Towards Sympathetic Cooling of Single Protons and Antiprotons

Markus Wiesinger[a,b], Matthew Bohman[a,b], Christian Smorra[b], Matthias Borchert[b,c], Jack Devlin[b,d], Stefan Erlewein[a,b,d], James Harrington[a,b], Andreas Mooser[a], Elise Wursten[b,d], Klaus Blaum[a], Yasuyuki Matsuda[e], Wolfgang Quint[f], Jochen Walz[g,h], Stefan Ulmer[b]

[a] Max-Planck-Institut für Kernphysik, Heidelberg, Germany.
[b] Ulmer Fundamental Symmetries Laboratory, RIKEN, Wako, Saitama, Japan.
[c] Leibniz Univeristät Hannover, Hannover, Germany.
[d] CERN, Geneva, Switzerland.
[e] Graduate School of Arts and Sciences, University of Tokyo, Tokyo, Japan.
[f] GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany.
[g] Helmholtz-Institut Mainz, Mainz, Germany.
[h] Institut für Physik, Johannes Gutenberg-Universität, Mainz, Germany.

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, of which are related to the free cyclotron frequency ν_c by the invariance theorem [3]

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

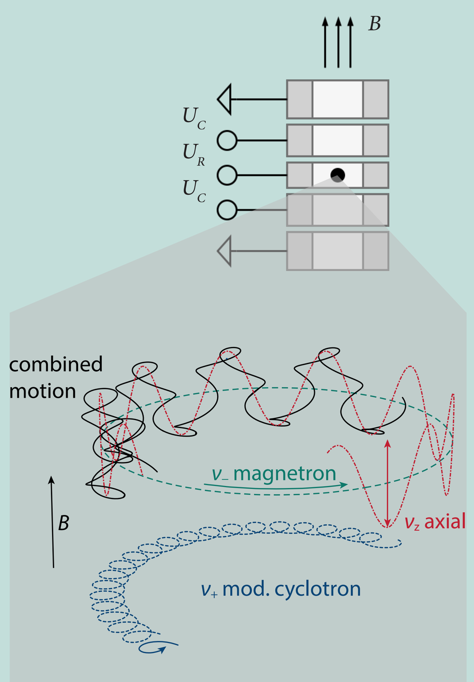


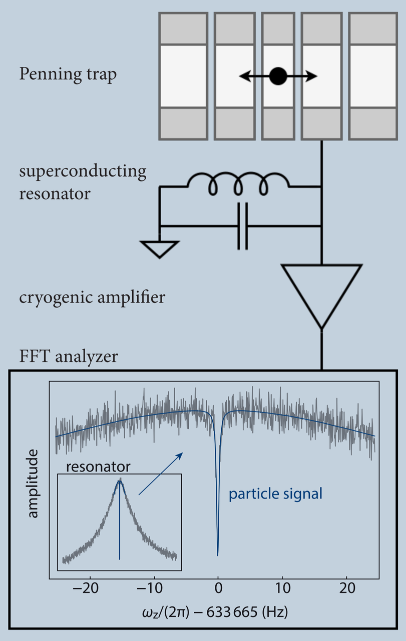
Image Current Detection

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 particles shorts the thermal noise of the resonator.

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



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

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 $g/2 = \mu_p/\mu_N = \nu_L/\nu_c$.

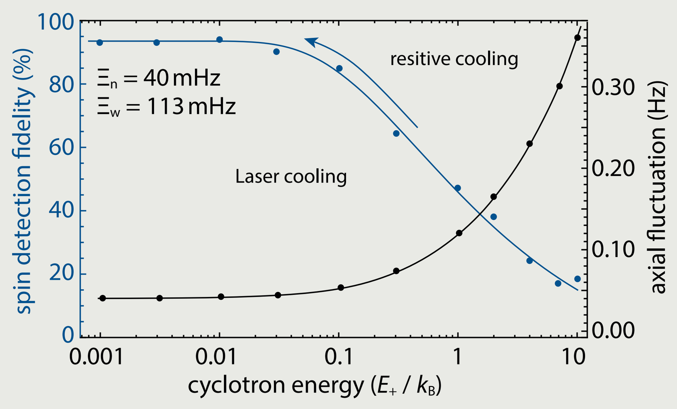
The spin-flip probability is obtained from a measurement of the spin state before and after the excitation. Therefore, high fidelity detection of the spin state in the analysis trap is required [4].

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

Transition rate:

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

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

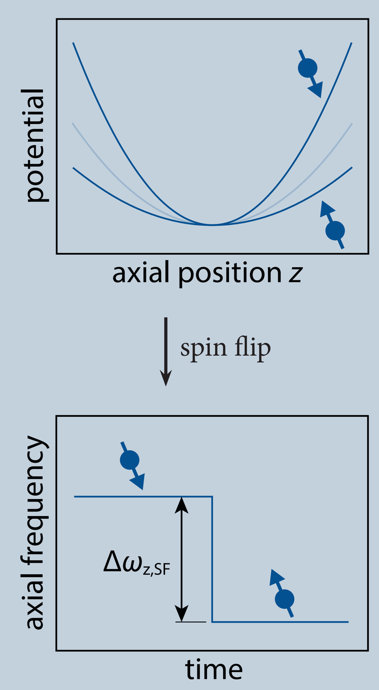


Spin State Detection

Based on the Continuous Stern-Gerlach effect [5]: A magnetic bottle $B = B_2 z^2$ is superimposed to the axial magnetic field which leads to a harmonic z-dependent energy difference for the two spin states.

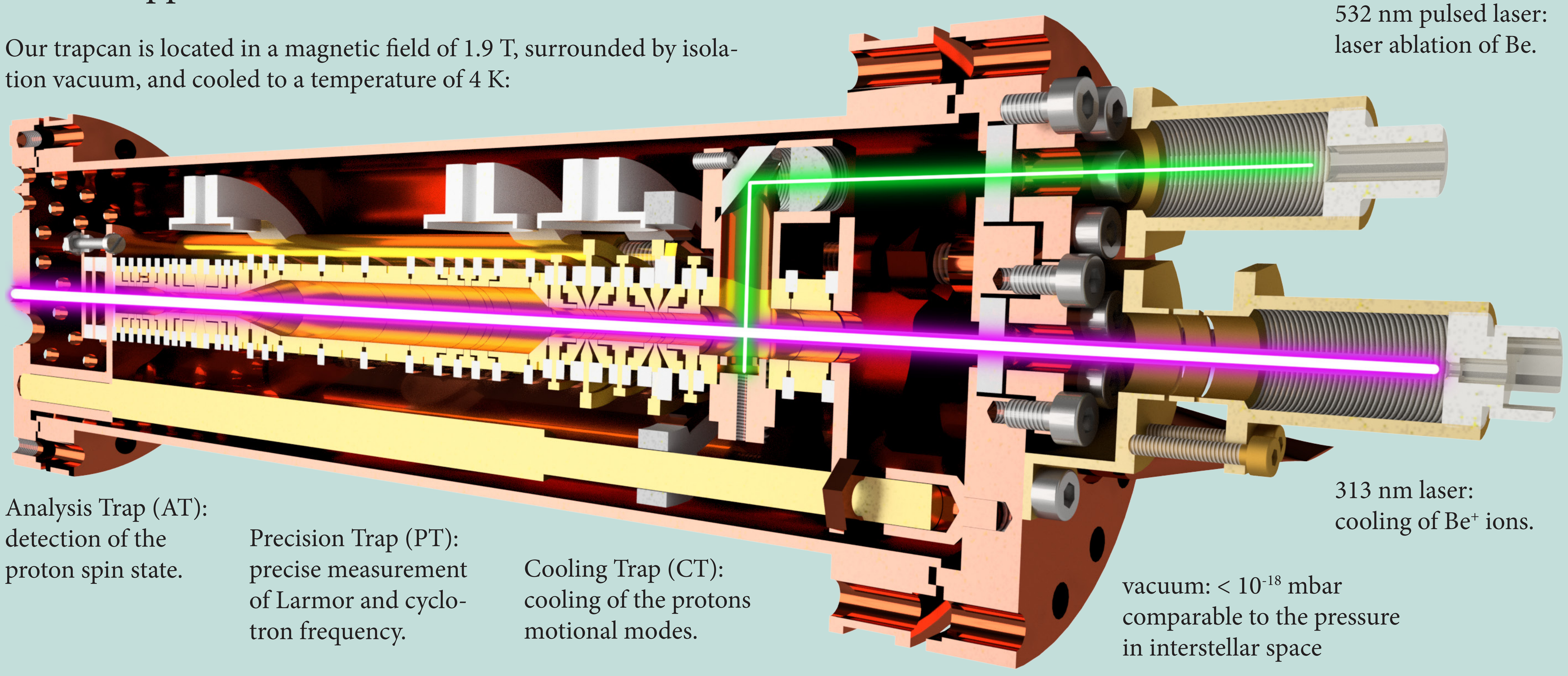
A spin transition shifts the axial frequency by 233 mHz out of 550 kHz and allows the determination of the spin state.

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

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



532 nm pulsed laser: laser ablation of Be.

313 nm laser: cooling of Be⁺ ions.

Analysis Trap (AT): detection of the proton spin state.

Precision Trap (PT): precise measurement of Larmor and cyclotron frequency.

Cooling Trap (CT): cooling of the protons motional modes.

vacuum: < 10^{-18} mbar comparable to the pressure in interstellar space

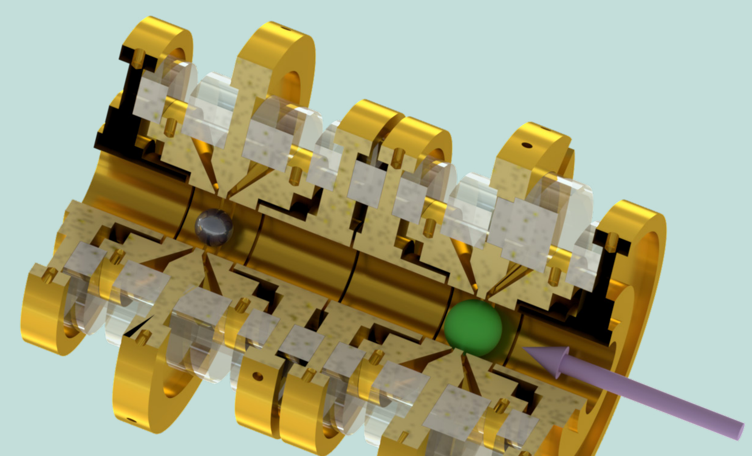
The Cooling Trap

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

Resonantly coupling laser-cooled ions to single (anti)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.



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

Fluorescence Detection

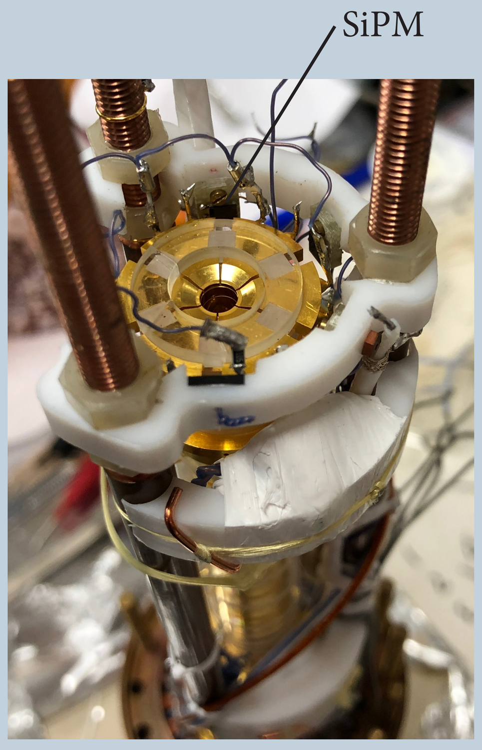
Silicon photomultipliers (SiPMs) are used as single photon sensitive detectors for fluorescence photons.

They are located inside the trapcan at a distance of 12 mm from the Be^+ ion cloud and operated at a temperature of 4 K.

Narrow slits in the electrode allow fluorescence photons to reach the detectors.

At 4 K a dark count rate smaller than 10 per second is observed.

SiPM



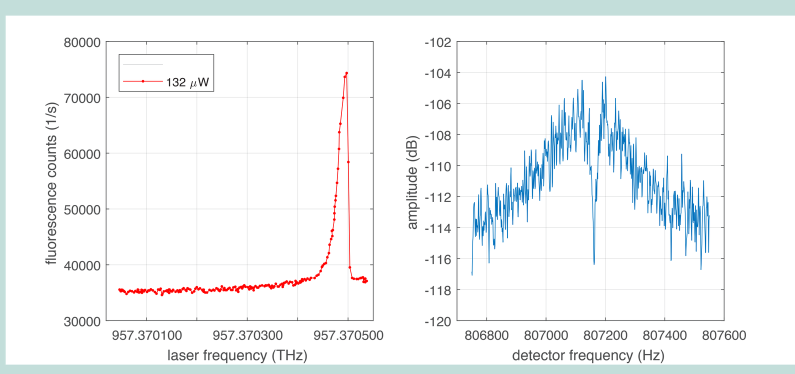
Recent Results: Laser Cooled Be⁺ Ions

A cloud of Be^+ ions is prepared in the cooling trap (CT).

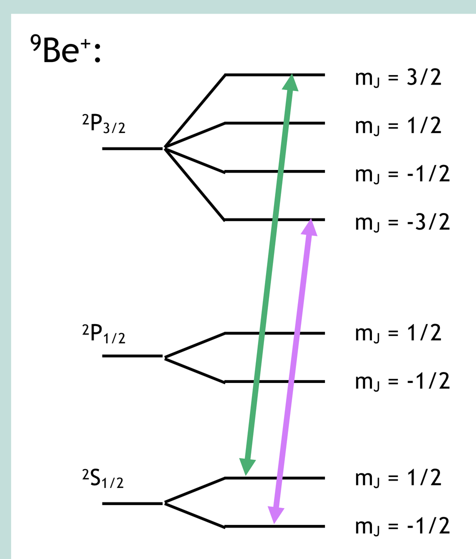
The axial mode is coupled to the radial magnetron mode using a drive at the sum frequency and a double dip is observed at the detector.

Scanning the laser frequency across the resonance, cooling can be observed simultaneously on the fluorescence signal and the image current detector.

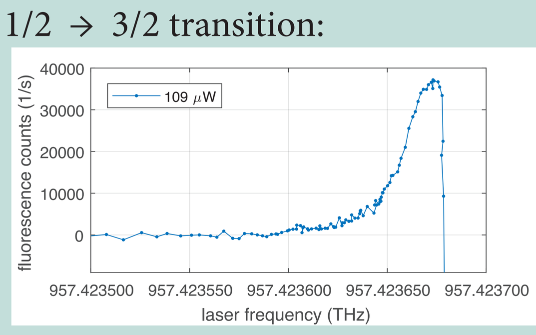
Close to the resonance the dip disappears, because Be^+ ions are no longer in thermal equilibrium with the detector.



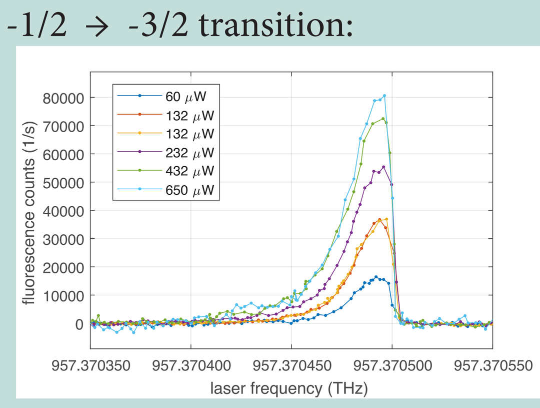
Recorded ⁹Be⁺ Cooling Transitions



1/2 → 3/2 transition:



-1/2 → -3/2 transition:



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