High-precision mass measurements with PENTATRAP for neutrino physics

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MAX-PLANCK-GESELLSCHAFT

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Some applications of high-precision PTMS

Mass-ratio measurements at a level of $\frac{\delta(m_1/m_2)}{m_1/m_2} \leq 10^{-11}$

Measurements at PENTATRAP | Measurements at other facilities/calculations

Neutrino physics $^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy} + \nu_e + E$

Direct test of $E = mc^2$ $E = \frac{hc}{\lambda} = \Delta m(^{36}\mathrm{Cl} - {}^{35}\mathrm{Cl} - n)c^2$

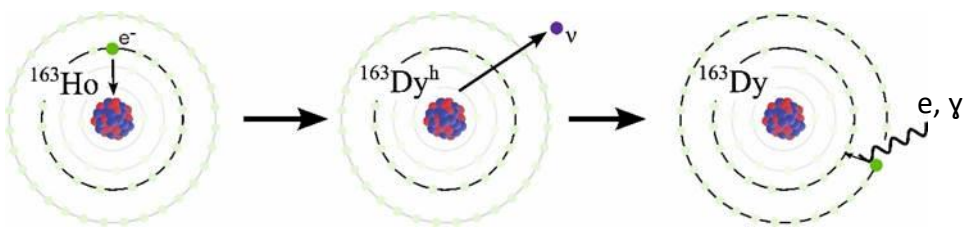
Test of QED

Binding energies: $E_B(\mathrm{Xe}^{17+}) = \Delta m(\mathrm{Xe}^{17+} - \mathrm{Xe}^{18+})c^2 - m_e c^2$

g-factor: $\Delta m(^{48}\mathrm{Ca}^{17+} - {}^{40}\mathrm{Ca}^{17+})$

Dark matter searches, transuranium elements, …

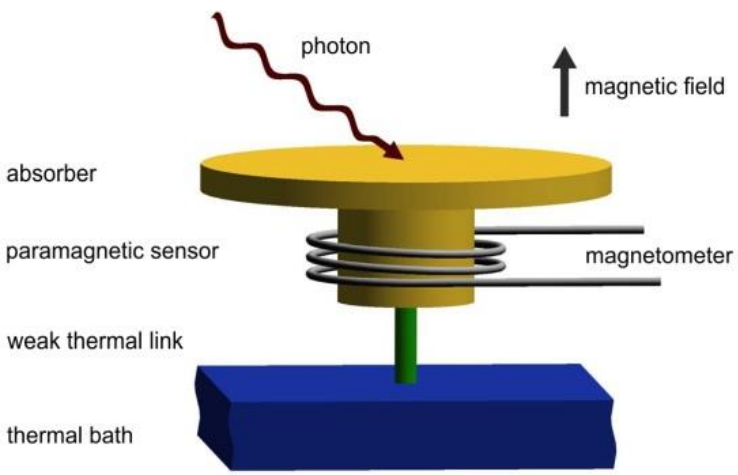
The electron neutrino mass



$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e \rightarrow {}^{163}\mathrm{Dy} + \nu_e + Q_{EC}$$

Electron **C**apture in **Ho**lmium experiment

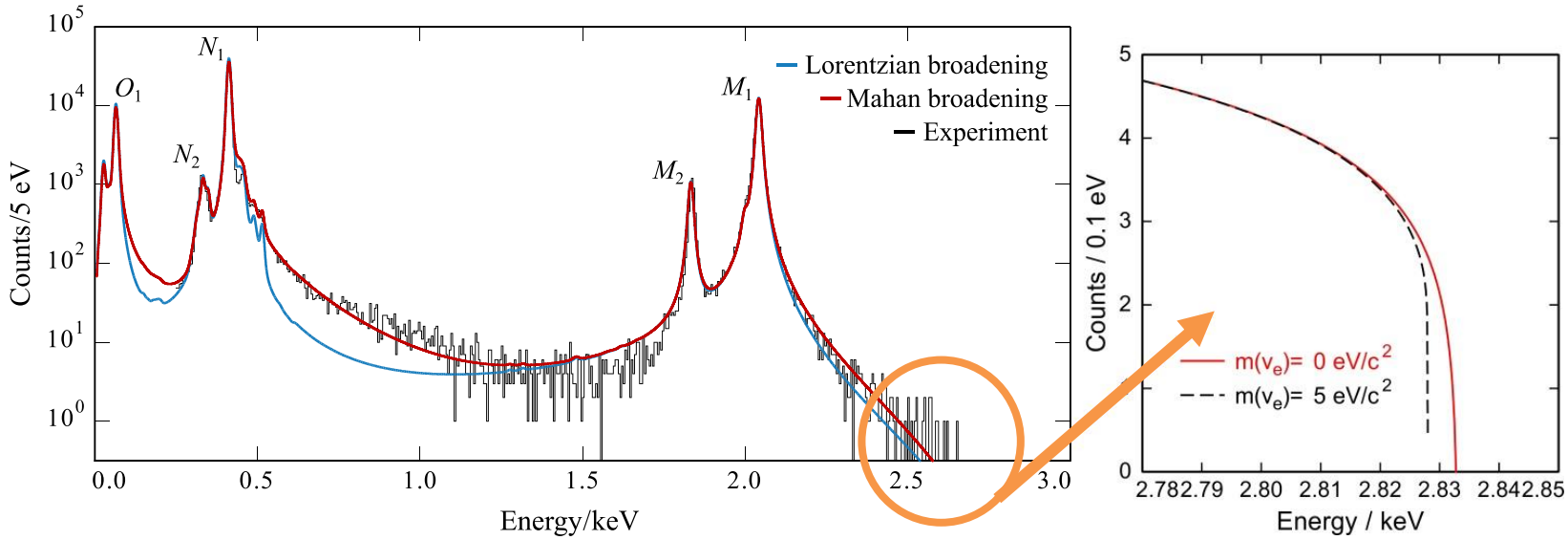
- m_{ν_e} via electron capture process in ^{163}Ho
- Current limit: $m_{\nu_e} < 150$ eV
- ECHo aims at: $m_{\nu_e} \approx 1$ eV



- Metallic magnetic calorimeters (MMCs) in a cryostat at 50 mK
- Energy resolution: 2 eV at 6 keV
- ^{163}Ho implanted directly in the absorber

Gastaldo, L. et al., *EPJ 226*, 1623 (2017)
Velte, C. et al., *EPJ 79*, 1026 (2019)

The electron neutrino mass



Check for systematic uncertainties:

From fitting a theoretical spectrum:

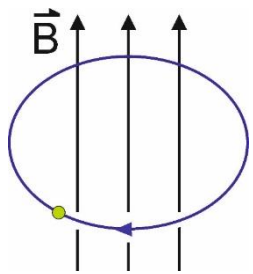
- Electron neutrino mass
- Q-value of the transition

$$Q_{\mathrm{EC}} = \Delta m(^{163}\mathrm{Ho} - {}^{163}\mathrm{Dy})\mathrm{c}^2$$

High-precision Penning-trap mass spectrometry

Gastaldo, L. et al., *EPJ 226*, 1623 (2017)
Velte, C. et al., *EPJ 79*, 1026 (2019)

Penning-trap mass spectrometry (PTMS)



Free-space
cyclotron frequency

$$\omega_c = \frac{q}{m} B$$

Brown, L. et al., Rev. Mod. Phys. 58, 233 (1986)

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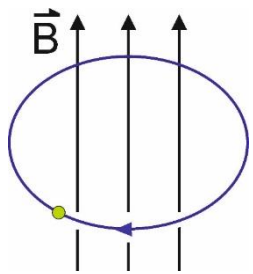

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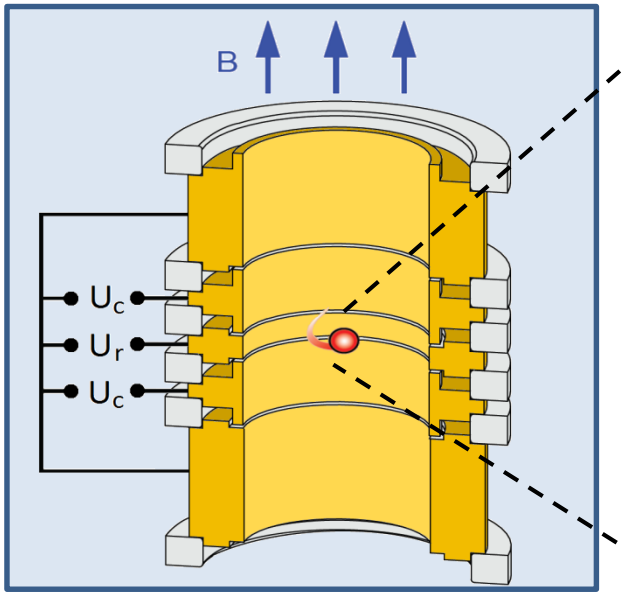
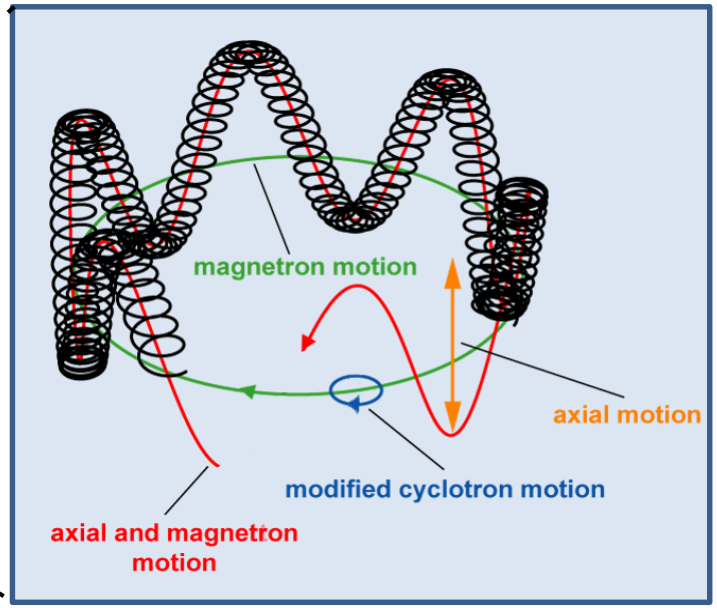




Invariance theorem:

$$\omega_c^2 = \omega_+^2 + \omega_z^2 + \omega_-^2$$

Three independent eigenmotions:

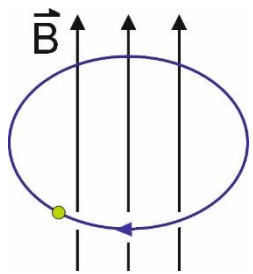
Modified cyclotron motion (ω_+)

Axial motion (ω_z)

Magnetron motion (ω_-)

Brown, L. et al., Rev. Mod. Phys. 58, 233 (1986)

Penning-trap mass spectrometry (PTMS)



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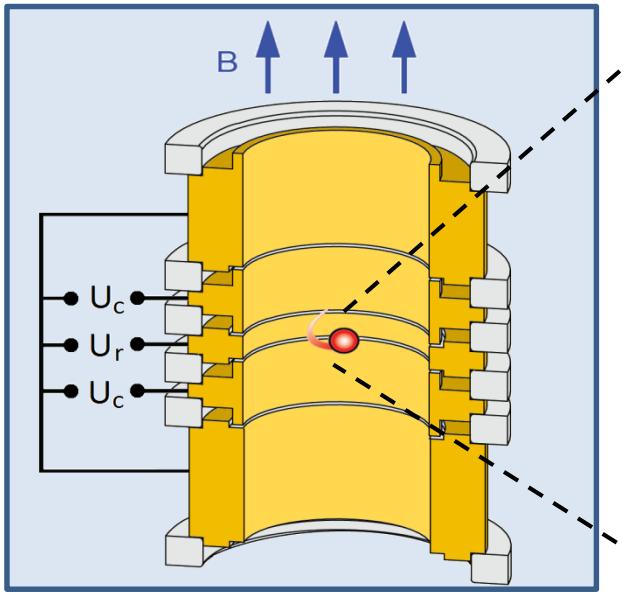

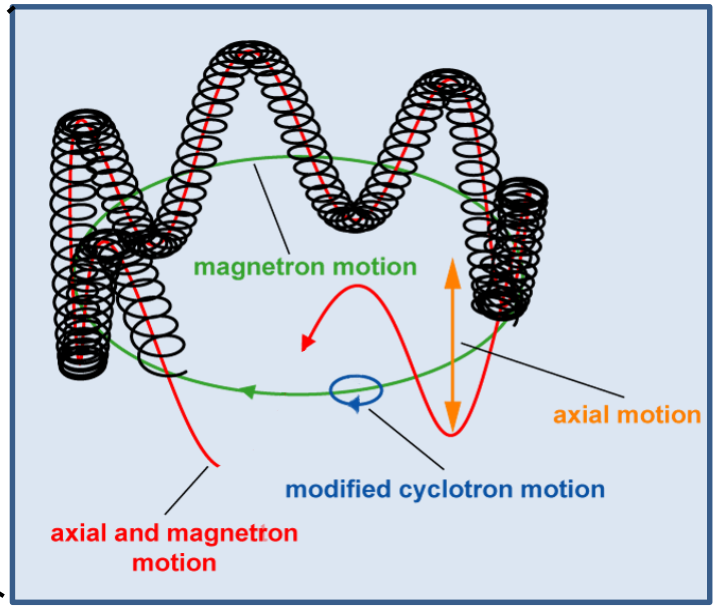

$$\omega_c = \frac{q}{m} B$$

Magnetic field has to be known as well!
-> Mass-ratio measurements

Invariance theorem:

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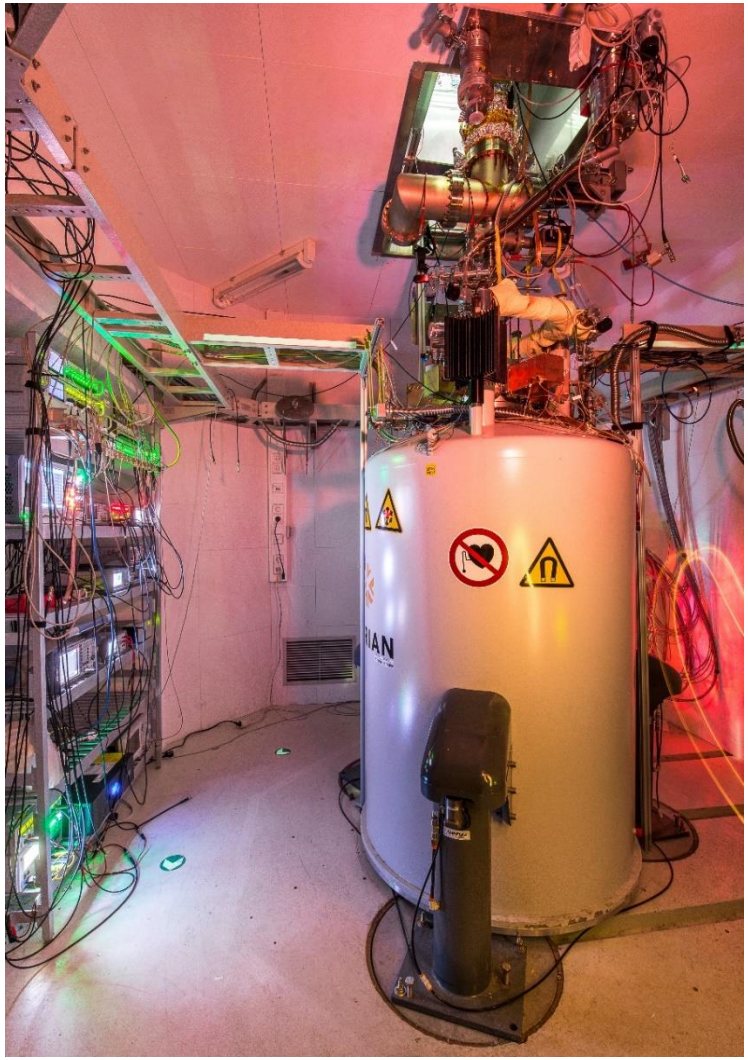
Brown, L. et al., Rev. Mod. Phys. 58, 233 (1986)

Features of the PENTATRAP experiment

Aim of the high-precision Penning-trap mass spectrometer PENTATRAP:
mass-ratio measurements of stable and long-lived highly charged ions with a relative uncertainty below 10^{-11}

Unique features

- Trap tower consisting of 5 cylindrical Penning traps
- Non-destructive image-current detection
- Strong magnetic field (7T)
- Pressure and level stabilization for the superconducting magnet
- Temperature stabilized lab (<0.02K/30 min)
- Ultra stable voltage source StaReP
- **Access to highly charged ions**



Highly charged ions for PTMS

- Free cyclotron frequency scales with the charge state
- Larger induced image current enhances SNR in detection system

Measurement of Q_{EC} of ^{163}Ho with PENTATRAP aiming at $\delta Q_{EC} \approx 1$ eV

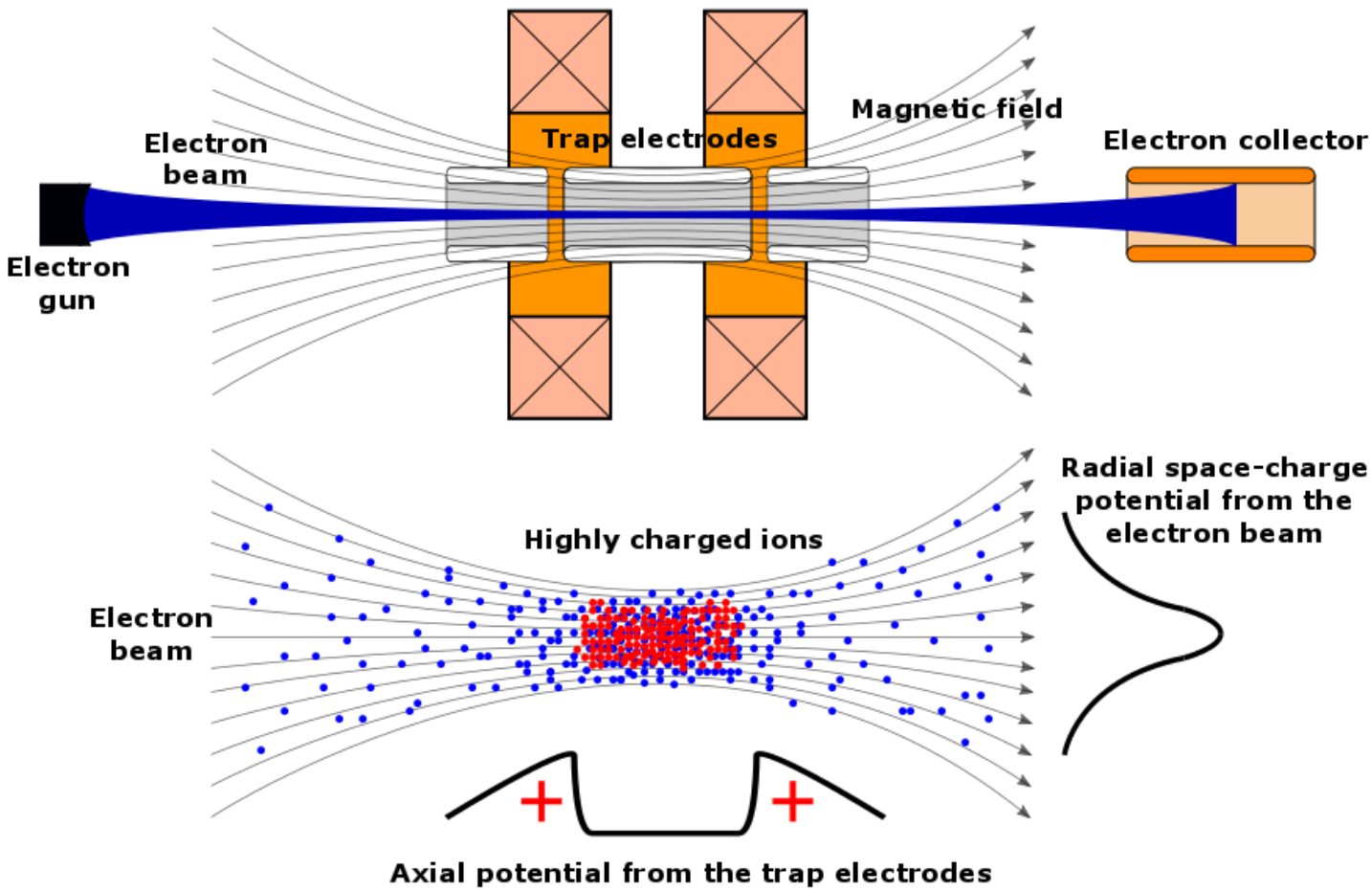
Requires highly charged ions (HCI)
=> Electron beam ion trap (EBIT)

Half-life of ^{163}Ho: 4570 years
→ synthetic radioisotope

produced by reactor irradiation
of enriched ^{162}Er

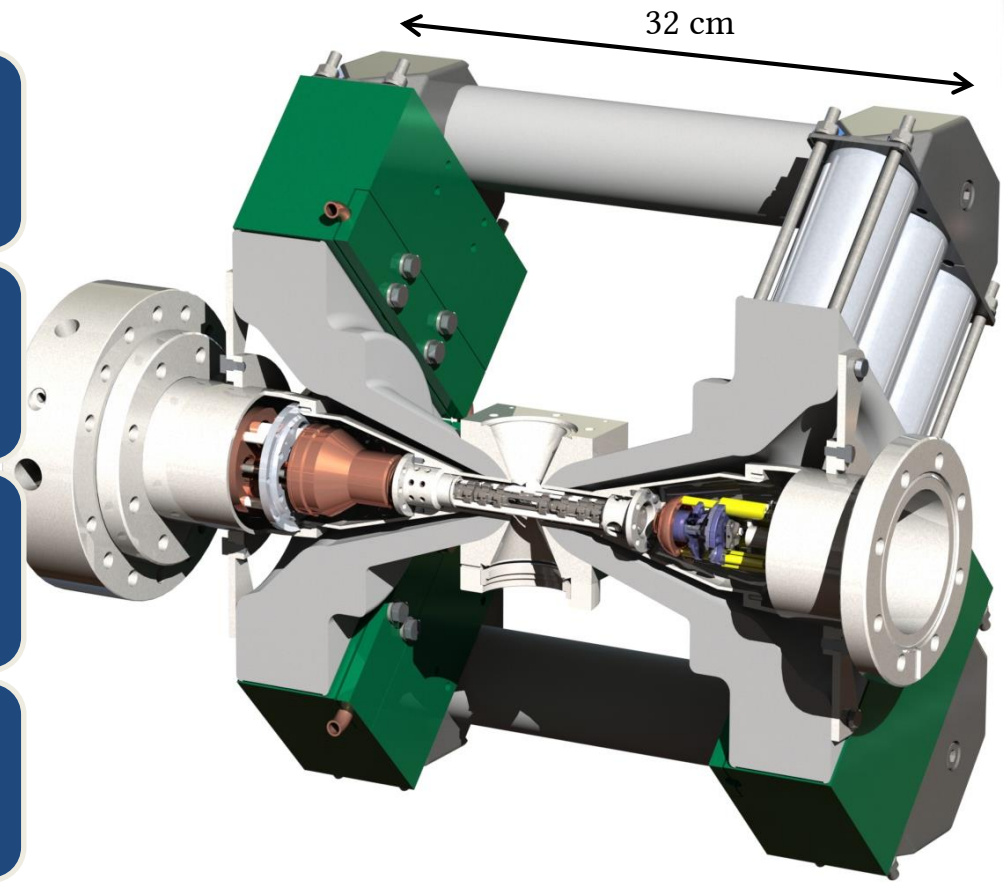
Production of HCI of ^{163}Ho from a sample of 10^{16} atoms (30 ng)?

Electron beam ion traps (EBITs)



Heidelberg compact EBITs

- Iron yoke with 72 permanent magnets
- Magnetic field: 850 mT in the trapping region
- Access to the trap region by four ports (opening angle 60°)
- Electron gun position adjustable using a linear manipulator



NdFeB permanent magnets

Micke, P. et al., Rev. Sci. Instr. 89, 063109 (2018)

Injection techniques for EBITs

- Gas injection
- Injection of volatile organic compounds
- External laser ablation

} **Efficiency not sufficient for small samples!**

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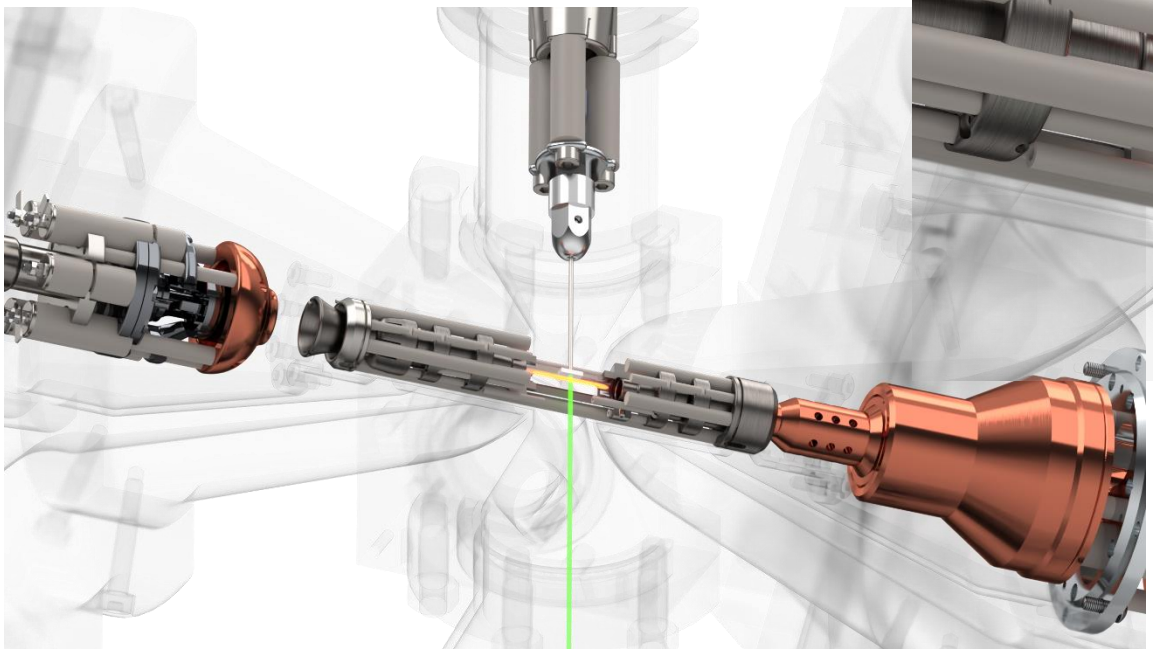
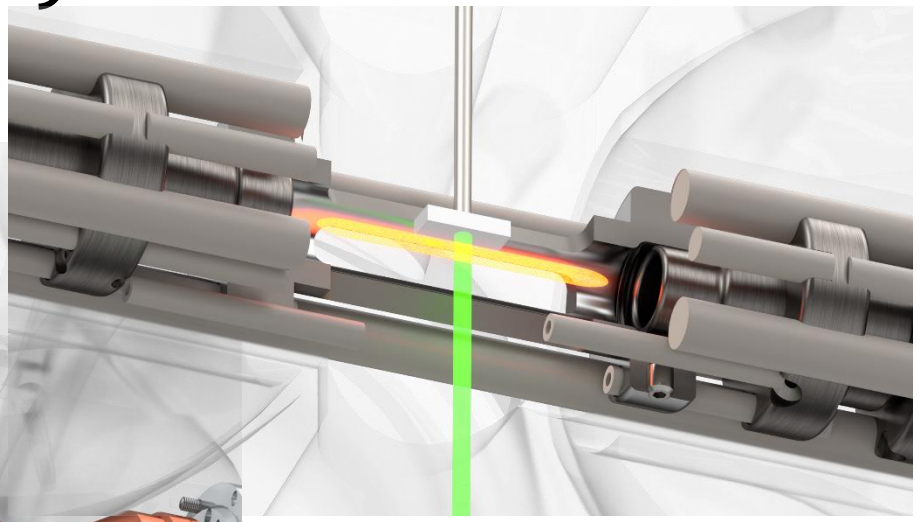
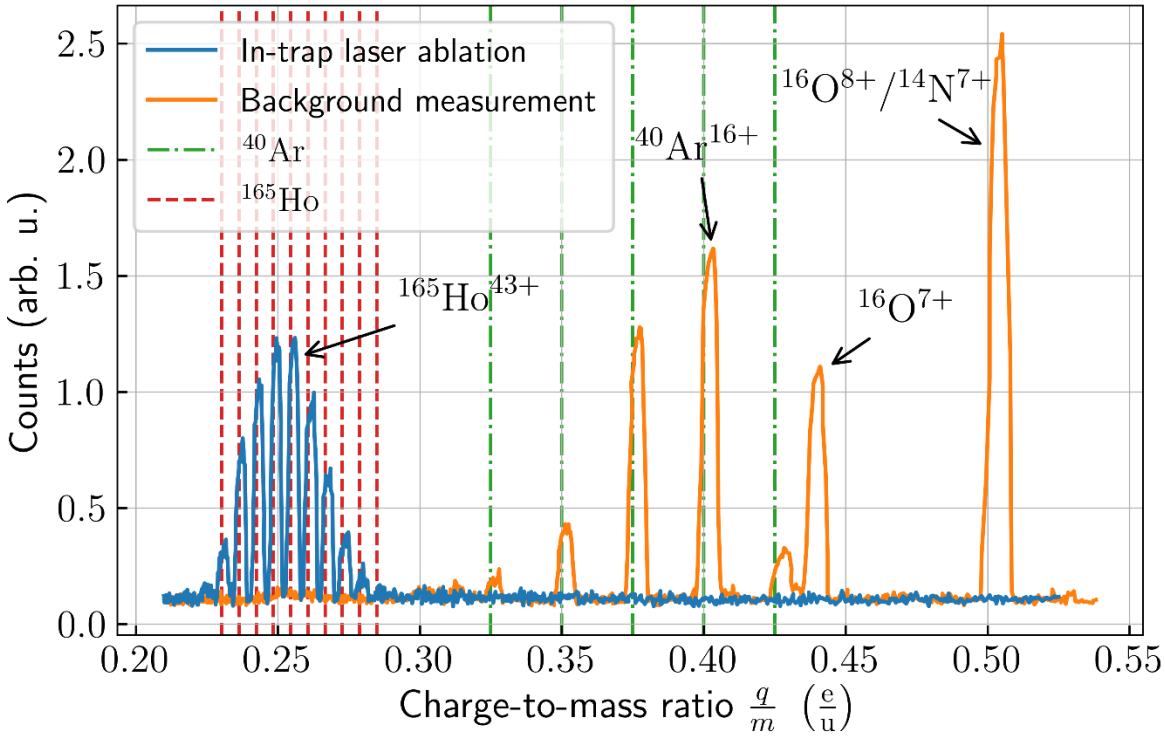
In-trap laser desorption technique





Schweiger, Ch. et al., *RSI 90*, 123201 (2019)

Massive ^{165}Ho target



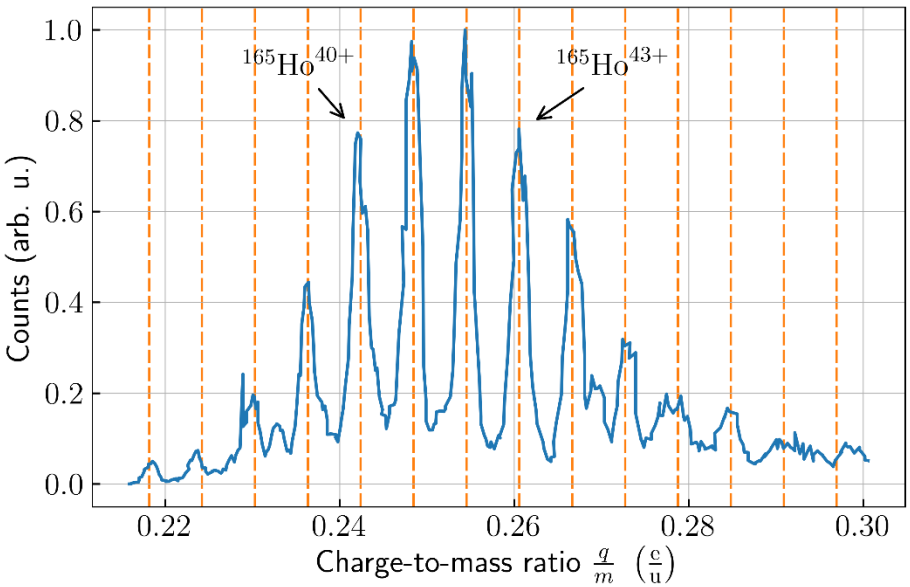
Blue curve: Laser ablation from ^{165}Ho target
Orange curve: Background measurement without laser

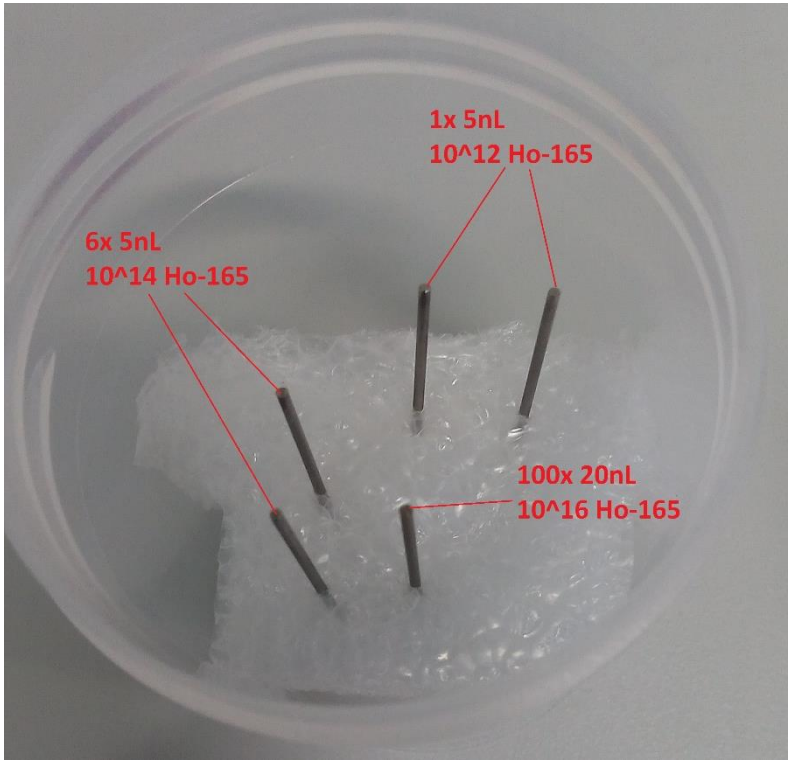
Schweiger, Ch. et al., *RSI 90*, 123201 (2019)

Small holmium targets

- 1 mm diameter Ti-wire
- Targets with known number of ^{165}Ho atoms on the surface:

  Drop-on-demand inkjet printing technique (group of Ch. Düllmann @ JGU Mainz)





Haas, R. et al., *NIM A* 874, 43 (2017)
Schweiger, Ch. et al., *RSI 90*, 123201 (2019)

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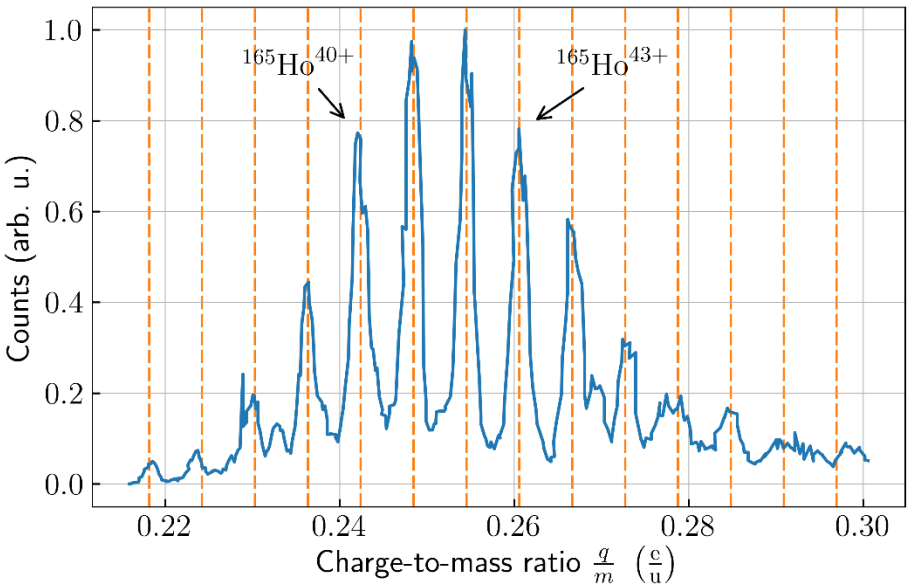
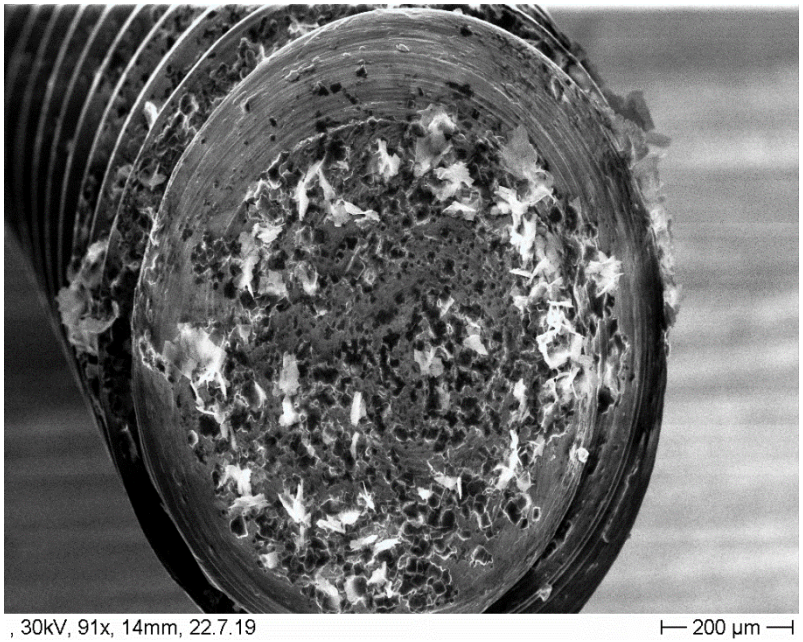
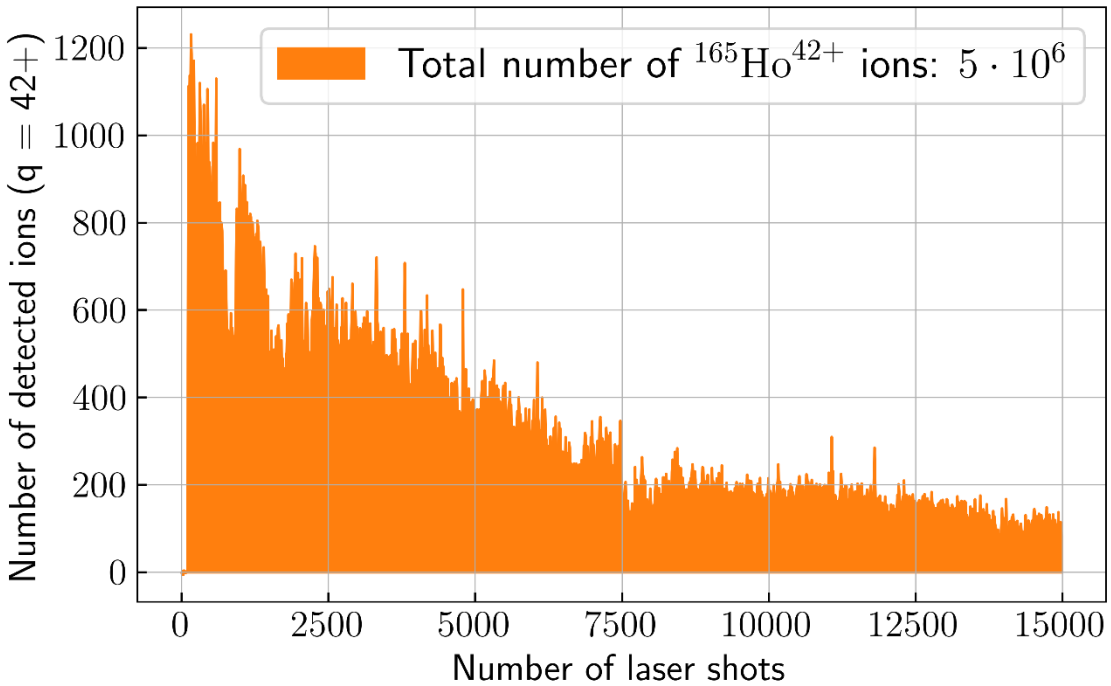




Lifetime of small holmium targets



10^{14} atoms:
> 100k laser shots
10^{12} atoms:
20k laser shots

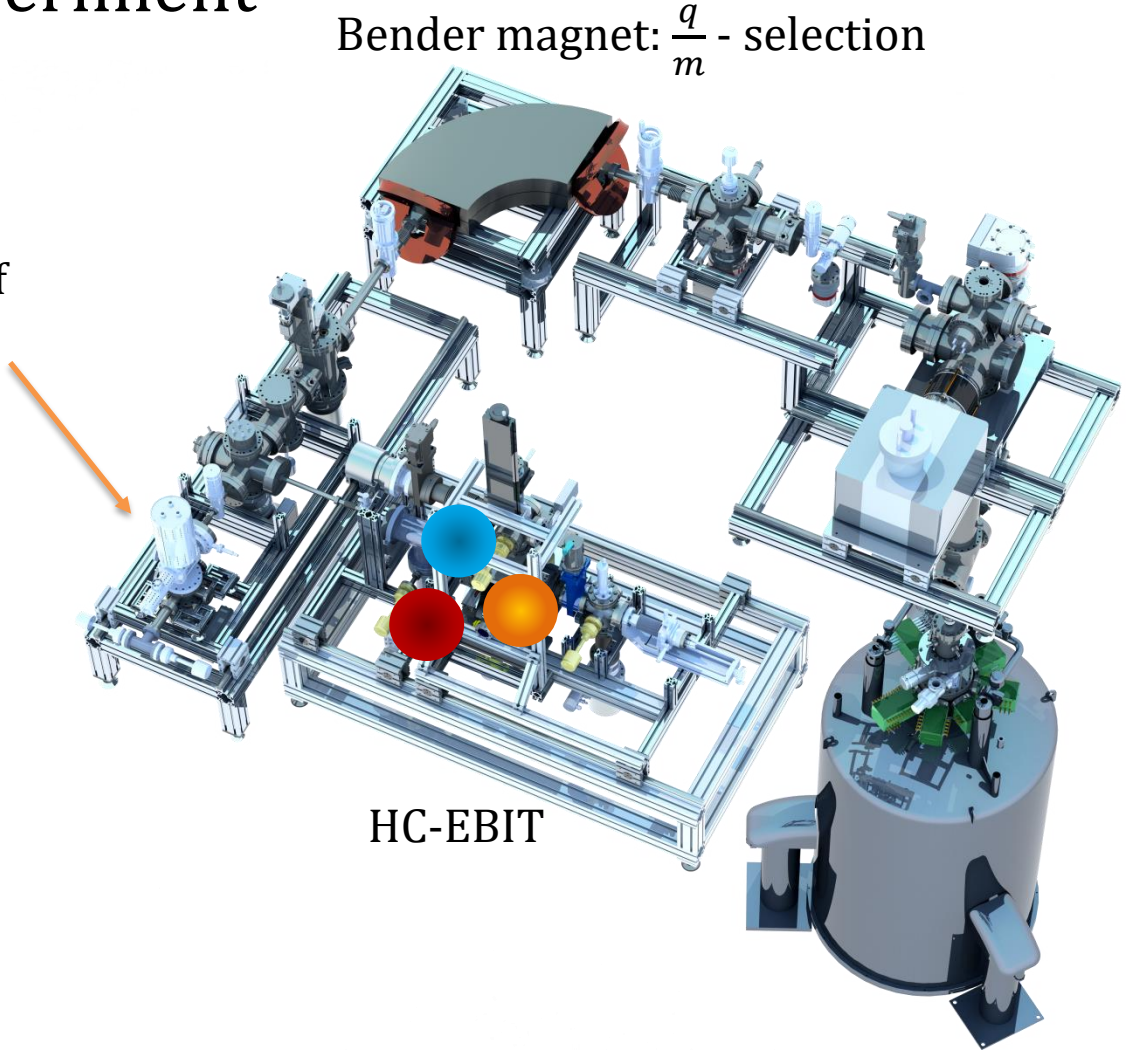
- Only one laser spot position
- Laser pulse energy not increased

Schweiger, Ch. et al., *RSI 90*, 123201 (2019)

The PENTATRAP experiment

Available **HCI sources**:

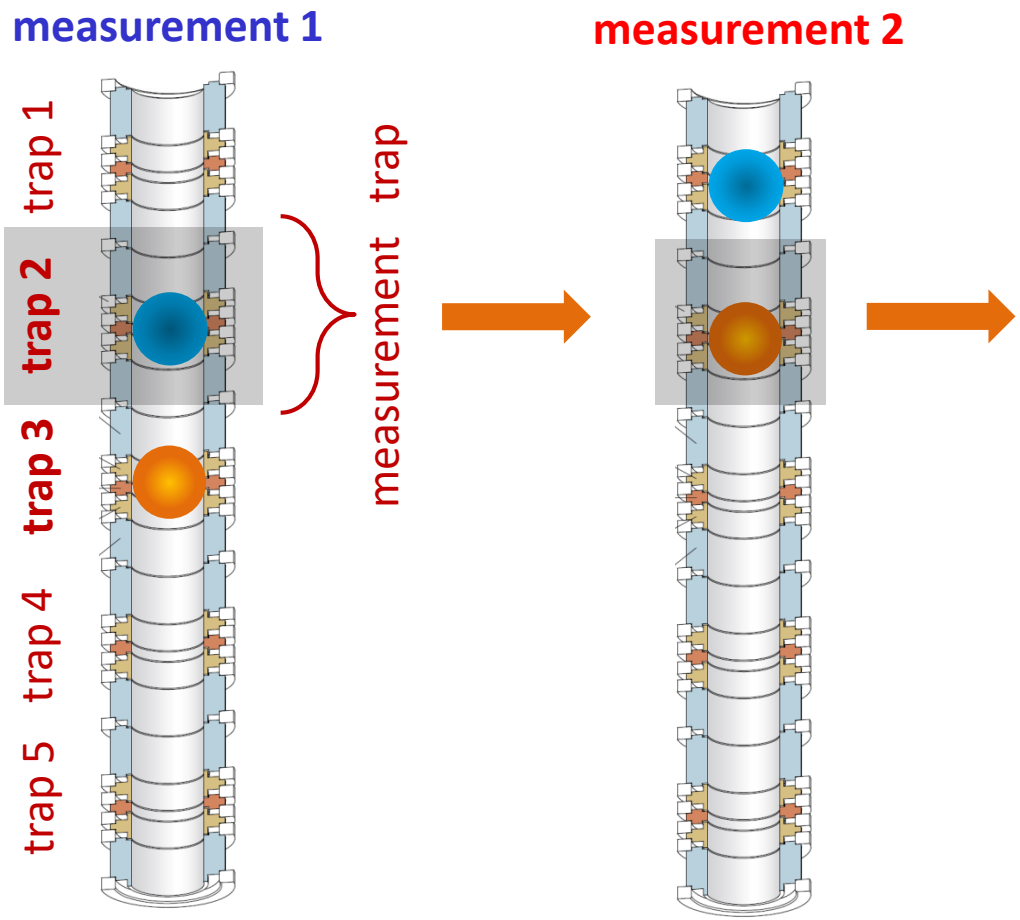
- **Dresden EBIT**: Injection of volatile compounds or gas injection
- In-trap laser desorption **HC-EBIT** for ^{163}Ho and other rare species
- **HD super-EBIT**: Highly charged ions up to Pb^{82+}

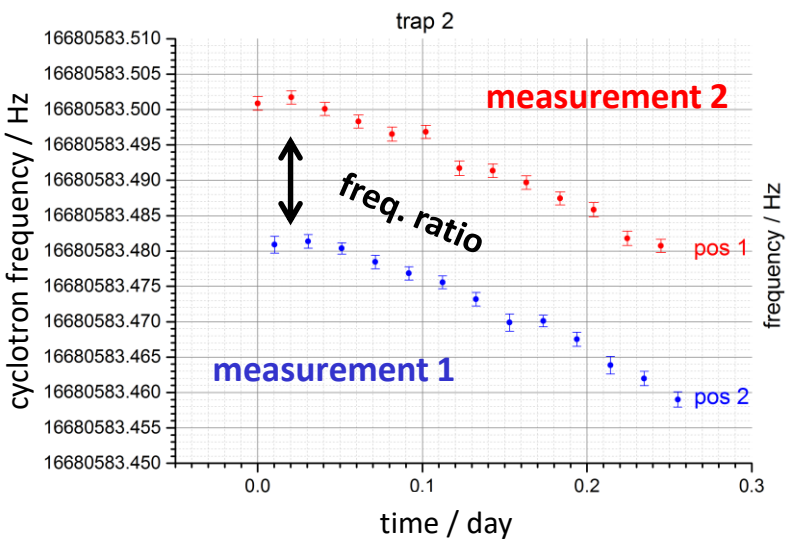


Measurement schemes with five traps – single trap

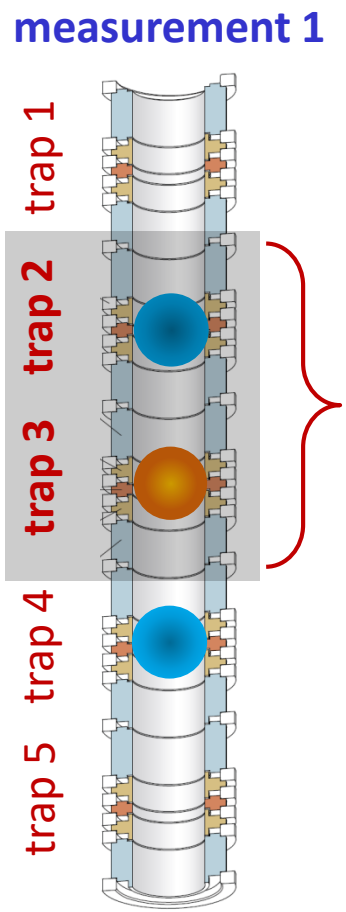
$$\omega_c = \frac{q}{m} B$$

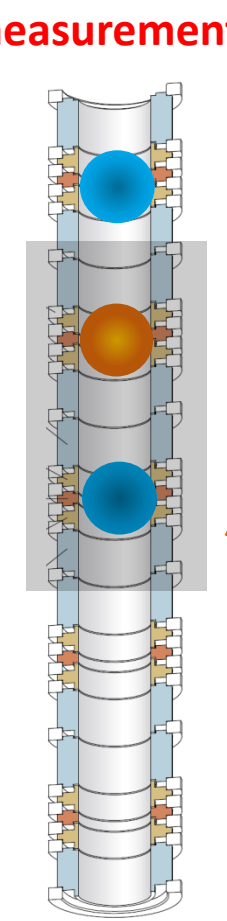
Magnetic field has to be measured as well!
-> Mass-ratio measurements

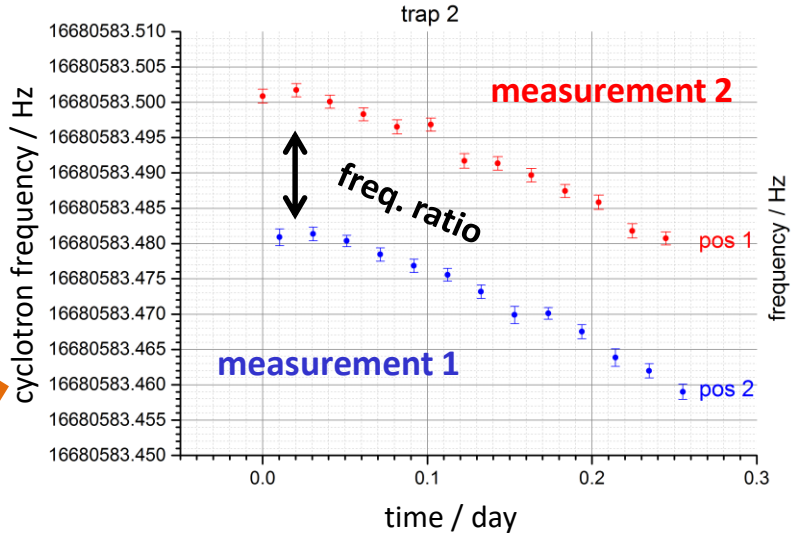


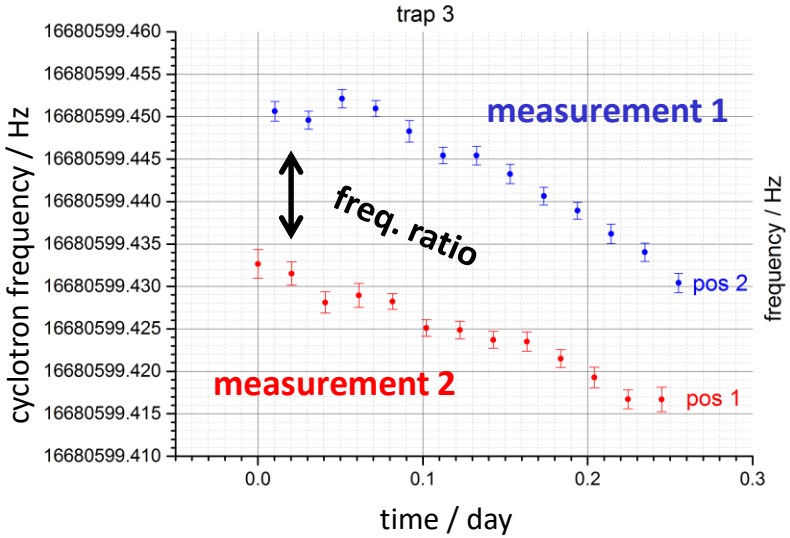


Measurement schemes with five traps – double trap

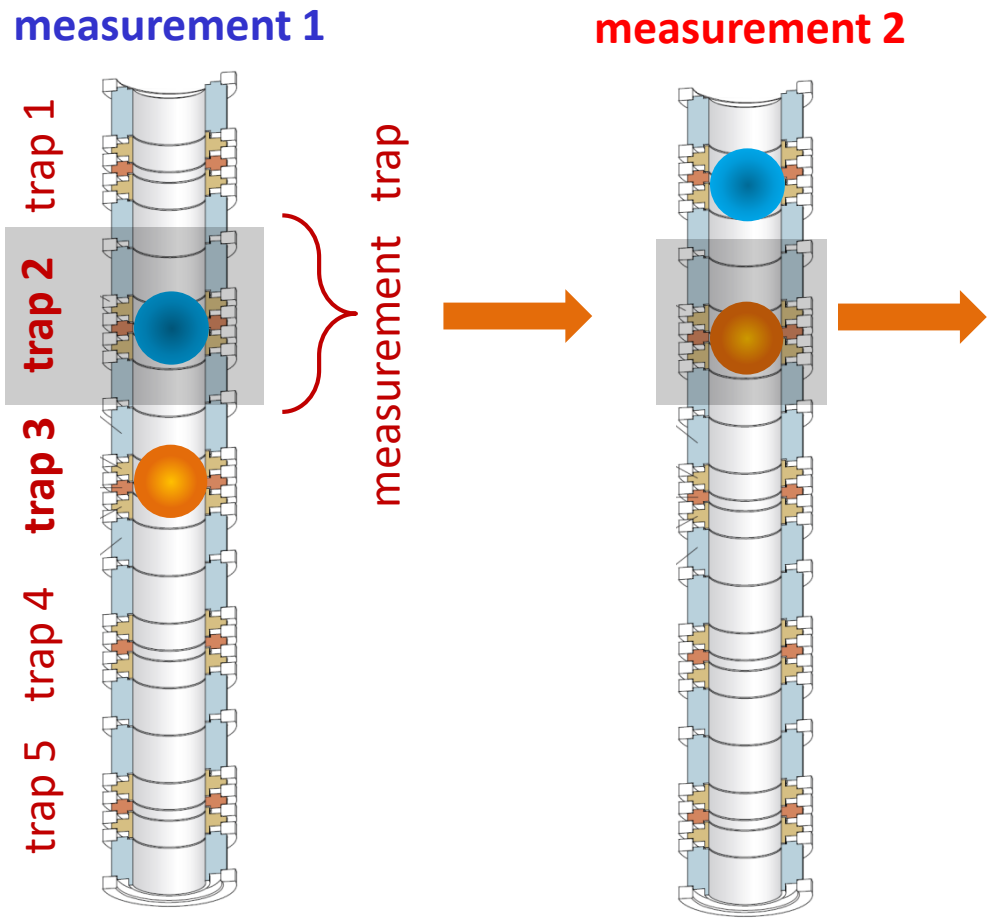


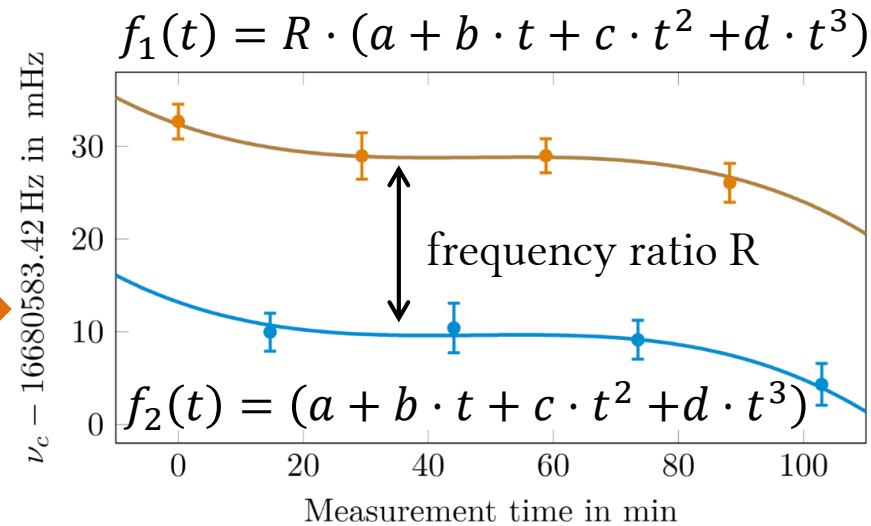






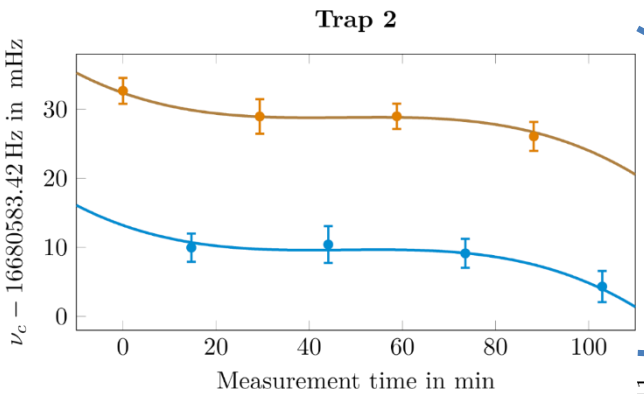
Data analysis: polynomial fit

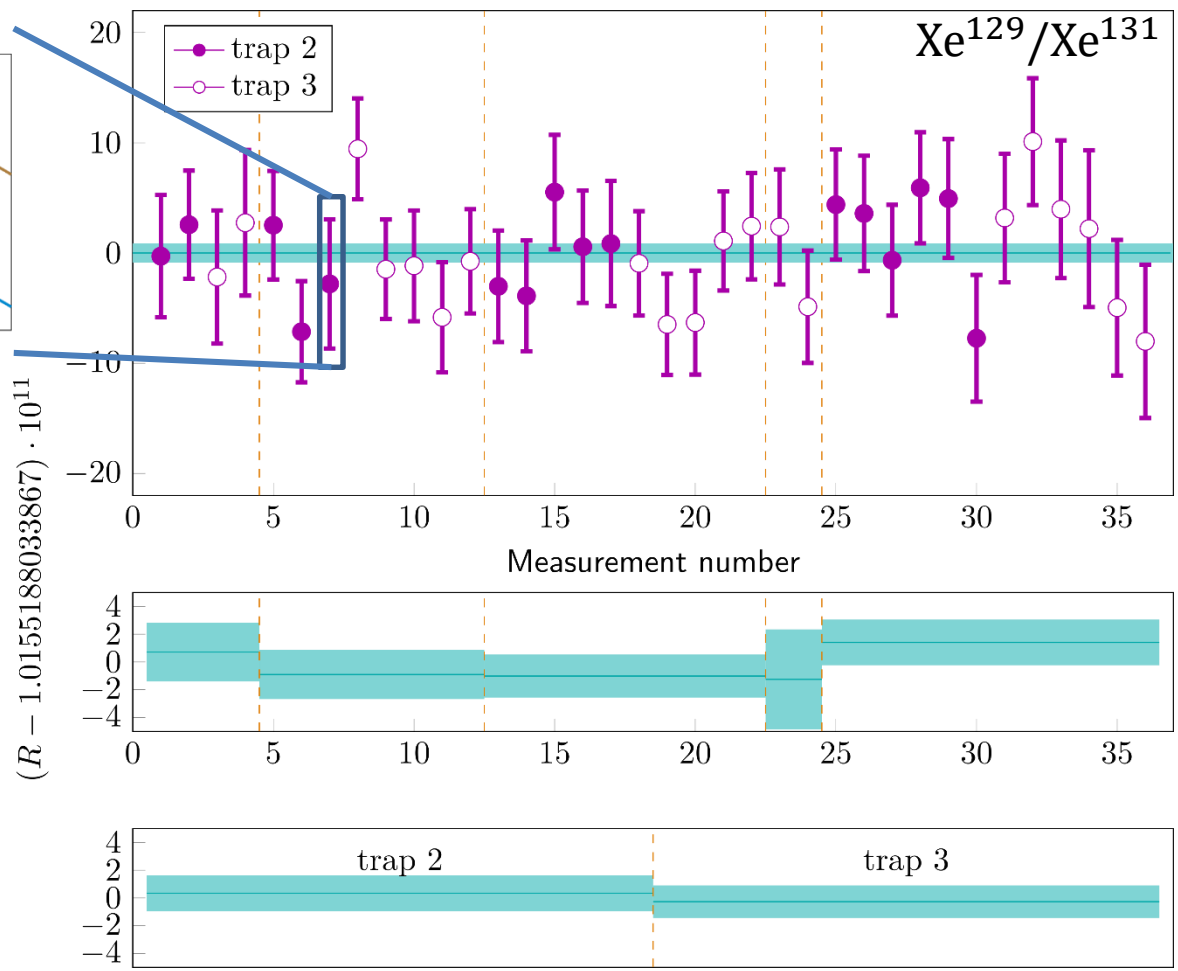




- Grouping of the data (4-5 data points per group)
- Simultaneous low order polynomial fit with the ratio as parameter

Data analysis: polynomial fit





R. Schüssler, PhD thesis (2019)

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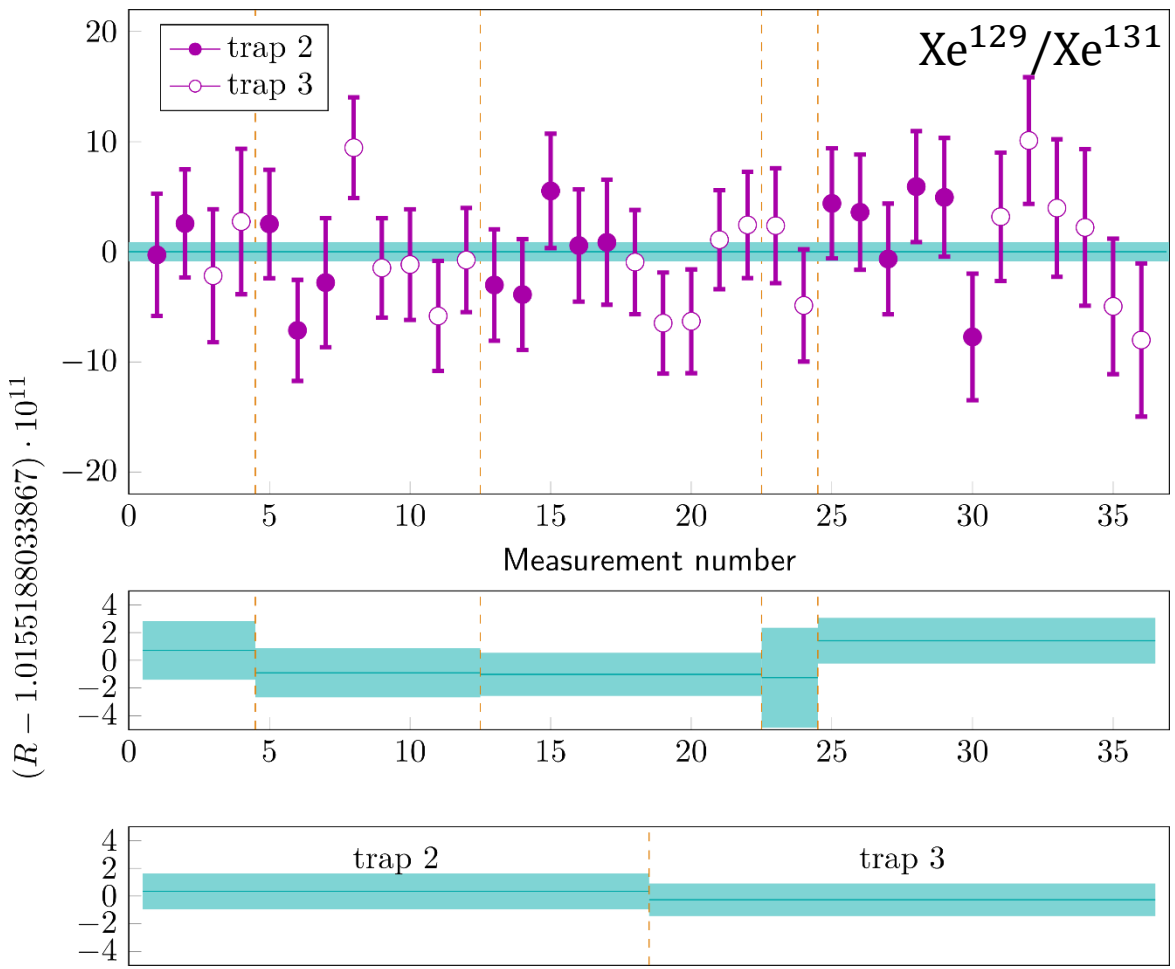


Ratios for different measurement runs with all ratios combined (blue)

$$\frac{\delta R}{R} = 1 \cdot 10^{-11}$$

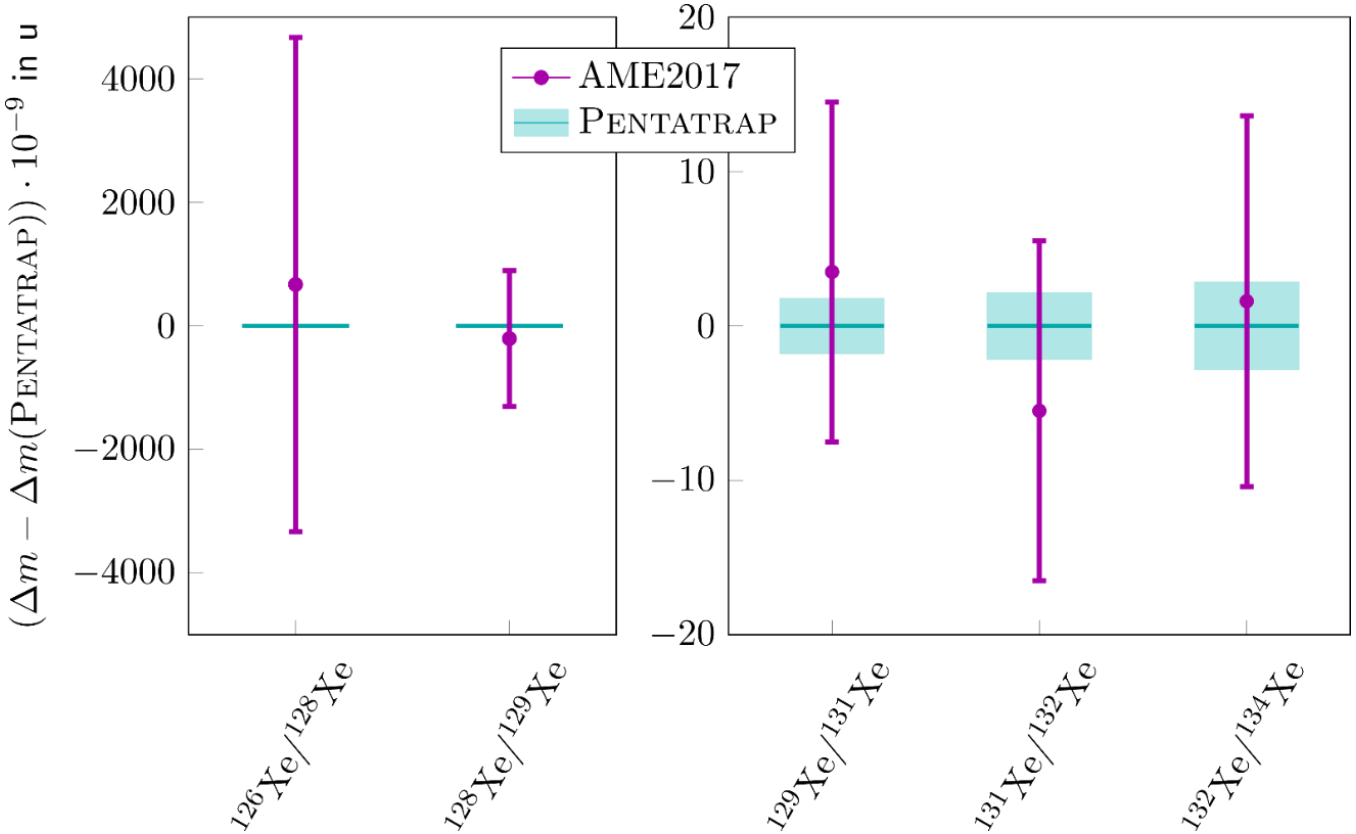
Ratios for each measurement run

Ratios for both traps

R. Schüssler, PhD thesis (2019)

Masses of xenon isotopes

Successful commissioning of PENTATRAP



Improvement by a factor of 1500/600

Improvement by a factor of at least 4

R. Schüssler, PhD thesis (2019)

Long-lived excited state in $^{187}\mathrm{Re}^{29+}$ / $^{187}\mathrm{Os}^{30+}$

- Original plan: Q-value of the beta-decay of ^{187}Re:

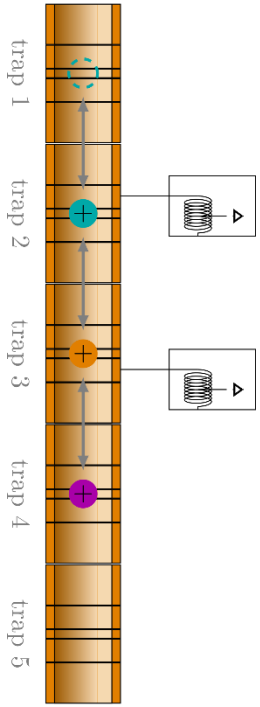
$$\underbrace{^{187}\mathrm{Re} \rightarrow \quad ^{187}\mathrm{Os}}_{\text{Q-value}} + \nu_e + e^-$$

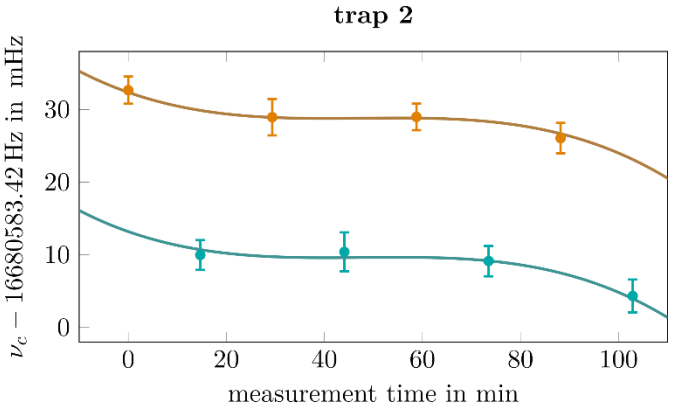
$$Q = M(^{187}\mathrm{Re})\text{-}M(^{187}\mathrm{Os}) = M(^{187}\mathrm{Re}^{29+})\text{–}M(^{187}\mathrm{Os}^{29+})\text{+}\Delta B$$

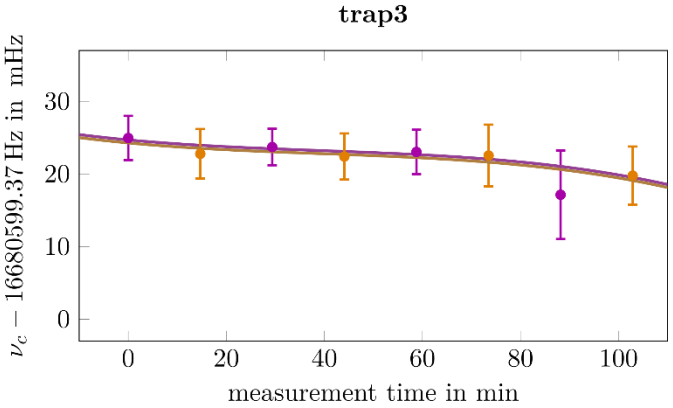
$$= M(^{187}\mathrm{Os}^{29+}) \cdot \ [R - 1] \text{+}\Delta B$$

Long-lived excited state in $^{187}Re^{29+}$ / $^{187}Os^{30+}$

- Original plan: Q-value of the beta-decay of ^{187}Re
- Consistently two ratios were found, difference $\sim 10^{-9}$ corresponding to $\sim$ 200 eV
- Measurement of „unity“ to investigate possible reasons: $^{187}Re^{29+}/^{187}Re^{29+}$







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- Consistently two ratios were found, difference $\sim 10^{-9}$ corresponding to $\sim$ 200 eV
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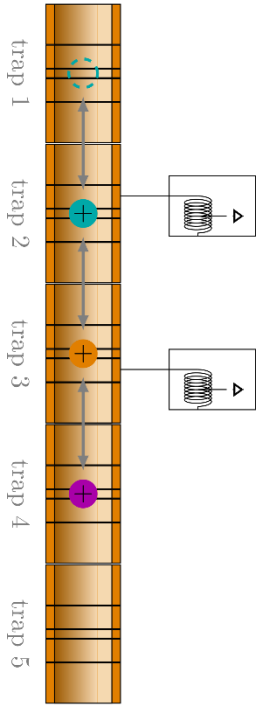
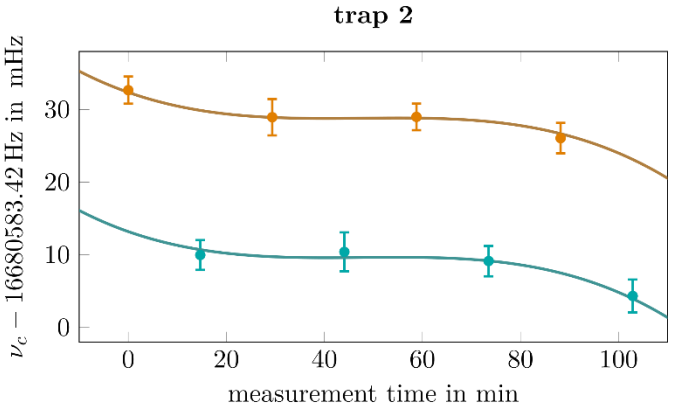
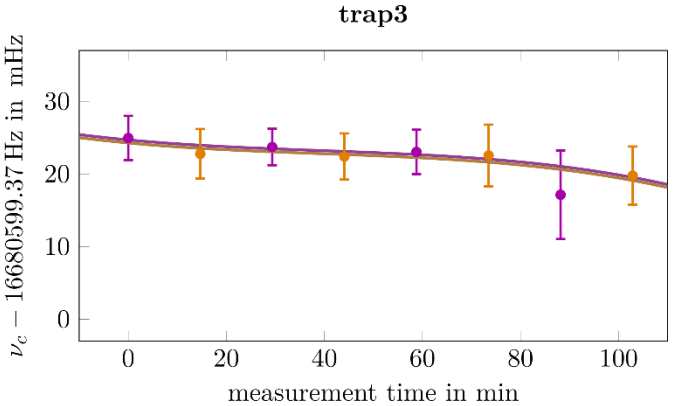
$\Rightarrow$ Very long-lived excited state in a highly charged ion (130 days lifetime)!

$\Rightarrow$ Confirmed by theory calculations







R. Schüssler, PhD thesis (2019)

Long-lived excited state in $^{187}Re^{29+}$ / $^{187}Os^{30+}$

- Long-lived excited state produced in the EBIT by electron impact excitation:

$$A^{q+} + e^- \rightarrow \left[A^{q+}\right]^* \rightarrow A^{q+} + e^- + h\nu$$

- Experimental and theoretical results agree very well:

$\Delta E^{\mathrm{Re}} = 202.2(1.6)$ eV

$\Delta E^{\mathrm{Os}} = 207(3)$ eV

$\Delta E^{\mathrm{DFT,\,Re}} = 203.95(0.35)$ eV

$\Delta E^{\mathrm{MCDF,\,Re}} = 202.1(2.7)$ eV

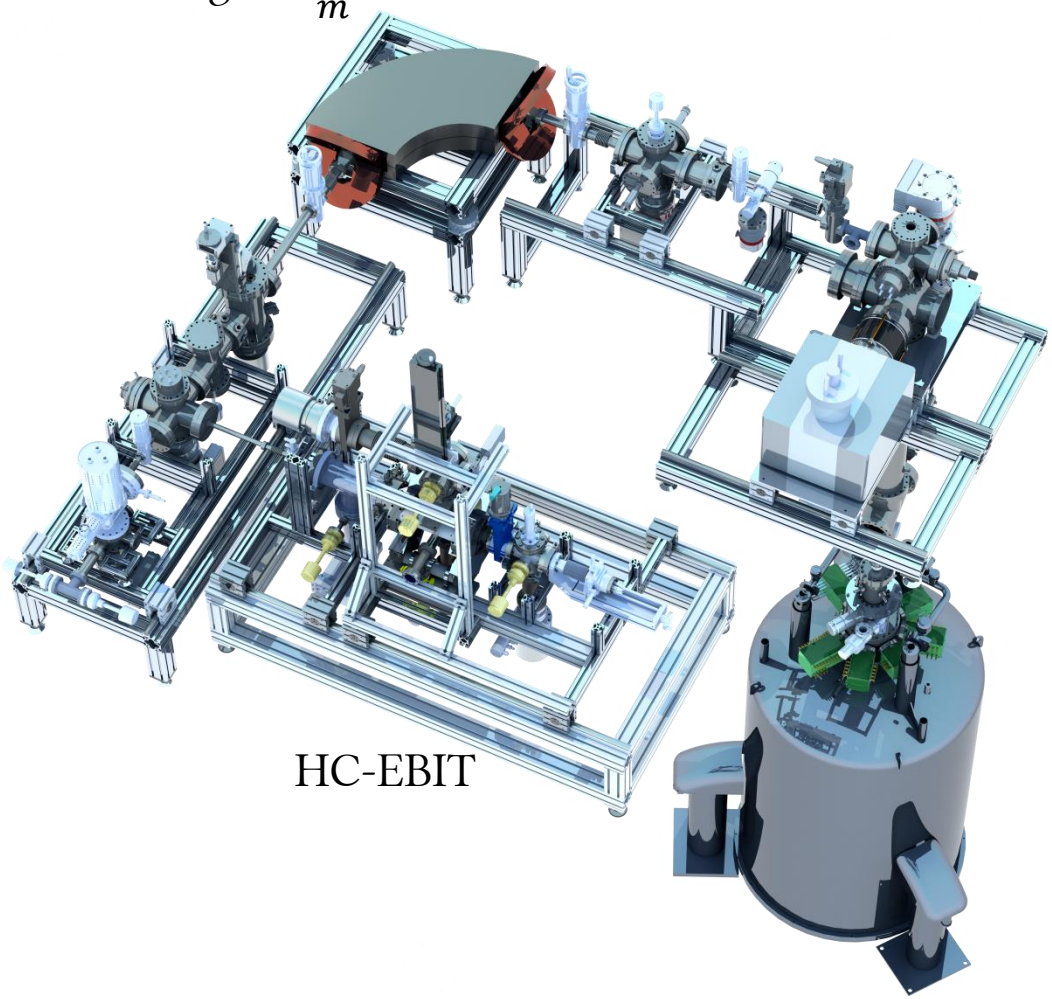
$\Delta E^{\mathrm{FAC,\,Re}} = 203.9$ eV

- First directly measured long-lived excited state in HCI found by PTMS
- Not accessible by narrow-linewidth laser spectroscopy
- Can provide experimental data to benchmark theory
- Finding clock transitions in HCI (few eV-regime)

R. Schüssler, PhD thesis (2019)

Current work on ^{163}Ho

Bender magnet: $\frac{q}{m}$ - selection



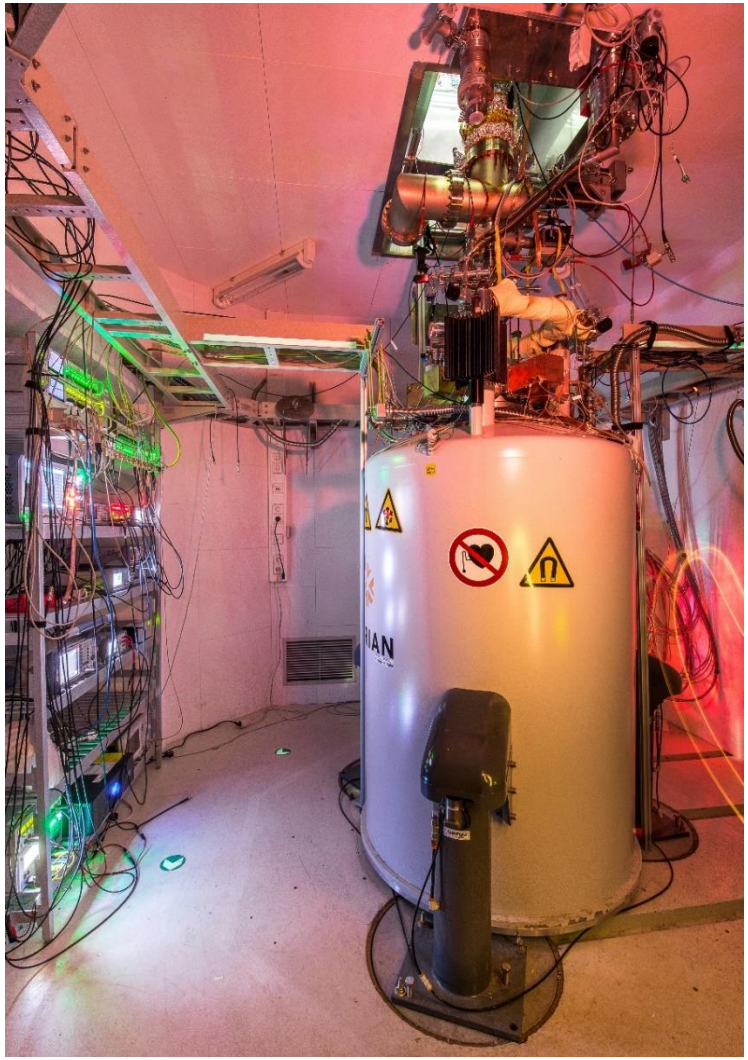
- Optimization of the beamline using 163-dysprosium
- Testing small samples of Dy
- Final measurement of the Ho/Dy electron capture Q-value

Summary & outlook

- Successful commissioning of PENTATRAP using HCI of xenon
- Long-lived excited state in HCI of Re

CURRENT AIMS:

- Measurement of Q_{EC} of the electron capture decay in ^{163}Ho



Thanks to

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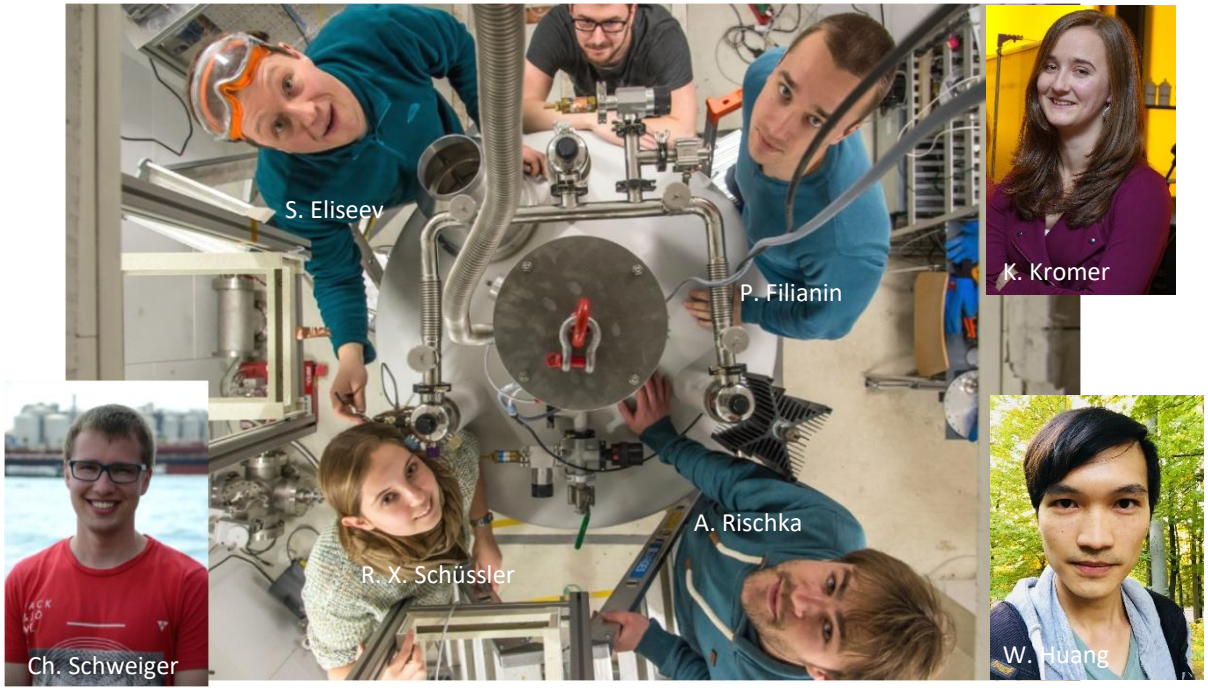

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and you, for your attention!