Direct high-precision determination of the electron capture Q-value in ^{163}Ho

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ISOLDE workshop and users meeting 2022

MAX-PLANCK-GESELLSCHAFT

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL PTFS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

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The electron neutrino mass

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

- **SM**: neutrinos are massless neutral fermions
- Experimental observation of neutrino flavour oscillations requires finite m_ν

Current best upper limits on m_{ν_e}:

Cosmology	0.12 eV/c^2 (95 % C.L.)
KATRIN ($\bar{\nu}_e$)	0.8 eV/c^2 (90 % C.L.)
ECHo (ν_e)	150 eV/c^2 (95 % C.L.)

Aghanim, N. et al., *A&A 641*, A6 (2020)
Aker, M. et al., Nat. Phys. 18, 160 (2022)
Gastaldo, L. et al., *EPJ 226*, 1623 (2017)
Velte, C. et al., *EPJ 79*, 1026 (2019)

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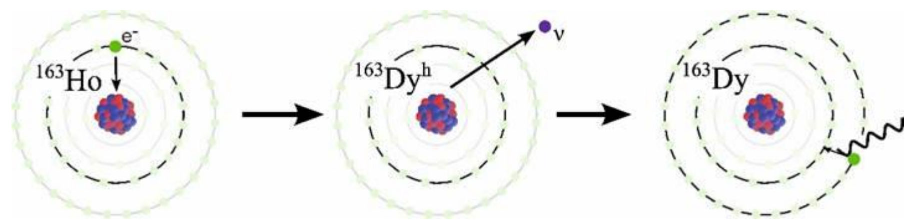
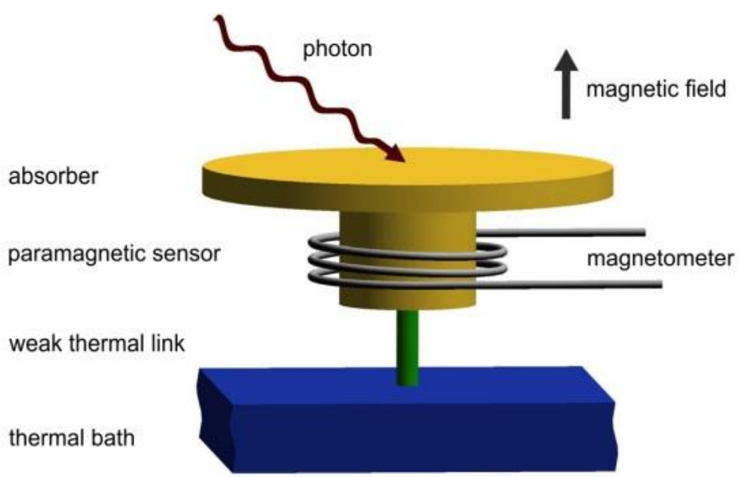


$$^{163}\mathrm{Ho} + e^- \longrightarrow {}^{163}\mathrm{Dy}^\star + \nu_e \longrightarrow {}^{163}\mathrm{Dy} + \nu_e + Q_{EC}$$



- Metallic magnetic calorimeters (MMCs) in a cryostat at 50 mK
- Energy resolution: ~ 1.6 eV @ 6 keV
- ^{163}Ho implanted directly in the absorber

Aghanim, N. et al., *A&A 641*, A6 (2020)
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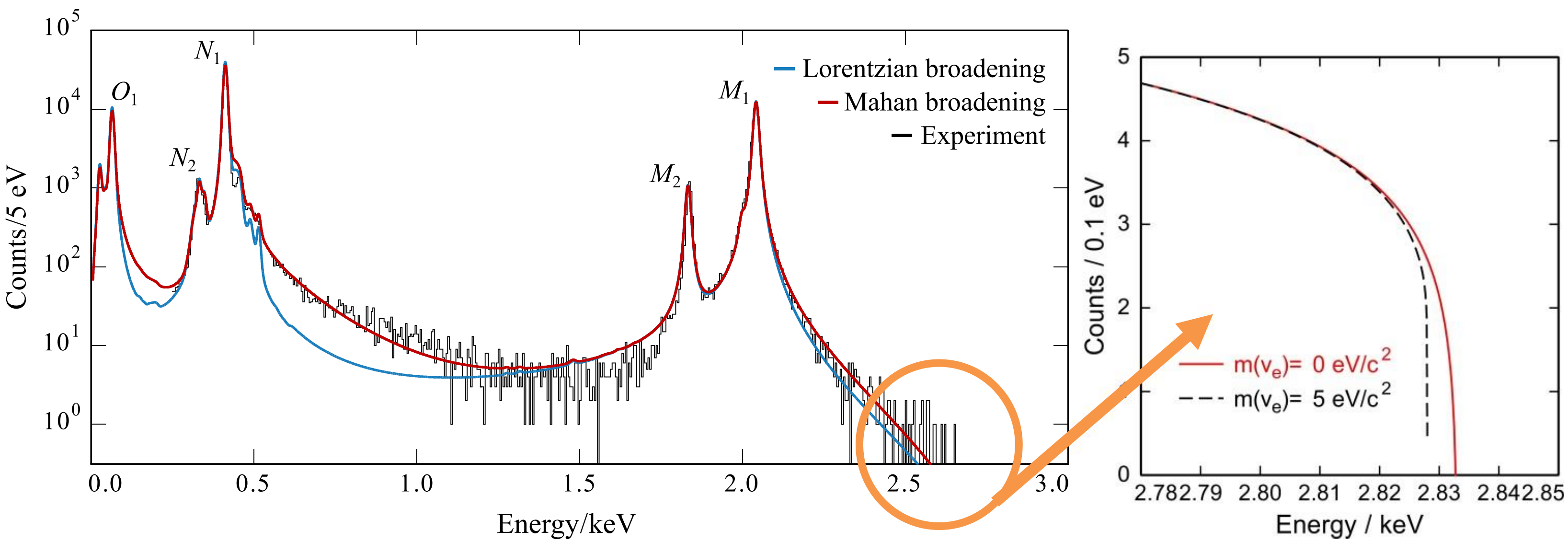

From fitting a theoretical spectrum:

- Electron neutrino mass
- Q-value of the transition

Gastaldo, L. et al., *EPJ 226*, 1623 (2017)
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The electron neutrino mass

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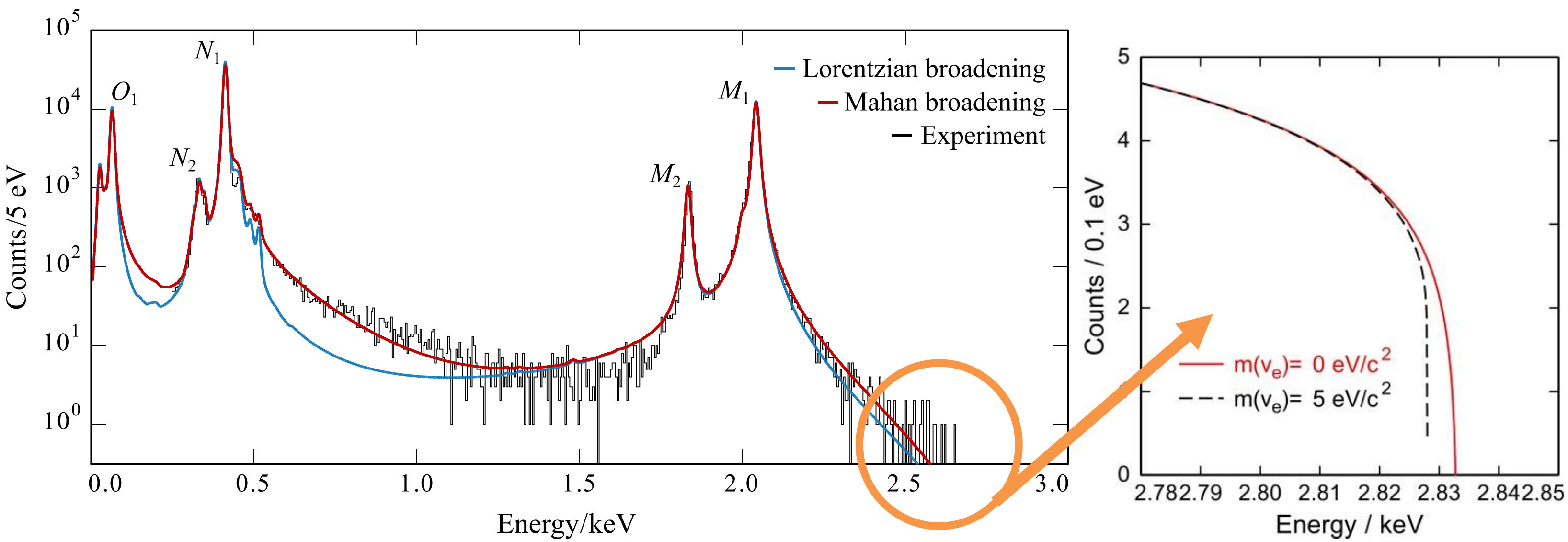


Check for systematic uncertainties:

From fitting a theoretical spectrum:

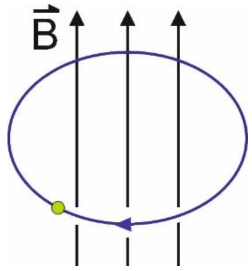
- Electron neutrino mass
- Q-value of the transition

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

High-precision Penning-trap mass spectrometry

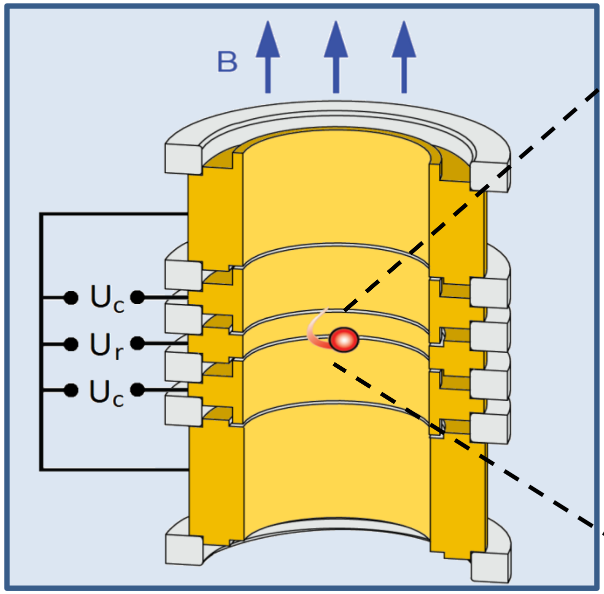
Gastaldo, L. et al., *EPJ 226*, 1623 (2017)
Velte, C. et al., *EPJ 79*, 1026 (2019)

Penning-trap mass spectrometry (PTMS)



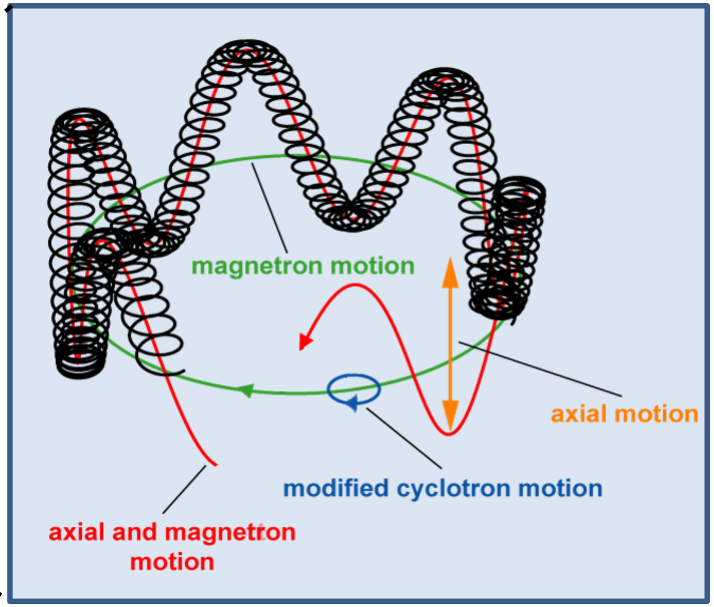
Free-space **cyclotron frequency**

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



Invariance theorem:

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



Three independent eigenmotions:

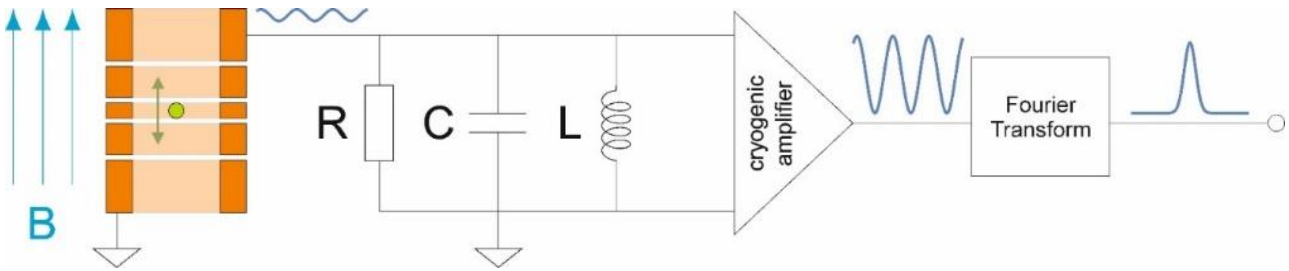
Modified cyclotron motion (ω_+)

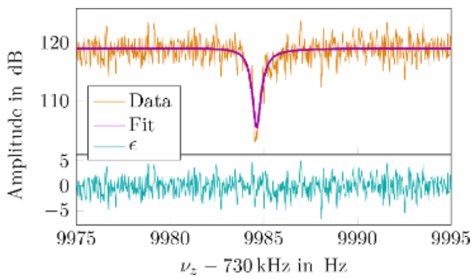
Axial motion (ω_z)

Magnetron motion (ω_-)

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

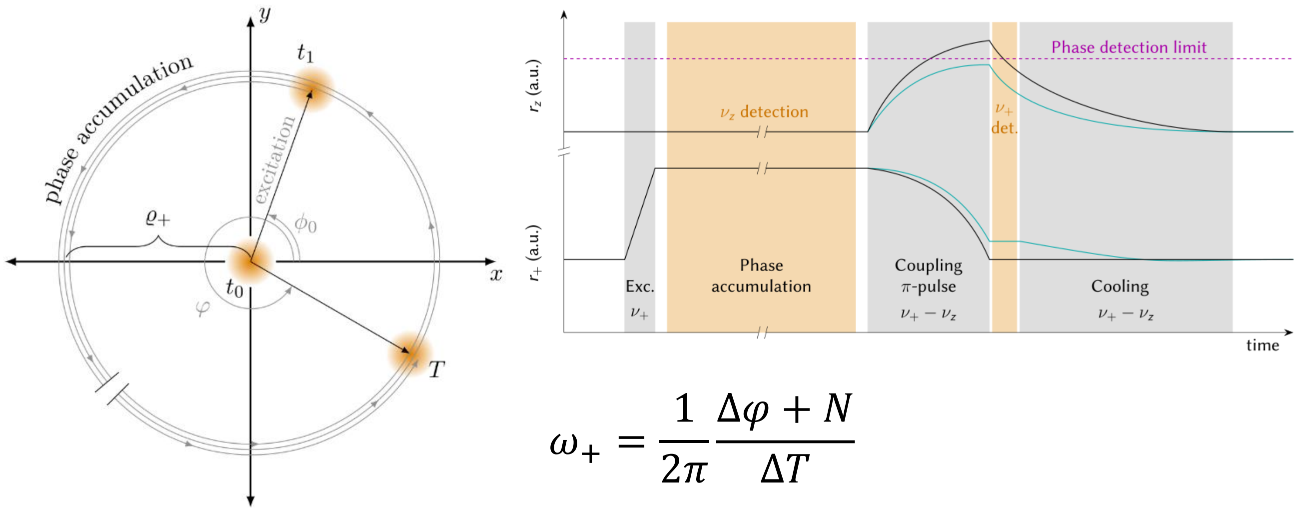
Eigenfrequency measuresment (FT-ICR)



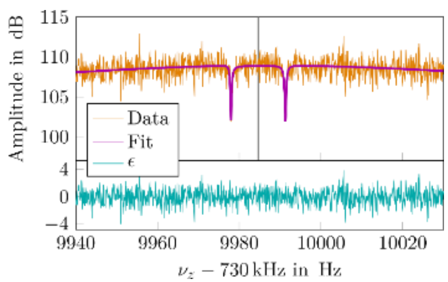


Direct measurement of ω_z by dip method

ω_+ Pulse and Phase (PnP) - method



$$\omega_+ = \frac{1}{2\pi}\frac{\Delta\varphi + N}{\Delta T}$$



Sideband – coupling of ω_- to ω_z

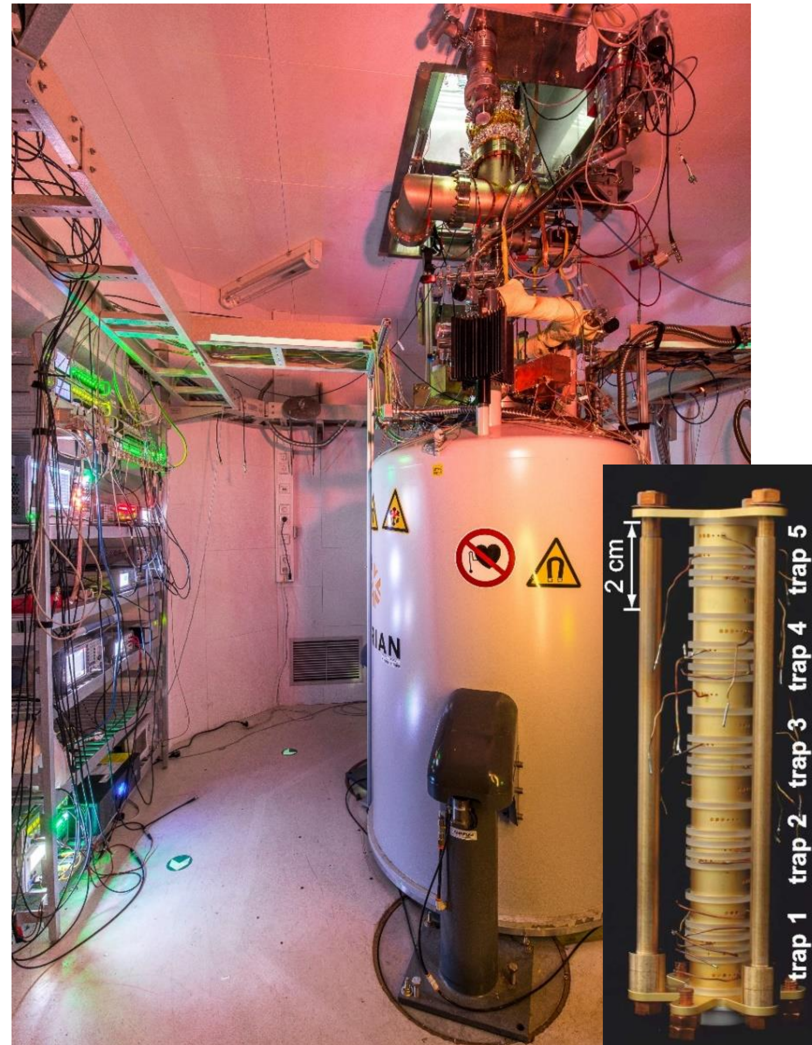
Sturm, S. et al., *PRL 107*, 143003 (2011)
Schüssler R., PhD thesis

Features of the PENTATRAP experiment

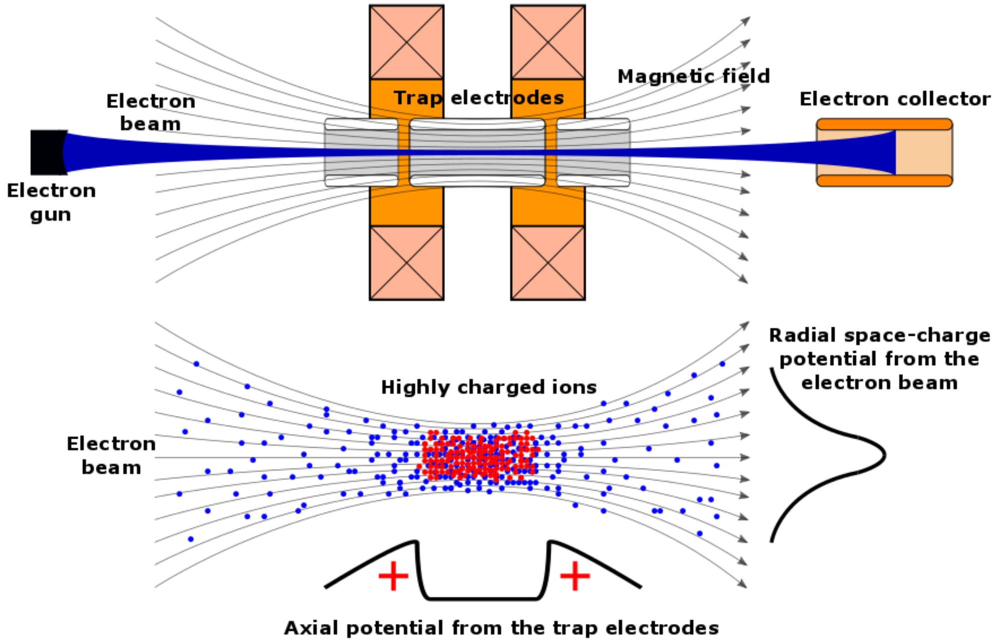
Mass-ratio measurements of stable and long-lived highly charged ions with a **fractional uncertainty below 10^{-11}**

Unique features

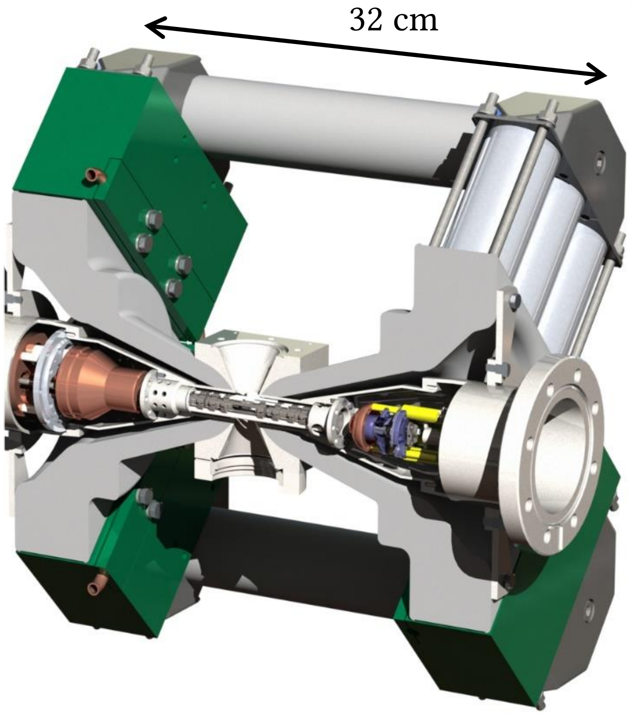
- Trap tower consisting of 5 cylindrical Penning traps
- Strong magnetic field (7 T)
- Pressure and level stabilization for the superconducting magnet
- Temperature stabilized lab (<0.05K/30 min)
- Non-destructive image-current detection and phase sensitive measurements
- Ultra stable voltage source StaReP
  Future: Josephson Junction voltage supply
- **Access to highly charged ions**



Heidelberg compact EBITs



72 NdFeB permanent magnets



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

Highly charged ions of ^{163}Ho

Challenge: ^{163}Ho is a synthetic radioisotope with a half life of ~4600 y

- Production by neutron irradiation of ^{162}Er and chemical separation
- Only small quantities available: 10^{16} atoms corresponding to 2.7 μg

Dorrer, H. et al., Radiochim. Acta 106, 535 (2018)

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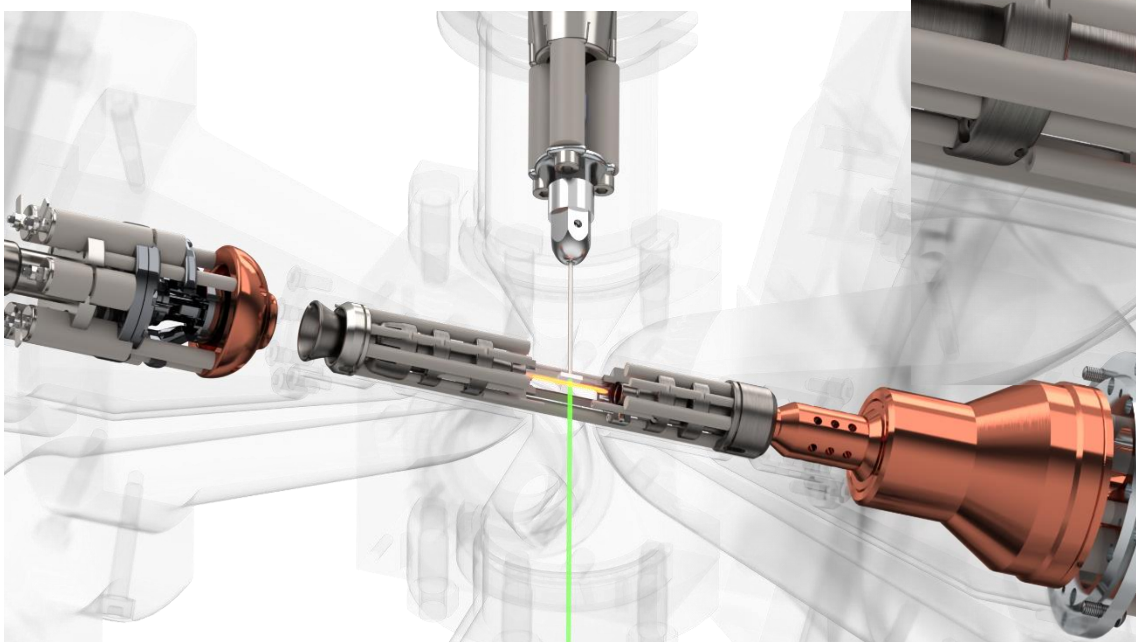
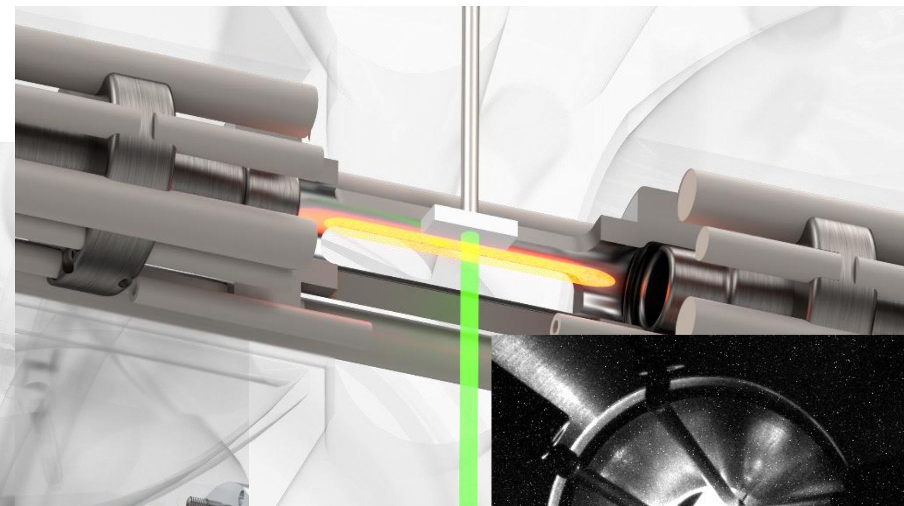
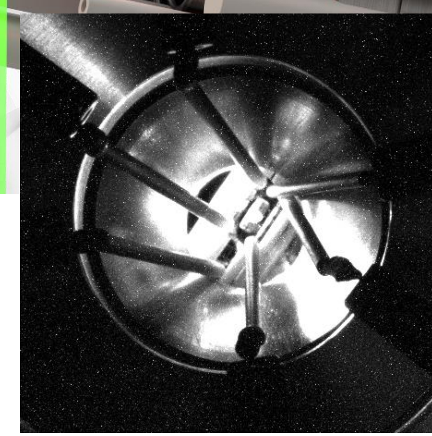
In-trap laser desorption technique





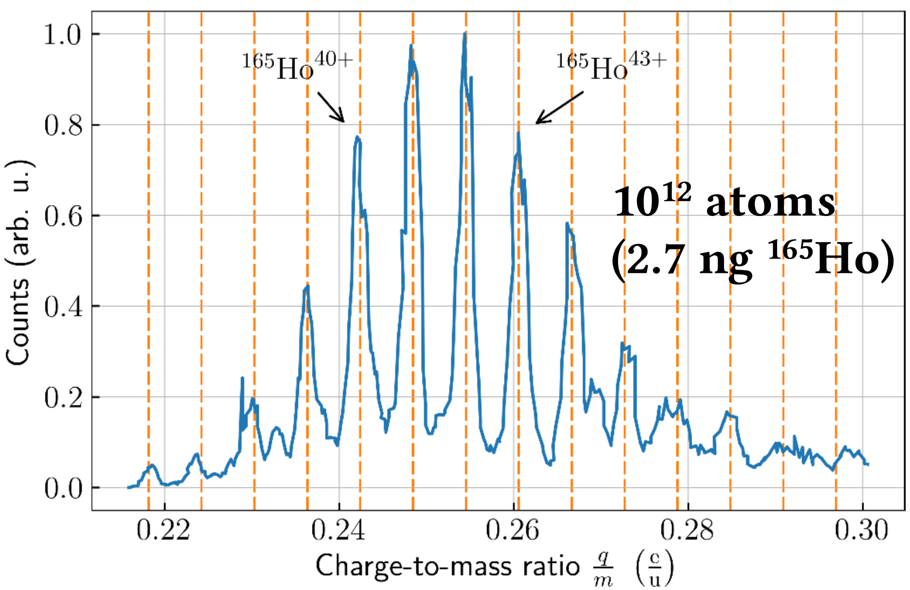


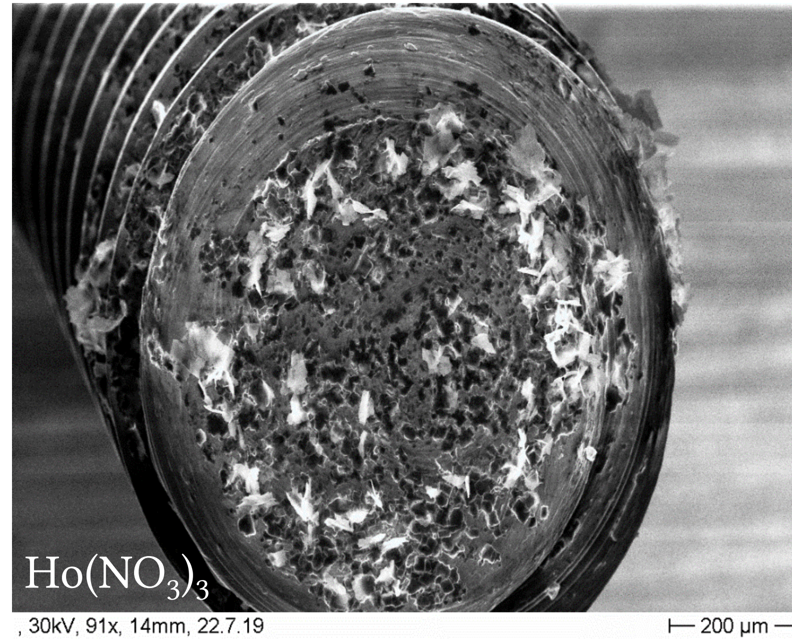
Dorrer, H. et al., Radiochim. Acta 106, 535 (2018)
Schweiger, Ch. et al., RSI 90, 123201 (2019)

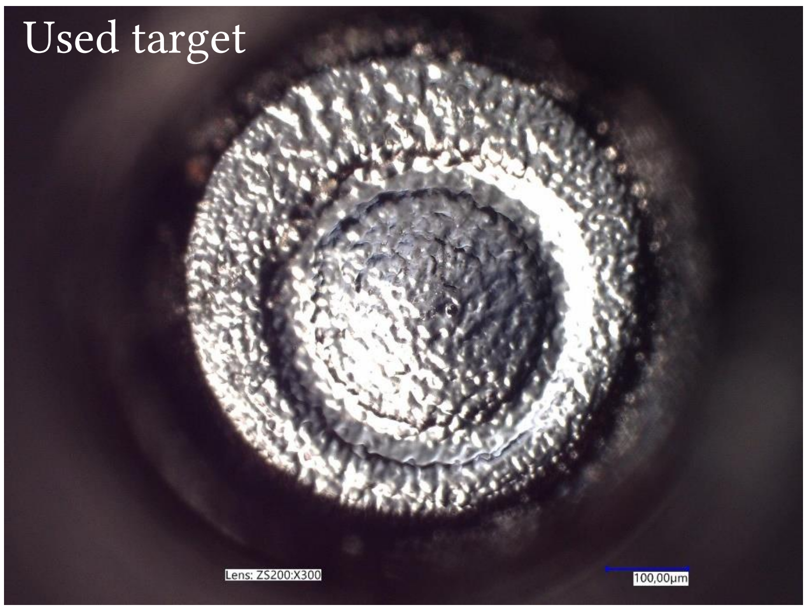
Small holmium targets

- 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)

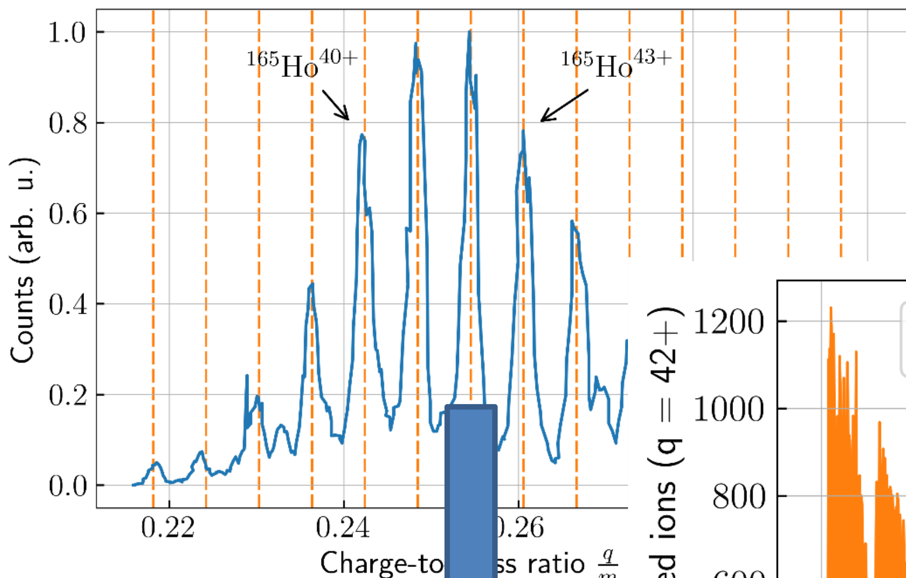




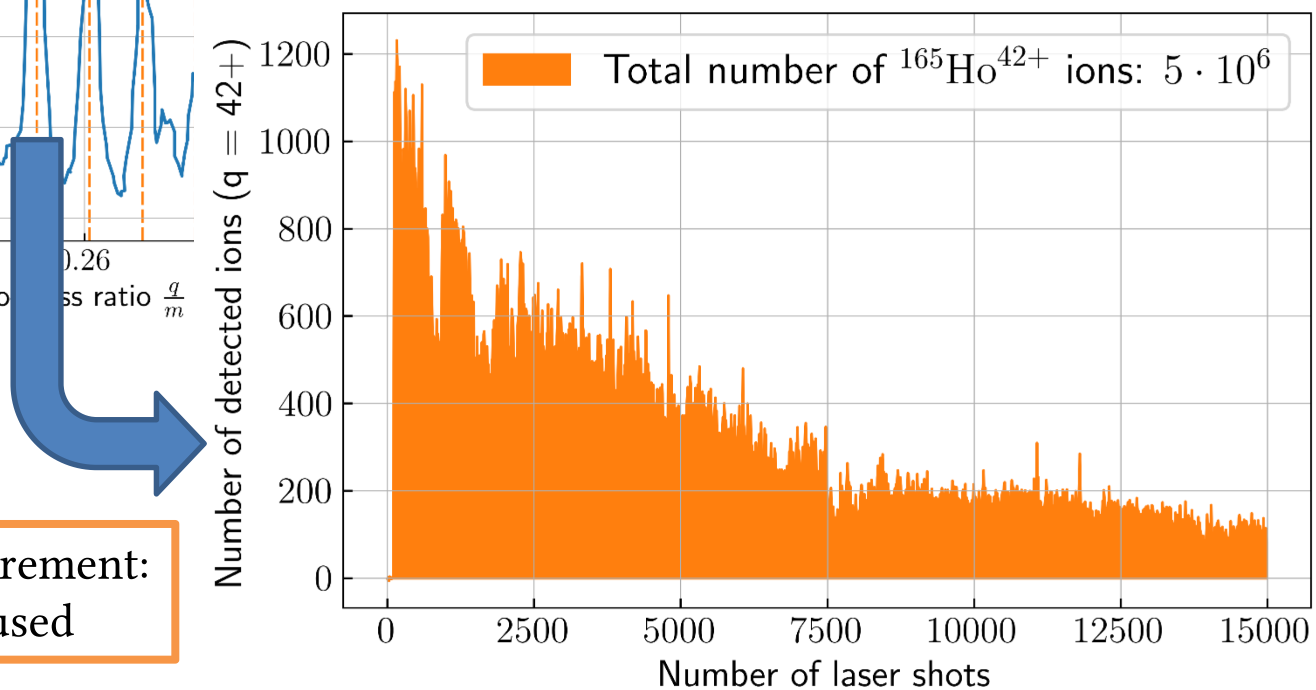


Schweiger, Ch. et al., RSI 90, 123201 (2019)
Haas, R. et al., NIM A 874, 43 (2017)

Small holmium targets



- Target with 10^{12} atoms
- At one laser spot position
- Laser pulse energy not increased

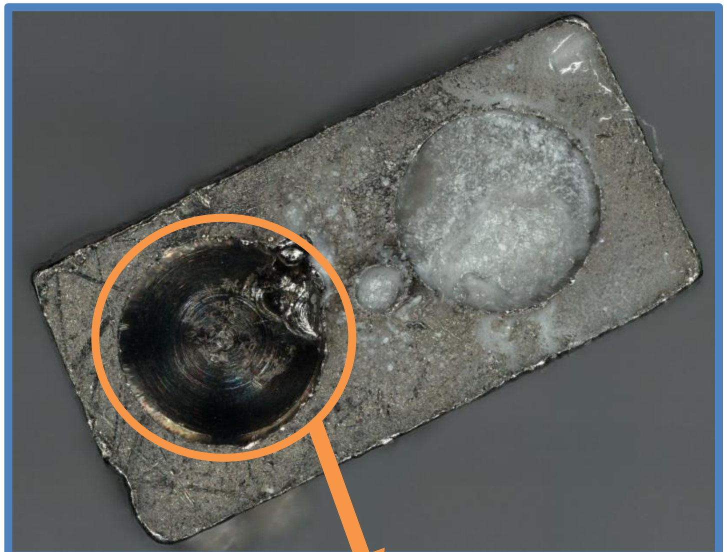


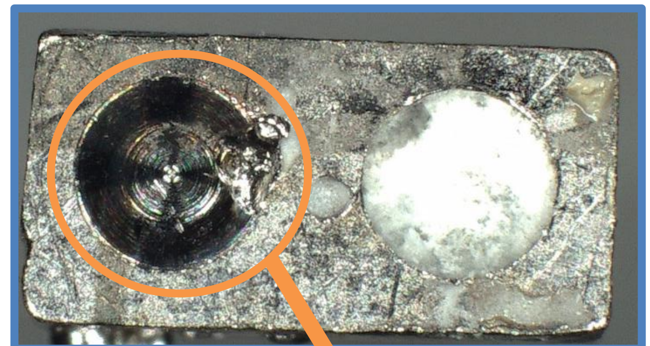
For the Q-value measurement:
2×10^{15} atoms of ^{163}Ho used

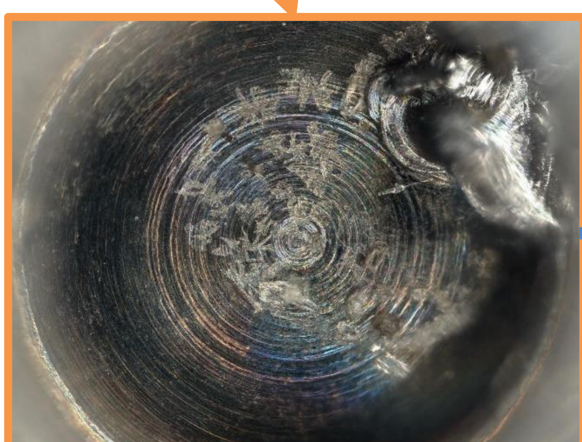
Schweiger, Ch. et al., *RSI 90*, 123201 (2019)
Haas, R. et al., *NIM A* 874, 43 (2017)

^{163}Ho/^{163}Dy targets

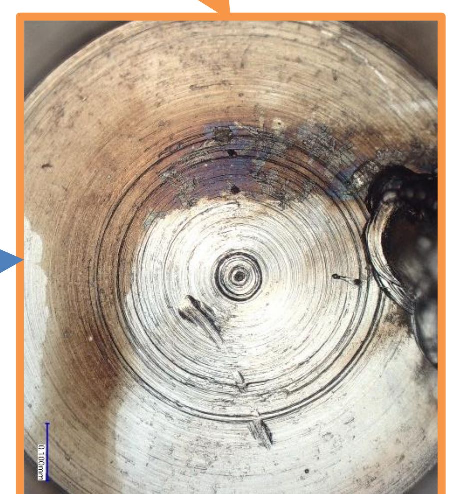
Target with 10^{14} atoms of ^{163}Ho corresponding to 27 ng/481 Bq



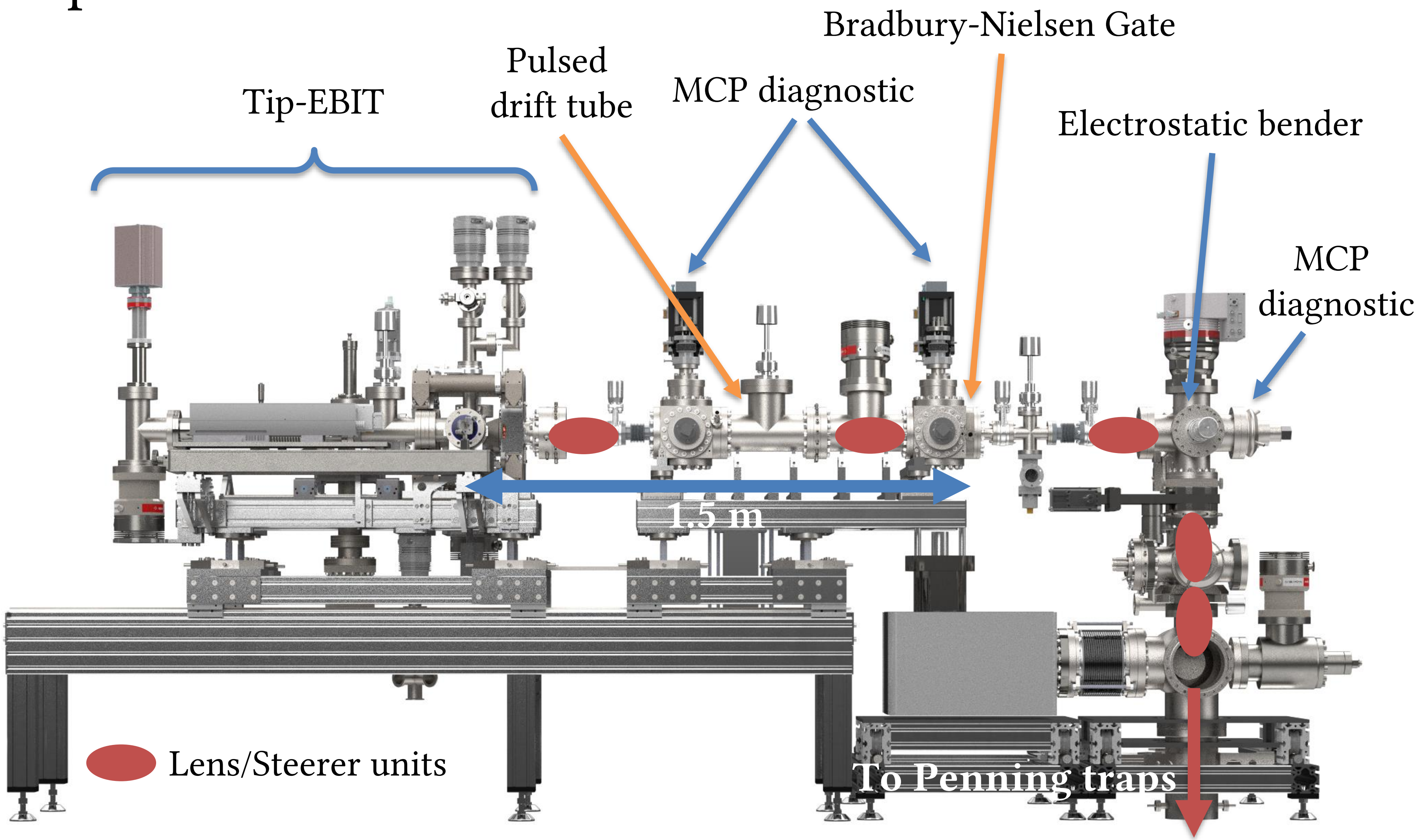




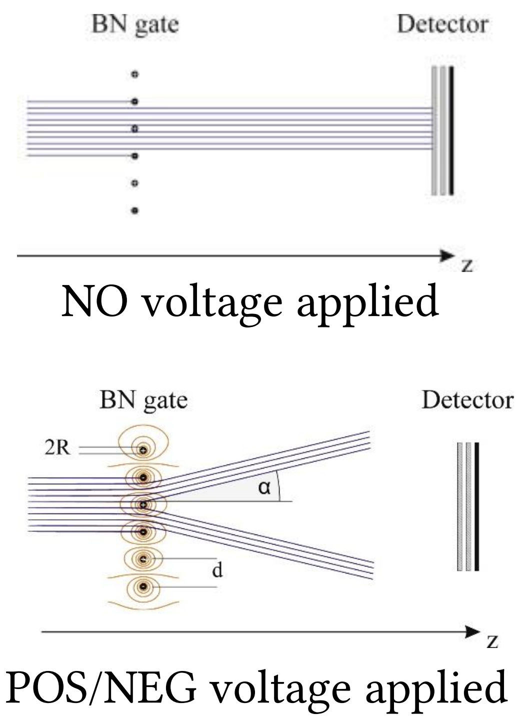
Laser desorption

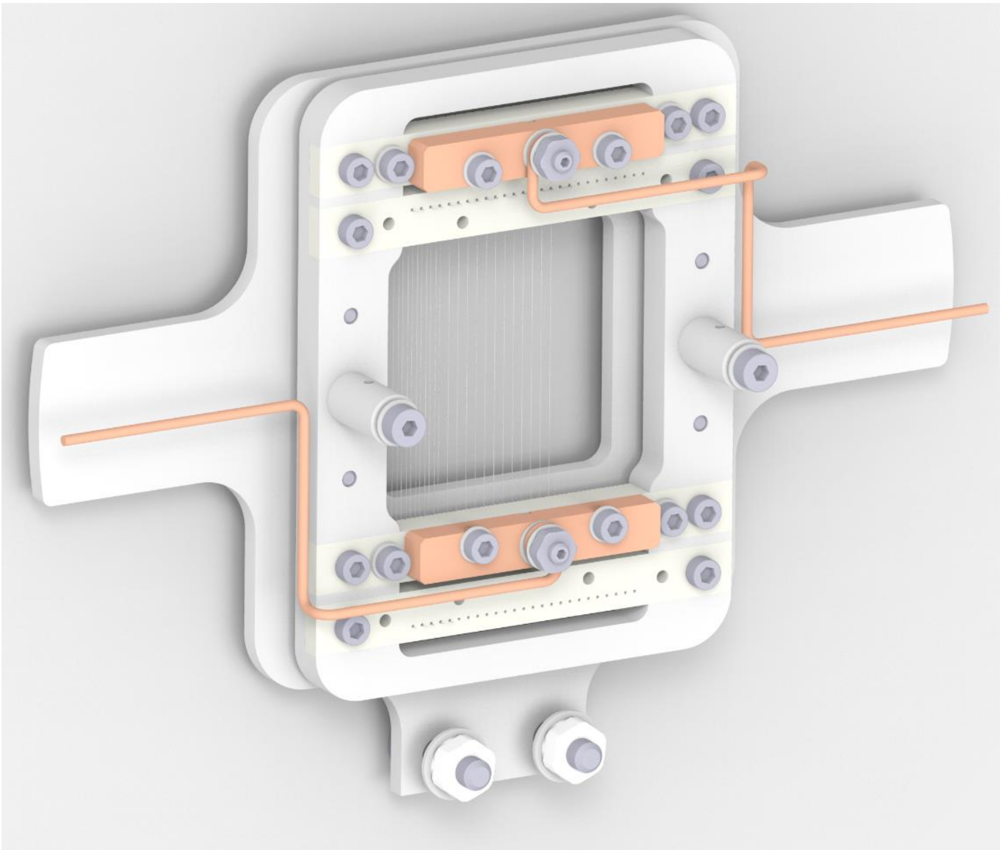


Tip-EBIT beamline



Bradbury-Nielsen Gate

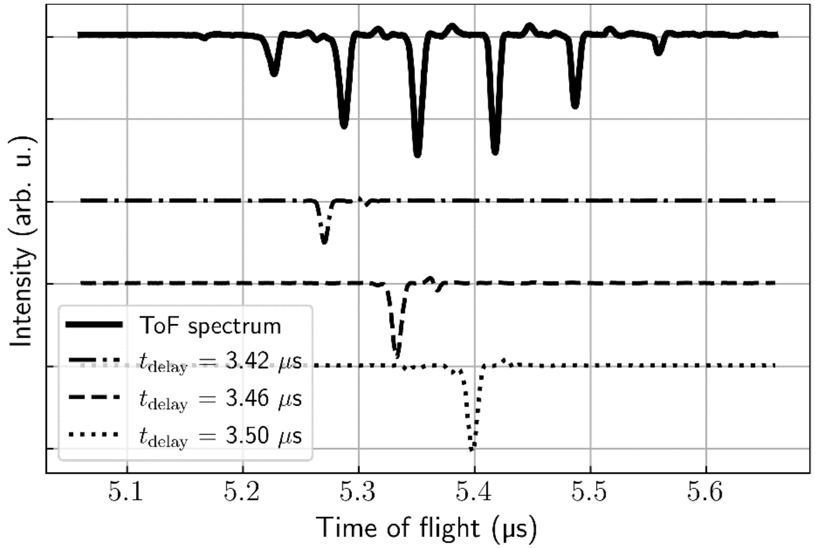


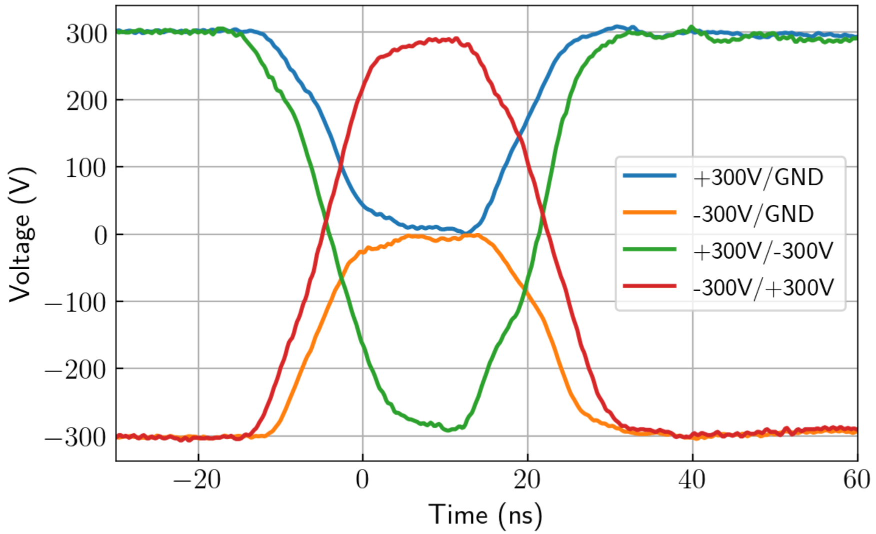


Wolf, R.N. et al., *NIMA 686, 82* (2012)
Brunner, T. et al., *IJMS 309*, 97 (2012)

Bradbury-Nielsen Gate performance

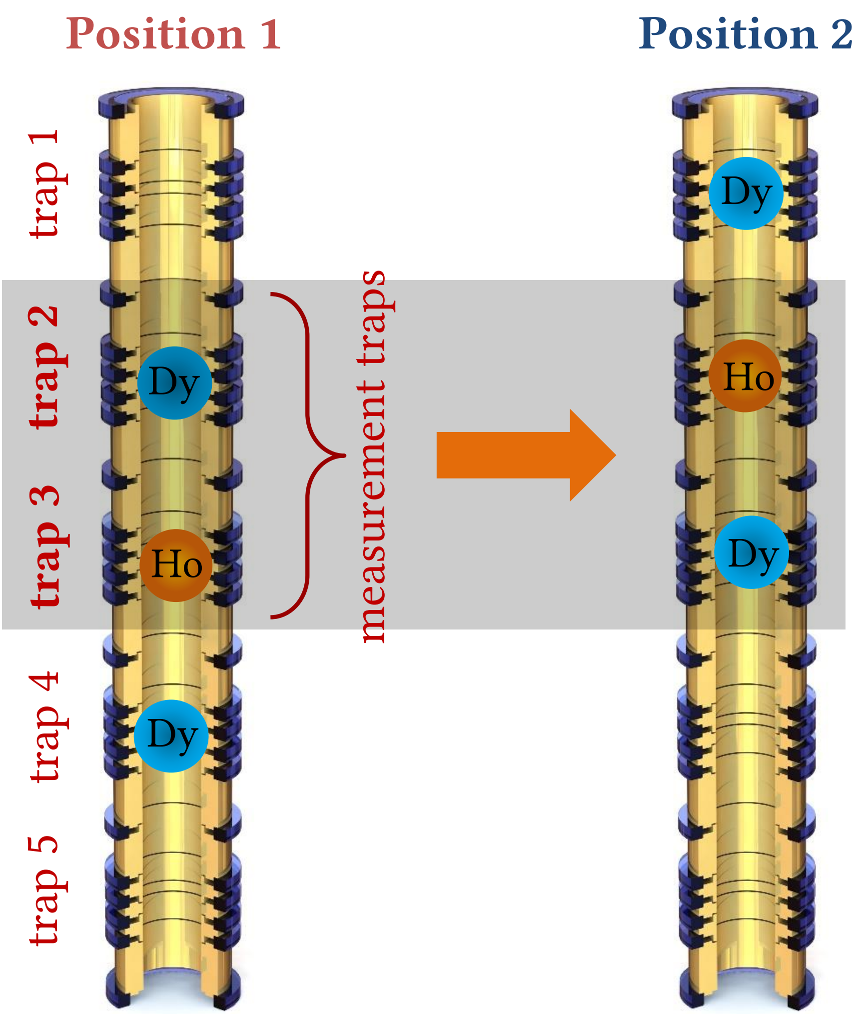
- Ion kinetic energy: ~ 4 keV/q
- Charge states ~70 ns separated in ToF





- Push-pull switch based on two N-channel power MOSFETs with gate drivers
- Pulse widths of ~20 ns and rise/fall times of ~10 ns

Measurement preparation and procedure



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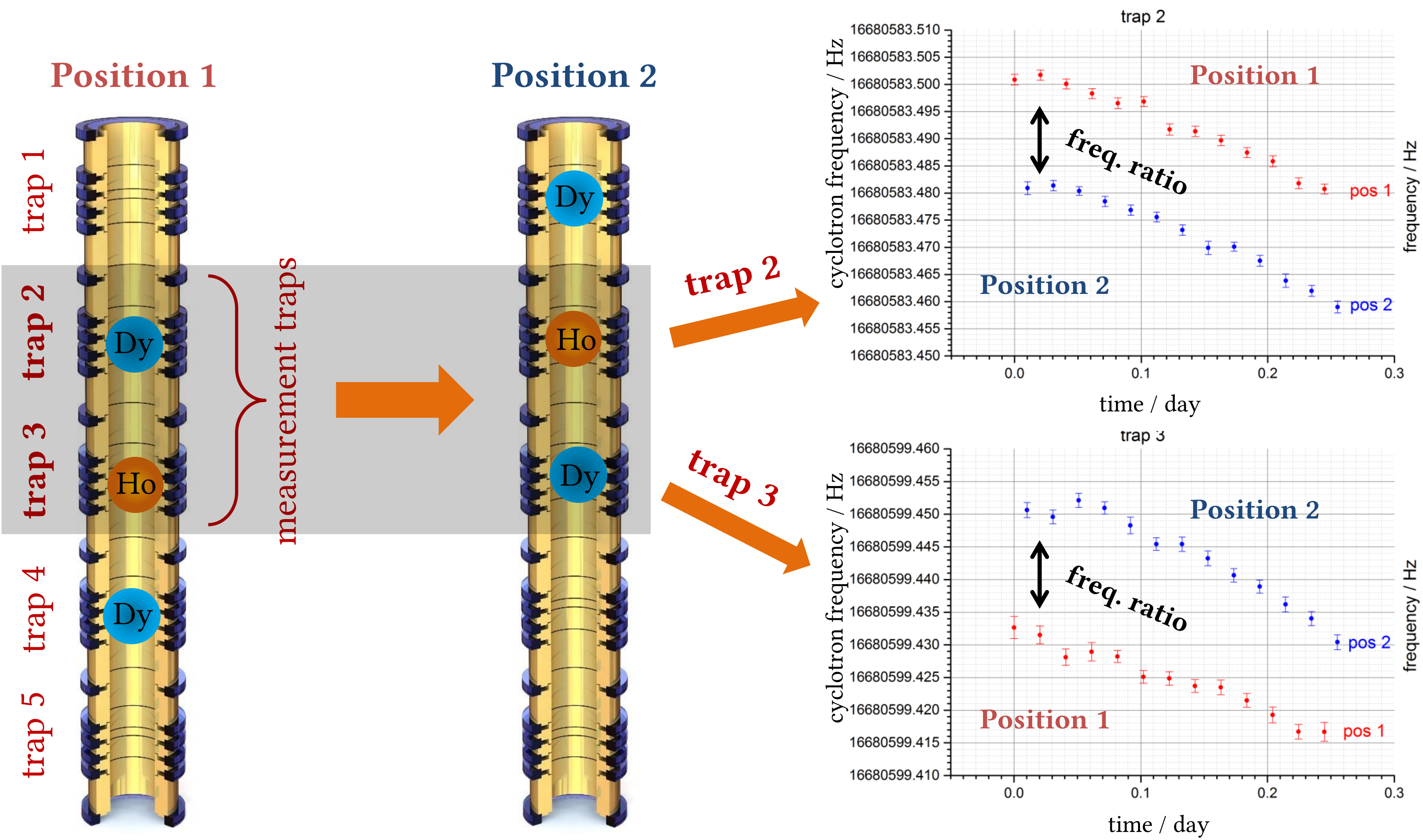
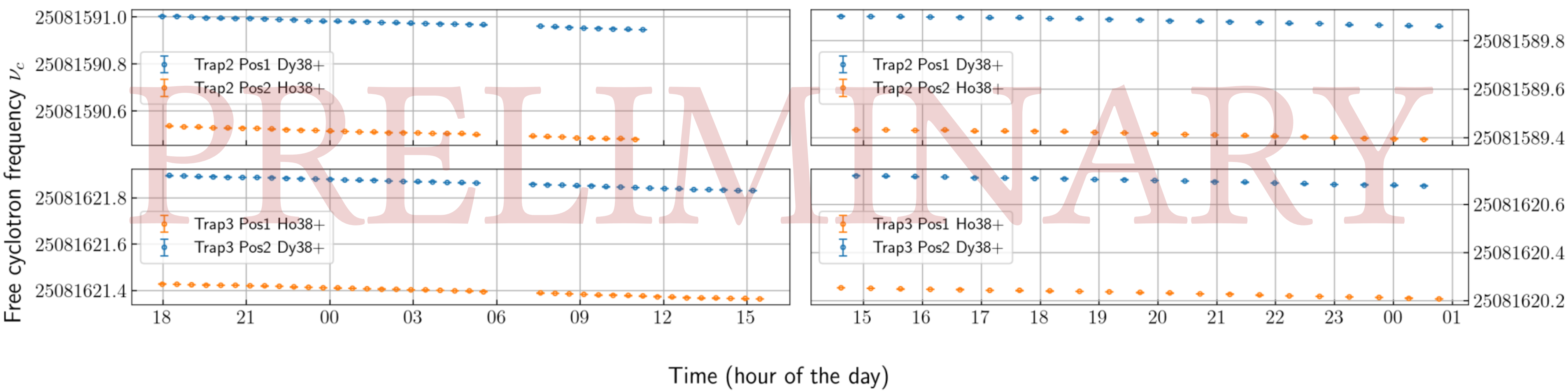


Measurement of charge state q=38+



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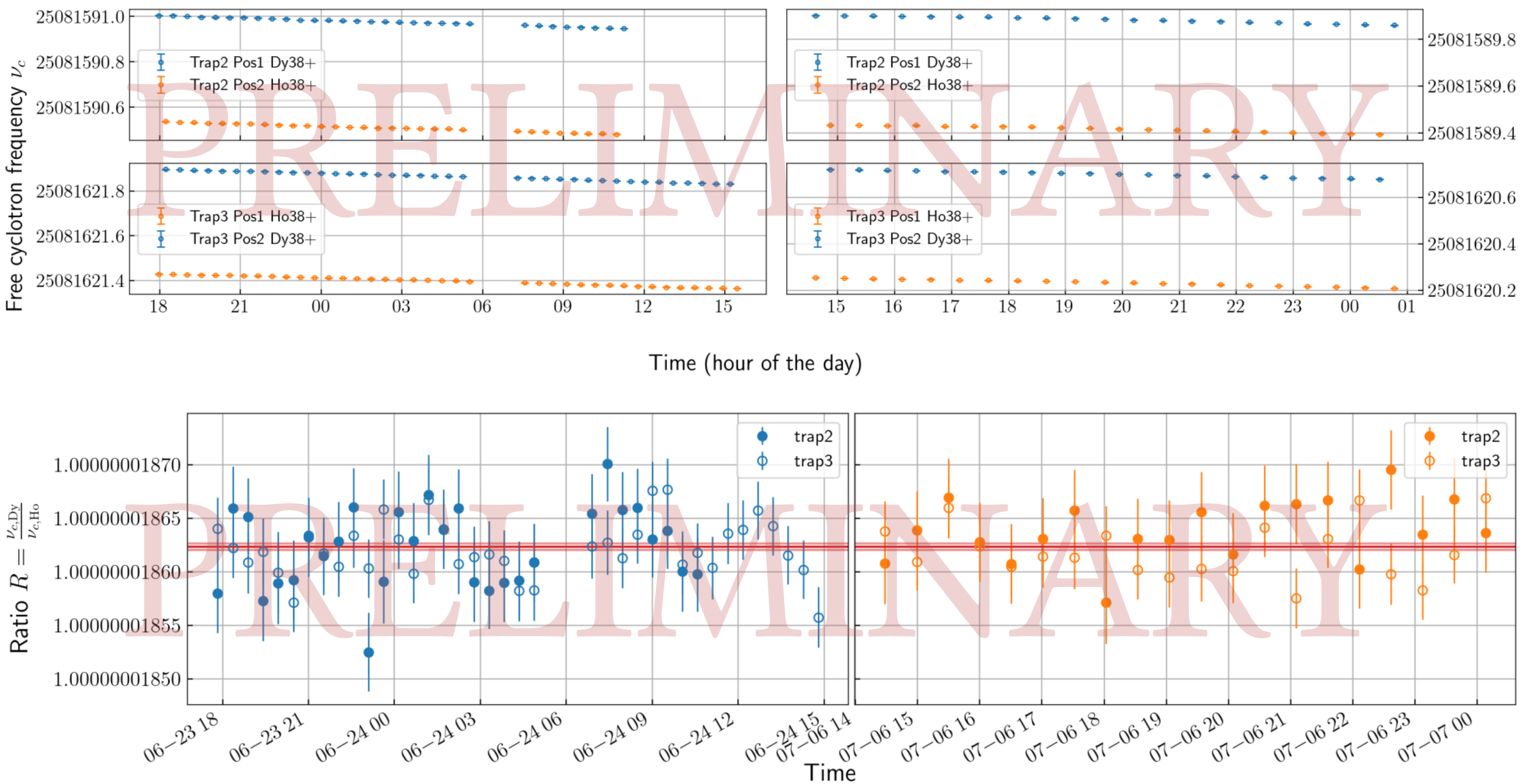
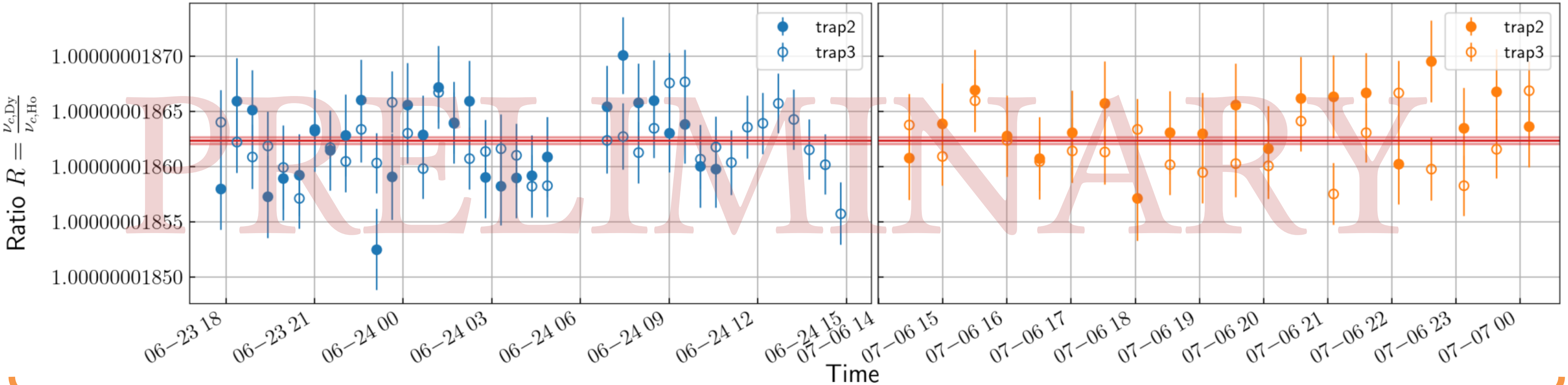


Measurement of charge state *q*=38+



$$Q = m_{\mathrm{Dy}}^{q+}\left(R_{q+} - 1\right) + \Delta E_{\mathrm{B}}^{q+}$$

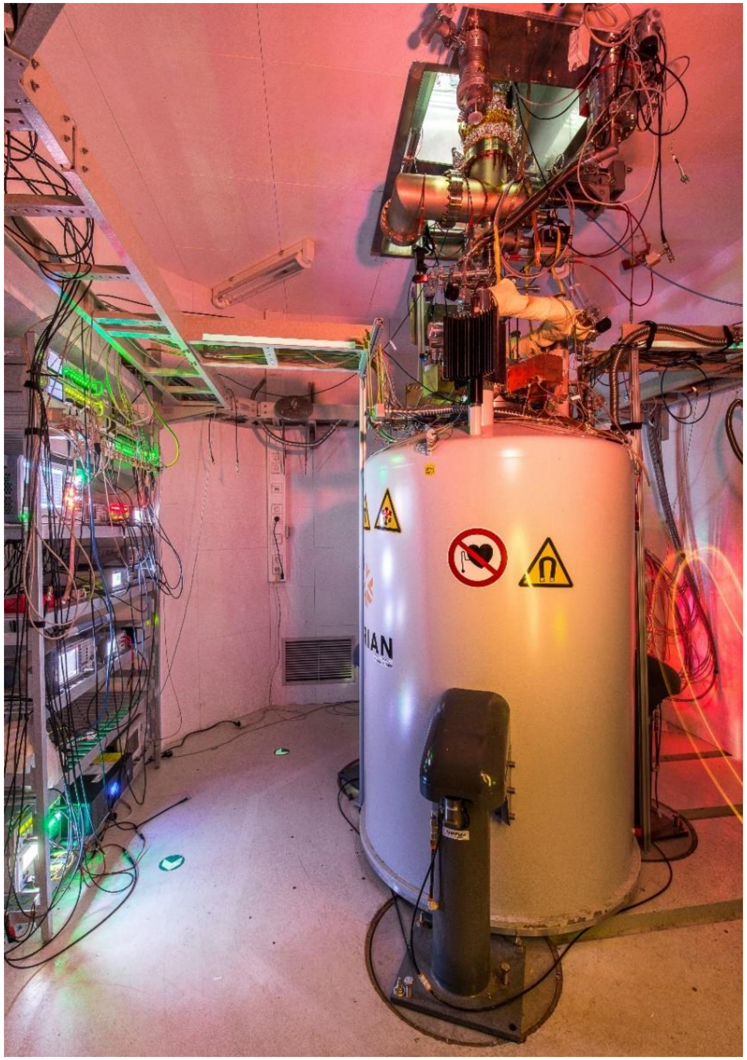
Calculated from AME, Electron mass (CODATA) and binding energies (NIST)

Z. Harman, P. Indelicato and M. Haverkort

q	R	dR	Eb	dEb	Q	dQ	dR/R
38	1.0000000186232842	3.025416337667 7894e-12	37.39	0.7	**2863.4**	**0.8**	3,0E-12
39	1.0000000113074665	4.079252483056971e-12	1147.33	0.7	**2863.2**	**0.9**	4,1E-12
40	1.0000000115156475	3.4868062799341045e-12	1115.71	0.7	**2863.2**	**0.9**	3,5E-12

Summary

- High-precision mass spectrometry for neutrino physics
- Requirements to reach this precision
- Production of HCI of rare isotopes
- Successful measurement of the ^{163}Ho *Q*-value



PENTATRAP

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Menno Door, Sergey Eliseev, Pavel Filianin, Jost Herkenhoff, Felix Herzog, Kathrin Kromer, Daniel Lange, Yuri N. Novikov, Alexander Rischka, Christoph Schweiger and Klaus Blaum

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Thank you for your attention!