Penning-Trap Mass Spectrometry
(PENTATRAP)
and
Neutrino Mass
(ECHo Project)

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Max-Planck-Institute for Nuclear Physics, Germany

MEDEX, Prague, 31 May 2019
Matrix **E**lements for the **D**ouble beta decay **EX**periments

Determination of neutrino mass with a sub-eV uncertainty

KATRIN
KARLSRUHE TRITIUM NEUTRINO EXPERIMENT

PROJECT 8

β^--decay of Tritium

current limit: $m_{\overline{\nu}_e} < 2.0\ eV/c^2$ (95% C.L.)

“Troitsk ν-mass” and “Neutrino Mainz” experiments

N. Aseev et al., Phys. Rev. D 84, 112003 (2011).
C. Kraus et al., Eur. Phys. J. C 40, 447 (2005).

ECHo

HOLMES

electron capture (EC) in ^{163}Ho

current limit: $m_{\nu_e} < 225\ eV/c^2$ (95% C.L.)

P. Springer et al., Phys. Rev. A 35, 679 (1987).

MINEBA & MANU

↓

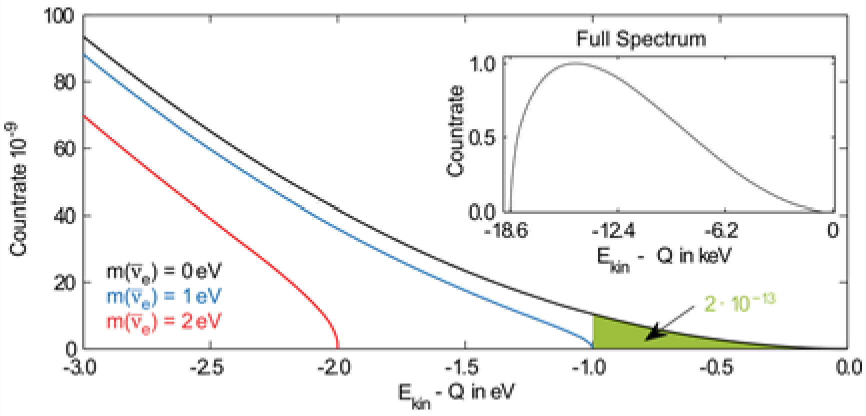
MARE

β^--decay of ^{187}Re

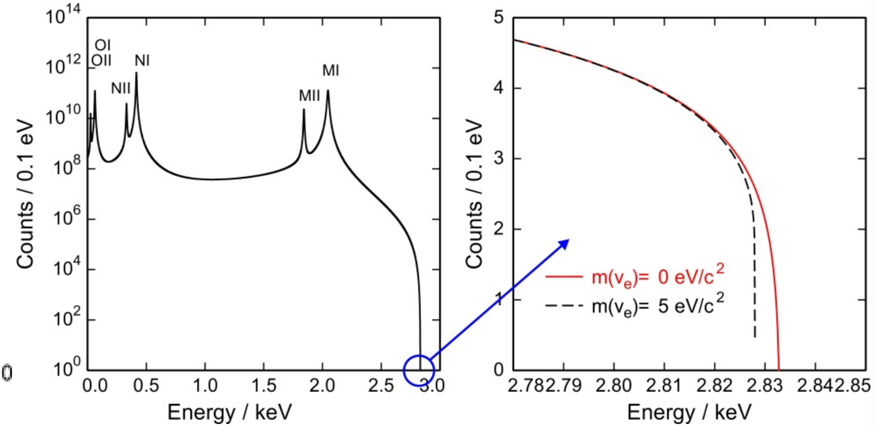
current limit: $m_{\overline{\nu}_e} < 15\ eV/c^2$ (95% C.L.)

Q-value = 2466.7 (1.6) eV

β^--decay of Tritium



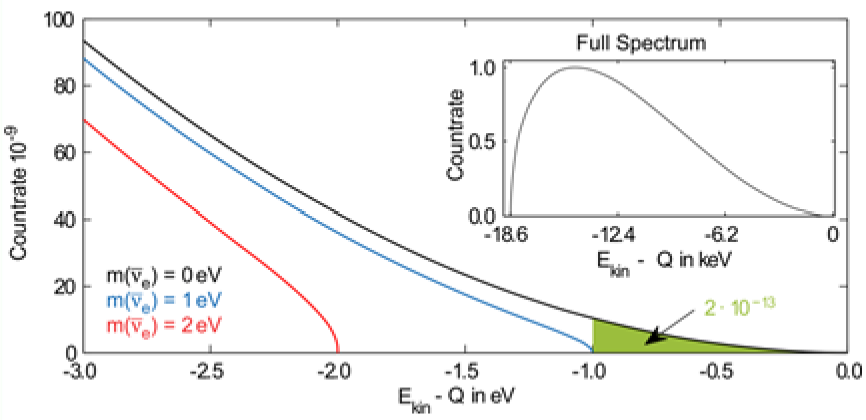
electron capture (EC) in ^{163}Ho



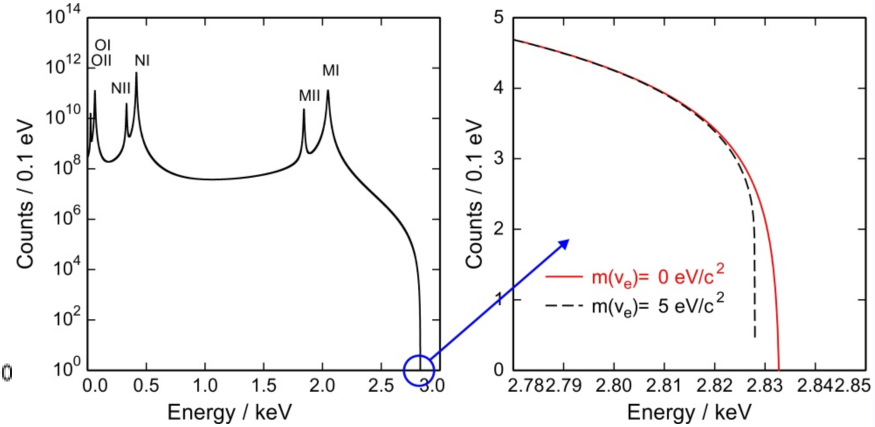
independently and precisely $\left({}^{\delta Q}/_{m} \approx 10^{-11}\right)$ measured *Q*-values are required

Penning traps are the only tool that can deliver *Q*-values with such precision

β^--decay of Tritium



electron capture (EC) in ^{163}Ho



uncertainty which has been achieved until now:

δQ (tritium decay) ≈ 70 meV
FSU-trap

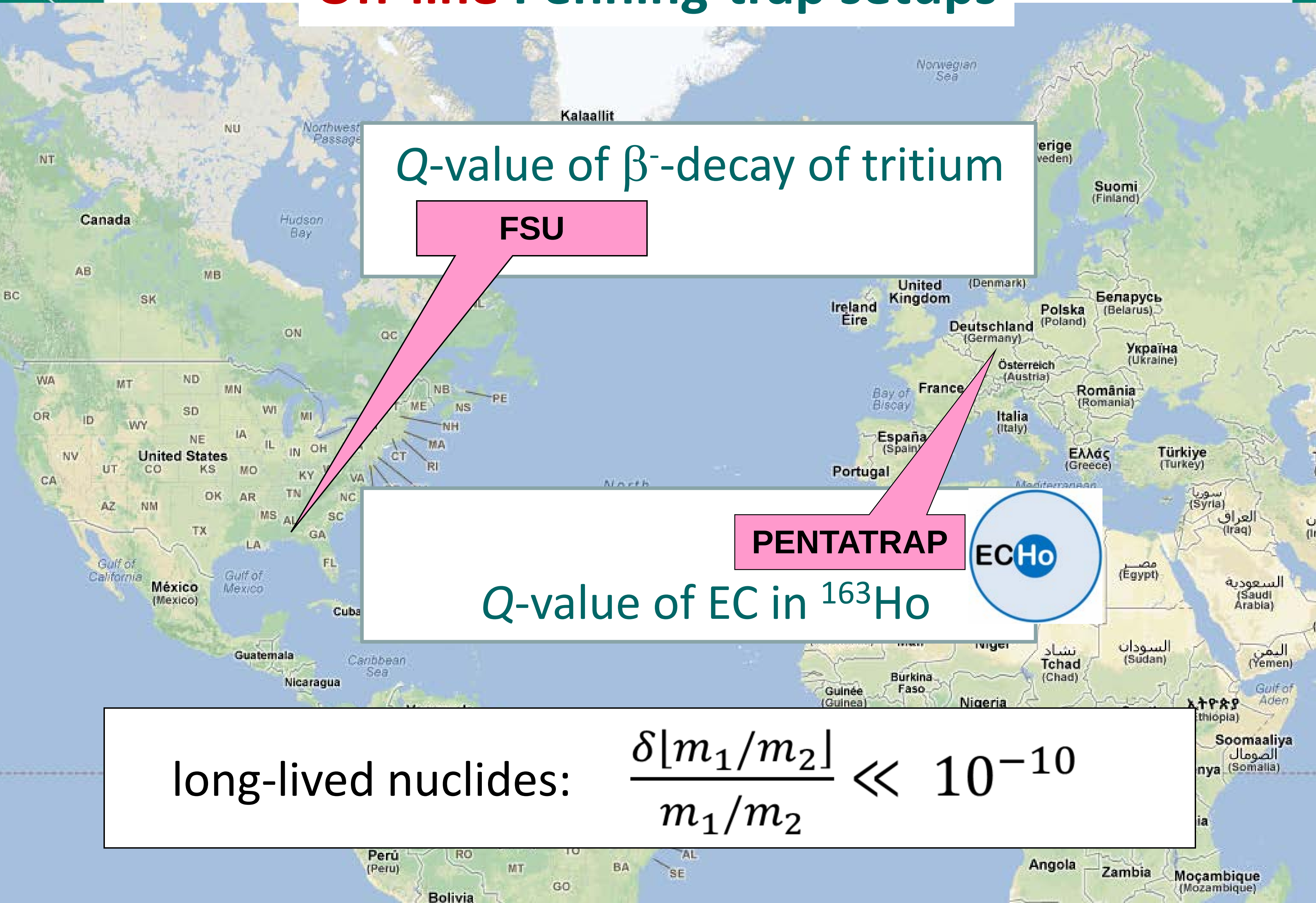
δQ (EC in ^{163}Ho) ≈ 30 eV
SHIPTRAP at GSI

required uncertainty in *Q*-value determination:

δQ (tritium decay) ≈ 1 meV
FSU-trap ???

δQ (EC in ^{163}Ho) ≈ 1 eV
PENTATRAP at MPIK

Off-line Penning-trap setups



Q-value of β⁻-decay of tritium

FSU

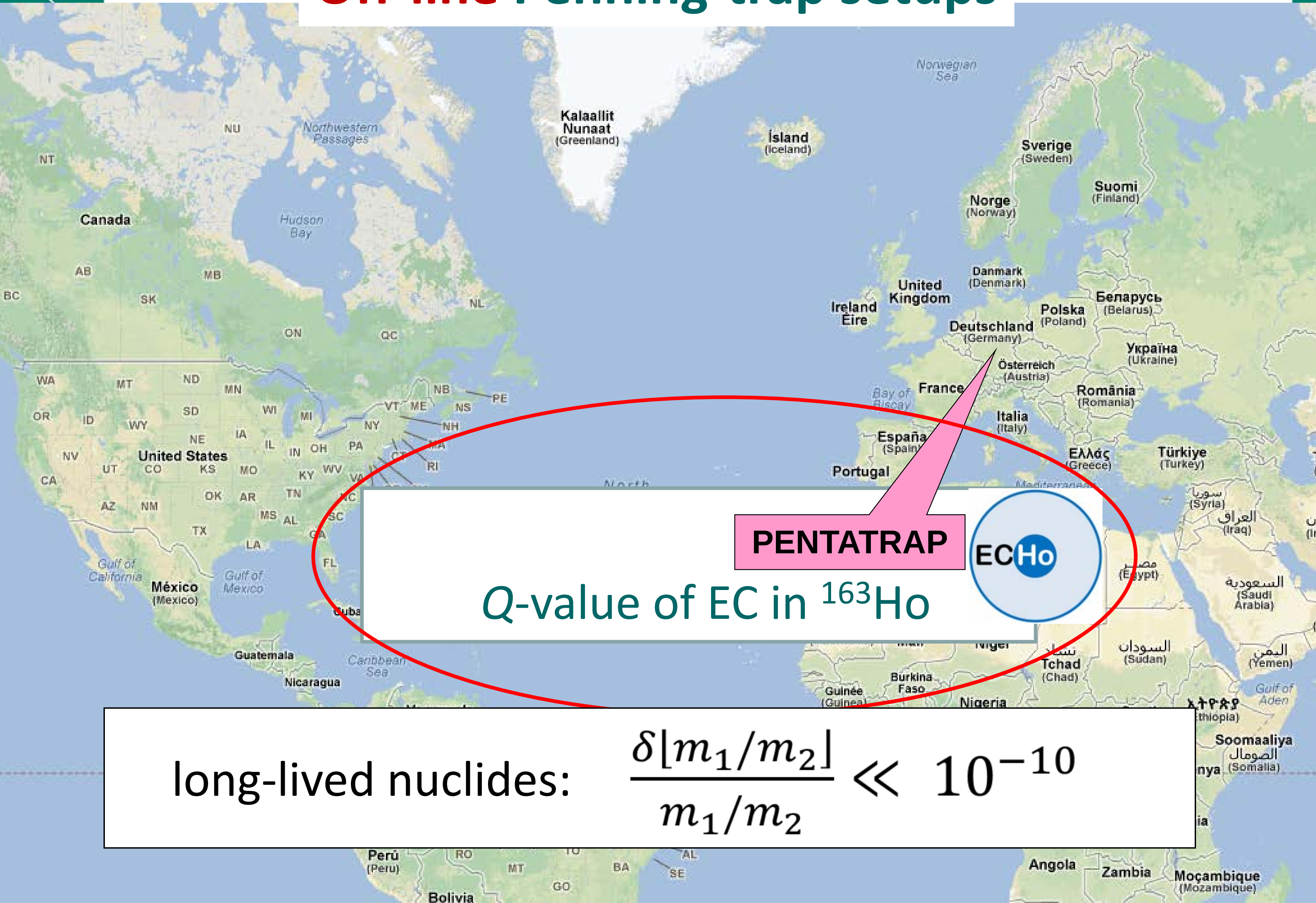
PENTATRAP

ECHo

Q-value of EC in ^{163}Ho

long-lived nuclides: $$\frac{\delta[m_1/m_2]}{m_1/m_2} \ll 10^{-10}$$

Off-line Penning-trap setups



PENTATRAP

ECHo

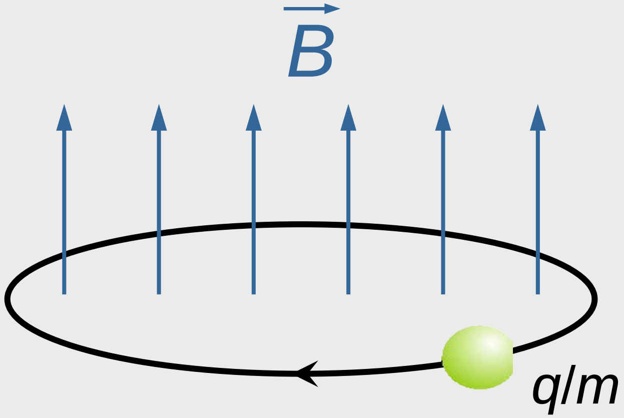
Q-value of EC in ^{163}Ho

long-lived nuclides: $$\frac{\delta[m_1/m_2]}{m_1/m_2} \ll 10^{-10}$$

Penning trap

(the most accurate mass spectrometer !!!)

strong uniform
static B-field



$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

- Mass ⟵ Frequency
- Magnetic field of a few Tesla
- Homogeniety of B-field: $10^{-7}/\text{cm}^3$
- Trapping volume: a few microns^3
- High temporal stability of B-field

⇓

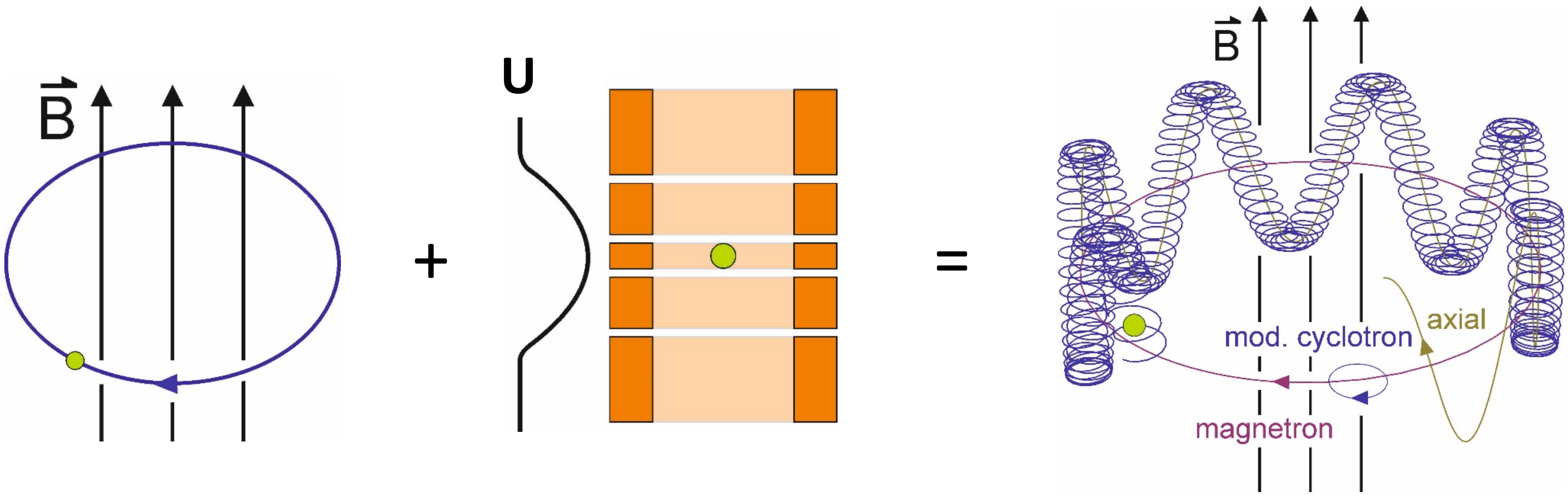
uncertainty of **< 10^{-11}**
in ***mass-ratio*** determination

$$Q = M_p - M_d = M_d \cdot \left(\frac{\nu_{c\_d}}{\nu_{c\_p}} - 1\right)$$

strong uniform magnetic field

harmonic electrical potential

3 eigenmotions in trap



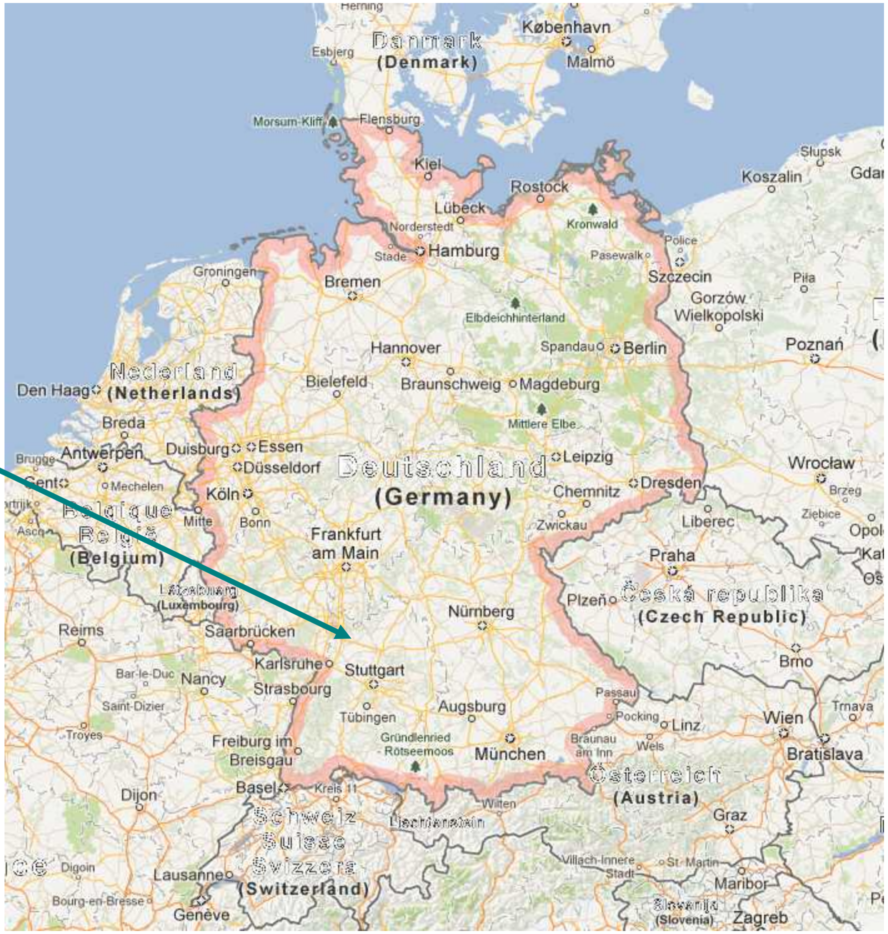
$$\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2$$

Rev. Mod. Phys. 58, 233 (1986).

Location of PENTATRAP

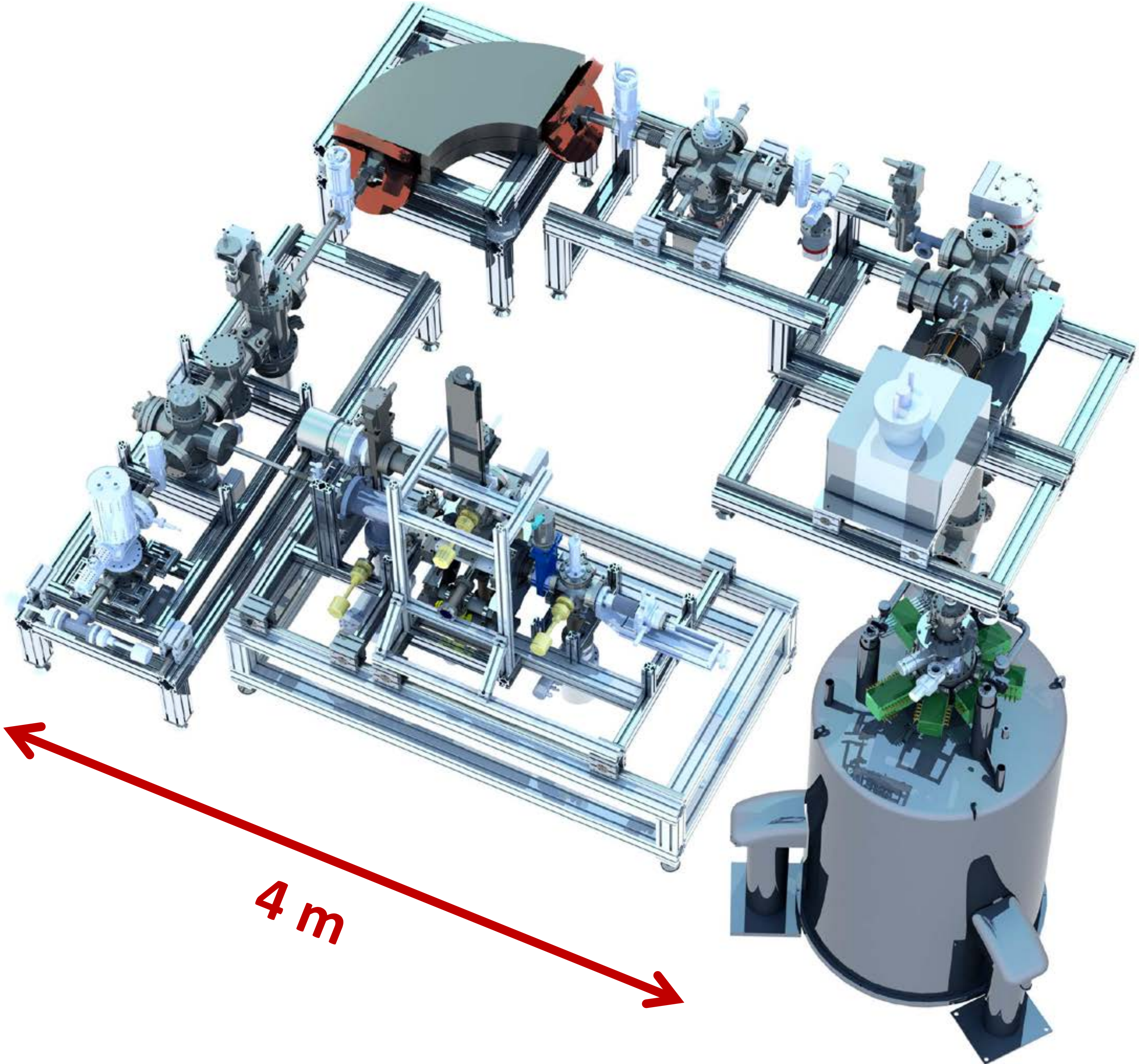
Max-Planck Institute for Nuclear Physics
(Heidelberg)

Division "Stored and Cooled Ions"
(Prof. Blaum)

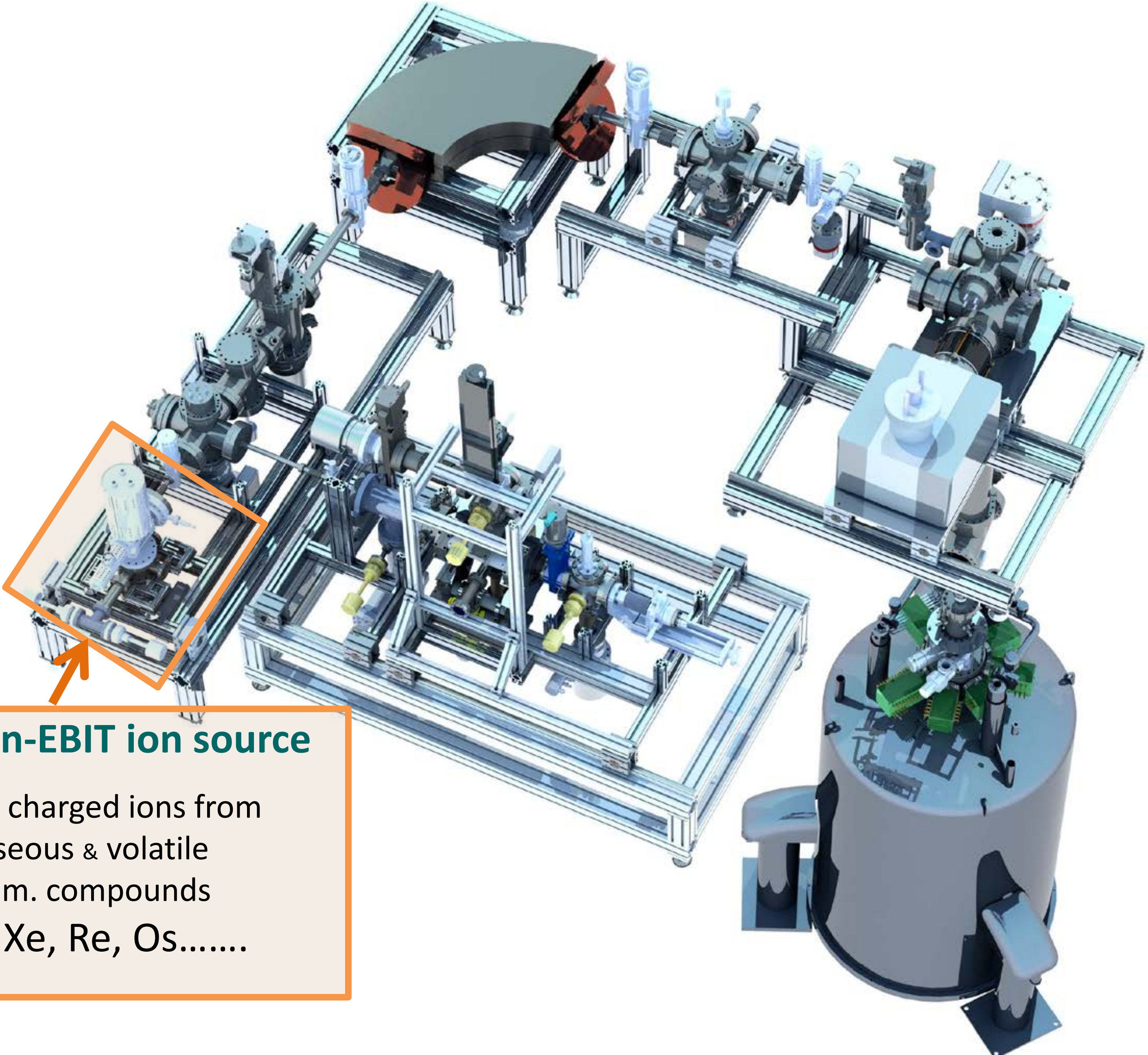


measurements of mass ratios of long-lived and stable nuclides up to uranium with an uncertainty < 10^{-11}

PENTATRAP setup



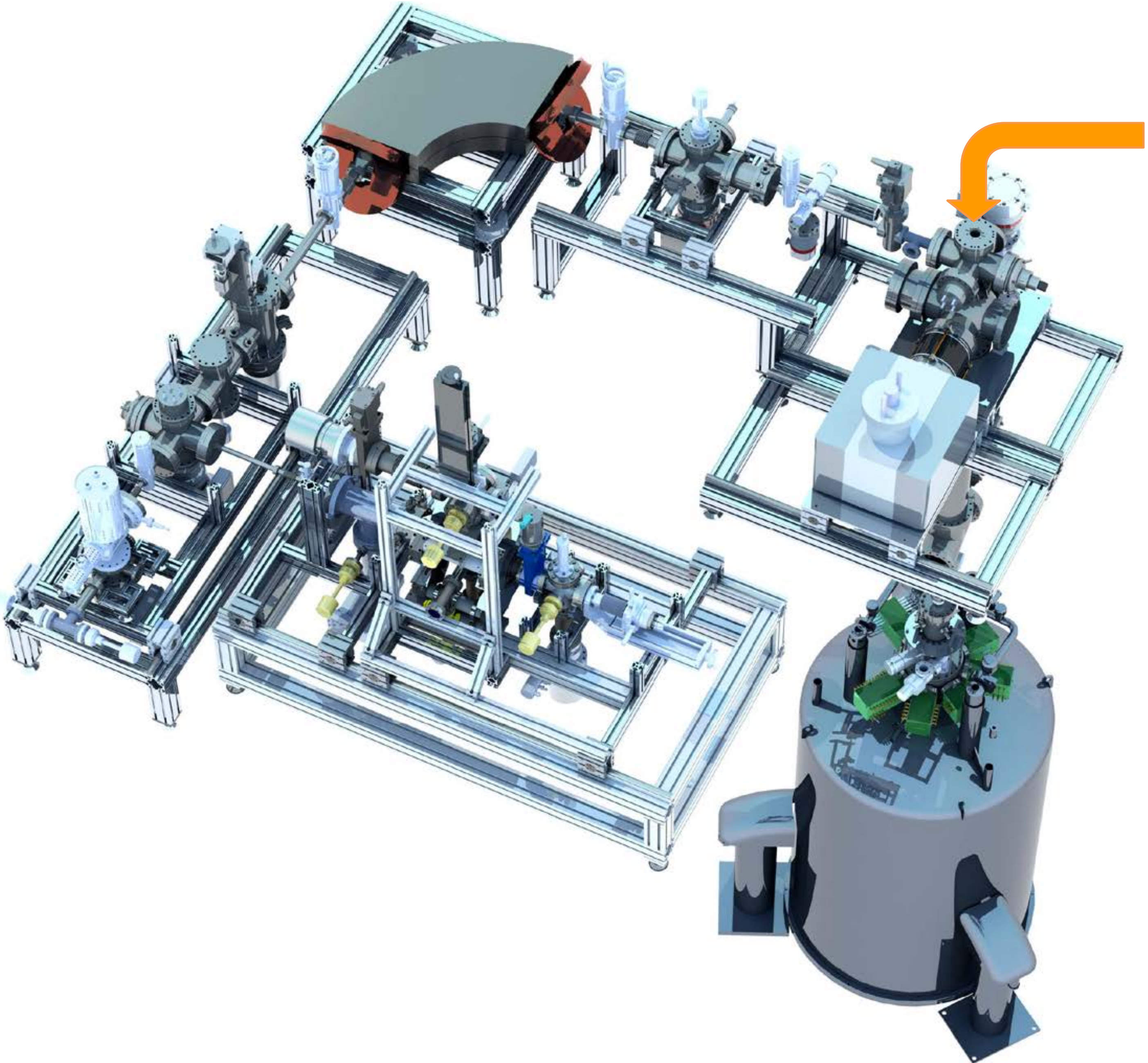
PENTATRAP setup



Dresden-EBIT ion source

highly charged ions from
gaseous & volatile
chem. compounds
Ar, Xe, Re, Os…….

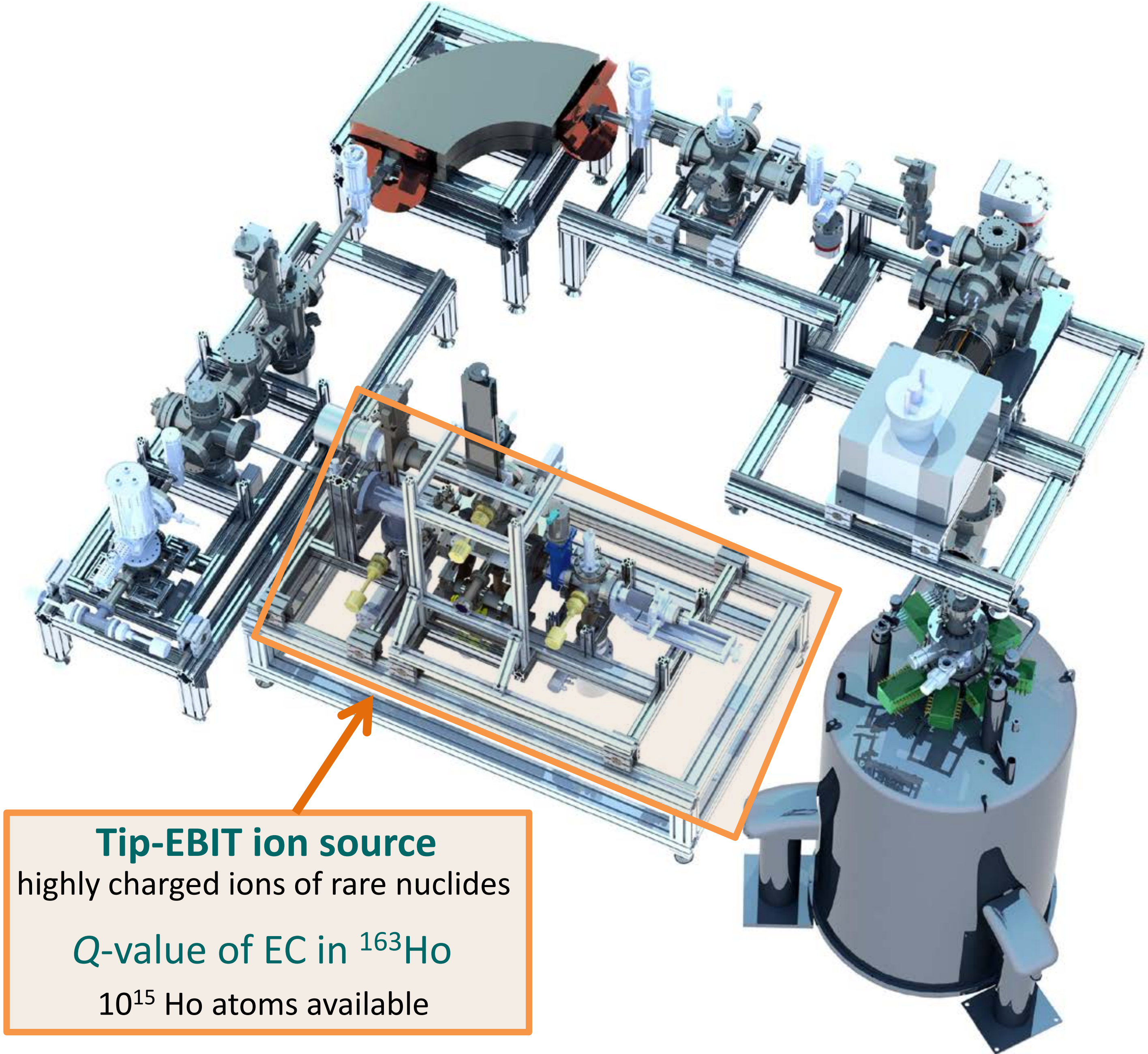
PENTATRAP setup



H-EBIT

Pb^{82+}, Pb^{81+}

PENTATRAP setup

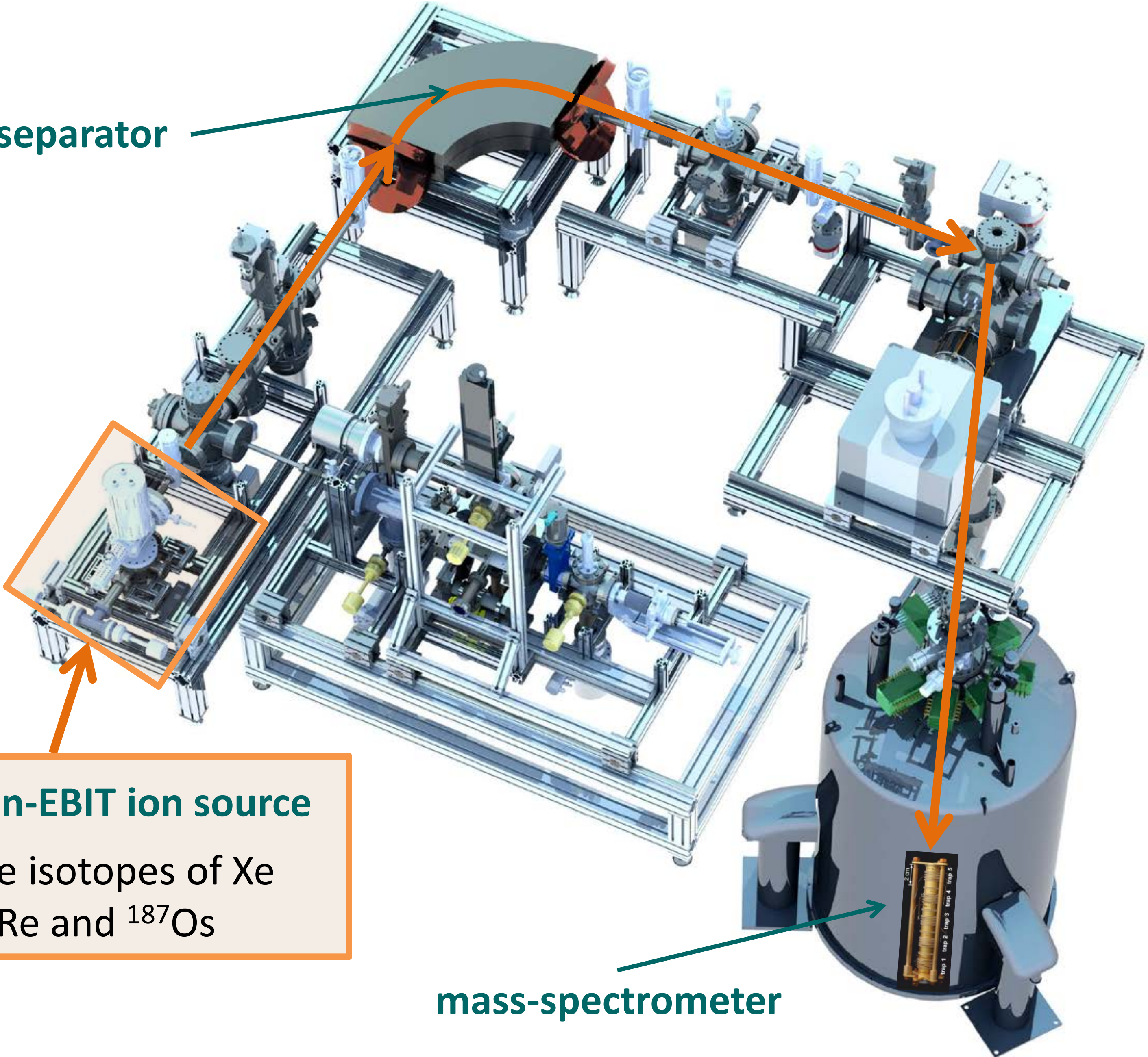


Tip-EBIT ion source
highly charged ions of rare nuclides

Q-value of EC in ^{163}Ho

10^{15} Ho atoms available

PENTATRAP setup



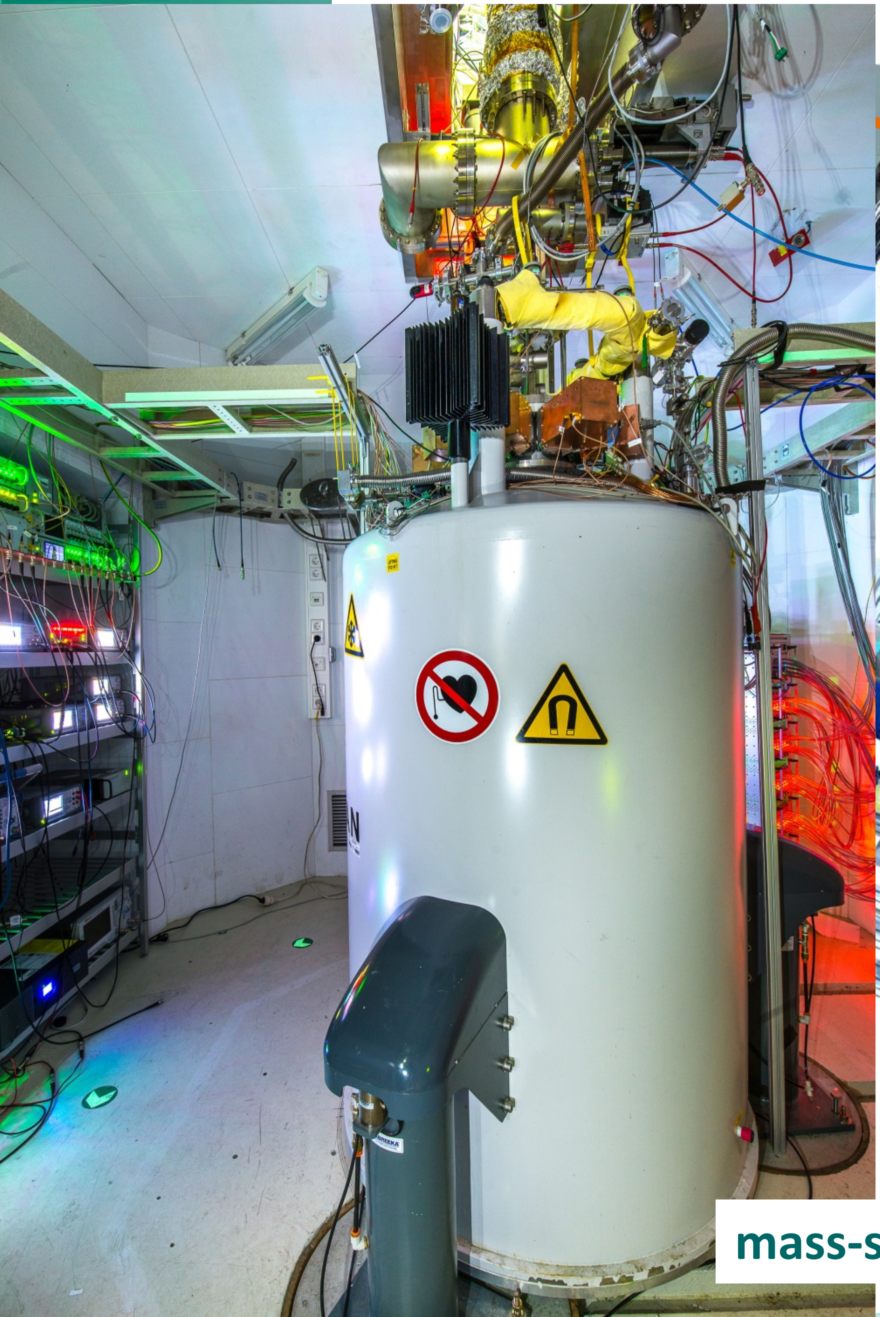
mass-separator

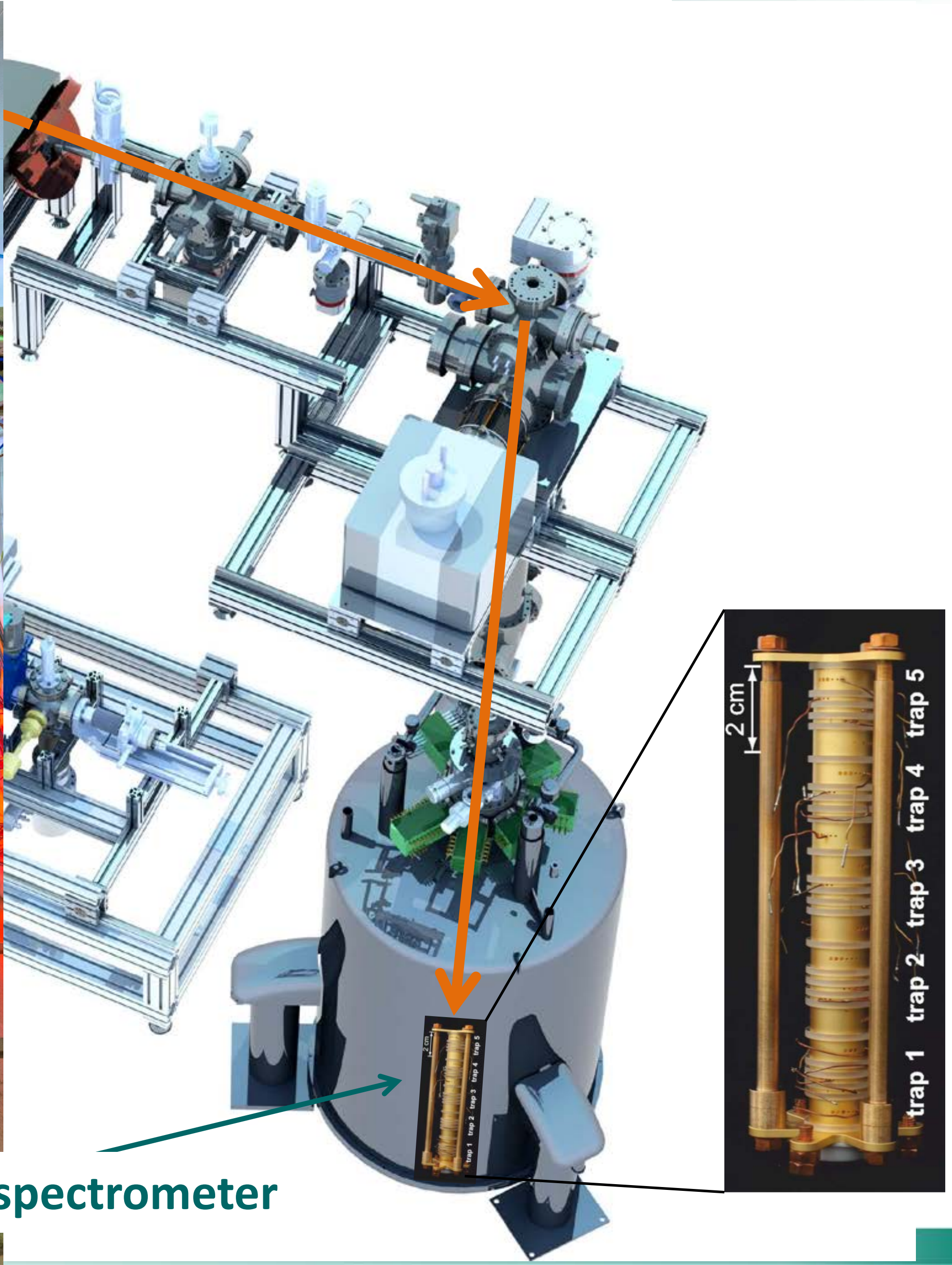
Dresden-EBIT ion source

stable isotopes of Xe
^{187}Re and ^{187}Os

mass-spectrometer

PENTATRAP setup





mass-spectrometer

PENTATRAP setup

unique features:

- **Stack of five Penning traps:**

  enable simultaneous measurements

- **Stable magnetic field:**

  $$\delta B/_{B} < 3 \cdot 10^{-10}\, h^{-1}$$

- **Highly charged ions:**

  increased measurement precision

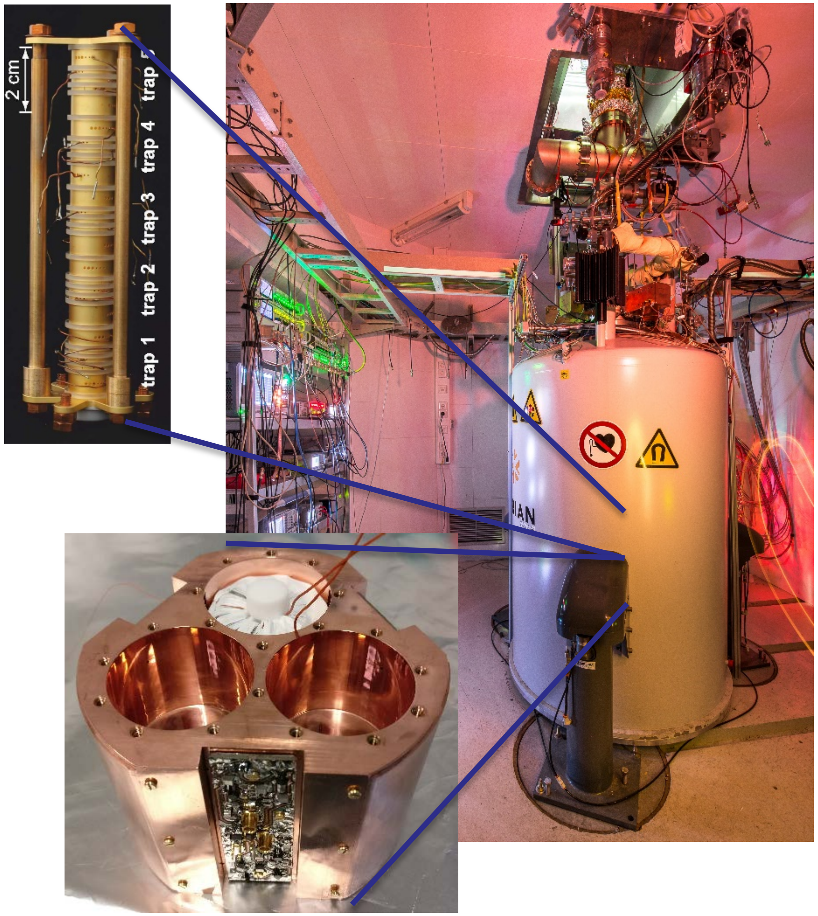
  and detection signal

- **Cryogenic (4.2 K) environment**

  (Penning-traps and electronics)

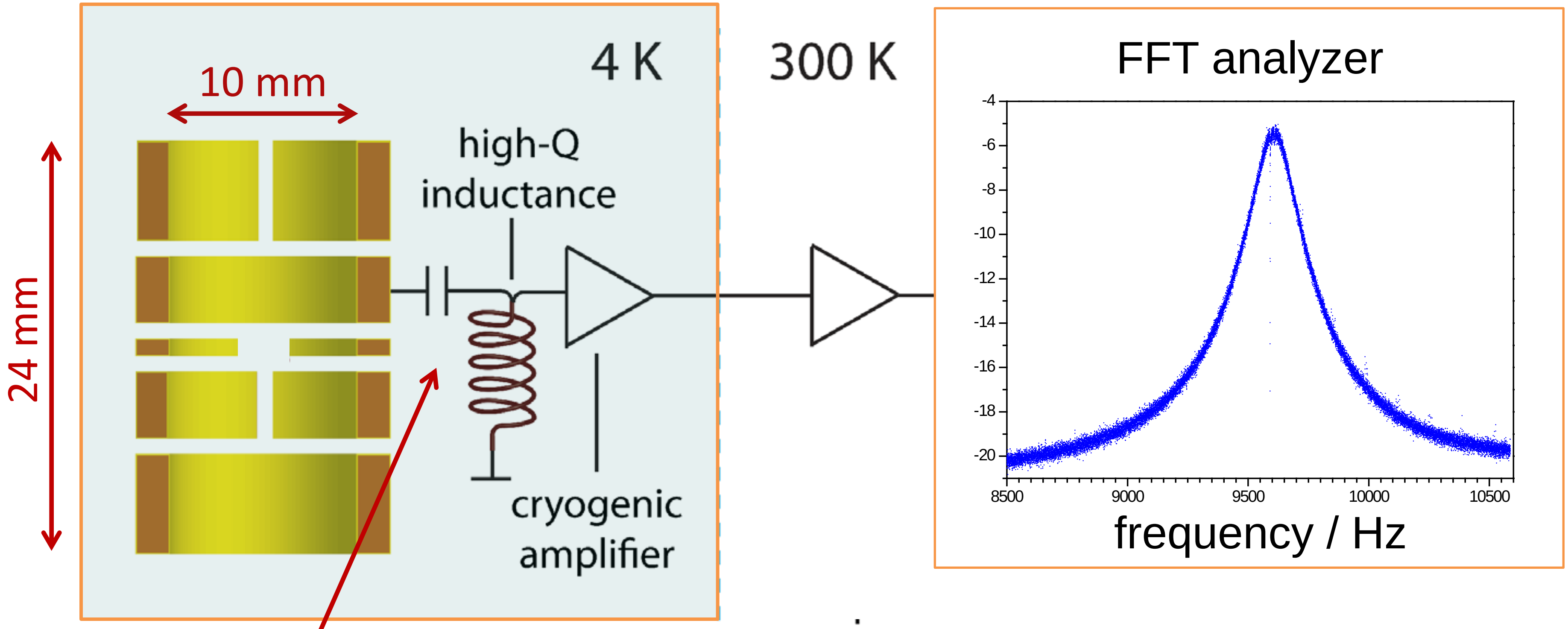
- **Phase sensitive detection methods**

- **In-house designed ultra-stable voltage source**



Repp, J. et al., Appl. Phys. B 107, 983 (2012)
Roux, C. et al., Appl. Phys. B 107, 997 (2012)
Sturm, S. et al., Phys. Rev. Lett. 107, 143003 (2011)
Böhm, C. et al., Nucl. Instrum. Meth. A 828, 125 (2016)

Measurement of trap frequencies with PENTATRAP



LC-circuit

(resonant circuit)

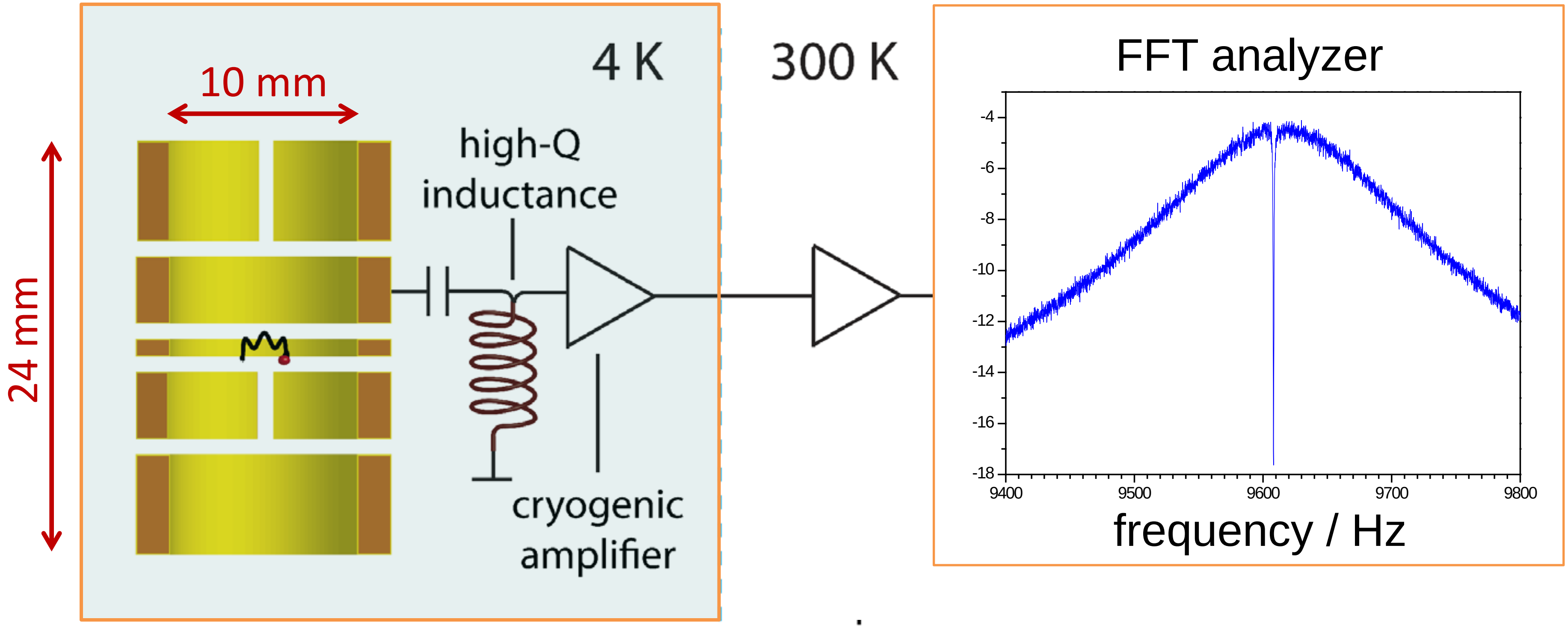
→

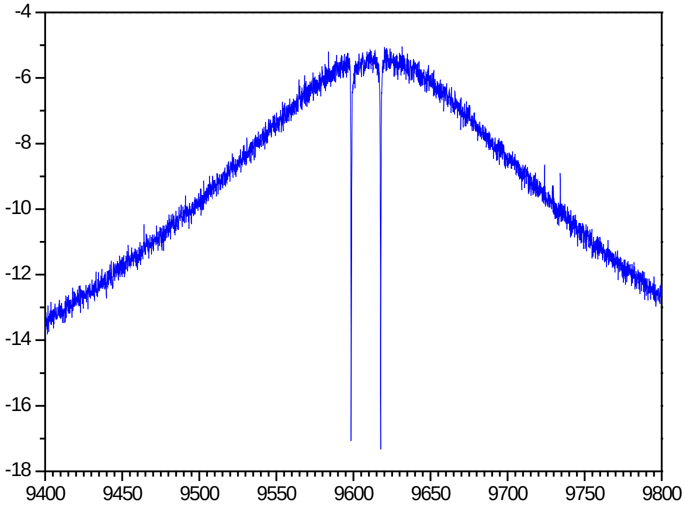
(1) thermal bath (4 K)

reduction of ion motional amplitudes

(2) frequency-measurement system

Measurement of trap frequencies with PENTATRAP

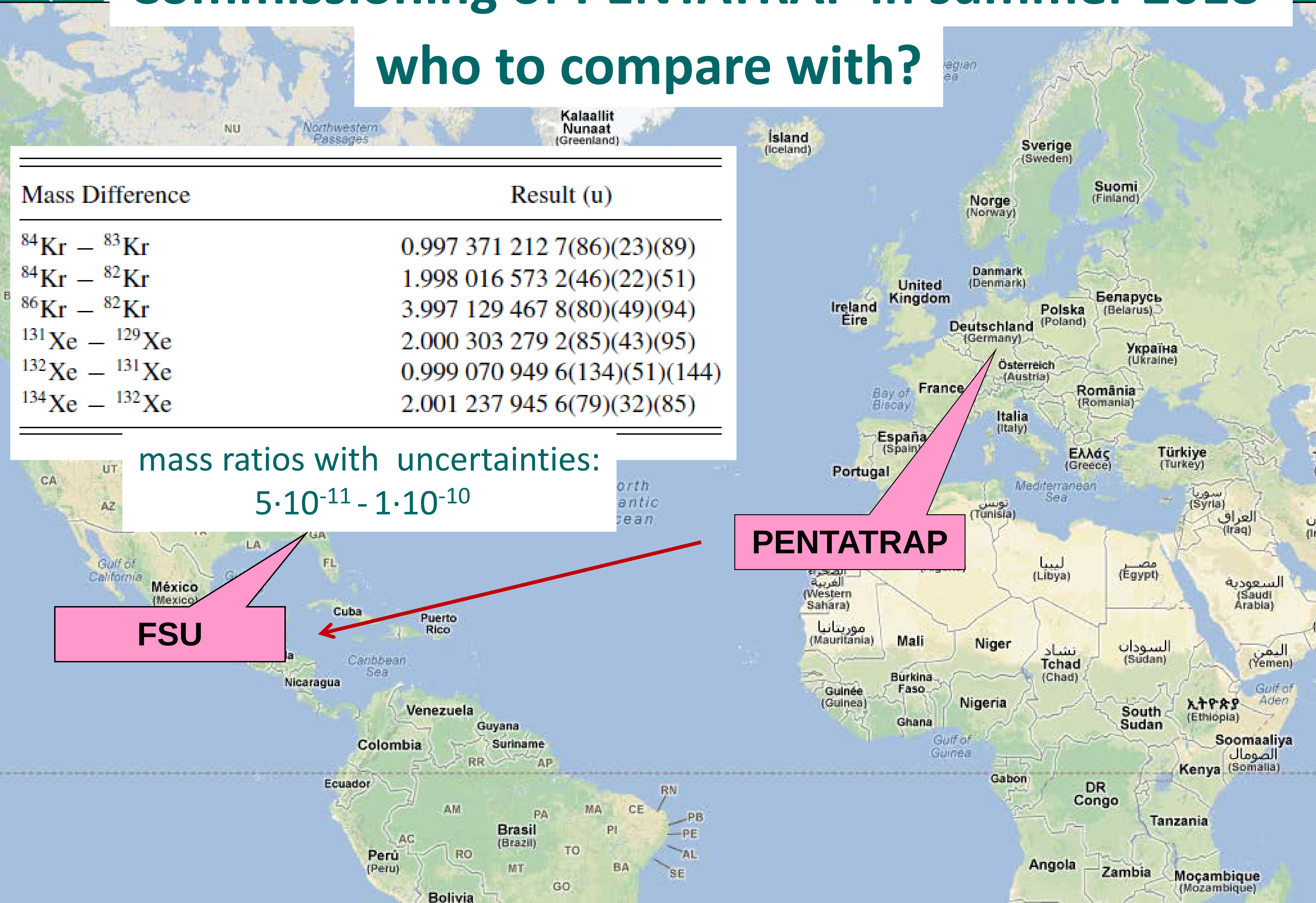




axial motion:	$\nu_z \sim f(\frac{q}{m}U)$	$\rho_z \sim 10\,\mu m$
cyclotron motion:	$\nu_+ \sim f(\frac{q}{m}B)$	$\rho_+ \sim 1\,\mu m$
magnetron motion:	$\nu_- \sim f(U)$	$\rho_- \sim 1\,\mu m$

Commissioning of PENTATRAP in summer 2018

who to compare with?



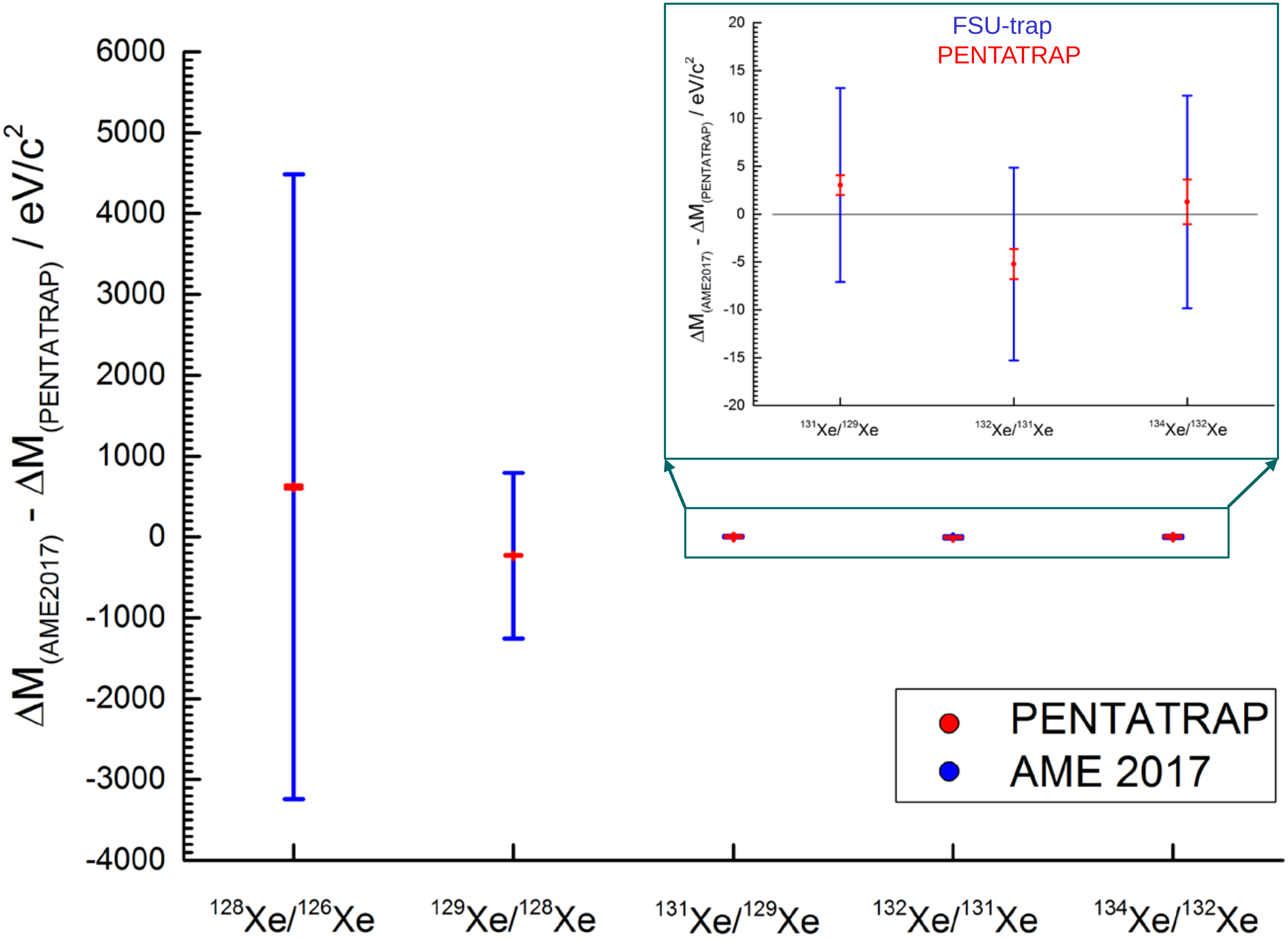
Mass Difference	Result (u)
$^{84}\mathrm{Kr} - {}^{83}\mathrm{Kr}$	0.997 371 212 7(86)(23)(89)
$^{84}\mathrm{Kr} - {}^{82}\mathrm{Kr}$	1.998 016 573 2(46)(22)(51)
$^{86}\mathrm{Kr} - {}^{82}\mathrm{Kr}$	3.997 129 467 8(80)(49)(94)
$^{131}\mathrm{Xe} - {}^{129}\mathrm{Xe}$	2.000 303 279 2(85)(43)(95)
$^{132}\mathrm{Xe} - {}^{131}\mathrm{Xe}$	0.999 070 949 6(134)(51)(144)
$^{134}\mathrm{Xe} - {}^{132}\mathrm{Xe}$	2.001 237 945 6(79)(32)(85)

mass ratios with uncertainties:
$5 \cdot 10^{-11} - 1 \cdot 10^{-10}$

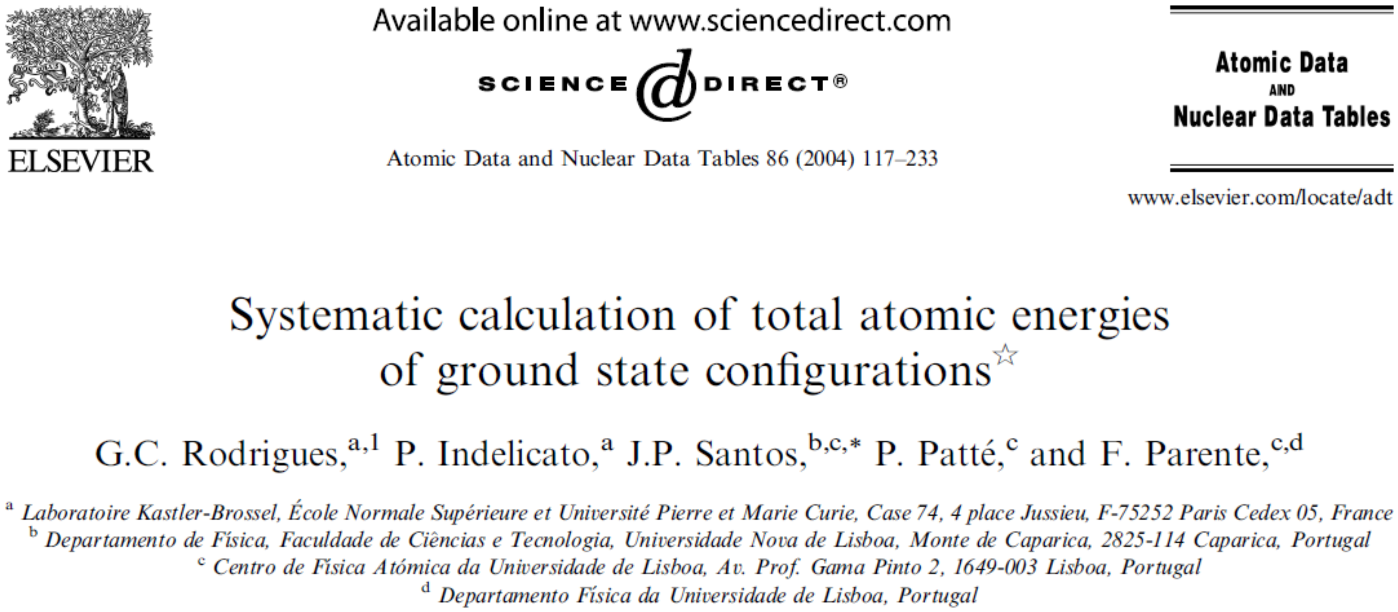
PENTATRAP

FSU

Commissioning of PENTATRAP in summer 2018



Binding Energy of 18th electron in Xe: $M(^{132}Xe^{18+}) - M(^{132}Xe^{17+})$



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Atomic Data and Nuclear Data Tables 86 (2004) 117–233

Atomic Data
AND
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Systematic calculation of total atomic energies of ground state configurations☆

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[b] *Departamento de Física, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Monte de Caparica, 2825-114 Caparica, Portugal*
[c] *Centro de Física Atómica da Universidade de Lisboa, Av. Prof. Gama Pinto 2, 1649-003 Lisboa, Portugal*
[d] *Departamento Física da Universidade de Lisboa, Portugal*

$$B^{18th\_e}(Xe)\Big|_{\text{P. Indelicato}} = 432.4(0.5)\ \text{eV}$$

↓

$$\delta[M(^{132}Xe^{18+})/M(^{132}Xe^{17+})] \approx 4\cdot 10^{-12}$$

Binding Energy of 18th electron in Xe: $M(^{132}Xe^{18+}) - M(^{132}Xe^{17+})$

$$B^{18th\_e}(Xe)\Big|_{\text{P. Indelicato}} = 432.4(0.5)\ \text{eV}$$

Measurement with PENTATRAP

$$\delta[M(^{132}Xe^{18+})/M(^{132}Xe^{17+})] \approx \begin{matrix} 1.1\cdot 10^{-11}\ \text{(stat)} \\ 2.0\cdot 10^{-11}\ \text{(sys)} \end{matrix}$$

$$B^{18th\_e}(Xe)\Big|_{\text{PENTATRAP}} = 433.0(3.0)\ \text{eV}$$

Commissioning of PENTATRAP in summer 2018

ongoing measurement:

Q-value of β^- decay of ^{187}Re

Q-value = 2466.7 (1.6) eV

ECHo

Q-value of EC in ^{163}Ho with ~ a few eV uncertainty

^{163}Ho lives ~ 4500 years

we have a ^{163}Ho sample with 10^{15} atoms

→

development of an EBIT for a production of highly charged ions of ^{163}Ho

ongoing measurement: Q-value of β^- decay of ^{187}Re

we measure : $R = \dfrac{\nu_c[^{187}Os^{29+}]}{\nu_c[^{187}Re^{29+}]}$

we want to determine :

$$Q = M[^{187}\mathrm{Re}] - M[^{187}\mathrm{Os}] = M[^{187}\mathrm{Os}^{29+}]\cdot[\boldsymbol{R}-1]+\boldsymbol{\Delta B}$$

Maurits Haverkort
Heidelberg University Institute for Theoretical Physics

Zoltan Harman
Max-Planck Institute for Nuclear Physics

Paul Indelicato
Directeur de Recherche au CNRS

optimal charge state for Re/Os ions is 29+:

- easy to achieve an uncertainty of 10^{-11} in R-measurement
- easy to produce 29+ Re/Os ions with our EBIT
- “easy” electron configurations: $^{187}\mathrm{Re}^{29+}$ - $[\mathrm{Kr}]^4\mathrm{d}^{10}$; $^{187}\mathrm{Os}^{29+}$ - $[\mathrm{Kr}]^4\mathrm{d}^{10}4\mathrm{f}^1$

ongoing measurement: *Q*-value of β^- decay of ^{187}Re

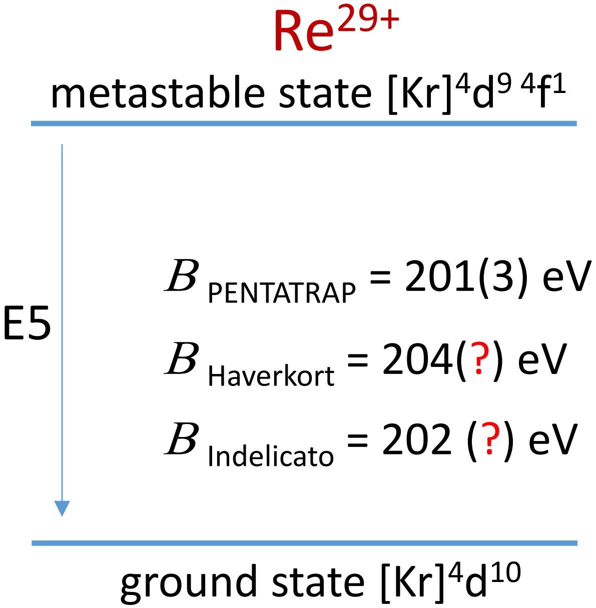
preliminary results

For Re^{29+} vs. Os^{29+} we measure two ratios with a 50/50 probability:

$$R_1 = 1.000000013886(15)$$

$$R_2 = 1.000000015024(12)$$

- Os^{29+} vs. Os^{29+} measurements yield always unity.
- Re^{29+} vs. Re^{29+} measurements yield either unity or $1+1.14\square10^{-9}$.



Re^{29+}

metastable state $[Kr]^4d^9\ ^4f^1$

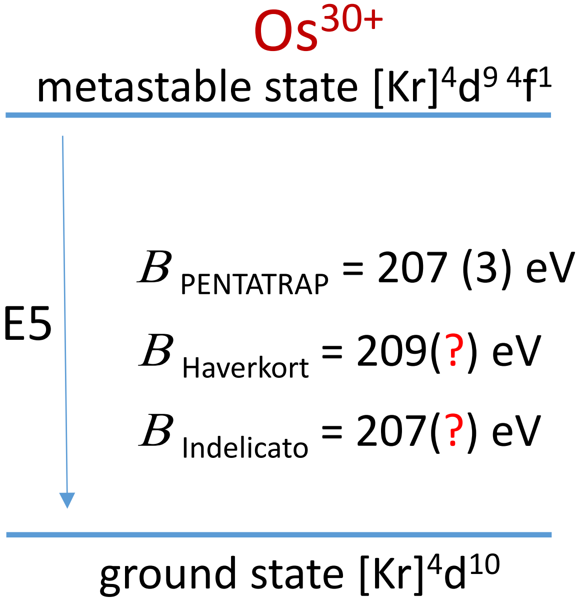
E5

$B_{\text{PENTATRAP}}$ = 201(3) eV

$B_{\text{Haverkort}}$ = 204(?) eV

$B_{\text{Indelicato}}$ = 202 (?) eV

ground state $[Kr]^4d^{10}$



Os^{30+}

metastable state $[Kr]^4d^9\ ^4f^1$

E5

$B_{\text{PENTATRAP}}$ = 207 (3) eV

$B_{\text{Haverkort}}$ = 209(?) eV

$B_{\text{Indelicato}}$ = 207(?) eV

ground state $[Kr]^4d^{10}$

ongoing measurement: *Q*-value of β^- decay of ^{187}Re

preliminary results

We assume that the smaller measured frequency ratio $R_1 = 1.000000013886(15)$ corresponds to the ground state in Re^{29+} . We use this ratio to calculate the *Q*-value of the beta-decay of ^{187}Re.

Maurits Haverkort has calculated the total electron binding energies for the missing 29 electrons in Re^{29+} and Os^{29+} :

$$\begin{tikzcd}[column sep=small] B(\mathrm{Os}^{29+}) = 10971.6\ \mathrm{eV} \arrow[dr] & & B(\mathrm{Re}^{29+}) = 10912.4\ \mathrm{eV} \arrow[dl] \\ & \Delta B = 59.2\ \mathrm{eV}\ (\text{uncertainty ???}) & \end{tikzcd}$$

$$\begin{array}{l} Q_{PENTATRAP} = 2477.4(2.9+???)\ \mathrm{eV} \\ Q_{AME} = 2466.7(1.6)\ \mathrm{eV} \end{array} \longrightarrow Q_{PENTATRAP} - Q_{AME} = 10.7(3.3+???)\ \mathrm{eV}$$

already good agreement;

theoreticians are working on the uncertainty of their calculations

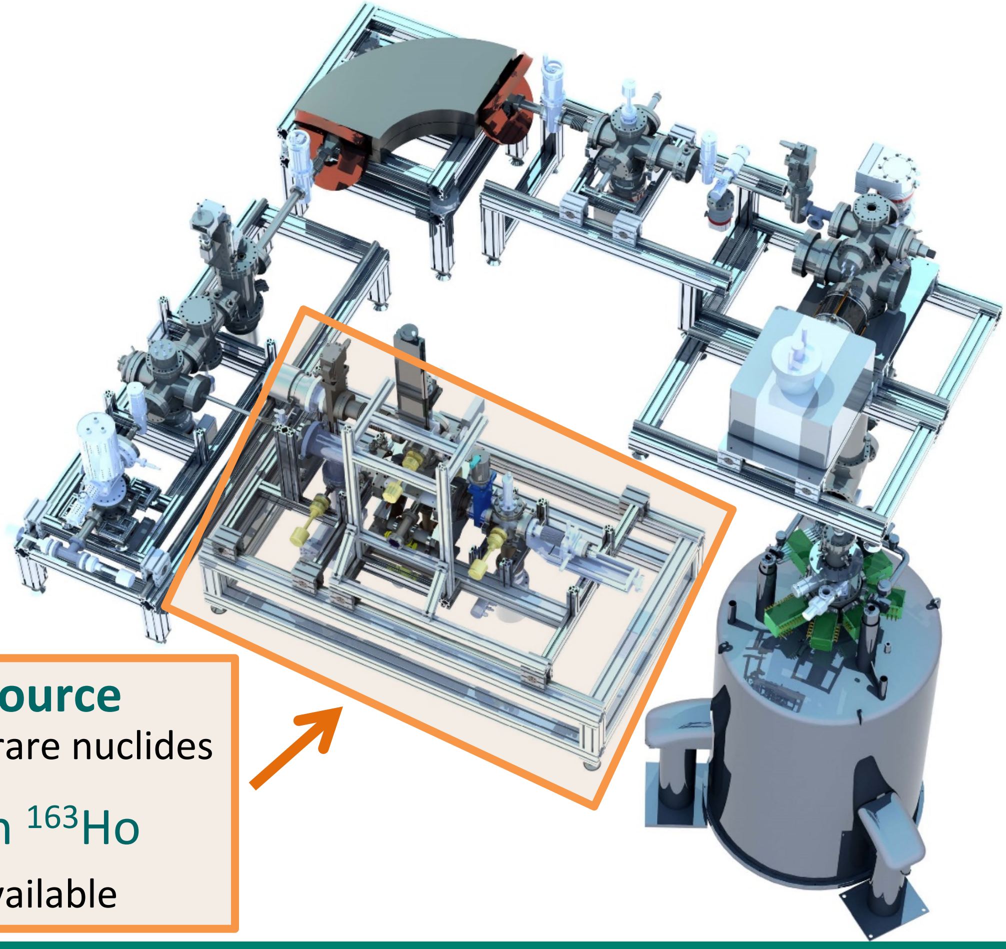
Q-value of EC in ^{163}Ho with ~ a few eV uncertainty

^{163}Ho lives ~ 4500 years

we have a ^{163}Ho sample
with 10^{15} atoms

→

development of the Tip-EBIT
for a production of
highly charged ions of ^{163}Ho



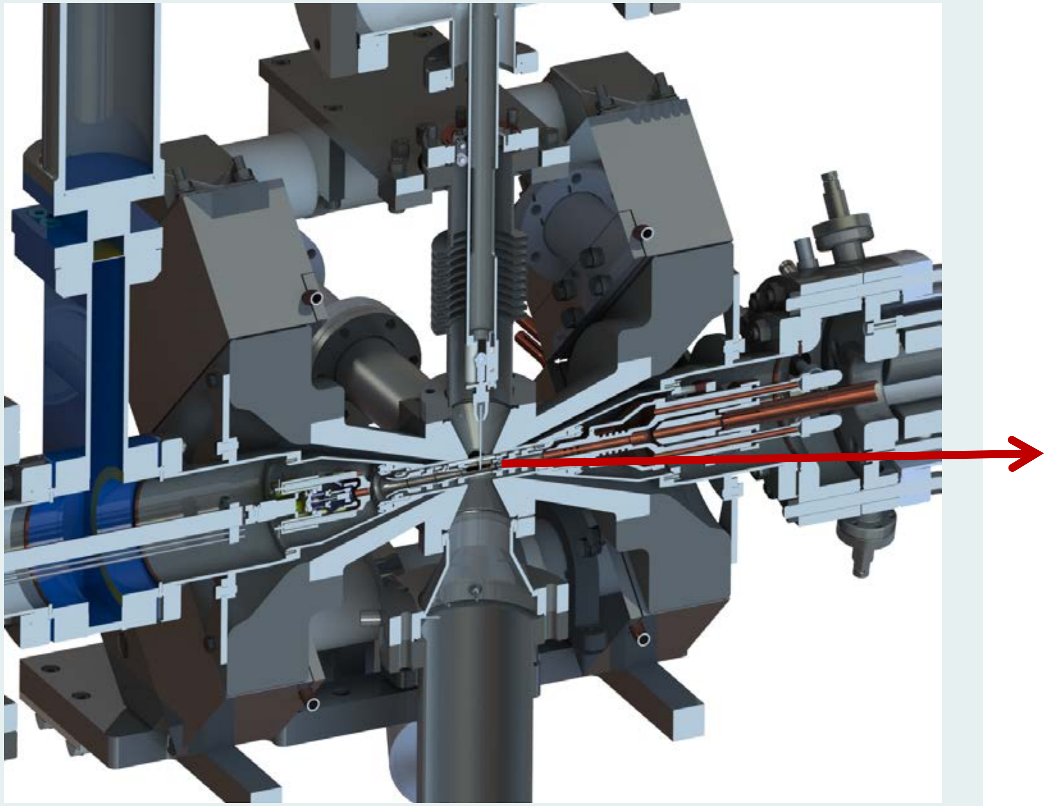
Tip-EBIT ion source
highly charged ions of rare nuclides

Q-value of EC in ^{163}Ho

10^{15} Ho atoms available

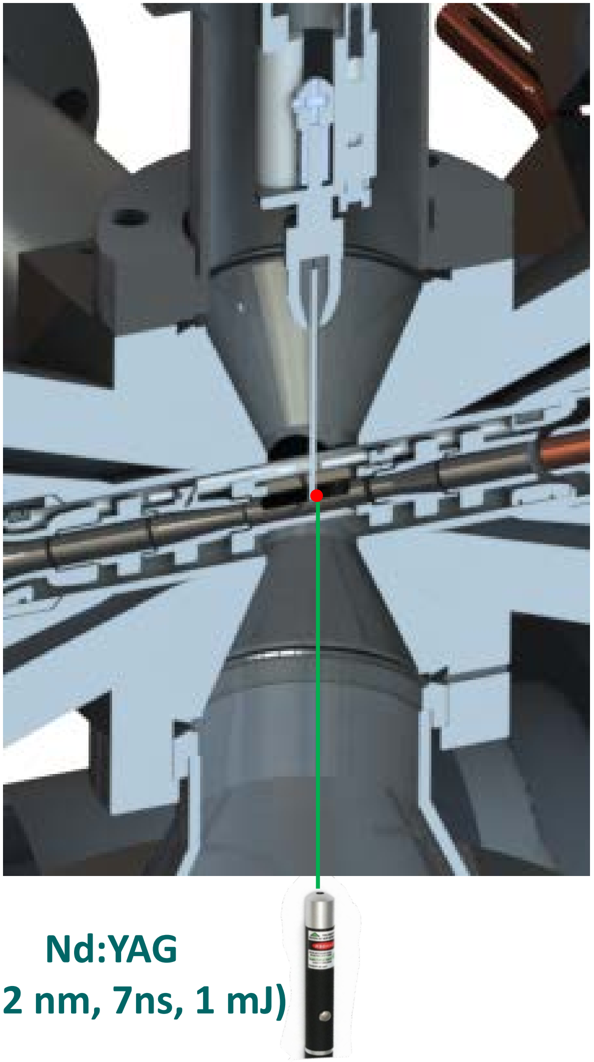
Development of the Tip-EBIT

Mini-EBIT developed in Crespo's group



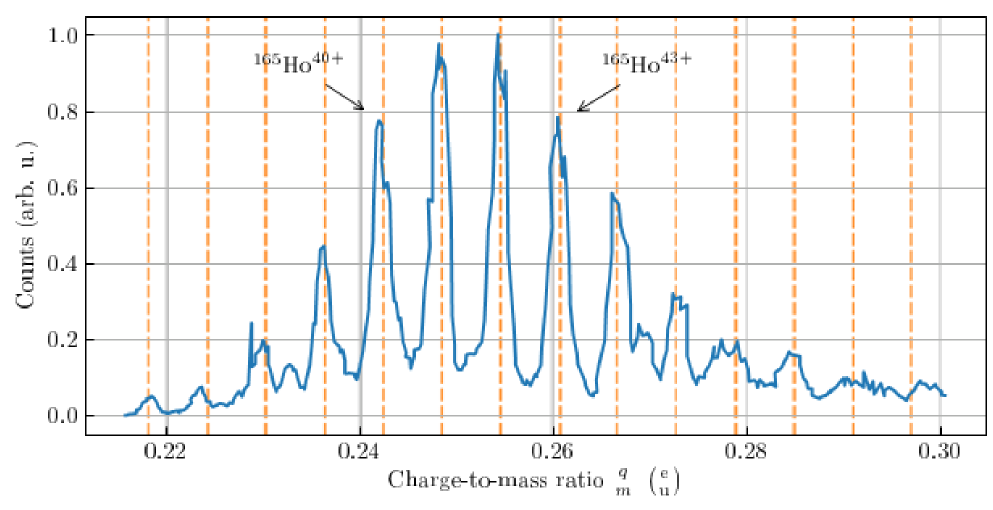
compact room temperature
permanent magnet, 0.8 T
max. electron current = 60 mA

Christoph Schweiger
Charlotte König



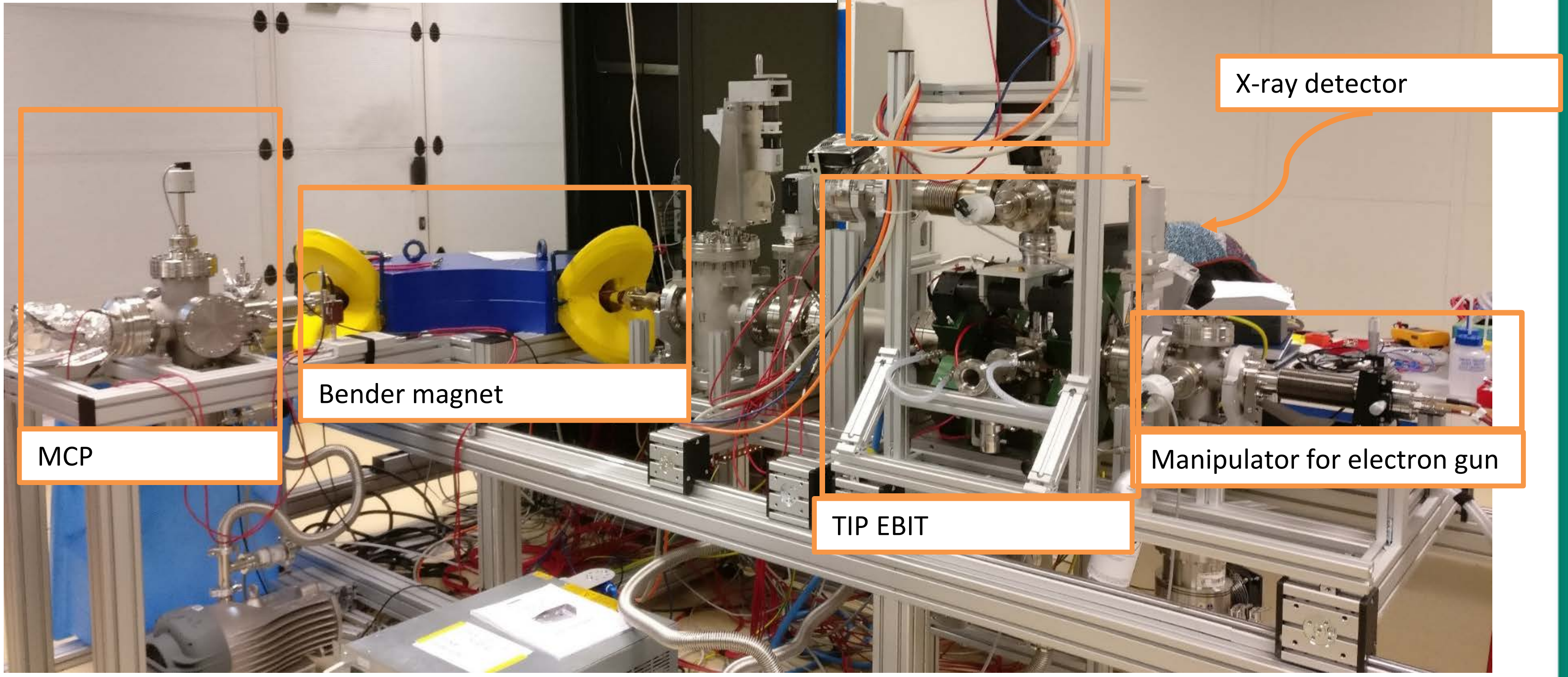
Nd:YAG
(532 nm, 7ns, 1 mJ)

Development of the Tip-EBIT

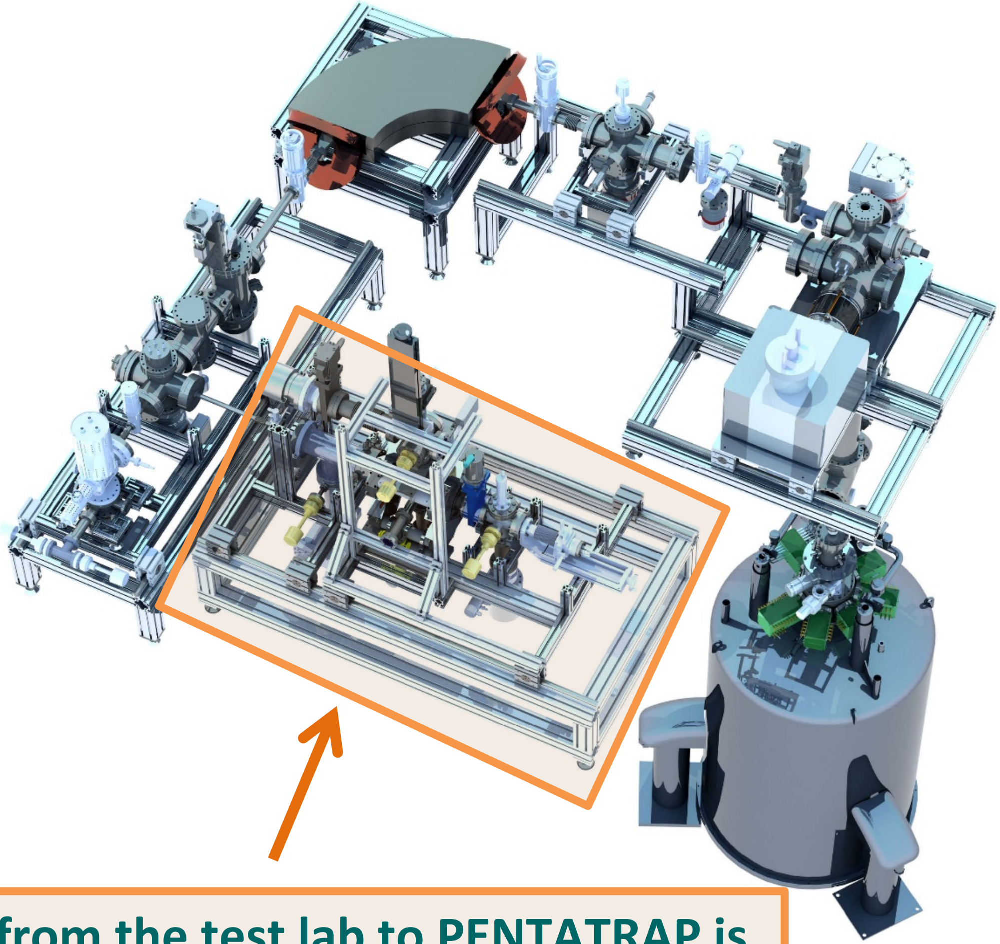


^{165}Ho sample: 10^{12} atoms

life time: 20000 laser shots



Q-value of EC in ^{163}Ho with ~ a few eV uncertainty

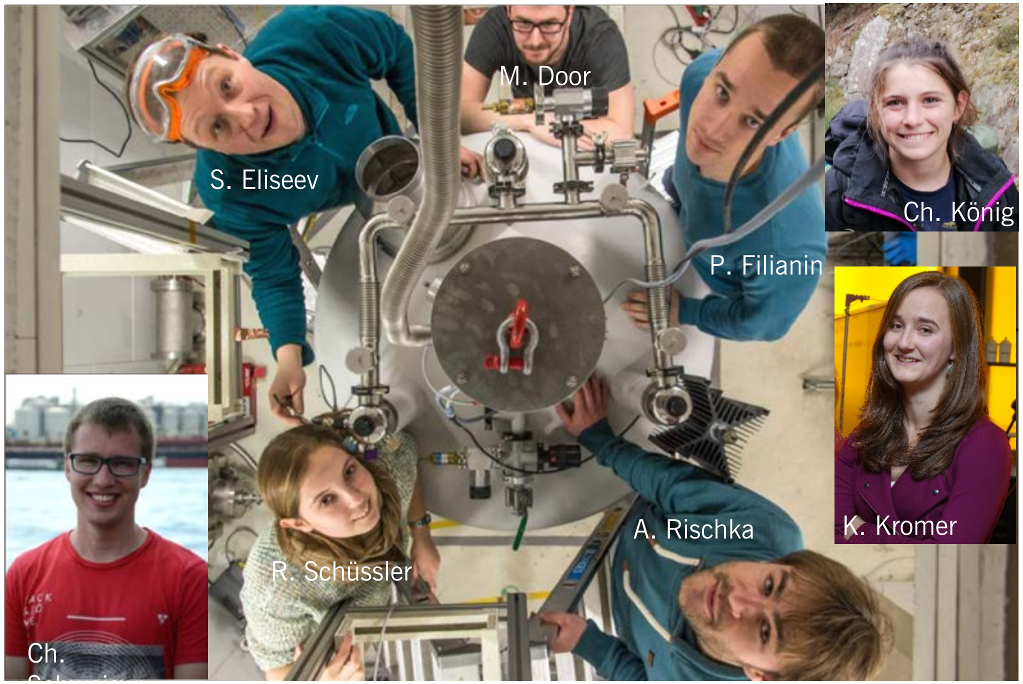


Movement from the test lab to PENTATRAP is scheduled for this summer.

This autumn - first measurements with ^{163}Ho

Thank you for your attention !

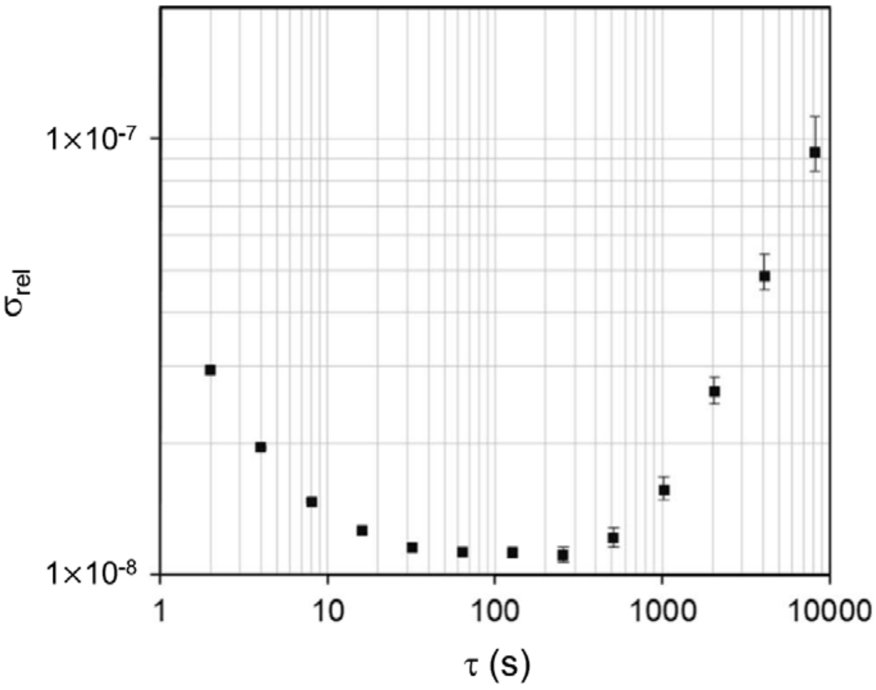
The PENTATRAP Team



DFG Research
Unit FOR 2202

Christoph Schweiger, José R. Crespo López-Urrutia, Menno Door, Sergey Eliseev, Pavel Filianin, Charlotte König, Kathrin Kromer, Marius Müller, Yuri N. Novikov, Alexander Rischka, Rima X. Schüssler, Stefan Ulmer, Sven Sturm and Klaus Blaum

StaRep – Ultra stable voltage source

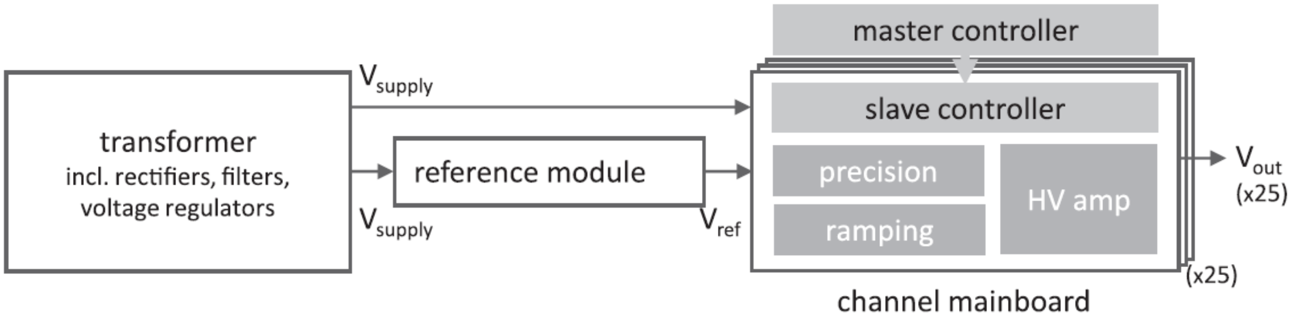


Voltage range: 0 V to -100 V

Rel. stability: < 10E-8 @ 10 min

Noise (0.1 Hz – 10 Hz): < 1.5 µV

Temp. coeff. < 0.1 ppm/K


transformer
incl. rectifiers, filters, voltage regulators

V_{supply}

reference module

V_{supply}

V_{ref}

master controller

slave controller

precision

ramping

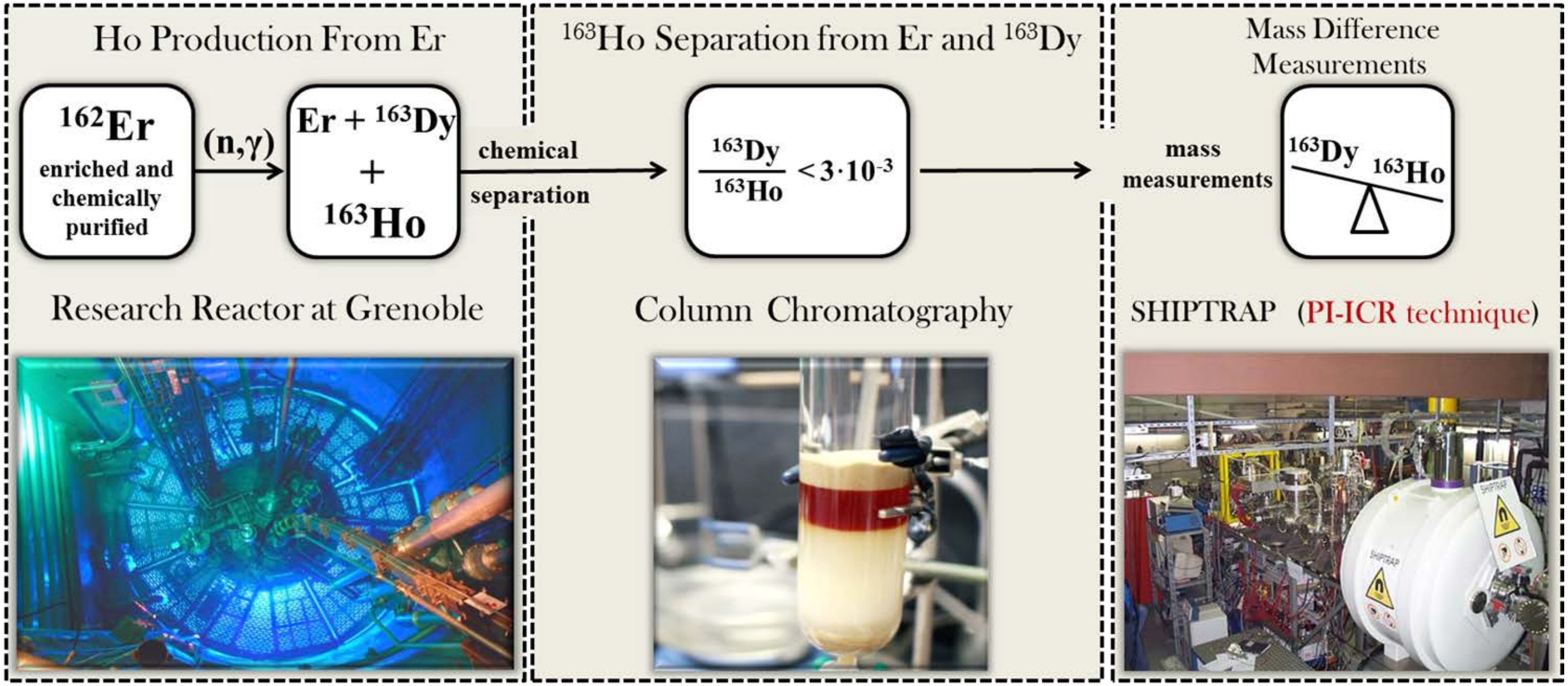
HV amp

V_{out} (x25)

(x25)

channel mainboard

^{163}Ho wire preparation



Ho Production From Er

^{162}Er enriched and chemically purified $\xrightarrow{(n,\gamma)}$ Er + ^{163}Dy + ^{163}Ho

Research Reactor at Grenoble

chemical separation

^{163}Ho Separation from Er and ^{163}Dy

$\frac{^{163}\text{Dy}}{^{163}\text{Ho}} < 3\cdot10^{-3}$

Column Chromatography

mass measurements

Mass Difference Measurements

^{163}Dy ^{163}Ho

SHIPTRAP (PI-ICR technique)

Mass-ratio measurements at a level of 10^{-11}

Neutrino physics

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

Test of $E = mc^2$

$$E = \frac{hc}{\lambda} = \Delta m\left({}^{36}\mathrm{Cl} - {}^{35}\mathrm{Cl} - n\right)c^2$$

Binding energies

$$E_B(\mathrm{Xe}^{17+}) = \Delta m(\mathbf{Xe^{26+}} - \mathbf{Xe^{25+}})c^2 - m_e c^2$$

g-factor

$$\Delta m\left({}^{48}\mathrm{Ca}^{17+} - {}^{40}\mathrm{Ca}^{17+}\right)$$

Thorium clock

$$E = \Delta m\left({}^{229m}\mathrm{Th} - {}^{229}\mathrm{Th}\right)c^2$$

The PENTATRAP experiment

Limitations in PTMS:

–Magnetic field fluctuations and sta
of the electrostatic potential

New in PENTATRAP:

–Stack of five Penning traps enable simulta
measurements

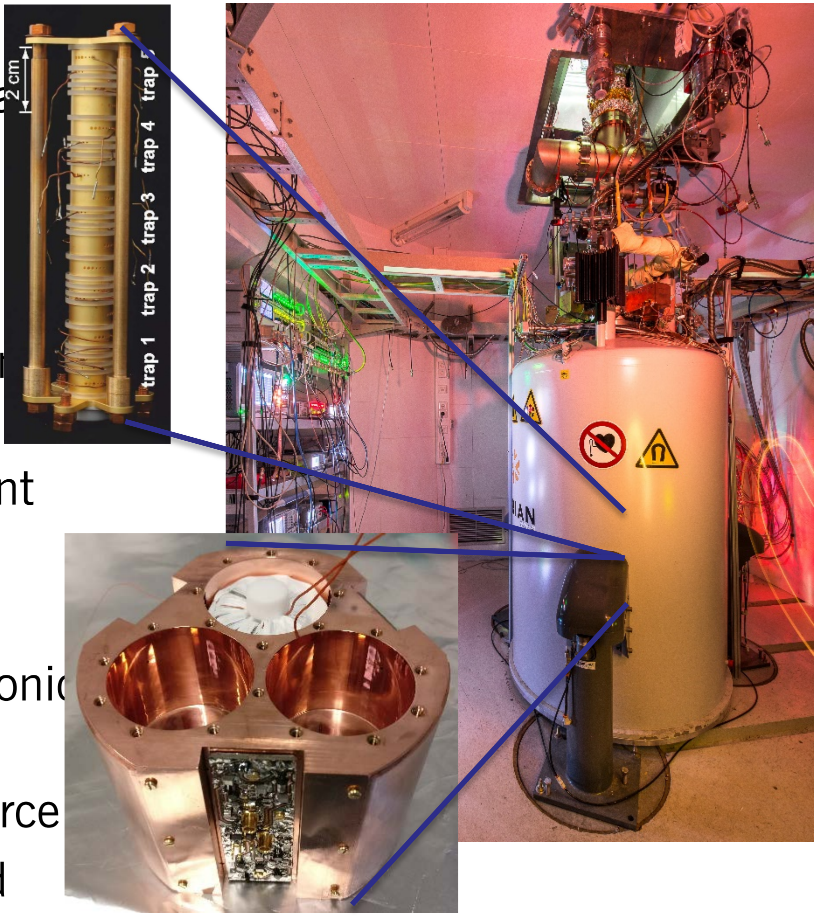
–Highly charged ions: Increase measurement precision and detection signal

–Phase sensitive detection methods

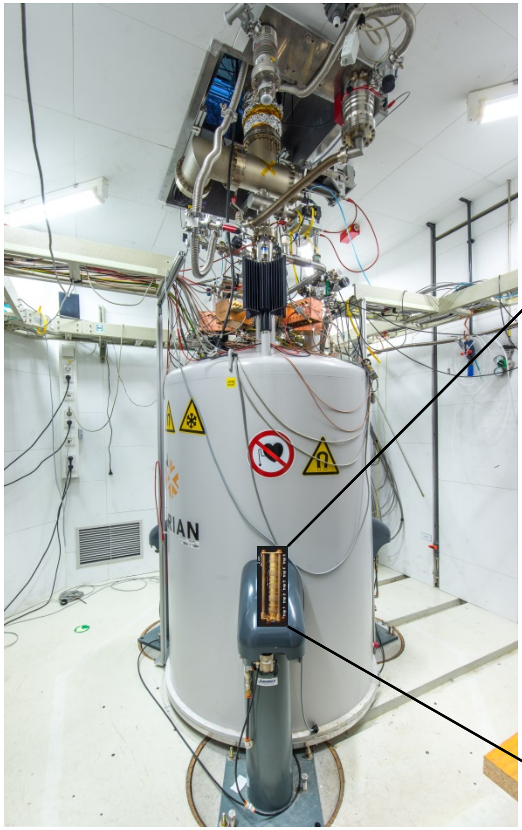
–Highly sensitive cryogenic detection electroni
(FT-ICR)

–In-house designed ultra-stable voltage source

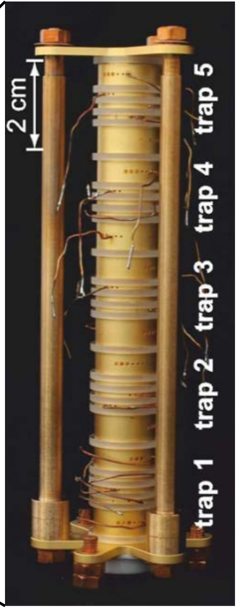
–Cryogenic environment (Penning-traps and electronics)



Repp, J. et al., Appl. Phys. B 107, 983 (2012)
Roux, C. et al., Appl. Phys. B 107, 997 (2012)
Sturm, S. et al., Phys. Rev. Lett. 107, 143003 (2011)
Böhm, C. et al., Nucl. Instrum. Meth. A 828, 125 (2016)

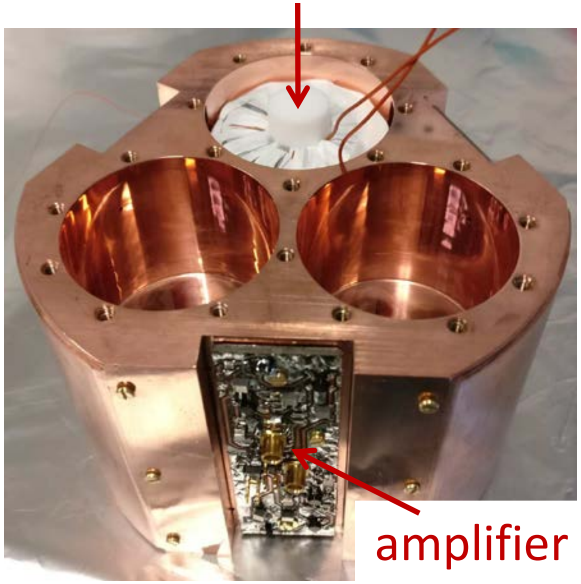


trap tower



trap electrodes

NbTi toroidal coil



amplifier

Systematic uncertainties

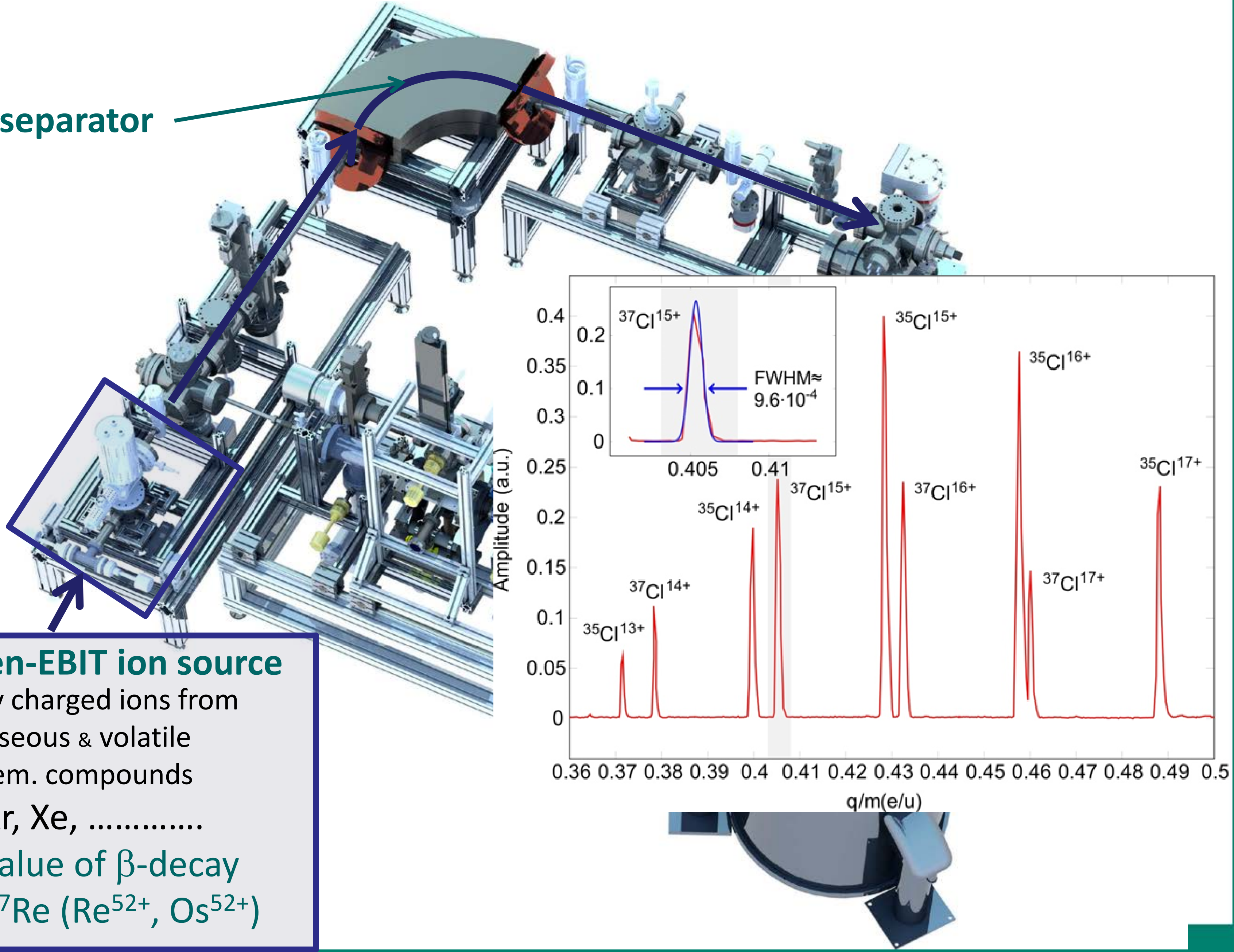
Effect	Estimate/Measurement
An ion in an adjacent trap	$\delta R \ll 10^{-11}$
Image charge effect	$\delta R = 0$ (same mass)
Relativistic shift	$\delta R < 5 \cdot 10^{-12}$
Shift associated with the resonator	$\delta R \ll 10^{-11}$
Higher order electric field components C_4/C_6	$\delta R\ (C_4) = 10^{-12}$
Magnetic field inhomogeneities B_1/B_2	effect of B_2: $\delta R \ll 10^{-11}$ **effect of B_1: $\delta R \sim 2 \cdot 10^{-11}$**
Grouping the data/Fit polynomial order	$\delta R = 1.2 \cdot 10^{-11}$

Preliminary value (E_B): 433.0 (3.0) eV

Theory value: 432.4 (0.5) eV

PENTATRAP setup

mass-separator



Dresden-EBIT ion source

highly charged ions from
gaseous & volatile
chem. compounds

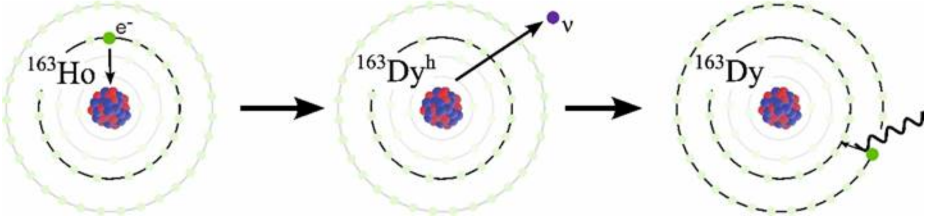
Ar, Xe, ...

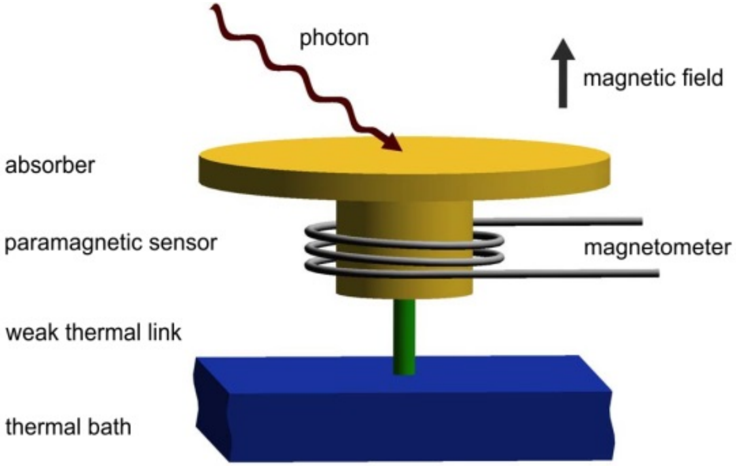
Q-value of β-decay
of ^{187}Re (Re^{52+}, Os^{52+})

The **E**lectron **C**apture in **Ho**lmium experiment

ECHo

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





Measurement of the de-excitation spectrum:

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

Gastaldo, L. et al., EPJ ST 226, 1623 (2017)
Fleischmann, L. et al., J. of Phys.: Conf. S. 150, 012013 (2009)

The **E**lectron **C**apture in **Ho**lmium experiment

ECHo Phase 1 (Proof of Principle): 1 kBq

ECHo Phase 2: 100 kBq

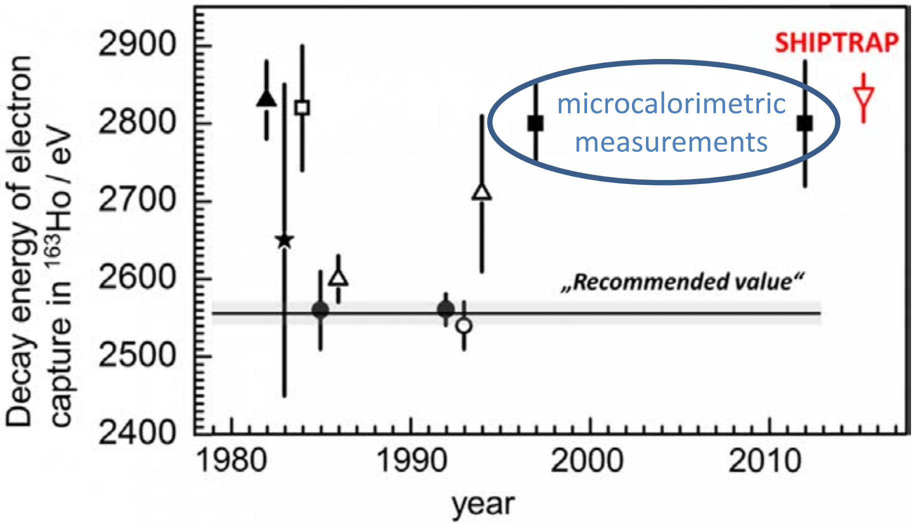
$$m_{\nu_e} < 10\,\frac{\mathrm{eV}}{\mathrm{c}^2}$$

Q_{EC} measurement at **SHIPTRAP**

ECHo Phase 3: 1 MBq

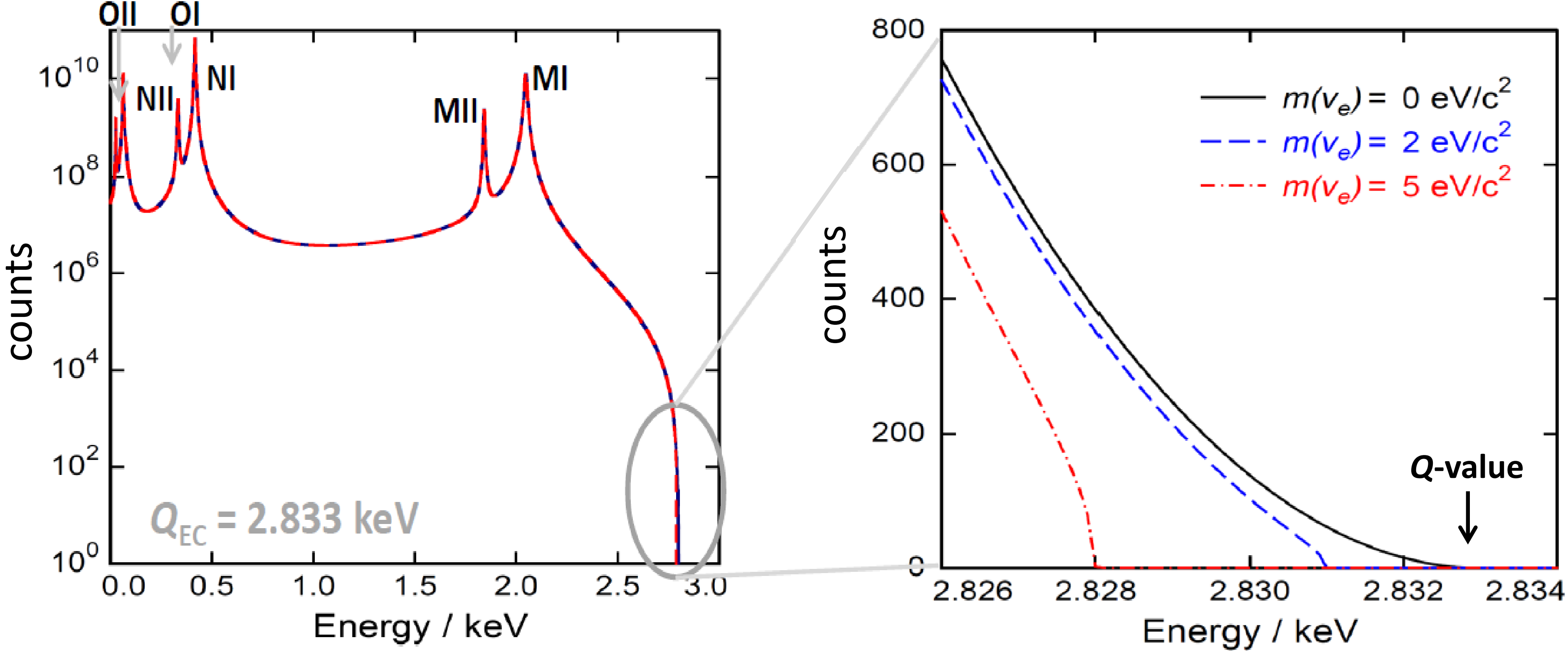
$$m_{\nu_e} \leq 1\,\frac{\mathrm{eV}}{\mathrm{c}^2}$$

Q_{EC} measurement at PENTATRAP



$$Q_{\mathrm{EC}} = 2833\,(30_{\mathrm{stat}})\,(15_{\mathrm{sys}})\ \ \mathrm{eV}$$

Eliseev, S. et al., PRL 115, 062501 (2015)

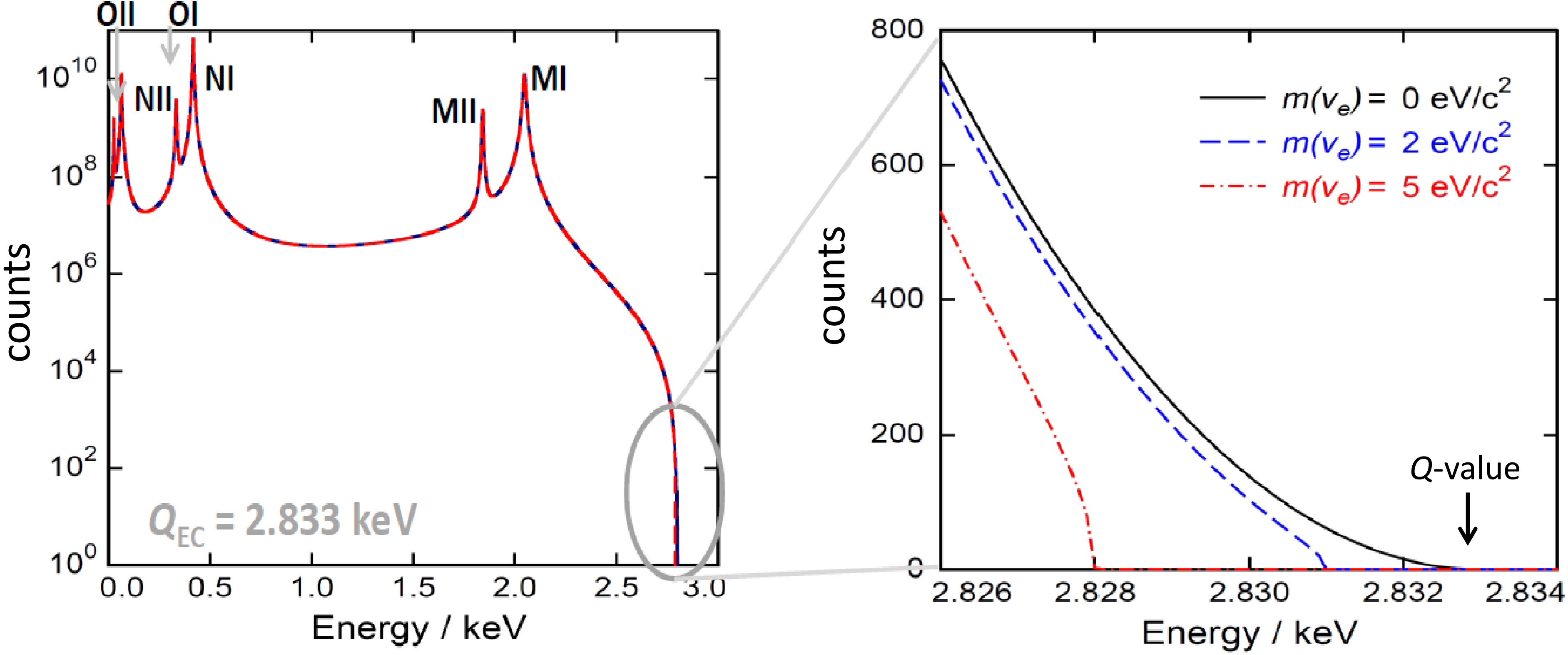


$$\frac{dN}{dE} = A(Q - E)^2 \sqrt{1 - \frac{m_\nu^2}{(Q-E)^2}} \sum C \phi_k^2(0) \frac{\Gamma_k/2\pi}{(E - B_k)^2 + \Gamma_k^2/4}$$

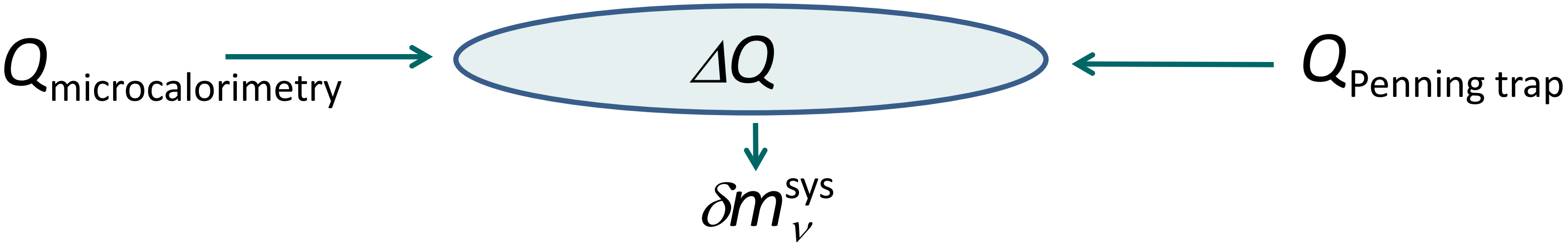
Underlying technique – cryogenic microcalorimetry

L. Gastaldo et al., J. Low Temp. Phys. 176 (2014) 876

P.C.-O. Ranitzsch et al., J. Low Temp. Phys. 167 (2012) 1004



$$\frac{dN}{dE} = A(Q-E)^2\sqrt{1-\frac{m_\nu^2}{(Q-E)^2}}\sum C\phi_k^2(0)\,\frac{\Gamma_k/2\pi}{(E-B_k)^2+\Gamma_k^2/4}$$



$Q_{\text{microcalorimetry}}$ → ΔQ ← $Q_{\text{Penning trap}}$

ΔQ → $\delta m_\nu^{\text{sys}}$

Penning traps: masses of nuclides

Field	Examples	δm/m
Nuclear structure physics	shell closures, shell quenching, regions of deformation, drip lines, halos, S_n, S_p, S_{2n}, S_{2p}, δV_{pn}, island of stability	10^{-6} to 10^{-7}
Astrophysics nuclear models mass formula	*rp*-process and *r*-process path, waiting-point nuclei, proton threshold energies, astrophysical reaction rates, neutron star, x-ray burst	
Weak interaction studies	CVC hypothesis, CKM matrix unitarity, *Ft* of superallowed *ß*-emitters	10^{-8}
Metrology, fundamental constants	α (h/m_{Cs}, m_{Cs}/m_p, m_p/m_e), m_{Si}	10^{-9} to 10^{-10}
Neutrino physics	$m_{mother} - m_{daughter}$: $0\nu\beta\beta$, $0\nu 2EC$ sterile neutrinos neutrino mass	10^{-8}-10^{-9} <10^{-11}
CPT tests QED in HCI	m_p and $m_{\bar{p}}$ m_{e-} and m_{e+} m_{ion}, electron binding energy	<10^{-11}

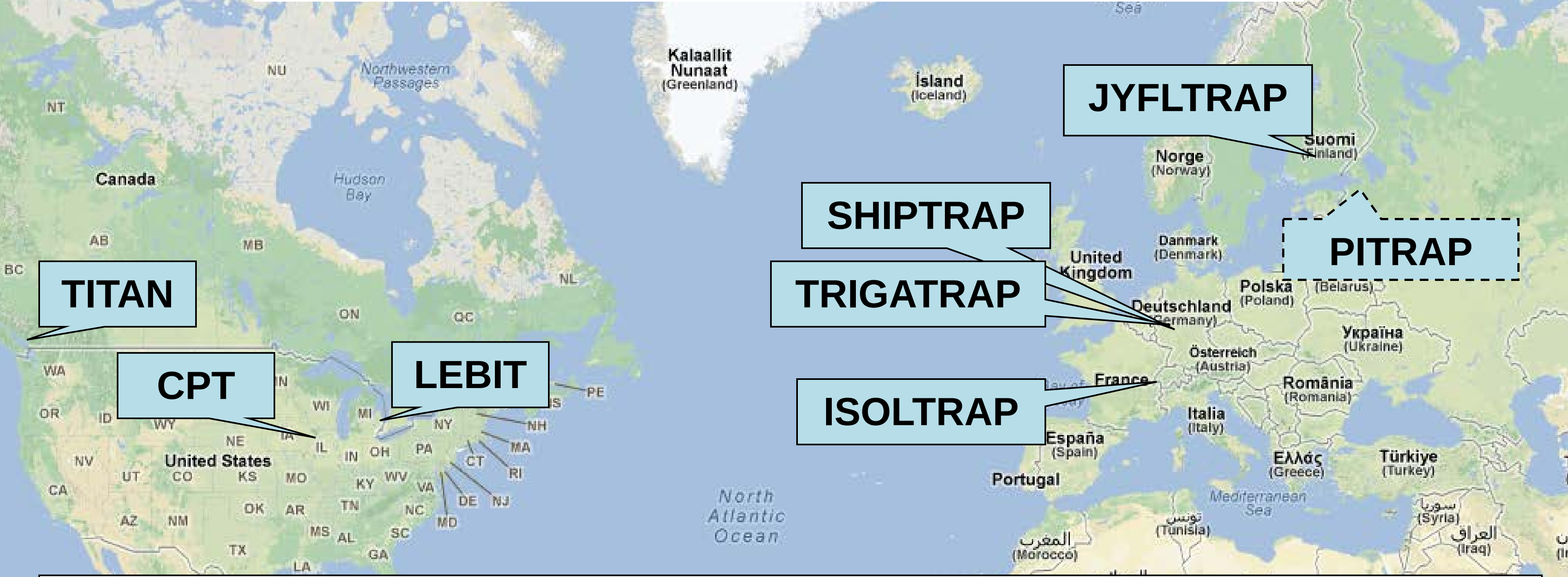
Penning traps: masses of nuclides

Field	Examples	δm/m
Nuclear structure physics	shell closures, shell quenching, regions of deformation, drip lines, halos, S S_p, S_{2n}, S_{2p}, δV_{pn}, islan	10^{-6} to 10^{-7}
Astrophysics nuclear models mass formula	ing-point rophysical star, x-ray burst	
Weak interaction studies	hypothesis, CKM matrix unitarity, *Ft* of superallowed *ß*-emitters	10^{-8}
Metrology, fundamental constants	α $(h/m_{Cs}$, m_{Cs}/m_p, m $)$, m_{Si}	10^{-9} to 10^{-10}
Neutrino physics	$0\nu2EC$	10^{-8}-10^{-9}
	eutrinos no mass	$<10^{-11}$
CPT tests QED in HCI	$_p$ and $m_{\bar{p}}$ m_{e-} and m_{e+} m_{ion}, electron binding energy	$<10^{-11}$

on-line facilities
short-lived nuclides

off-line setups
long-lived nuclides

On-line Penning-trap facilities for experiments on exotic nuclides



achievable accuracy of mass measurements

short-lived nuclides : $\delta m/m \sim 10^{-6} - 10^{-8}$

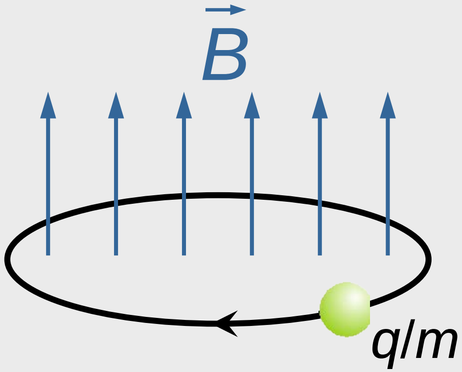
long-lived nuclides : $\delta m/m \sim 10^{-10}$

PENTATRAP

Max-Planck Institute for Nuclear Physics, Heidelberg

$$\frac{\Delta B}{B} < 3 \cdot 10^{-10}\ \mathrm{h}^{-1}$$

strong uniform static B-field



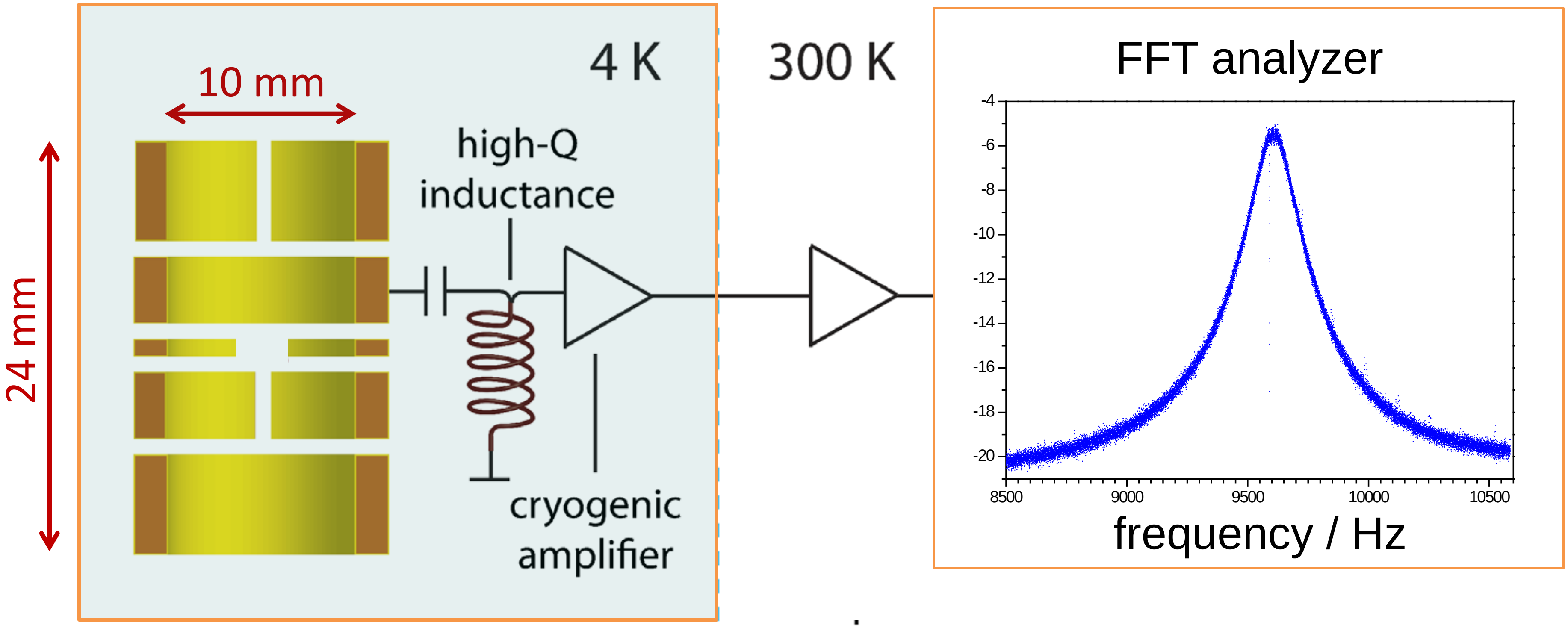
$$\nu_c = \frac{1}{2\pi} \frac{q}{m} B$$

THe-TRAP

Max-Planck Institute for Nuclear Physics, Heidelberg

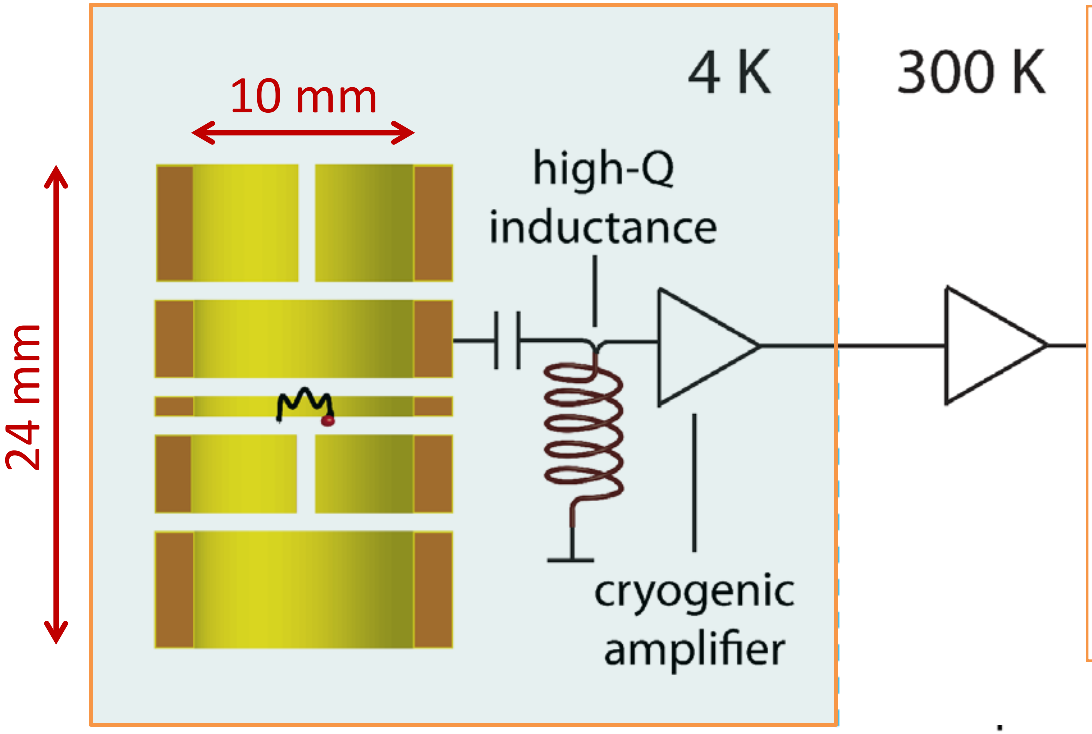
$$\frac{\Delta B}{B} < 10^{-11}\ \mathrm{h}^{-1}$$

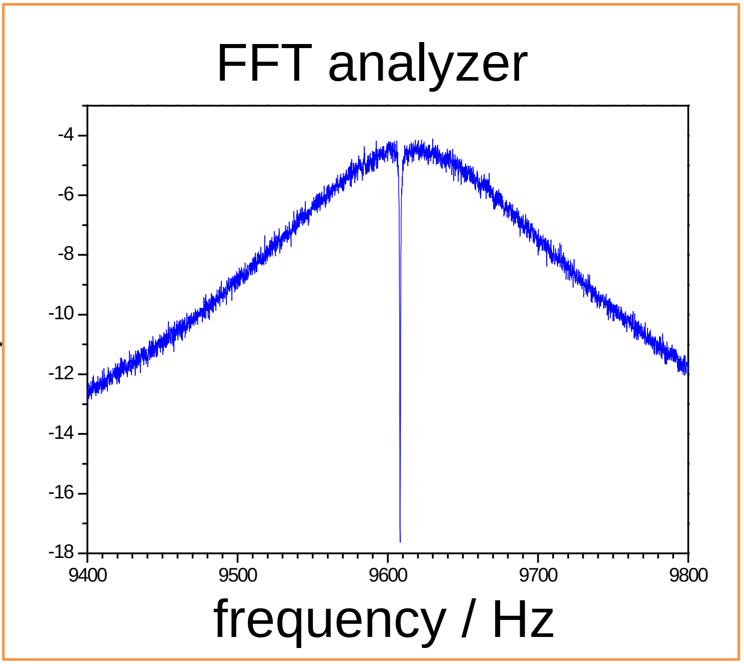
Measurement of trap frequencies with PENTATRAP



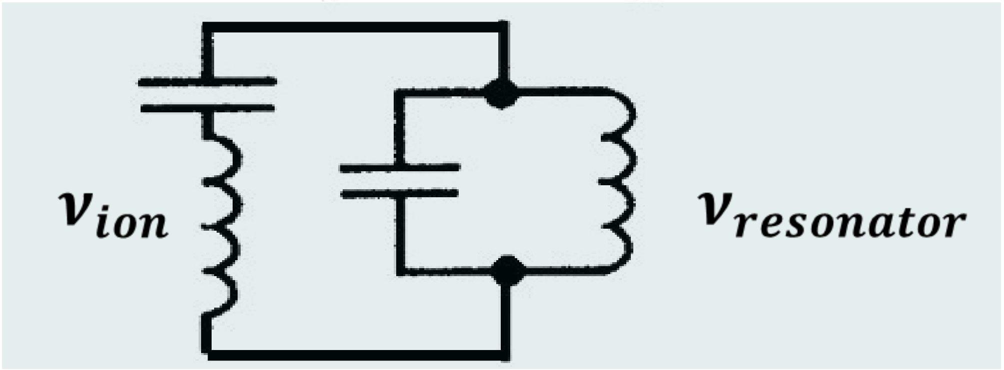
$$\frac{signal}{noise} = \sqrt{\frac{k^2 4 k_B T R + k^4 R^2 i^2}{e^2}}$$

Measurement of trap frequencies with PENTATRAP

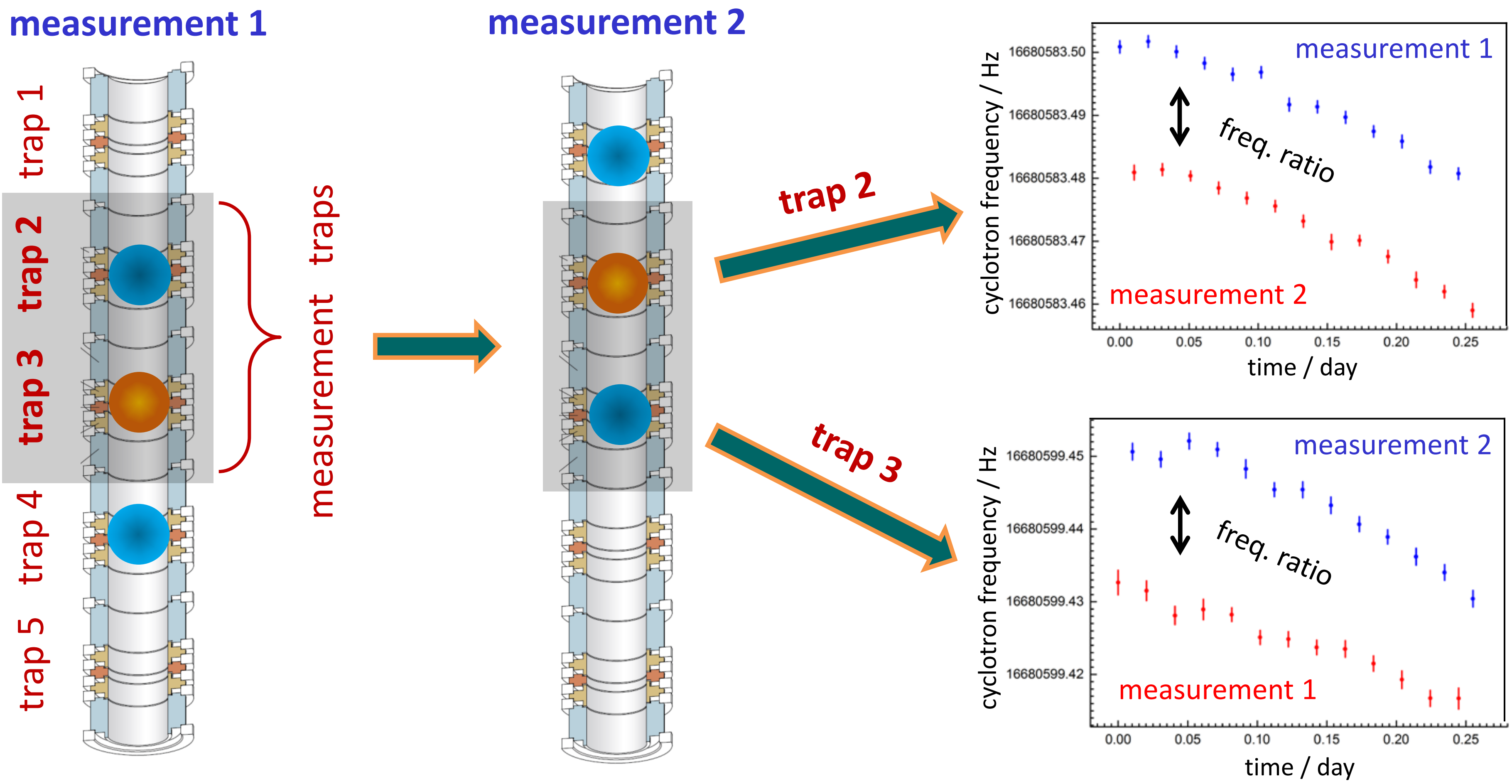




equivalent electronic circuit

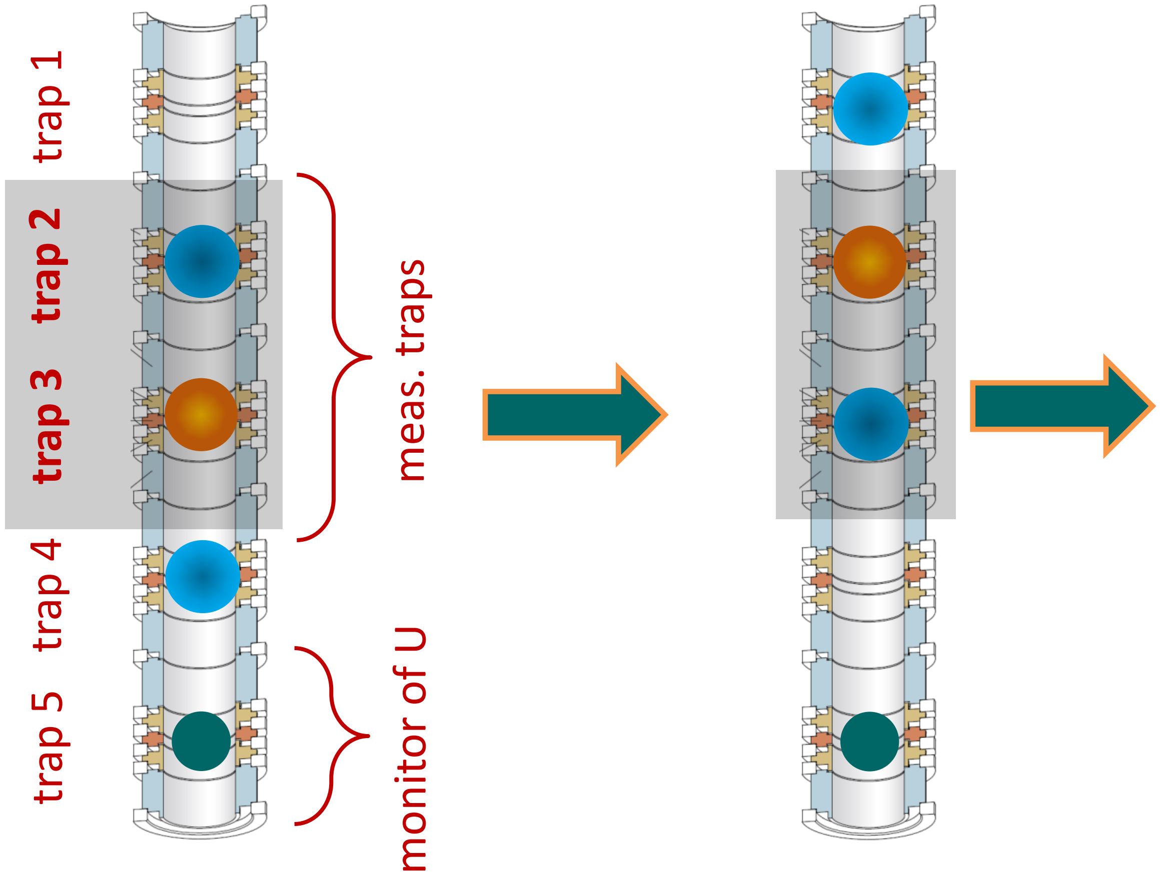


Measurement scheme at PENTATRAP



Measurement scheme 2 at PENTATRAP

measurement 1 **measurement 2**



$$\sqrt{R(t_1)R(t_2)} = \frac{m_2}{m_1}$$

$$\frac{B_1}{B_2} \approx \text{Const}$$

$$R(t_1) = \frac{\nu_1(t_1)}{\nu_2(t_1)} = \frac{m_2}{m_1}\,\frac{B_2(t_1)}{B_1(t_1)}$$

$$R(t_2) = \frac{\nu_1(t_2)}{\nu_2(t_2)} = \frac{m_2}{m_1}\,\frac{B_1(t_2)}{B_2(t_2)}$$