The high-precision Penning trap mass spectrometer PENTATRAP

June 18th 2012

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Andreas Dörr[1,2]

K. Blaum[1,2], Ch. Böhm[1,2,3], J. Crespo Lopez-Urrutia[1], S. Eliseev[1], M. Goncharov[1,2], C. Hökel-Schmöger[1,2], Yu. N. Novikov[3,4], J. Repp[1,2], C. Roux[1,2], S. Sturm[1], S. Ulmer[1,5]

[1] Max-Planck-Institut für Kernphysik, Heidelberg, Germany

[2] Fakultät für Physik und Astronomie, Ruprecht-Karls-Universität, Heidelberg, Germany

[3] Extreme Matter Institute EMMI, Helmholtz Gemeinschaft, Darmstadt, Germany

[4] Petersburg Nuclear Physics Institute, Gatchina, Russia

[5] RIKEN Advanced Science Institute, Hirosawa, Wako, Saitama, Japan

The physics program at PENTATRAP

Mass ratio measurements of
single, highly charged, long-lived ions up to uranium
with an accuray of $<10^{-11}$

Q-values for neutrino physics.

For example:

- $\bar{\nu}_e$ mass:
  $^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os}$
  (β-decay)
- ν_e mass:
  $^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}$
  (EC)

test of the energy-mass-relation $E=mc^2$

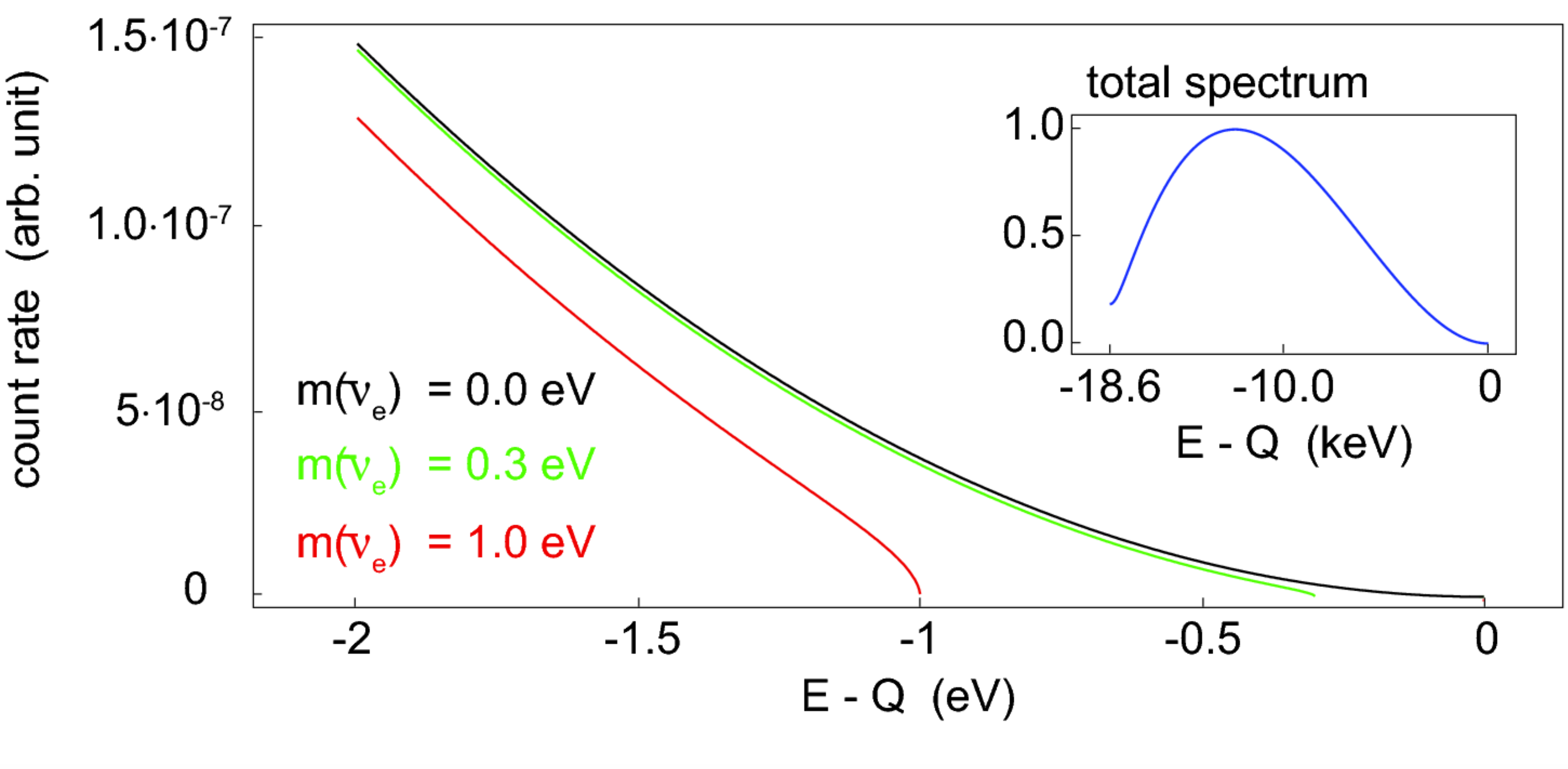
QED in strong electromagnetic field:

Binding energies of remaining electrons in highly charged ions.

Q-values for neutrino physics

β-decay $^{3}H \rightarrow {}^{3}He^{+} + e^{-} + \bar{\nu}_e$

part of total decay energy Q required for neutrino mass



measure:

- e^{-}-spectrum: KATRIN
- Q-value (independently): THe-Trap

Q-values for neutrino physics

β-decay $^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_e$

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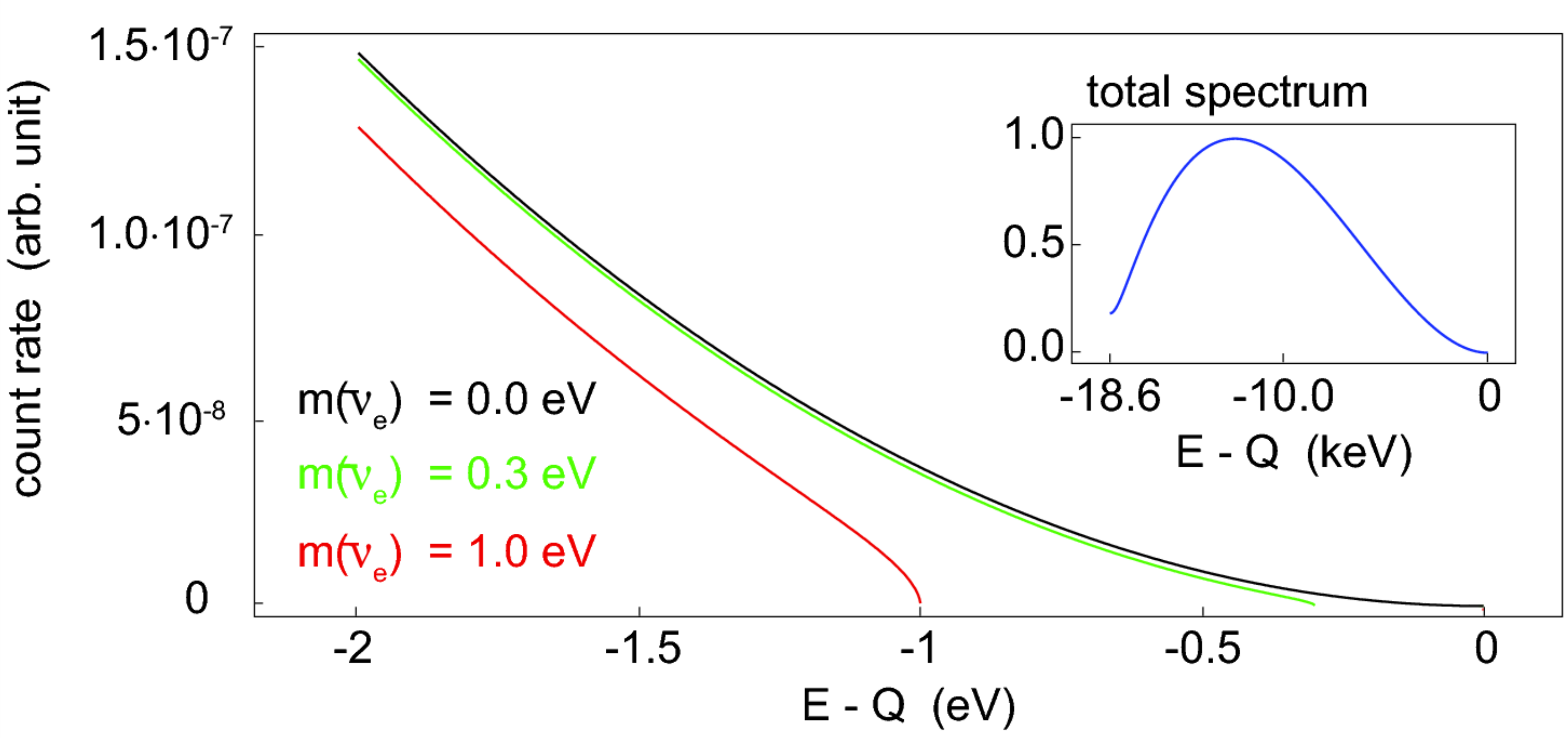


alternative: β-decay $^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os}^{+} + e^{-} + \bar{\nu}_e$

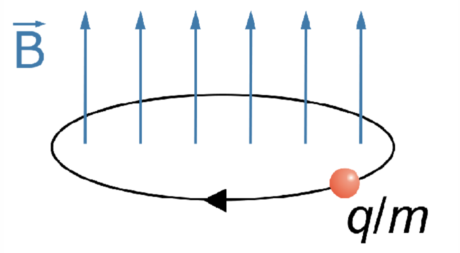
measure:

- spectrum: MARE
- Q-value (independently): PENTATRAP

Penning traps

Lorentz force

homogeneous
B-field

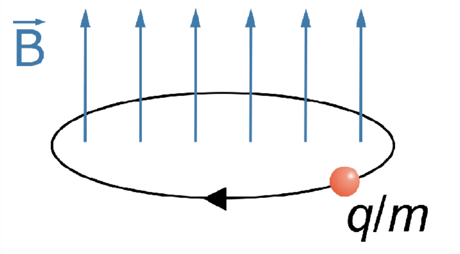


$$\boxed{\nu_c} = \frac{1}{2\pi}\frac{qB}{\boxed{m}}$$

Penning traps

Lorentz force

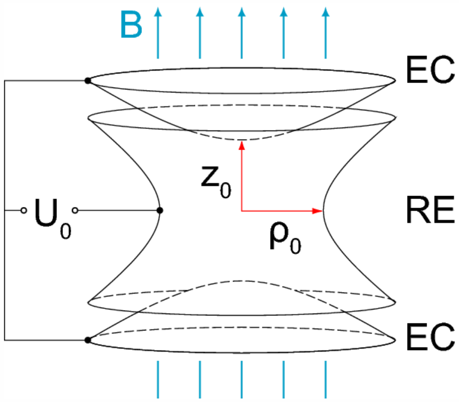
homogeneous
B-field



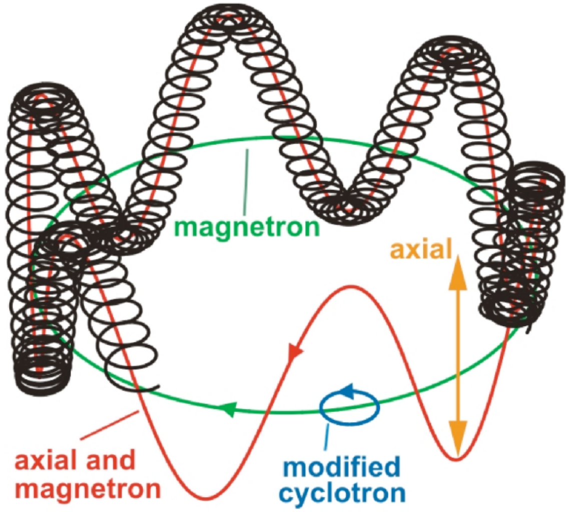
$$\nu_c = \frac{1}{2\pi}\frac{qB}{m}$$

Axial force

quadrupolar
electrostatic field



3D confinement



Penning traps

Lorentz force

homogeneous
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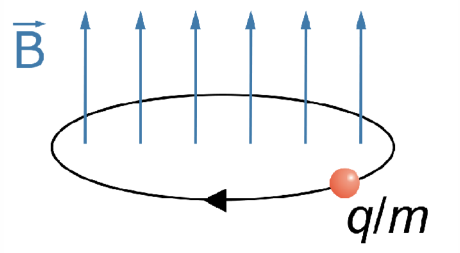

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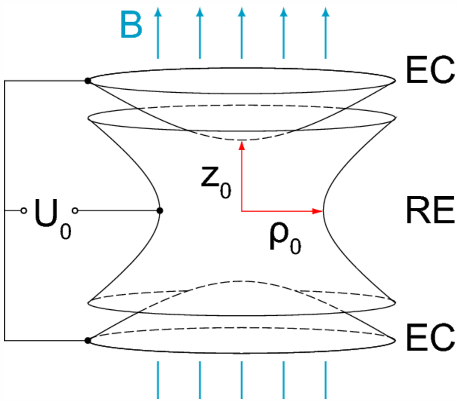

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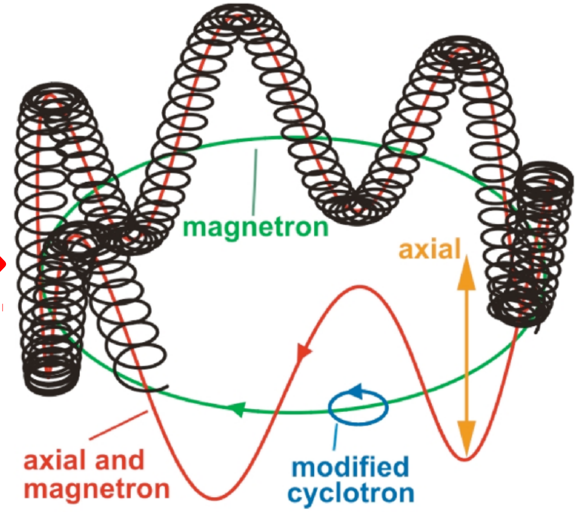


Trap frequencies

$$\nu_+ = \frac{\nu_c}{2} + \sqrt{\frac{\nu_c^2}{4} - \frac{\nu_z^2}{2}}$$

modified cyclotron

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{qU_0}{md^2}}$$

axial

$$\nu_- = \frac{\nu_c}{2} - \sqrt{\frac{\nu_c^2}{4} - \frac{\nu_z^2}{2}}$$

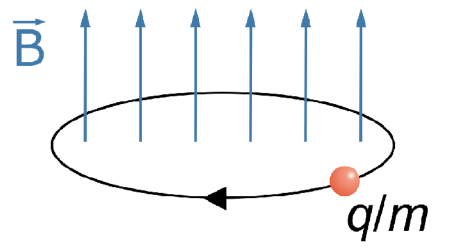
magnetron

$$d^2 = \frac{1}{2}\left(z_0^2 + \frac{\rho_0^2}{2}\right)$$

Penning traps

Lorentz force

homogeneous
B-field



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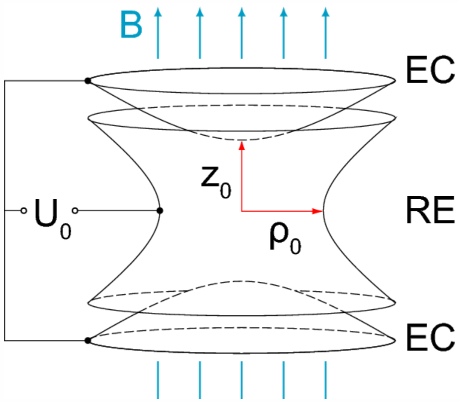

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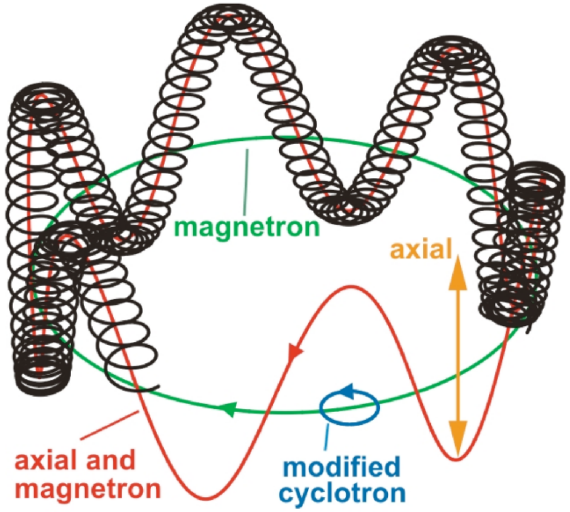

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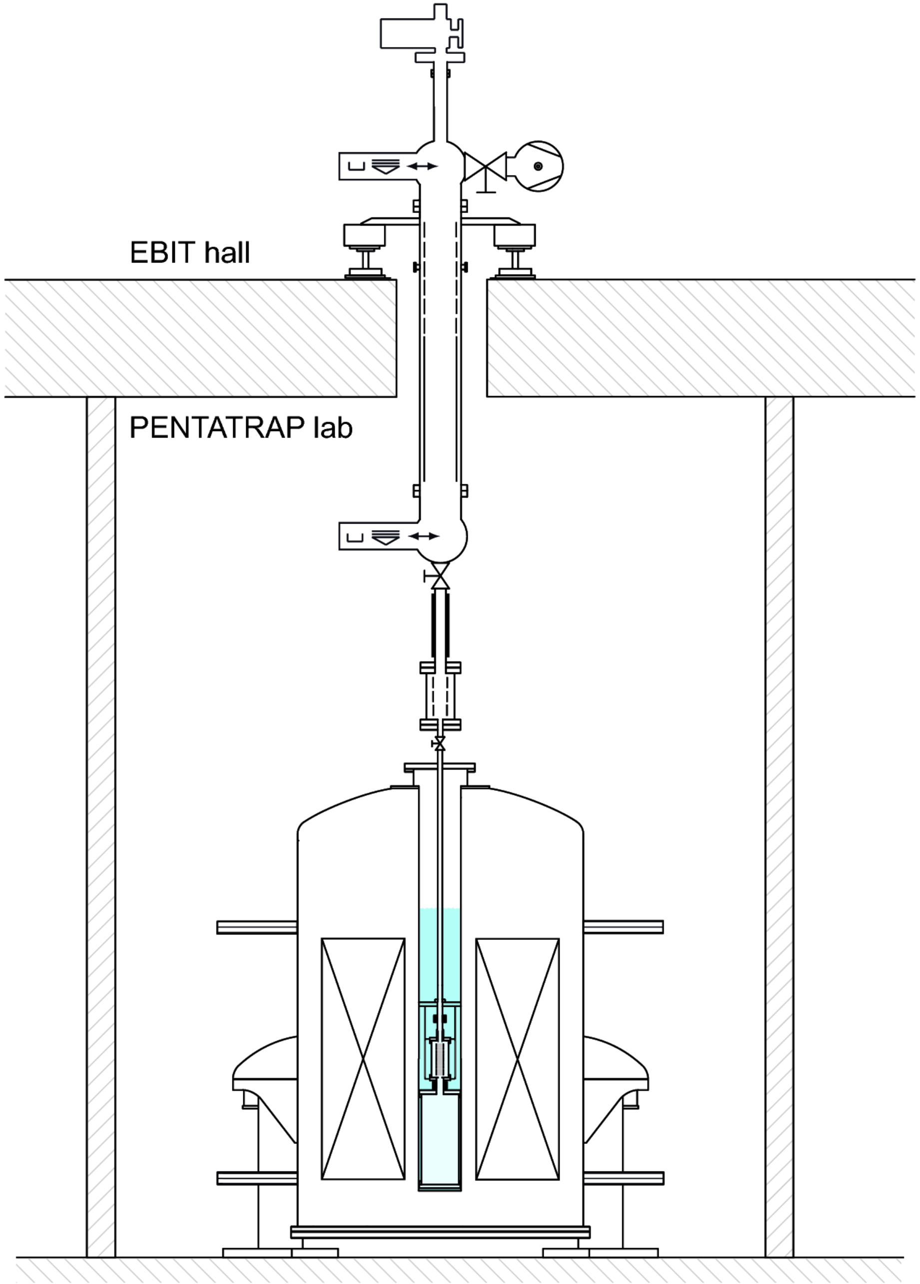
magnetron

Invariance theorem $\boxed{\nu_c} = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$

L. S. Brown, G. Gabrielse,
Phys. Rev. A 25, 2423 (1982)

PENTATRAP Overview

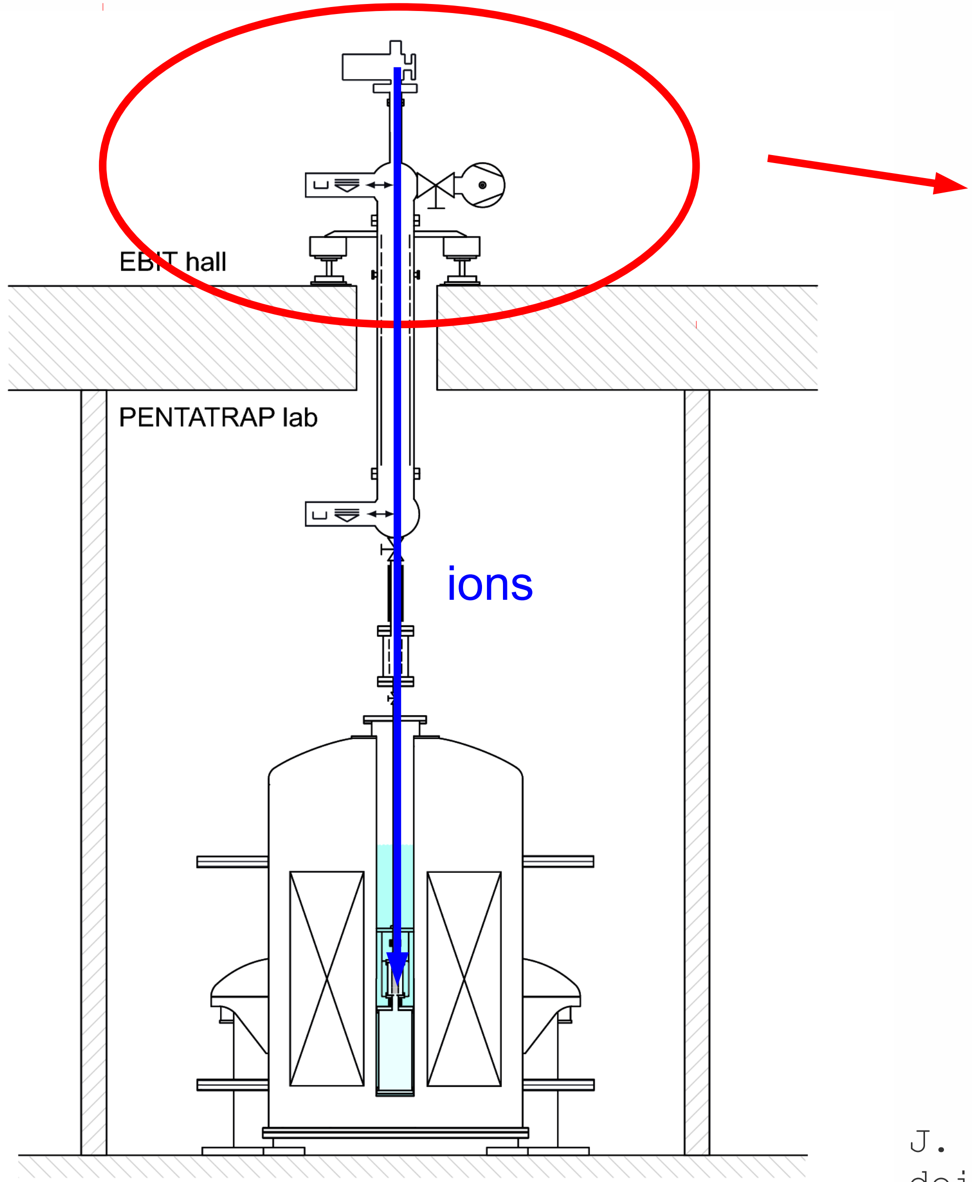


The magnet

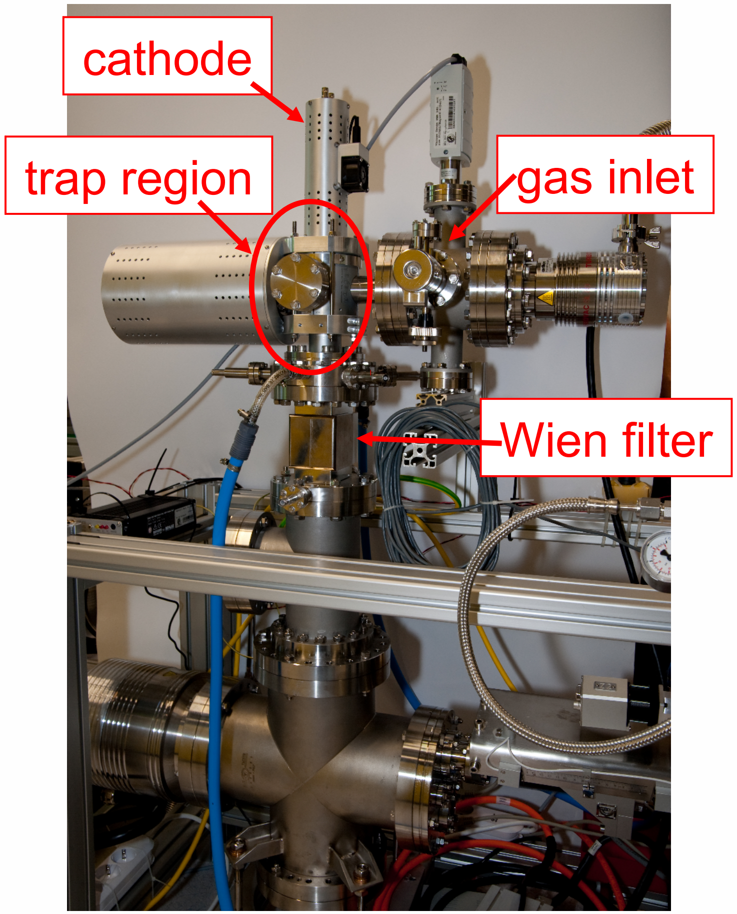
- superconducting 7 T magnet
- cold bore with 160mm diameter
- spacial homogeneity: 0.7 ppm in central cm^3, 44 ppm in trap volume
- temporal stability: <10^{-9}/h
- pressure and He-level stabilization
- vibration damped
- earth field fluctuation correction with large Helmholtz coils and fluxgate sensor

Electron Beam Ion Trap (EBIT)

→ production of highly charged ions



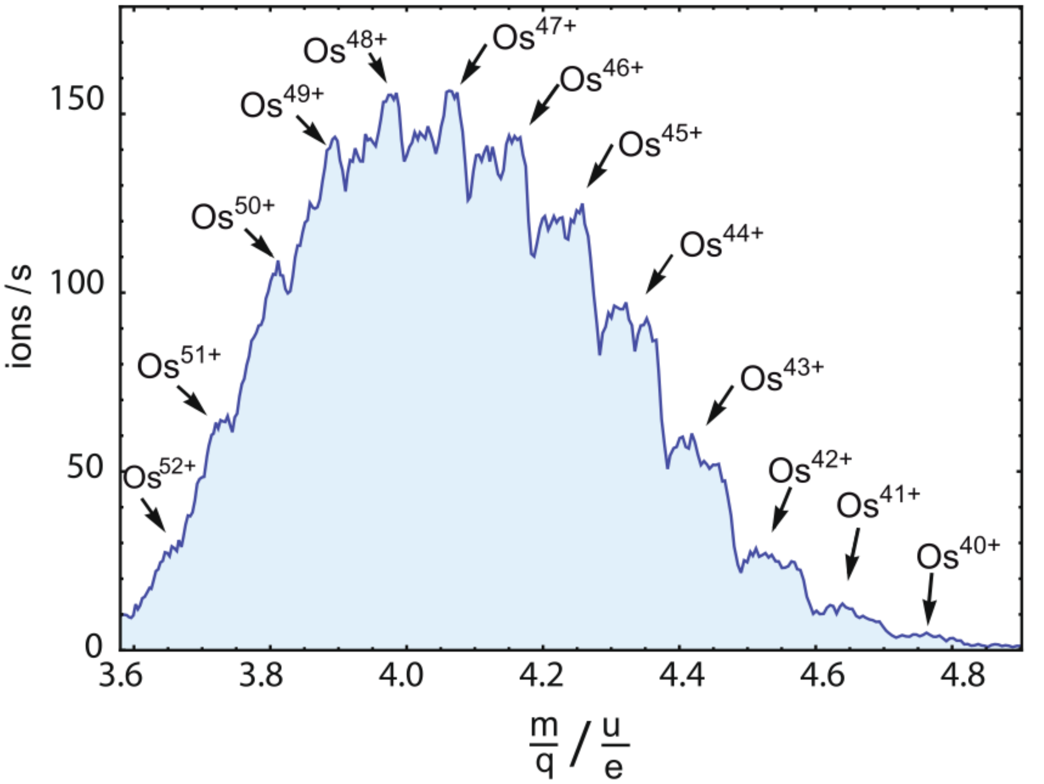
1st experimental phase:
commercial Dresden-EBIT3



J. Repp et al., Appl. Phys. B, doi:10.1007/s00340-011-4823-6(2012)

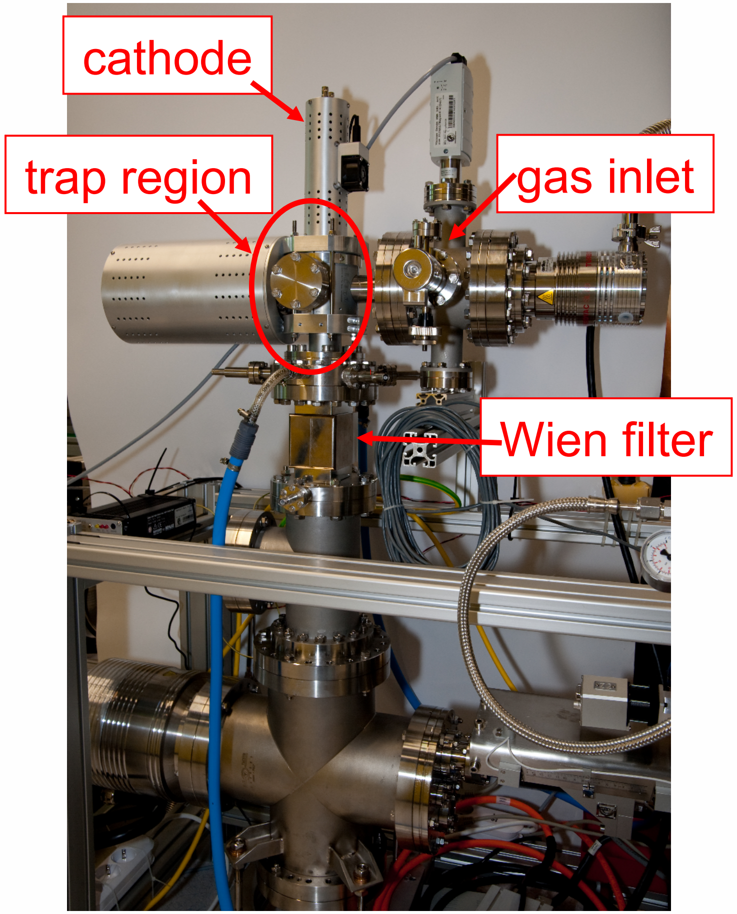
Electron Beam Ion Trap (EBIT)

example: production of highly-charged Osmium



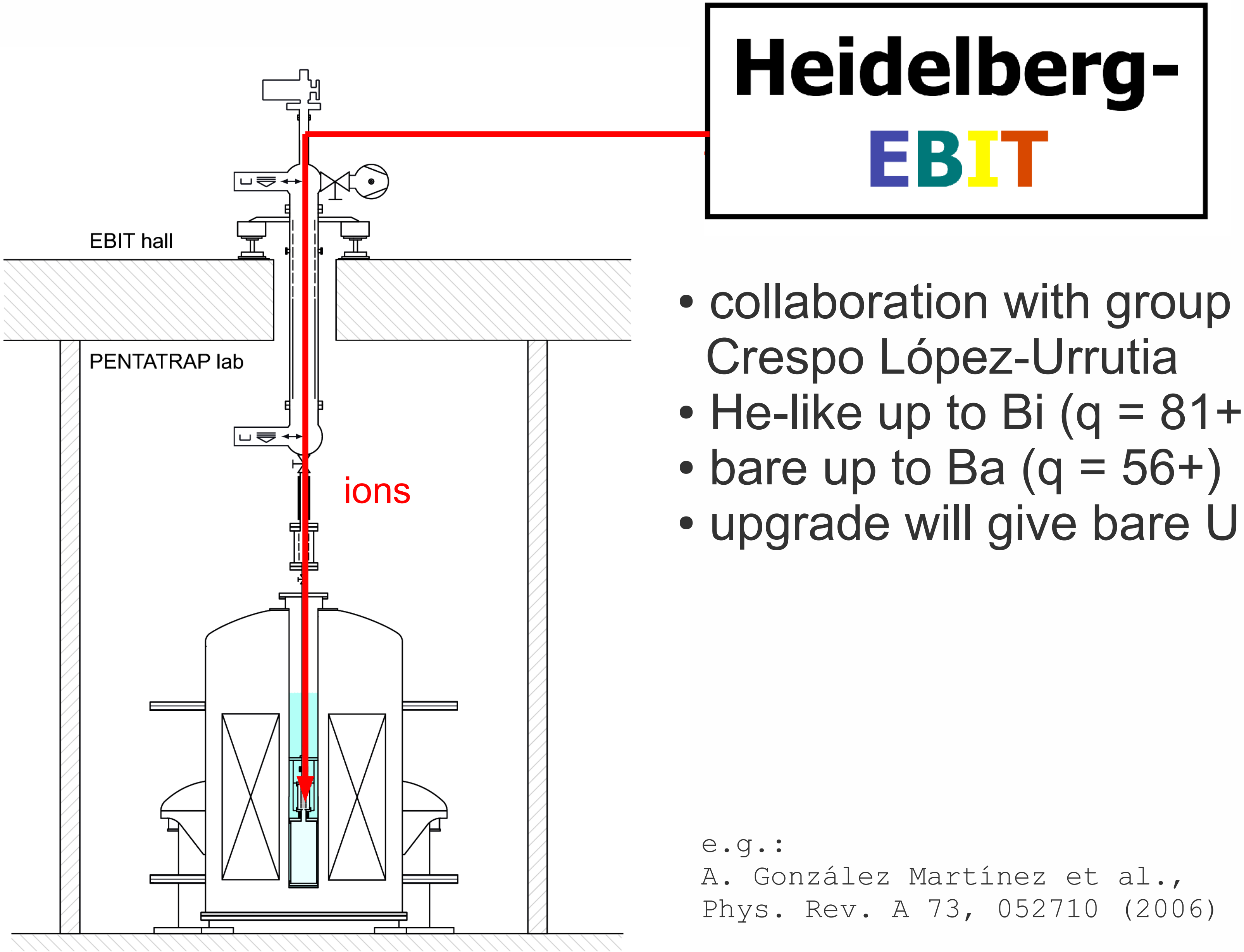
- trapping time: 800ms
- electron current: 30 mA
- electron energy: 7.9 keV

commercial Dresden-EBIT3



Electron Beam Ion Trap (EBIT)

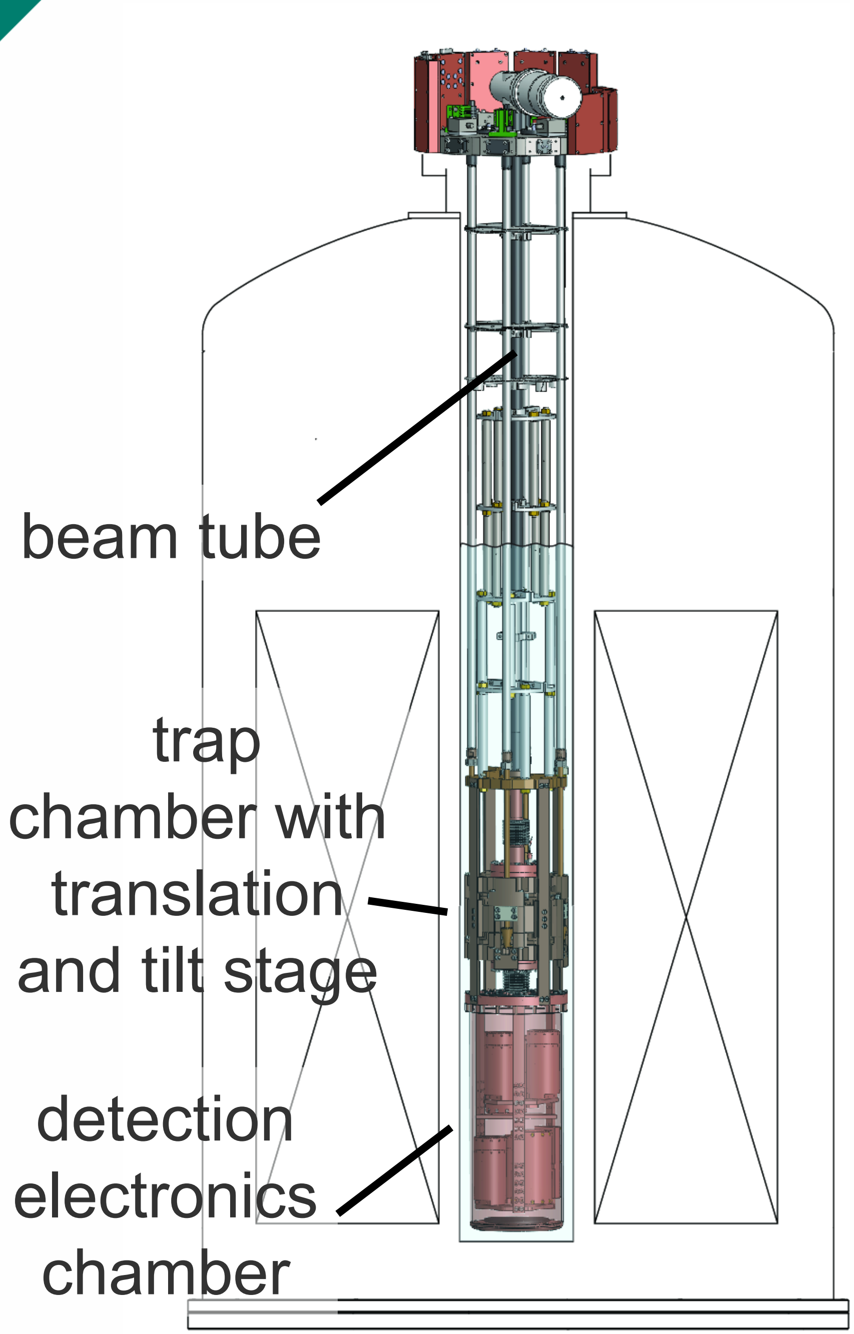
Second experimental phase

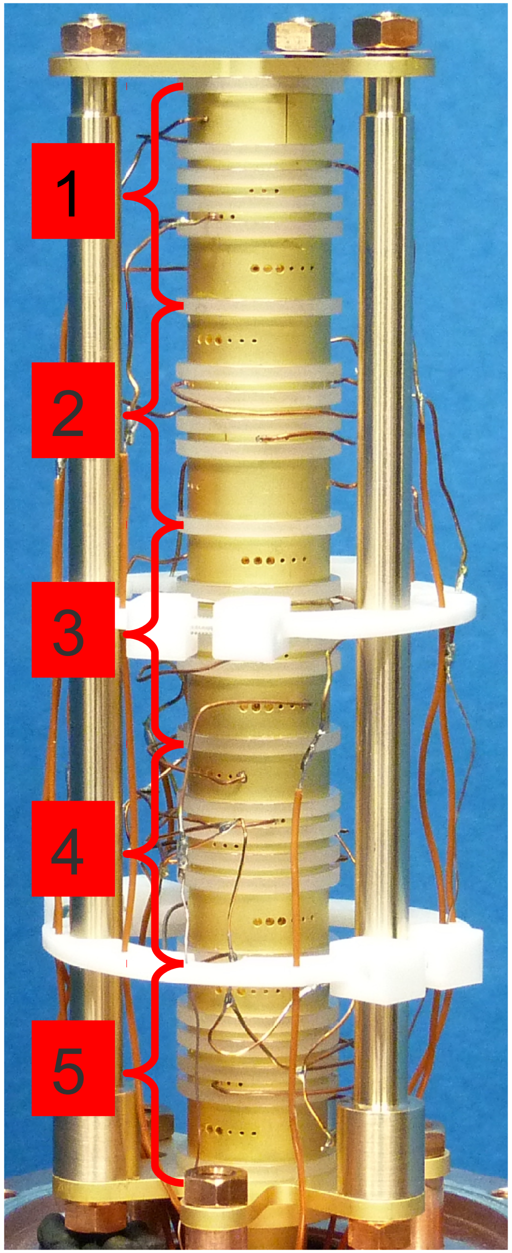


- collaboration with group of J. R. Crespo López-Urrutia
- He-like up to Bi (q = 81+)
- bare up to Ba (q = 56+)
- upgrade will give bare U (soon)

e.g.:
A. González Martínez et al.,
Phys. Rev. A 73, 052710 (2006)

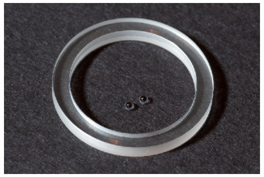
Traps and cryogenic assembly





- 5 traps
- traps are compensated and orthogonal
- gold plated OFHC copper electrodes
- sapphire spacers
- 3 µm machining precision

ring electrode

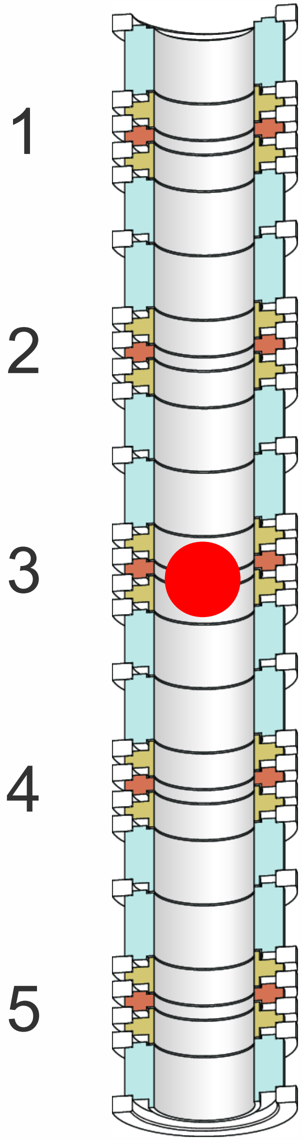


spacer

C.Roux et al., Appl. Phys. B, doi:10.1007/s00340-011-4825-4(2012)

Measurement scheme

→ cyclotron frequency $\nu_c = \frac{1}{2\pi}\frac{q_1 B}{m_1}$



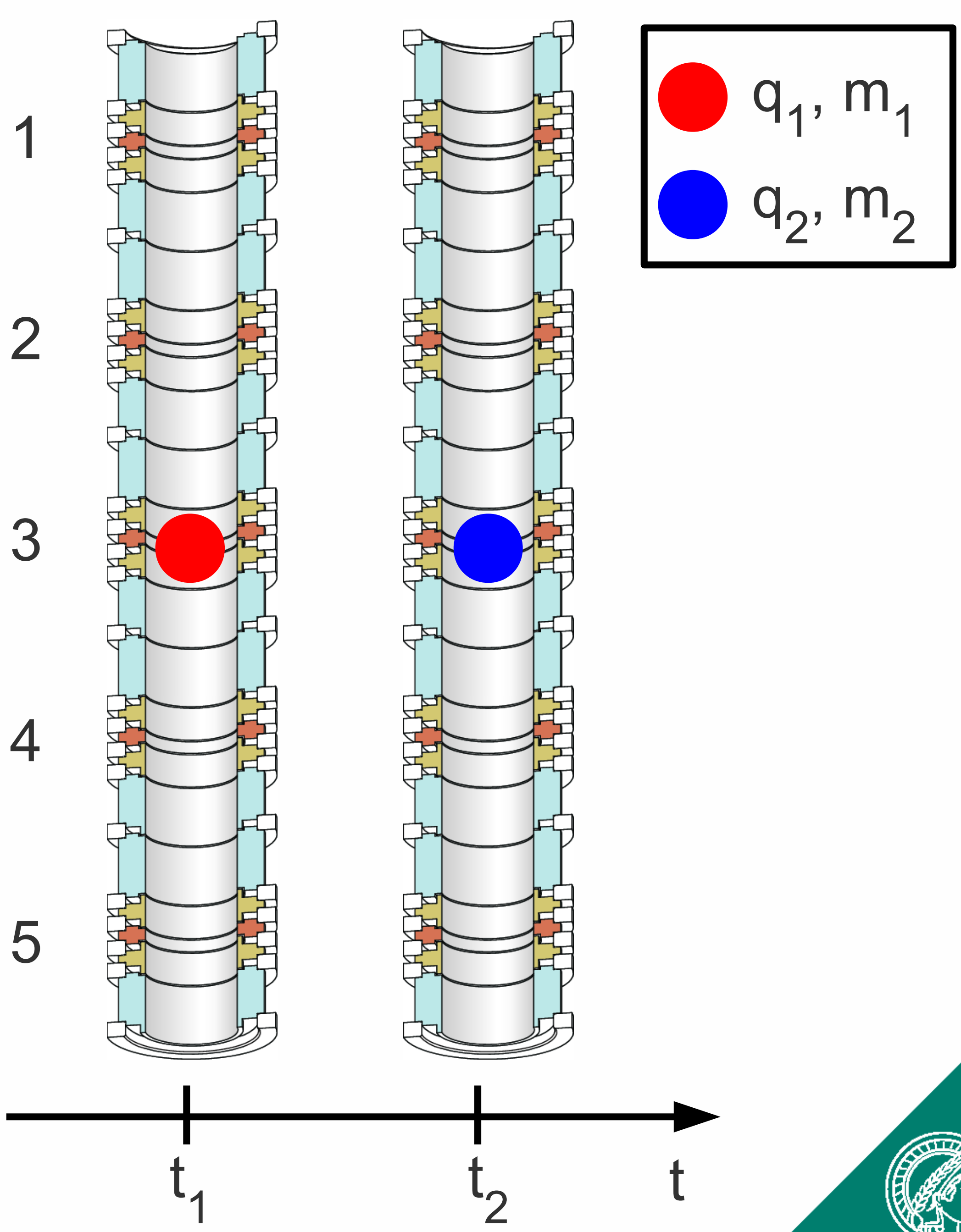
● q_1, m_1

Measurement scheme

→ cyclotron frequency $\nu_c = \frac{1}{2\pi}\frac{q_1 B}{m_1}$

B not precisely known

→ take the ratio $\frac{\nu_{c,1}}{\nu_{c,2}} = \frac{m_2}{m_1}\frac{B(t_1)}{B(t_2)}$



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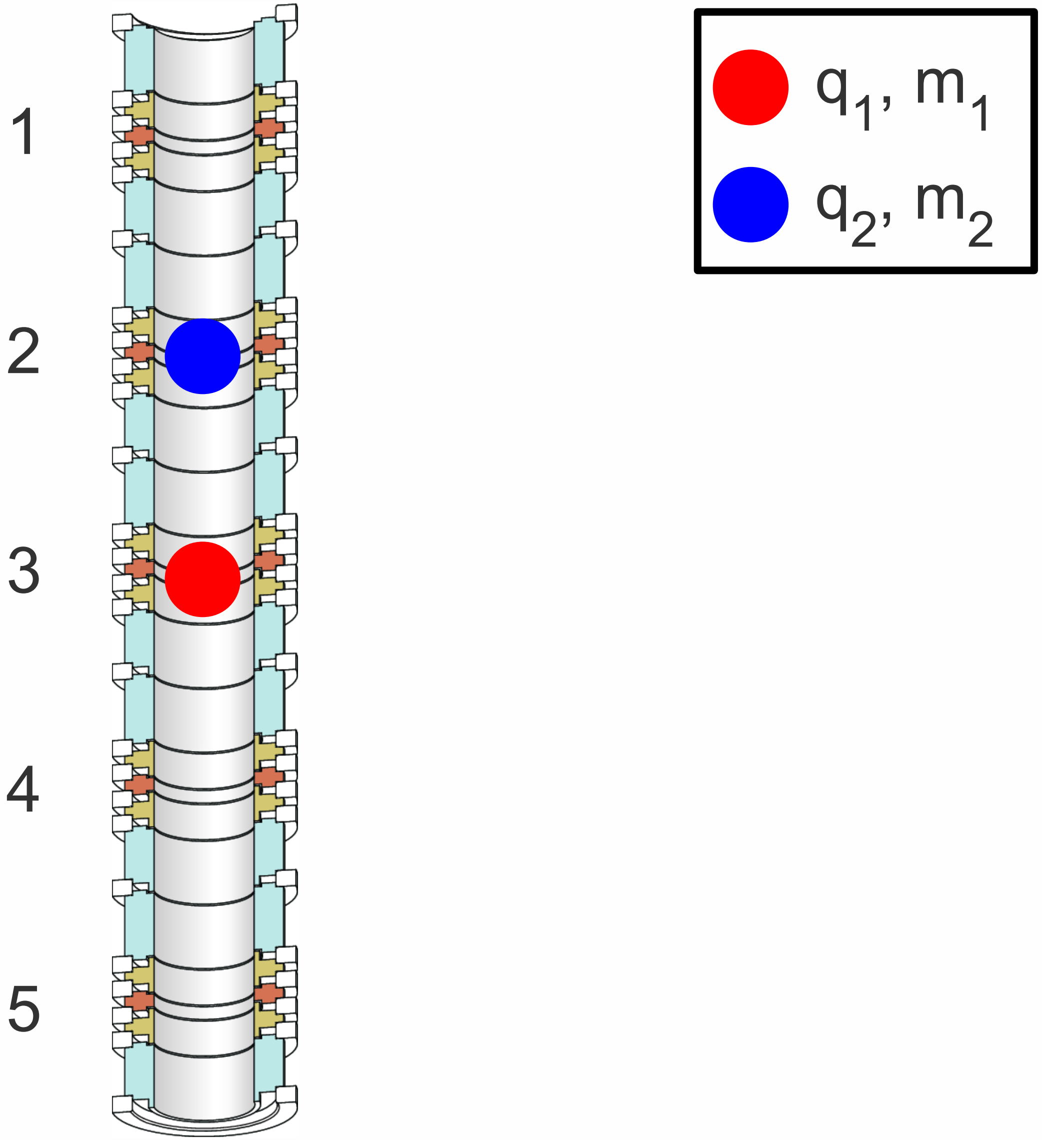
temporal B-fluctuations

→ simultaneous $\frac{\nu_{c,1}}{\nu_{c,2}} = \frac{m_2}{m_1}\frac{B_3}{B_2}$



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temporal B-fluctuations

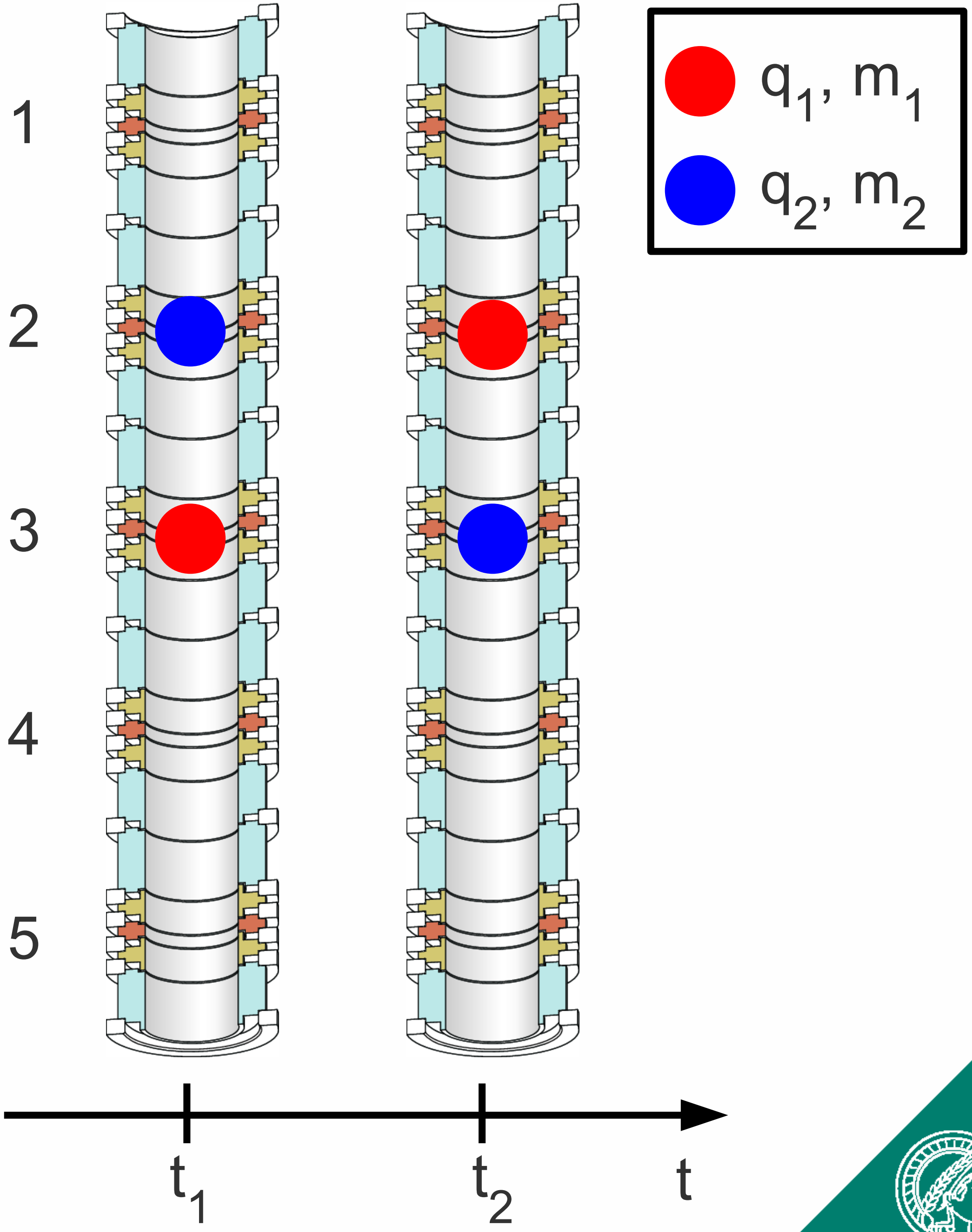
→ simultaneous $\frac{\nu_{c,1}}{\nu_{c,2}} = \frac{m_2}{m_1}\frac{B_3}{B_2}$

spacial B-variation

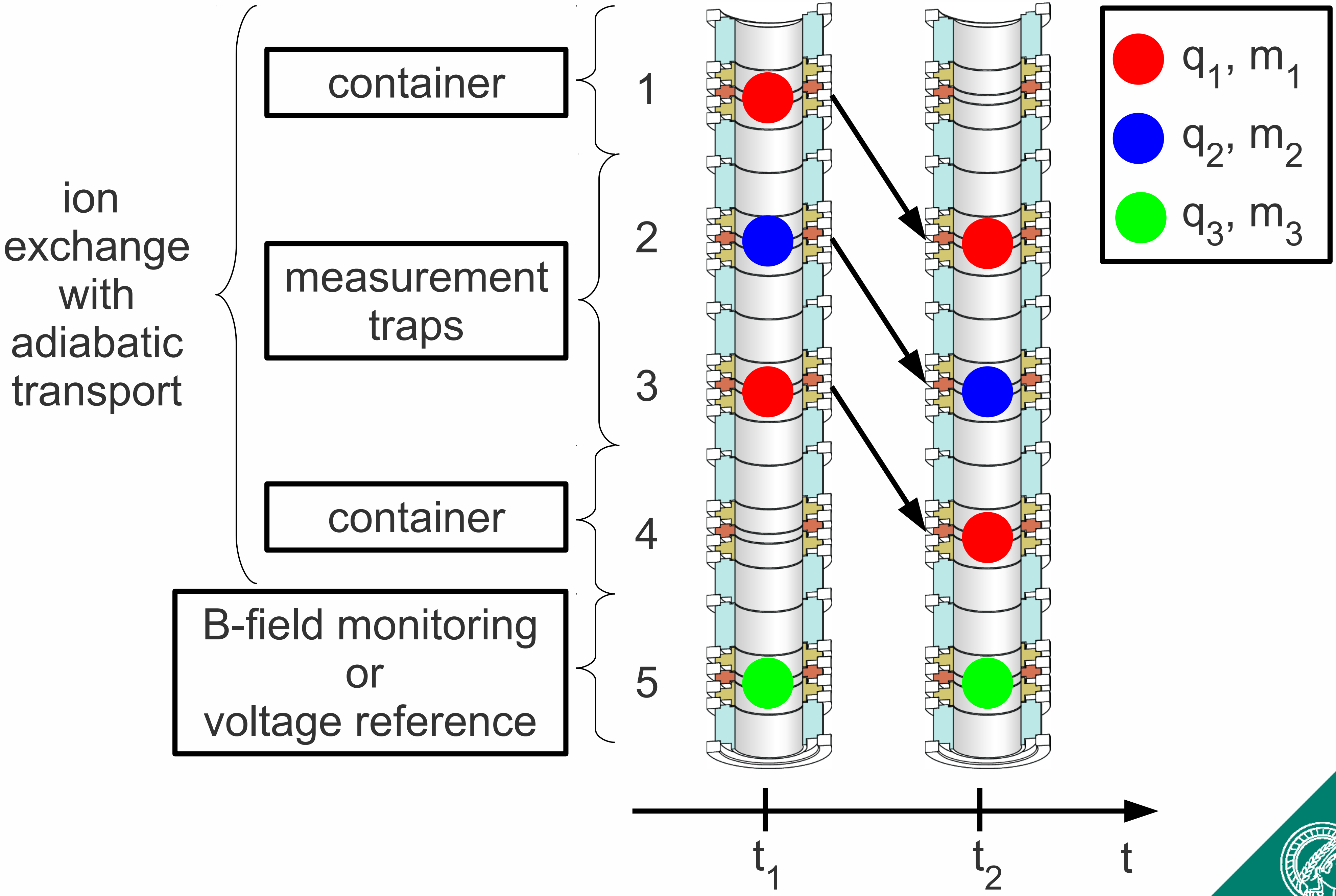
→ exchange and repeat

$$\sqrt{\frac{\nu_{c,1}(t_1)}{\nu_{c,2}(t_1)}\cdot\frac{\nu_{c,1}(t_2)}{\nu_{c,2}(t_2)}} = \sqrt{\left(\frac{m_2}{m_1}\right)^2}\cdot\sqrt{\frac{B_3}{B_2}\cdot\frac{B_2}{B_3}}$$

$$= \frac{m_2}{m_1}$$



Measurement scheme



ion exchange with adiabatic transport

container

measurement traps

container

B-field monitoring
or
voltage reference

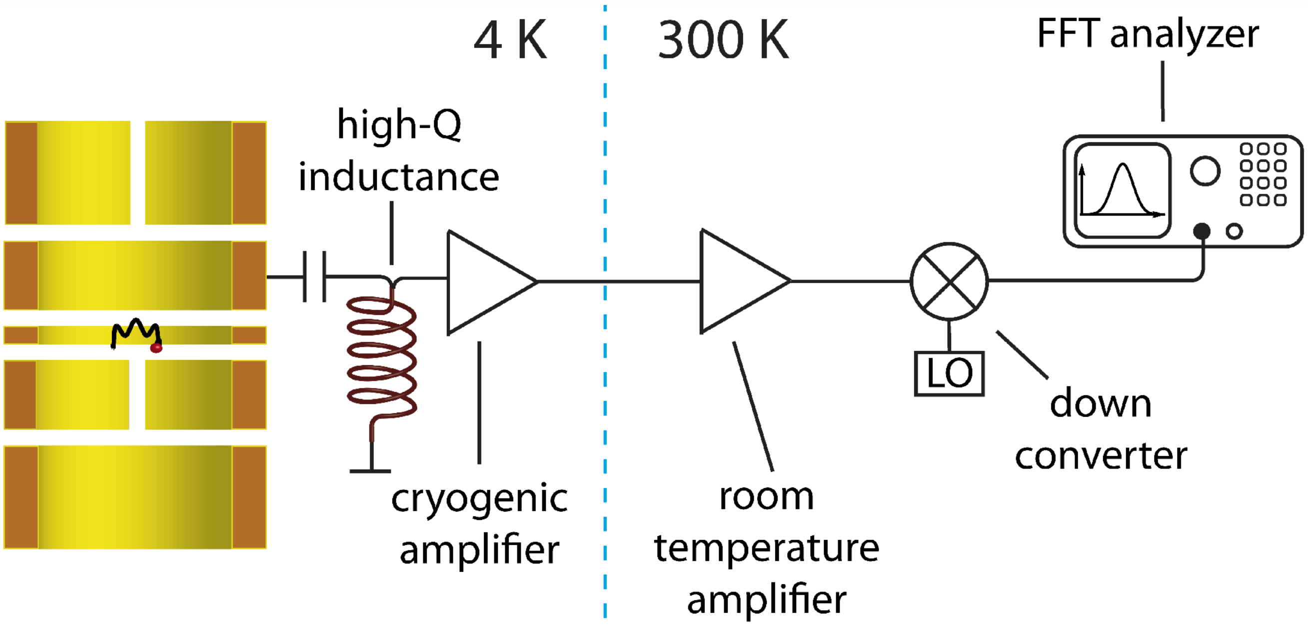
● q_1, m_1

● q_2, m_2

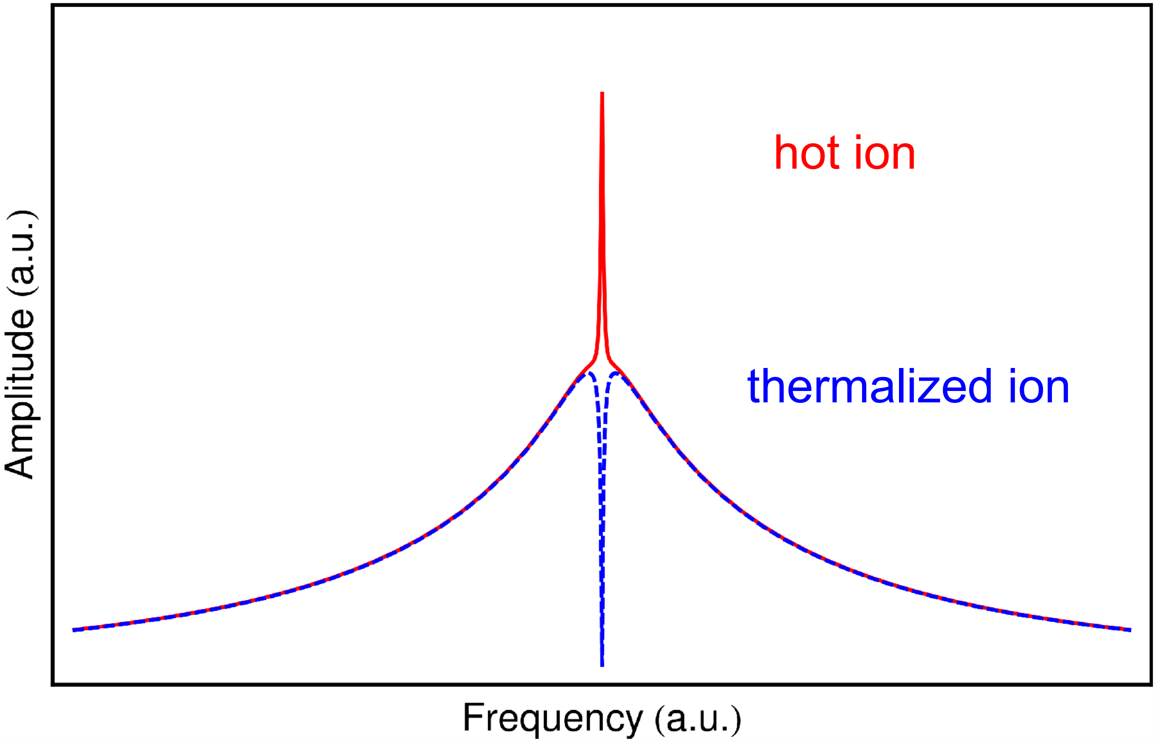
● q_3, m_3

How to measure trap frequencies

Setup for detection of image currents of a single ion

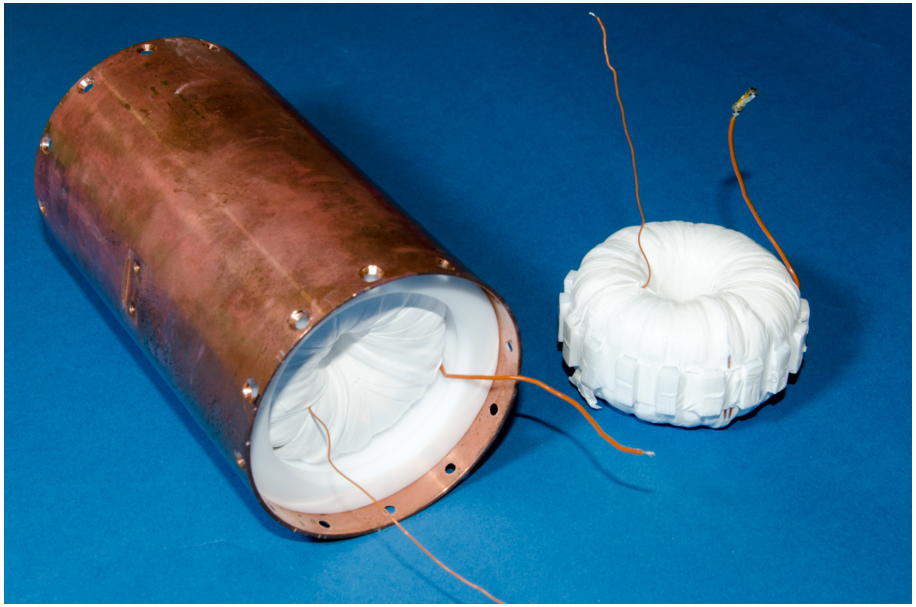


Detector signal (sketch)

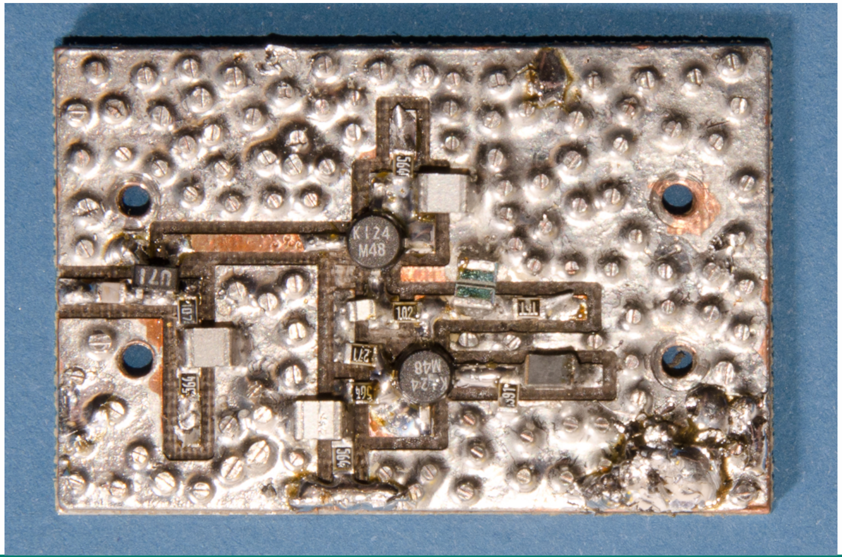


Example: Cryogenic axial detector

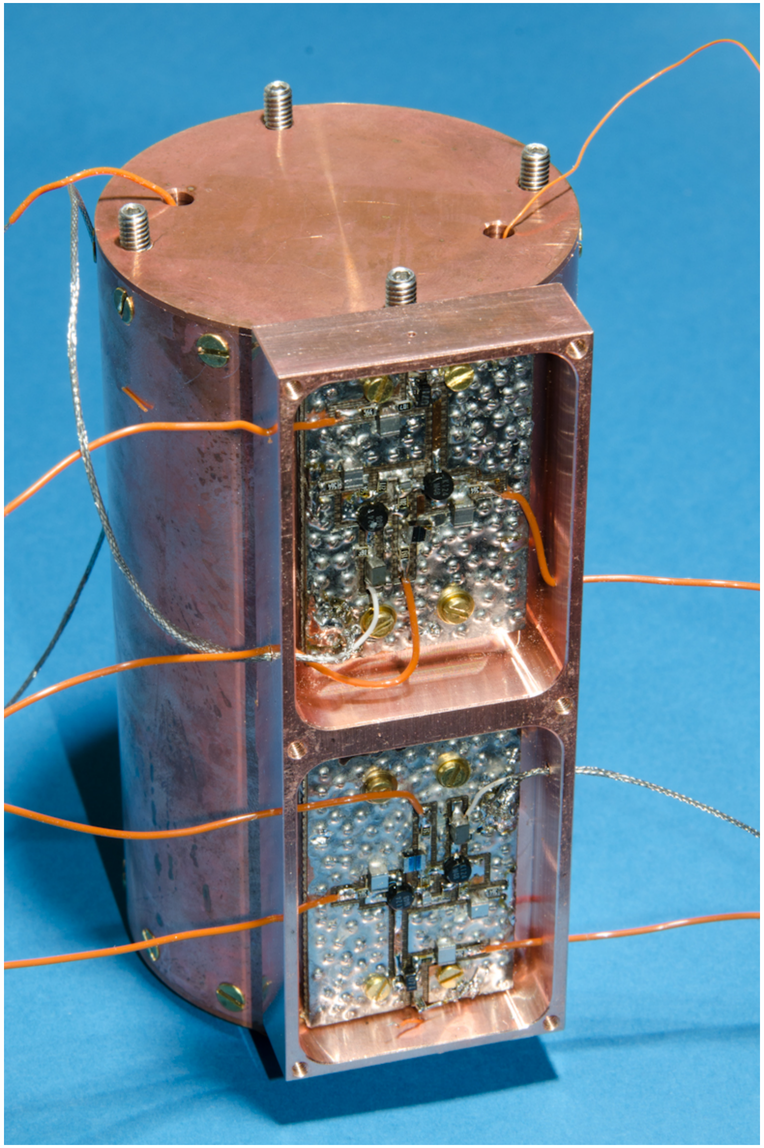
Superconducting toroidal coil



GaAs-FET based amplifier

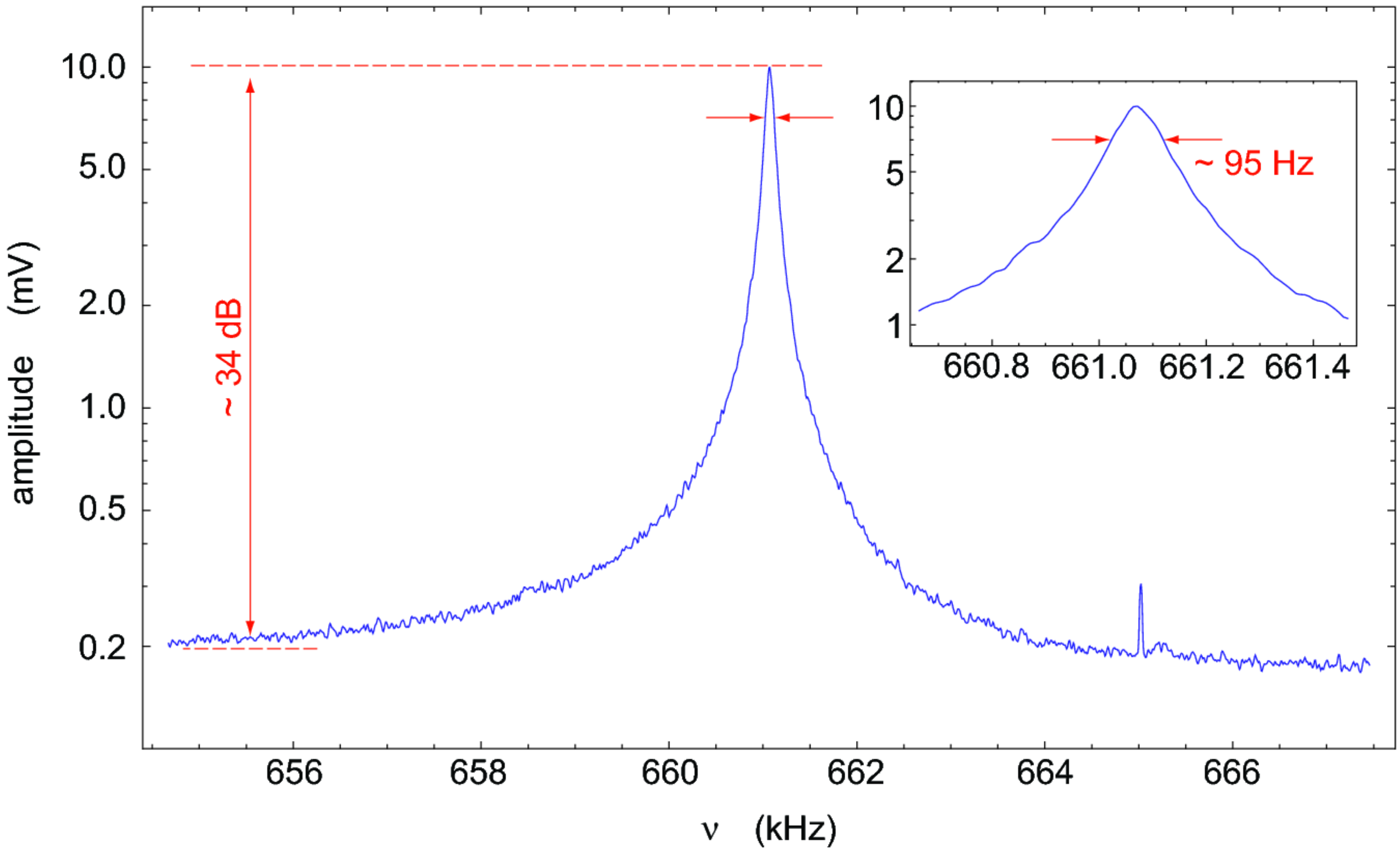


Two cryogenic axial detectors



Axial detector performance

Thermal noise resonance



On resonance effective R_p of ~100 MΩ

→ single ion dip detection possible

→ fast cooling to detector temperature (4K)

Acknowledgements

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MAX-PLANCK-GESELLSCHAFT

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EMMI

Helmholtz Alliance
(HA 216)

Thank you for your attention!