PENTATRAP: A high-precision Penning trap mass spectrometer for highly-charged ions

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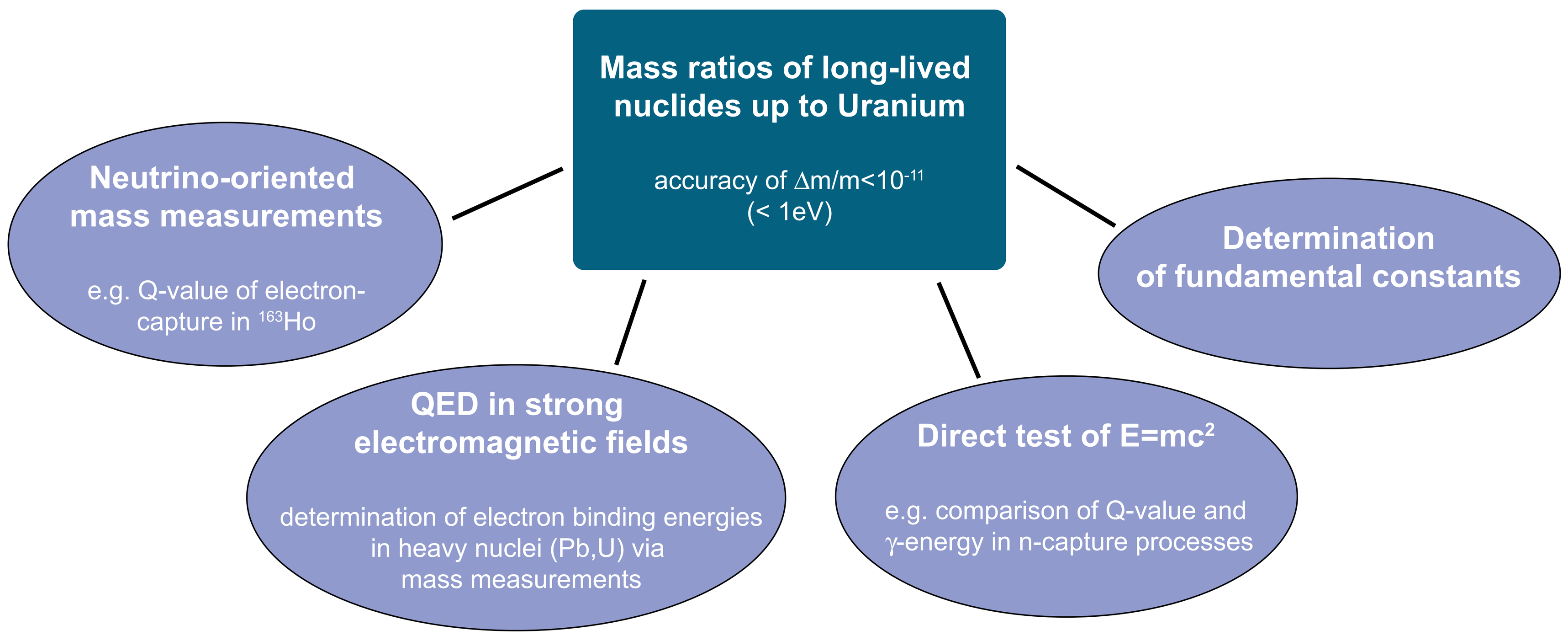
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

STORED AND COOLED IONS

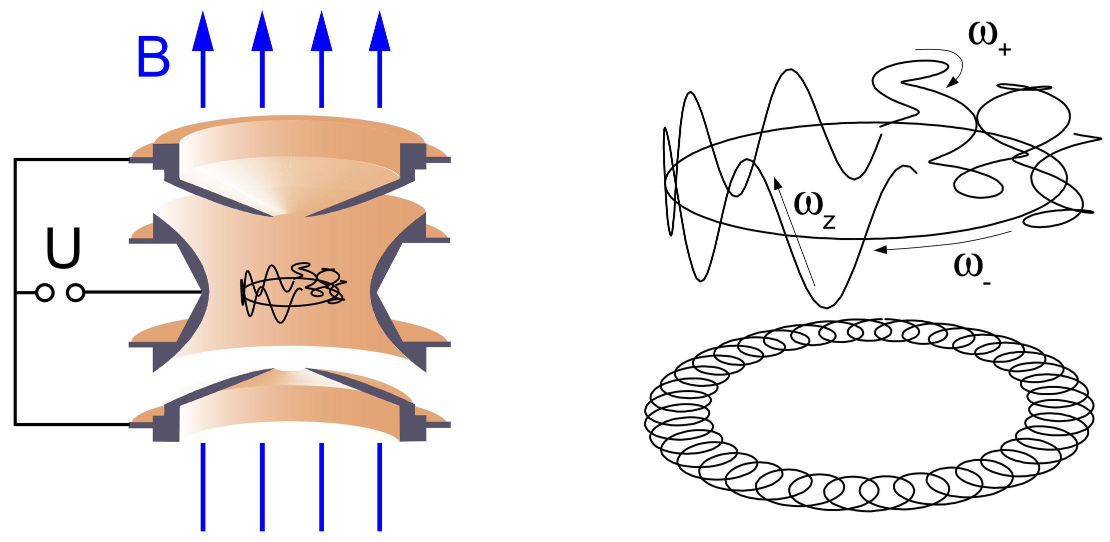
Physics at PENTATRAP

A novel cryogenic Penning trap facility called PENTATRAP is currently under construction at Max-Planck-Institut für Kernphysik in Heidelberg, Germany. The project aims for high-precision measurements of mass-ratios on highly-charged stable and long-lived ions with an accuracy of $\Delta m/m<10^{-11}$. Around A=100, this relative mass uncertainty corresponds to an energy determination of less than 1eV. Therefore, mass measurements on this level open a broad field of applications in fundamental physics [1,2].

Examples of applications are precise atomic mass ratios for neutrino mass determination, test of QED binding energies in heavy, highly-charged ions or direct tests of Einstein's energy-to-mass relation $E=mc^2$ [3].



Ions in a Penning Trap



A charged particle confined in a superposition of a strong homogeneous magnetic field B and a weak harmonic electric field supplied by voltages U at the trap electrodes, performs three independent eigenmotions: An axial oscillation with frequency ω_z and two radial motions called reduced cyclotron motion ω_+ and the slow magnetron motion ω_-.

$$\omega_z = \sqrt{\frac{qU}{md}} \qquad \omega_\pm = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

From these independent motions, the mass of an ion can be derived from the so-called Brown-Gabrielse invariance theorem [4]:

$$\frac{q}{m}B = \omega_c = \sqrt{\omega_z^2 + \omega_+^2 + \omega_-^2}$$

Experimental Setup

The PENTATRAP experimental setup is currently under construction at Max-Planck-Institut für Kernphysik in Heidelberg, Germany. It consists of three main parts:

i) Ion Sources:

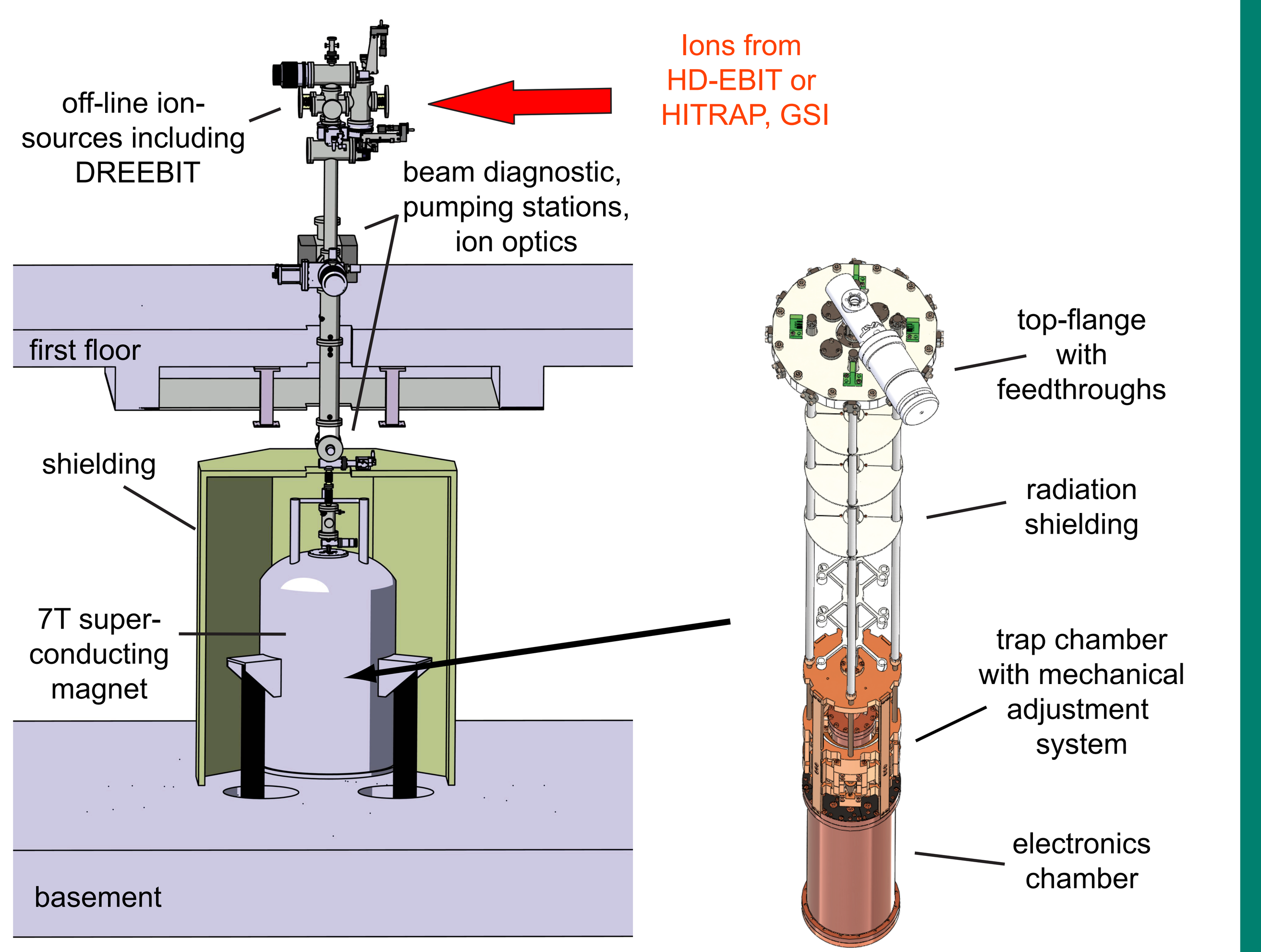
- Off-line EBIT (DREEBIT) with charge states up to $^{131}Xe^{46+}$ for systematic studies and first mass measurements
- Heidelberg EBIT with charge states up to $^{238}U^{92+}$ at 7 keV/q
- future: HITRAP facility at GSI, Darmstadt

ii) Beam Line:

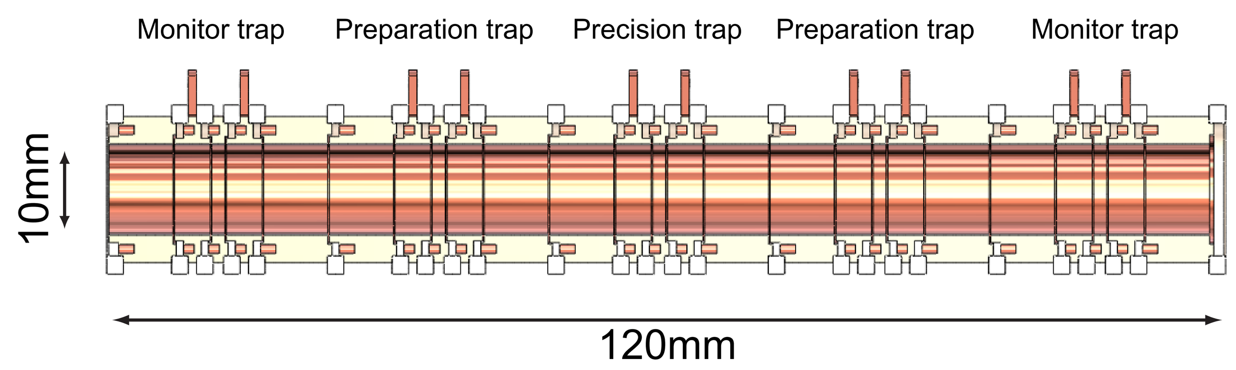
- Faraday cups and multi-channel plates for beam diagnostics
- ion-optic elements such as Einzel lenses and pulsed drift-tubes
- extremely good vacuum conditions

iii) Cryogenic Trap Setup:

The heart of the experiment will be a 7T superconducting magnet with a vertical cold bore (4K), housing the cryogenic Penning trap setup. In order to avoid possible environmental influences, the magnet will be located on a vibration-free concrete cushion in a pressure and temperature stabilized room. The trap chamber, into which the ions will be injected from the top, is located in the homogeneous field region of the magnet. The whole chamber will be adjustable to align and center the traptower in the magnetic field. Underneath the trap, another chamber housing the cryogenic detection electronics will be located.



Trap Tower



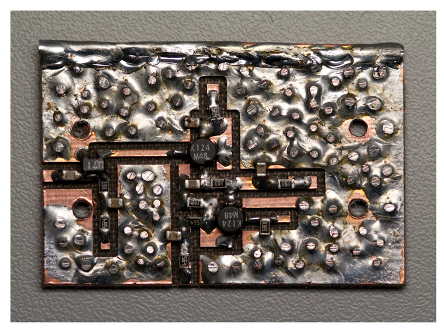
The PENTATRAP-tower consists of five identical cylindrical open-endcap Penning traps. The inner diameter is *10mm* and the length of a single trap is *24mm*. The five-pole structure of each trap allows for compensation of electrostatic anharmonicities. Therefore, the axial frequencies are independent on the ion's energy, which is crucial for high-precision experiments where tiny frequency shifts have to be detected.

The most important design criteria are listed below:

- *orthogonality:* for specific lengths of the correction electrodes, it is possible to make the potential depth independent of the applied correction voltage ($d_2/c_2 \sim 10^{-4}$ for final setup).
- *image charge effects:* highly-charged ions induce image-charge potentials in the trap electrodes which add up to the applied trap potential ($\Delta\omega_c/\omega_c \sim m/r^3$).
- *ion-ion interactions in adjacent traps:* due to Coulomb repulsion, two adjacent ions shift the axial frequency of each other ($\Delta\omega_c/\omega_c \sim q_1\, m_2/q_2$). This effect can be reduced by a large distance between the traps or small inner diameter of the traps (due to shielding).
- *homogeneous region of the magnetic field:* the total length of the trap is limited to the homogeneous region of the magnetic field.

Detection Electronics

toroidal superconducting resonator



cryogenic GaAs-amplifier

The motion of the ions will be detected by the non-destructive image current method. With this method the very tiny image current (~fA) induced in the trap electrodes by the ion's motion is detected. Therefore, the trap electrodes are connected to tuned circuits, which consist of a high-*Q* inductor followed by a high-impedance amplifier. To ensure sufficient signal-to-noise ratios, these circuits will be placed close to the trap in the electronics chamber with the 4K environment of the magnet's bore.

Typical values:

resonators:

$Q > 6 * 10^4$ @ 500 kHz
$Q > 4 * 10^3$ @ 30 MHz

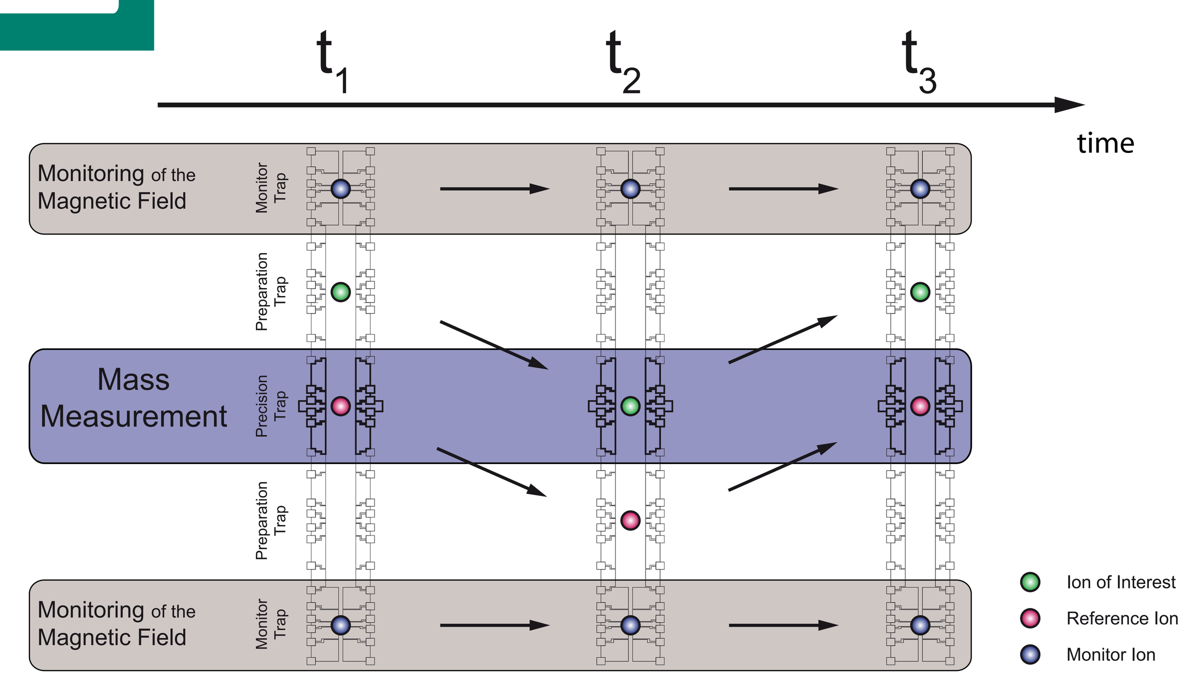
cryogenic amplifiers:

gain ~ 10-12 dB
noise < 1 nV/(Hz)$^{1/2}$ @ 500 kHz

Detection Scheme

The novel five trap structure of the PENTATRAP tower will allows reduction of systematic effects on the mass measurements, making it possible to reach an uncertainty of 10^{-11} for a broad range of nuclides.

The mass measurements will take place in the central Precision trap. To keep the time for the measurement cycles as short as possible, the Preparation traps are used. In these traps, single ions can be stored. Therefore, exchanging a reference ion and the ion-of-interest reduces to shifting them from the Precision trap to the Preparation trap. This can be done on a *ms*-time scale. Additionally, in the Monitor traps continuous observation of the cyclotron frequency of a Monitor ion is possible. The operation of all five traps should substantially reduce the systematic error due to temporal fluctuations of the magnetic field.



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