Sympathetic Cooling of Single Protons (and Antiprotons)

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This contribution is based on our recent paper:

BASE Collaboration, Sympathetic cooling of a trapped proton mediated by an LC circuit. *Nature* **596,** 514–518 (2021).
https://doi.org/10.1038/s41586-021-03784-w

Motivation for Cooling

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.

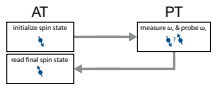
Using advanced Penning-trap methods, we have recently determined the magnetic moments of the proton and the antiproton with a relative precision of 0.3 p.p.b. and 1.5 p.p.b., respectively [1, 2].

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.

(Anti)Proton *g*-Factor Measurement

Double Penning-trap method:

excitation of spin transition in homogeneous precision trap (PT)

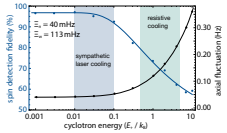


spin-state detection in magnetic bottle trap (AT)

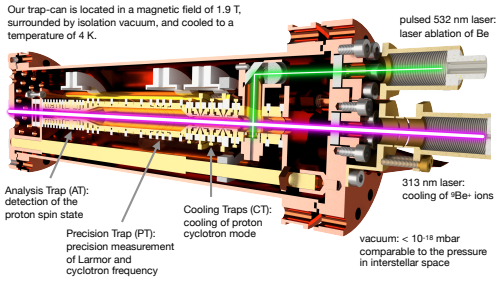
Continuous Stern-Gerlach effect:

spin state is determined by jump in axial frequency [3,4]

caveat: cyclotron quantum jumps lead to axial frequency fluctuation

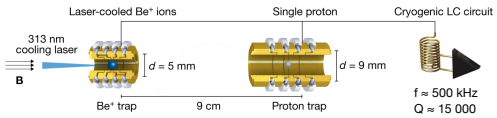


Experimental Apparatus



Cooling Technique

LC circuit connected to two traps:

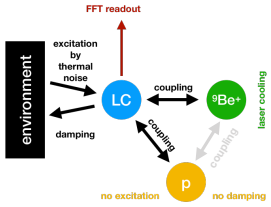


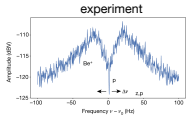
⇒ system of three coupled, damped ($^9Be^+$ by the cooling laser), and excited (LC circuit by thermal noise) oscillators

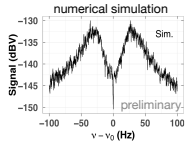
BASE Collaboration, *Nature* **596,** 514–518 (2021)

Coupled Oscillator System

Readout: FFT of time-domain signal of the LC circuit





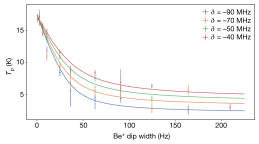


Cooling Results

Temperature reduction: 85 %

cooling time constant: ≈ 1s

first ever sympathetic cooling of a proton by induced (image) currents



final proton temperature: 2.6(2.5) K

limitations:
heating by RLC circuit: ≈ 2 K
temperature resolution: ≈ 2 K

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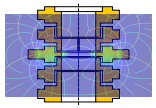
Outlook

Additional trap for precise temperature measurement:

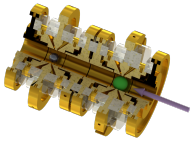
magnetic bottle leads to energy dependent axial frequency shift due to CSG effect

temperature resolution: ≈ 10 mK



Application of more advanced cooling techniques will allow to reach even lower temperatures:

coupling mediated by common end-cap electrode [5]



References & Funding

[1] Schneider, G. *et al.*, *Science* **358**, 1081 (2017)

[2] Smorra, C. *et al.*, *Nature* **550**, 371 (2017)

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[5] Heizen, D. J. & Wineland, D. J., *Phys. Rev. A* **42**, 2977 (1990)

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