Towards a high precision measurement of the magnetic moment of the antiproton

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RIKEN – Initiative Research Unit

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Motivation

Compare magnetic moment of the (free) proton and the antiproton with high precision → provide another high precision comparison of matter/antimatter symmetry

So far: proton and antiproton magnetic moments are compared at a level of 10^{-3} only. T. Pask et al., J. Phys. B **41**, 081008 (2008)

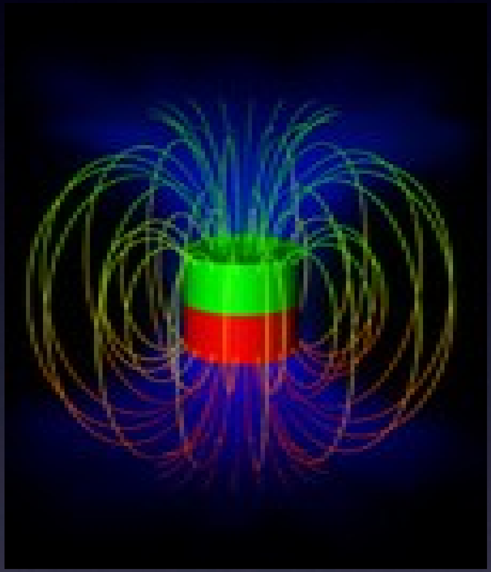
Millionfold improvement to 10^{-9} is aimed!

- Use single particle stored in a cryogenic Penning trap
- Very clean simple system → high precision
- Can be directly applied to the antiproton

This talk: First proton spin flips observed
→ Major step towards this aim

The Magnetic Moment

Every spin carrying charged particle behaves as a tiny bar-magnet



The magnetic moment

$$\vec{\mu}_p = g_p \frac{e}{2m_p} \vec{S}$$

characterizes its strength

Do the magnets in the proton and the antiproton have the same strenght ?

Basic Experimental Principle

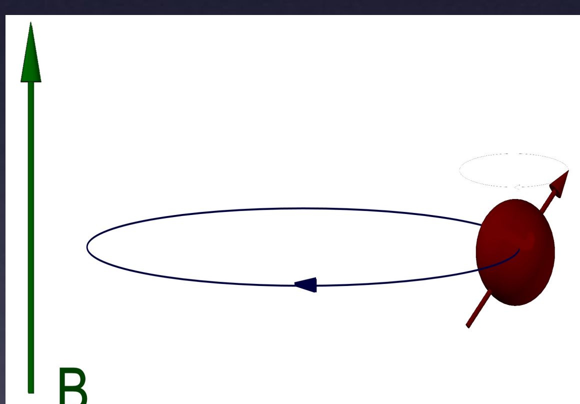
Spin carrying charged particle in a magnetic field

CYCLOTRON

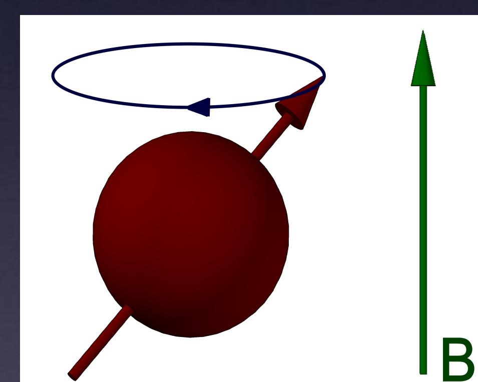
$$\omega_c = \frac{e}{m_p} B$$

LARMOR

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



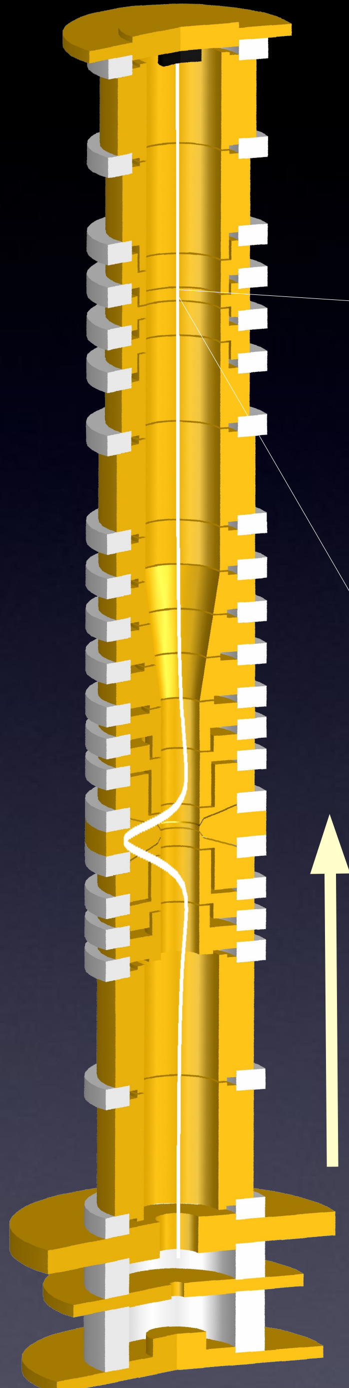
$$g_p = 2 \frac{\omega_L}{\omega_c}$$



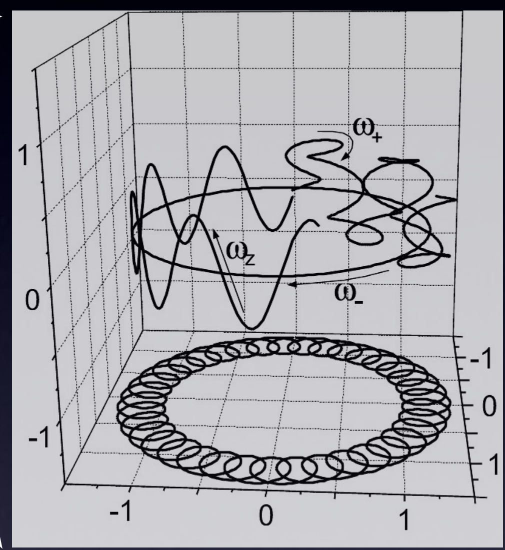
...reduces to measurement of a simple frequency ratio

The Penning Trap

Superposition of homogeneous magnetic field and electrostatic quadrupolar potential



B

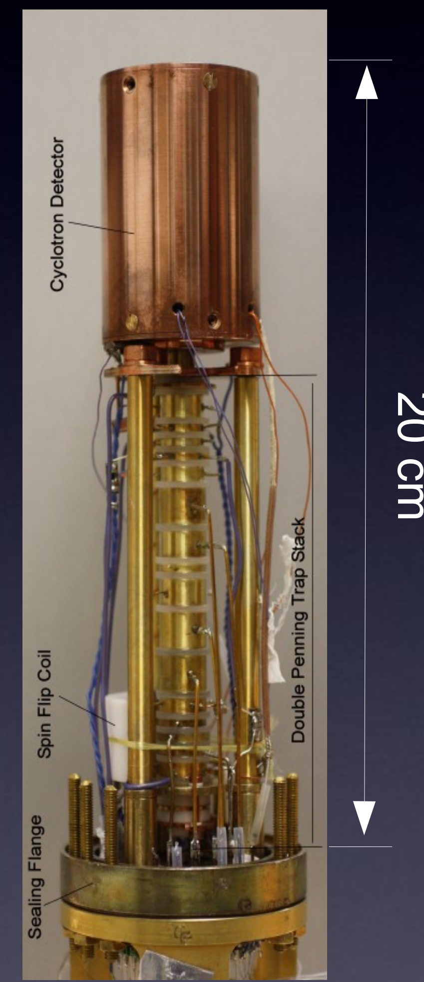


FREQUENCIES

Axial: 700 kHz

Modified Cyclotron: 29 MHz

Magnetron: 8 kHz



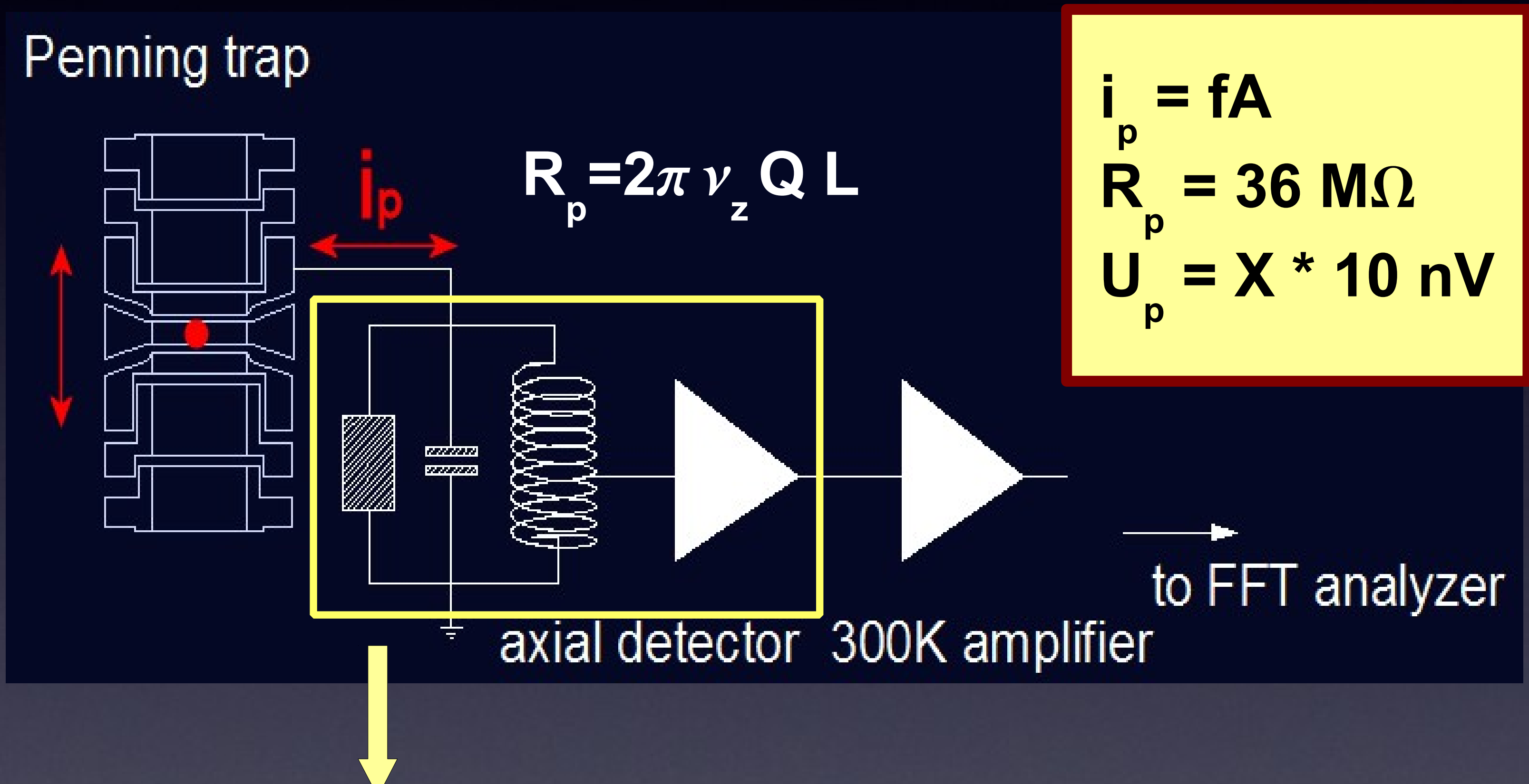
$$\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2$$

“Brown-Gabrielse Invariance Theorem” makes Penning traps strong

Frequency Measurements in a Penning Trap

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

Trapped charged particle induces image currents

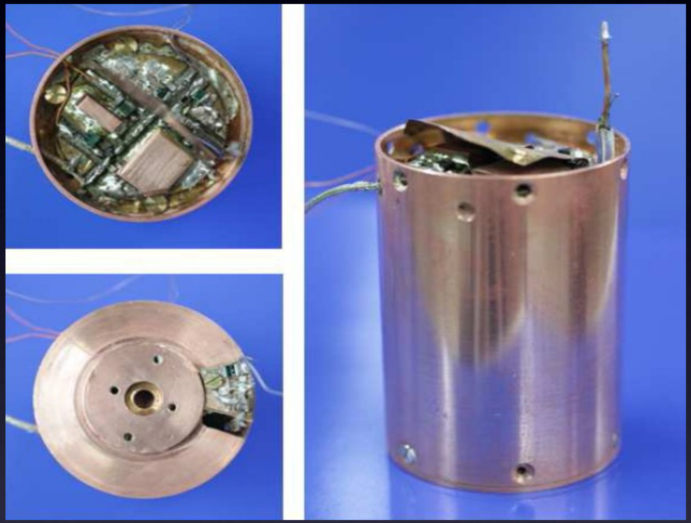


Challenging hardware component

Highly sensitive oscillator + active device

Detection Systems

Cyclotron

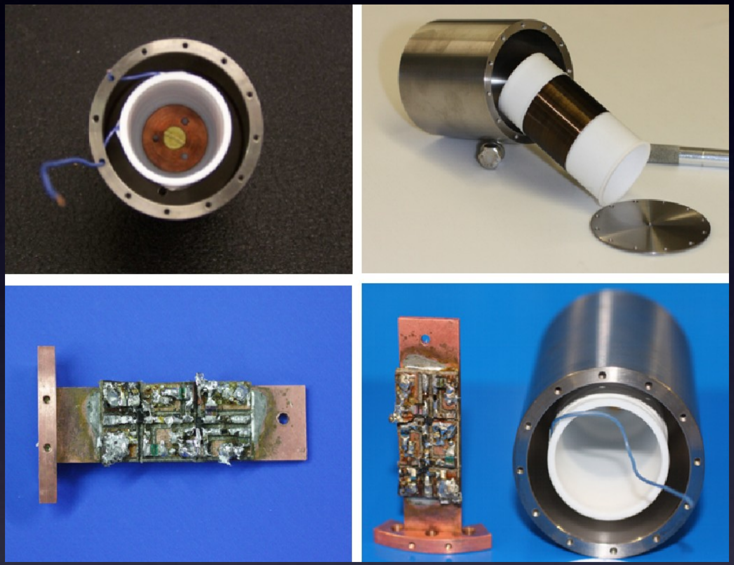


ν_+ = 28.969.000 Hz

Q = 1250

R_p = 680 kΩ

Axial



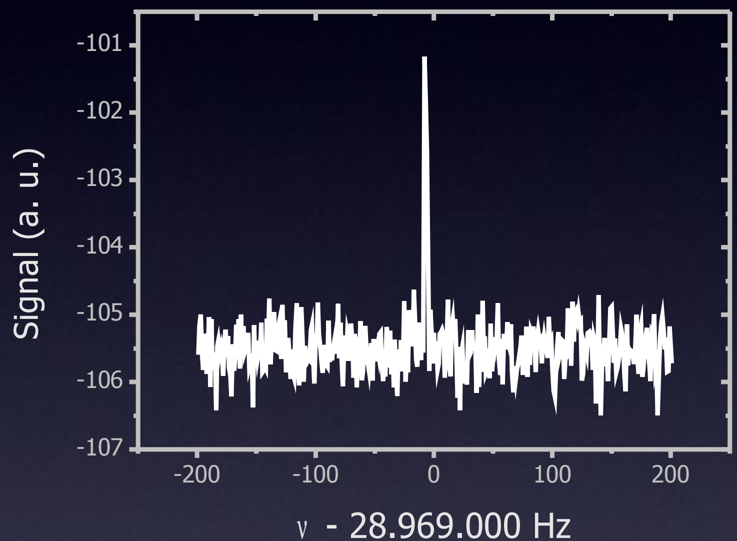
ν_z = 680.000 Hz

Q = 5600

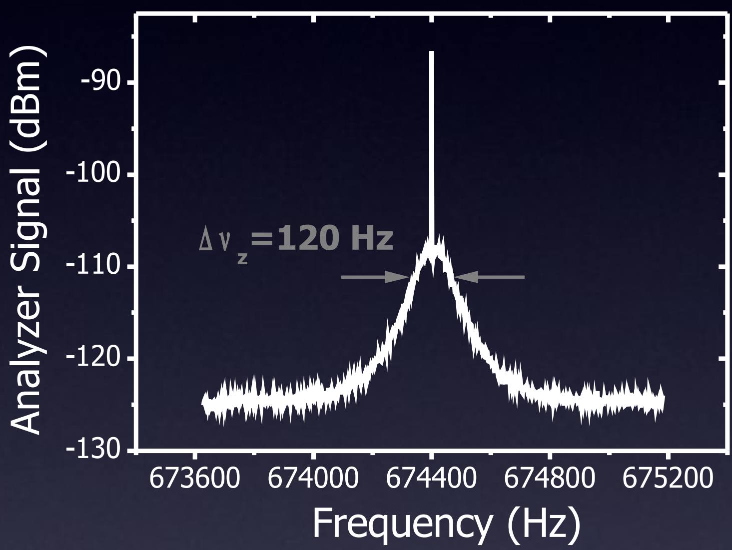
R_p = 36 MΩ

Detection Systems - Performance

Single proton cyclotron



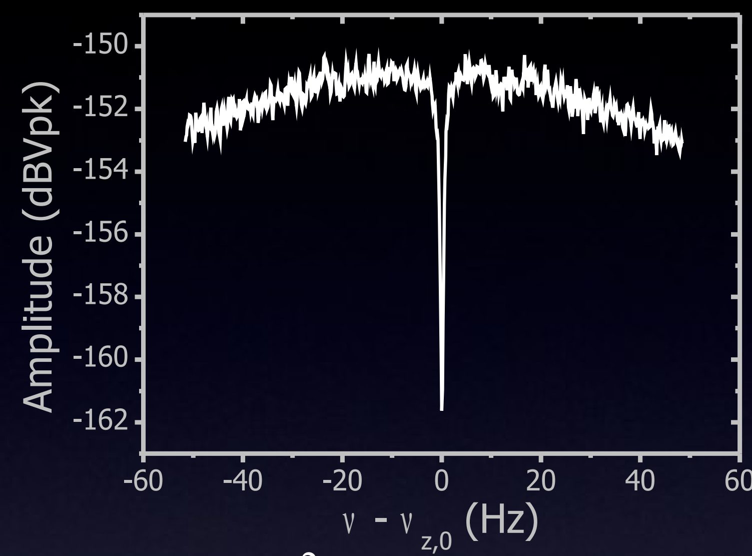
Single proton axial



Single trapped proton?

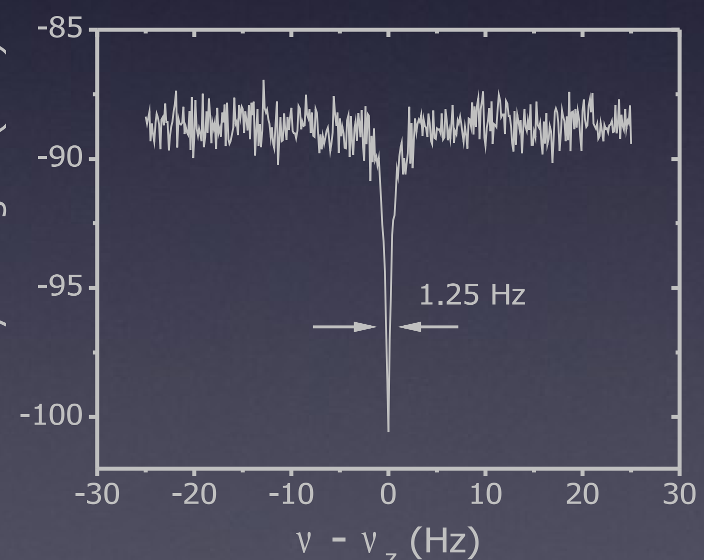
The “Noise-Dip”

- Eq. of Motion: Particle in thermal equilibrium can be understood as a perfect short
- Measures frequency in thermal equilibrium (4K) → High Precision

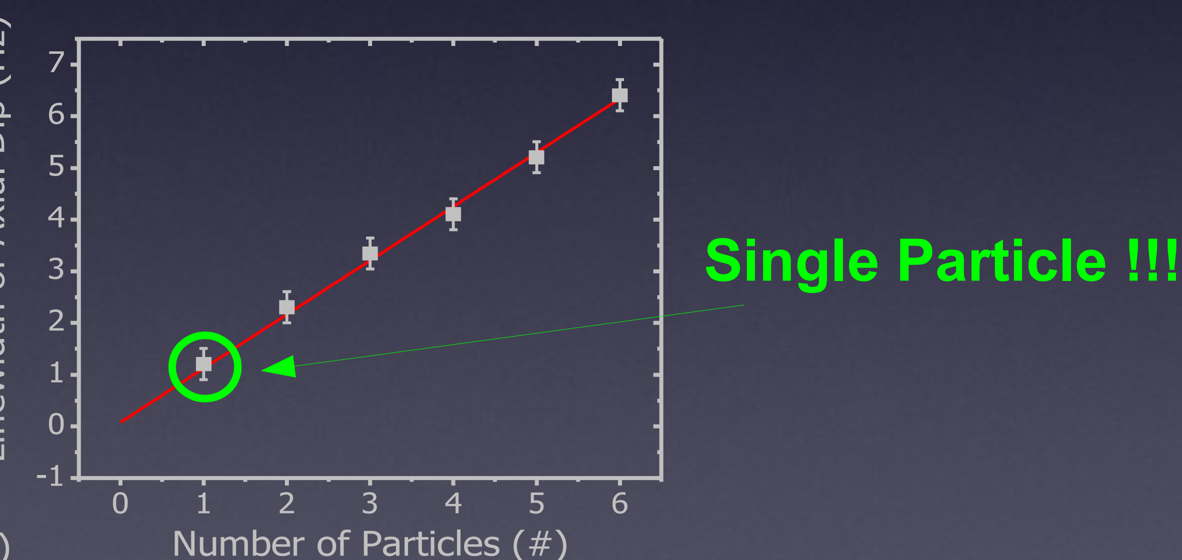


Linewidth:

$$\delta \nu_z = \frac{N_p}{2\pi} \frac{R_p e^2}{m_p D^2}$$



a.)



b.)

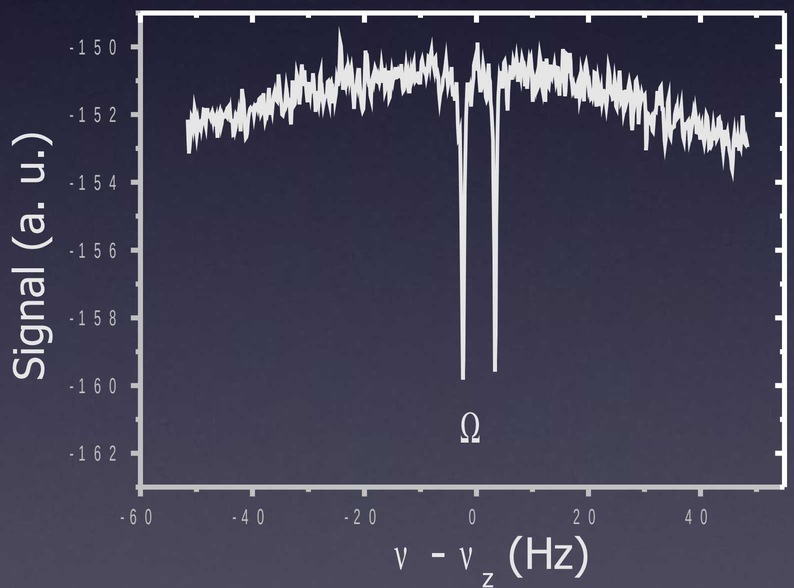
Radial Frequency Measurements at low T

Principle also applicable to measure radial frequencies at low T ?

Adequate rf-drives at sum and difference frequencies of eigenmotions transfer energy from one mode into the other.

Effectively: Amplitude modulation of particle motion

$$z(t) = z_0 \cos\left(\frac{\Omega}{2} t\right) \sin(\omega_z t + \phi_z)$$



Classical "Dressed states"

$$\nu_l = \nu_z - \frac{\delta}{2} - \frac{\Omega}{4\pi} \qquad \nu_r = \nu_z - \frac{\delta}{2} + \frac{\Omega}{4\pi}$$

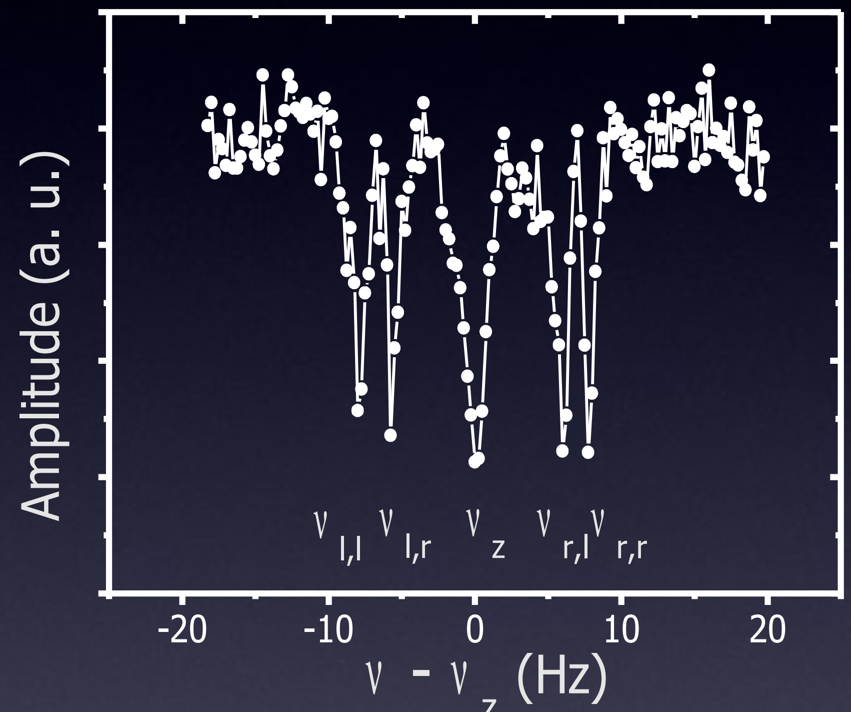
$$\nu_l + \nu_r = \nu_z + \nu_{rf} - \nu_{\pm}$$

Together with axial frequency measurement

→ Radial frequency at low T

Novel Method → Fivefold Dip

Double dressing gives four equations at five unknowns – additional information by **switching → fivefold dip** gives required information

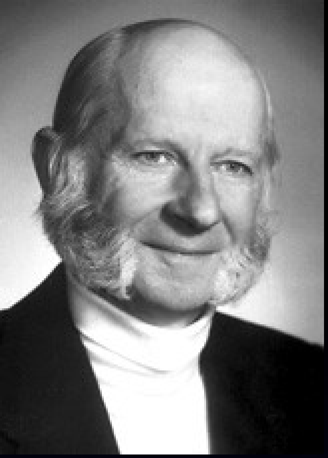


Five simultaneous signals by one single trapped particle

Spectrum contains all required frequency information

FIRST DIRECT MEASUREMENT OF FREE CYCLOTRON FREQUENCY ($\Delta\nu_c/\nu_c$ = 5*10^{-9})

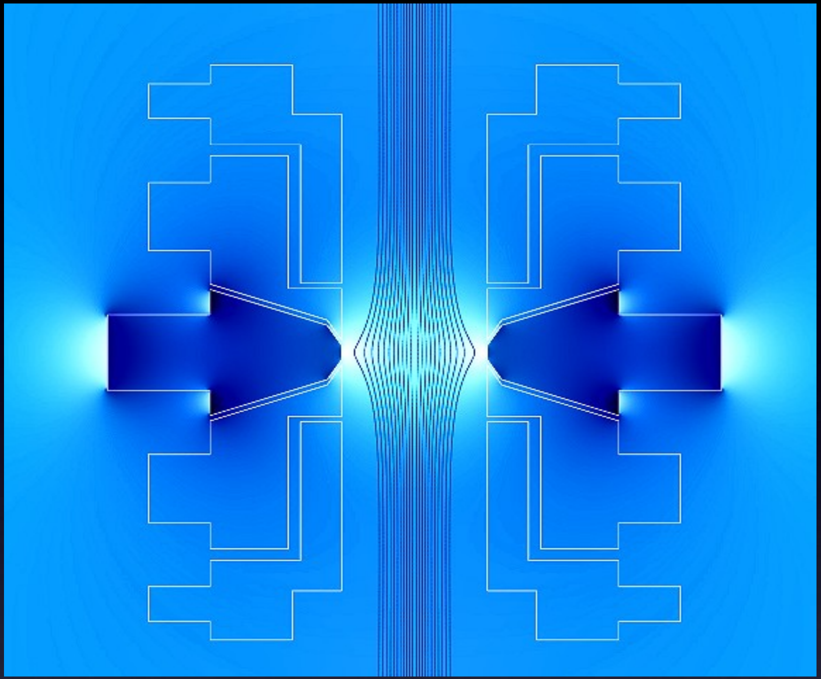
S. Ulmer *et al.* **Phys. Rev. Lett** 107, 130005 (2011)



Continuous Stern-Gerlach Effect

Magnetic dipole in B-field

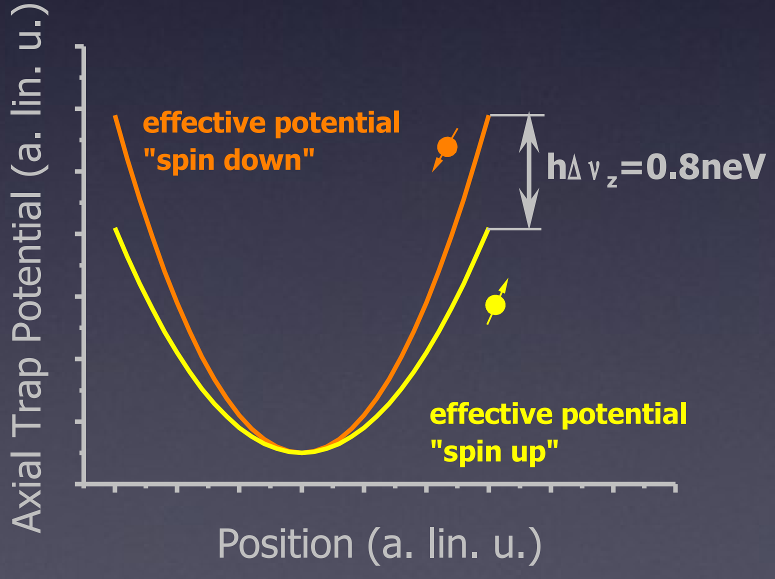
$$\Phi_M = -\left(\vec{\mu}_p \cdot \vec{B}\right)$$

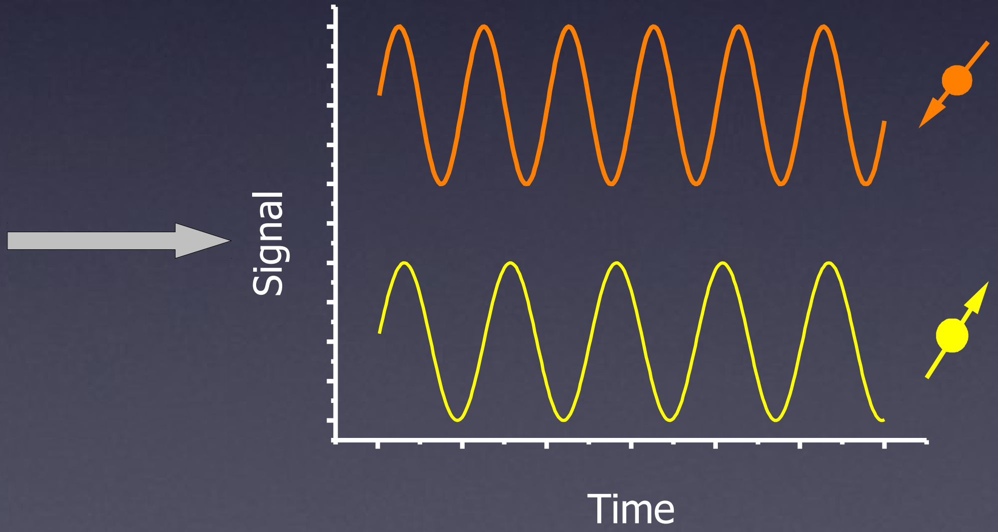


Magnetic bottle...

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

...adds spin dependent quadratic potential to axial potential...





Some Numbers

Spin flip shifts axial frequency by $$\Delta \nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

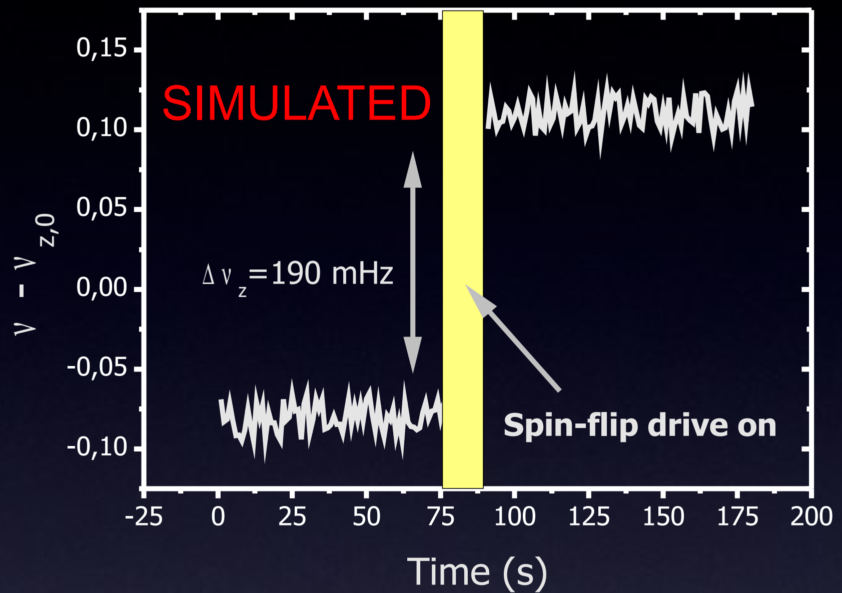
Compare electron to proton: $$\frac{\alpha_e}{\alpha_p} > 10^6$$ **CHALLENGING!!!**

Magnetic bottle of 300000 T/m² used: 1.5 mm shift → 1 T !

Most extreme magnetic conditions which have ever been superimposed to a single trapped particle

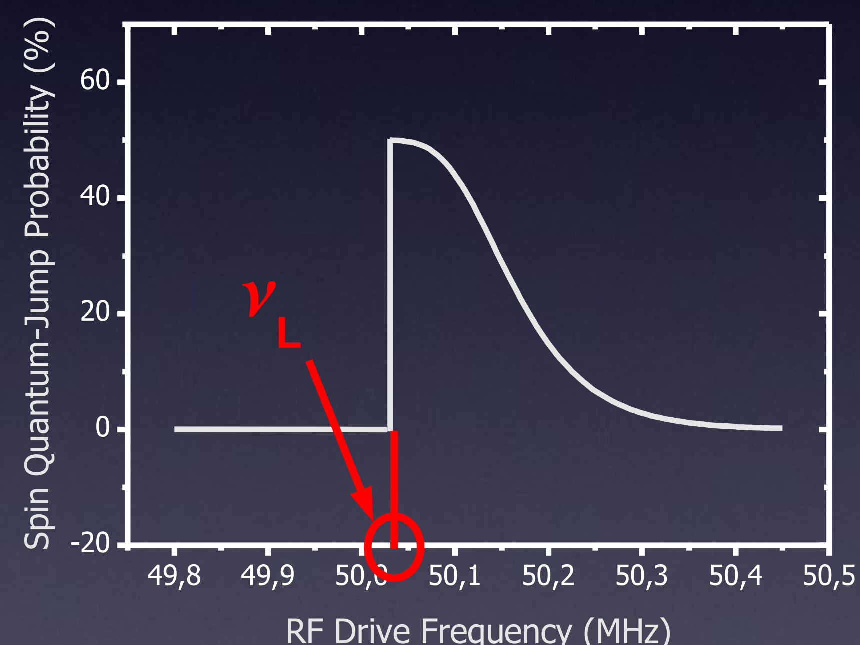
Under these extreme conditions: frequency shifts by 190 mHz out of 1 MHz → $2*10^{-7}$

The Larmorfrequency



Measure this several hundred times for different drive frequencies

$$\rightarrow P_{SF}(\nu_{rf})$$

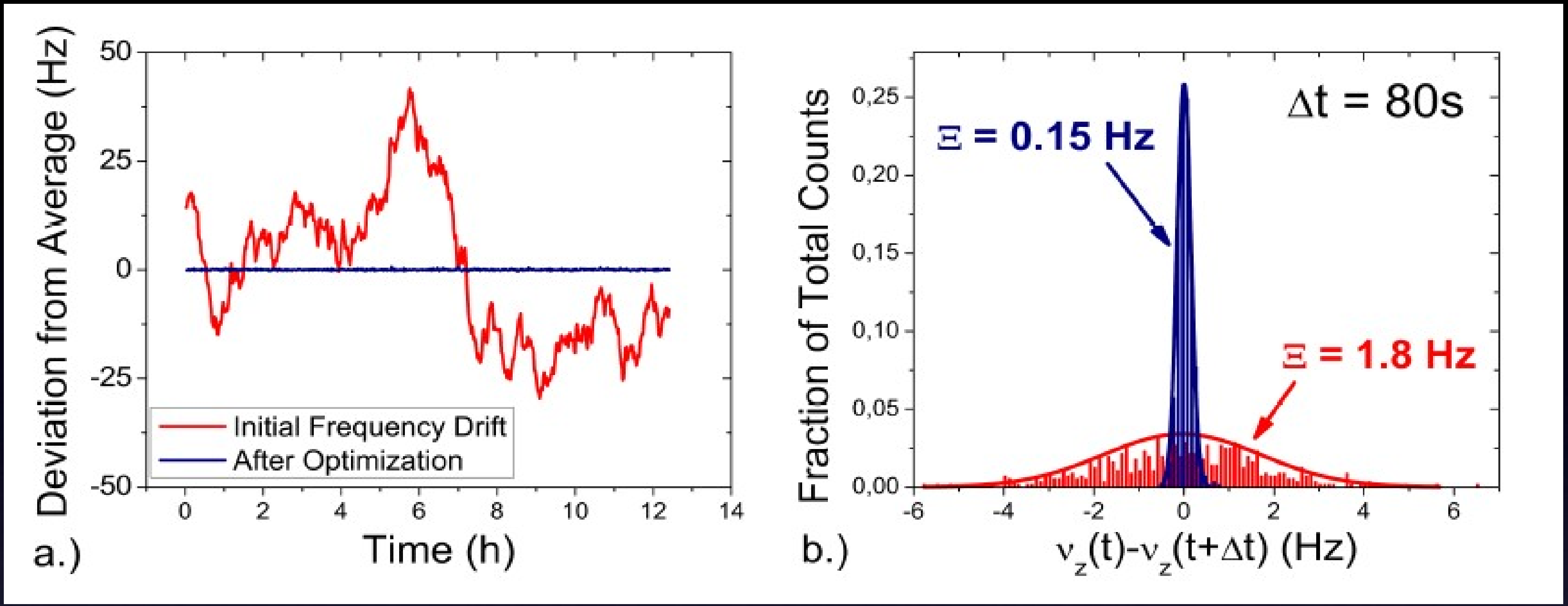


$$\nu_L = \frac{1}{2\pi} g_p \frac{e}{2m_p} \left(B_0 + B_2 z^2\right)$$

Sharp “cutoff” reflects zero temperature Larmor Frequency

Absolute frequency stability below 190 mHz needed

Laboratory Reality



Difference of two subsequent frequency measurements

Origin?

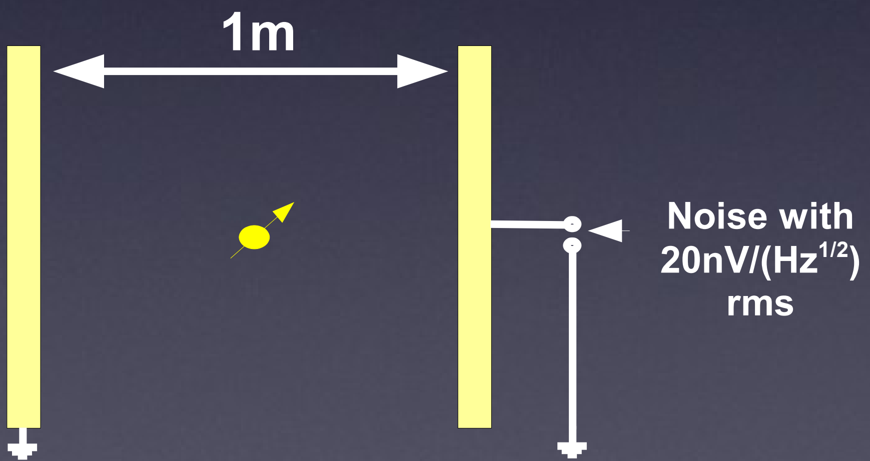
Coupling of radial angular magnetic momenta to axial frequency

$$\Delta\nu_z = \frac{1}{4\pi^2 m_p \nu_z}\frac{B_2}{B_0}E_\rho \rightarrow \frac{\Delta\nu_z}{\Delta E_\rho} = 1\,\frac{Hz}{\mu eV}$$

Frequency Fluctuation

Ξ = 150 mHz achieved

→ Noise: 20nV/(m Hz$^{1/2}$)

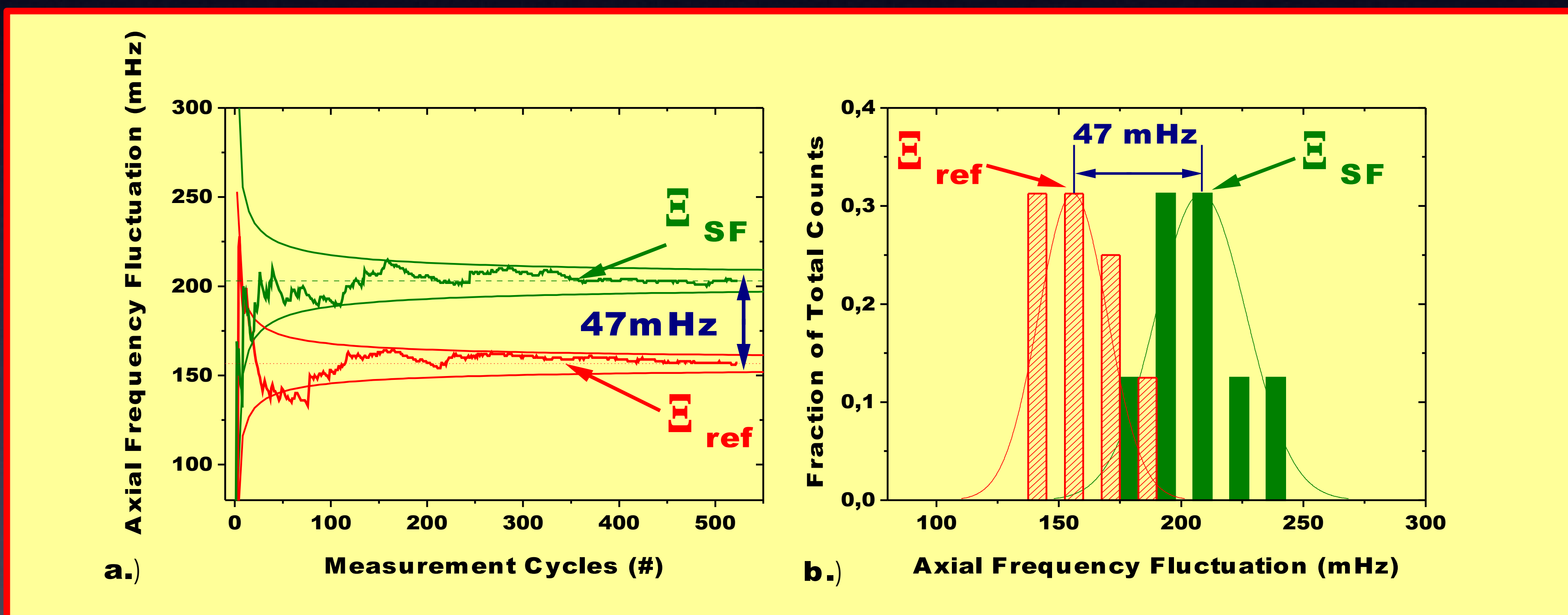


- What happens if we drive spin flips?

  → Axial frequency jumps add to background frequency fluctuation

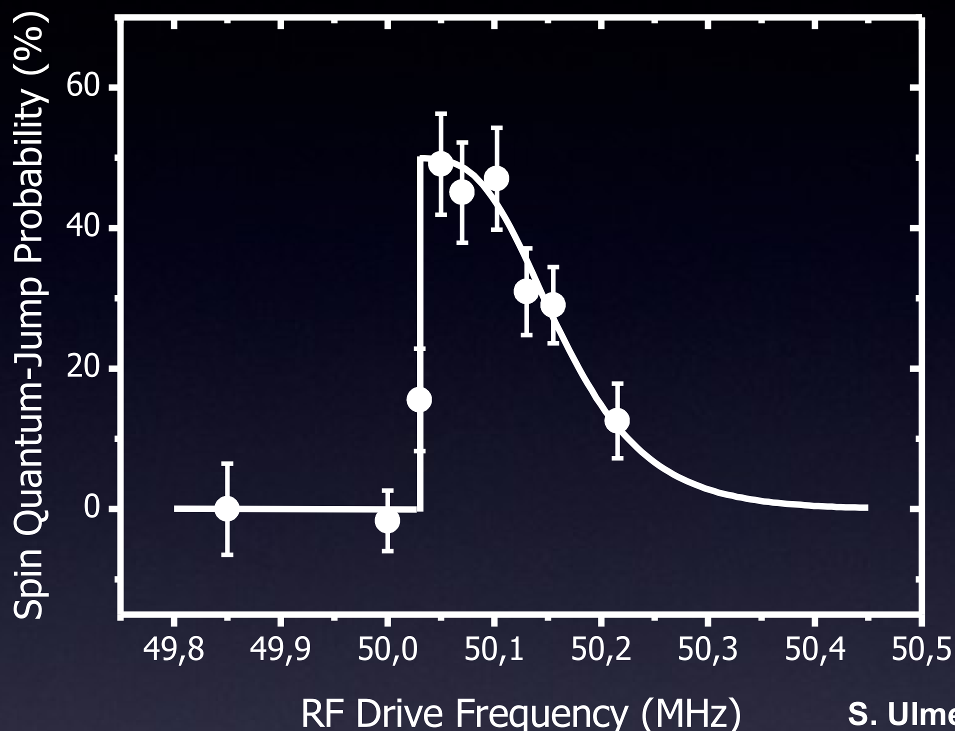
$$\Xi_{SF} = \sqrt{\Xi_{ref}^{2} + P_{SF}\Delta\nu_{z,SF}^{2}}$$

First Proton Spin Flips Ever Observed



We did that for different drive frequencies

First Larmor Resonance Curve



S. Ulmer, C. C. Rodegheri, K. Blaum, H. Kracke, A. Mooser, W. Quint, J. Walz , Phys. Rev. Lett 106, 253001 (2011)

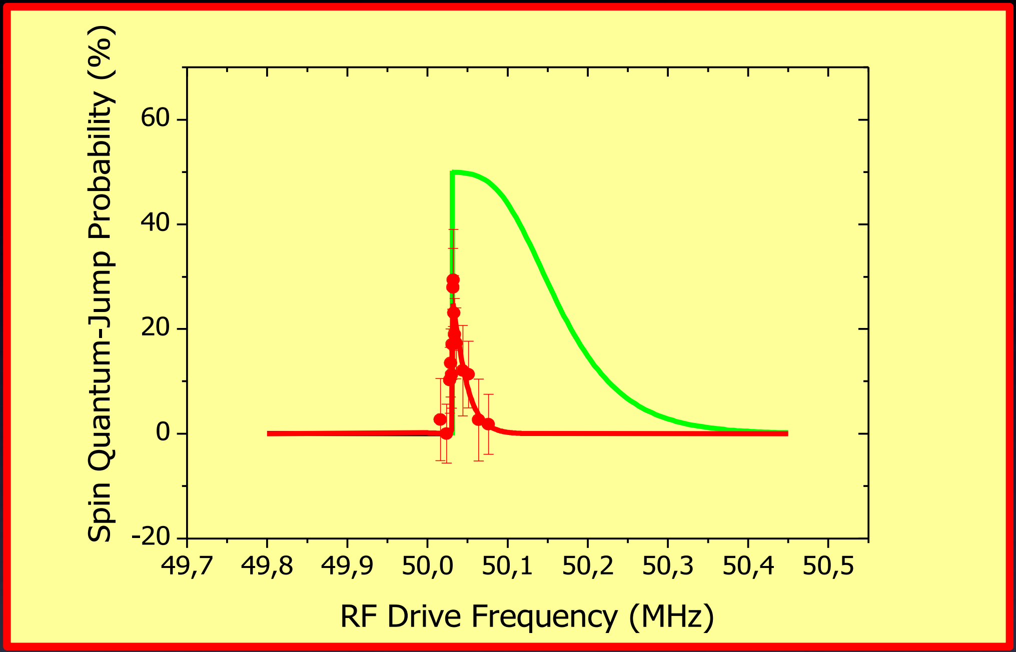
Relative Precision: 10^{-4}

→ would improve antiproton *g*-factor by factor of ten

Further Improvement

Temperature reduction by active electronic feedback reduces the line width

$$\nu_L = \frac{1}{2\pi} g_p \frac{e}{2 m_p} (B_0 + B_2 z^2)$$



→ **Larmor frequency measurement with $1.2 \cdot 10^{-6}$**

→ **With cyclotron frequency measurement**

g/2 = 2.792 848 (24)

C.C Rodegheri et *al.*, NJP 14, 063011 (2012)

g/2 = 2.792 846 (7)

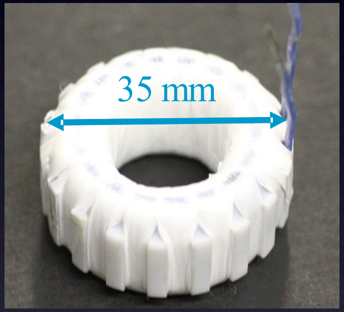
J. di Sciacca, G. Gabrielse PRL 108 153001 (2012)

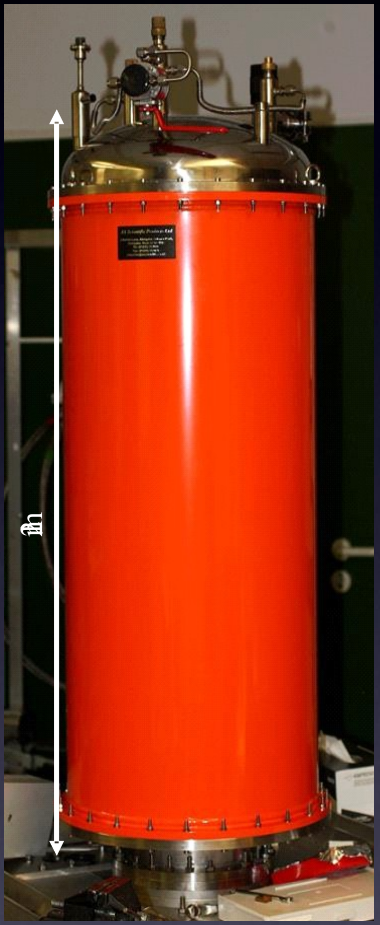
H. Kracke

New Apparatus

A. Mooser

- Detection systems improved by factor of 3, e.g. Q=12500 @ 600 kHz (A. Mooser)

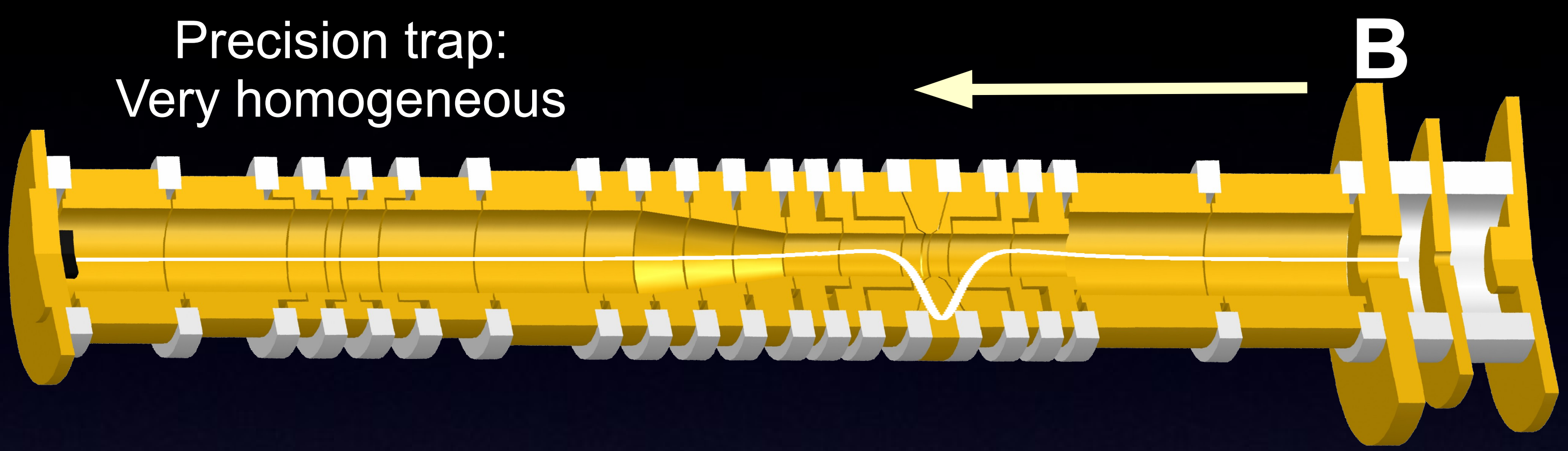




- Noise reduction due to improved electronics
- Reduced vibration

Result: Total noise of apparatus improved by factor of 10!

Double Penning Trap: Towards 10^{-9}



- Apply the very same principle but flip spins in homogeneous field of the precision trap.

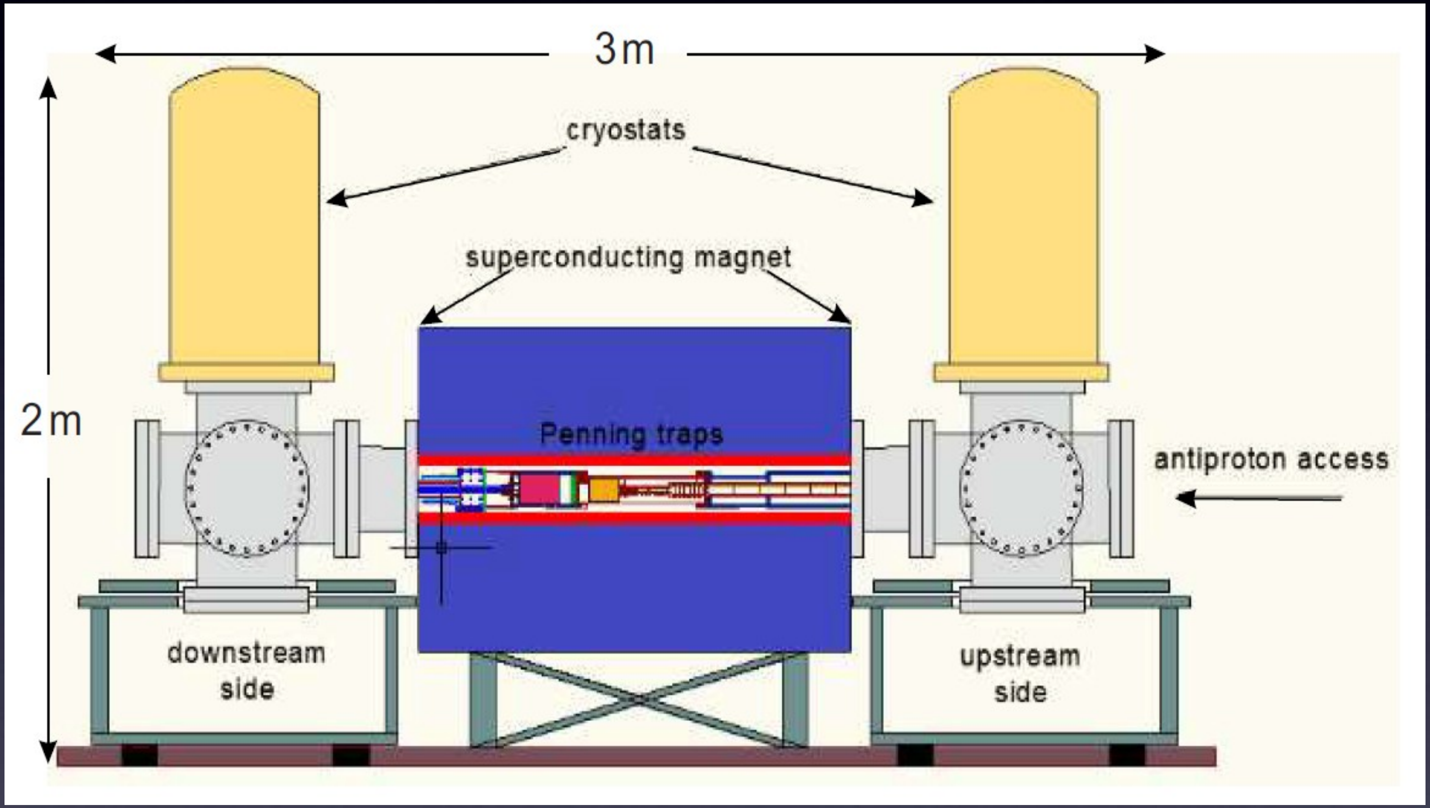
- Transport particle to analysis trap and look if the spin flipped....

- Higher field homogeneity will lead to better resolution

Required: discrete spin flip resolution

RIKEN/CERN Project

Open PhD and Post Doctoral Positions

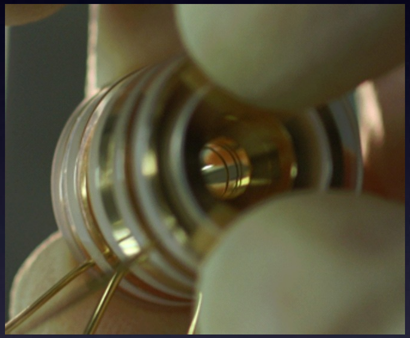


Contact:

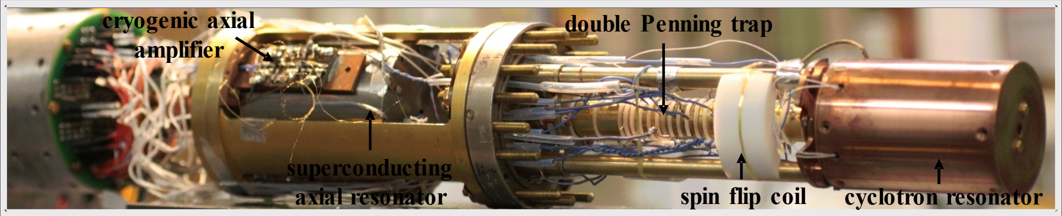
Stefan.Ulmer@cern.ch

Summary

- First spin flips observed with a single proton
- Major step towards new test of matter/antimatter symmetry (100!)



- Future:
  - Apply double trap method
  - Achieve 10^{-9} level
  - Prepare antiproton experiment
- Hope you are awaiting our future data as excited as we do !!!



Funding

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

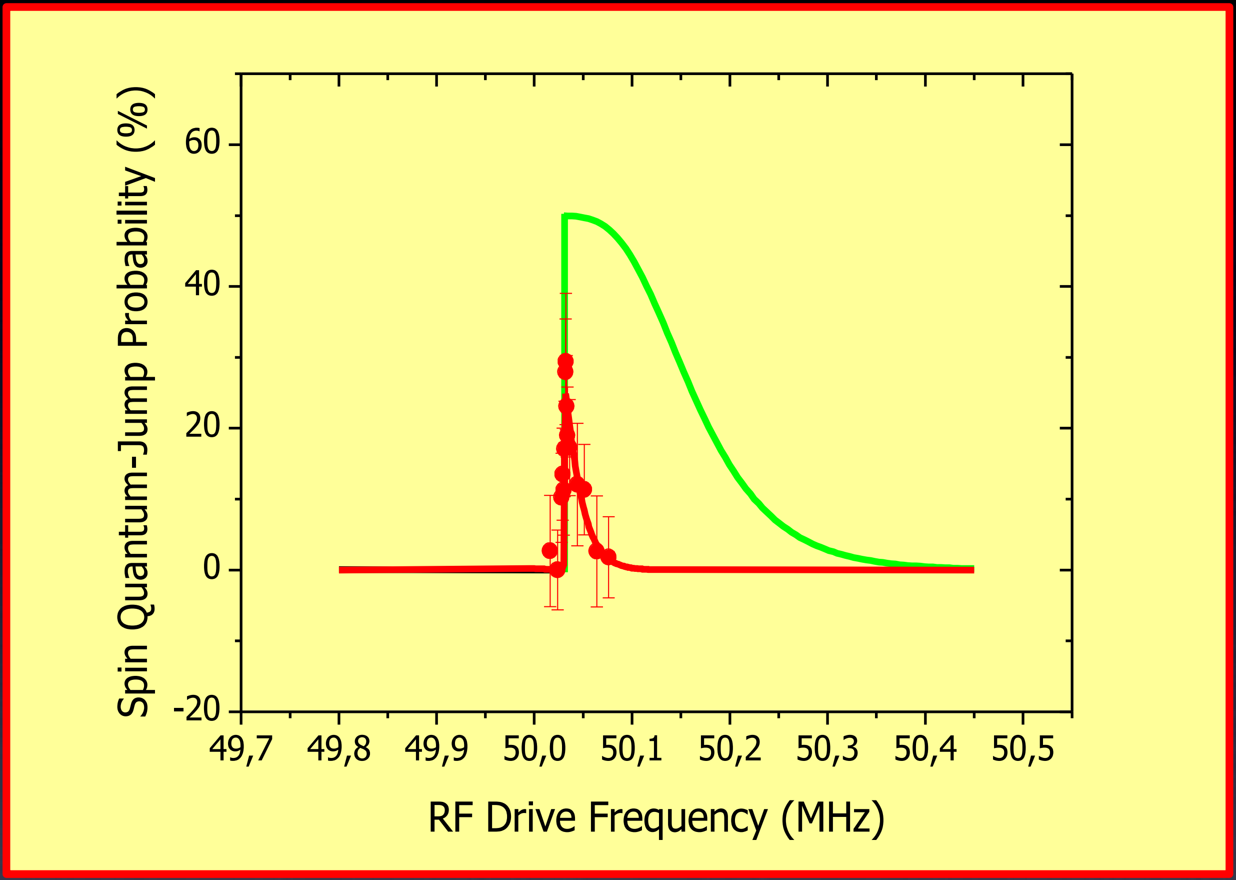
GSI

RIKEN

HELMHOLTZ GEMEINSCHAFT
Helmholtz-Institut Mainz

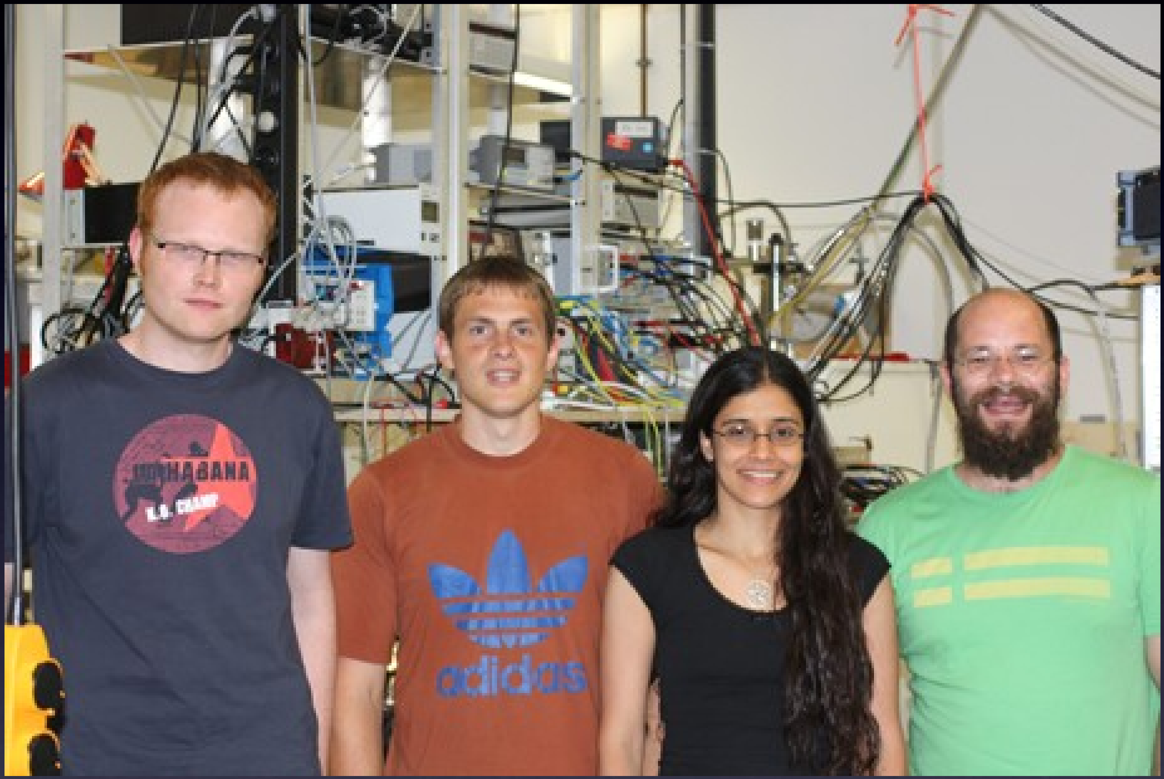
!!! Thanks for your attention !!!

Further Improvement Applying Feedback Cooling



Narrowed resonance by a factor of 50

Proton g-Factor Team



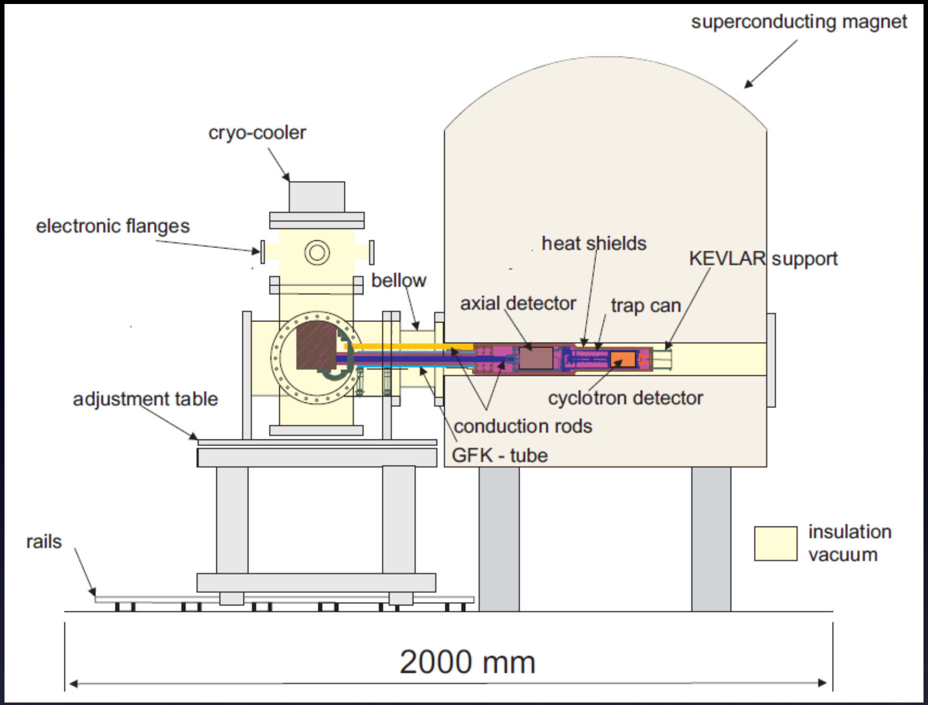
Andreas Mooser Holger Kracke Cricia Rodhegeri Stefan Ulmer

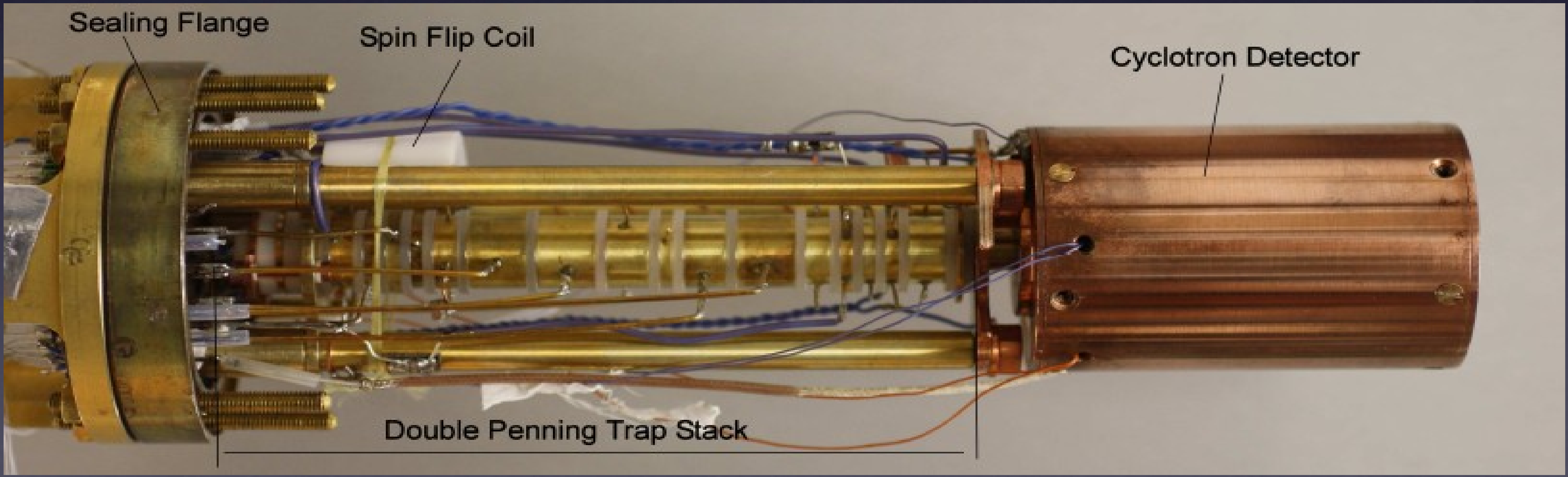
together with K. Blaum, W. Quint and J. Walz

SPARE SLIDES

Ingredients

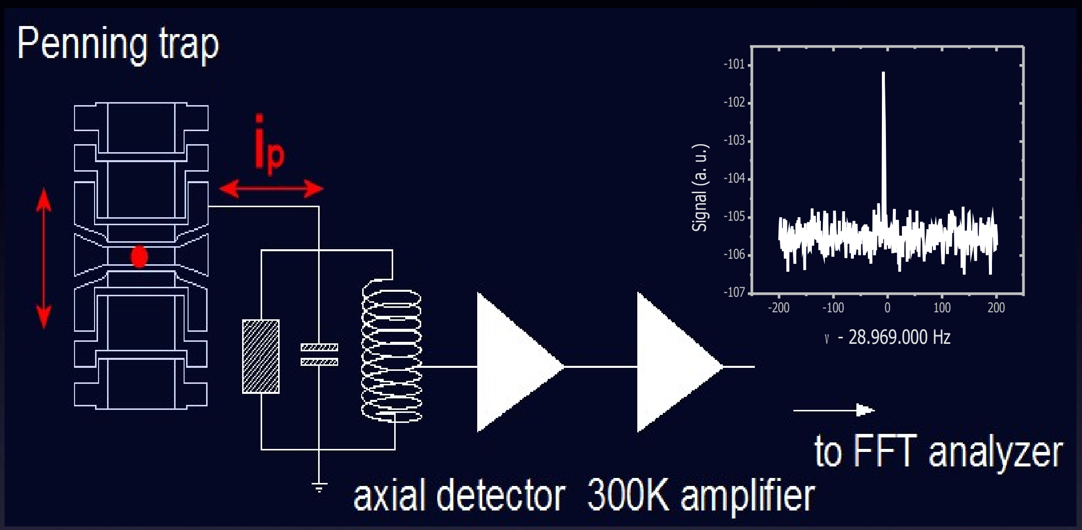
- Cryogenic apparatus
- Penning trap
- Superconducting magnet
- Highly sensitive detection systems
- Radio frequency shielding



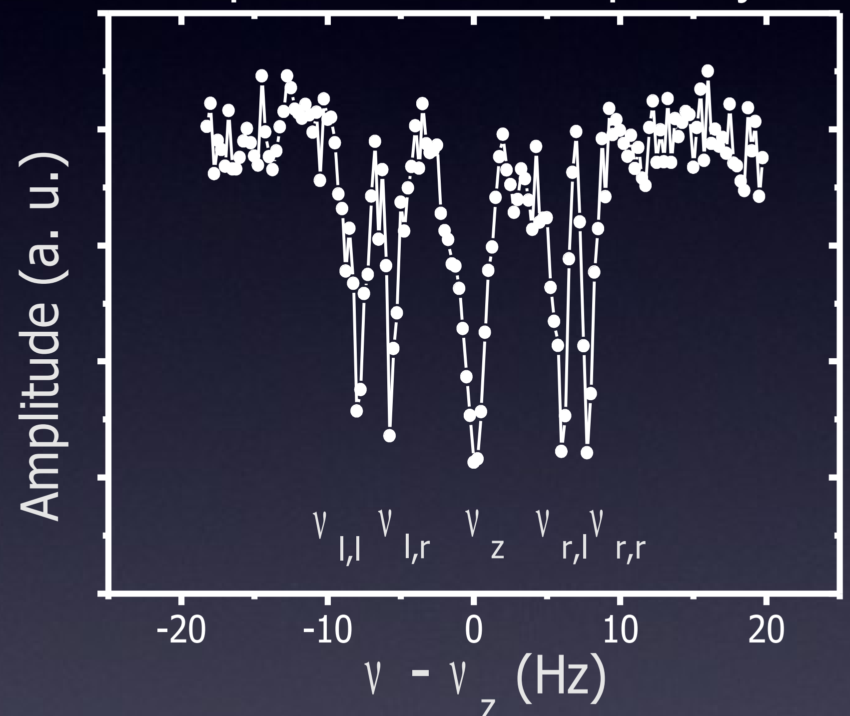


Frequency Measurements in a Penning Trap

Trapped charged particle induces image currents



Novel method developed: Both radial modes simultaneously coupled to axial frequency



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

FIRST DIRECT MEASUREMENT OF THE FREE CYCLOTRON FREQUENCY ($\Delta\nu_c/\nu_c = 5*10^{-9}$)

S. Ulmer *et al.*, Phys. Rev. Lett 107, 103002 (2011)