The high-precision Penning-trap mass spectrometer PENTATRAP for fundamental studies

Alexander Rischka

IMPRS-PTFS Seminar

OUTLINE

Basics of Penning-Trap Mass Spectrometry

Motivation for precision mass spectrometry

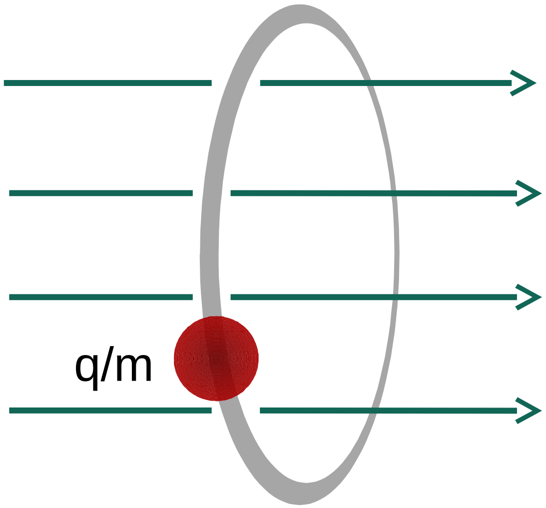
- **Test of special relativity**
- **Contribution to neutrino physics**

The PENTATRAP experiment

Basics of Penning-Trap Mass Spectrometry

Frequency to mass relation

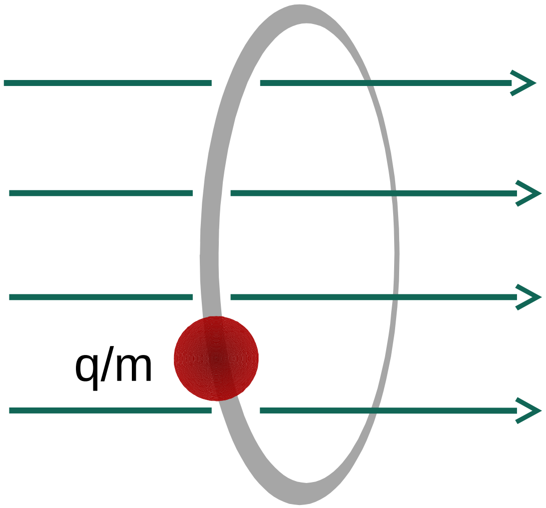
Homogeneous magnetic field *B*



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

Frequency to mass relation

Homogeneous magnetic field B

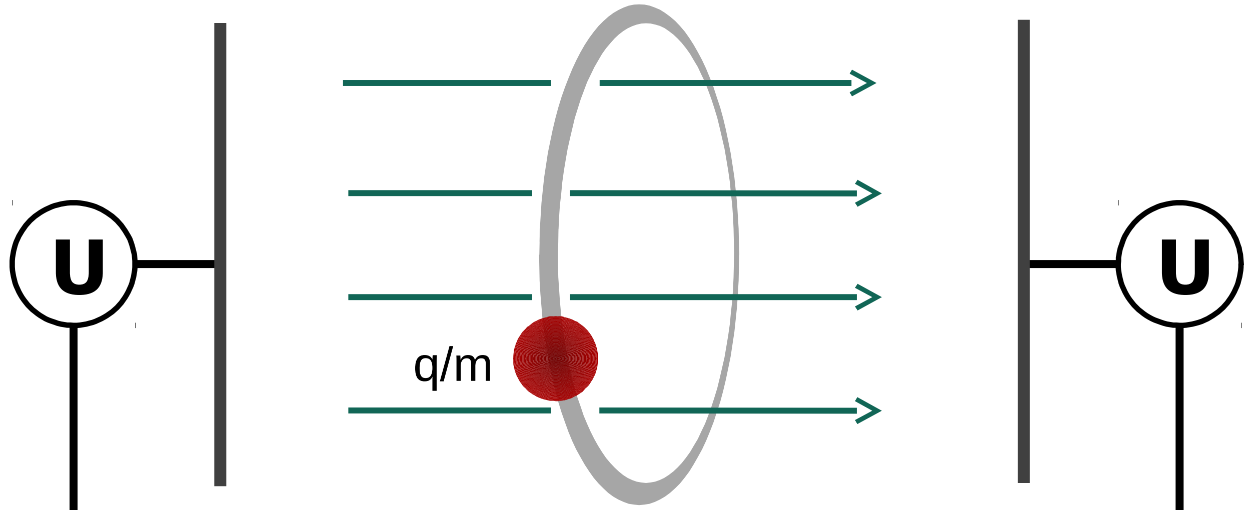


$$\omega_c = \frac{q}{m} B$$

q, B drops at mass difference

Confinement of the ion of interest

Homogeneous magnetic field *B*
+ electrical field *E*



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Confinement of the ion of interest

Homogeneous magnetic field **B**
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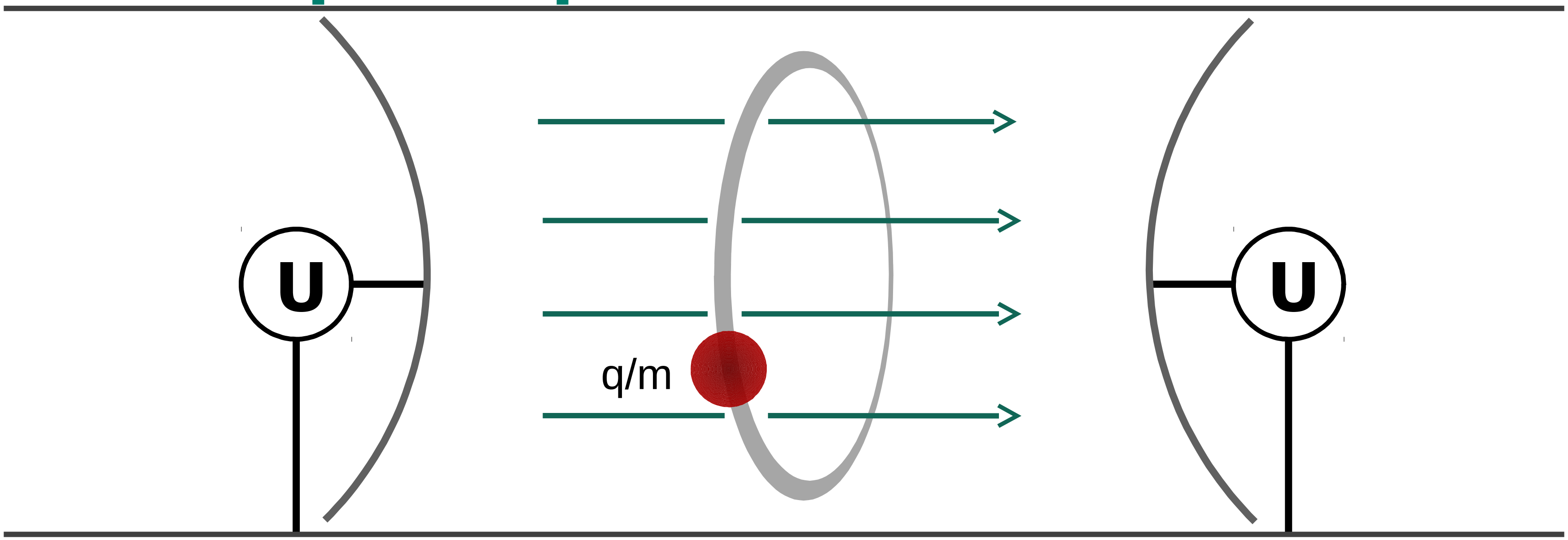

$$\omega_c = \frac{q}{m} B$$

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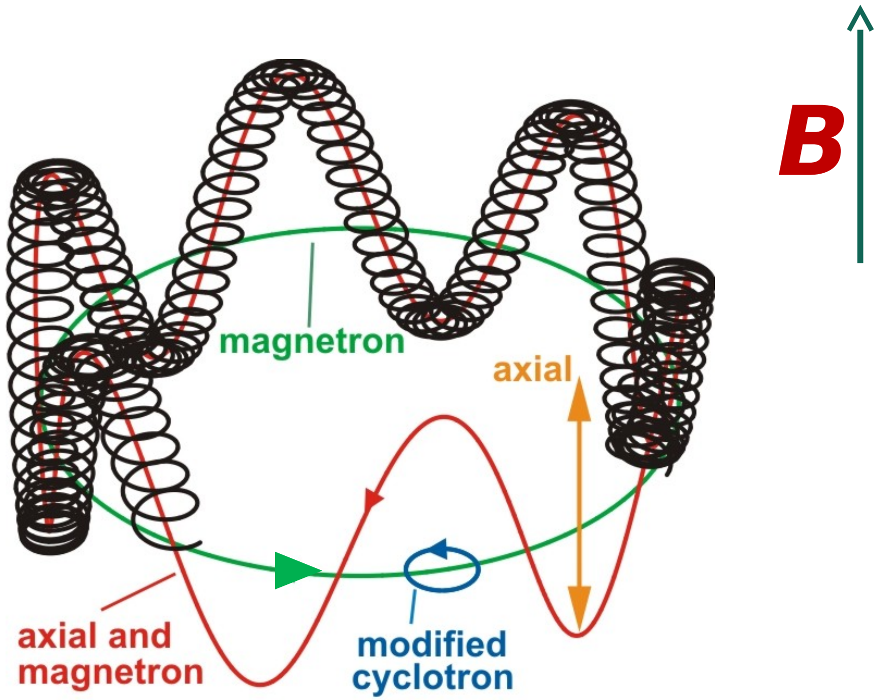
Movement of the confined ion

Three eigenmotions



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

modified cyclotron motion

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c{}^2}{4} - \frac{\omega_z{}^2}{2}}$$

magnetron motion

$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c{}^2}{4} - \frac{\omega_z{}^2}{2}}$$

axial motion

$$\omega_z = \sqrt{\frac{q}{m}\frac{U}{d}}$$

Brown & Gabrielse, Rev. Mod. Phys. 58, 233 (1986)

Frequency hirachy

ncy hirachy: the cyclotron frequency is the most import

$$\omega_+ \gg \omega_z \gg \omega_-$$

A typical 10^-11 measurement needs:

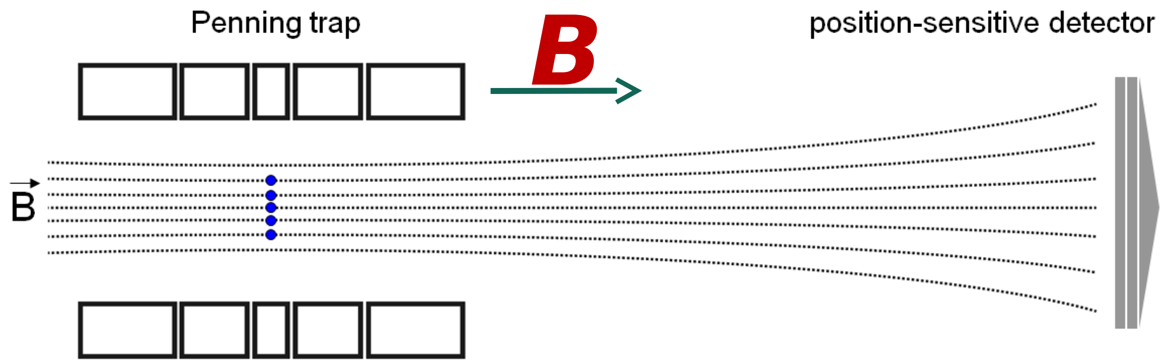
modified cyclotron motion: $\frac{\Delta\omega_+}{\omega_+} < 10^{-11}$ → ***B*** drift < 10^{-11}

axial motion: $\frac{\Delta\omega_z}{\omega_z} < 10^{-8}$ → ***E*** stability < 10^{-8}

magnetron motion: $\frac{\Delta\omega_-}{\omega_-} < 10^{-6}$

Types of PTMS

ojecting radial motions on a position sensitive detector, **c**



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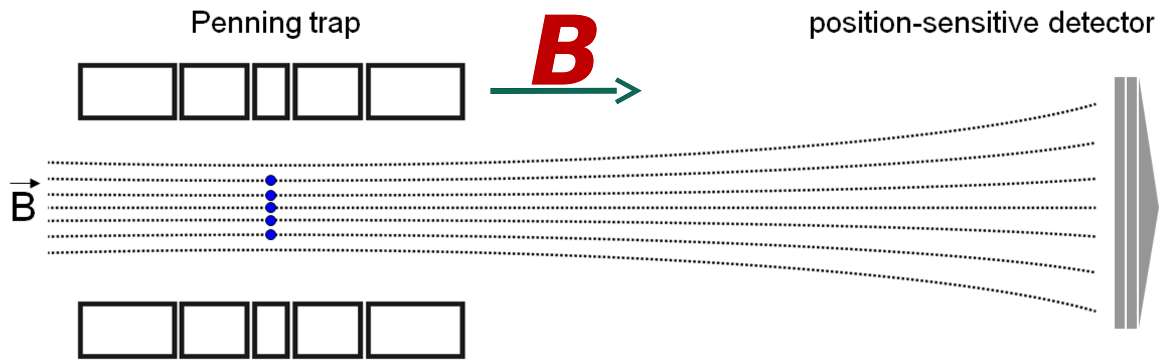
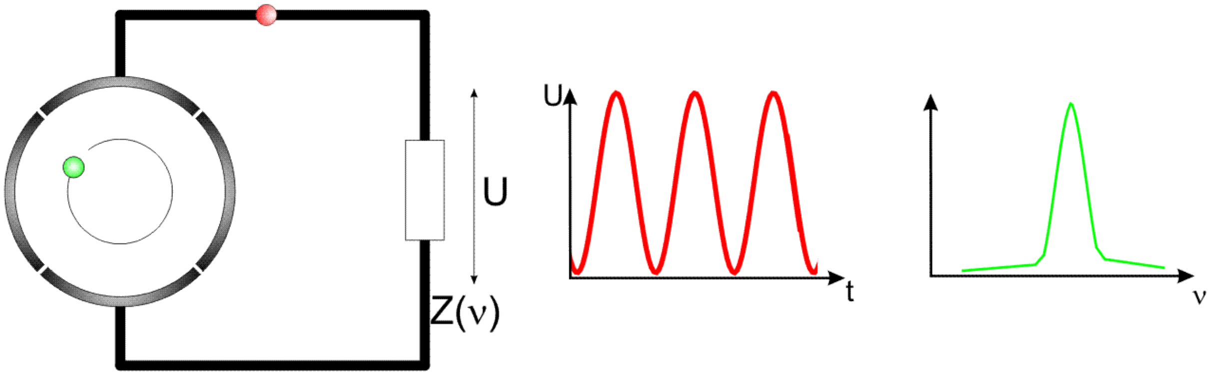


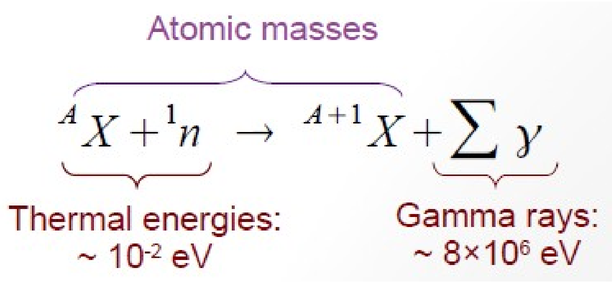
fourier transform the induced image current, **non destru**



Motivation for precision mass spectrometry

Field	Examples	δm/m	δE (A=100)
Nuclear structure physics	shell closures, shell quenching, regions of deformation, drip lines, halos, *seperation energies*	10^{-6} to 10^{-7}	100 keV to 10 keV
Astrophysics nuclear models mass formula	δV_{pn}, island of stability *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 *β*-emitters	10^{-8}	1 keV
Metrology, fundamental constants	α (h/m_{Cs}, m_{Cs}/m_p, m_p/m_e), m_{Si}	10^{-9} to 10^{-10}	100 eV – 10 eV
Neutrino physics	**Contribution to neutrino physics research**	**~10^{-10}** **<10^{-11}**	10 eV < 1 eV
Neutrino physics	**Test of *E*=*mc*²**	**~10^{-10}** **<10^{-11}**	10 eV < 1 eV
CPT tests QED in HCI	m_p and m_p m_{e-} and m_{e+} m_{ion}, electron binding energy	<10^{-11}	< 1 eV

Test of $E=mc^2$ with PTMS



AMS 5, measuring the energy of the gamma

PENTATRAP, measuring the $\Delta m(^{36}Cl, {}^{35}Cl)$

Current value:

$$n + {}^{32}S \rightarrow {}^{33}S + \gamma$$

$1-\Delta mc^2/E = (-1.4 \pm 4.4) \times 10^{-7}$

S. Rainville *et al.*, Nature 438, 1096 (2005)

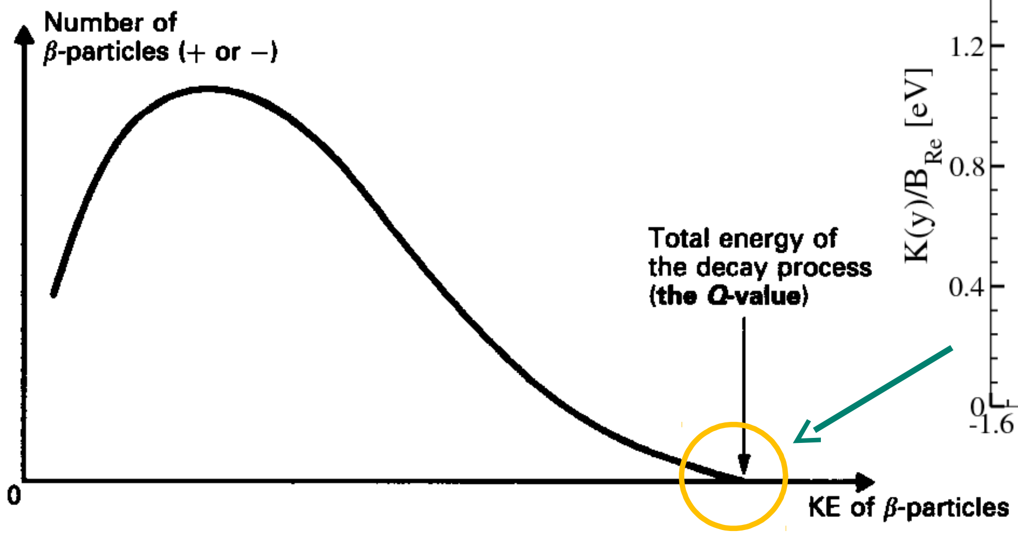
Future measurement:

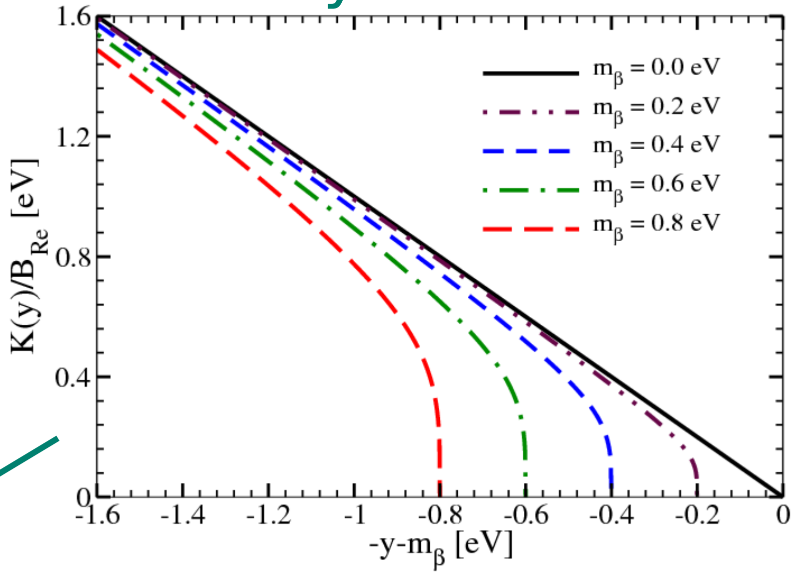
$$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma$$

$1-\Delta mc^2/E < 10^{-8}$

Contribution to neutrino physics research

Looking for missing energy in β-decay,
since the dectecion efficiency of ν is too small





m_ν = ***Q***-Value - Endpoint of spectrum

Types of decays: β^- and EC

KATRIN – Project , MAC-E filter **β^- - Decay of Triti**

- Anti electron neutrino, < 2 eV/c^2 (90% C.L.)
- THe-Trap Experiment for *Q*-Value

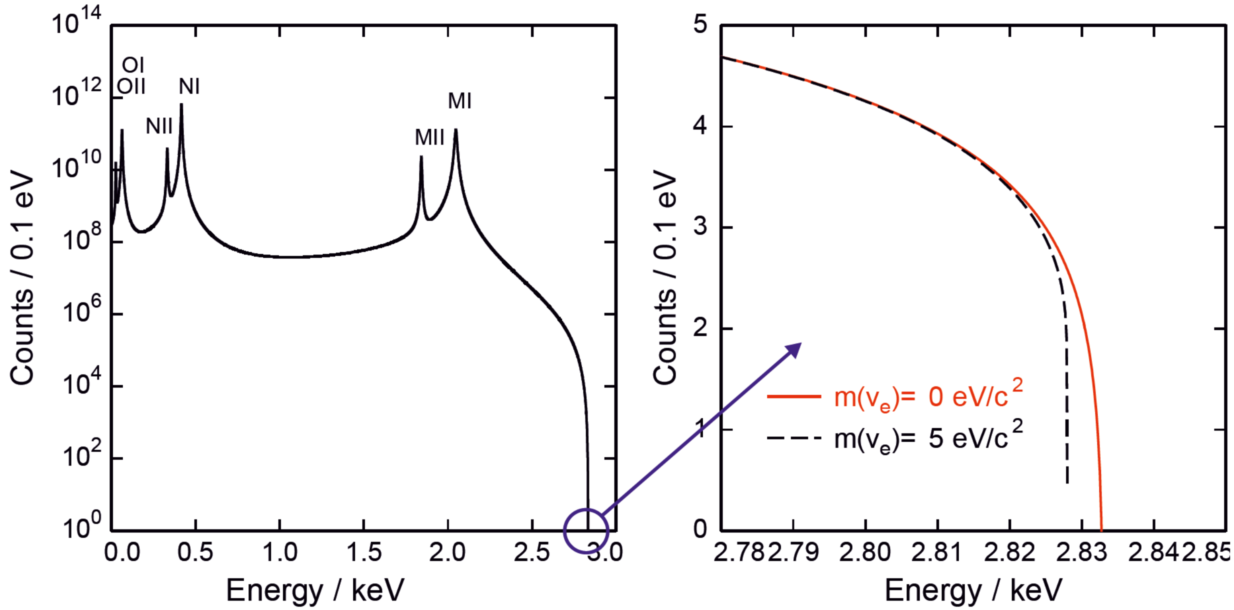
ECHo – Project , µCalorimter **EC in ^{163}Ho**

- electron neutrino, ^{163}Ho: mν ≤ 225 eV/c^2 (90% C.L.)
- PENTATRAP Experiment for *Q*-Value

ires *Q*-Value with a relative uncertainty of (δm/m) <

EC in Holmium, ECHo Collaboration

cay spectrum of ^{163}Ho from µCalorimeter measuren



value to check for systematic uncertainties neede

Q-value measurement of ^{163}Ho @SHIPTRAP

Q-value of EC in ^{163}Ho

^{163}Ho

$T_{1/2}$: 4570a

EC 100%

^{163}Dy

$T_{1/2}$: stable

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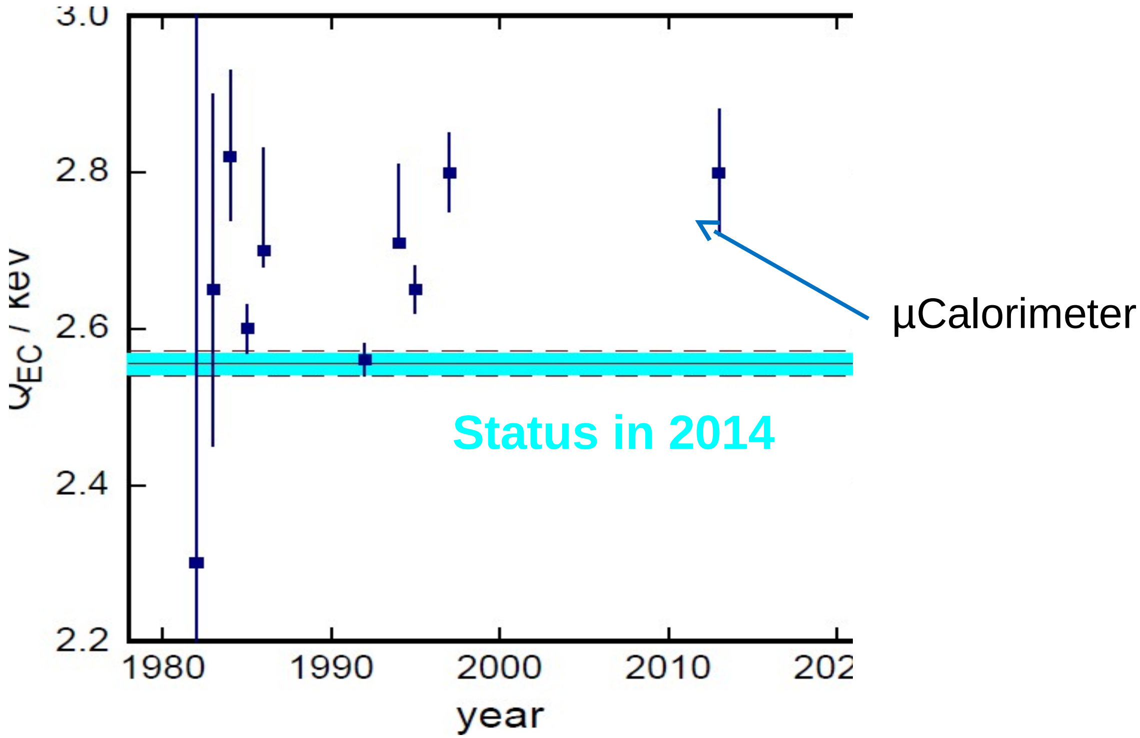

S. Eliseev, *et al.* , Phys. Rev. Lett. 115, 062501 (2015)

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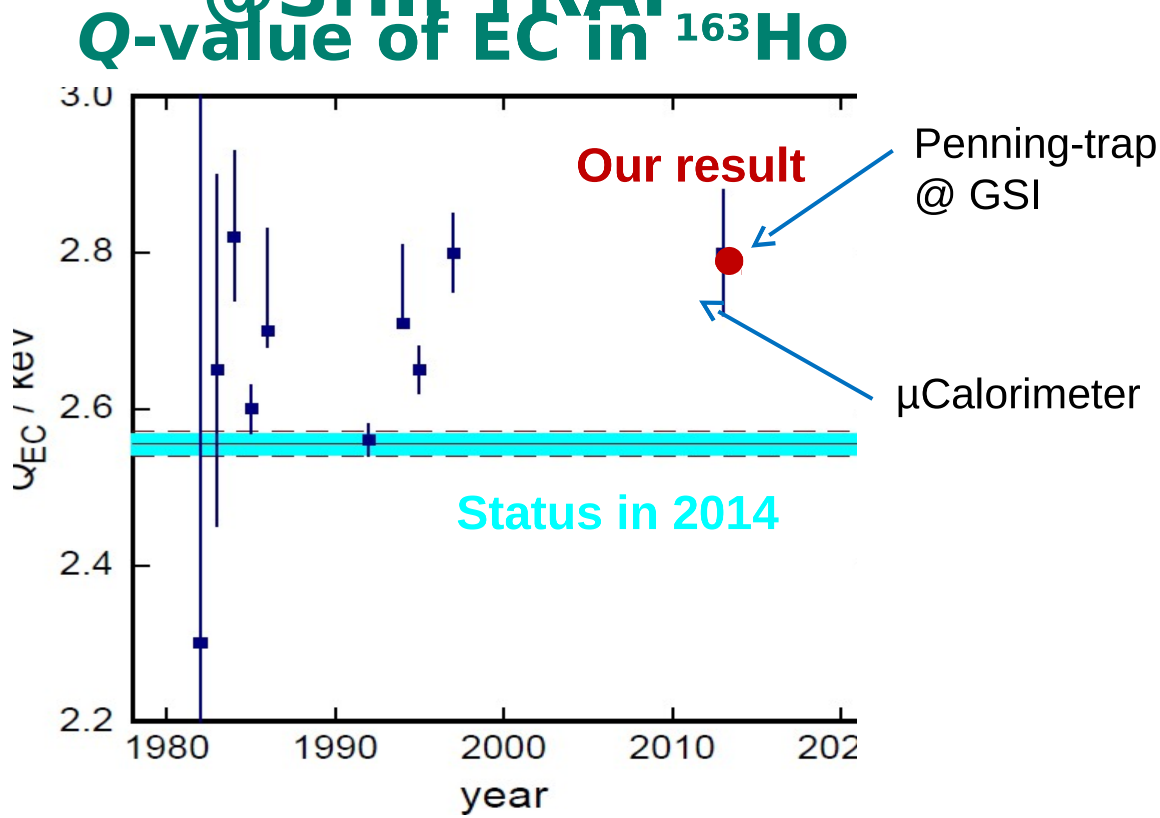

Q-Value: ~ 2.8 keV with an 20 eV uncertainty for ECHo Phase 1

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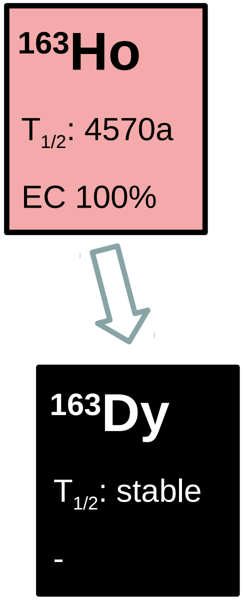
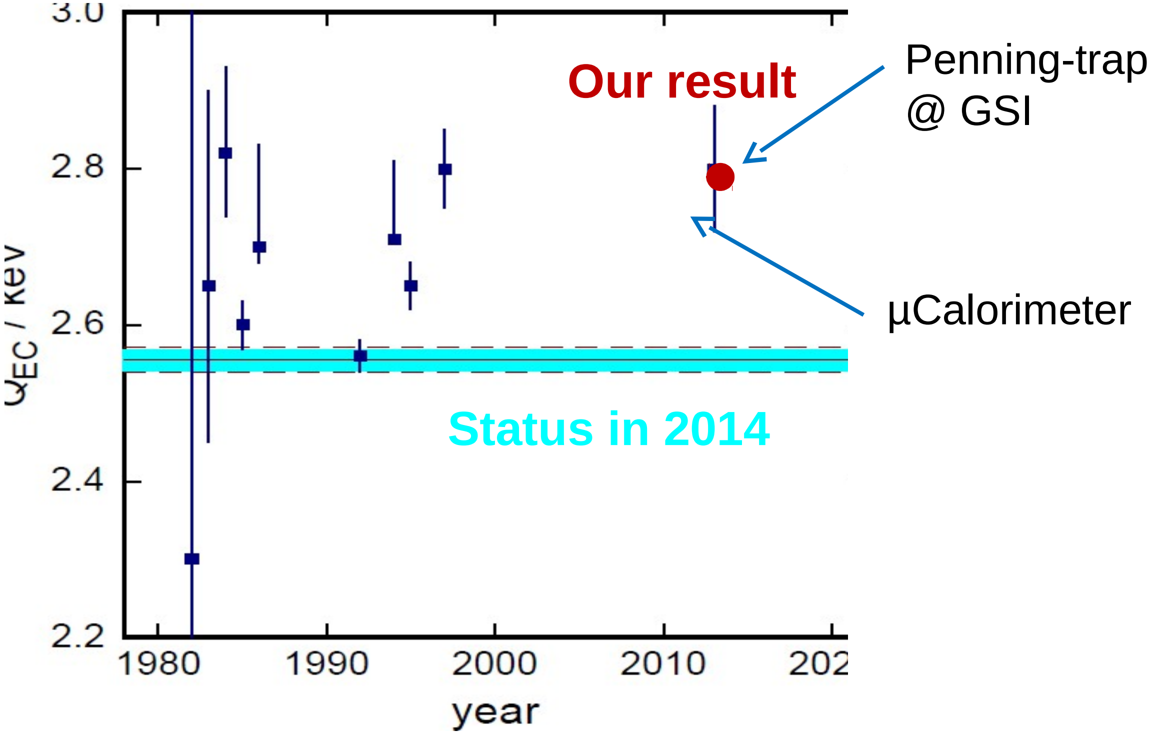
Q-value of EC in ^{163}Ho





Q-Value: ~ 2.8 keV with an 20 eV uncertainty for ECHo Phase 1

2 eV uncertainty is needed for ECHo Phase 2

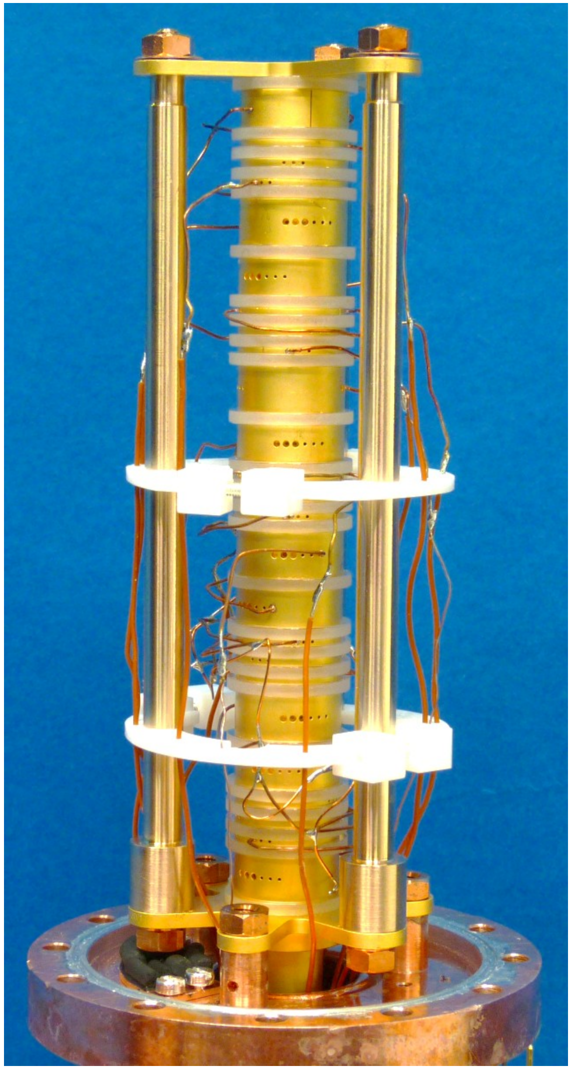
S. Eliseev, *et al.* , Phys. Rev. Lett. 115, 062501 (2015)

The PENTATRAP Experiment

Features of the PENTATRAP experiment

External ion-source:

- Access to higly charge ions
- Simple switching between species



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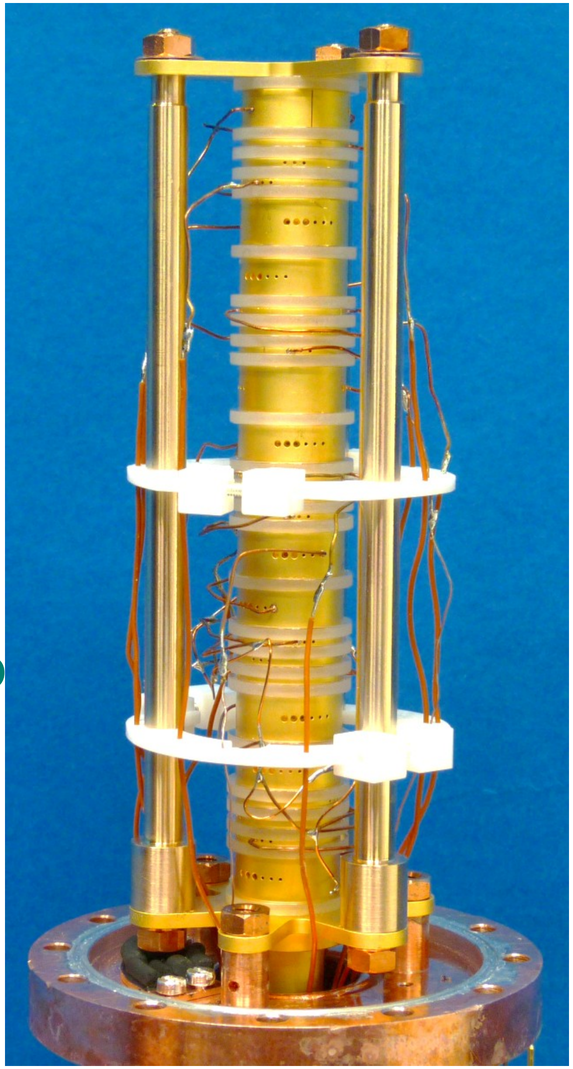
Five Penning traps:

- Fast switching of ions
- New measurement schemes possib



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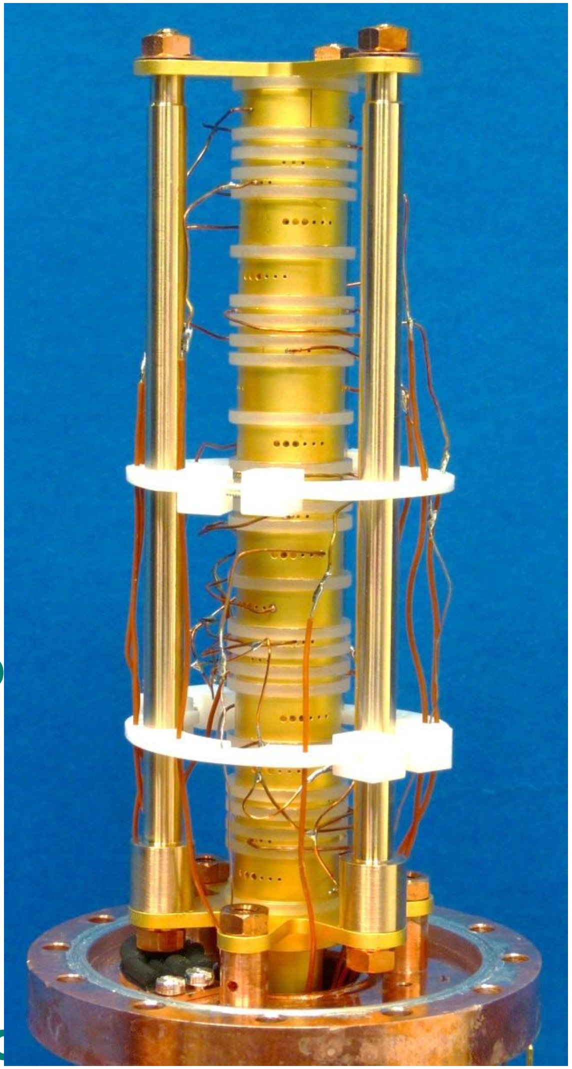
Cryogenic trapping region:

- UHV, aiming for $< 10^{-15}$ mbar
- reducing thermal noise and excitatio



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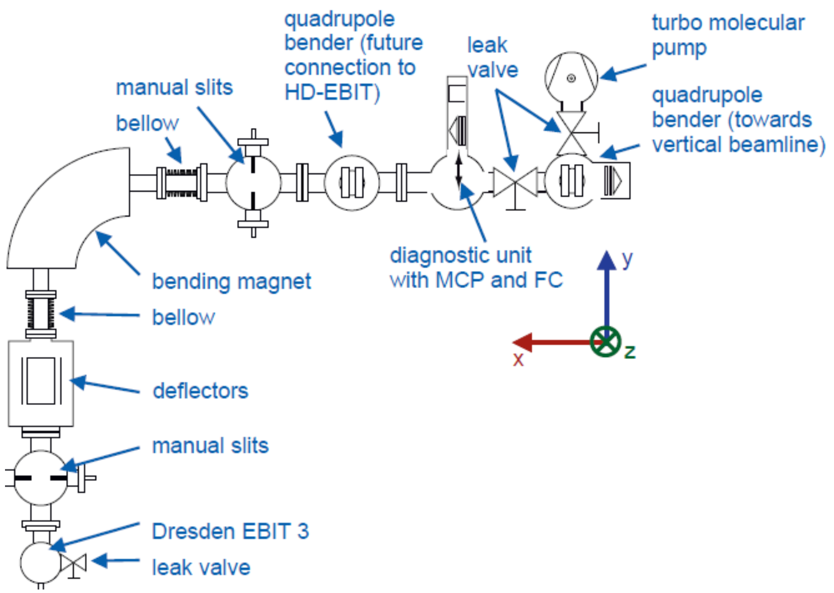
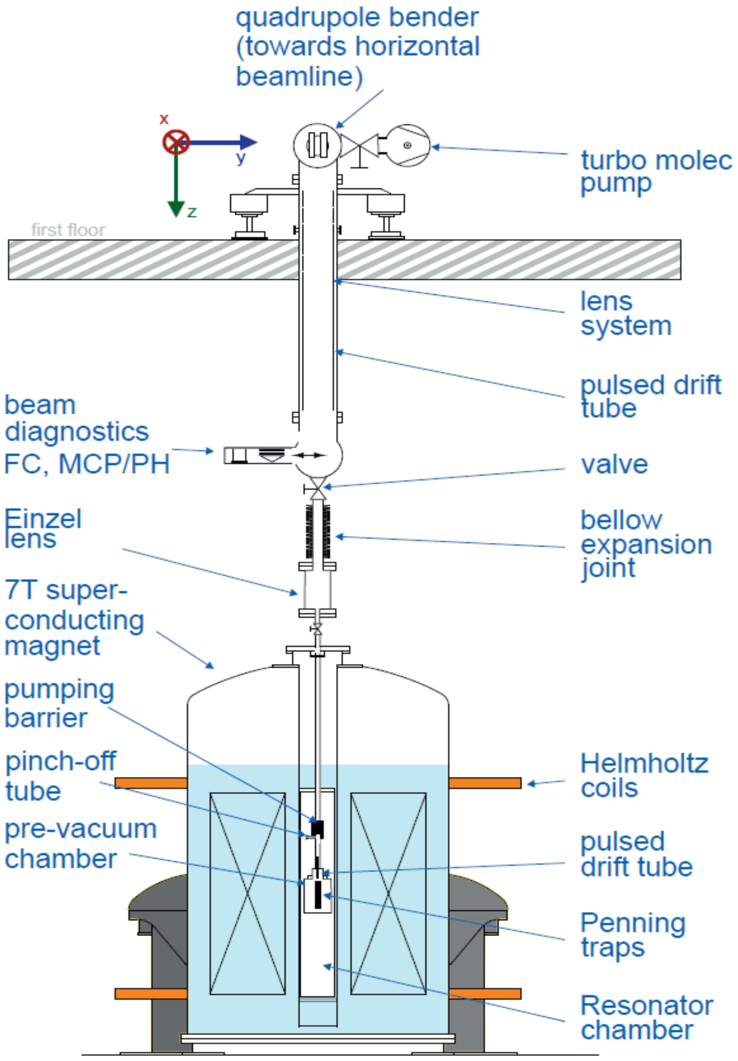
Ion-source and beamline





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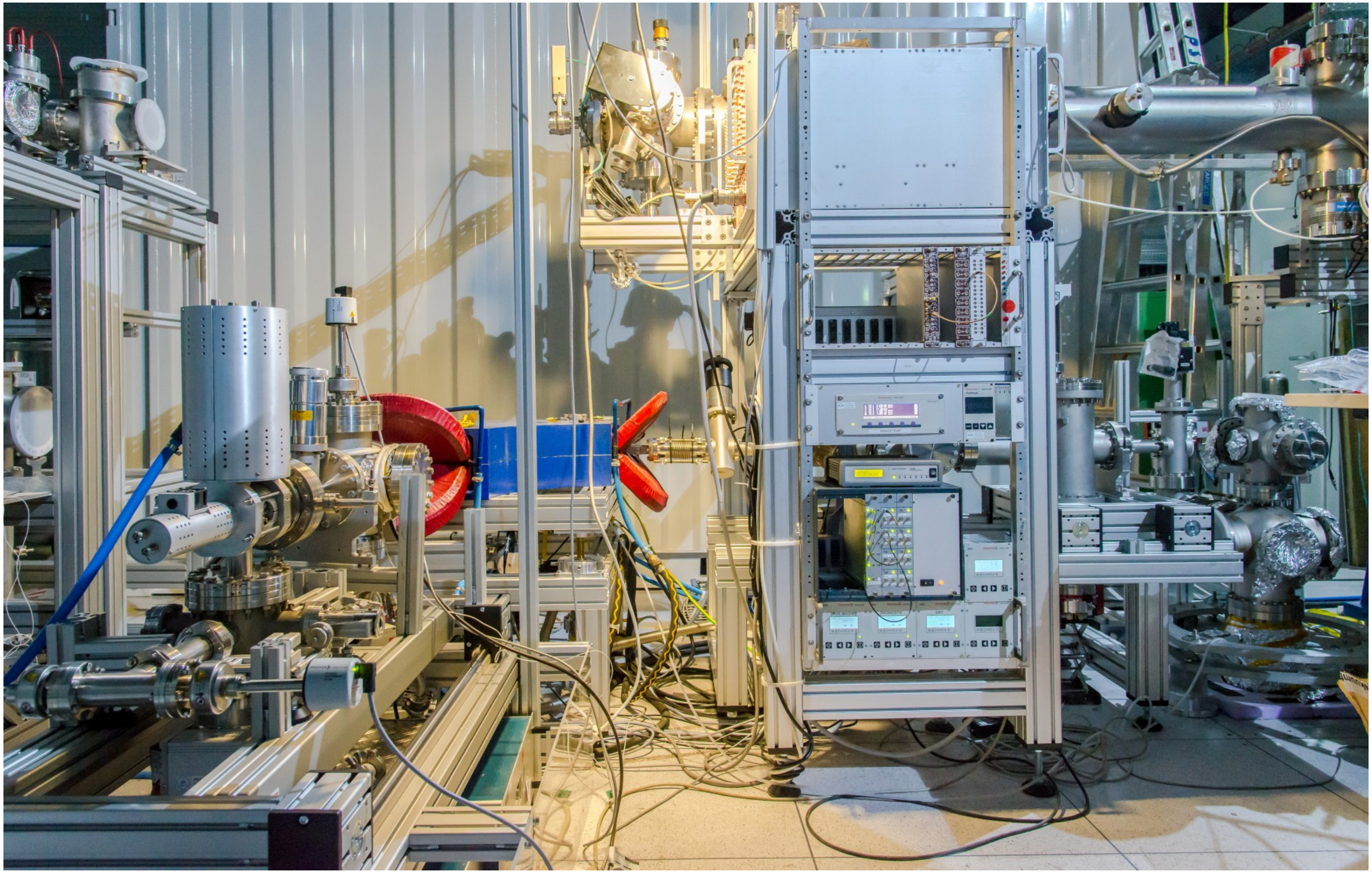

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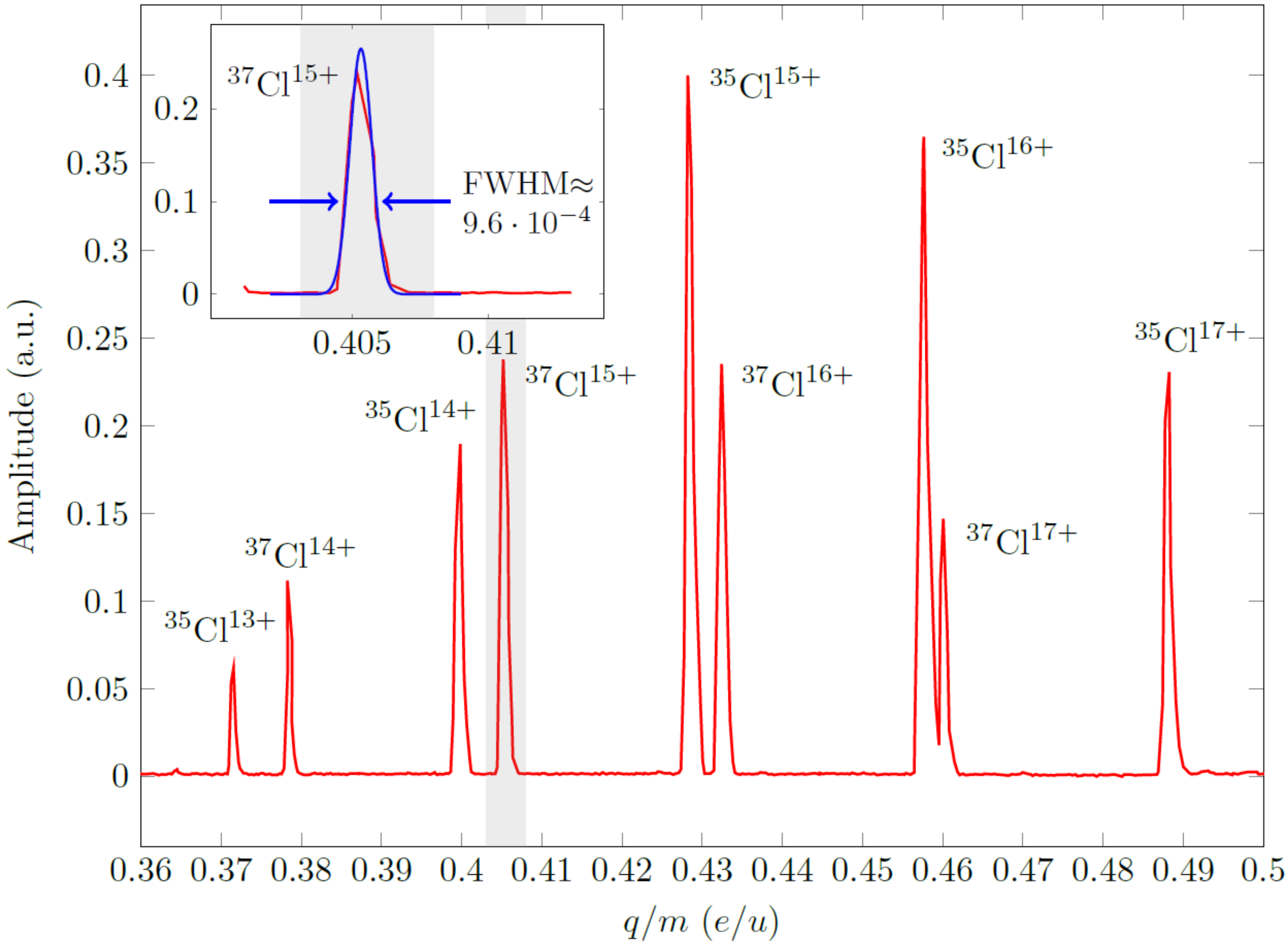

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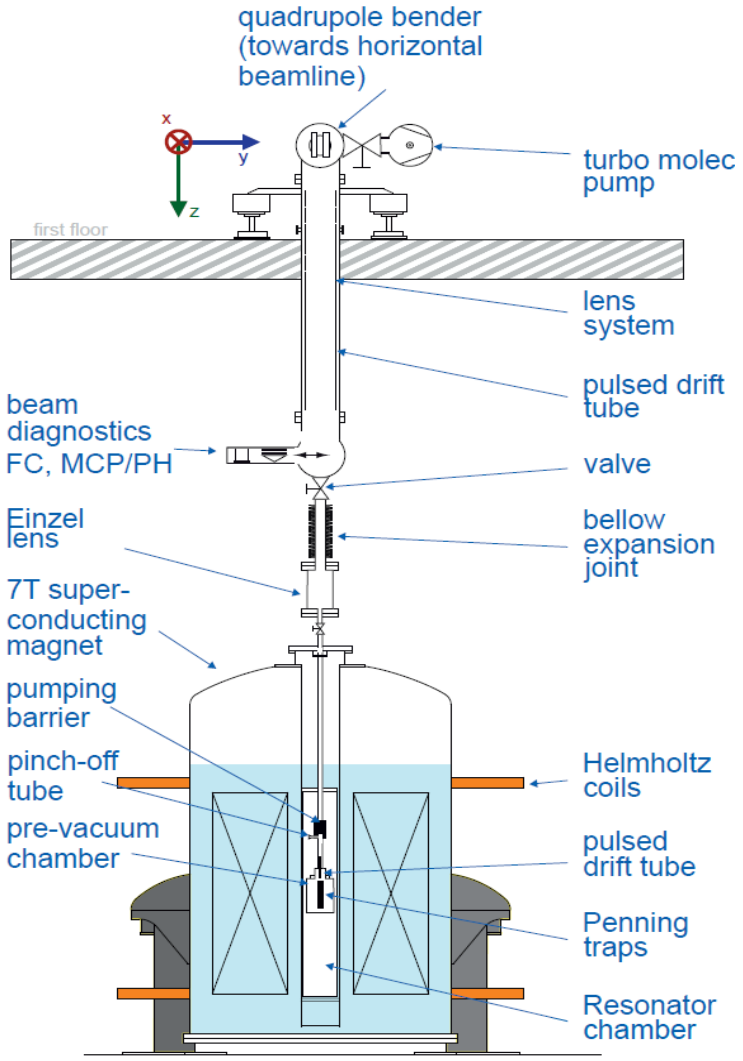
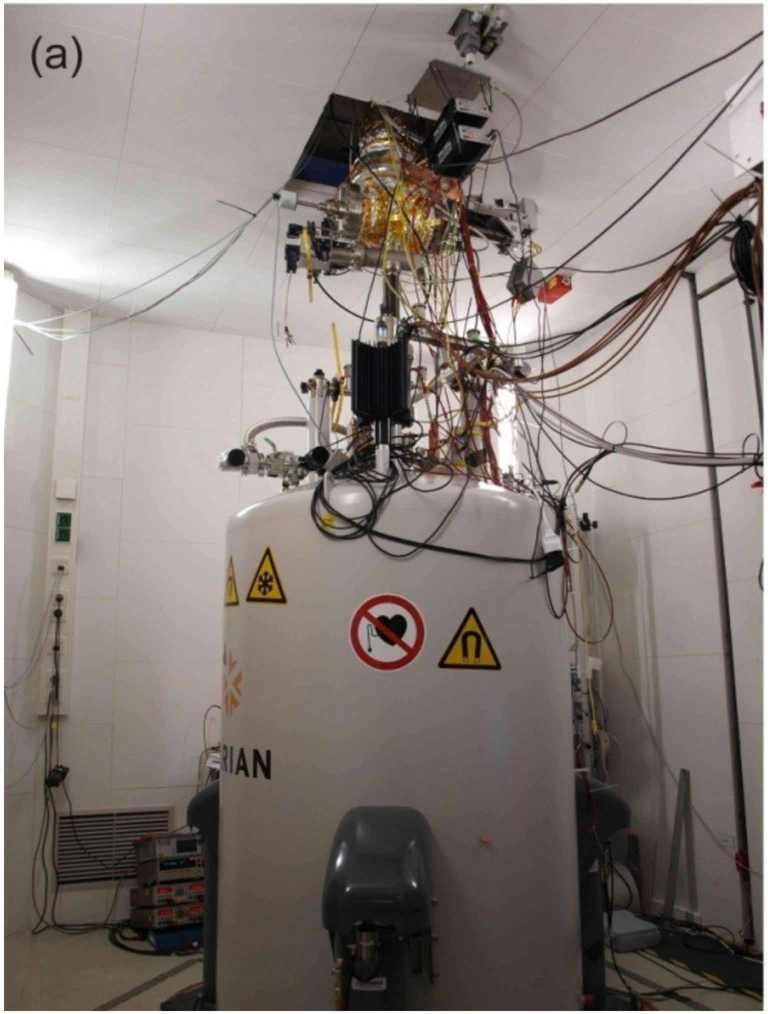
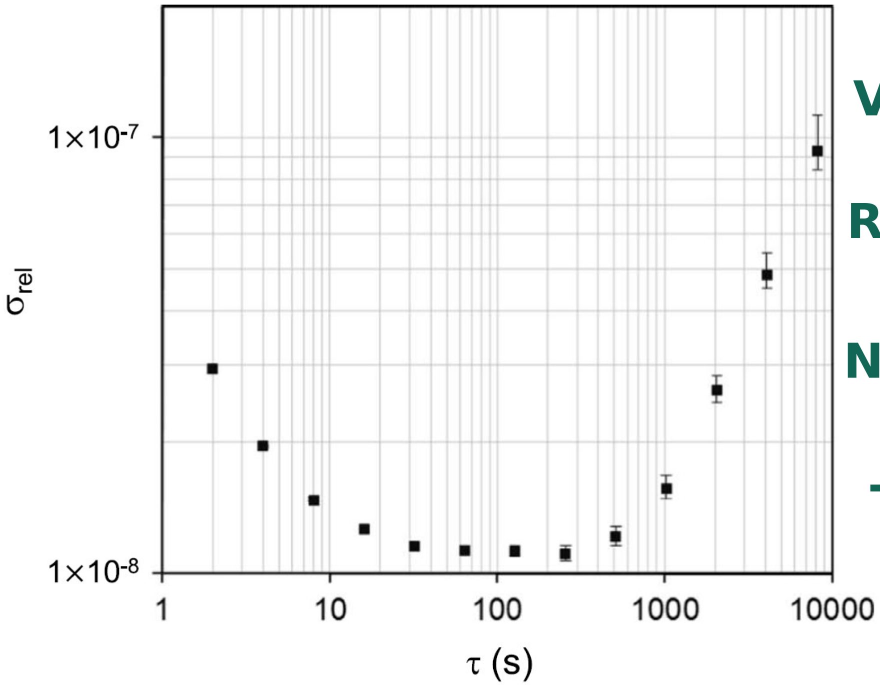




Ultra-stable voltage source

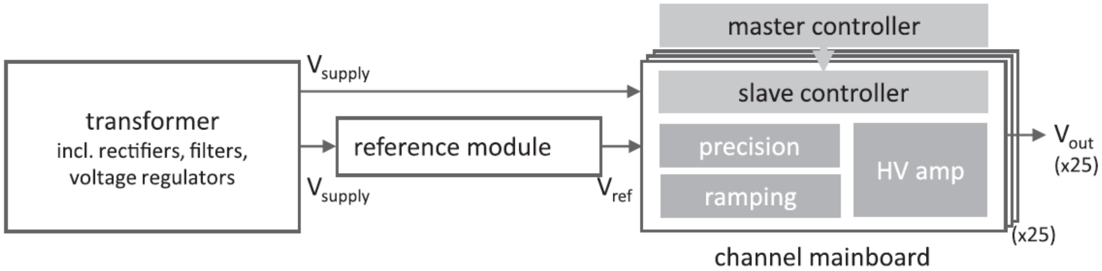


Voltage range: 0 V to -100 V

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

Noise (0.1 Hz – 10 Hz): < 1.5 µV

Temp. coeff. < 0.1 ppm/K



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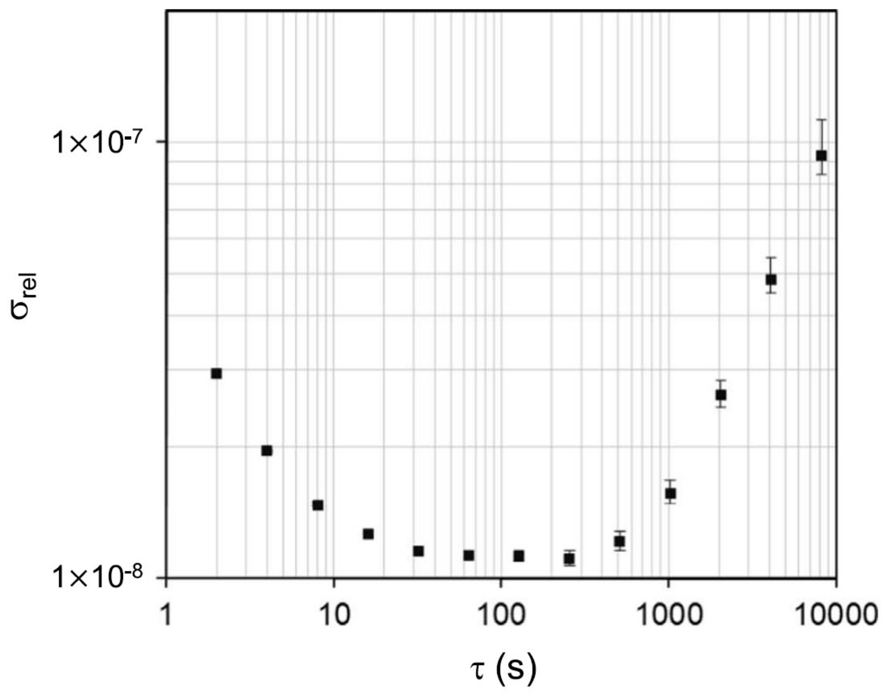
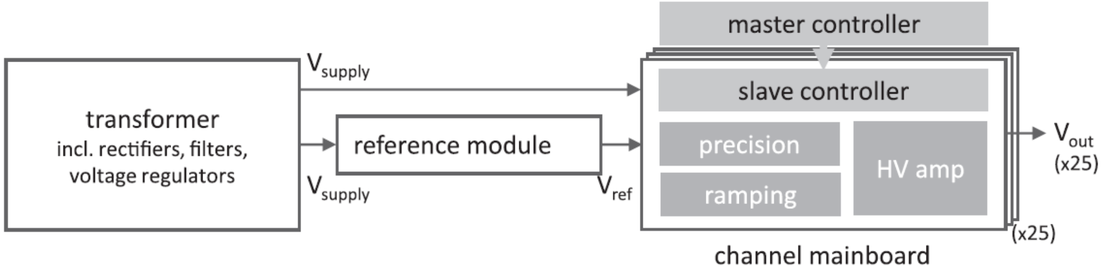




Summary & Outlook

Summary:

- *Q*-value of EC in ^{163}Ho with 20 eV uncertainty
- Beamline commissioned and ready
- StaRep – in commissioning at THe-Trap

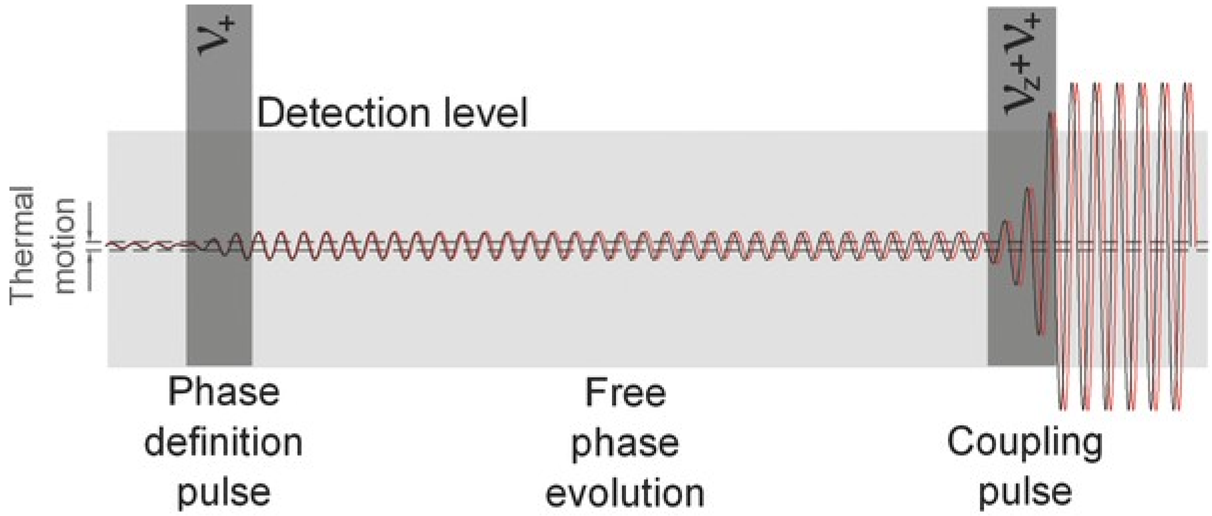
Outlook:

- Cryogenic setup in workshop, ready end of 2016
- Measuring ^{193}Pt as alternative candidate to ^{163}Ho

Thank you for your attention

Phase-Sensitive Methods for ω_+

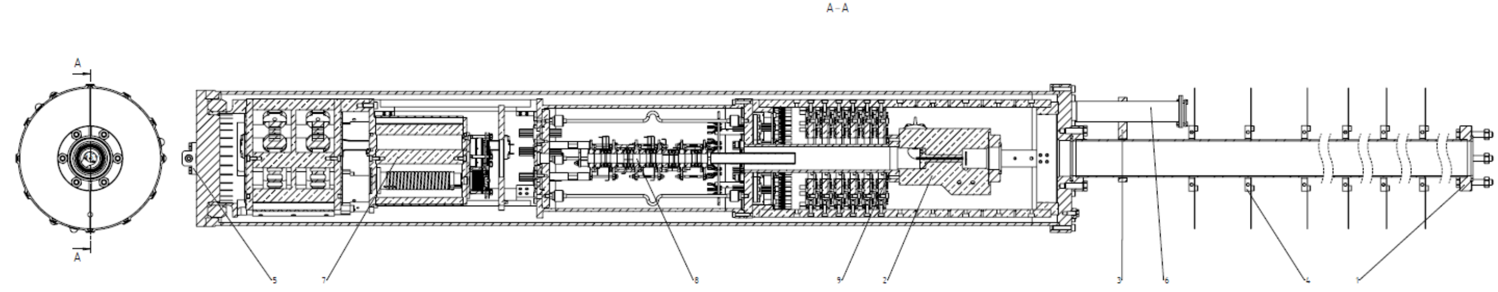
Pulse and amplify (PNA)



hase evolution with low energy, ion probe less anharm

eadout via axial mode, axial resonators have better SN

New cryogenic setup



Improvements:

- simpler
- less vacuum challenges
- less assembly time and smaller debug cycle

Types of PTMS

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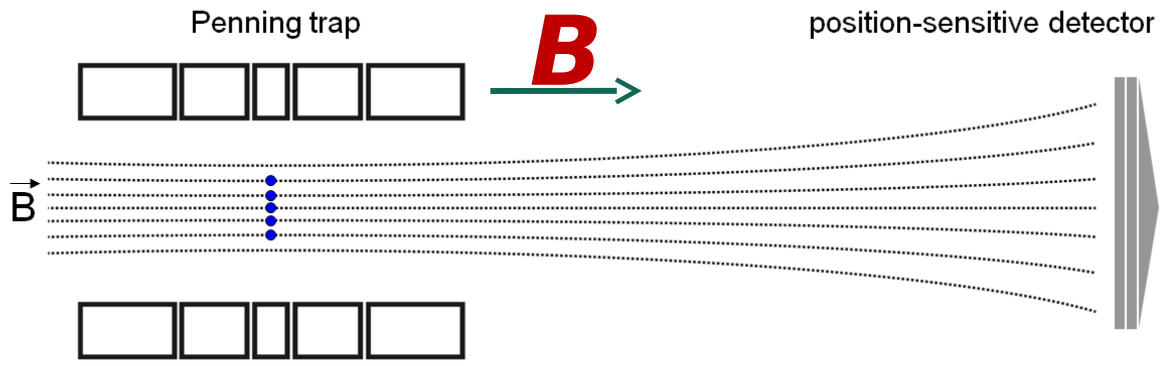

fourier transform the induced image current, **non destru**