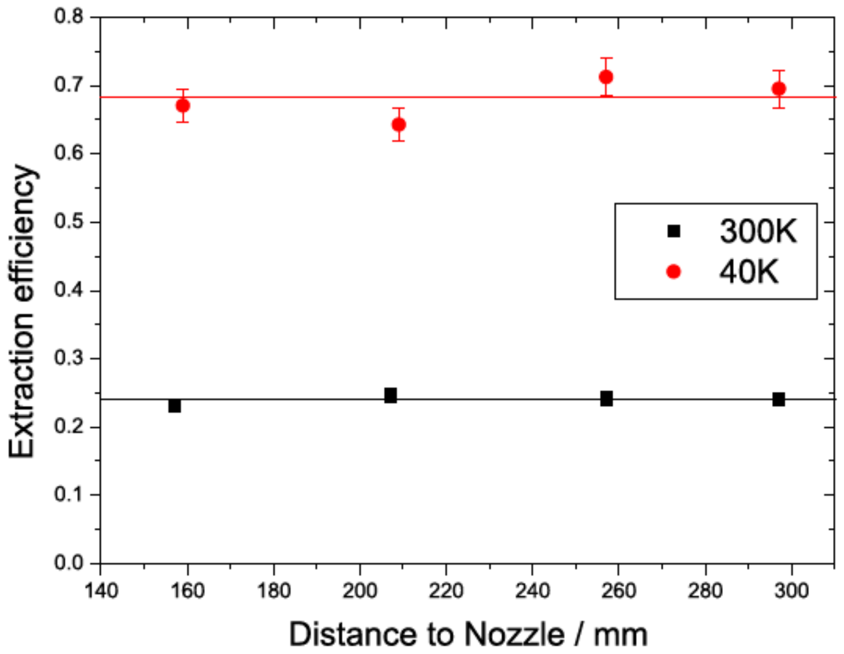
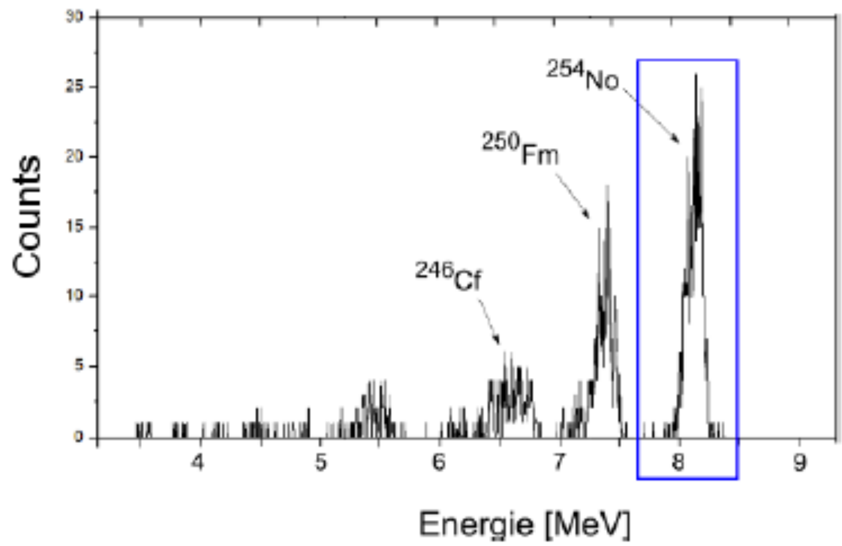
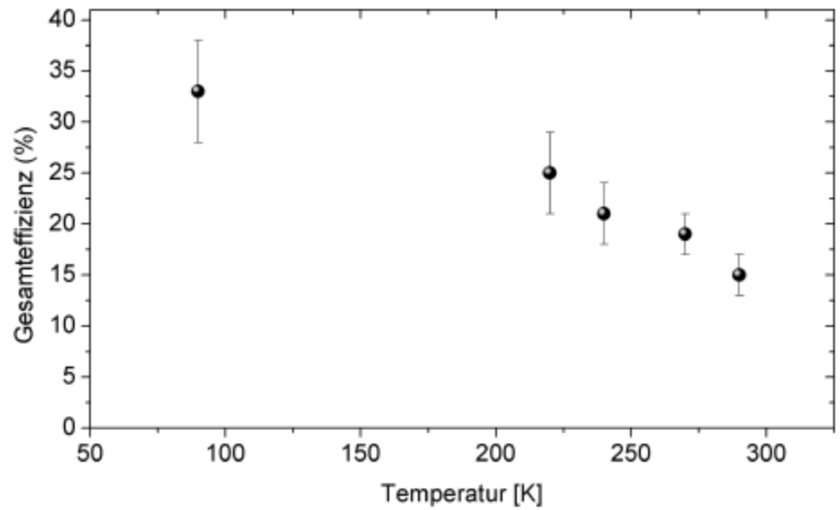
Commissioning of Cryogenic Gas Cell





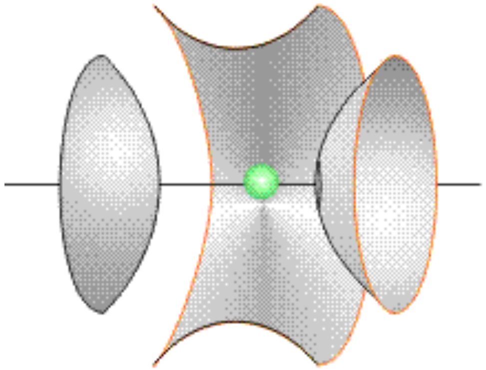


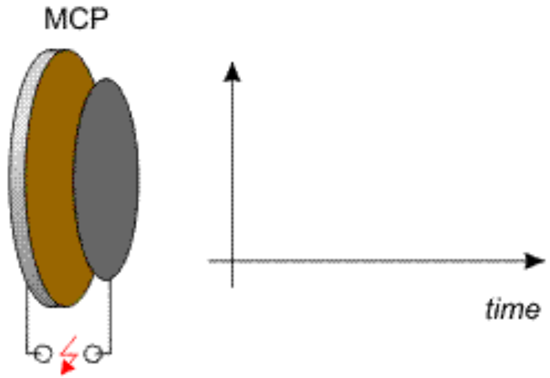
- Gain in efficiency by factor of 5 compared to first generation gas cell already demonstrated

O. Kaleja Master Thesis, TU Darmstadt (2016)

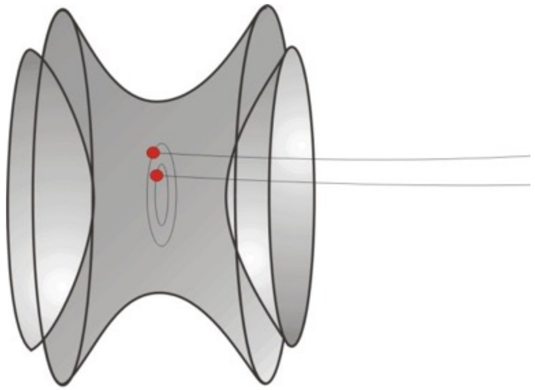
Recent Breakthrough

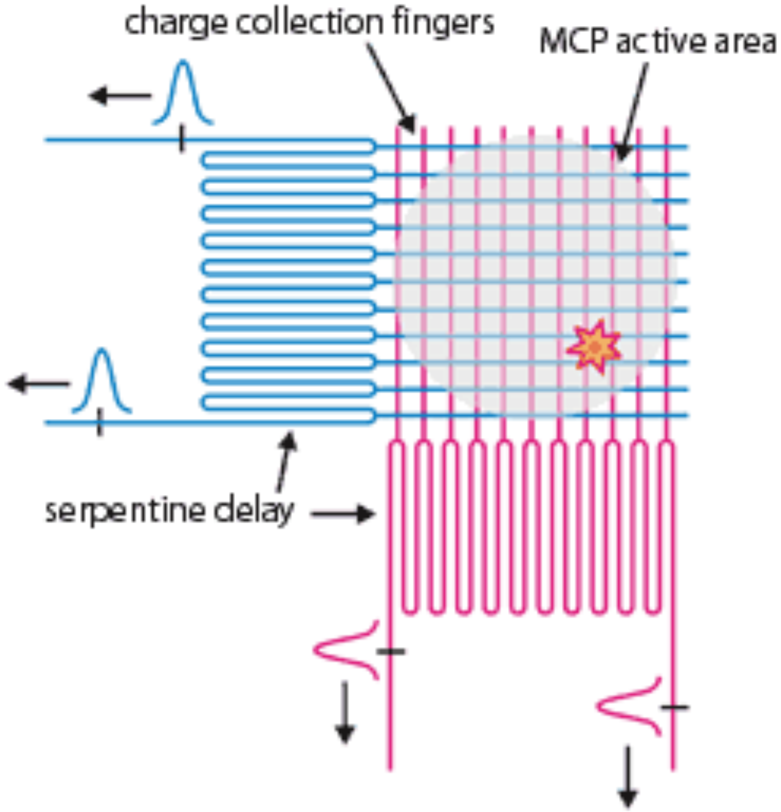
Destructive time-of-flight detection



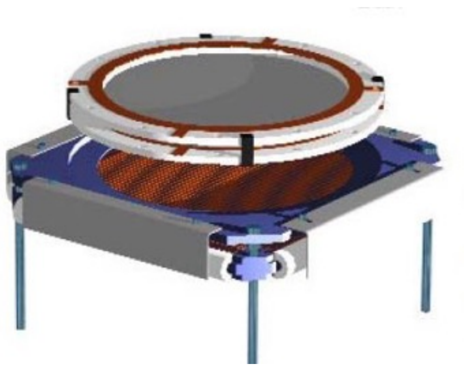


Spatially resolved detection



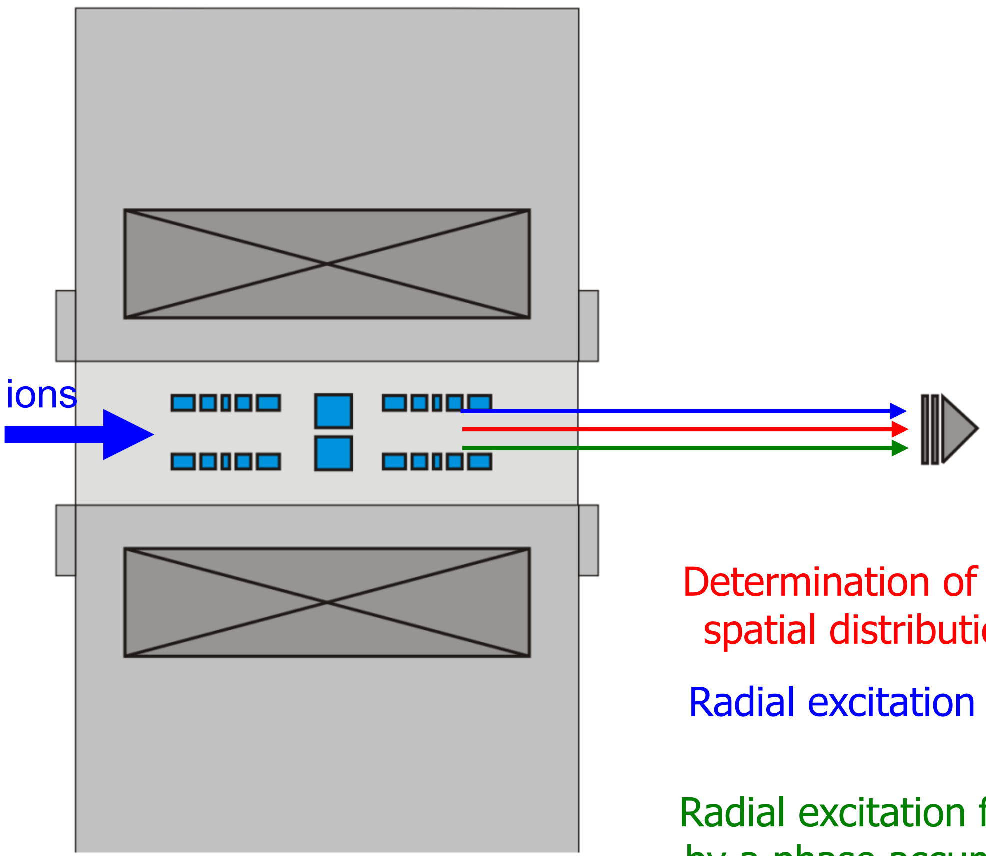


Delay-line detector



S. Eliseev et al., Appl. Phys. B114, 107 (2014)

Phase-Imaging Ion-Cyclotron-Resonance Method



D   or

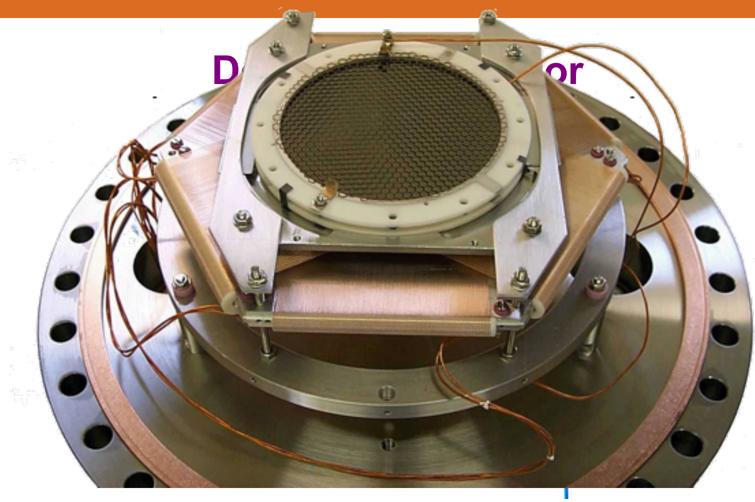
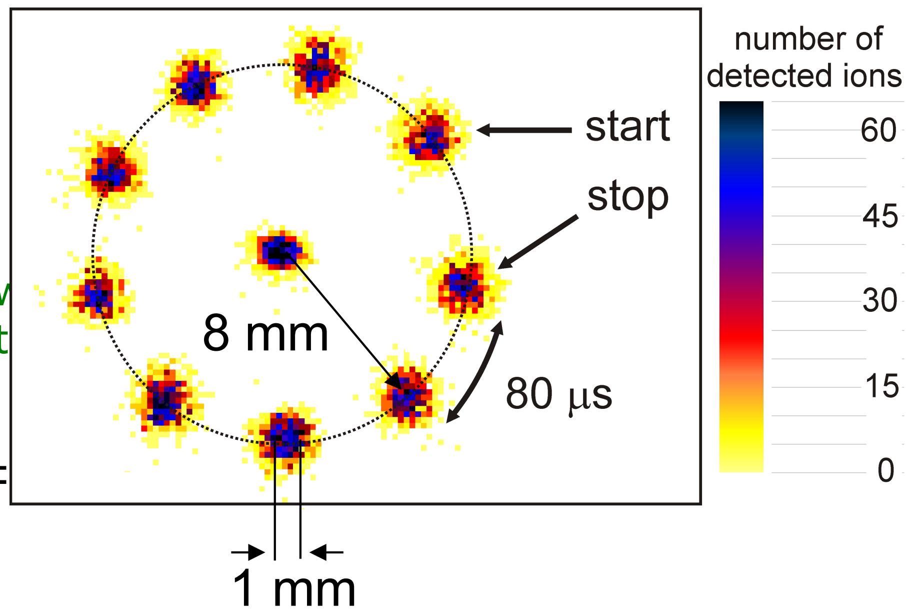


image of magnetron motion ($G \approx 20$)



Determination of the spatial distribution

Radial excitation

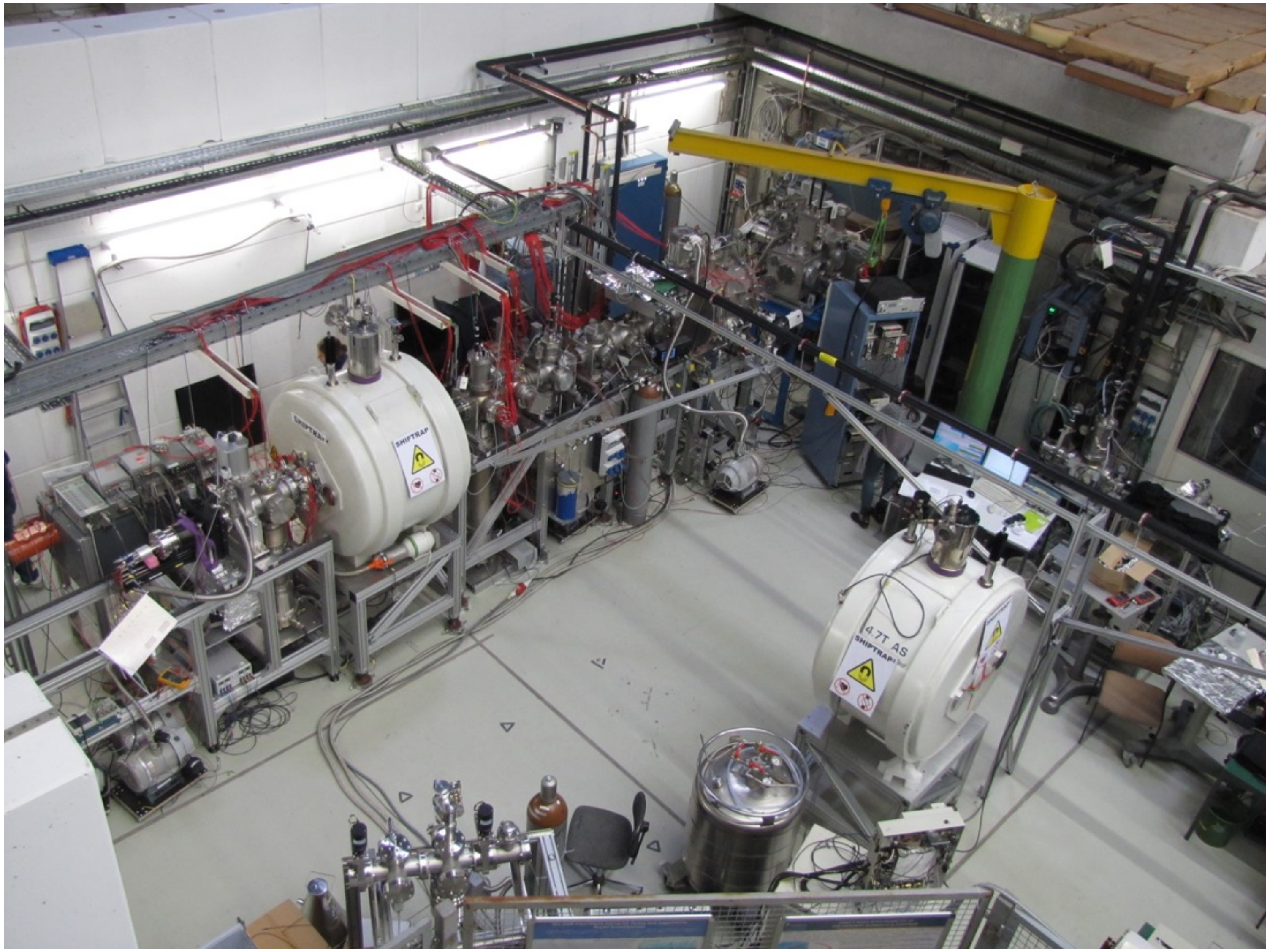
Radial excitation follow
by a phase accumulat

$$\phi + 2\pi n = 2\pi \nu t$$

$$\Delta \nu = \frac{\Delta \phi}{2\pi t} =$$

S. Eliseev et al., Phys. Rev. Lett. 110, 082501 (2013)

SHIPTRAP Setup



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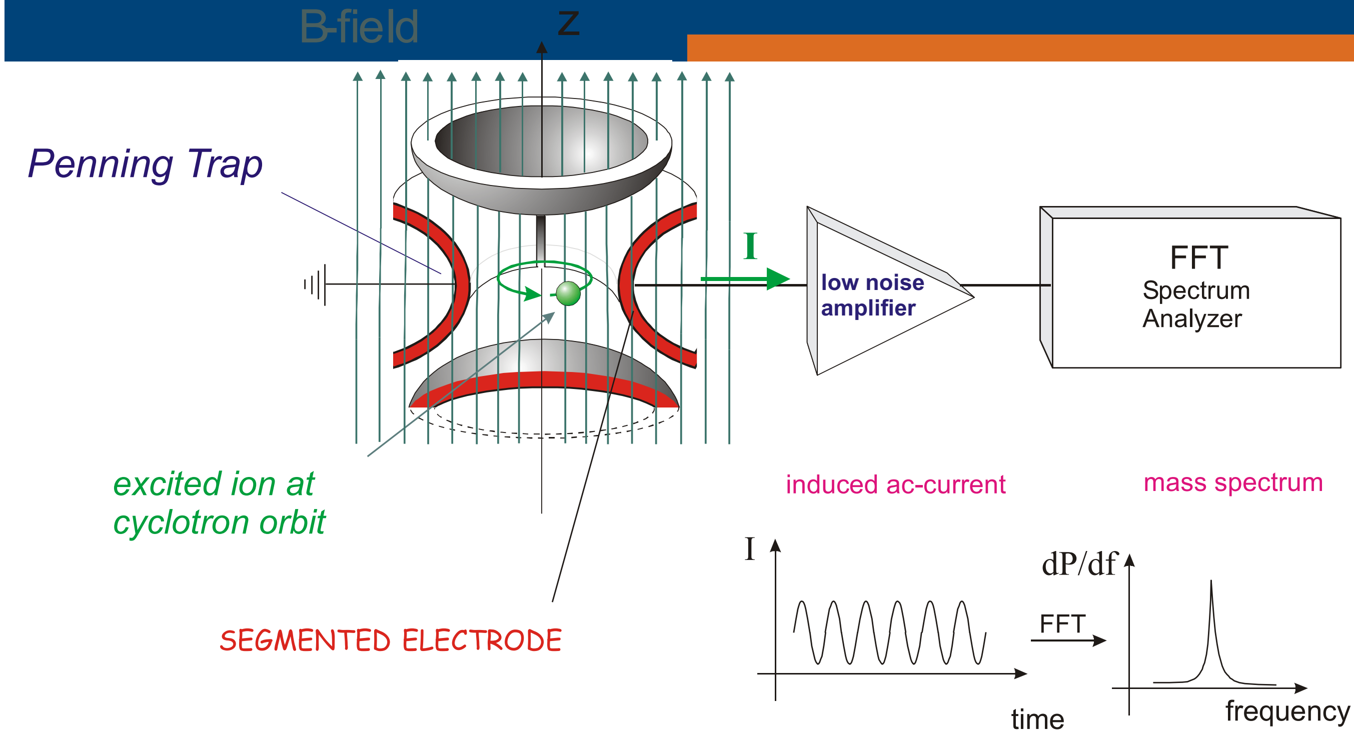
Single-ion Mass Measurement



$$\frac{S}{N} \propto \frac{r_{ion}}{D} \cdot q \cdot \sqrt{\frac{\nu}{\Delta\nu}} \cdot \sqrt{\frac{Q}{kT \cdot C}}$$

Summary and Conclusions

- State-of-the-art mass spectrometry provides masses of heavy nuclides with high accuracy – anchor points
- High-precision mass measurements allow mapping shell effects in the heaviest elements
- Technical and methodical improvements extend the reach towards more exotic nuclides with lower yield
- S3 can contribute by exploiting in particular asymmetric reactions and high beam intensity (phase 1++)

Thank you for your attention!

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