The Magnetic Moment of the Proton

A. Mooser
for the BASE collaboration

Programs for
Junior Scientists

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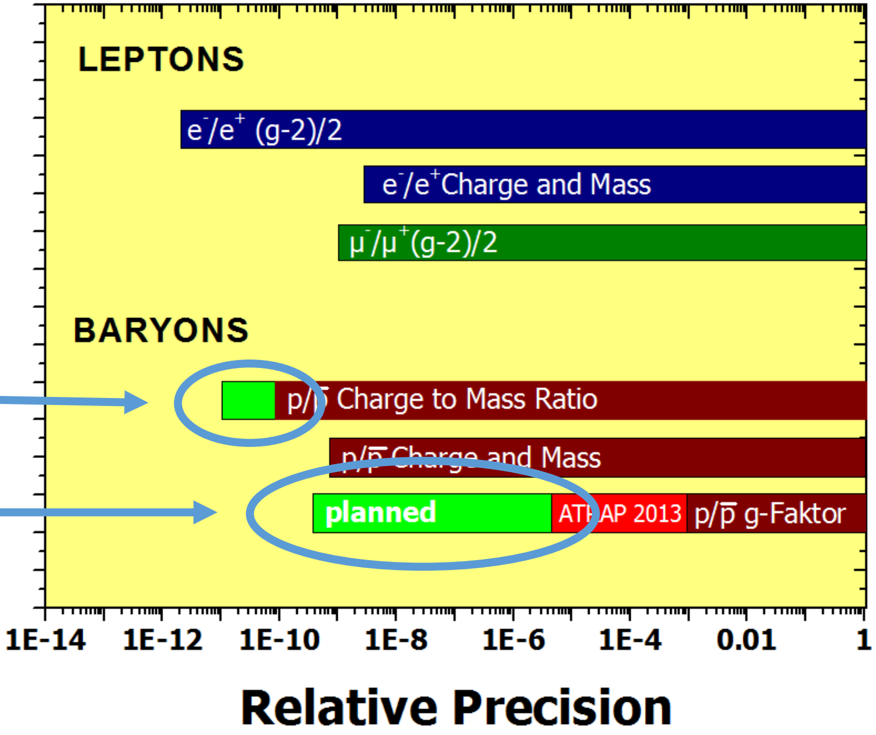
Motivation

- CPT-Symmetry fundamental cornerstone of Standard Model
- Strategy: Compare properties of matter and antimatter conjugates with high precision.



S. Ulmer et al., *Nature* **524** 196 (2015)

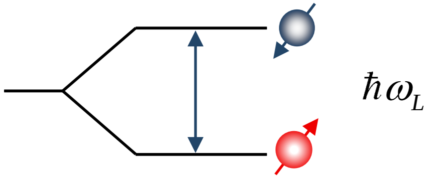
A. Mooser et al., Nature **509**, 596 (2014)

- Measured proton magnetic moment with ppb precision – plan to improve
- Plan to apply methods to magnetic moment of antiproton
- Plan to improve on our recent charge-to-mass ratio comparison

How to measure these?

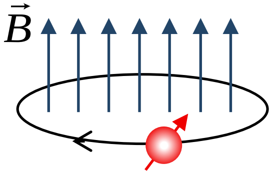
Determination of Larmor frequency in a given magnetic field

$$\omega_L = g \frac{e}{2m_p} B$$



Monitoring magnetic field via simultaneous measurement of the free cyclotron frequency

$$\omega_c = \frac{e}{m_p} B$$

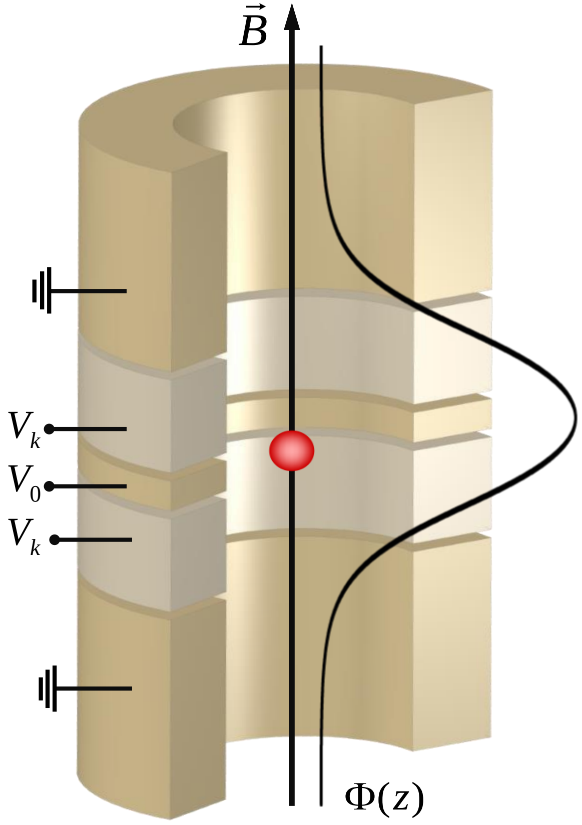


$$g = 2\frac{\omega_L}{\omega_c} = 2\frac{\nu_L}{\nu_c}$$

$$\frac{\omega_{c,\bar{p}}}{\omega_{c,p}} = \frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p}$$

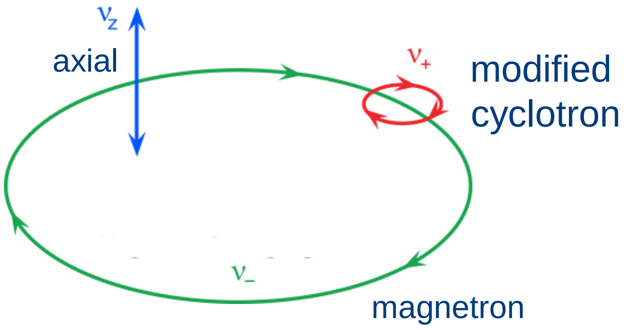
The Penning Trap

Superposition of homogeneous magnetic field and electrostatic quadrupole potential



$\vec{B} = B\vec{e}_z$ → radial confinement

$\Phi(z,\rho) = U_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$ → axial confinement



axial	$\nu_z = 700\,\mathrm{kHz}$
modified cyclotron	$\nu_+ = 29\,\mathrm{MHz}$
magnetron	$\nu_- = 10\,\mathrm{kHz}$

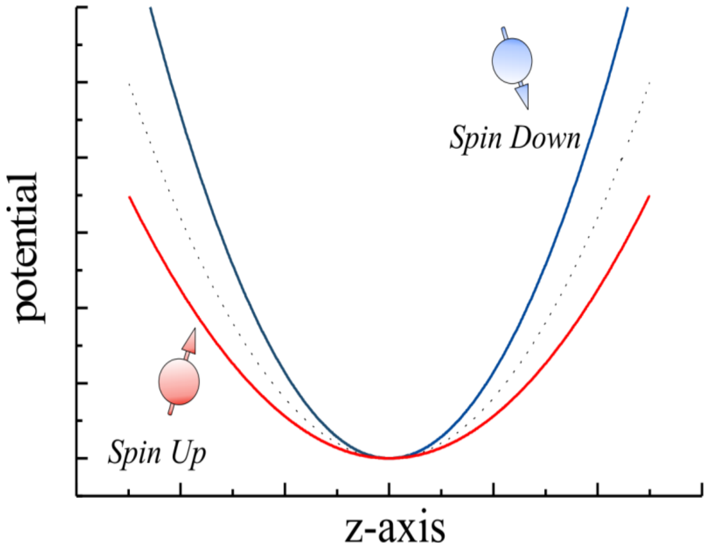
Invariance Theorem: $\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$

[L. S. Brown and G. Gabrielse, Phys. Rev. A, 25:2423, 1982.]

Detection of the spin state
The continuous Stern-Gerlach effect

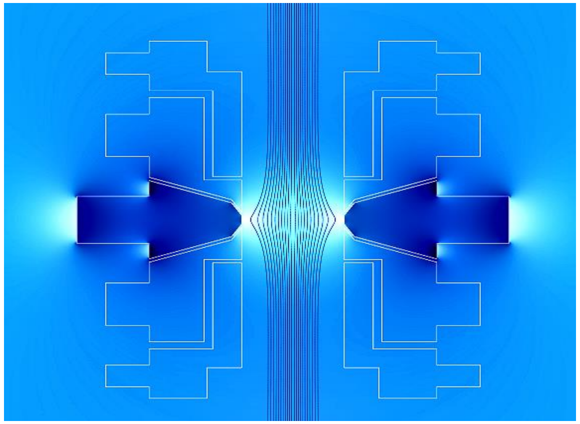
Introduce magnetic inhomogeneity, the magnetic bottle

$$B_z = B_0 + B_2\left(z^2 - \frac{\rho^2}{2}\right)$$



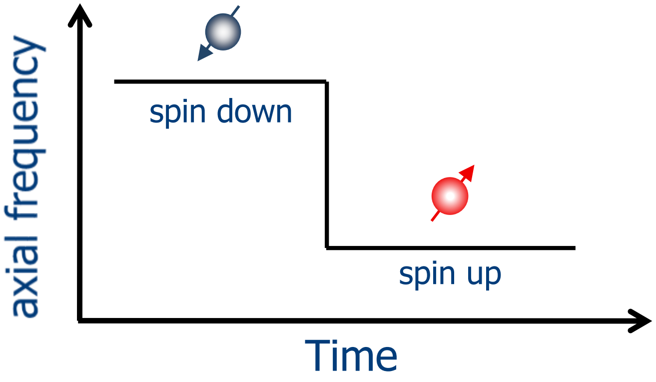
Spin flip results in shift of the axial frequency

$$\Delta\nu_z \propto \frac{\mu_p}{m} B_2$$



Coupling of spin moment to axial oscillation

$$\Phi_z = \pm\mu_p B_z$$

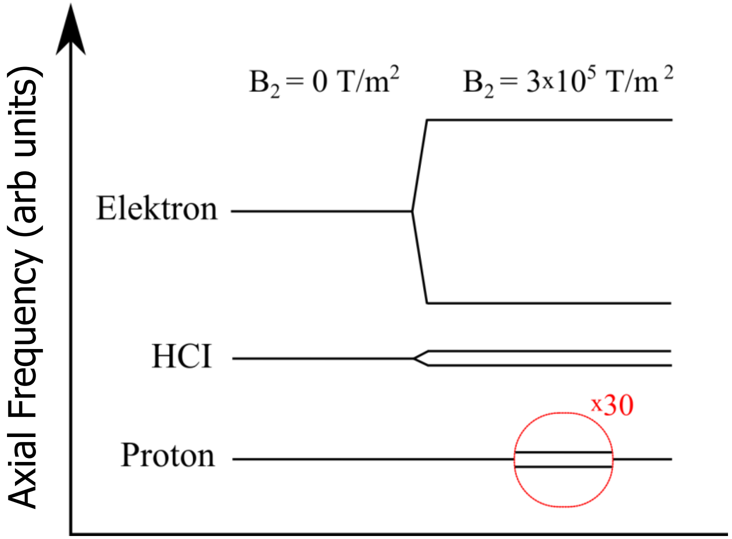


Detection of the spin state
Challenge I

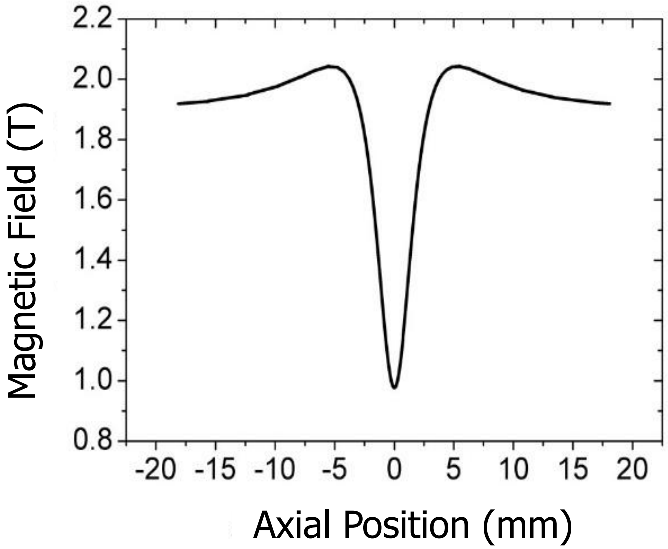
Applied with great success for electron g-factors – Bohr magneton

$$\nu_z \propto \pm \frac{\mu_z}{m} B_2$$

spin
momentum



Additional factor of 4 for ^{3}He



Dealing with nuclear magneton requires magnetic bottle of

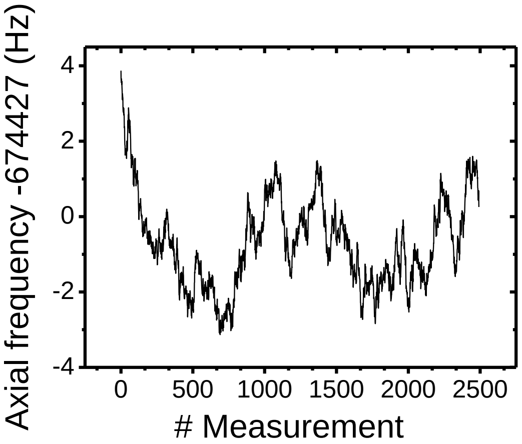
$$\boxed{B_2 = 30\ \mathrm{T/cm^2}}$$

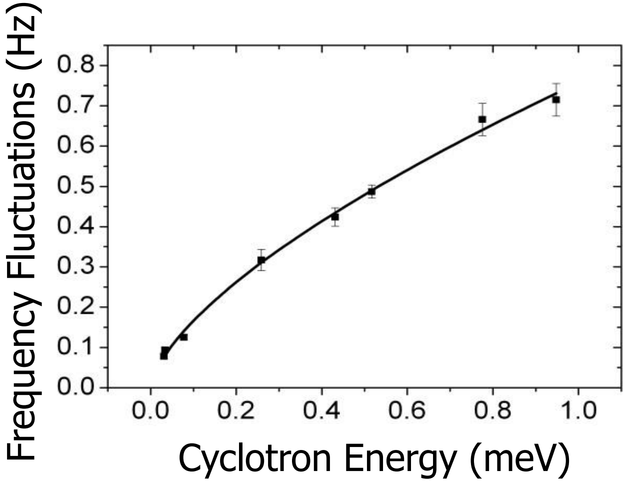
Detection of the spin state
Challenge II

In addition strong coupling of radial modes to axial mode

$$\nu_z \propto \frac{1}{m_p \nu_{z,0}} \frac{B_2}{B_0} E_{+,-}$$

3 cyclotron quantum (210neV) jumps
shift axial frequency by same amount as spin flip





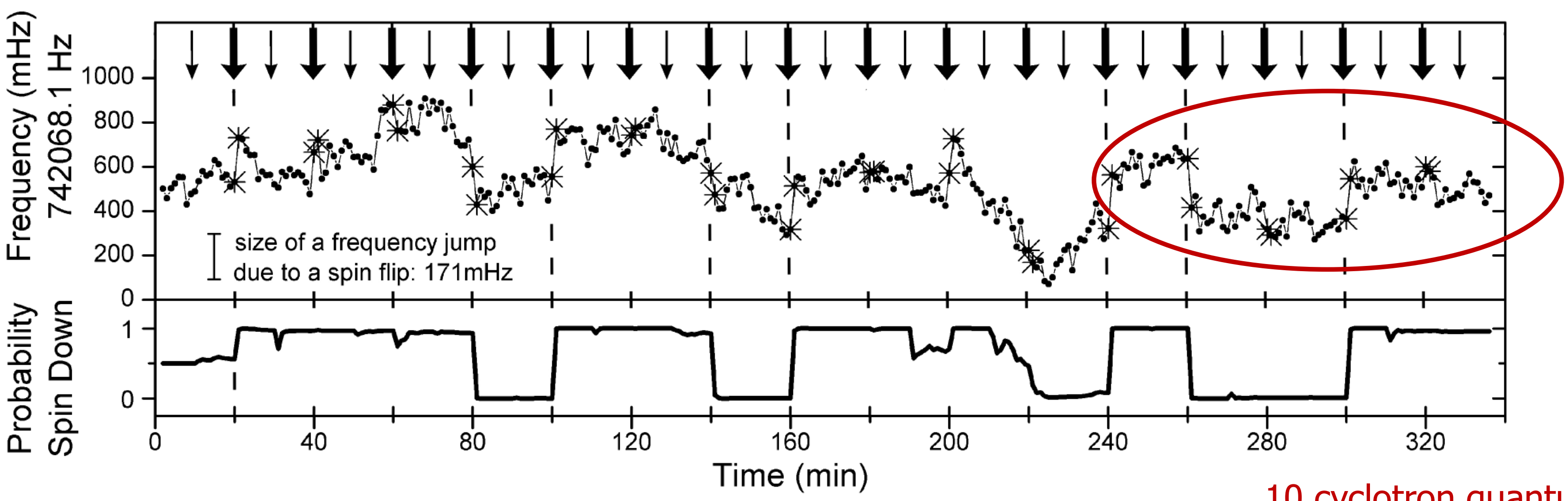
$$R_{n\to n\pm1} = \frac{q^2}{2m_\mathrm{p}\,\hbar\omega}\left(n+\frac{1}{2}\pm\frac{1}{2}\right)\underbrace{\int_{\mathbb{R}}\mathrm{d}t'\,\mathrm{e}^{\pm\mathrm{i}\omega t}\left\langle E^{(1)}(t)E^{(1)}(t+t')\right\rangle}_{S(\pm\omega)}$$

Consistent with external power spectral density of: $\omega S(\omega) = 1.6 * 10^{-12}\ \mathrm{V^2/m^2}$

Sub-thermal energies needed for spin state detection – 2 hours of preparation

Observation of Single Spin Flips

Series of axial frequency measurements in AT



10 cyclotron quantum jumps in 1 hour

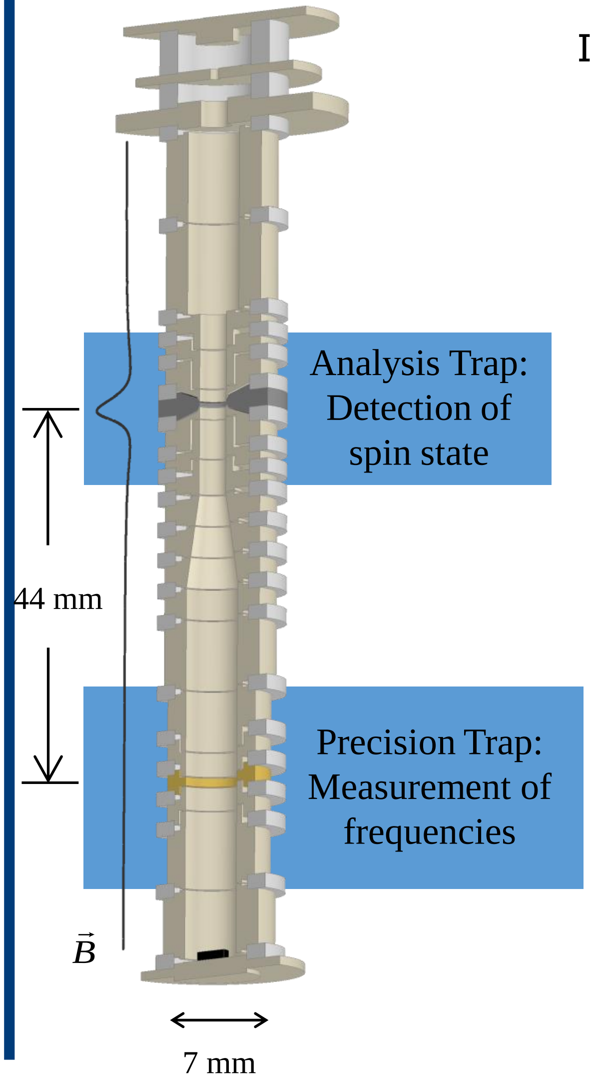
<u>Statistical Bayes rule </u>– conditional probability of particle being in spin state

- Bayes method allows for spin state detection fidelity of 88%

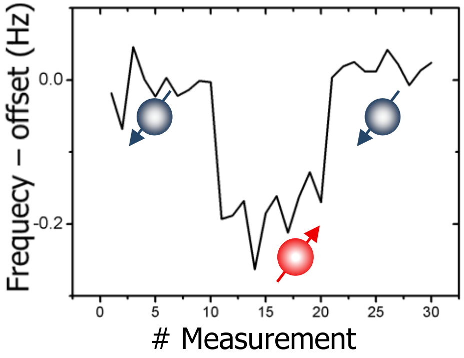
A. Mooser and K. Franke *et al.,* Phys. Rev. Lett. **110**, 140405 (2013).
A. Mooser and S. Ulmer *et al.*, Phys. Lett. B **723**, 78–81 (2013).

Double Penning-trap method

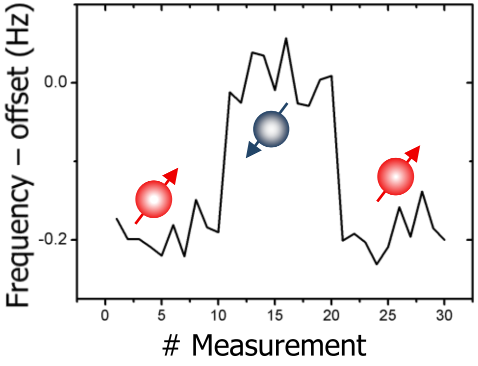
- High Precision measurement demands homogeneous magnetic field
- Introduce two traps – double Penning trap setup (*H. Häffner, Phys. Rev. Lett.85, 5308 (2000)*)



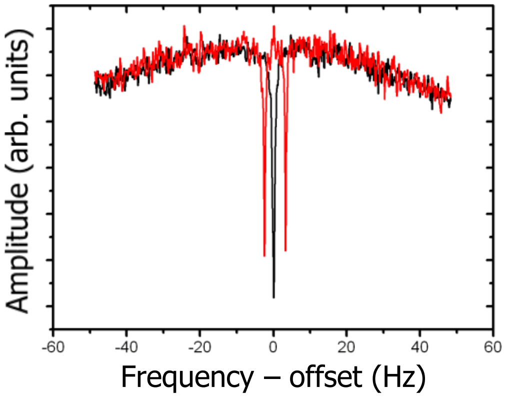
I. Determination of Spin State (AT)



V. Determination of Spin State (AT)



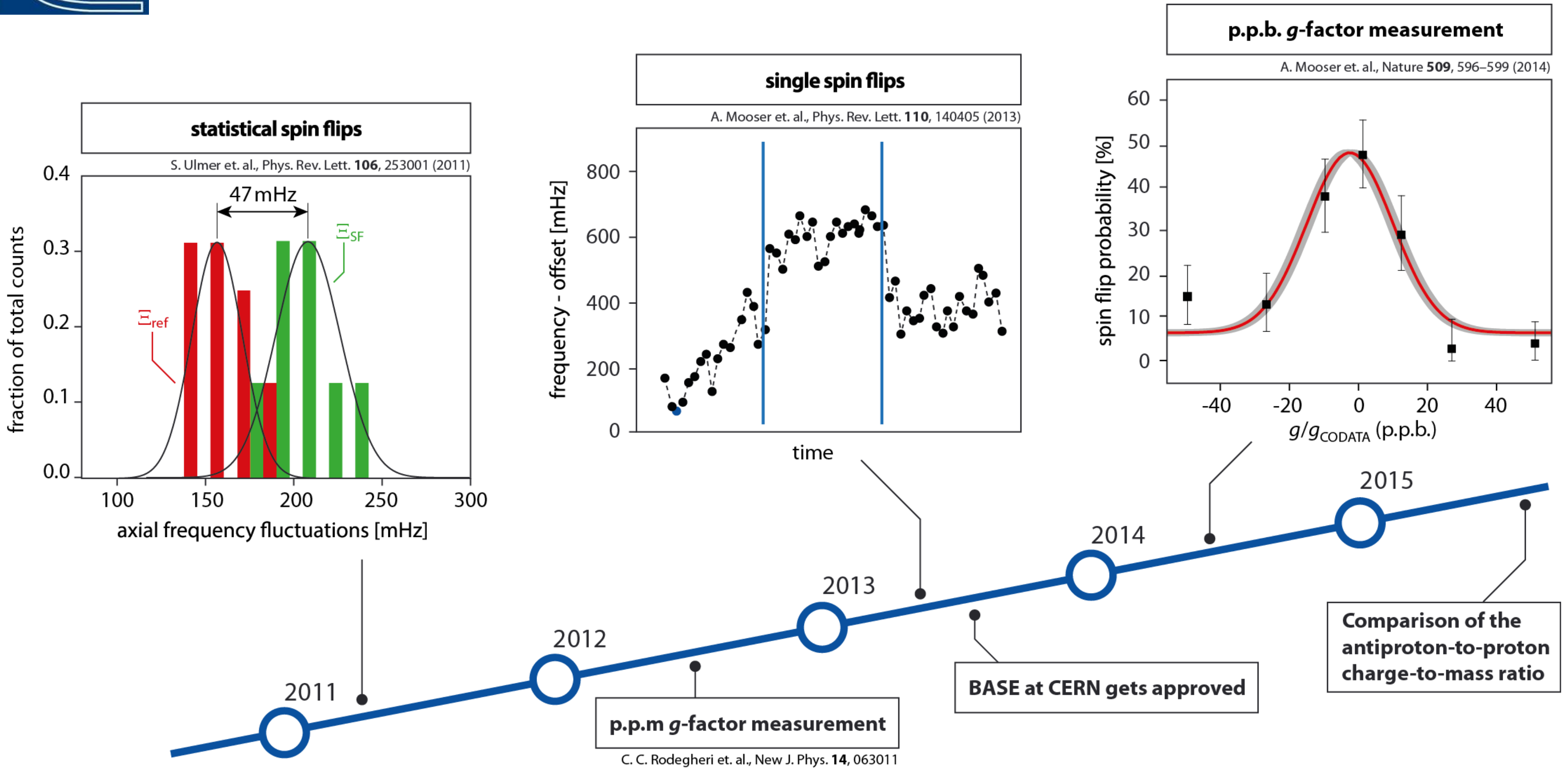
II. Transport to PT



IV. Transport to AT

III. Driving Spin Transition and measure B-field(PT)
g-factor measurement

Milestones



statistical spin flips

S. Ulmer et. al., Phys. Rev. Lett. **106**, 253001 (2011)

single spin flips

A. Mooser et. al., Phys. Rev. Lett. **110**, 140405 (2013)

p.p.b. *g*-factor measurement

A. Mooser et. al., Nature **509**, 596–599 (2014)

p.p.m *g*-factor measurement

C. C. Rodegheri et. al., New J. Phys. **14**, 063011

BASE at CERN gets approved

Comparison of the antiproton-to-proton charge-to-mass ratio

In 2014 we performed the most precise and first direct high-precision measurement of the proton g-factor

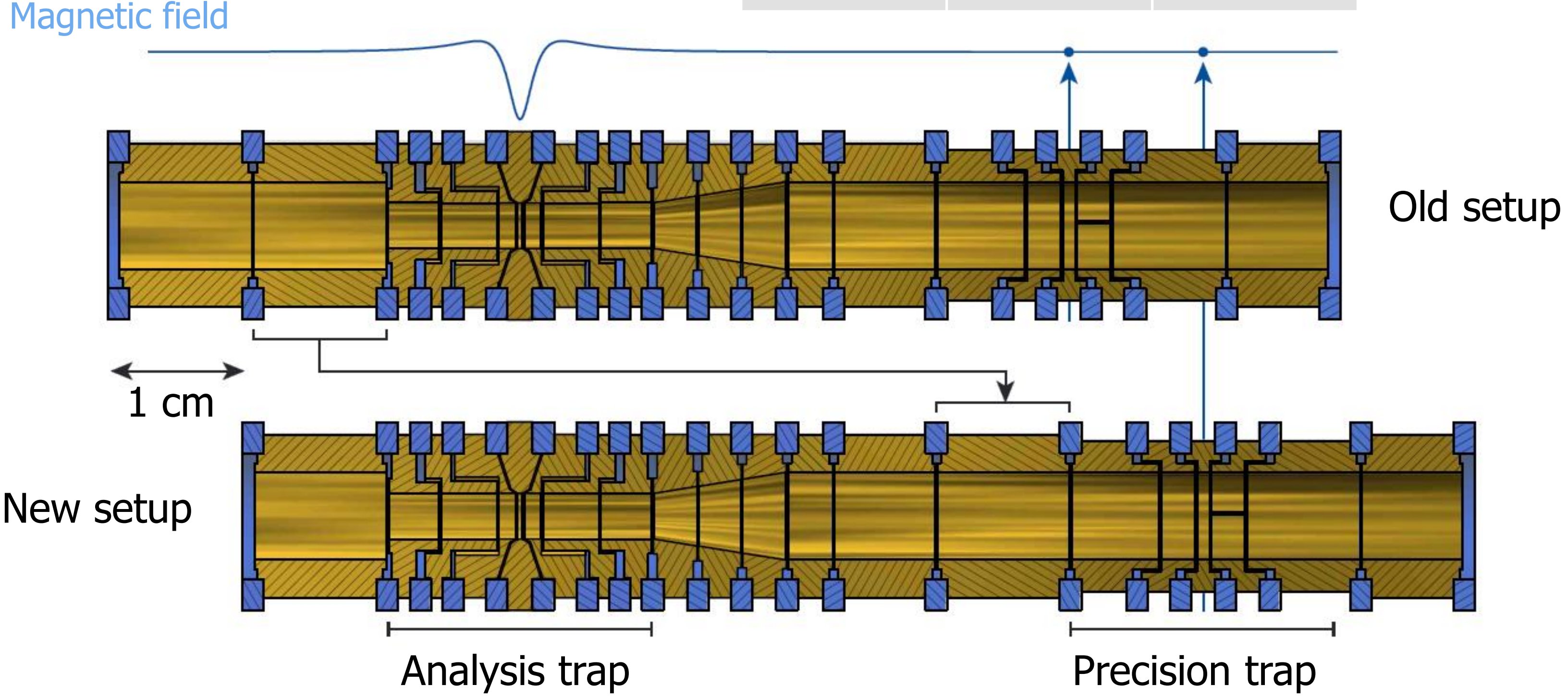
$$g_p = 5.585\ 694\ 700\ (14)^{stat}\ (12)^{syst}$$

Can be applied to the antiproton to obtain thousand fold improved CPT-test

Limitations of recent measurement

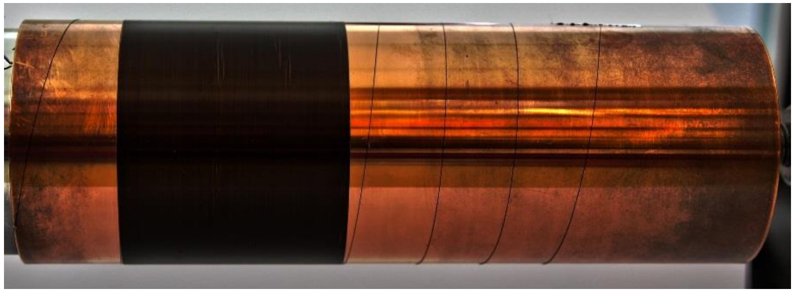
- Main limitations in the previous measurement
  - B_2 in precision trap constraints on line width
  - Saturation broadening of the Larmor resonance

	old	new
B_2	$4 T/m^2$	$0.5 T/m^2$
Line-witdh	200 mHz	40 mHz
relative prec.	10^{-9}	10^{-10}

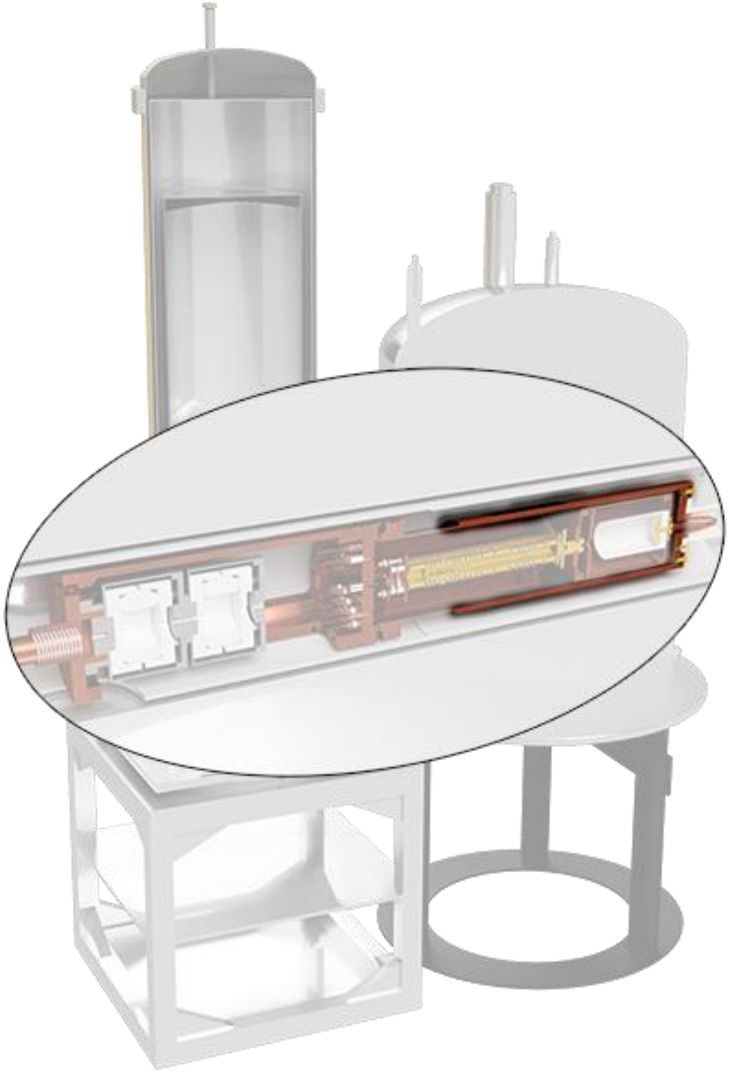


Improvement of appartus

- Implementation of self-shielding coil



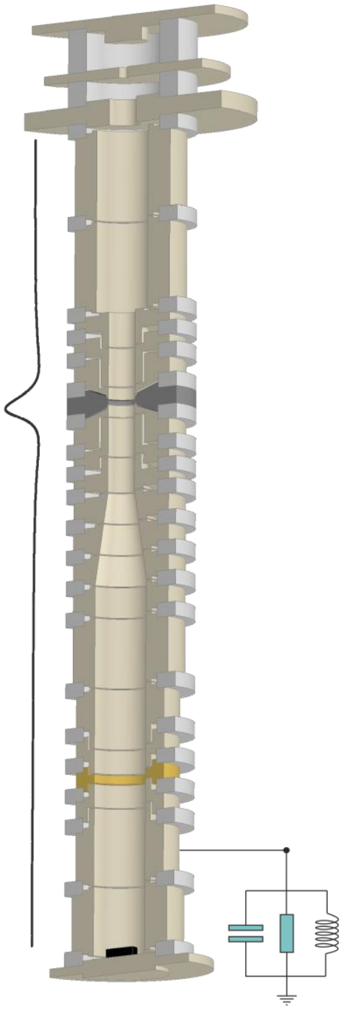
- Reduction of external magnetic field fluctuations by a factor of 50

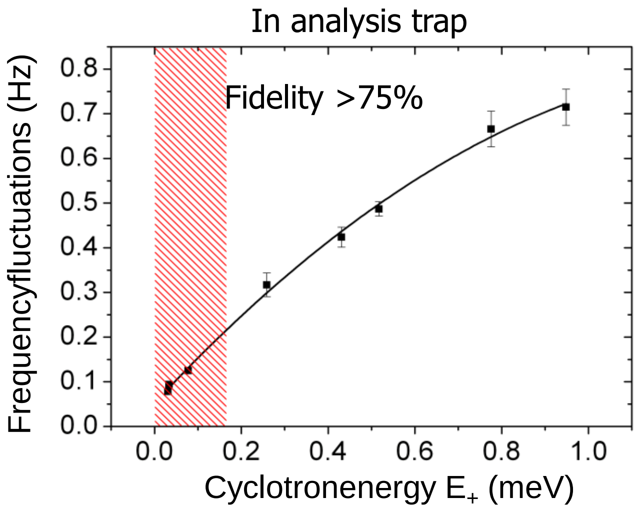


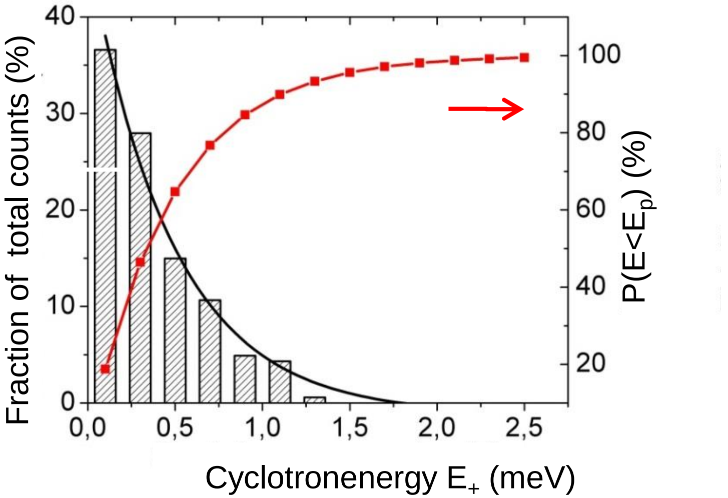
G.Gabrielse and J. Tan, J. Appl. Phys. **63**, 10 (1988).

Limitation on statistics

- Cyclotron frequency measurement heats cyclotron mode to 30 meV
- Low energies required in analysis trap for high fidelity spin state detection





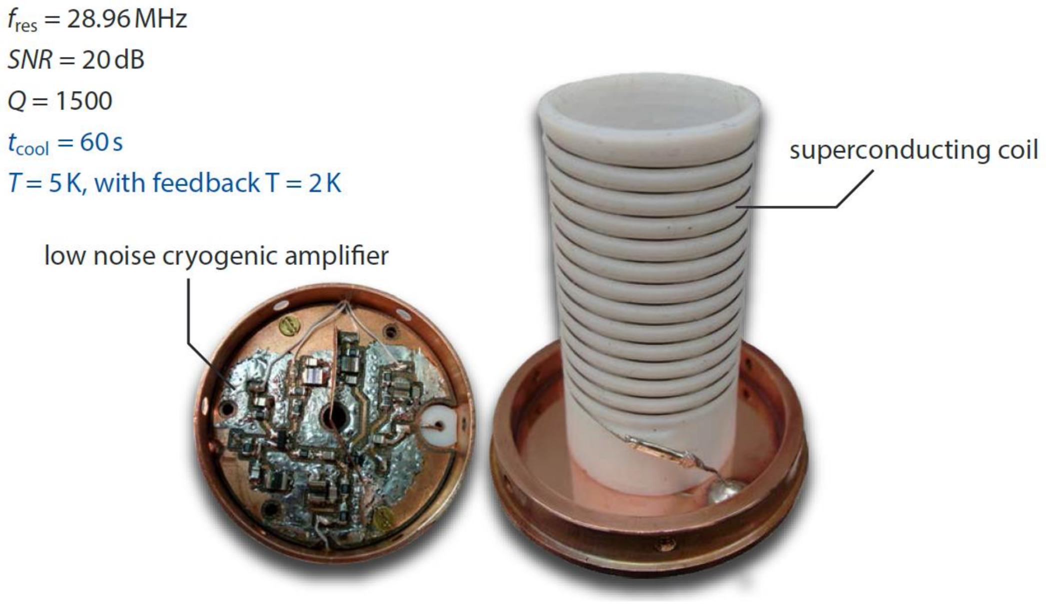


- Coupling to thermal bath in precision trap
- Preparation of subthermal E_+

3 hours for one spin flip trail in precision trap with fidelity of 75%

Improvement of Measurement Time

- Old setup t_{cool}=120s at T=5K

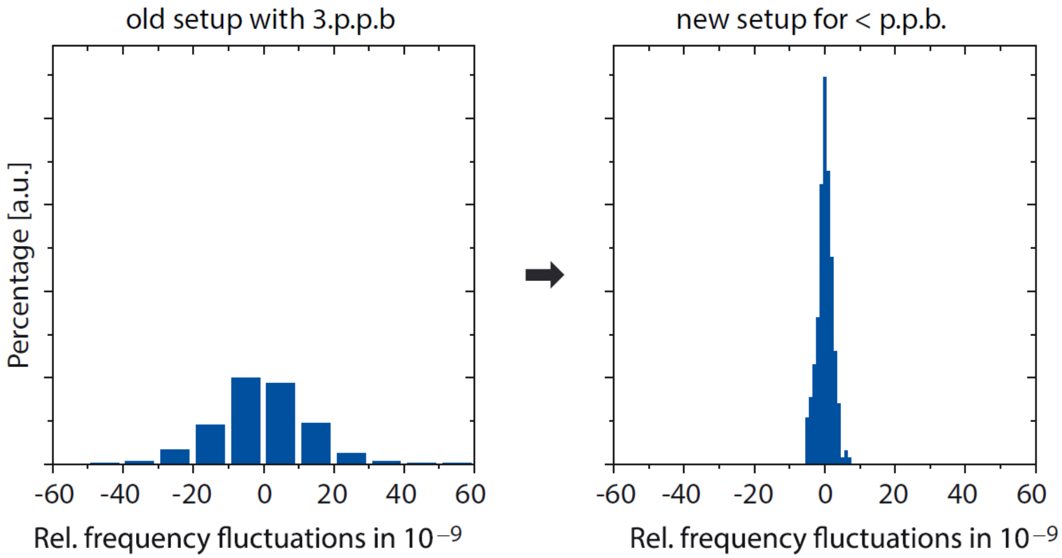


- New superconducting cyclotron detector t_{cool}=40s at T=2K
- Reduces measurement time for one g-factor datapoint from 3h to 1h

C. Smorra, Hyperfine Interactions **228**, 31 (2014).

Optimization of Precision Trap

- Cyclotron frequency stability in precision trap



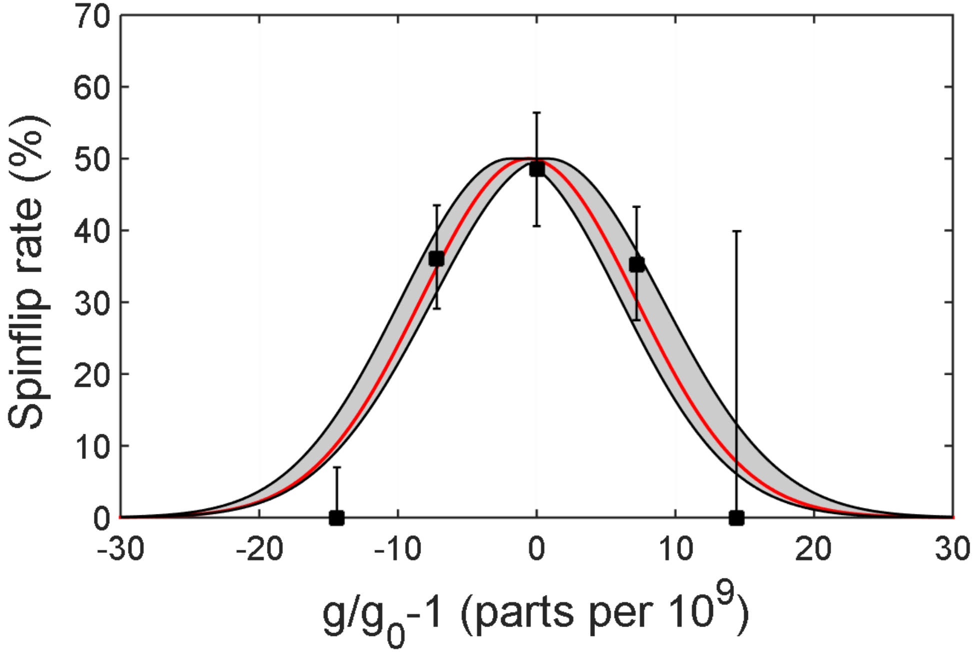
old setup with 3.p.p.b

new setup for < p.p.b.

- Improvement by one order magnitude – reduced magnetic field inhomogeneity, improved detection system and self-shielding coil

First Results

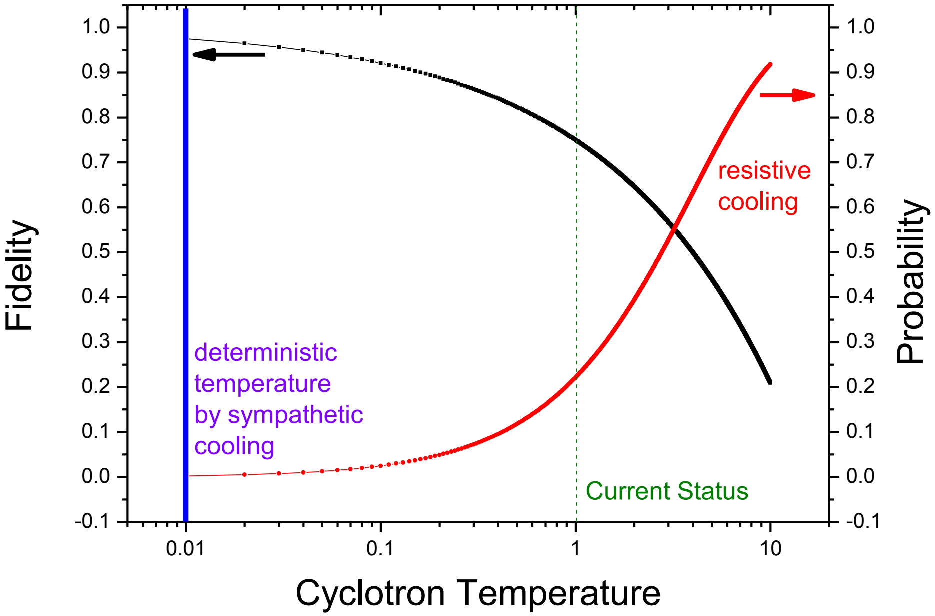
- Started double trap method



- Saturation broadening – further optimization going on

Next – Laser Cooling

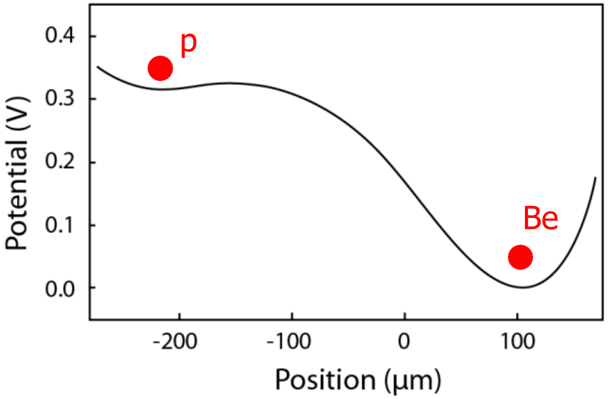
- Heating rates and stability scale with cyclotron energy
- Limits spin state detection fidelity



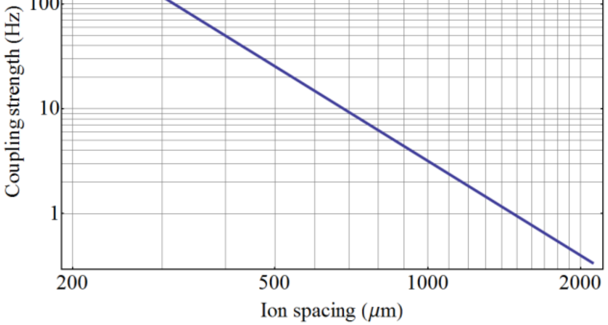
- Cool cyclotron mode by sympathetically coupling the proton/antiproton to an laser-cooled ion – we use Beryllium
- Faster measurement cycles at higher spin state detection fidelity
- Lower phase uncertainty - higher precision for phase methods

Coupling I

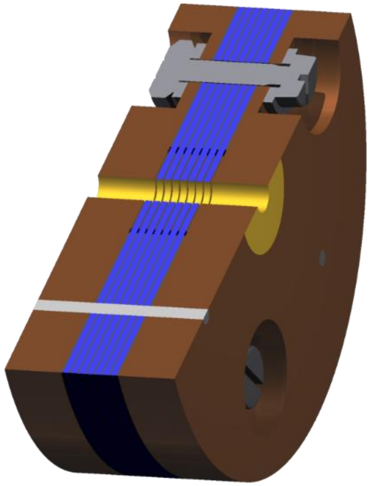
- Direct coulomb coupling with ions at close proximity



$$\Omega_{exc} = \frac{1}{4\pi\varepsilon_0 r^3 \omega} \frac{q^2}{\sqrt{m_p m_{Be}}}$$

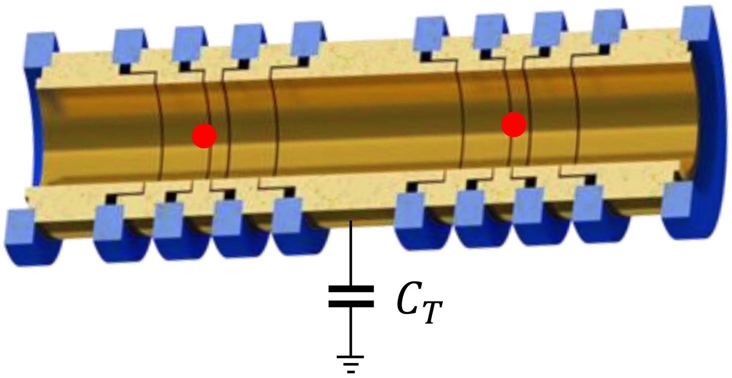


- Coupling strengths up 100 Hz
- Demands construction of miniature Penning trap, e.g. inner diameter 400µm
- Sensitive to offset and patch potentials
- Potential wall for protons in the order of mV only
- Potentials configurations for both ions coupled

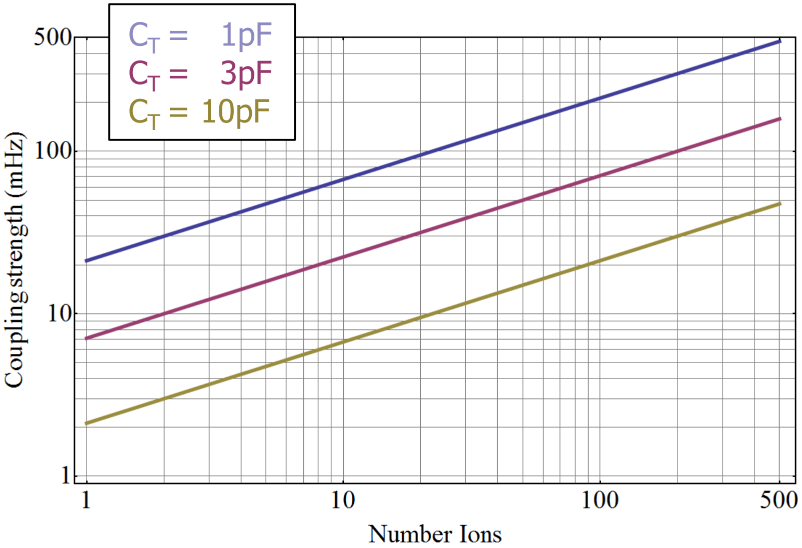


Coupling II

- Coupling via common end cap (D. Wineland, Phys. Rev. A 42, 2977 (1990))



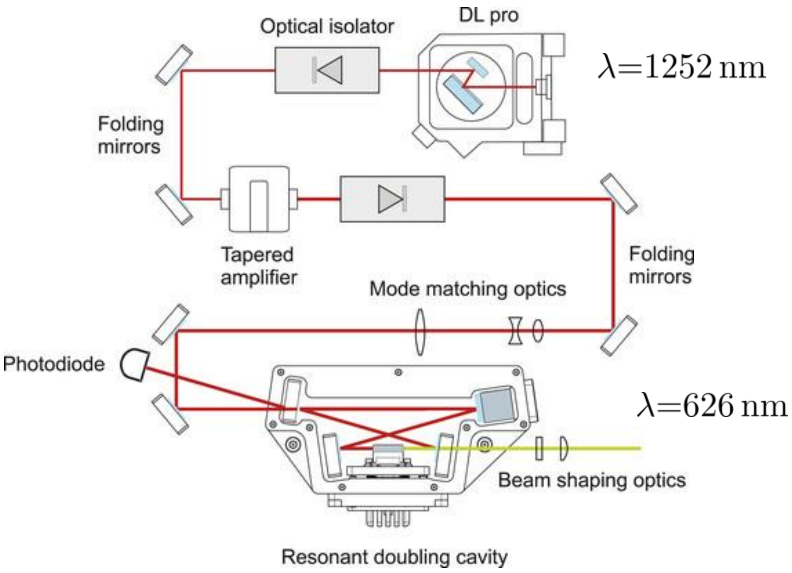
$$\Omega_{exc} = \frac{1}{4\,\omega}\frac{1}{D_{eff}\,C_T}\frac{q^2}{\sqrt{m_p m_{Be}}}\sqrt{N}$$

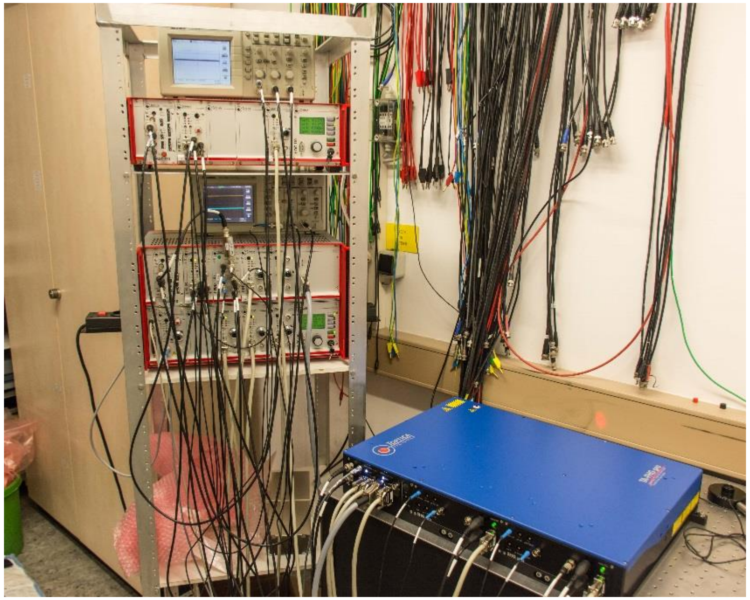


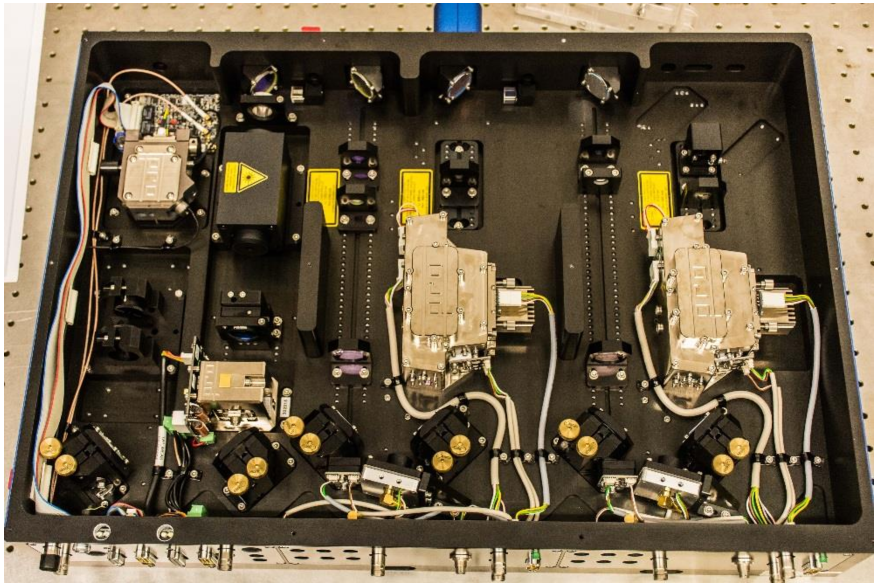
- Lower coupling strengths compared to direct coupling
  – still 100mHz sufficient / expected heating rates of 100μHz
- Allows for easy adjustment of laser position with ion position – less optics
- Allows for easy matching of ion frequencies – resonance condition
- „Insensitive“ to offset and patch potentials

We pursue this option

313nm







- 400mW @ 313nm
- Linewidth 100kHz

Nuclear Magnetic Moment of ^{3}He

- So far no direct measurement of μ_{He}
- Application polarized ^{3}He magnetometers – e.g. Muon *g-2*

60ppt Meyers

0.76ppt Gabrielse

$$a_\mu = 2 g_e \frac{\omega_a}{\omega_s} \frac{\mu_s}{\mu_e} \frac{m_\mu}{m_e}$$

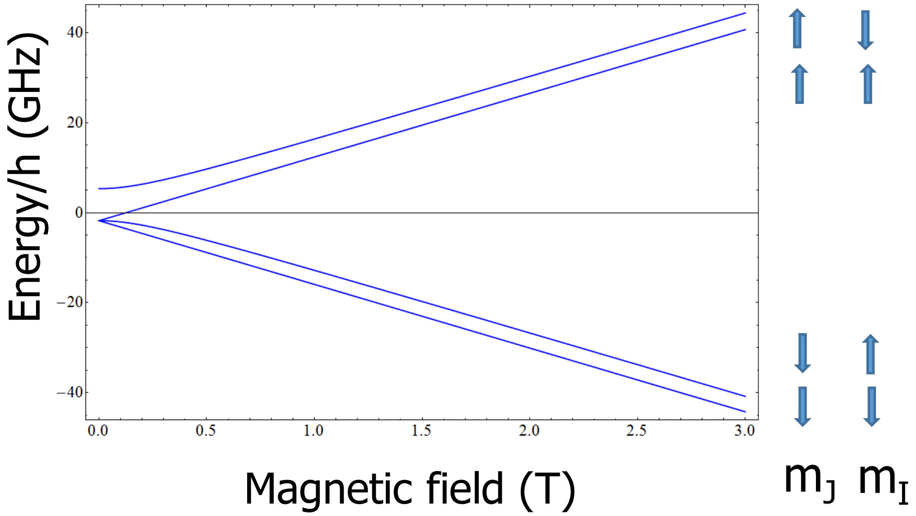
$$\frac{\mu_h'}{\mu_e} = \frac{\mu_h}{\frac{e\hbar}{2m_3}} \frac{m_u}{m_h} \frac{m_e}{m_u} \frac{1}{g_e} (1 - \sigma_{He})$$

Penning trap

30ppt Sturm

2ppb Neronov

- Indirect measurement via HFS of single charged ^{3}He in magentic field



- Direct measurement by application of laser cooling
- New methods beyond standard g-factor techniques

Summary

- Sub parts per billion measurement in reach – measurements on going
  - Started on implementation of laser cooling
    - Started work on ^{3}He measurement

BASE Collaboration: Stefan Ulmer, Christian Smorra, Hiroki Nagahama, Takashi Higuchi, Andreas Mooser, Mustafa Besirli, Mathias Borchert, James Harrington, Nathan Leefer, Stefan Sellner, Georg Schneider, Toya Tanaka, Klaus Blaum, Yasuyuki Matsuda, Christian Ospelkaus, Wolfgang Quint, Jochen Walz, Yasunori Yamazaki

BASE

Thank you for your attention

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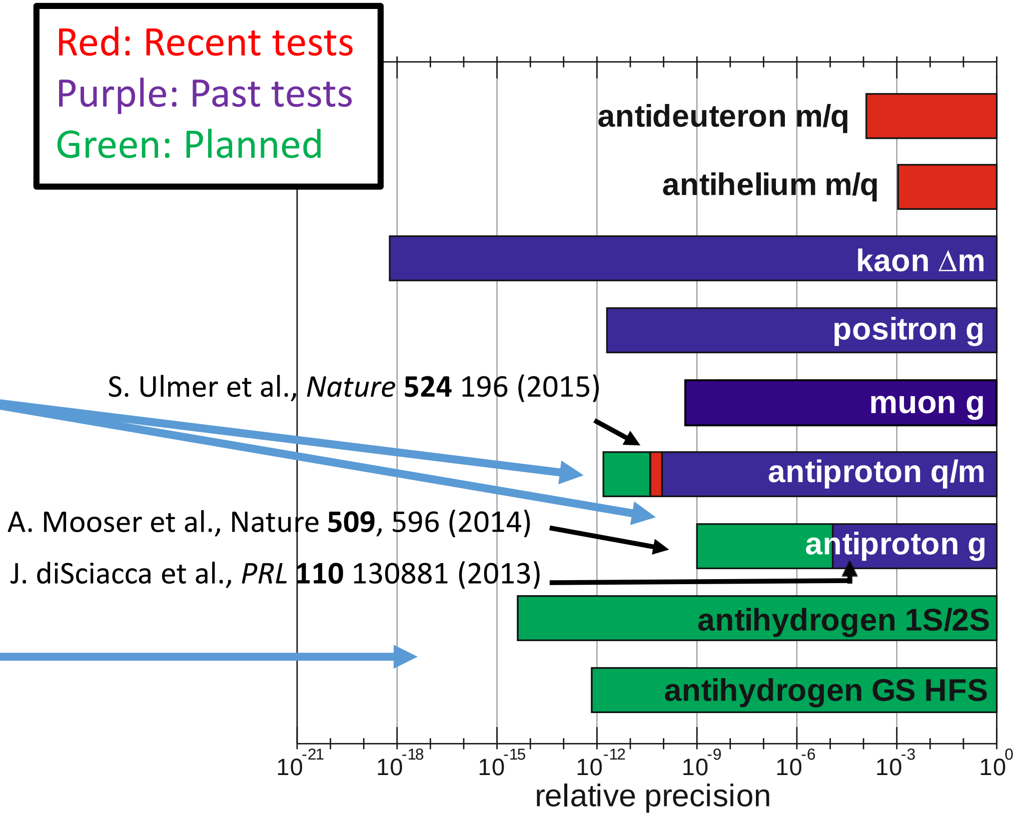
Different CPT tests

- CPT invariance is the most fundamental symmetry in the Standard Model
- Strategy: Compare properties of matter and antimatter conjugates with high precision.



S. Ulmer et al., *Nature* **524** 196 (2015)

A. Mooser et al., Nature **509**, 596 (2014)

J. diSciacca et al., *PRL* **110** 130881 (2013)

ALICE

Nature Physics
(10.1038/nphys3432)

CERN
AD

Planned by others

ASACUSA / ALPHA / ATRAP

CPT test with fractional precision of 10^{-18} available… why continue measuring?

Concept of CPT violation

- Basic idea: Add CPT violating extension to Hamiltonian of Standard Model
  Treat CPT violating terms perturbative

$$H' = \underbrace{H_{SM}}_{\boxed{\text{System based on SM}}} + \underbrace{\Delta V}_{\boxed{\text{CPT violating term}}} \quad \Longrightarrow \quad < \psi^* | \Delta V | \psi > = \Delta E$$

- Contributions at absolute energy scale -

  ⇨ Absolute energy resolution might be more appropriate measure of sensitivity with respect to CPT violation

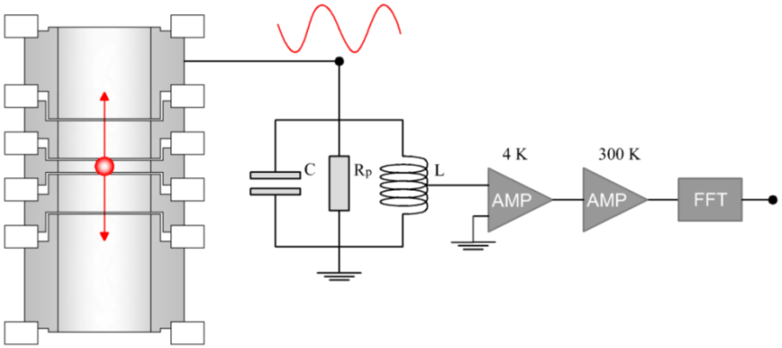
- High sensitivity - precise measurement at small intrinsic energy

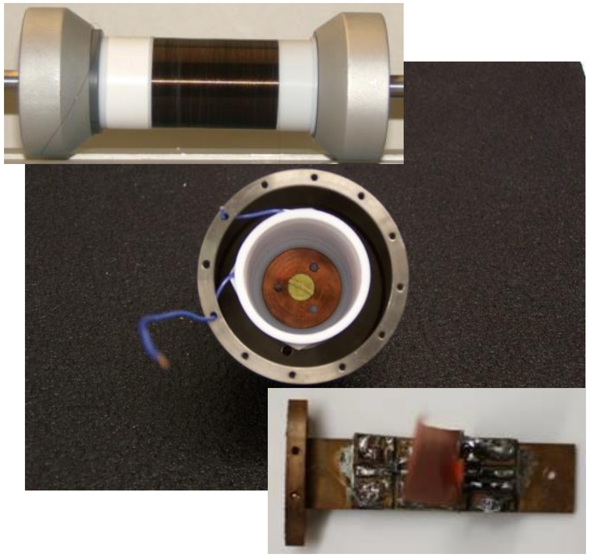
  ⇨ Single particles in Penning traps - precise measurement of frequencies at ueV-energy scales

	Relative precision	**Energy resolution**
Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV
p-p̄ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV

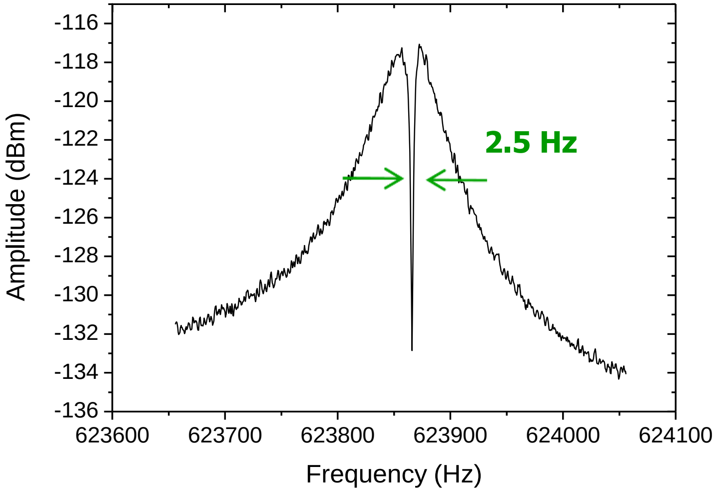
⇦ BASE aims to improve with 10^{-9} relative precision

Detection of particle motion



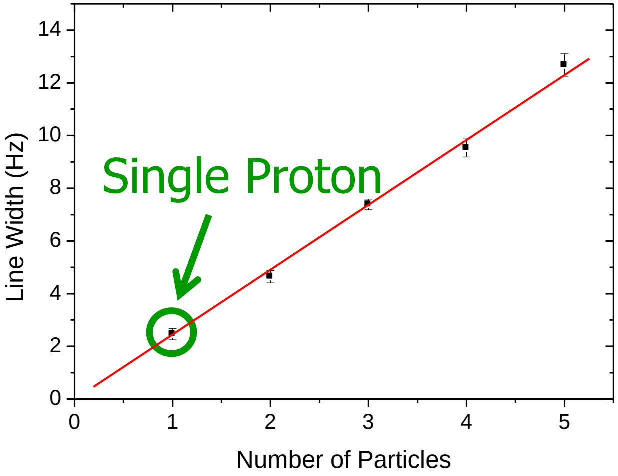


Particle acts as a perfect short



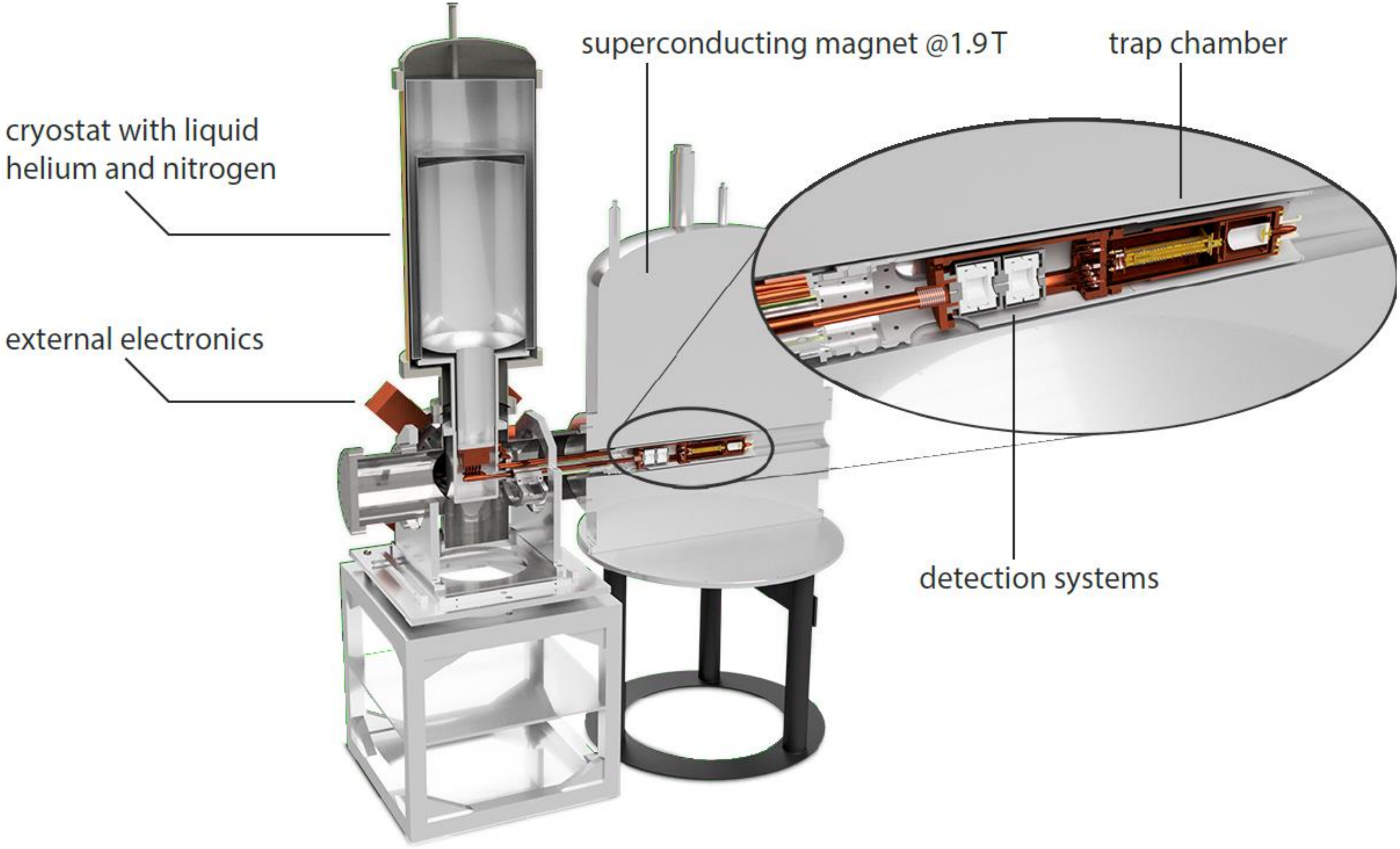
Linewidth:

$$\delta\nu_z \propto N_p$$



Enables cyclotron frequency measurement at 1ppb

Setup


superconducting magnet @1.9T
trap chamber
cryostat with liquid helium and nitrogen
external electronics
detection systems