Towards Sympathetic Cooling of a Single (Anti)Proton in a Penning Trap for a High-Precision Measurement of the Particle's Magnetic Moment

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Motivation

Precise comparisons of the fundamental properties of protons and antiprotons, such as magnetic moments and charge-to-mass ratios, provide stringent tests of CPT invariance, and thus, matter-antimatter symmetry.

Using advanced Penning-trap methods, we have recently determined the magnetic moments of the proton and the antiproton with a relative precision of 0.3 p.p.b. and 1.5 p.p.b., respectively [1, 2].

Both experiments rely on sub-thermal cooling of the particle's modified cyclotron mode using feedback-cooled tuned circuits. We aim to replace this time-consuming process (several hours) by sympathetic cooling with laser-cooled beryllium ions.

Penning Trap

A homogeneous magnetic field and an electric quadrupole field confine a charged particle in the center of the trap.

$$\vec{B} = B\vec{e}_z \qquad \vec{E} = U_r c_2(\rho\vec{e}_\rho - 2z\vec{e}_z)$$

The particle motion is a superposition of three oscillations, the frequencies of which are related to the free cyclotron frequency ν_c by the invariance theorem [3]

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

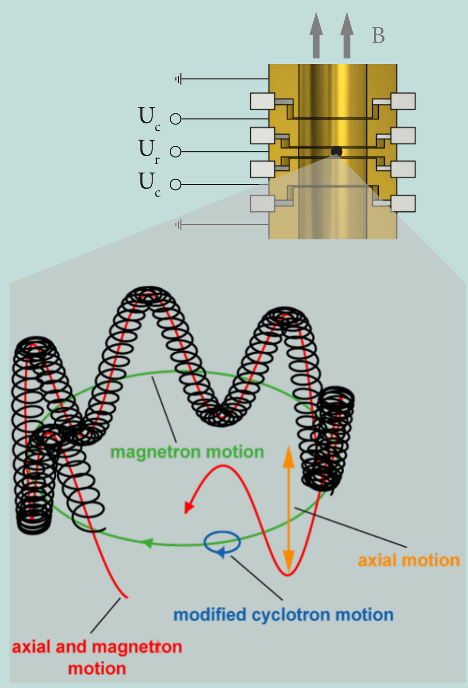


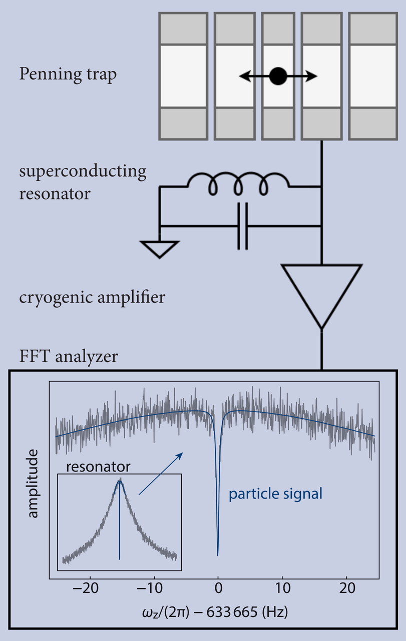
Image Current Detection

The axial motion of the trapped (anti)proton is detected by monitoring the image current induced in an electrode.

Currents (~fA) are transformed into measureable voltages by a superconducting resonant circuit with high Q and the voltage is amplified by a cryogenic amplifier.

At the frequency ν_z the the thermal noise of the resonator is shorted.

Sideband coupling allows to measure the frequencies of the radial motion.



The Double Penning-trap Method for Measurements of the Proton Magnetic Moment

Relies on the excitation of proton spin transitions in the very homogeneous magnetic field of the precision trap (PT) and subsequent analysis of the spin state in the strong magnetic bottle of the analysis trap (AT):

Application of a drive at the excitation frequency ν_{rf} and simultaneous measurement of the cyclotron frequency ν_c in the precision trap yields the ratio ν_{rf}/ν_c and probes the *g*-factor resonance (the spin-flip probability as a function of the ratio ν_{rf}/ν_c).

The *g*-factor is reconstructed utilizing the relation $g/2 = \mu_p/\mu_N = \nu_L/\nu_c$.

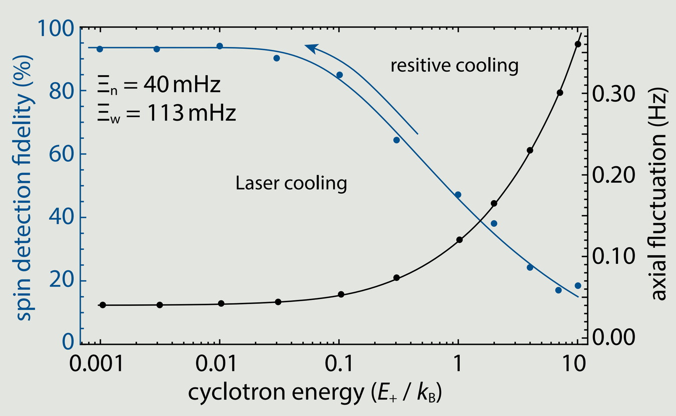
The spin-flip probability is determined by the spin state before and after the excitation. Therefore, high fidelity detection of the spin state in the analysis trap is required [4].

The challenge: cyclotron quantum jumps lead to axial frequency fluctuations.

Transition rate:

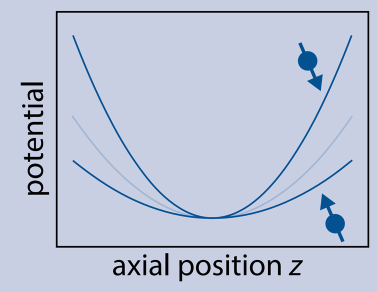
$$\frac{\delta n_+}{\delta t} = \frac{2\pi}{\hbar}\Delta_+\rho(E_+)\Gamma^2_{i\to f}$$

$$\Gamma_{i\to f} = qE_0\sqrt{\frac{\hbar}{m_p\omega_+}\frac{n_+}{2}}$$

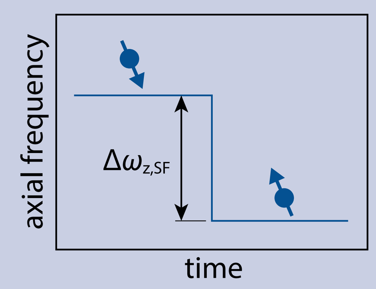


Spin State Detection

Based on the Continuous Stern-Gerlach effect [5]: A magnetic bottle $B = B_2z^2$ is superimposed to the axial magnetic field which leads to a harmonic z-dependent energy difference for the two spin states.



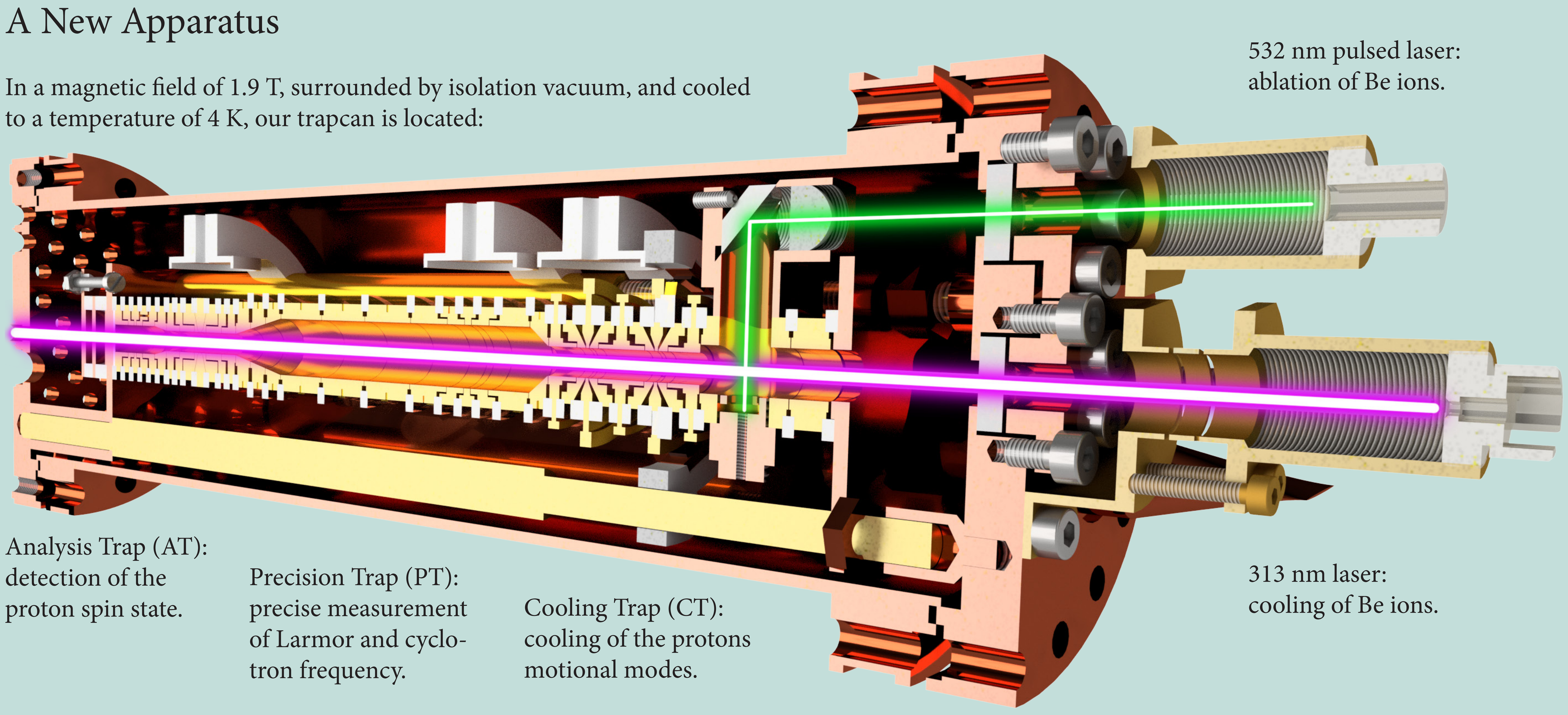
A spin transition shifts the axial frequency by 233 mHz out of 550 kHz and allows the determination of the spin state.



The small magnetic moment of the proton makes this measurement especially challenging: $\frac{\mu_B/m_e}{\mu_p/m_p} \approx 10^6$

A New Apparatus

In a magnetic field of 1.9 T, surrounded by isolation vacuum, and cooled to a temperature of 4 K, our trapcan is located:

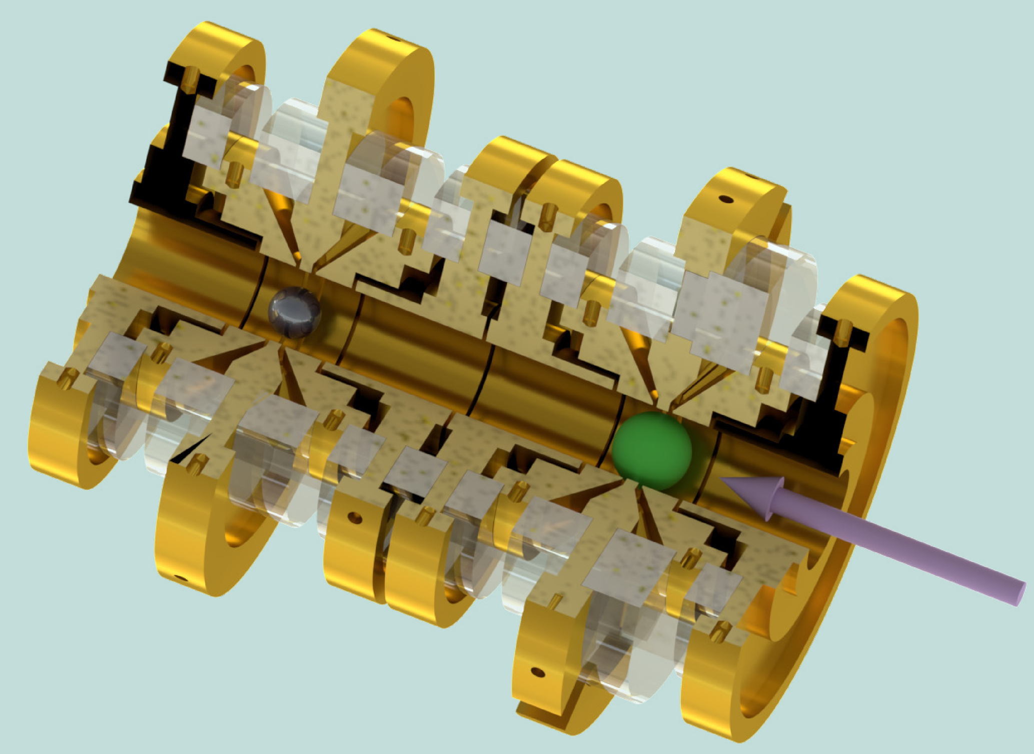


The Cooling Trap

Its purpose is to sympathetically cool single protons by coupling them to laser-cooled beryllium ions [6,7].

Resonantly coupling laser-cooled ions to single protons across a common endcap electrode provides a novel cooling mechanism for particles without suitable transitions for laser cooling.

The trap consists of two identical 5-pole Penning traps, connected by a common endcap:



A cloud of Be ions (green) is laser cooled to the Doppler-limit temperature of several mK, and interacts with a single proton (grey) via the image charge induced on the common endcap electrode.

Coupling time constant τ: $\tau = \pi\omega_z d^2 C_T \frac{\sqrt{m_p m_{Be}}}{e^2}\frac{1}{\sqrt{N}}$

The traps are small in diameter and optimized for low capacitance, leading to short coupling times (tens of seconds).

In our experiment this cooling method will enable us to deterministically prepare single protons with temperatures in the mK range within tens of seconds, which will ultimately reduce our particle preparation times by a factor of at least 50. Furthermore, this method is directly applicable to the antiproton and other particles as well.

Apparatus Improvements

Compared to the apparatus used for the most precise measurement of the proton magnetic moment carried out by our collaboration [1] the new apparatus features several upgrades:

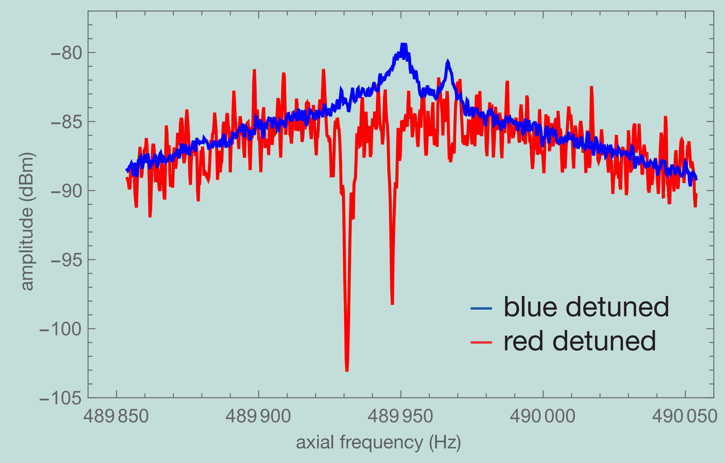
- The sympathetic cooling method will allow to prepare much colder particles in minutes, compared to several hours in the previous experiment, greatly increasing statistics.
- A larger diameter of the precision trap leads to a smaller image-charge shift, one of the main systematic effects.
- An optimized Penning-trap geometry will lead to a more homogeneous magnetic field in the precision trap.
- A new self-shielding coil allows stabilization of magnetic field (cyclotron frequency) fluctuations in the precision trap.

Early Results: Laser Cooled Be Ions

A cloud of Be ions is loaded into the cooling trap (CT).

Then the axial mode is coupled to the radial magnetron mode using a drive at the sum frequency. A double dip appears.

By tuning the laser frequency to resonance, cooling or heating of both modes can be observed.



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