High precision measurement of the antiproton g-factor

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for the BASE collaboration

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Outline

- Motivation
- penning trap and Measurements
- BASE apparatus and current situation
- Ground loop detection
- Summery

Why should we test CPT invariance?

CPT invariance ⟷ matter/antimatter assymmetry

Experiment : Measure the fundamental properties of matter/antimatter in high precision.

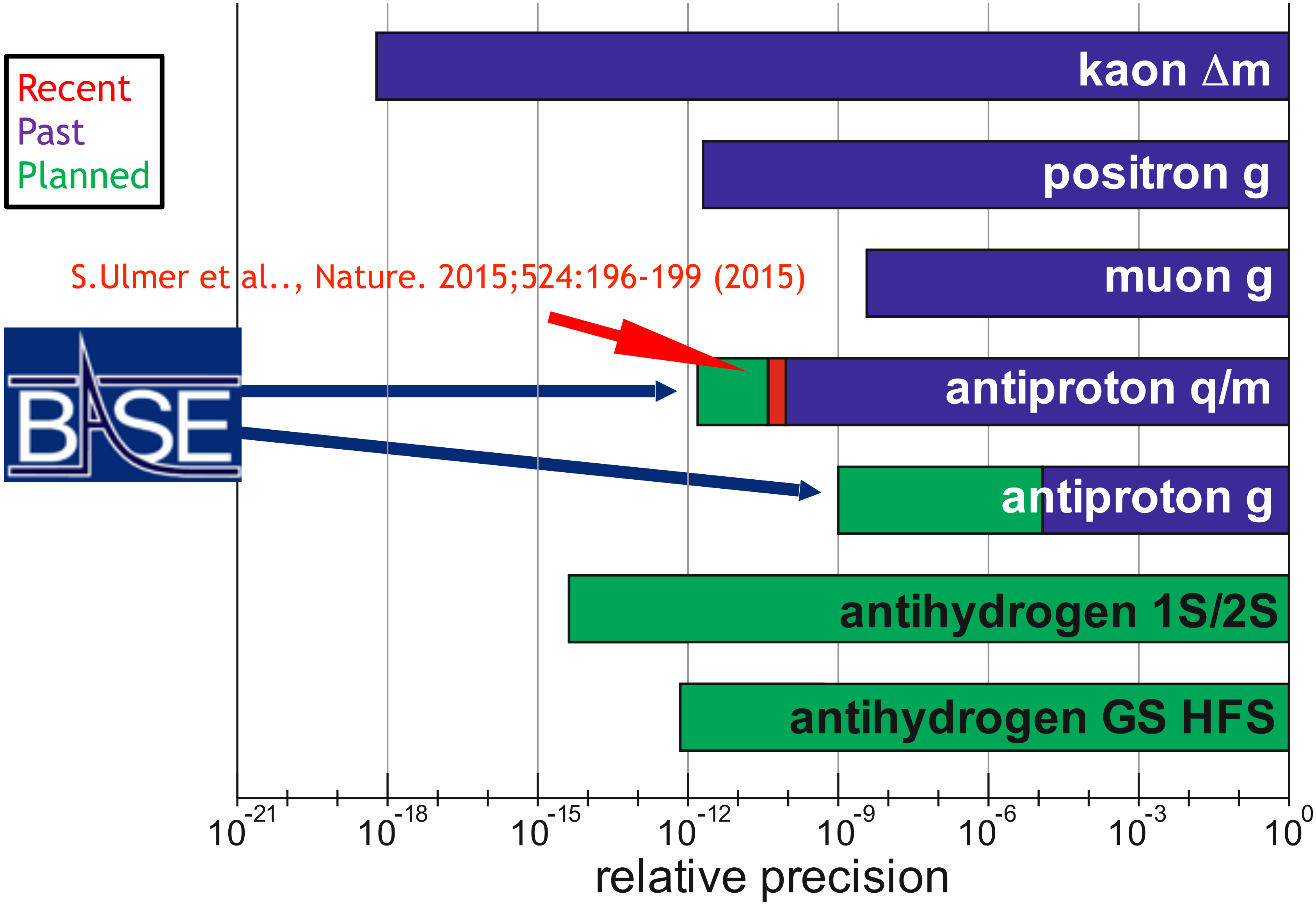
Aim of BASE

- precise measurement of proton-antiproton g-factor by penning trap method

g: magnetic Moment in units of nuclear magneton

$$\vec{\mu} = g\frac{q}{2m}\vec{S}$$

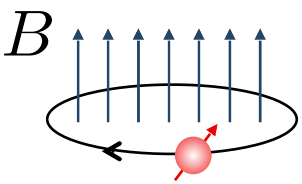
CPT tests



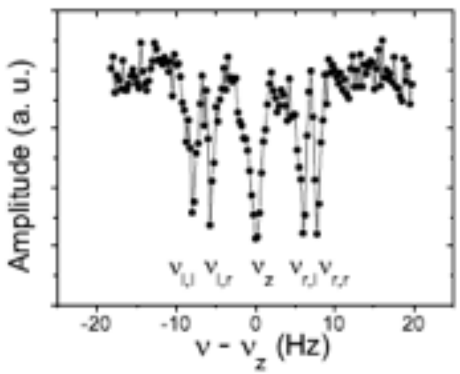
Recent
Past
Planned
S.Ulmer et al.., Nature. 2015;524:196-199 (2015)
kaon Δm
positron g
muon g
antiproton q/m
antiproton g
antihydrogen 1S/2S
antihydrogen GS HFS
10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{0}
relative precision

Measurements

Cyclotron Motion



$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$



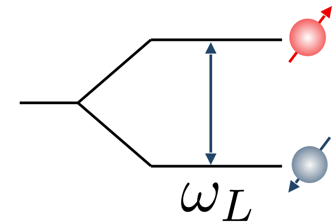
S. Ulmer, A. Mooser *et al*. PRL 107, 103002 (2011)

g: magnetic Moment in units of nuclear magneton

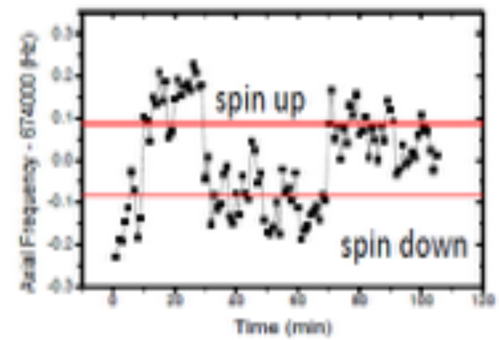
$$\frac{g}{2} = \frac{\nu_L}{\nu_c}$$

g: dimensionless

Larmor Precession



$$\nu_L = \frac{g}{4\pi}\frac{q}{m}B$$



S. Ulmer, A. Mooser *et al*. PRL 106, 253001 (2011)

g-factor measurement reduces to measurement of a frequency ratio

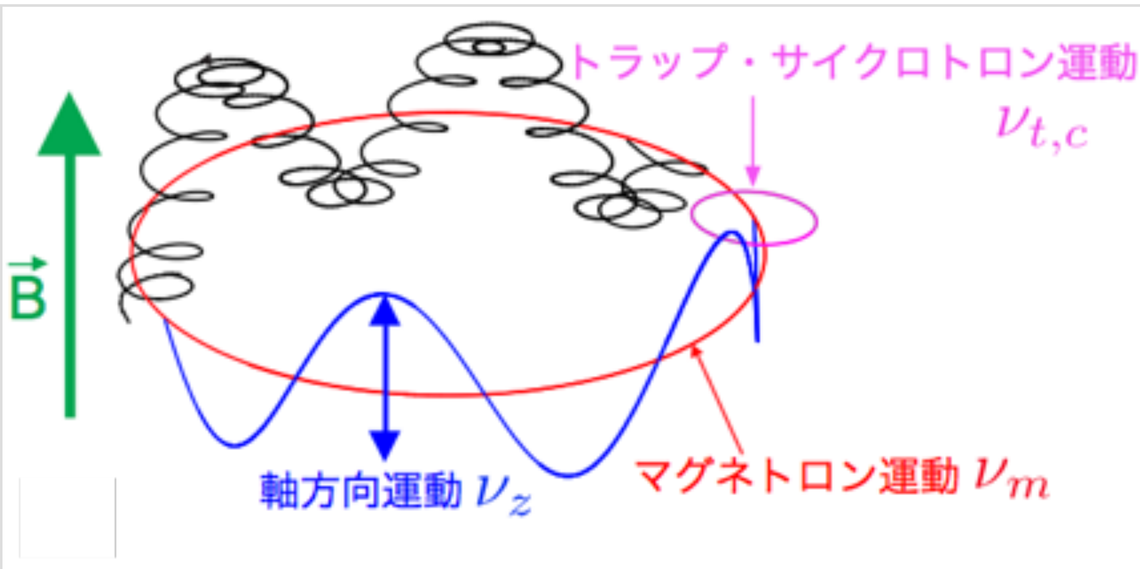
In principle **a very simple** experiment

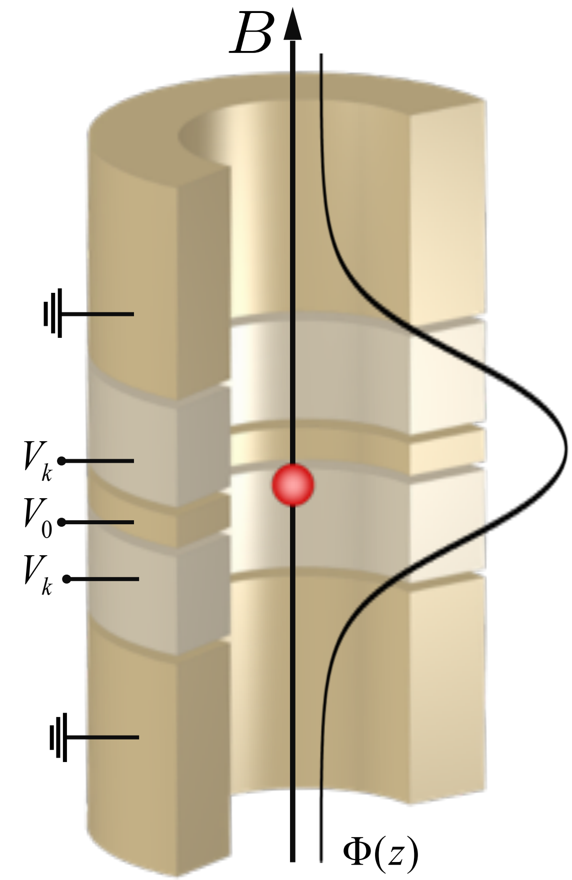
-> **full control, no theoretical corrections**

Cyclotron frequency and penning trap

radial confinement: $\vec{B} = B_0 \hat{z}$

axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$





Invariance-Relation: $\nu_c = \sqrt{\nu_+^2 + \nu_-^2 + \nu_z^2}$

L. S. Brown and G. Gabrielse, Phys. Rev. A **25**, 2423 (1982).

3 eigenfrequencies of cyclotron frequency

- axial frequency $\nu_z = \sqrt{\frac{2qC_2}{m}V_0}$

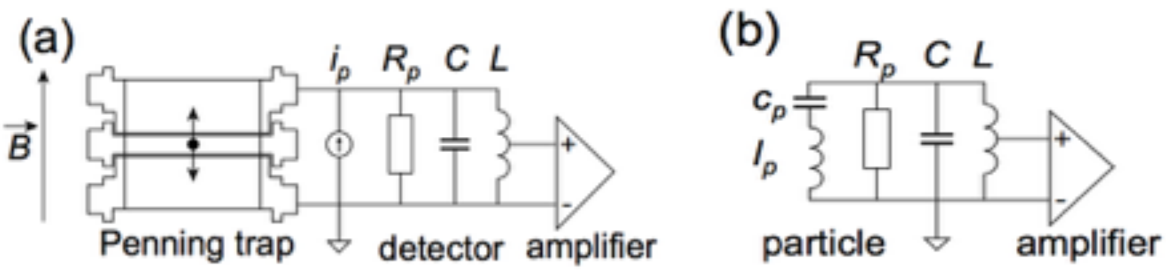
- modified cyclotron and magnetron frequency

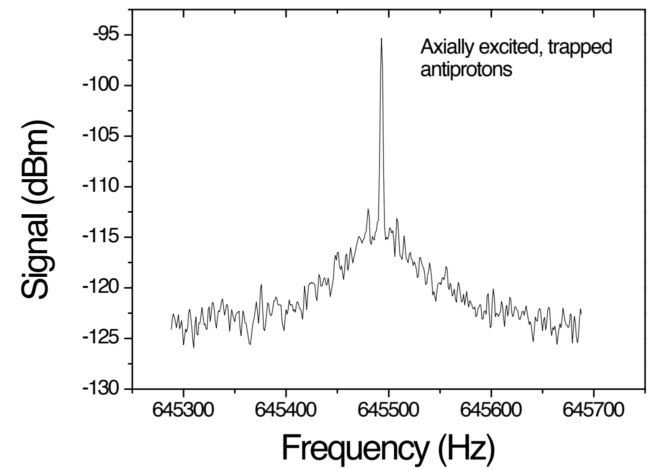
$$\nu_\pm = \frac{1}{2}(\nu_c \pm \sqrt{{\nu_c}^2 - 2{\nu_z}^2})$$

Axial(軸方向)	$\nu_z = 680\,\mathrm{kHz}$
Magnetron(マグネトロン)	$\nu_- = 8\,\mathrm{kHz}$
Modified Cyclotron(トラップサイクロトロン)	$\nu_+ = 28{,}9\,\mathrm{MHz}$

Frequency Measurements

Measurement of tiny image currents induced in trap electrodes

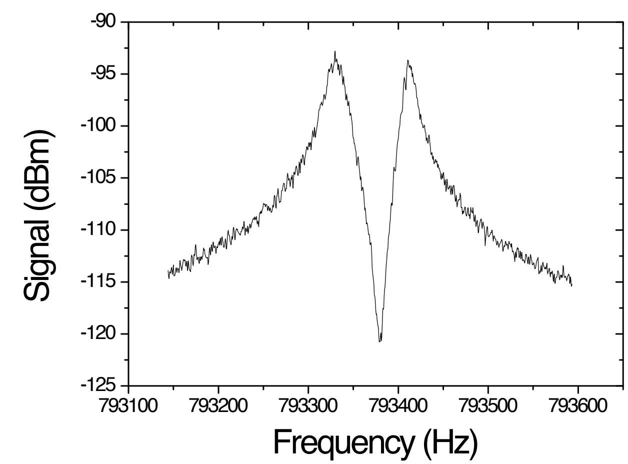




In thermal equilibrium:

- Particles short noise in parallel
- Appear as a dip in detector spectrum
- Width of the dip → number of particles

$$\Delta\nu = \frac{1}{2\pi}\frac{R}{m}\left(\frac{q}{D}\right)^2 \cdot N$$

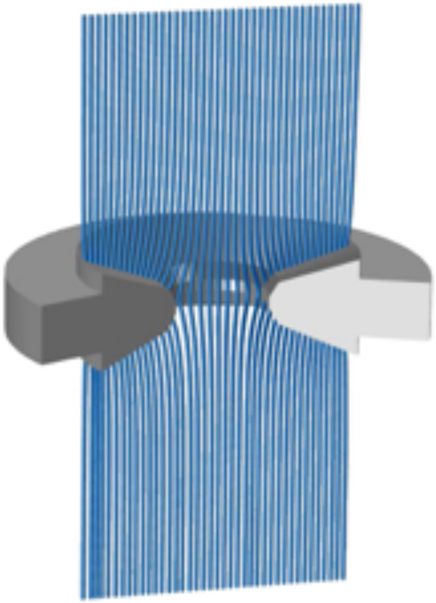


Measurements in thermal equilibrium → tiny volumina / homogeneous condititions

Enables cyclotron frequency measurement at ~1 ppb

Larmor Frequency

Measurement based on continuous Stern Gerlach effect



Energy of magnetic dipole in magnetic field $\Phi_M = -(\vec{\mu_p} \cdot \vec{B})$

Leading order magnetic field correction $B_z = B_0 + B_2\,(z^2 - \frac{\rho^2}{2})$

Spin dependent quadratic axial potential
→ Axial frequency becomes function of spin state

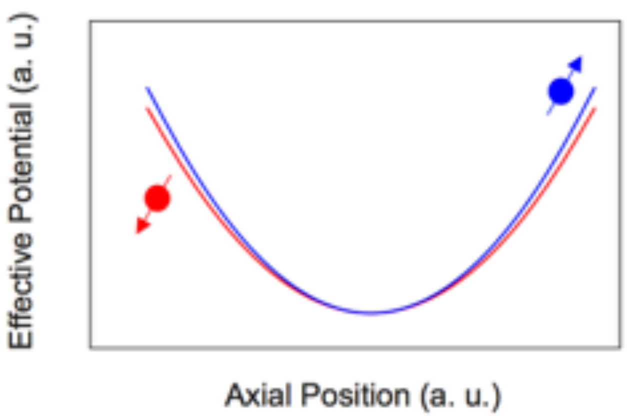
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

Very difficult for the proton/antiproton system

$$B_2 \sim 300000\, T/m^2$$

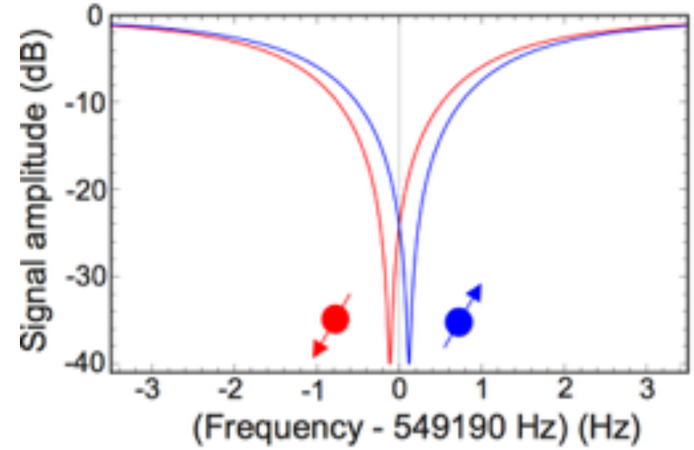
Most extreme magnetic conditions ever applied to single particle.

$$\Delta\nu_z \sim 170 mHz(\nu_z \sim 660kHz)$$

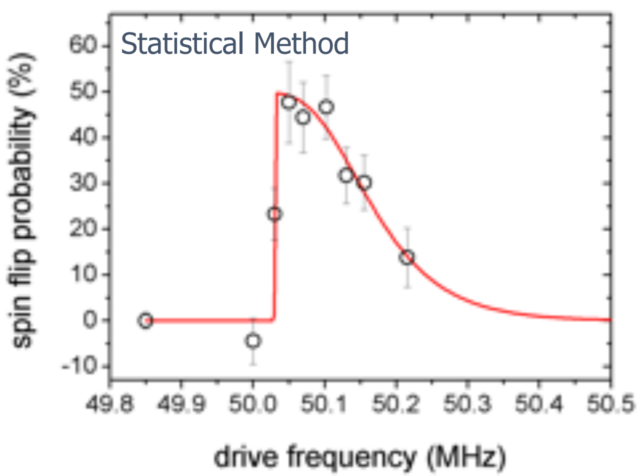


Larmor Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement



Larmor Frequency is measured by repetition and evaluating the spin flip probability



Together with cyclotron frequency measurement:

g/2 = 2.792 848 (24) Rodegheri et al., NJP 14, 063011, (2012)

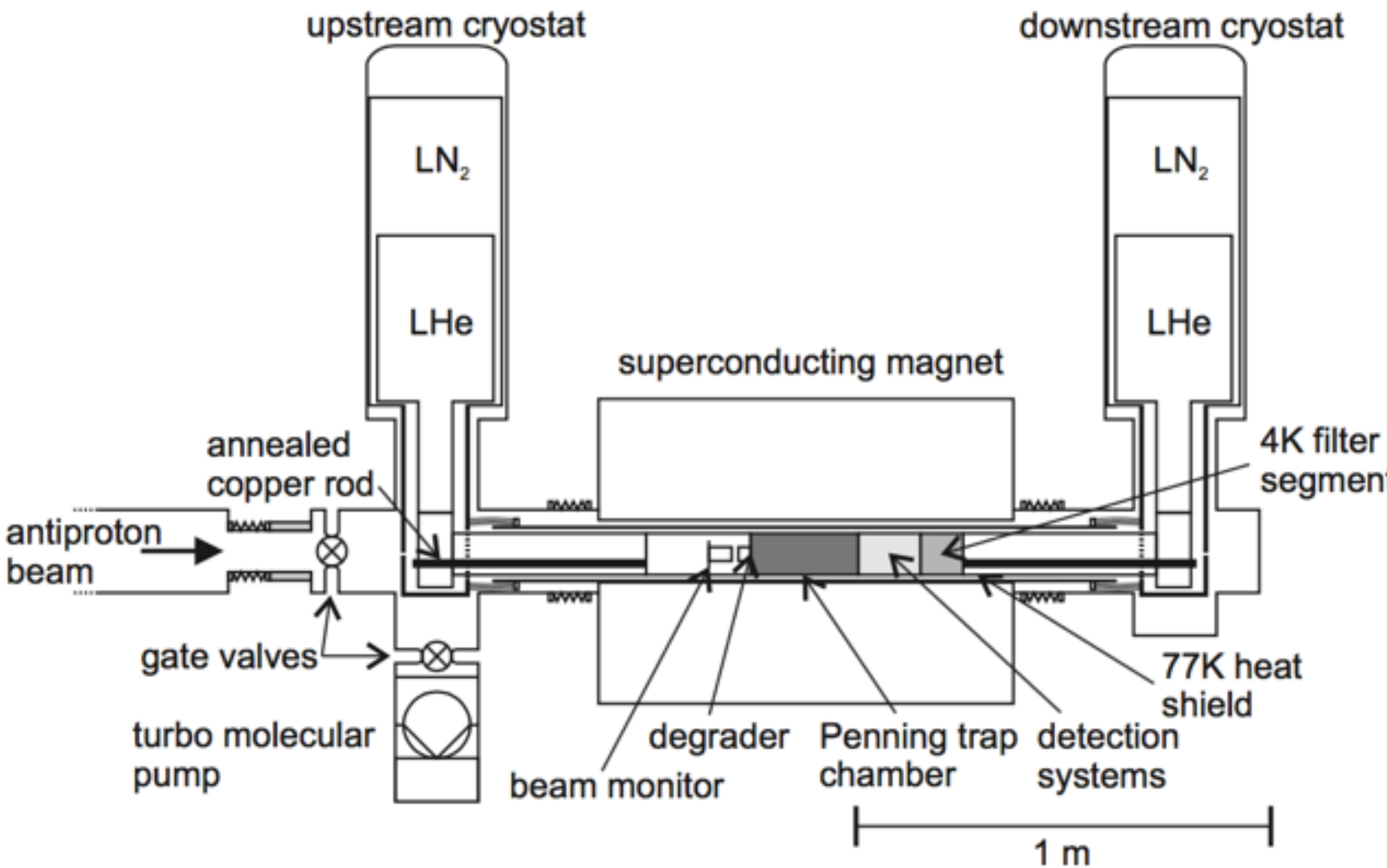
g/2 = 2.792 846 (7) di Sciacca et al., PRL 108, 153001 (2012)

Statistical Method:

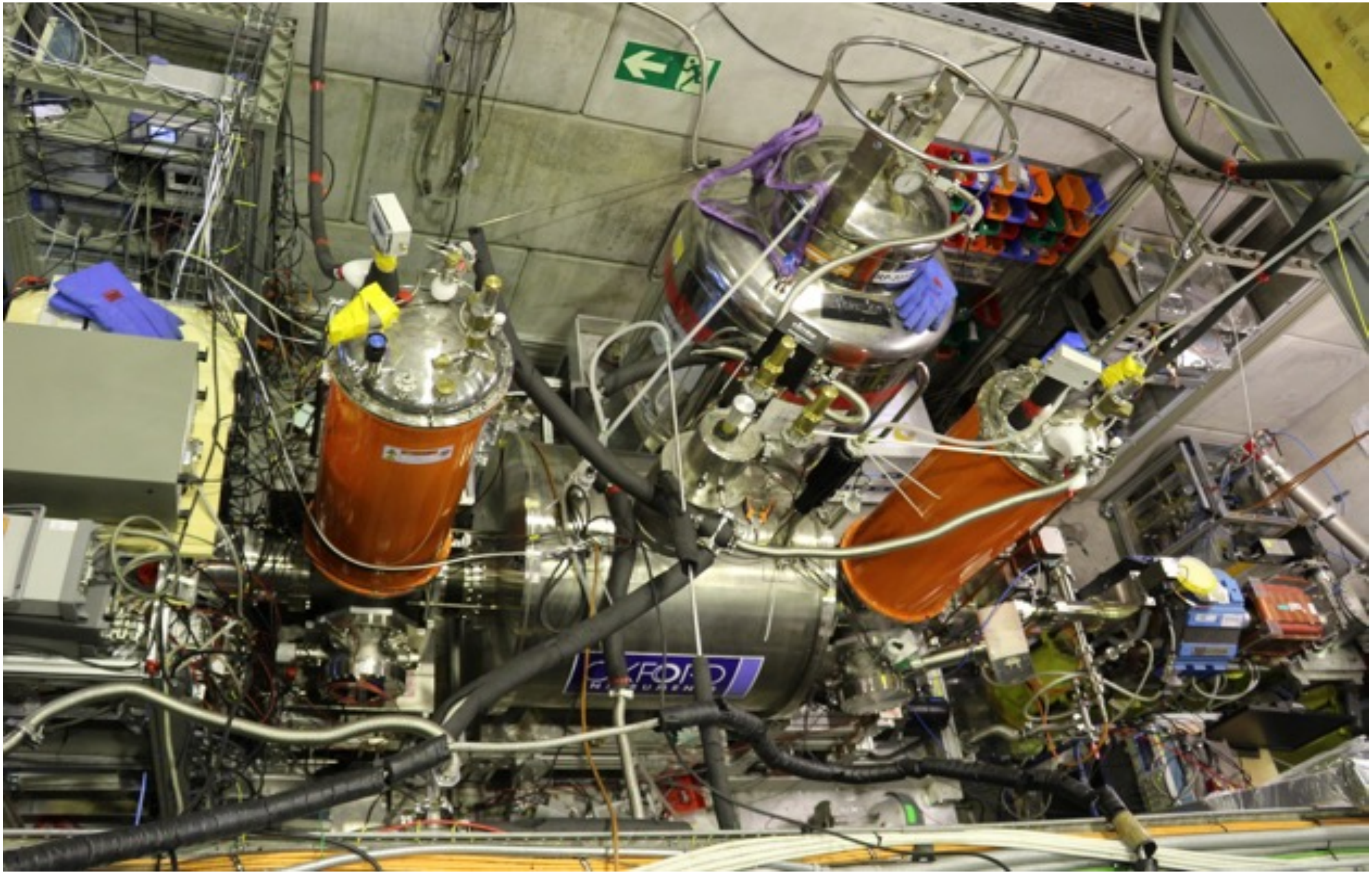
Limited to the ppm level due to the strong magnetic bottle.

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

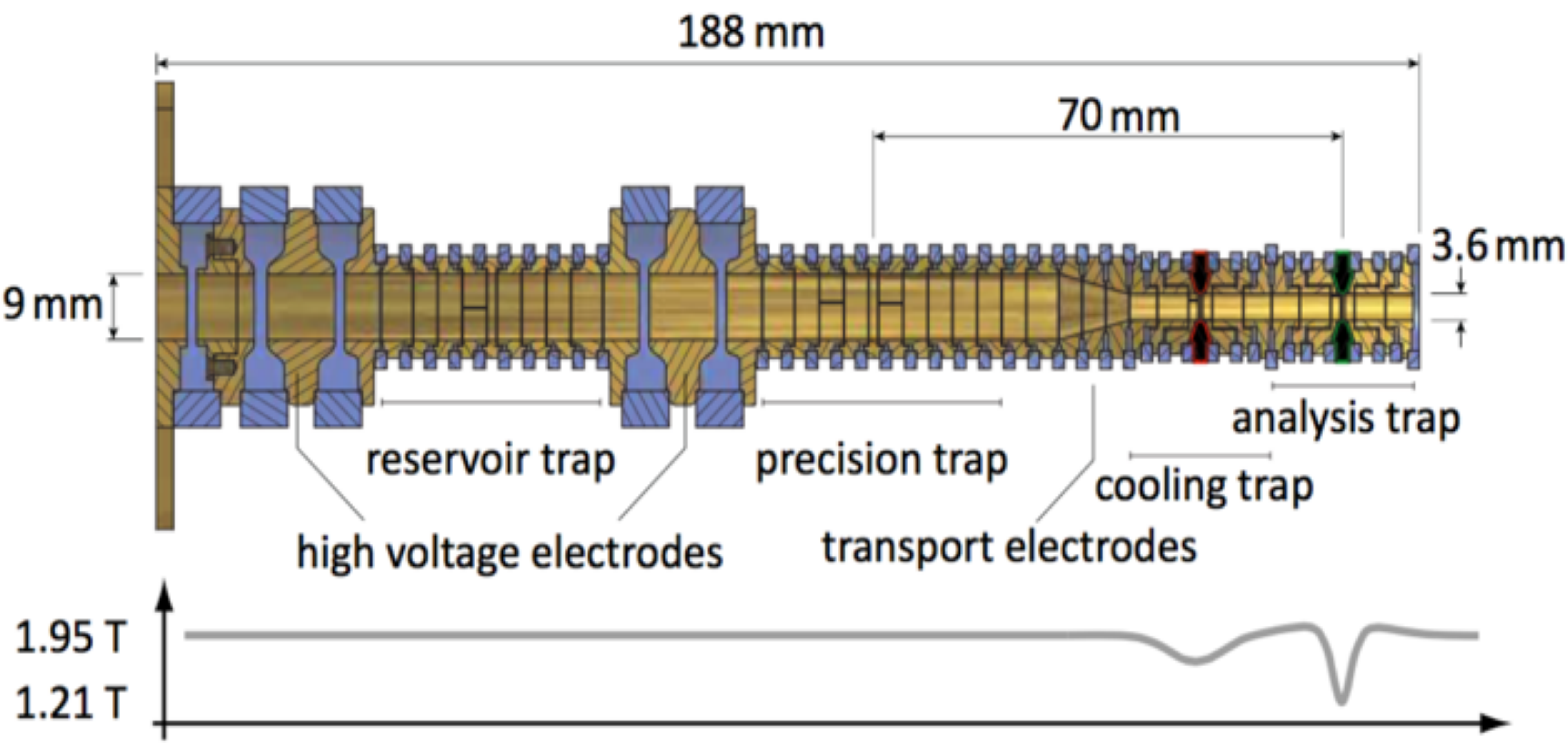
BASE apparatus



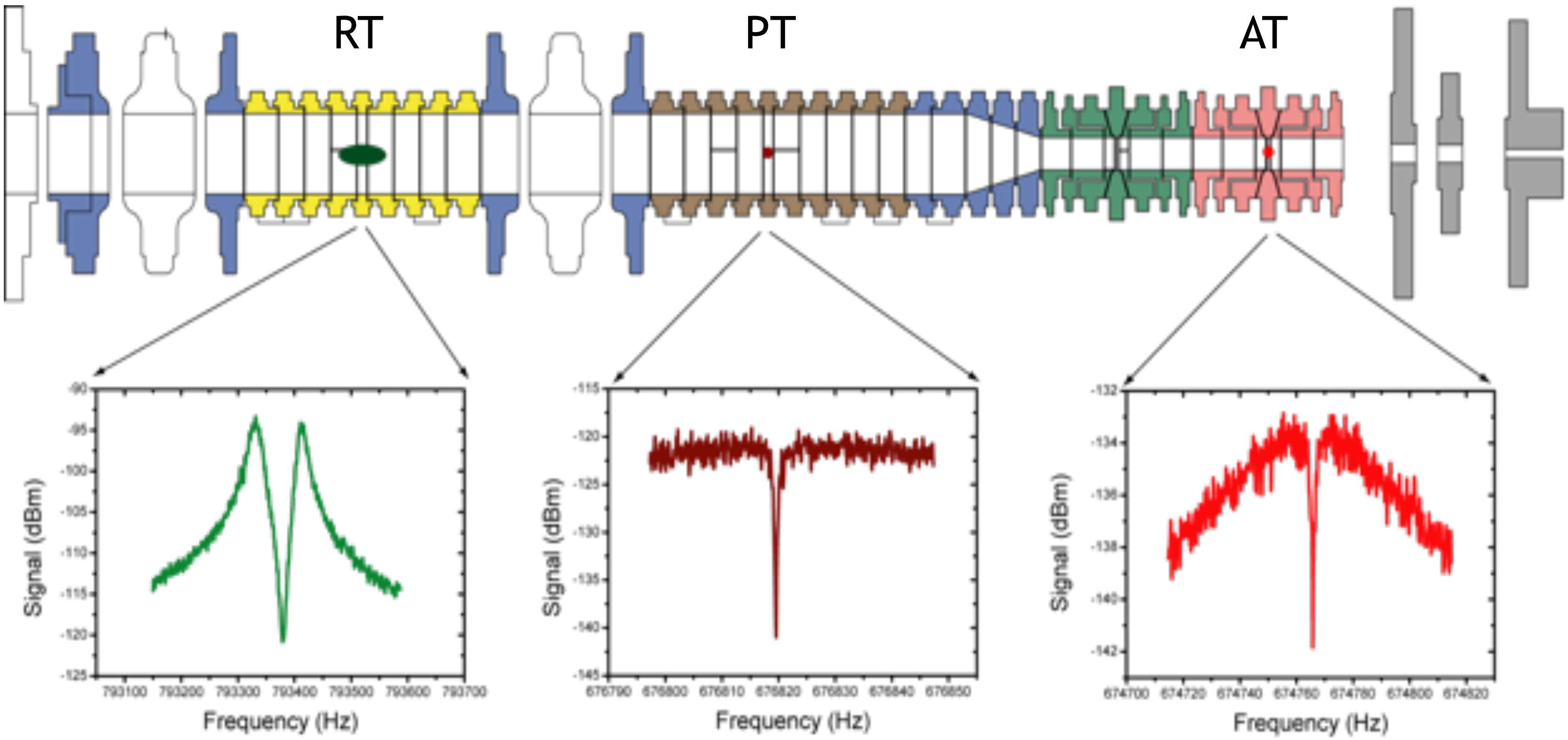
Picture of BASE apparatus



BASE double penning trap



BASE double penning trap



50 antiprotons in reservoir trap

Single antiproton in precision trap

Single antiproton in analysis trap

Signals observed in all trap and g-factor measurement is still ongoing.

Ground loop detection

- By ground loop, extra low signal will be on the background and the voltage fluctuation directly affects to the axial frequency!

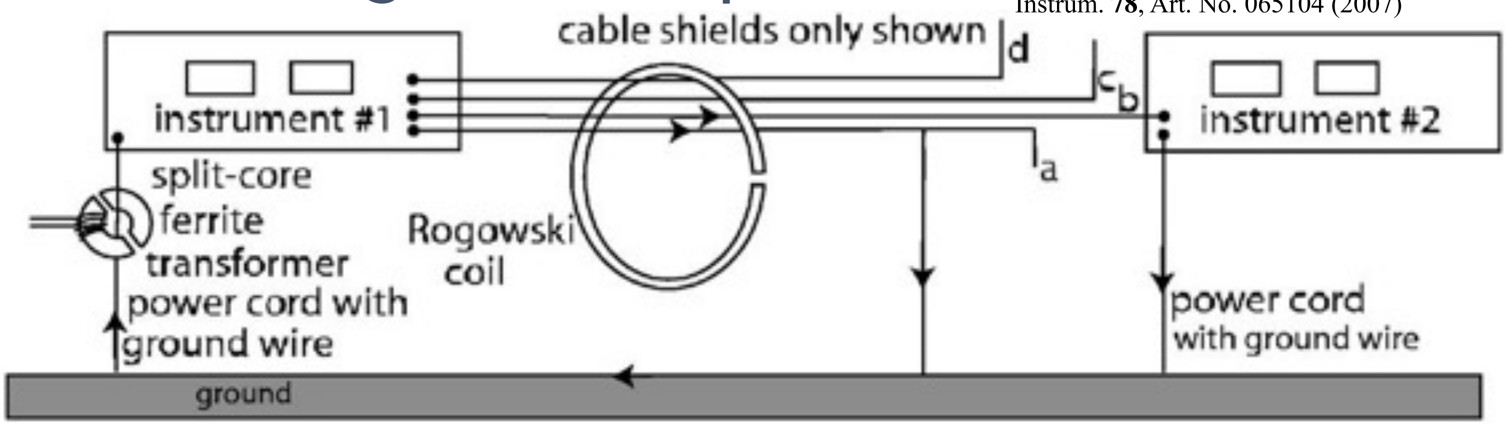
$$\nu_z = \sqrt{\frac{2qC_2}{m}V_0}$$

$$\Delta\nu_z \sim 170mHz(\nu_z \sim 660kHz)$$

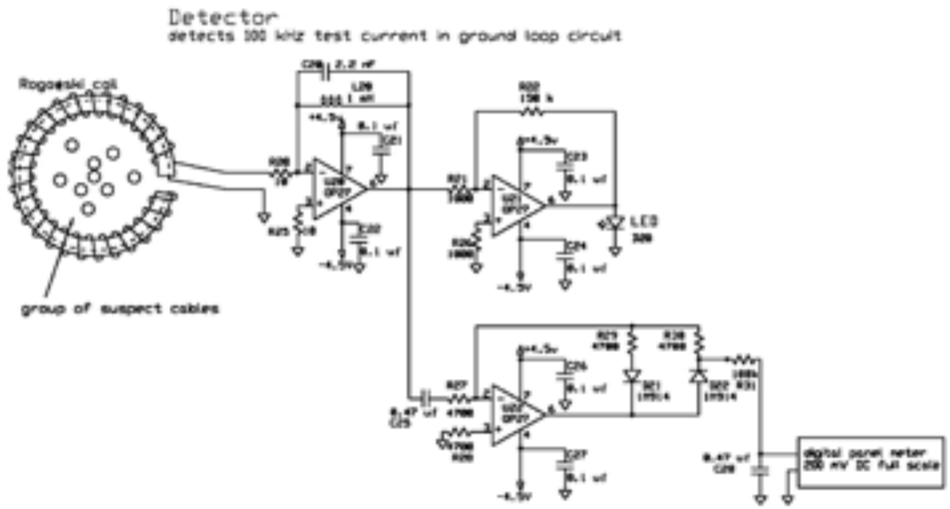
$$\frac{\Delta V}{V_0} < 10^{-6}$$

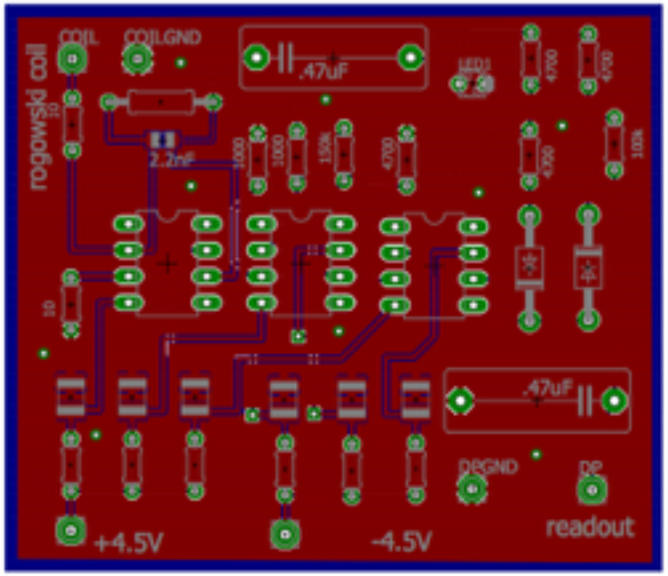
- To avoid it, we should plug out suspect cables or detect the ground loop.

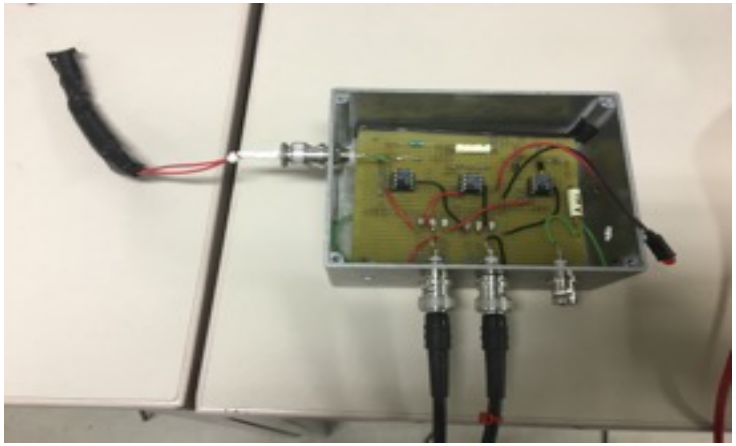
P. M. Bellan, *Simple system for locating ground loops*, Rev. Sci. Instrum. **78**, Art. No. 065104 (2007)



Making prototype







- Under Construction…

Summery

- For measuring g-factor, only Cyclotron and Lamour frequency should be measured. Principally simple but practically difficult.
- By Double penning trap method, the antiproton g-factor measurement is now ongoing even off beam time.
- For further measurement, there are many things to be improved, e.g ground loop detector.

Thanks for your attention!

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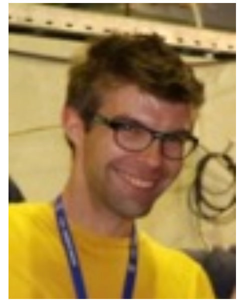

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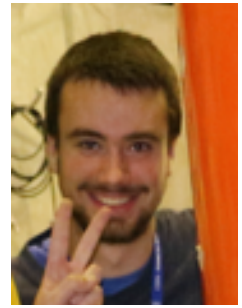

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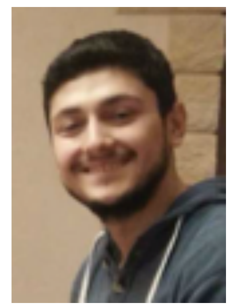

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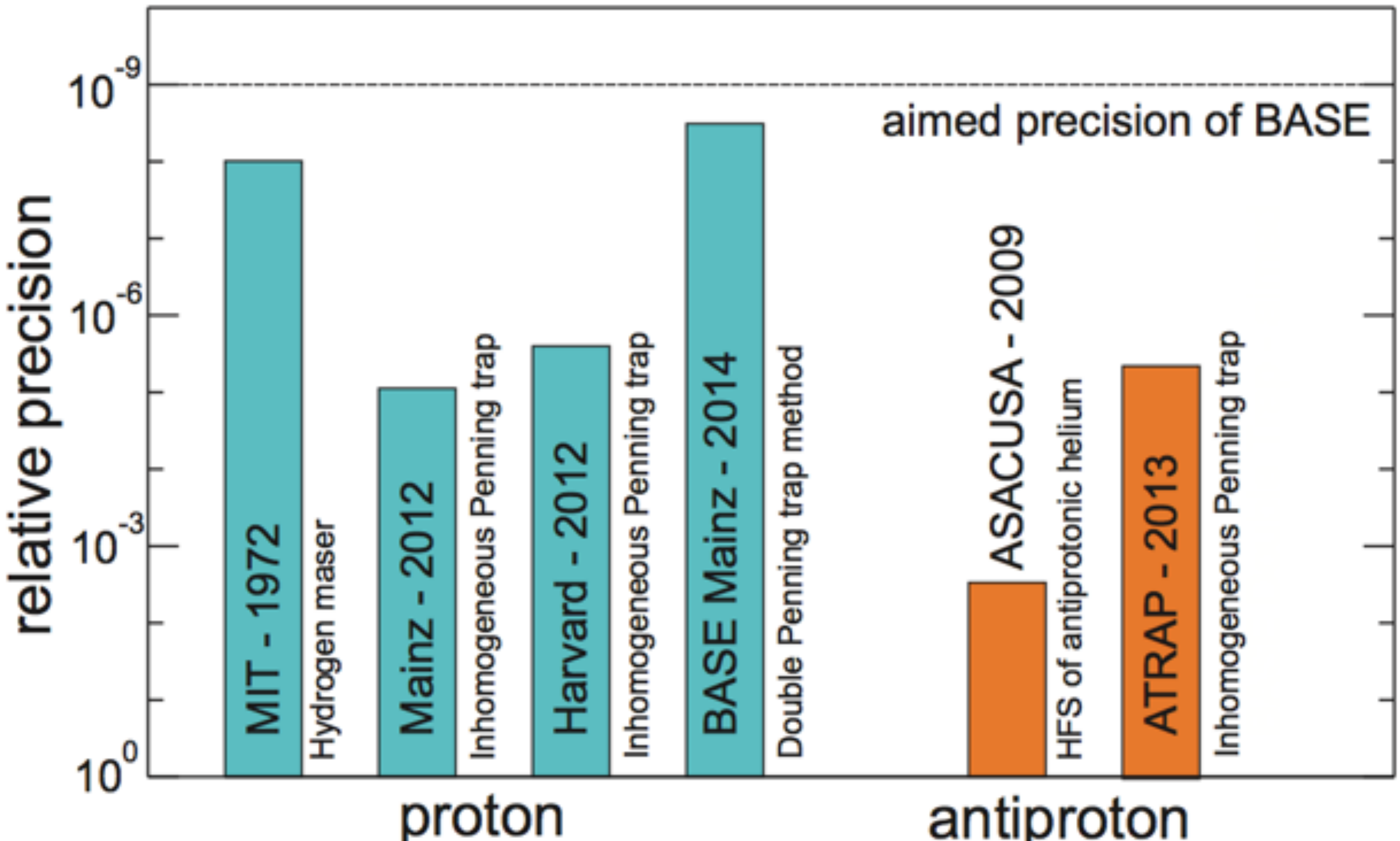
Appendix:results of the proton & antiproton g-factor



Appendix: Concept of CPT violation

- Add CPT violating term to a hamiltonian based on Standard Model and treat as a perturbation theory

  → Absolute energy change ΔE will be derived

$$H' = H_{SM} + \Delta V \quad \Longrightarrow \quad <\psi^* | \Delta V | \psi> = \Delta E$$

System based on SM (H_{SM})

CPT violating term (ΔV)

different C's

$$\mathcal{L}_p = \frac{\lambda}{M} \langle T \rangle \bar{\psi} \Gamma (i\partial)^k \psi$$

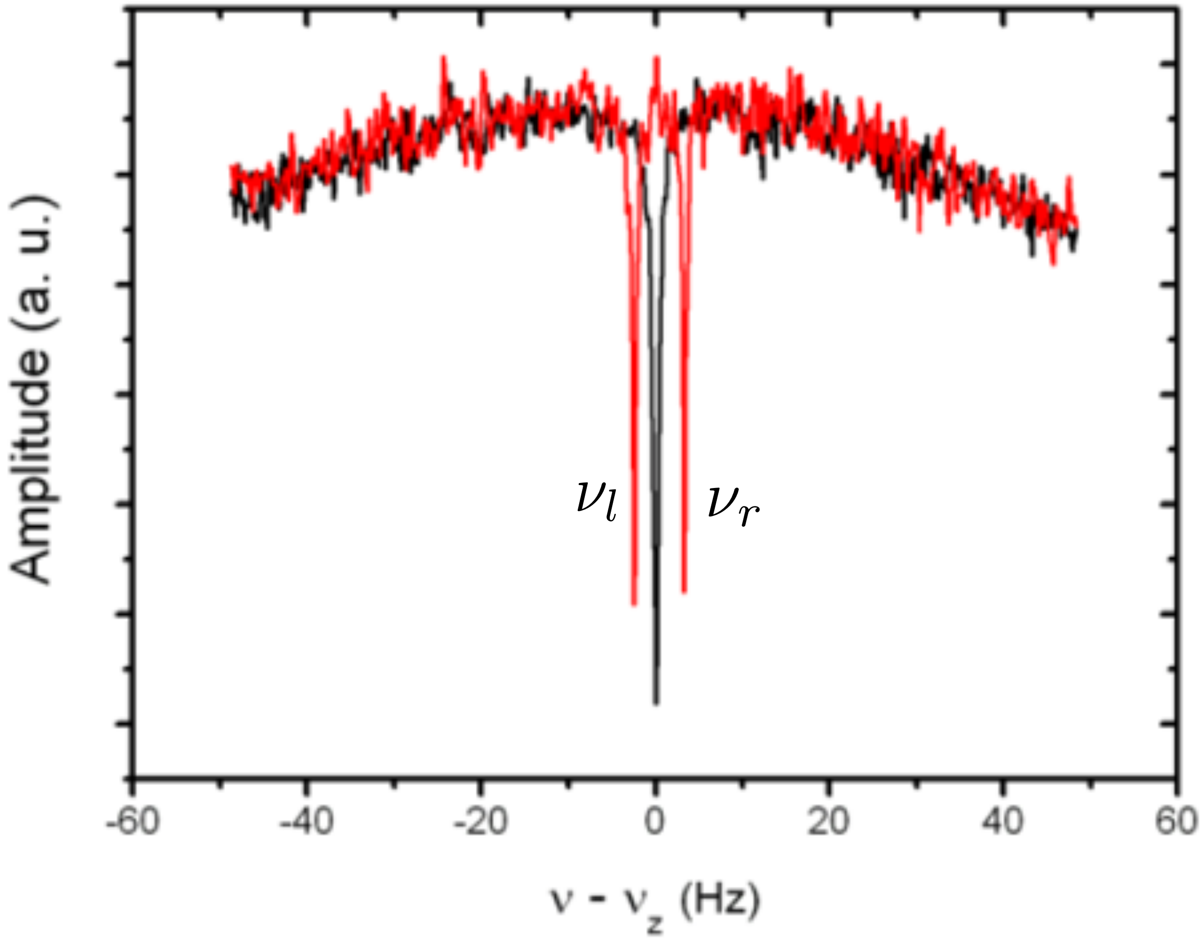
Kostelecky et al.

Absolute energy resolution (normalized to m-scale) is the relevant measure to characterize sensitivity of an experiment to CPT violation. Single particle measurements in Penning traps give high energy resolution

			Relative precision			Energy resolution		
	Relative precision	Energy resolution		Relative precision	Energy resolution		Relative precision	Energy resolution
Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV	Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV	Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV
p-$\bar{p}$ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV	p-$\bar{p}$ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV	p-$\bar{p}$ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV
p-$\bar{p}$ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV	p-$\bar{p}$ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV	p-$\bar{p}$ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV
	Relative precision	Energy resolution		Relative precision	Energy resolution		Relative precision	Energy resolution
Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV	Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV	Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV
p-$\bar{p}$ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV	p-$\bar{p}$ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV	p-$\bar{p}$ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV
p-$\bar{p}$ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV	p-$\bar{p}$ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV	p-$\bar{p}$ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV
	Relative precision	Energy resolution		Relative precision	Energy resolution		Relative precision	Energy resolution
Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV	Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV	Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV
p-$\bar{p}$ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV	p-$\bar{p}$ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV	p-$\bar{p}$ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV
p-$\bar{p}$ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV	p-$\bar{p}$ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV	p-$\bar{p}$ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV

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

Appendix: How to measure ν±



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

$$\nu_- = \frac{{\nu_z}^2}{2\nu_+}$$

$$(\nu_+ << \nu_z << \nu_-)$$