Direct High-Precision Measurement of the g-factor of a Single Antiproton stored in a Cryogenic Penning Trap

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GSI

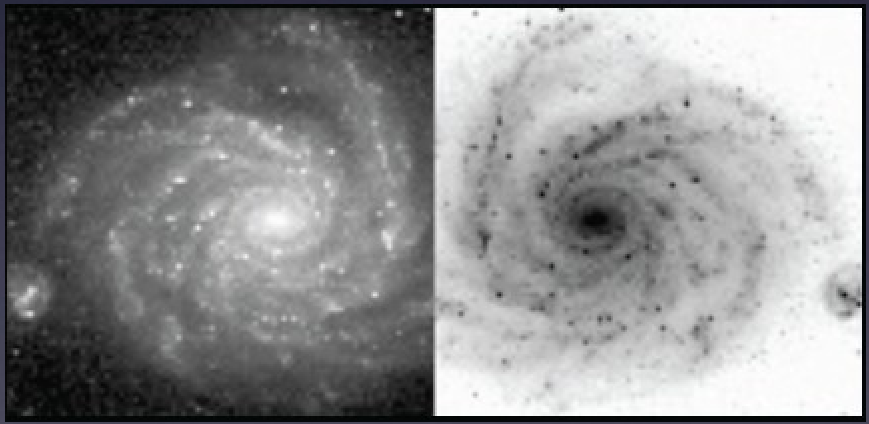
SPSC Meeting - 2012 / 06 / 26

Motivation

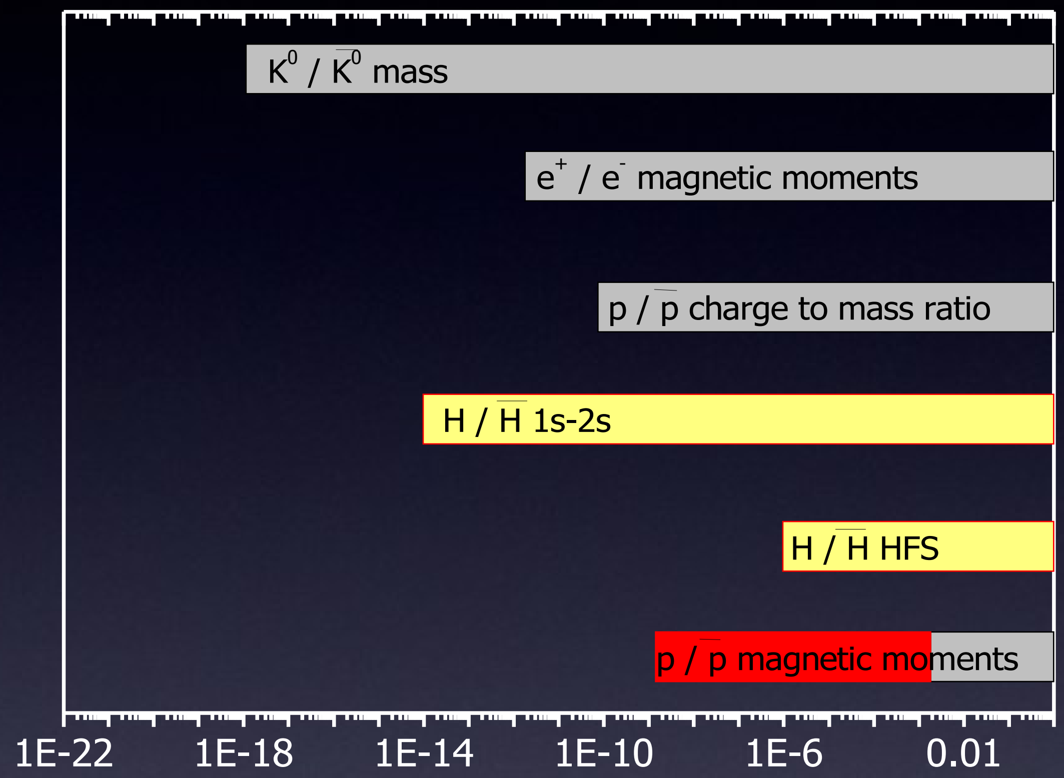
- We propose another test of matter/antimatter symmetry
- Comparison of the magnetic moment of the proton and the antiproton with high precision.

Test of CPT Symmetry

- Standard Model: Conserves CPT symmetry
- Cosmological Scale: Large matter/antimatter asymmetry – (baryonic) universe is made out of matter



CPT Tests



10^{-6} achieved for proton / at least 10^{-9} possible

GOAL: Millionfold Improvement

SME – CPT Test Framework

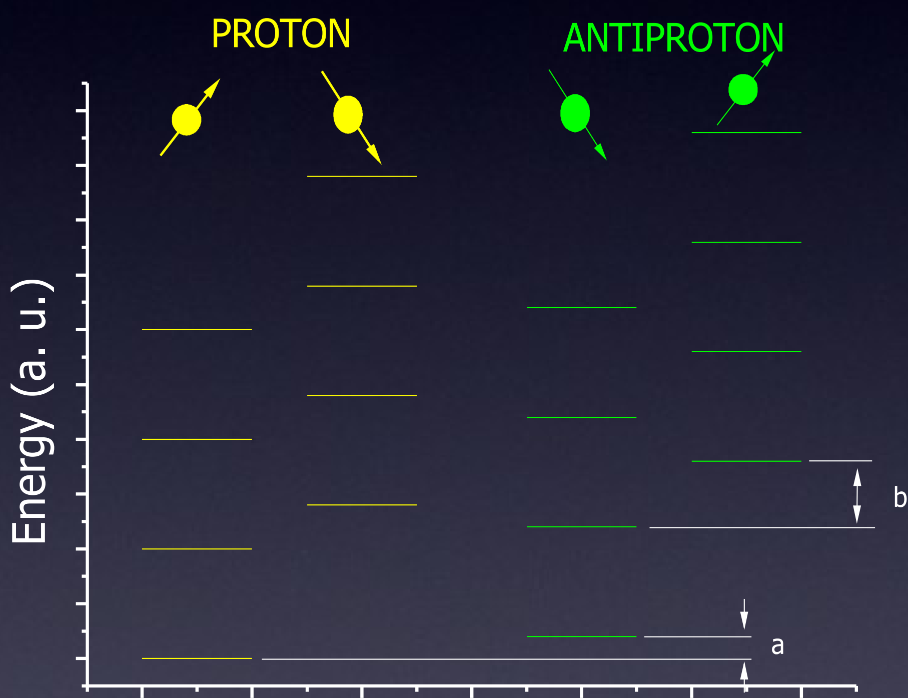
$$\left(i\gamma^{\mu}D_{\mu}-m-a_{\mu}\gamma^{\mu}-b_{\mu}\gamma^{5}\gamma^{\mu}\right)\psi=0$$

Model to discuss effects of CPT violation on experimental reality.

Idea of CPT violating background field.

Figure of Merit

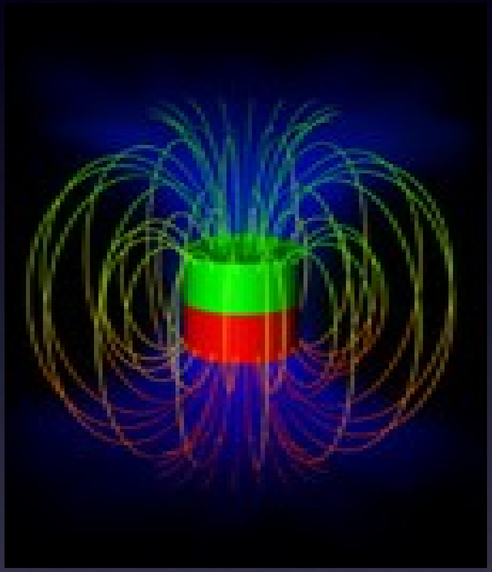
$$r_g=\frac{E_p-E_{\bar{p}}}{E_p}=\frac{\delta\omega_a}{m}$$



In this framework: high sensitivity against CPT violation

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

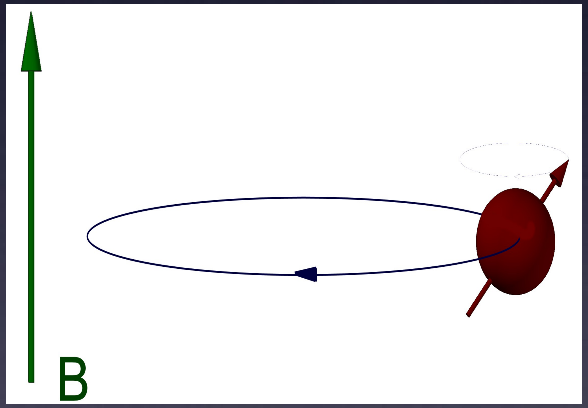
Spin carrying charged particle in a magnetic field

CYCLOTRON

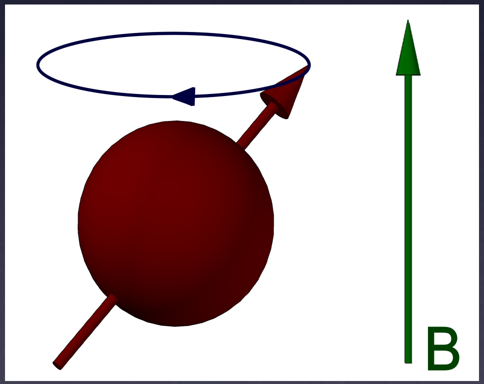
$$\omega_c = \frac{e}{m_p} B$$

LARMOR

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



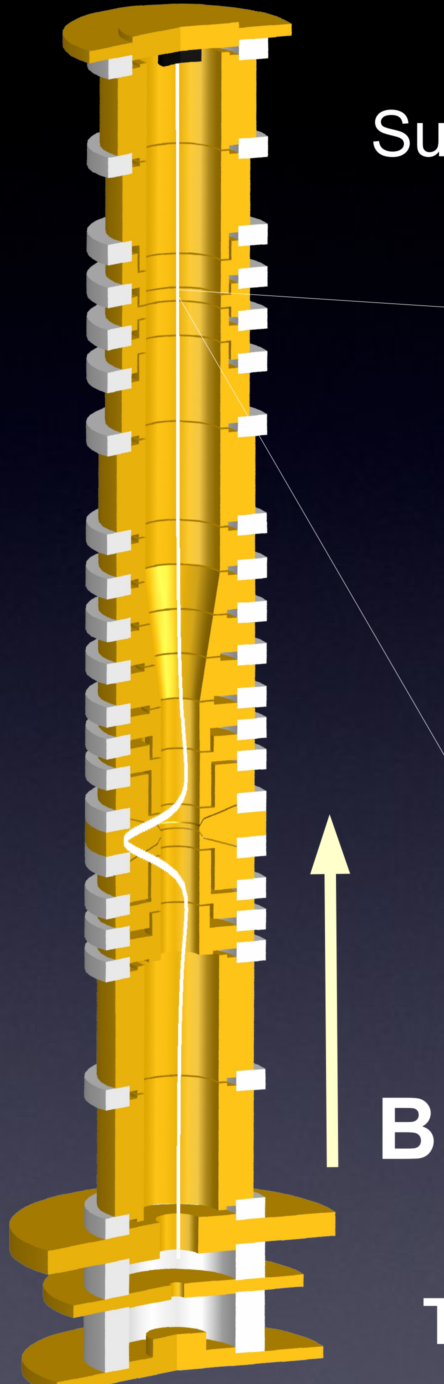
$$g_p = 2\frac{\omega_L}{\omega_c}$$

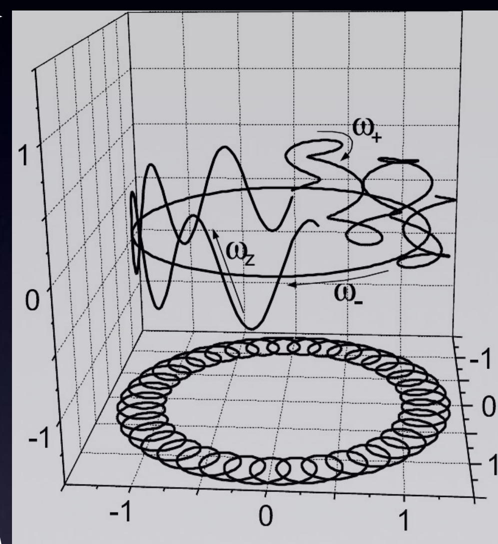


...reduces to measurement of a simple frequency ratio

The Penning Trap

Superposition of homogeneous magnetic field and electrostatic quadrupolar potential



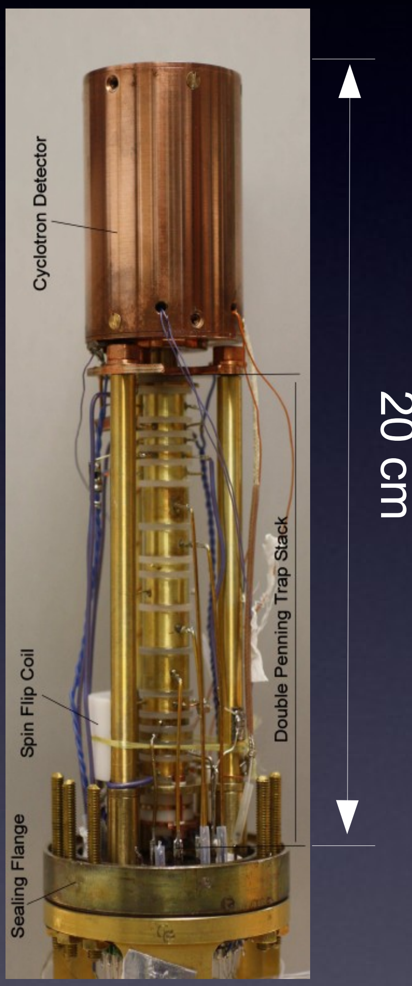


FREQUENCIES

Axial: 700 kHz

Modified Cyclotron: 29 MHz

Magnetron: 8 kHz

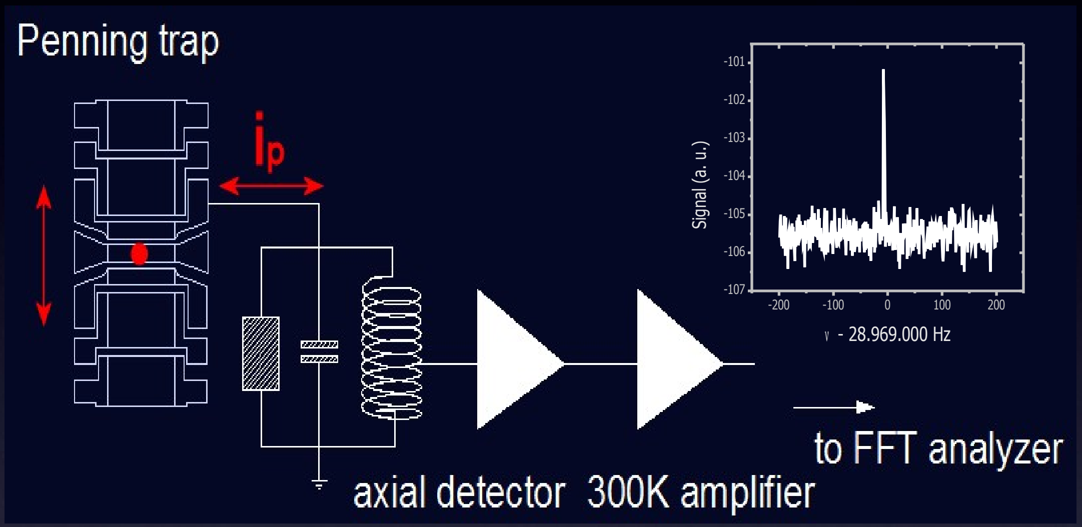


$$\nu_c^{\,2} = \nu_+^{\,2} + \nu_-^2 + \nu_z^{\,2}$$

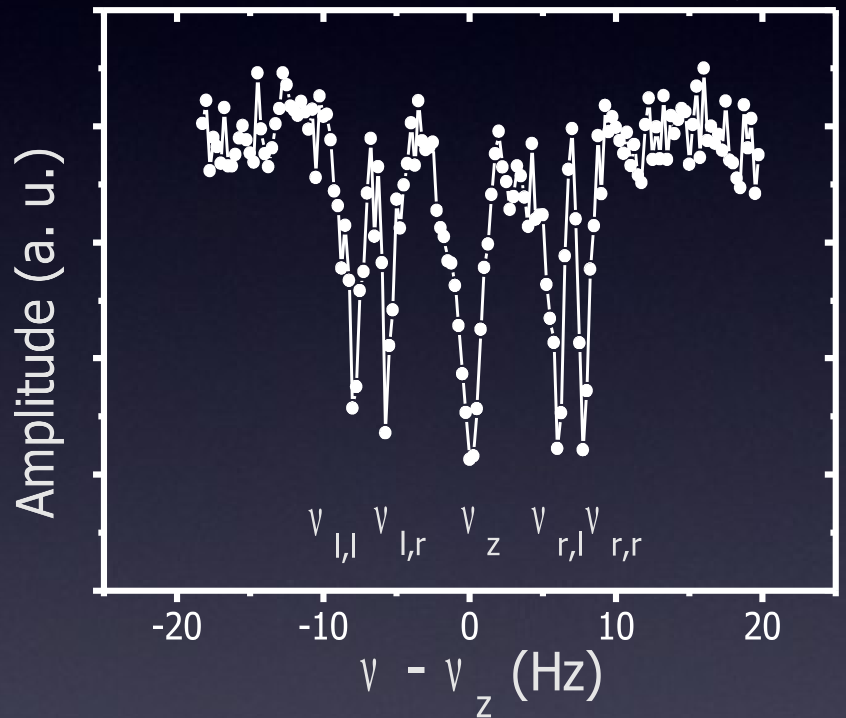
“Brown-Gabrielse Invariance Theorem” makes Penning traps strong

Frequency Measurements in a Penning Trap

Trapped charged particle induces image currents



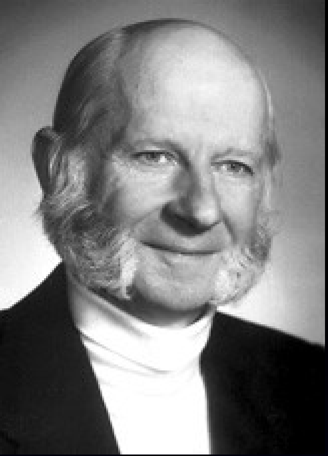
Novel method developed: Both radial modes simultaneously coupled to axial frequency



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

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

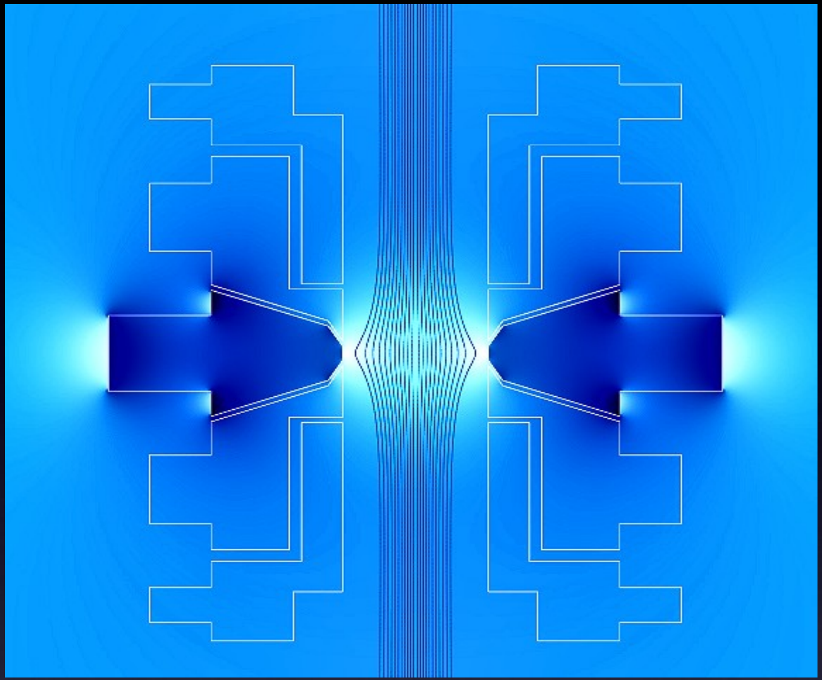
S. Ulmer *et al.*, Phys. Rev. Lett 107, 103002 (2011)



Continuous Stern-Gerlach Effect

Magnetic dipole in B-field

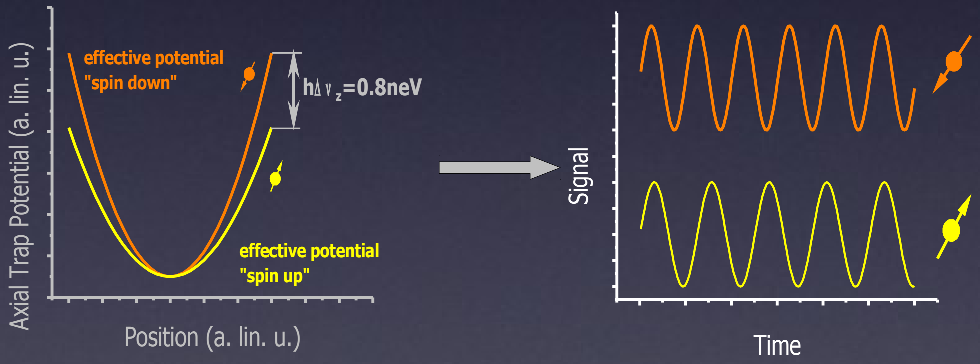
$$\Phi_M = -\left(\vec{\mu}_p \cdot \vec{B}\right)$$



Magnetic bottle...

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

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

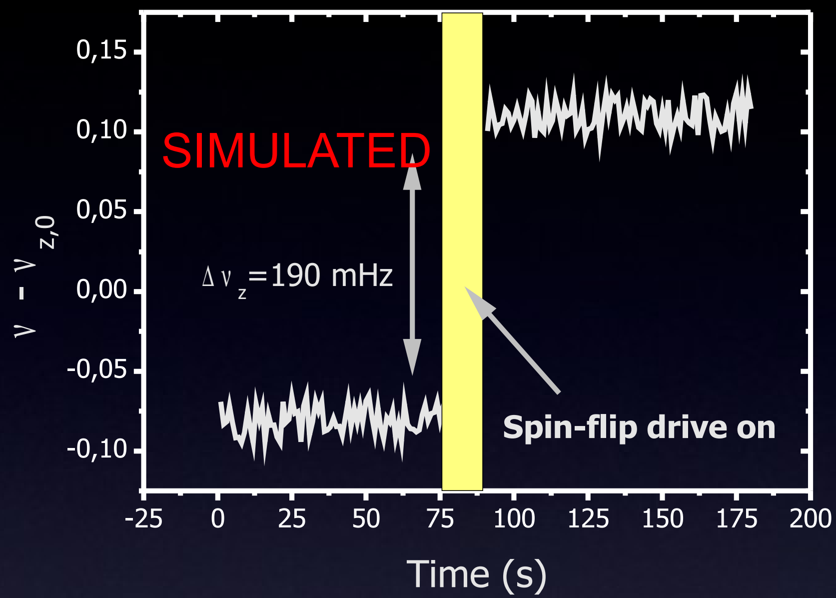


$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z} \qquad \frac{\alpha_e}{\alpha_p} > 10^6$$

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

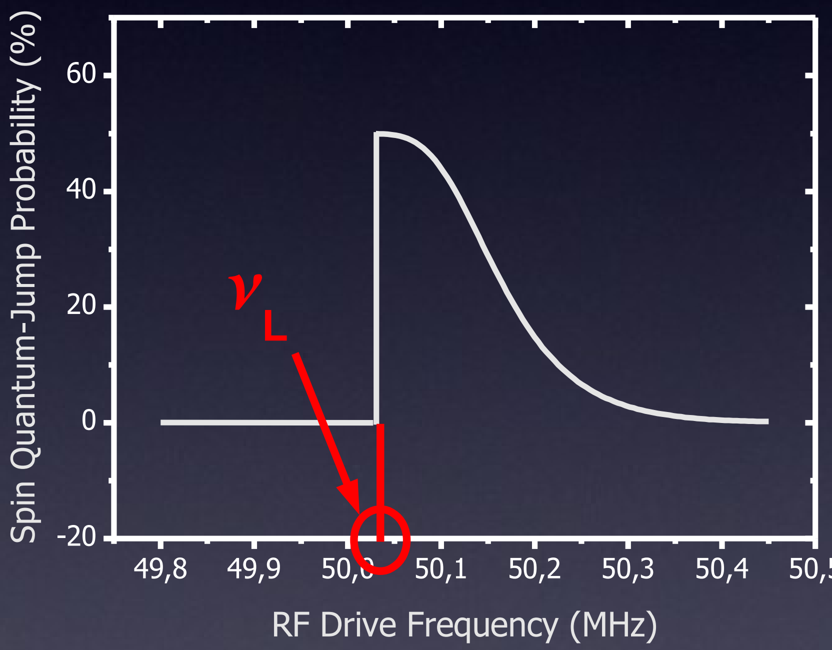
Under these extreme conditions: frequency shifts by 190 mHz out of 1 MHz → $2 \cdot 10^{-7}$

The Larmorfrequency



Measure this several hundred times for different drive frequencies

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



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

Sharp “cutoff” reflects zero temperature Larmor Frequency

Absolute frequency stability below 190 mHz needed

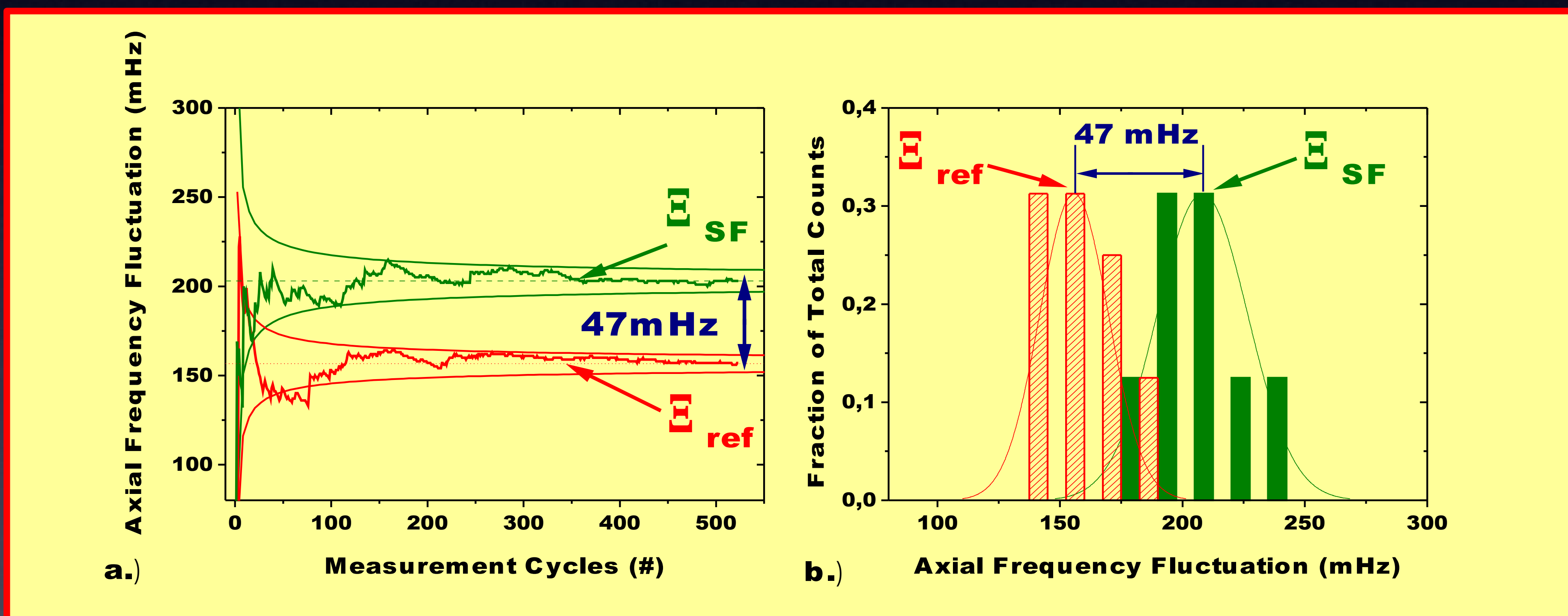
$$\Delta\nu_z = \frac{1}{4\pi^2 m_p \nu_z} \frac{B_2}{B_0} E_\rho \rightarrow \frac{\Delta\nu_z}{\Delta E_\rho} = 1 \frac{Hz}{\mu eV}$$

- Spin Flip Detection using a statistical method

→ Axial frequency jumps add to background frequency fluctuation

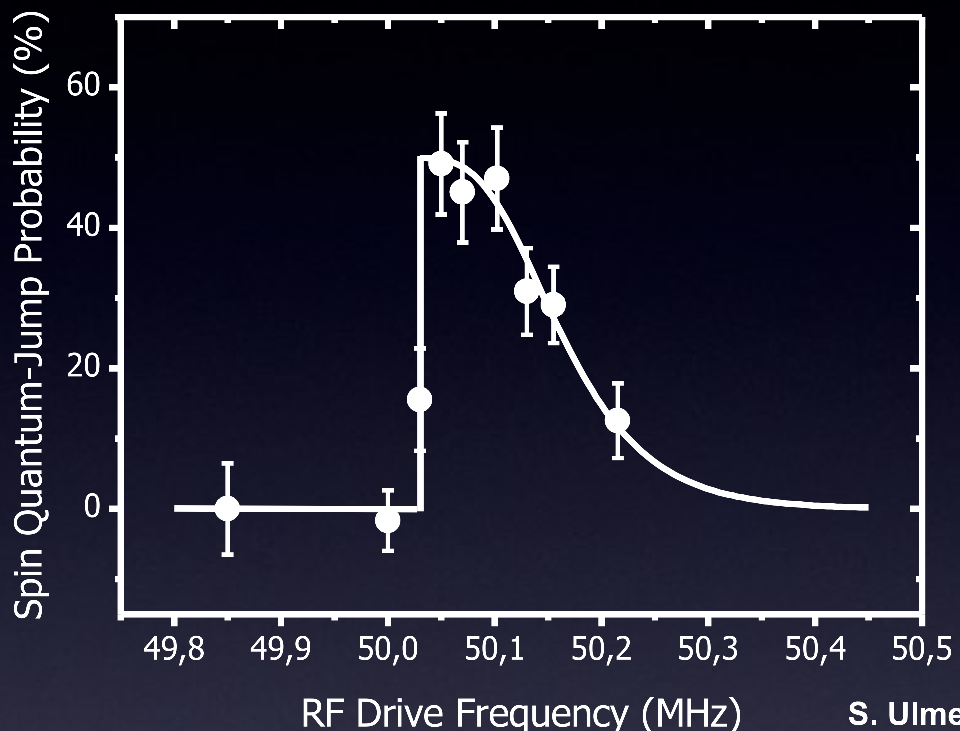
$$\Xi_{SF} = \sqrt{\Xi_{ref}^{2} + P_{SF}\Delta\nu_{z,SF}^{2}}$$

First Proton Spin Flips Ever Observed



We did that for different drive frequencies

First Larmor Resonance Curve



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

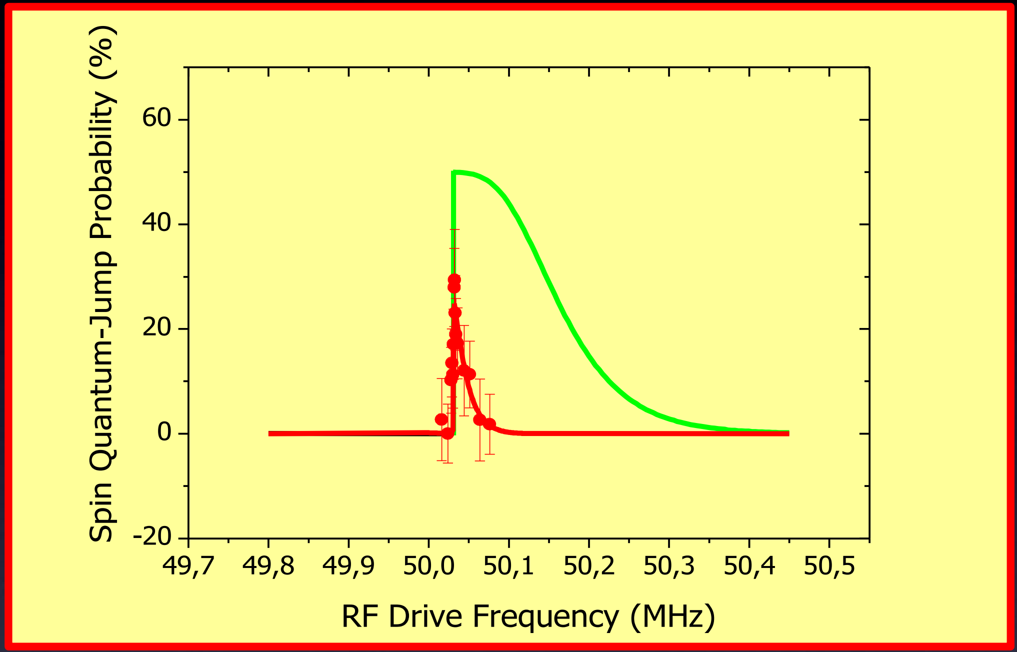
Relative Precision: 10^{-4}

→ 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*10^{-6}

→ With cyclotron frequency measurement

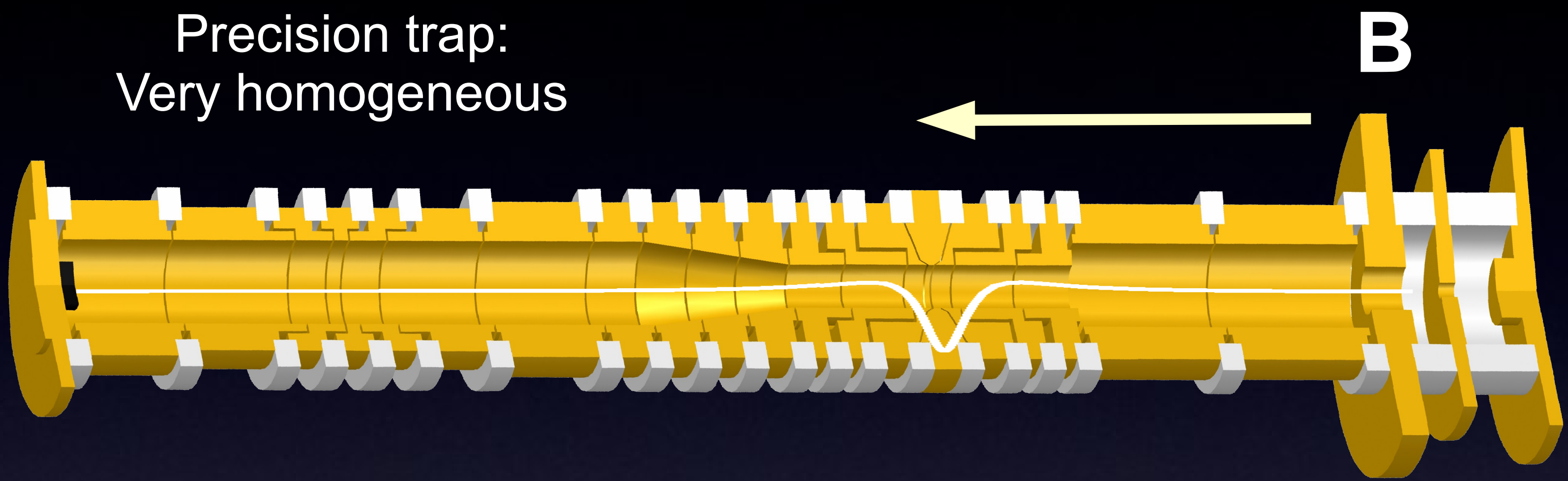
g/2 = 2.792 848 (24)

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

g/2 = 2.792 846 (7)

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

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

Technical / Administrative

Collaboration

RIKEN

Stefan Ulmer / Yasunori Yamazaki

Christian Smorra (PD)

Klaus Blaum

Kurt Franke (PhD)

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Jochen Walz

Wolfgang Quint

GSI

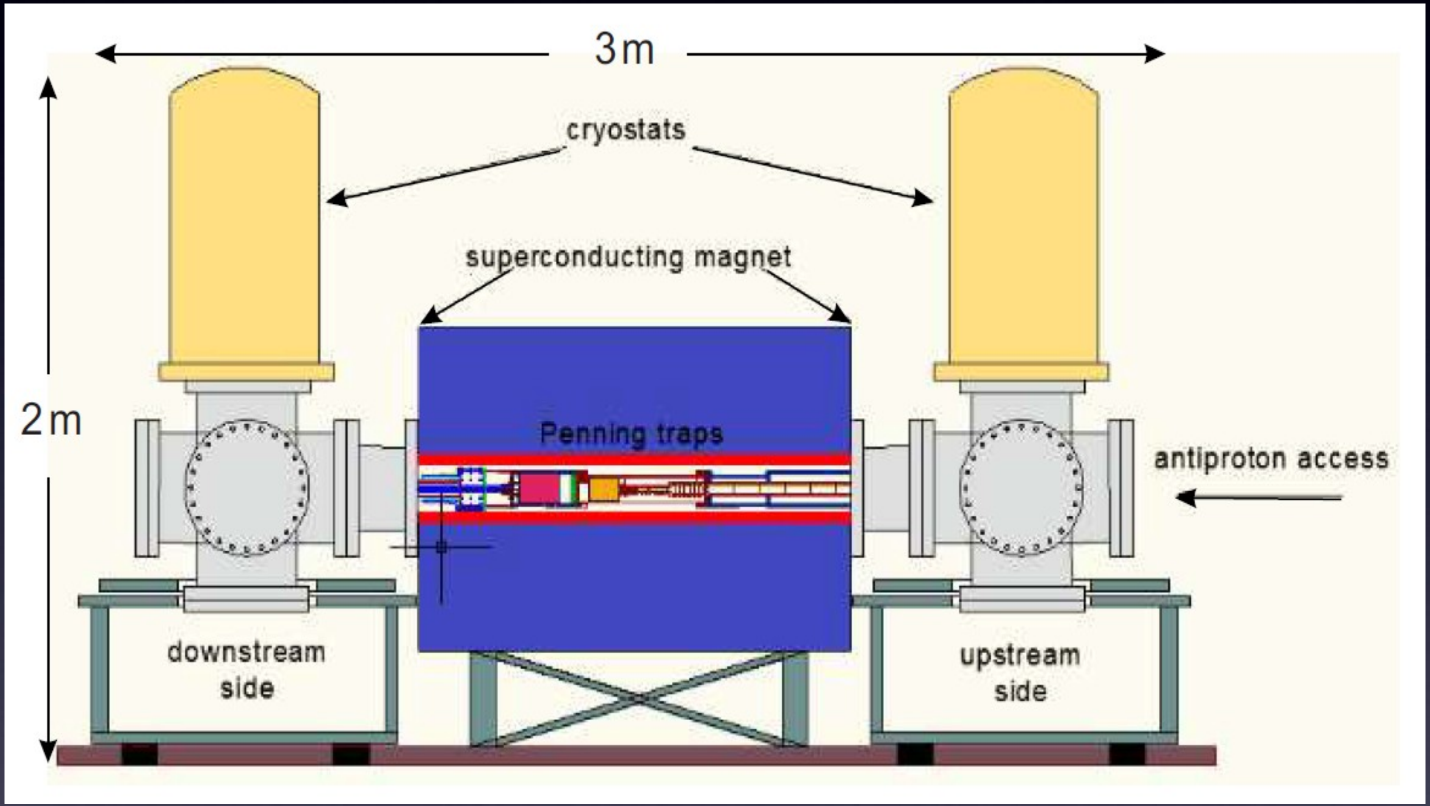
Budget and Positions

- Budget estimate for experiment is about 1.250.000,-

- Stefan Ulmer: RIKEN IRU 1.925.000,- (5 yrs)
- Yasunori Yamazaki/Stefan Ulmer: JSPR grant (5 yrs)
- Klaus Blaum: Max Planck Society and ERC grant (5yrs)

Experiment will be operated by one group leader / two post-docs / two PhD students

Preliminary Design Studies

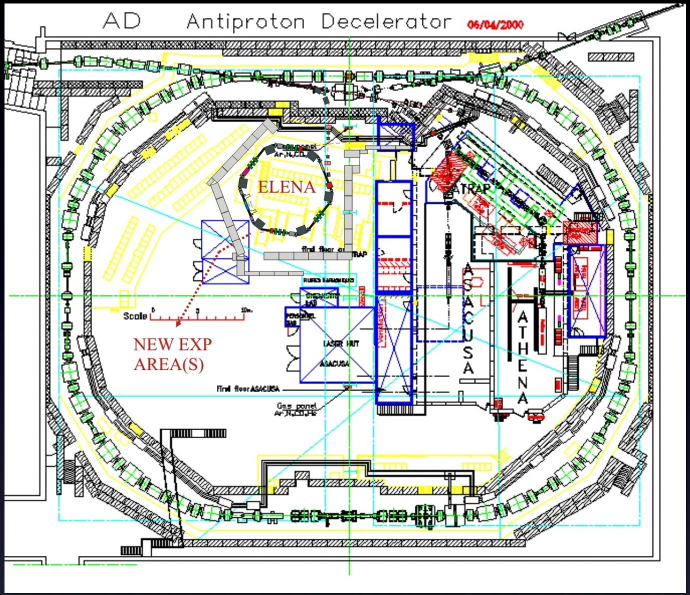


Milestones and Timeline

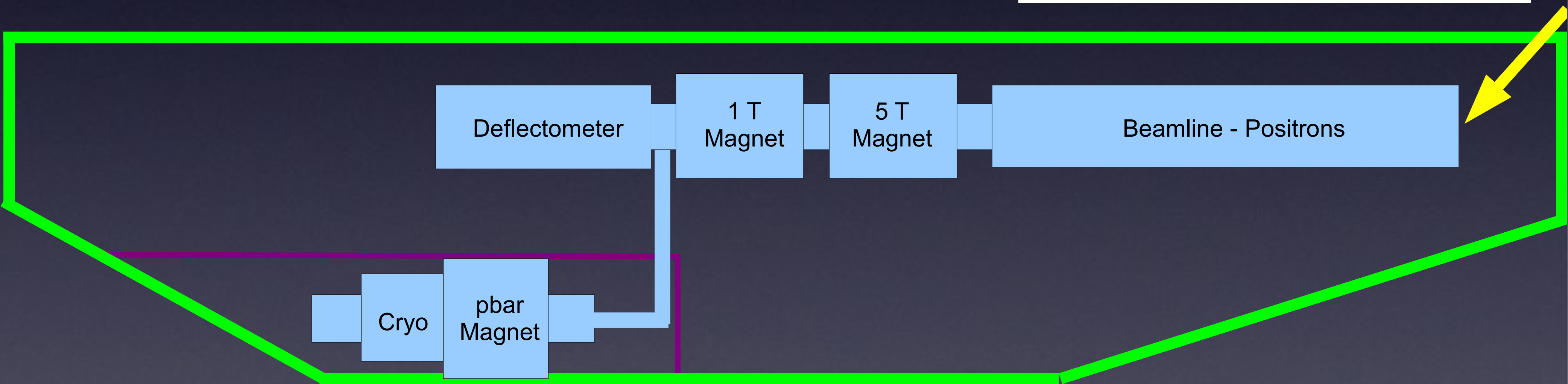
- Construction of experiment – ready to take beam in 2014.
- Trapping of a single antiproton and transport to magnetic bottle (beamtime 2014).
- Measurement of the magnetic moment of the antiproton at a level of 10^{-6} (beamtime 2014/2015).
- ...towards 10^{-9}

Implementation in AEgIS

- Detailed discussion with AEgIS collaboration going on.



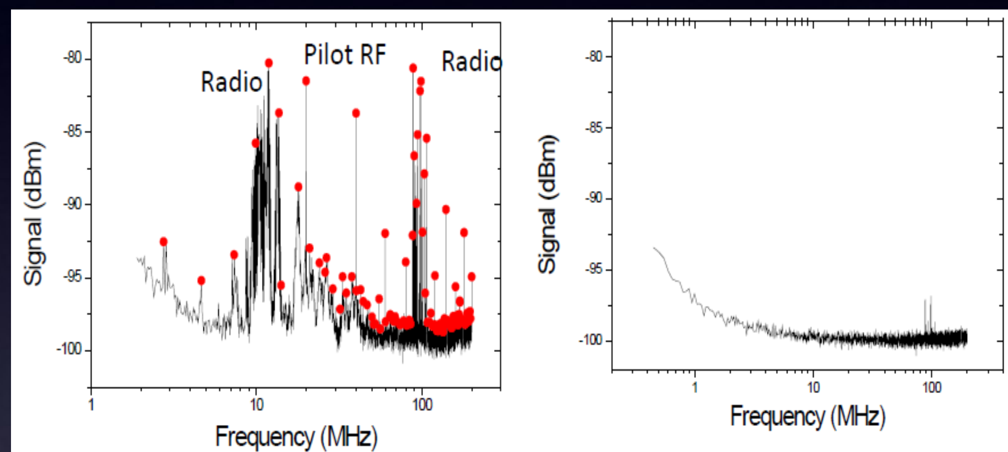
- Possible scenario:

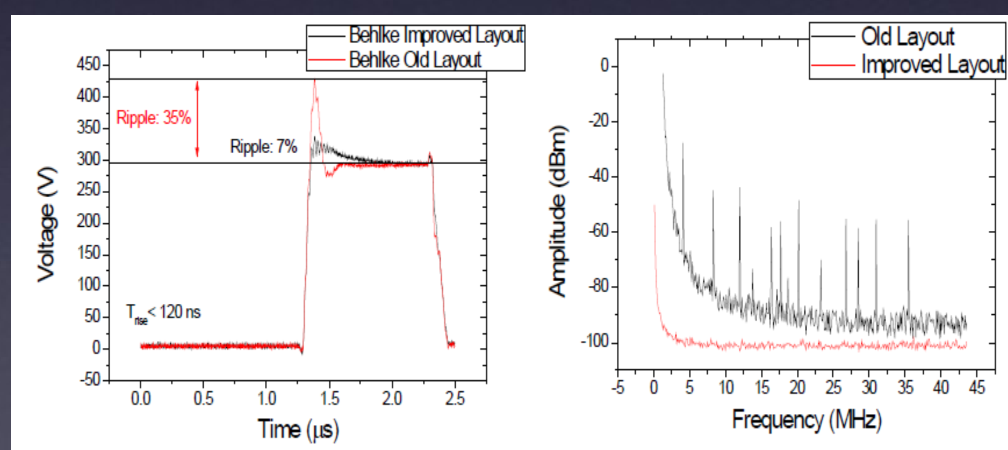


Actively shielded superconducting magnet < 5G/m

AD Noise Reduction

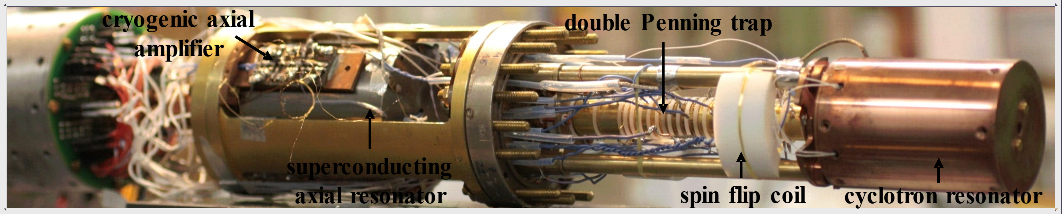
- Electronics developed for AD noise reduction





Summary

- First spin flips observed with a single proton → a major step towards new test of matter/antimatter symmetry.
- Proposed to perform this experiment at CERN/AD with a single antiproton.
- Secure funding for experiment
- Design studies and discussion with AEgIS going on.



Funding

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!!! Thanks for your attention !!!