ECCTI – CERN/Switzerland – 2020-01-16

High precision tests of Proton-Antiproton symmetry: Towards a 100 p.p.t. antiproton g-factor measurement

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RIKEN

Stefan Erlewein

on behalf of the
BASE collaboration

Programs for Junior Scientists

MAX-PLANCK-GESELLSCHAFT

TC FS CERN

東京大学
THE UNIVERSITY OF TOKYO

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

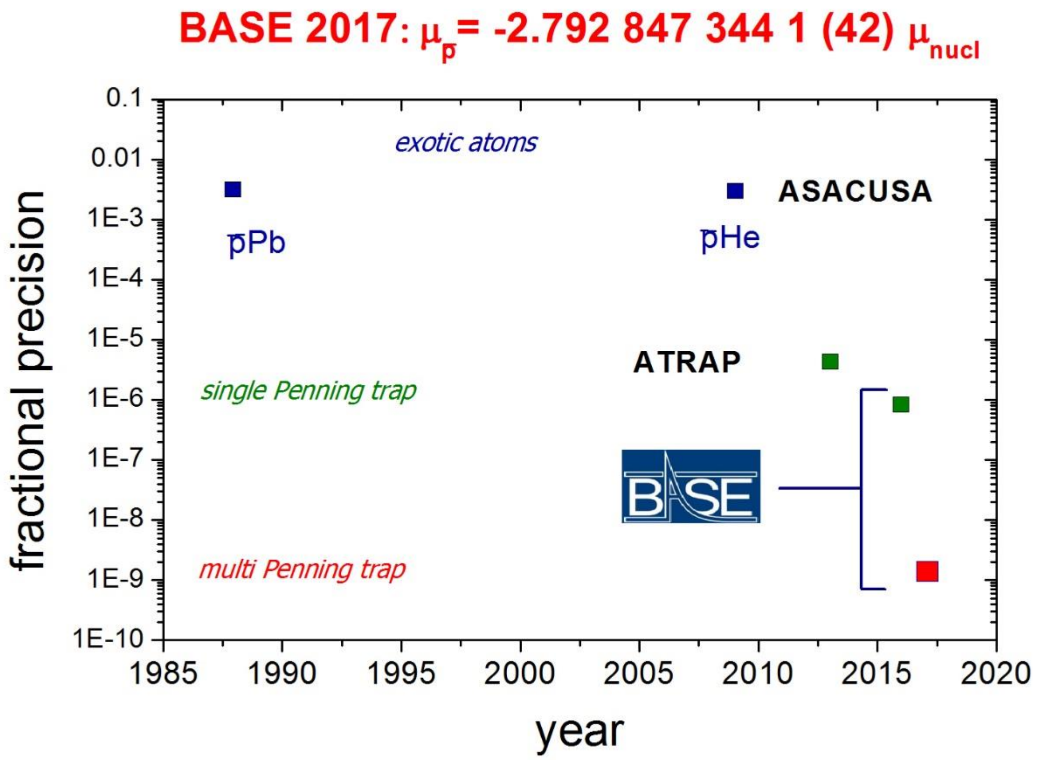
GSI

Leibniz Universität Hannover

PTB

Outline

- Introduction
    - Measurement principle
    - The BASE apparatus
- State of the Art
    - The Triple Trap Method (TTM)
    - Limitations
- Path towards 100 p.p.t. precision
    - Hardware upgrades
    - Dispersive spinflip detection



BASE 2017: $\mu_{\bar{p}} = -2.792\,847\,344\,1\,(42)\,\mu_{nucl}$

Measurement principle

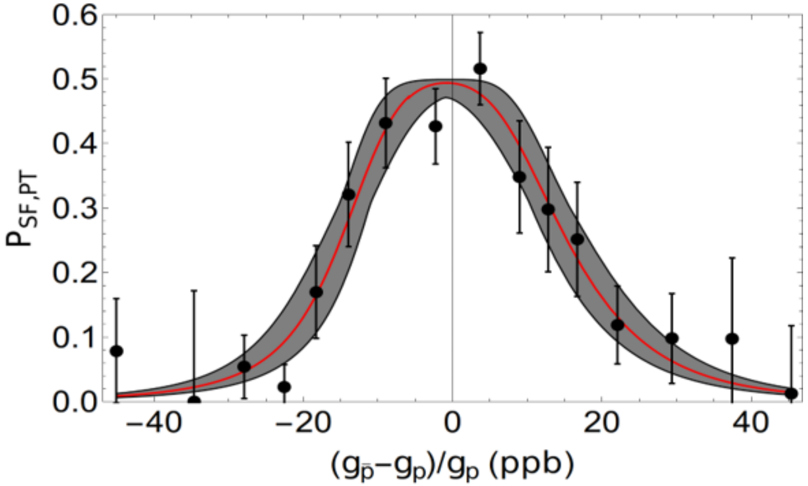
$$\overrightarrow{\mu_S} = g \frac{q}{2m} \vec{S}$$

Measurement principle

$$\Delta E = g \frac{q\hbar}{2m} B_z$$

Measurement principle

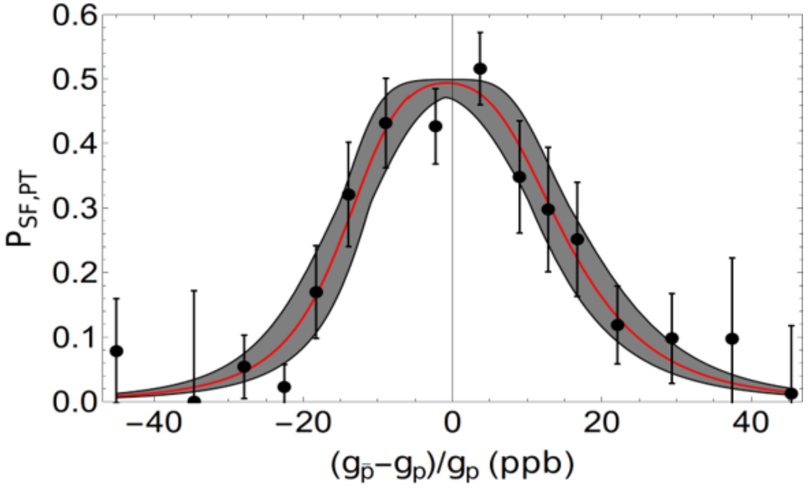
$$\omega_L = g\frac{q}{2m}B_z$$

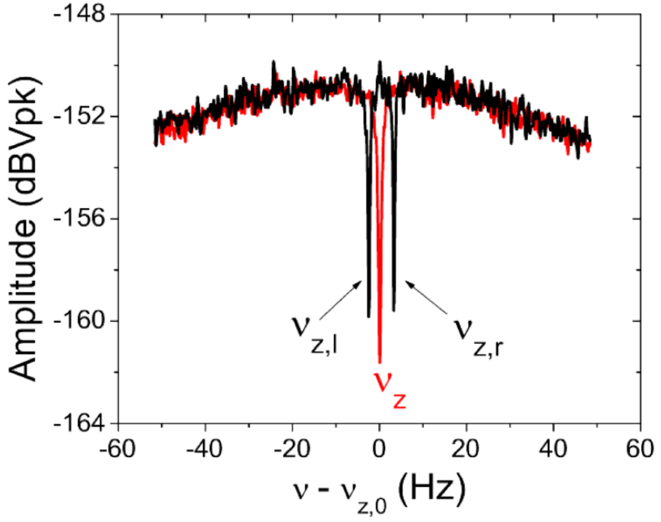


Measurement principle

$$\omega_L = g\frac{q}{2m}B_z$$

$$\omega_C = \frac{q}{m}B_z$$



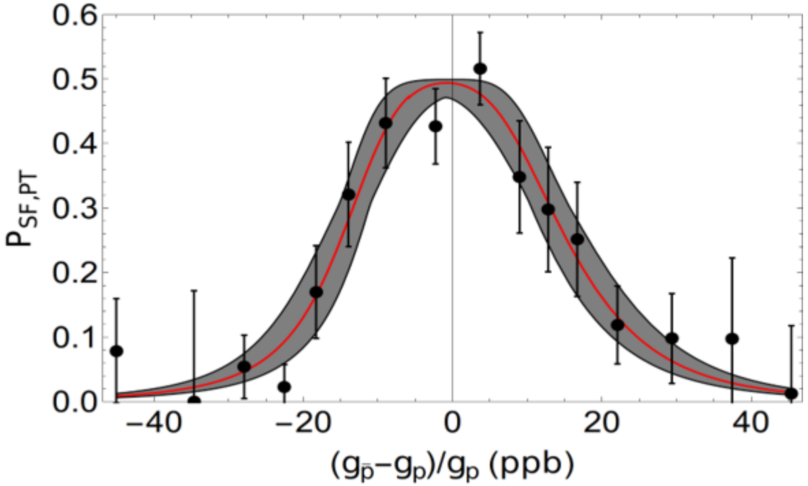


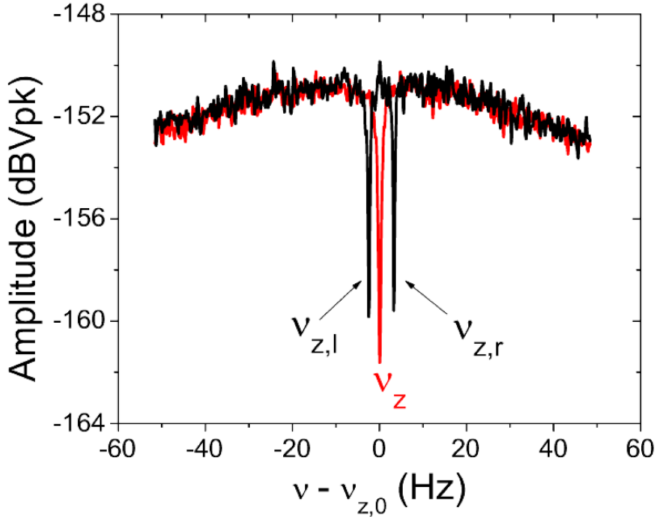
Measurement principle

$$\omega_L = g\frac{q}{2m}B_z$$

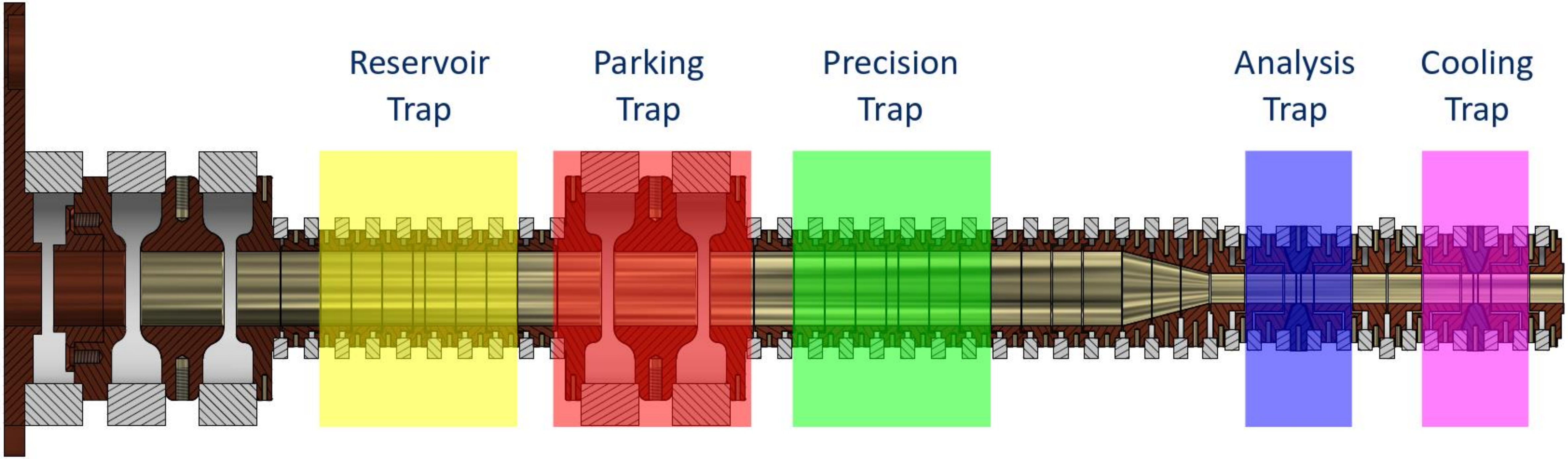
$$\omega_C = \frac{q}{m}B_z$$

$$g = 2\frac{\omega_L}{\omega_C}$$





The BASE apparatus



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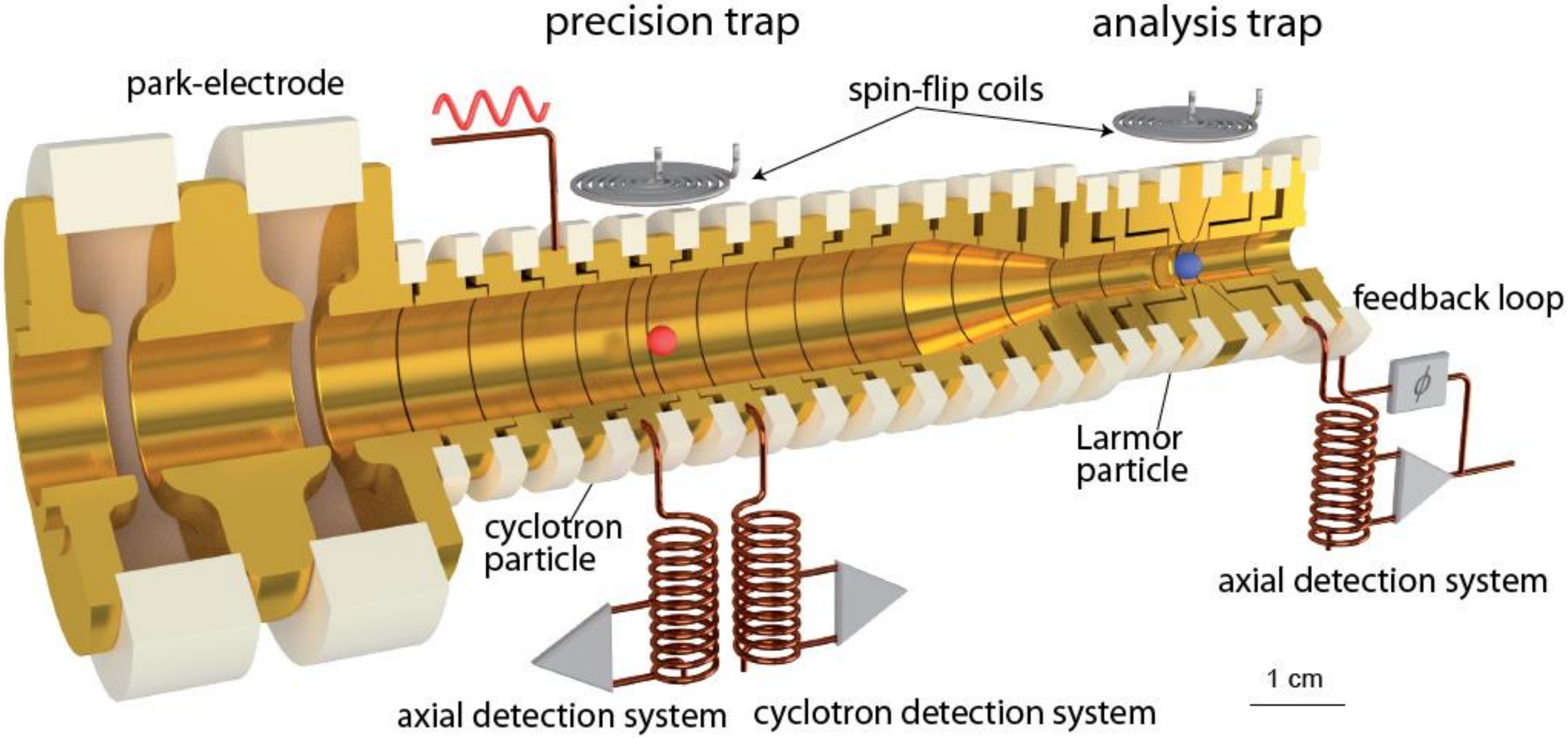
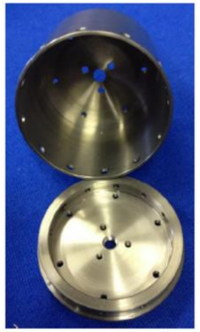
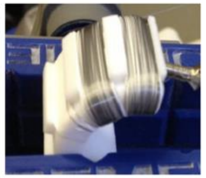


The BASE apparatus

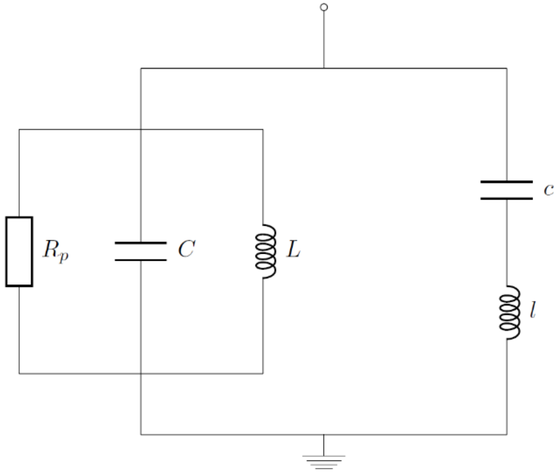
Resonator

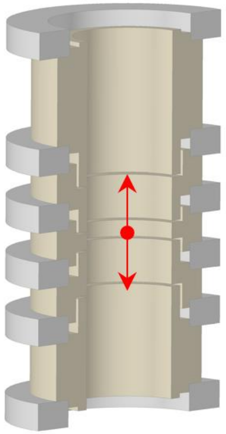


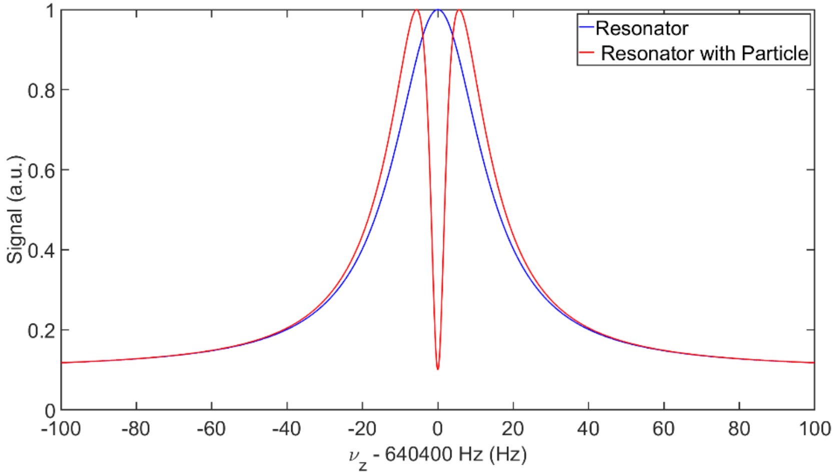
Toroidal coil



N = 950 – 1200
Q = 200k – 500k
L = 2-3 mH
Rp > 1 GΩ







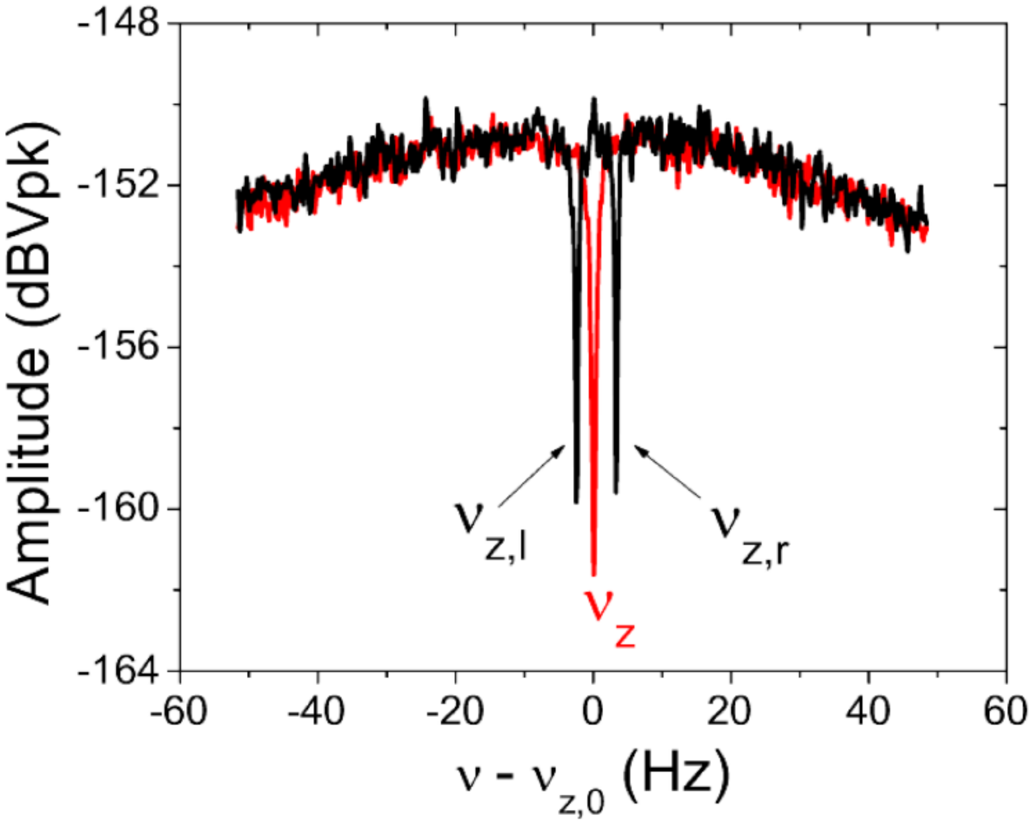
$$\mathrm{Re}(Z) = \frac{R_P}{1+\left[\dfrac{\dfrac{Q}{\omega_0}(\omega^2-\omega_P^2)(\omega_0^2-\omega^2)+\gamma\omega}{\omega(\omega^2-\omega_P^2)}\right]}$$

The Triple Trap Method

1. Determination of ω_C

Measure axial frequency and mod. cyclotron sidebands

Use invariance theorem to determine free cyclotron frequency



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

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

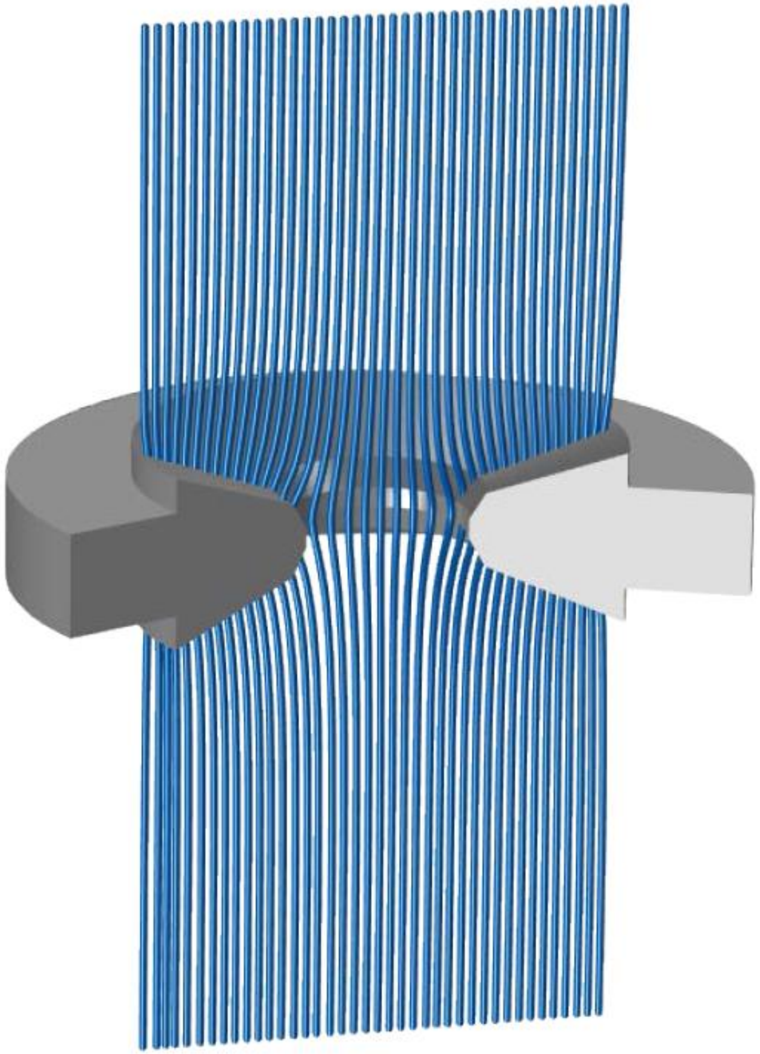
The Triple Trap Method

2. Determination of ω_L

Couple spinstate to axial frequency by superimposing a magnetic bottle ($B_2 \approx 300\,000$ T m^{-2})

$$\Delta\omega_z = \frac{\hbar\,\omega_+}{m\,\omega_z}\frac{B_2}{B_0}\left(\left(n_+ + \frac{1}{2}\right) + \frac{\omega_-}{\omega_+}\left(n_- + \frac{1}{2}\right) + m_s\frac{g}{2}\right)$$

$$\begin{aligned}\Delta\nu_+ &\approx 62\,mHz\\ \Delta\nu_- &\approx 0.04\,mHz\\ \Delta\nu_S &\approx 172\,mHz\end{aligned}$$



The Triple Trap Method

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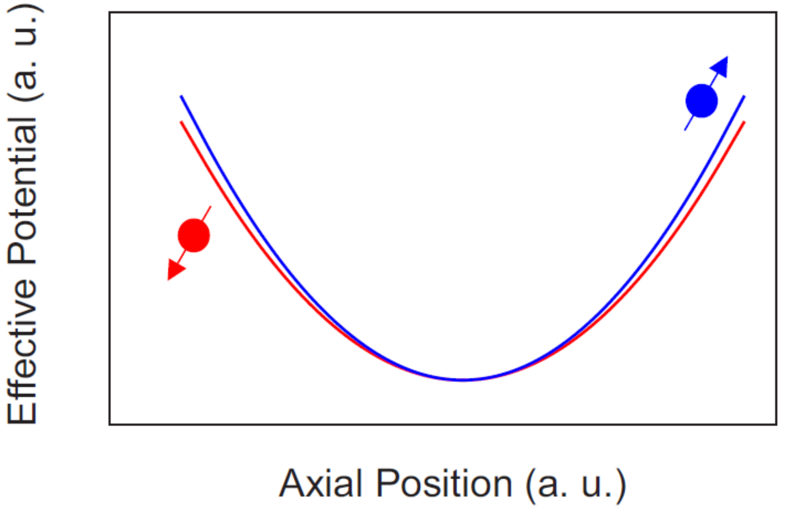

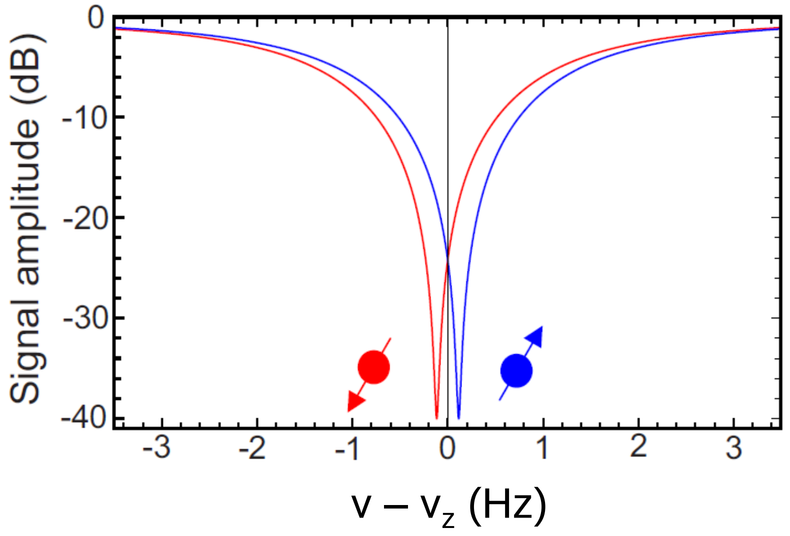

SMORRA, Christian, et al. Base–the baryon antibaryon symmetry experiment. *The European Physical Journal Special Topics*, 2015, 224. Jg., Nr. 16, S. 3055-3108.

The Triple Trap Method

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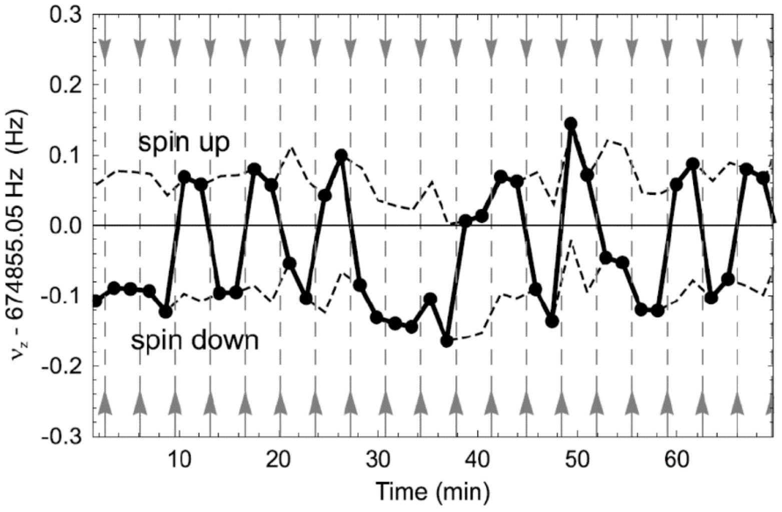
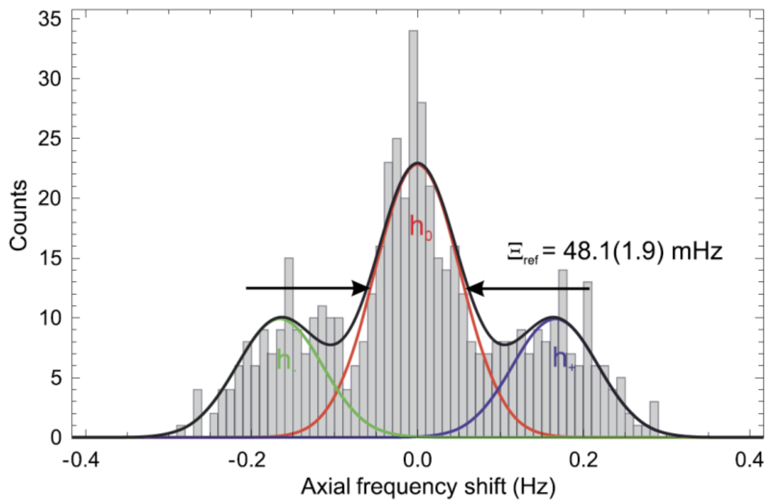
Probe spinflip probability as function of drive frequency ω_{RF}





SMORRA, Christian, et al. Observation of individual spin quantum transitions of a single antiproton. *Physics Letters B*, 2017, 769. Jg., S. 1-6.

The Triple Trap Method

2. Determination of ω_L

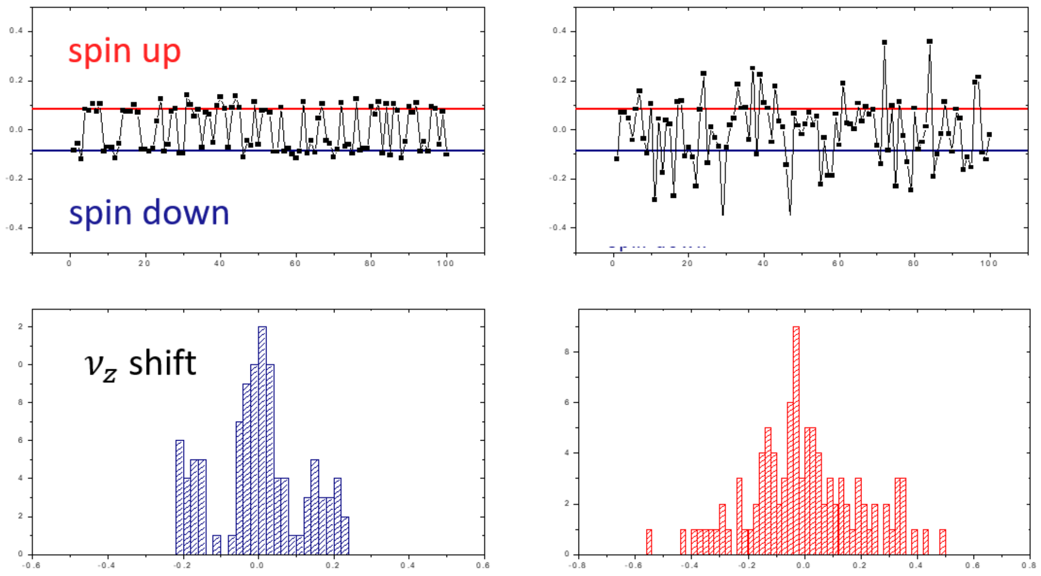
Cyclotron heating rate increases with cyclotron temperature

$$\zeta_+ = n_+ \frac{q^2}{2\hbar m\,\omega_+} S_E(\omega_+)$$

Measurement requires cold particle
→ Cooling

cold particle (50mK)

hot particle (1K)



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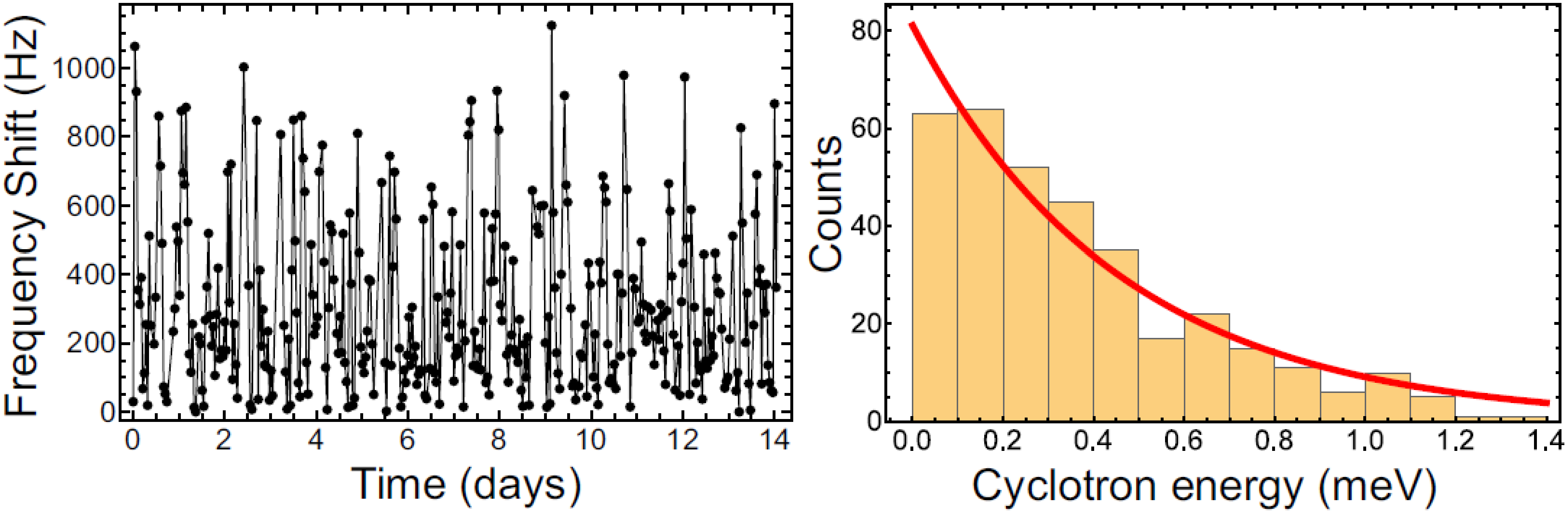

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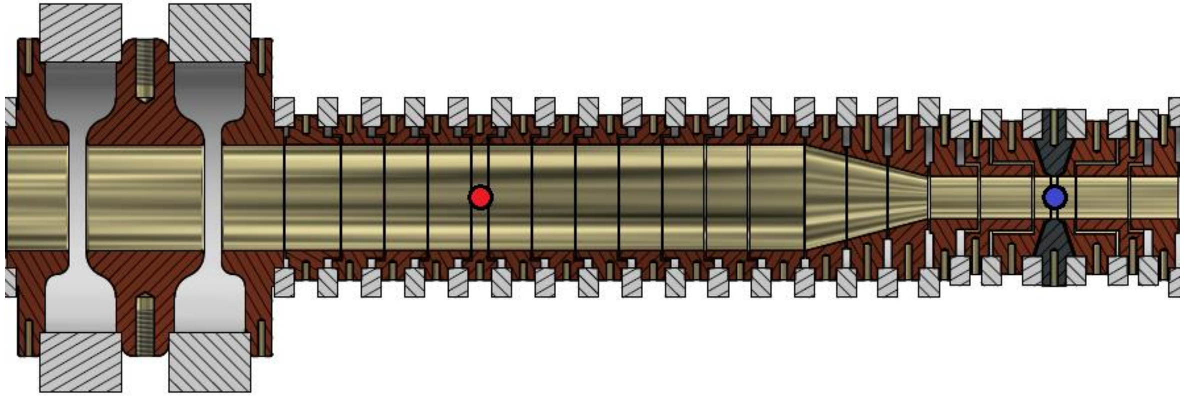

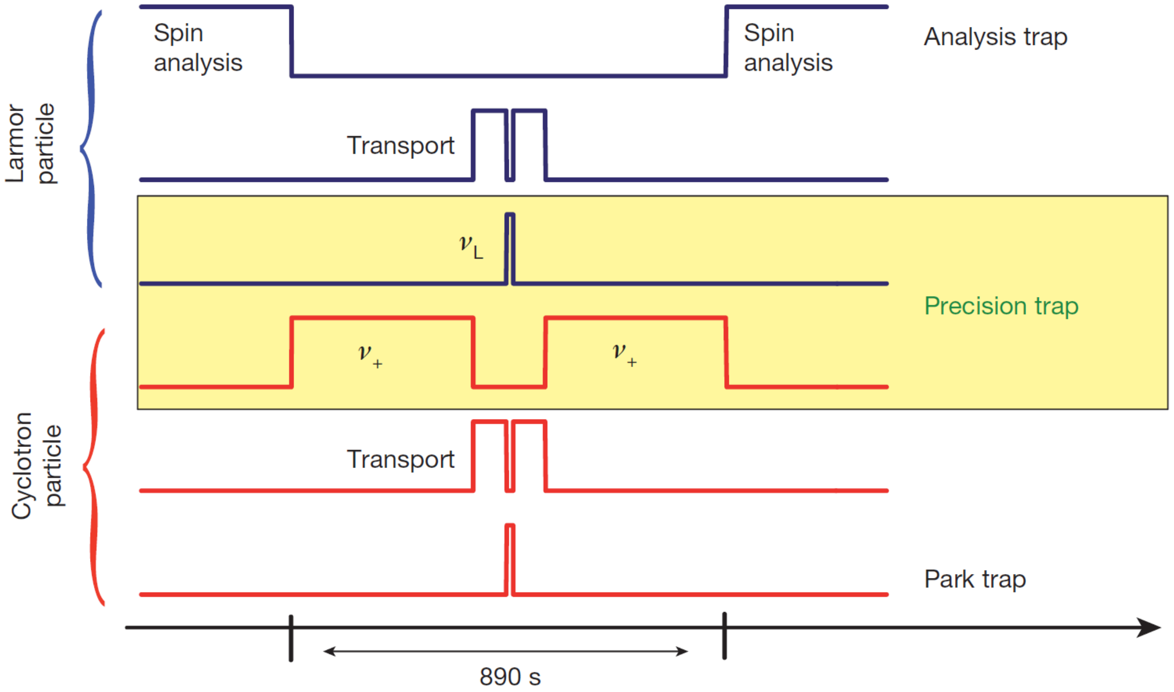

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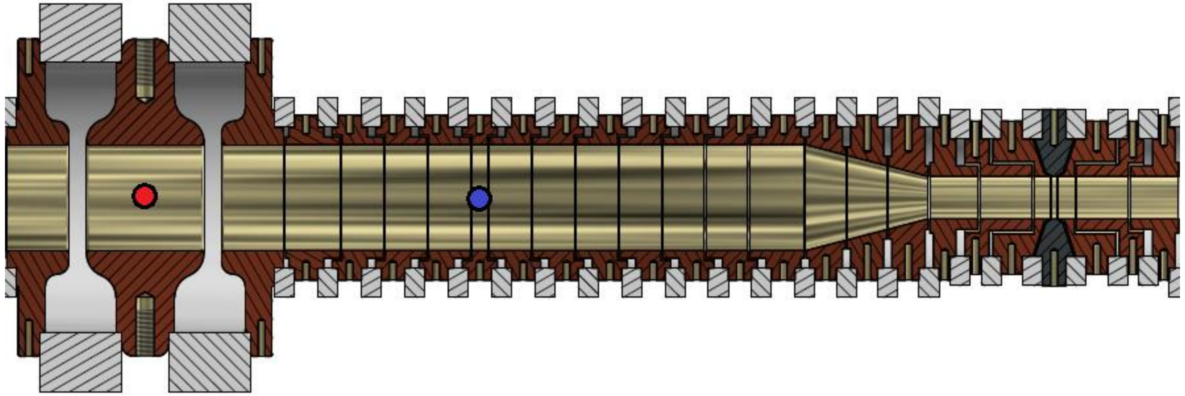

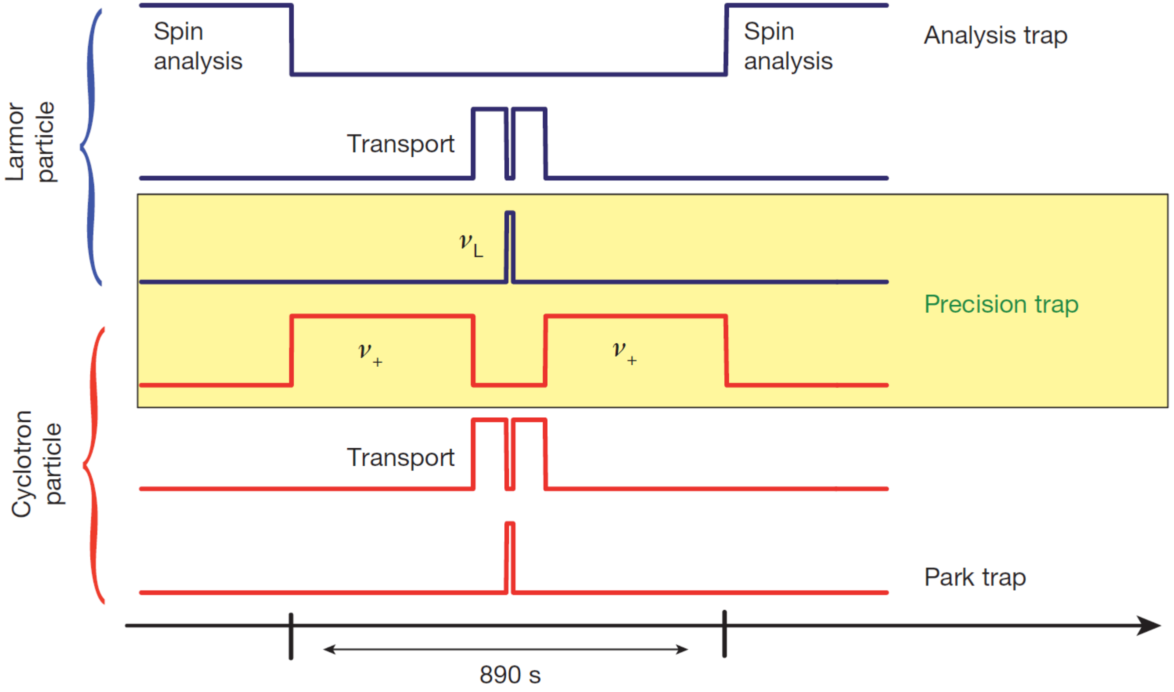

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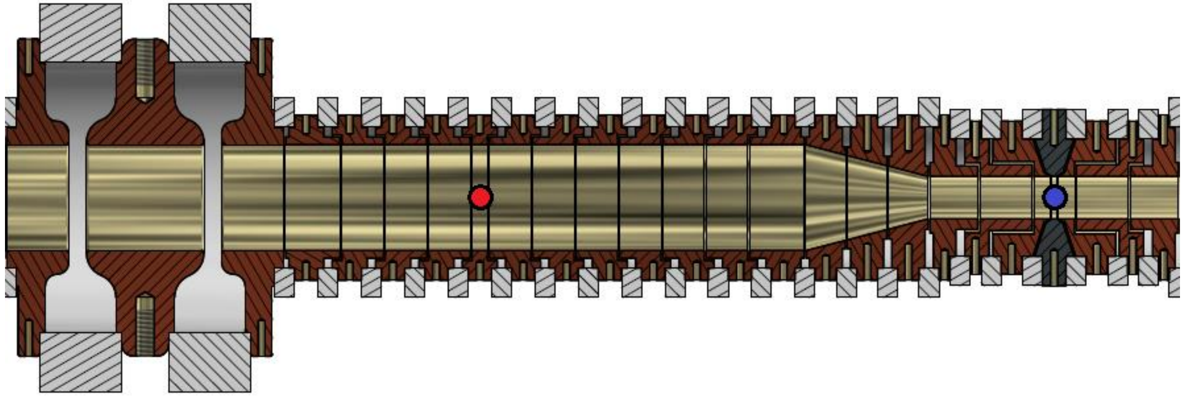

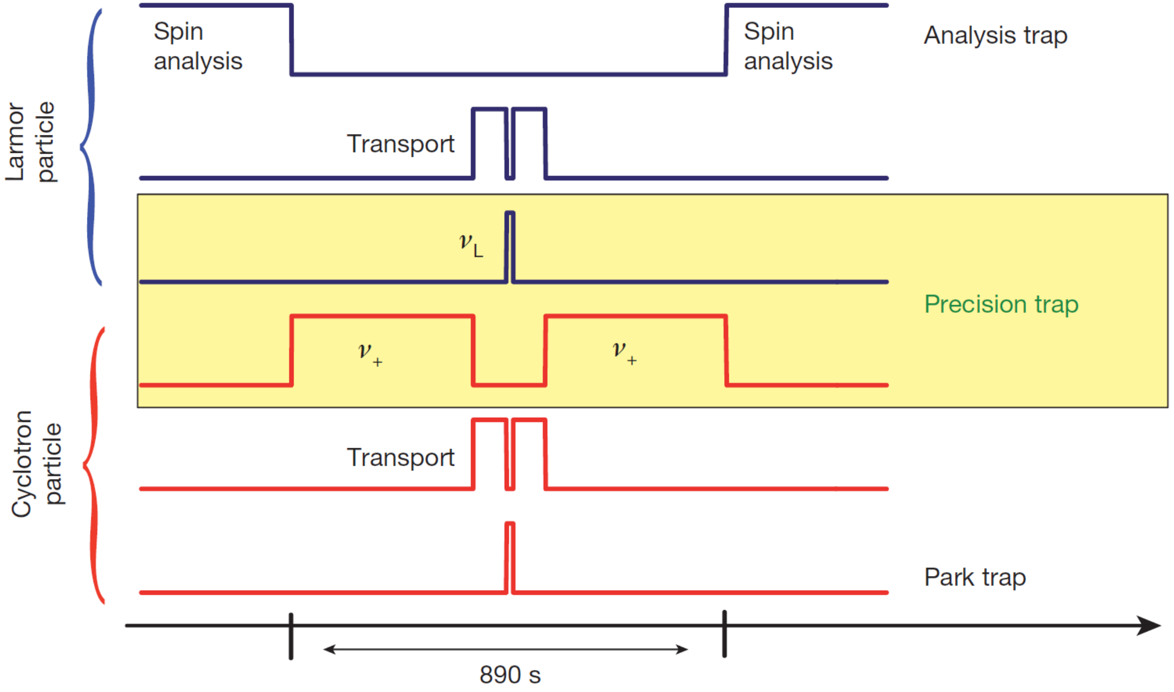

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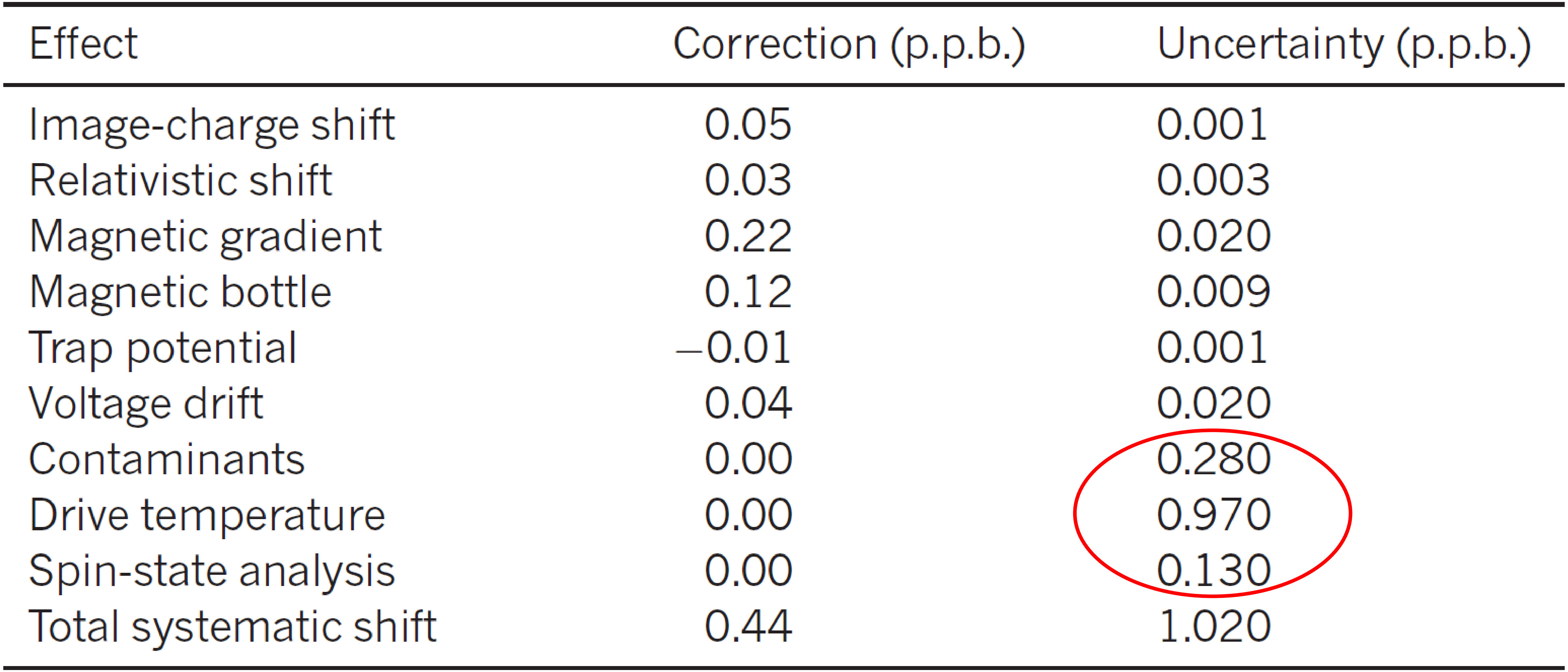
Limitations



Effect	Correction (p.p.b.)	Uncertainty (p.p.b.)
Image-charge shift	0.05	0.001
Relativistic shift	0.03	0.003
Magnetic gradient	0.22	0.020
Magnetic bottle	0.12	0.009
Trap potential	–0.01	0.001
Voltage drift	0.04	0.020
Contaminants	0.00	0.280
Drive temperature	0.00	0.970
Spin-state analysis	0.00	0.130
Total systematic shift	0.44	1.020

Limitations

1. Contaminants

   → Compare charge-to-mass ratio for both particles

   → Limited by statistics of comparison measurement

2. Drive temperature

   → Larmor drive could increase noise floor of axial detector

   → ω_L and ω_C are probed at different magnetic fields

3. Spin-state analysis

   → Spinflip detection is stochastic process with 80% - 90% fidelity

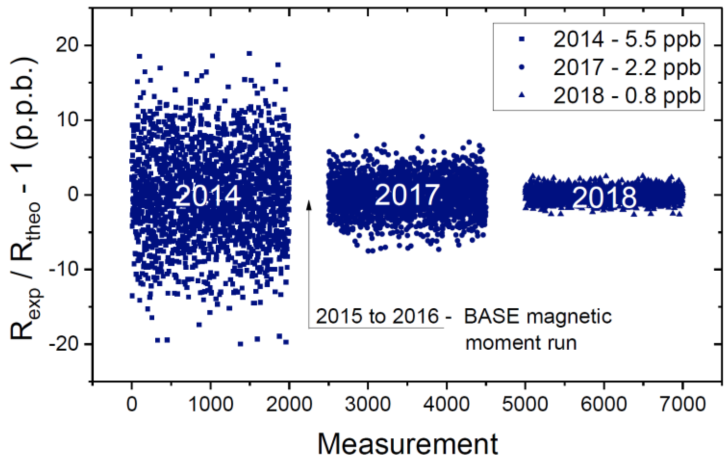
   → Uncertainty in cyclotron fluctuations

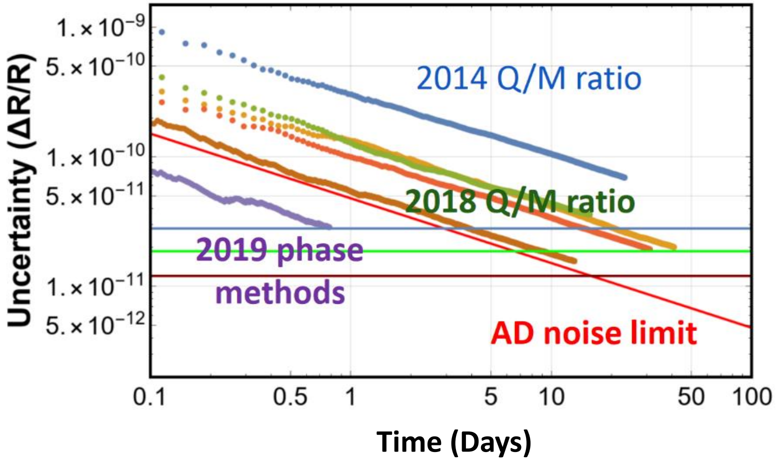
Upgrades

- Improved Magnetic field stability

- Implementation of phase-sensitive methods

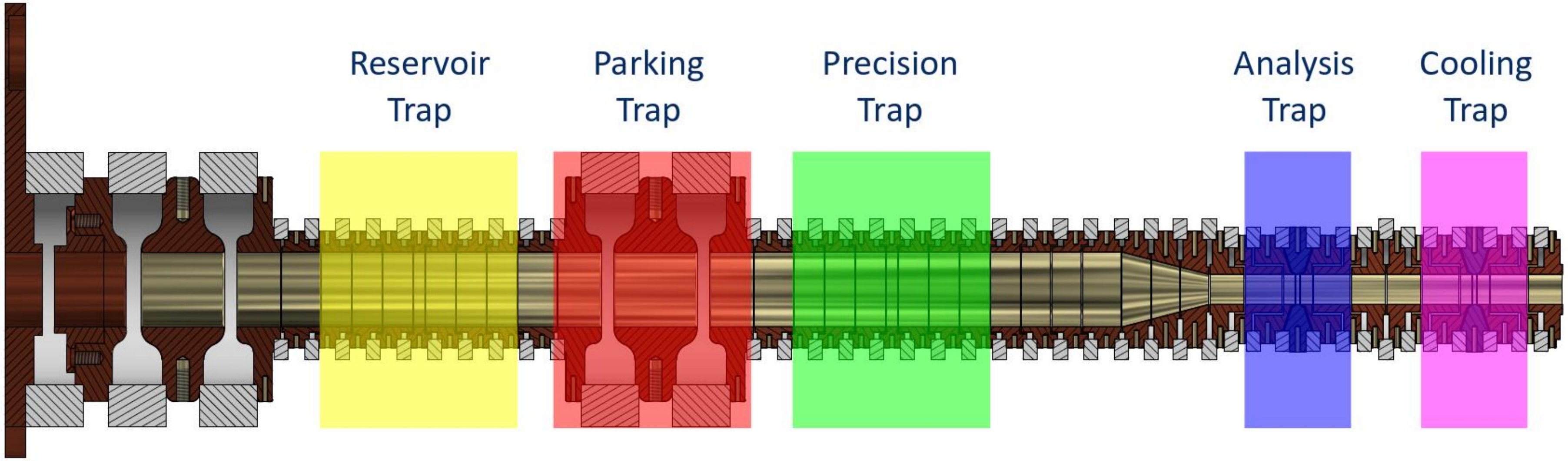
→ Improved uncertainty for contaminants exclusion



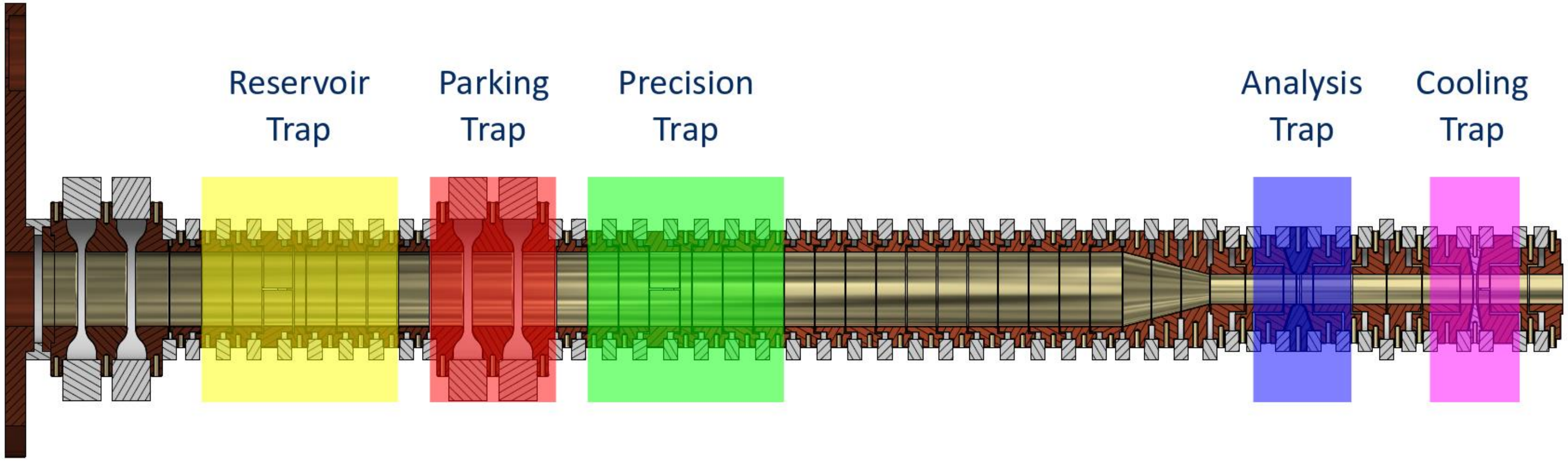


Upgrades

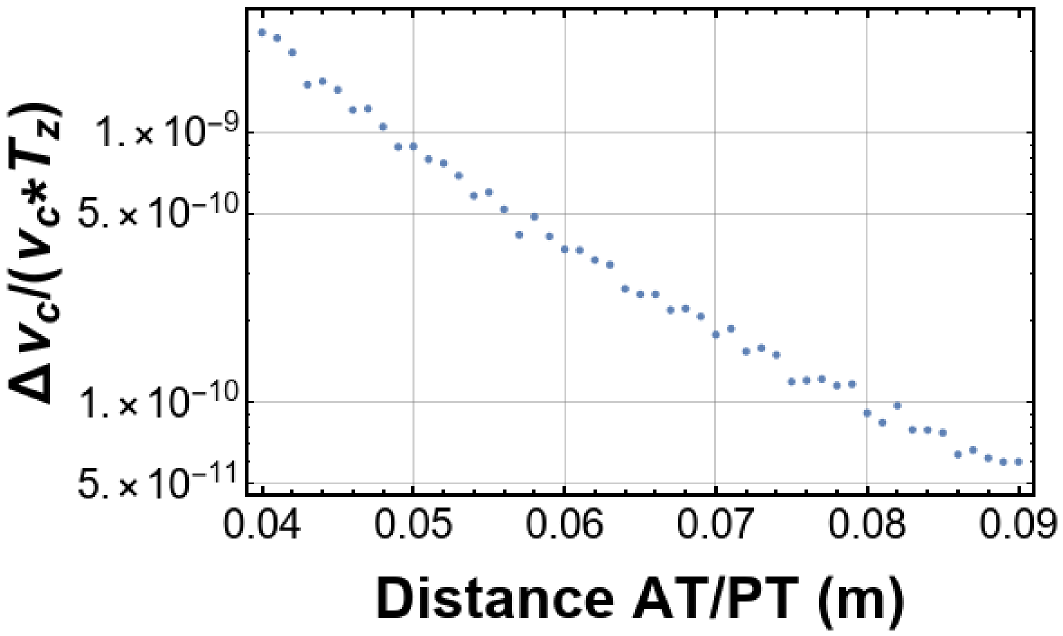
2017:

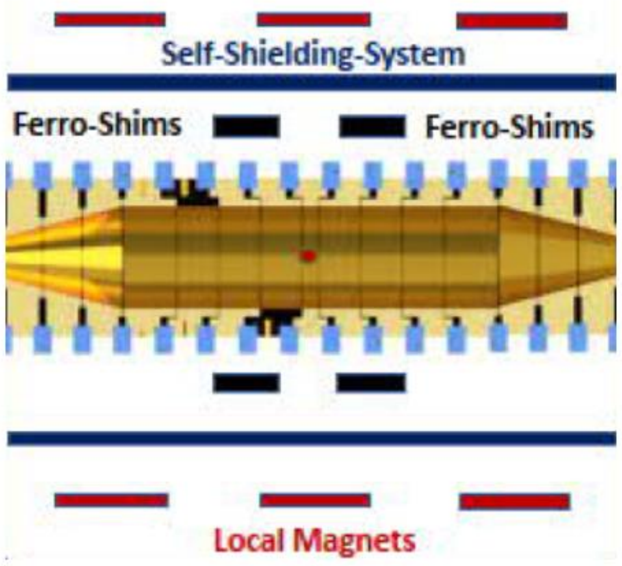


2020:



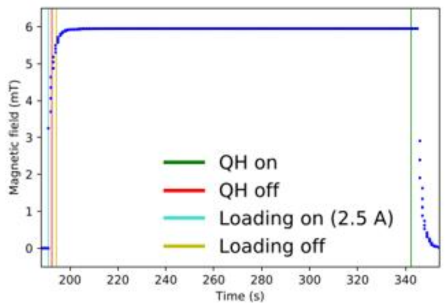
Upgrades





quench-free

charge range 2A

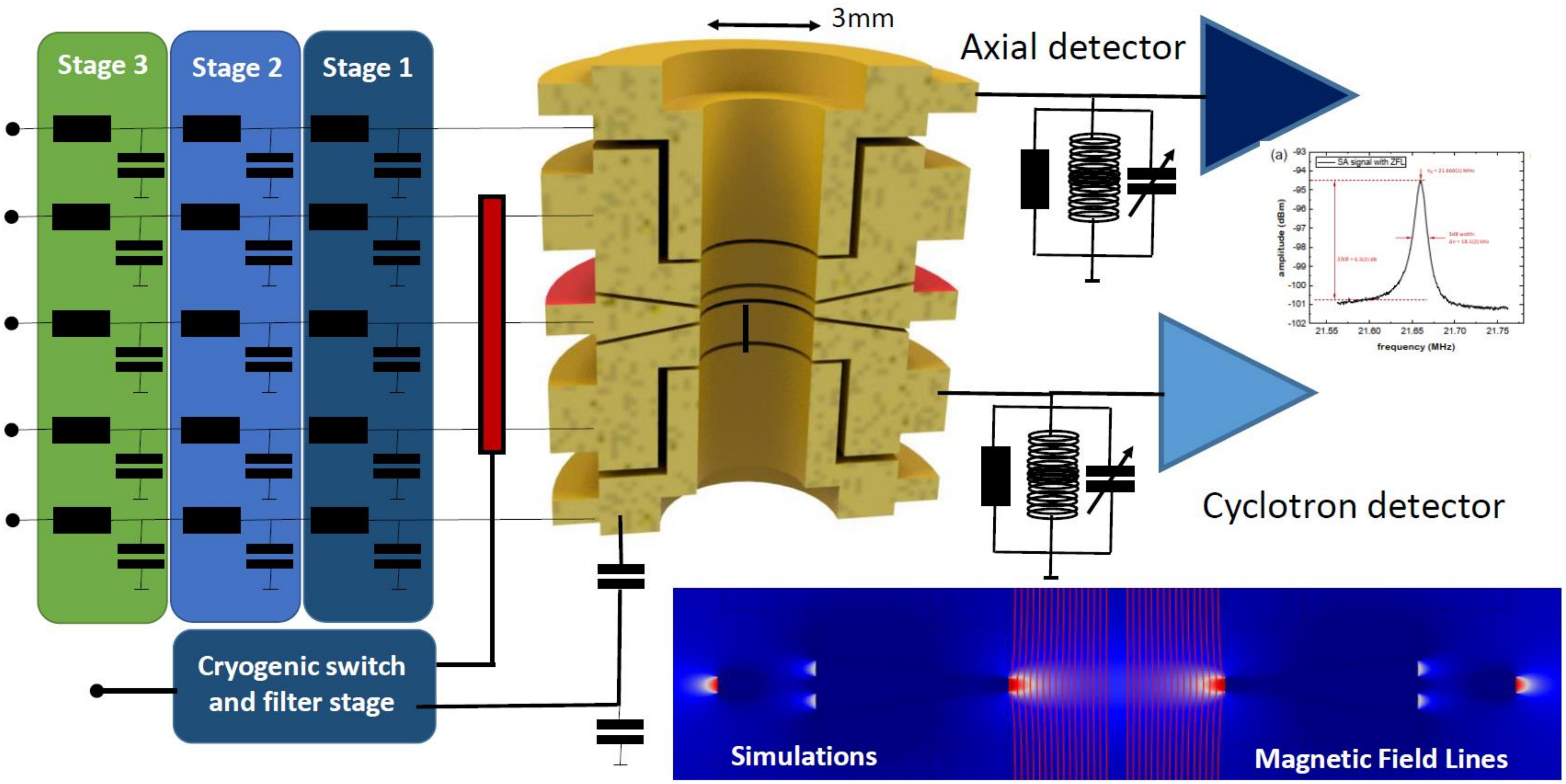


Tuning range: $B_1 = 80\ mT/m$

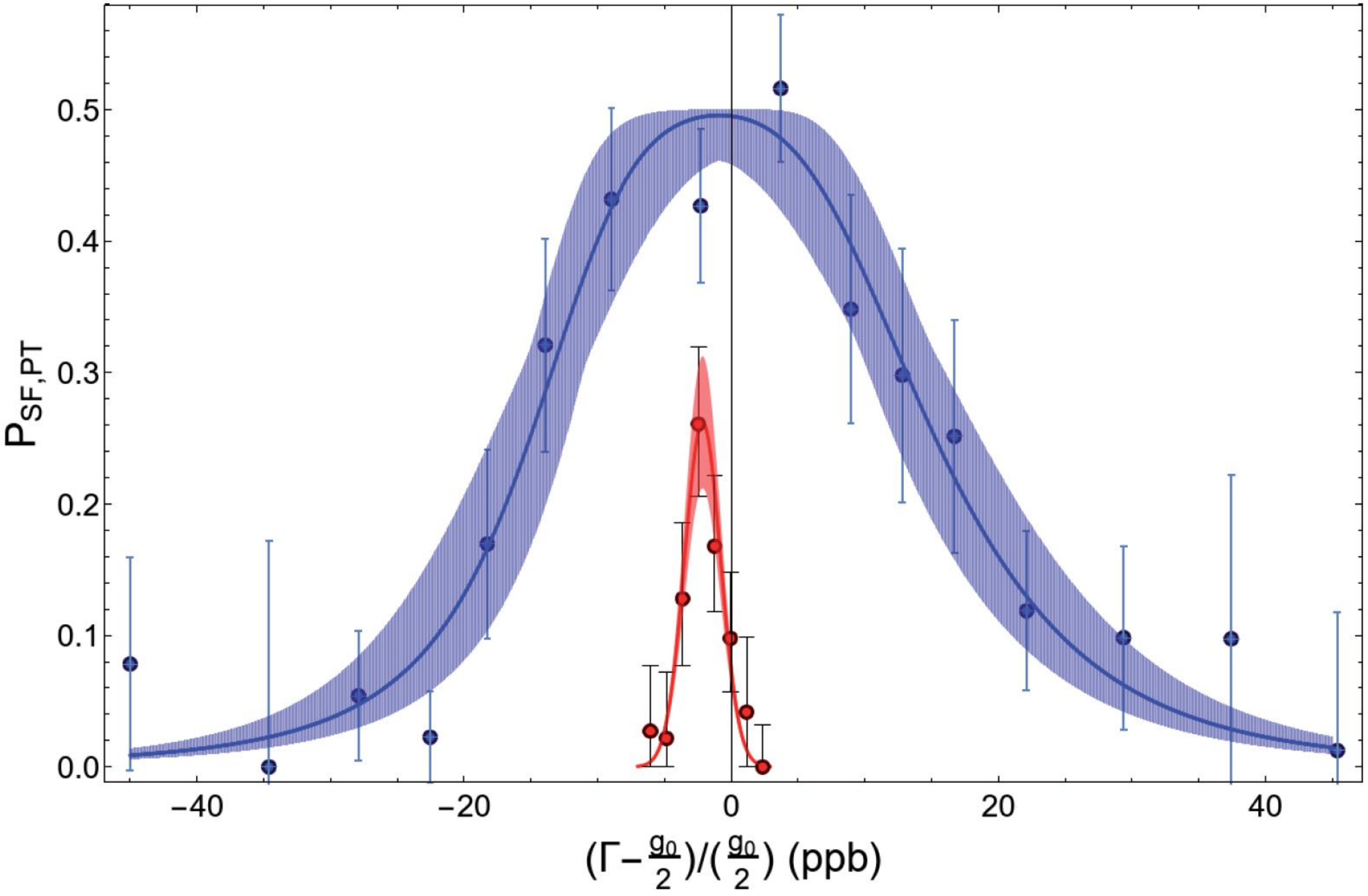
$B_2 = 2\ T/m^2$

Upgrades

Cooling Trap Layout



Upgrades



SMORRA, C., et al. A parts-per-billion measurement of the antiproton magnetic moment. *Nature*, 2017, 550. Jg., Nr. 7676, S. 371.
SCHNEIDER, Georg, et al. Double-trap measurement of the proton magnetic moment at 0.3 parts per billion precision. *Science*, 2017, 358. Jg., Nr. 6366, S. 1081-1084.

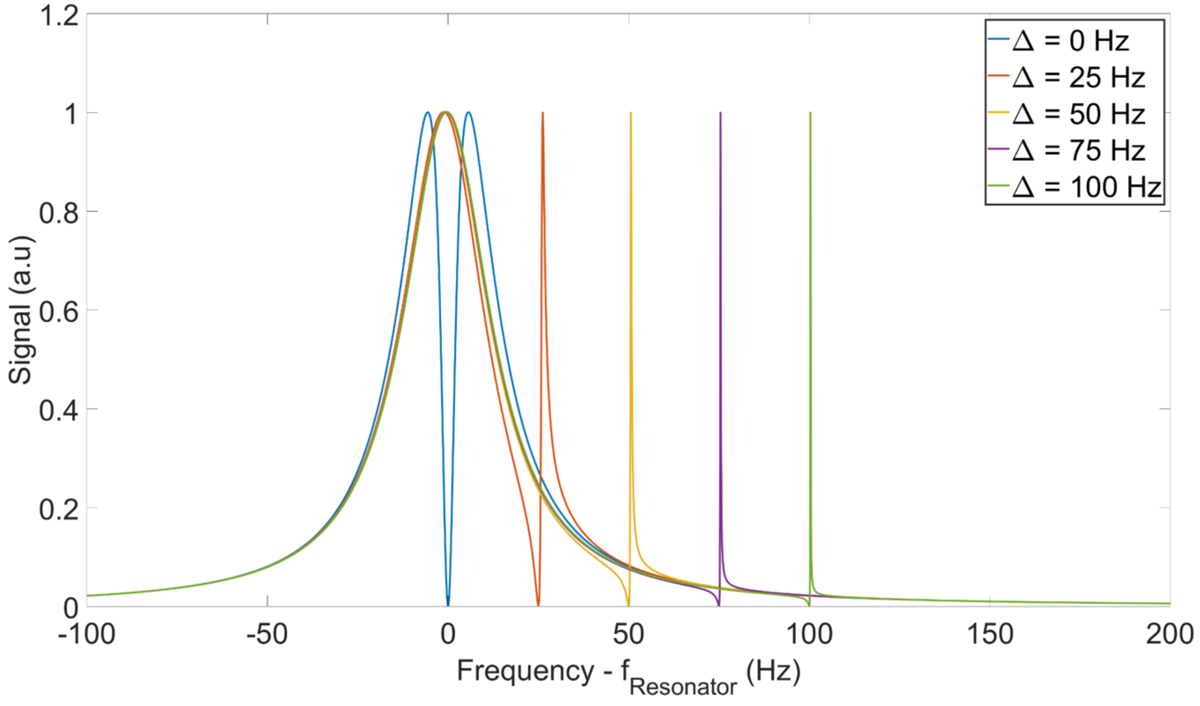
Dispersive Spinflip Detection

- Detune resonator from particle

- Fit narrow peak feature

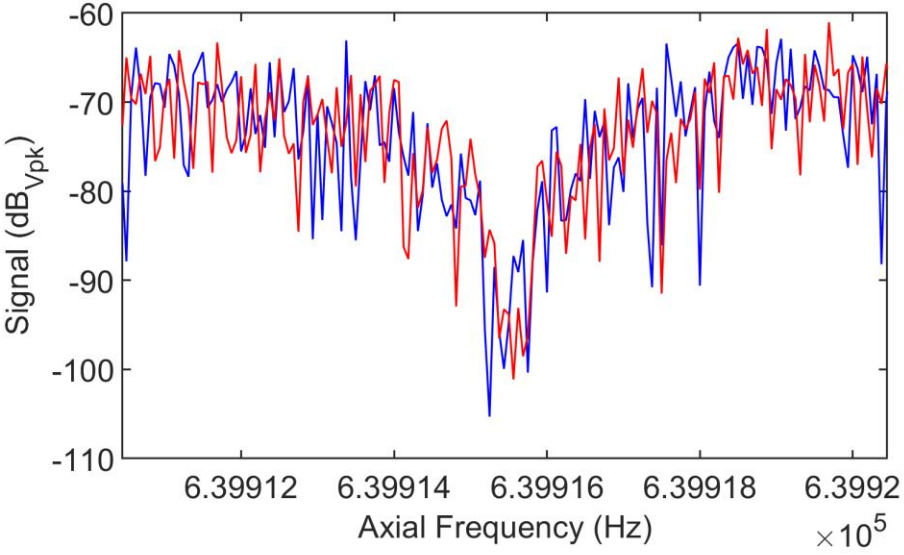
- Unknown systematatics

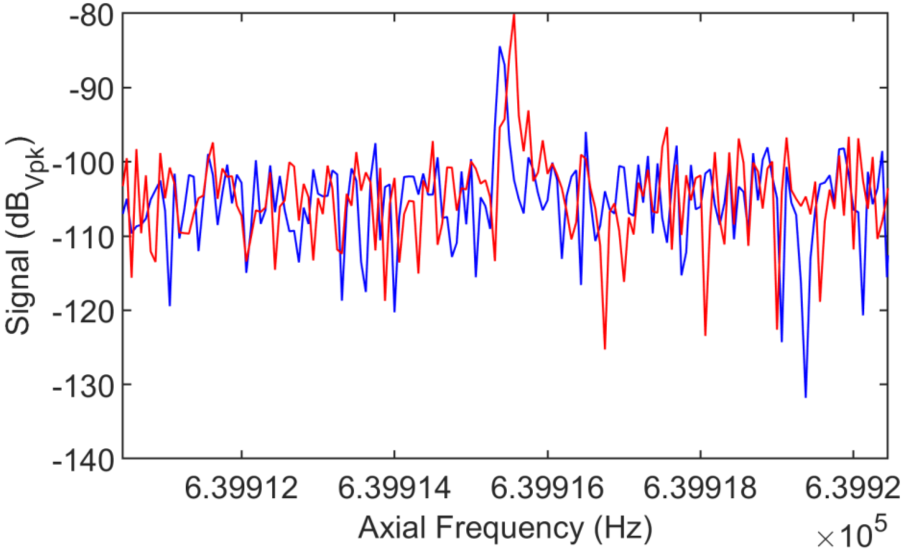
→ Useful for relative frequency measurements



$$\mathrm{Re}(Z) = \frac{R_P}{1 + \left[\frac{\frac{Q}{\omega_0}(\omega^2 - \omega_P^2)(\omega_0^2 - \omega^2) + \gamma\omega}{\omega(\omega^2 - \omega_P^2)}\right]}$$

Dispersive Spinflip Detection





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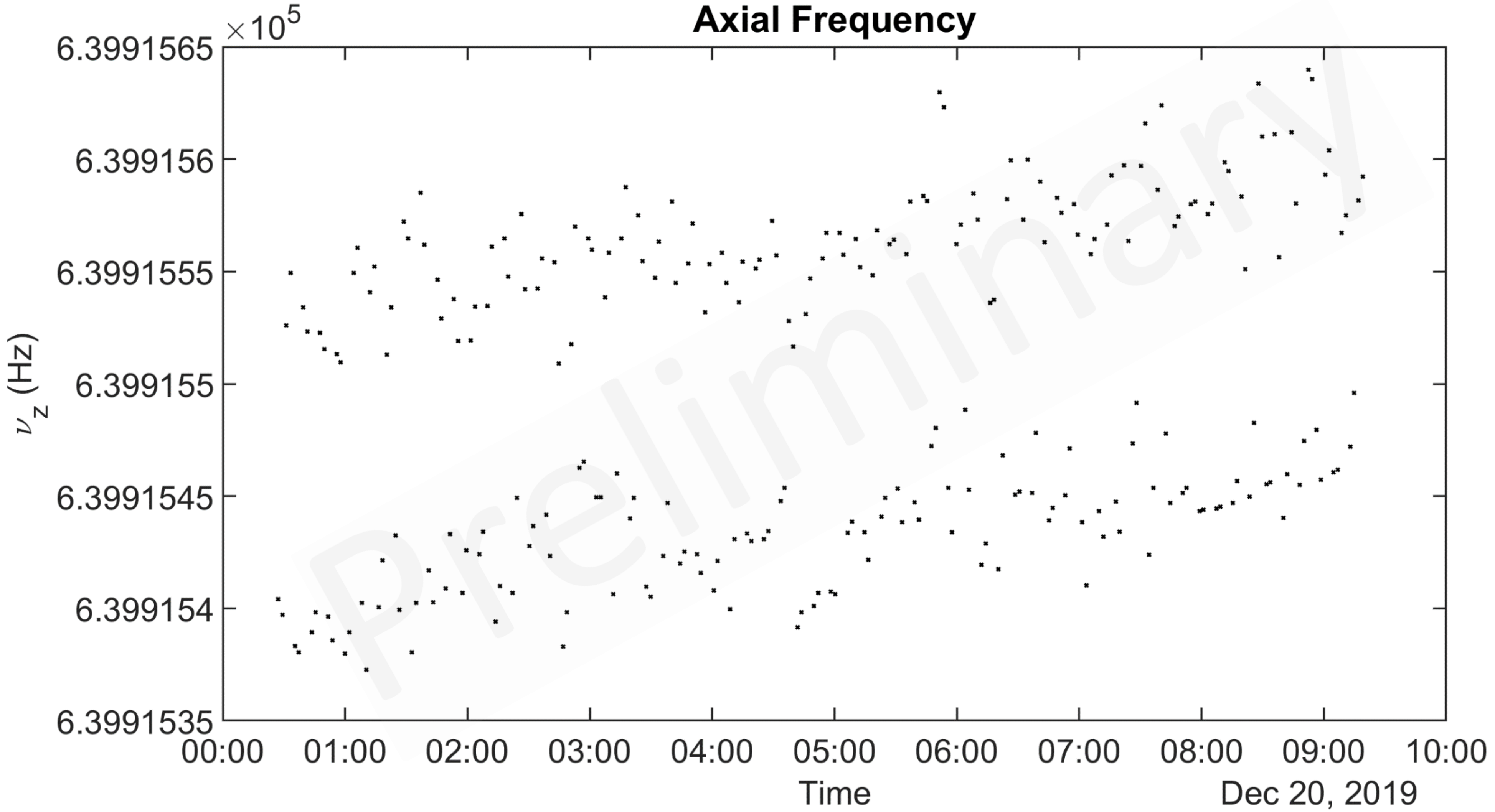

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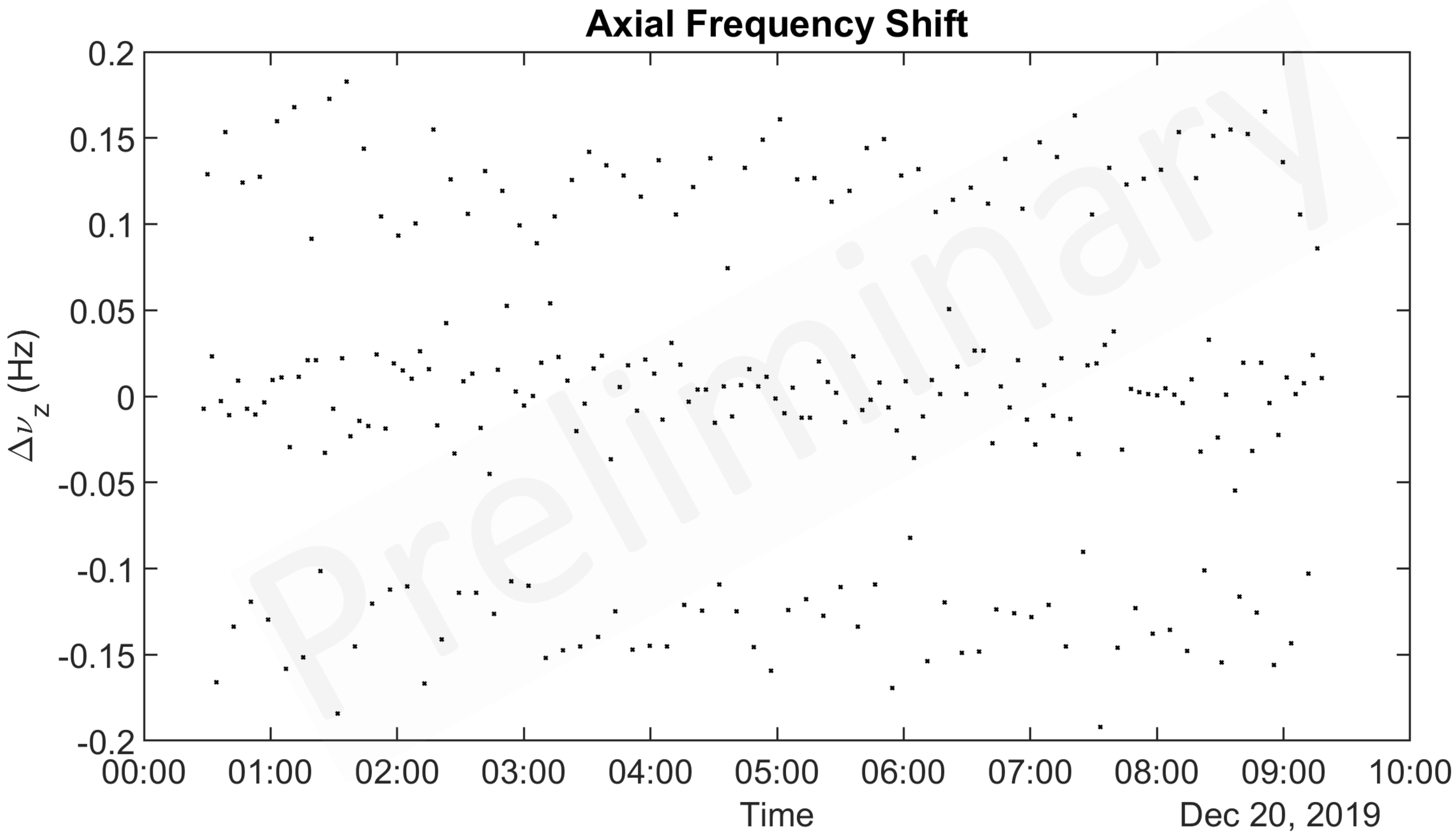
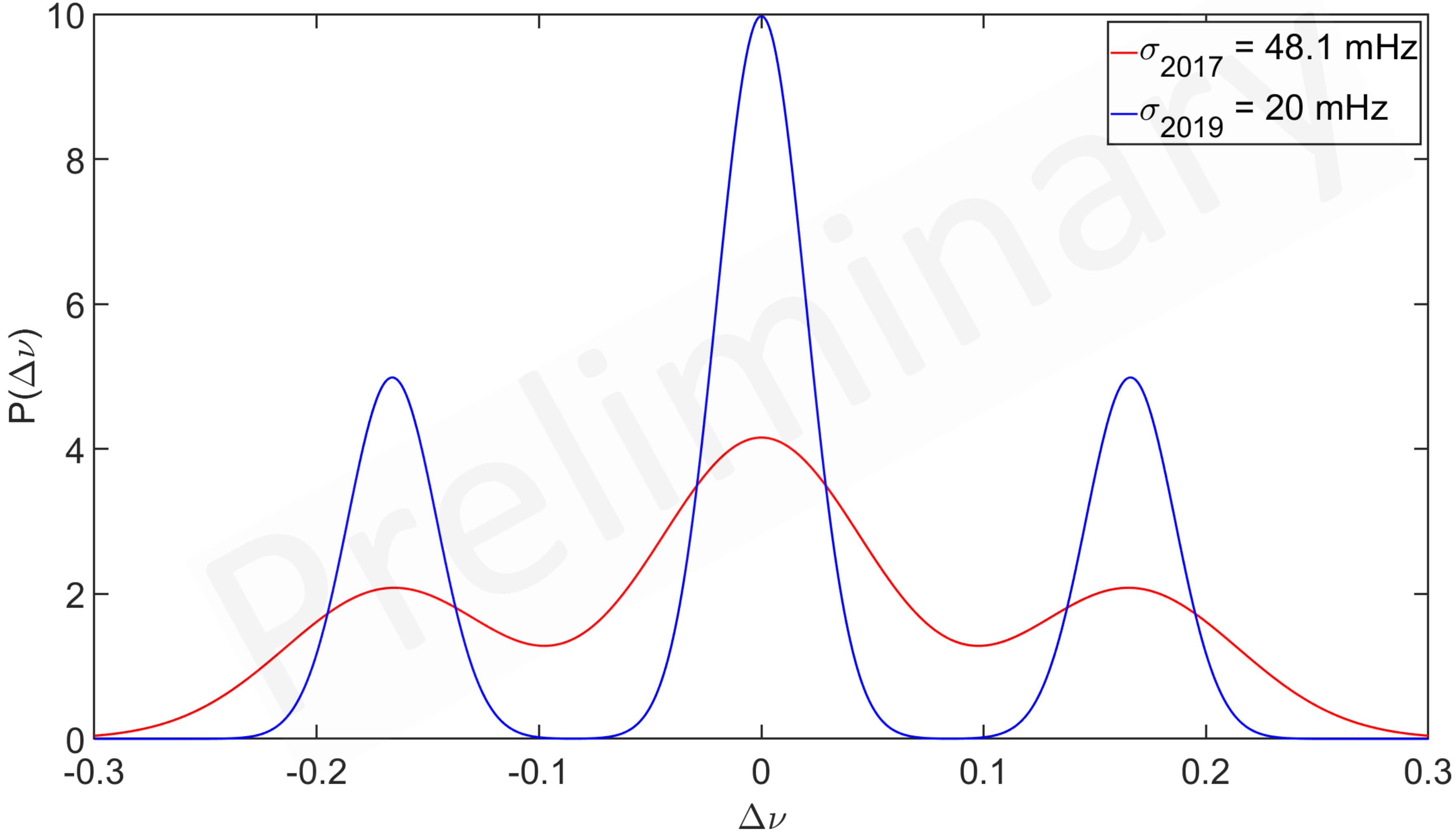


Preliminary

Dispersive Spinflip Detection



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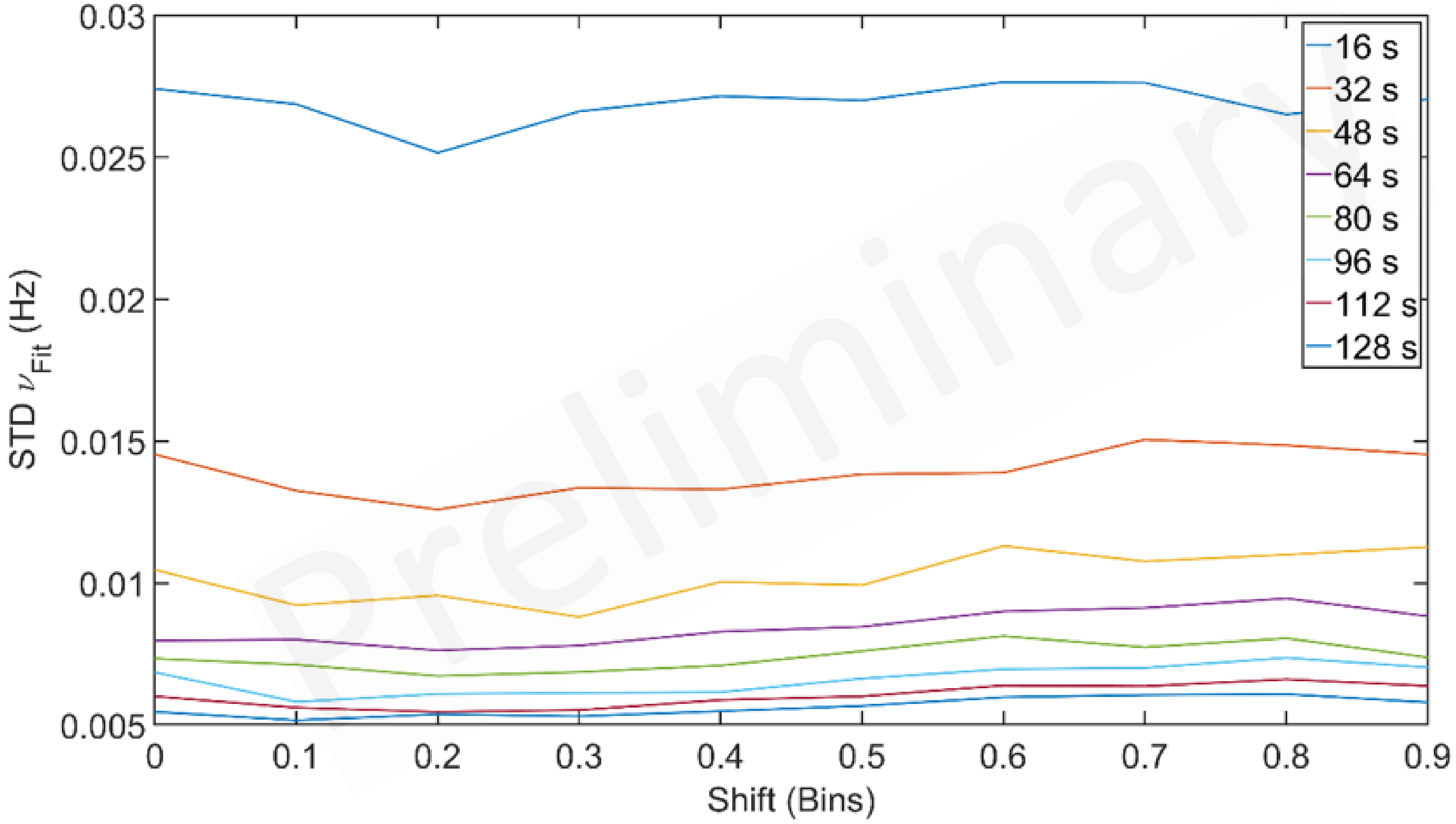

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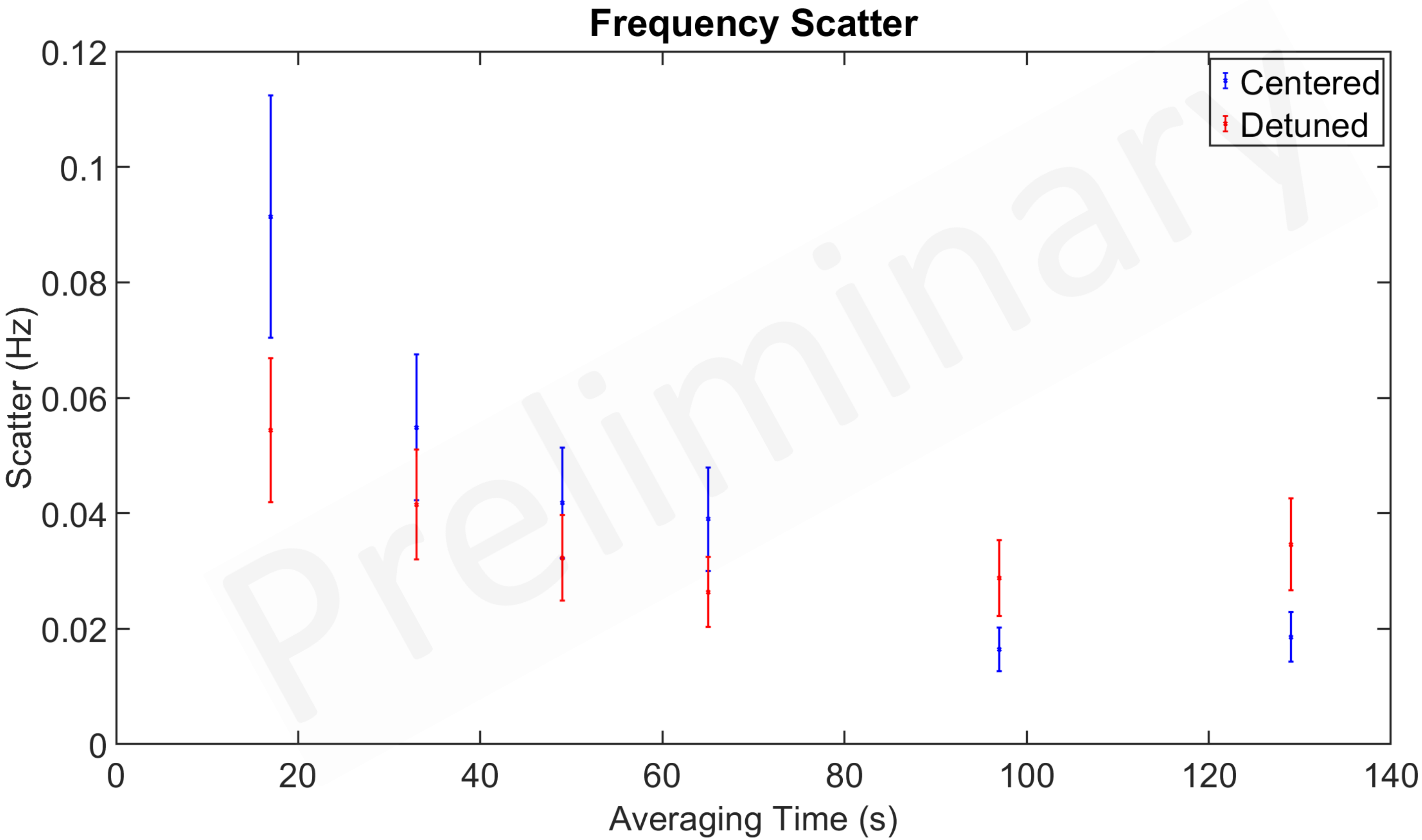

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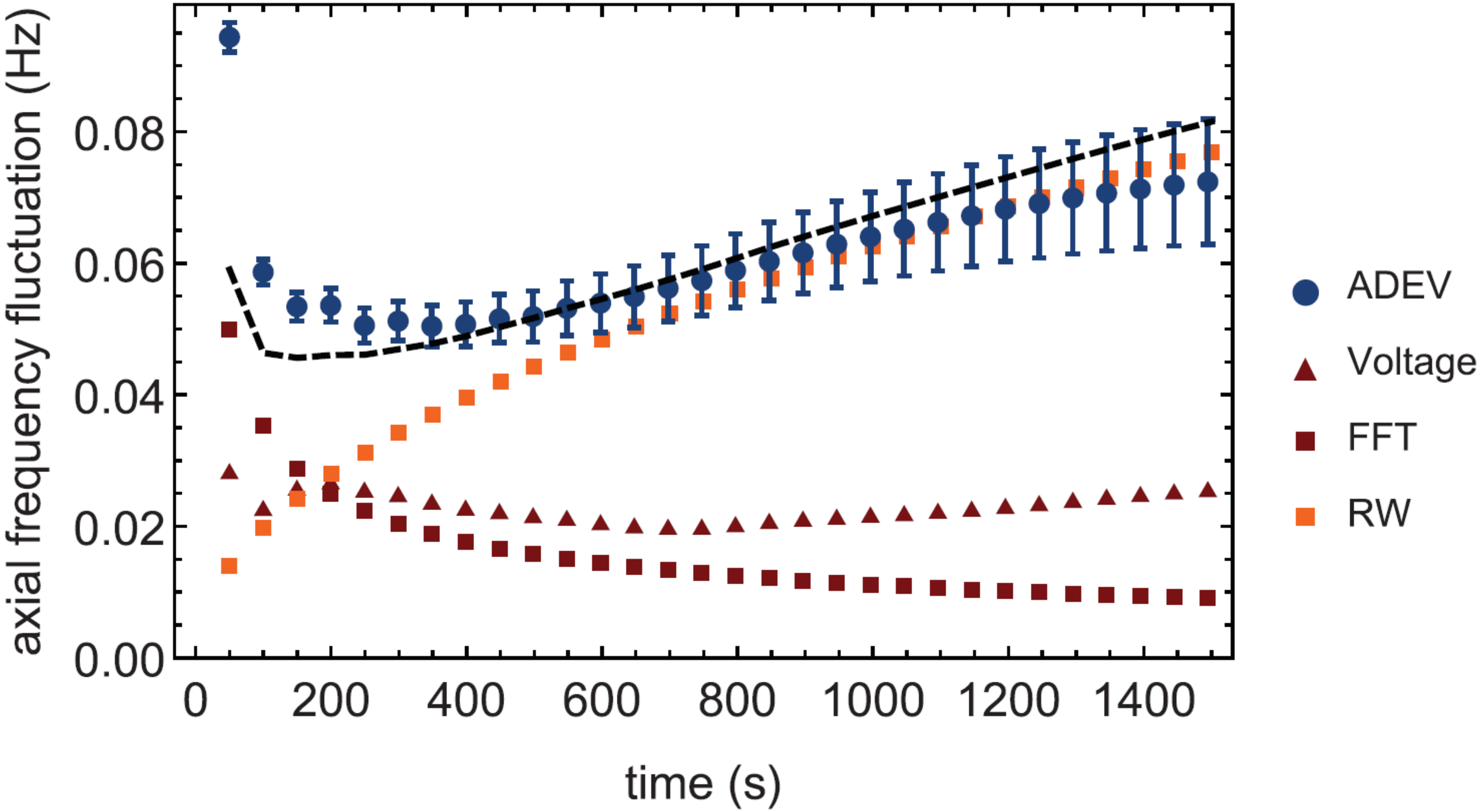
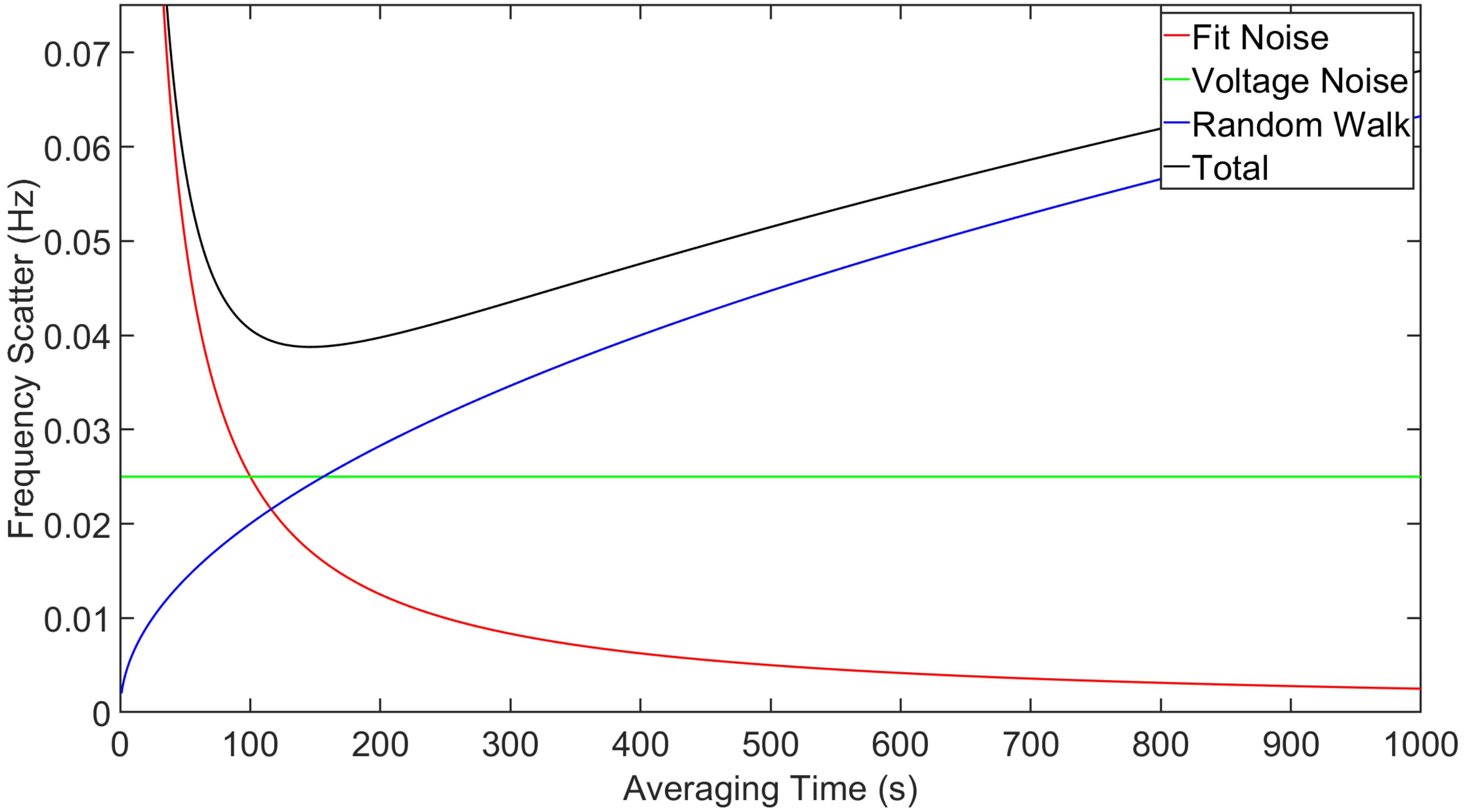


BORCHERT, M. J., et al. Measurement of Ultralow Heating Rates of a Single Antiproton in a Cryogenic Penning Trap. *Physical review letters*, 2019, 122. Jg., Nr. 4, S. 043201.

Dispersive Spinflip Detection



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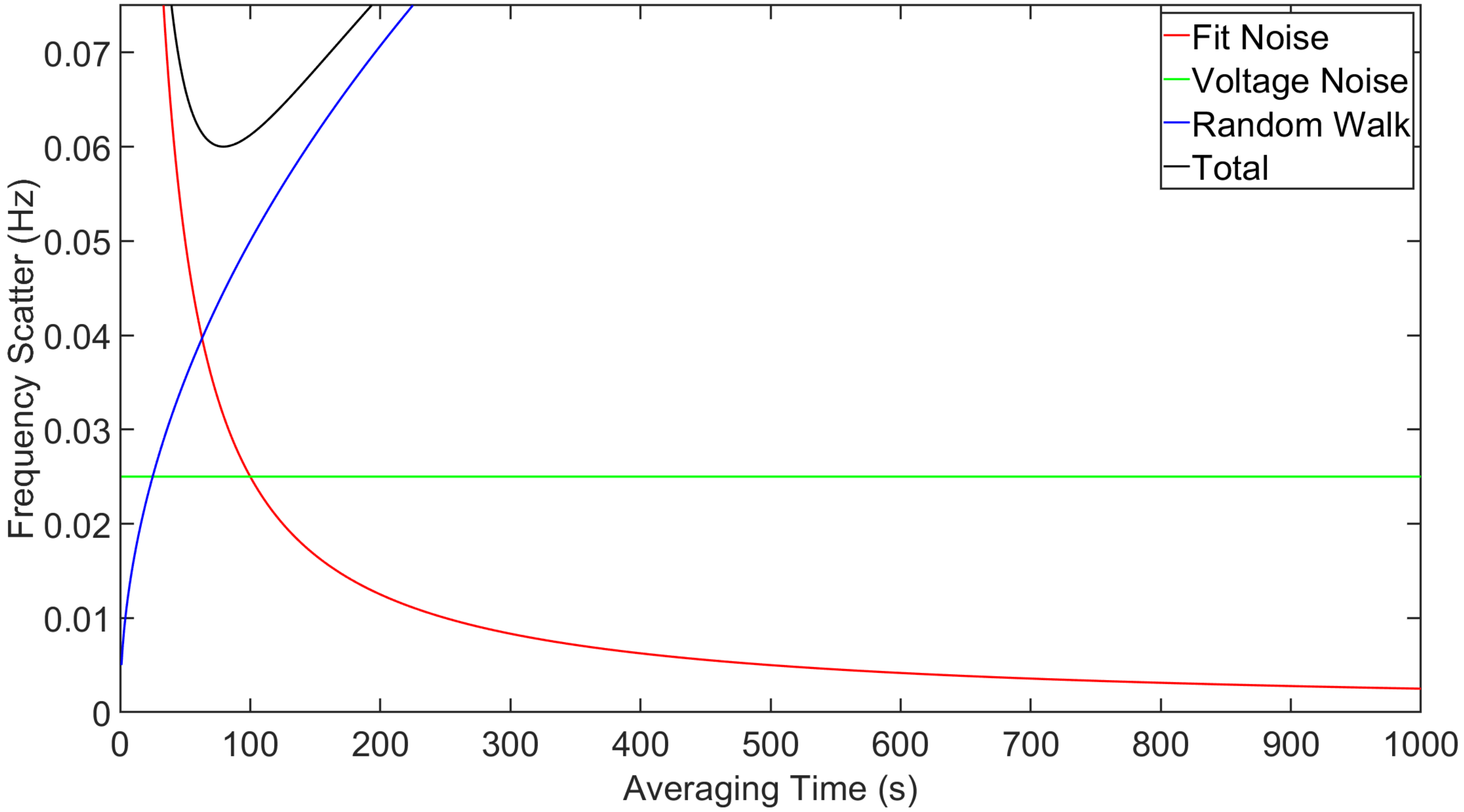

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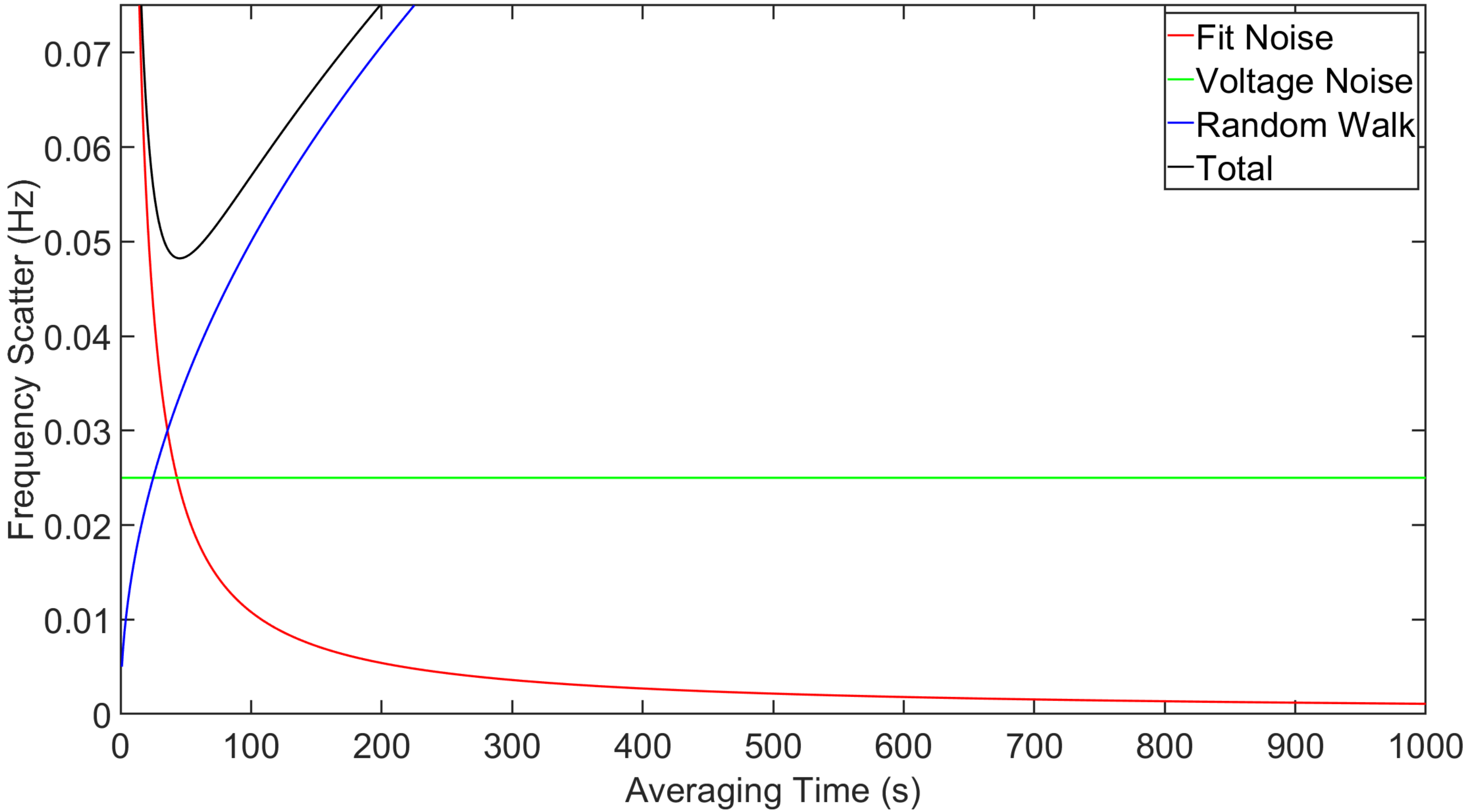

Conclusion

- Triple Trap technique allows determination of the antiproton *g*-factor at a fractional precision of 1.5 p.p.b.

- Clear path towards a 100 p.p.t. measurement after LS2 exists

- Upgrades open possibility for single particle scheme

BASE

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