Phase-sensitive modified cyclotron Frequency Measurements with a single trapped Antiproton

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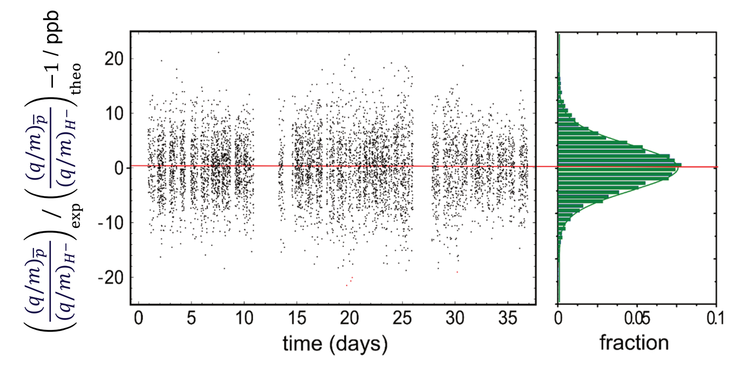
Baryon Antibaryon Symmetry Experiment

Motivation

Measurements at BASE CERN [1]

- p and $\bar{p}$ **charge-to-mass ratio** relative to each other to remove B dependence (H^- used instead of p due to opposite charge)

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



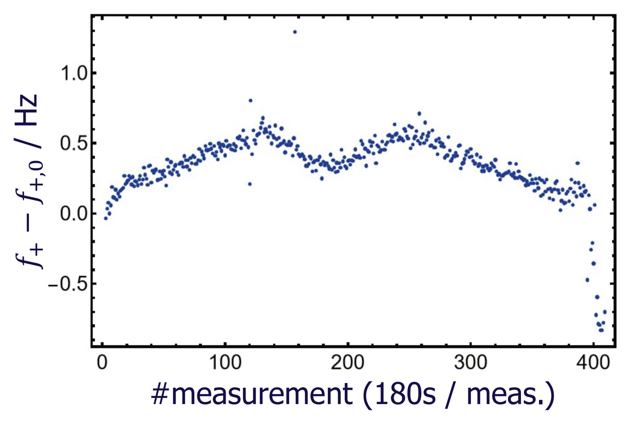
$$\frac{(q/m)_{\bar{p}}}{(q/m)_p} + 1 = -3(16) \times 10^{-12}$$ **16ppt** [2]

- p and $\bar{p}$ **magnetic moment** relative to the (anti-)nuclear magnetron

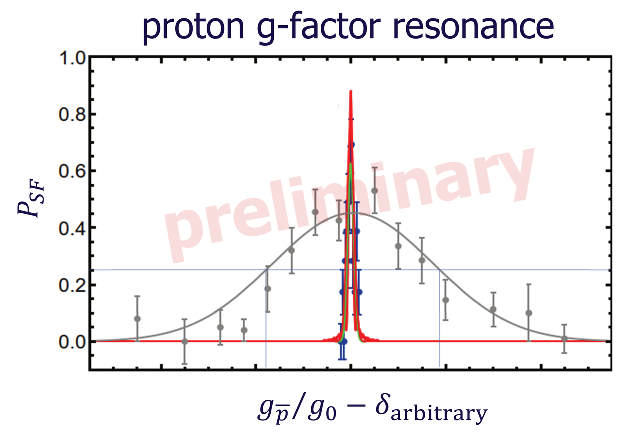
$$\frac{q_{\bar{p}}}{m_{\bar{p}}} B = \omega_{c,\bar{p}} = \frac{2\mu_{\bar{N}} B}{\hbar}$$
$$\frac{g_{\bar{p}}}{2} \frac{q_{\bar{p}}}{m_{\bar{p}}} B = \omega_{L,\bar{p}} = \frac{\mu_{\bar{p}} B}{\hbar} \quad \Longrightarrow \quad \frac{g}{2} = \frac{\omega_{L,\bar{p}}}{\omega_{c,\bar{p}}} = \frac{\mu_{\bar{p}}}{\mu_{\bar{N}}}$$

- $\Delta g_{\bar{p}} \gtrsim \Delta\omega_{c,\bar{p}} \gg \Delta\omega_{L,\bar{p}}$
- $\Delta\omega_{L,\bar{p}} \approx$??? (coherence limited)
- $\Delta\omega_{c,\bar{p}} \approx$???

$$\frac{g_p}{2} = 2.792\,847\,344\,62(82)$$ **0.3ppb** [3]
$$\frac{g_{\bar{p}}}{2} = 2.792\,847\,344\,1(42)$$ **1.5ppb** [4]

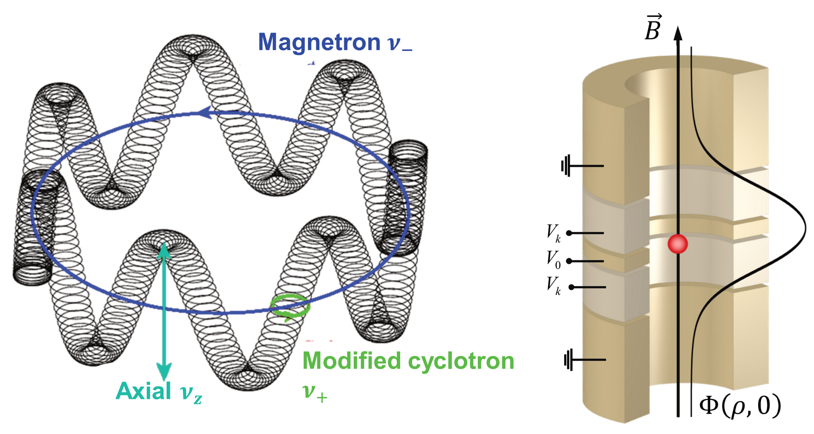


proton g-factor resonance



Determining $\omega_{c,\bar{p}}$

- BASE uses Penning traps to confine particles [5]

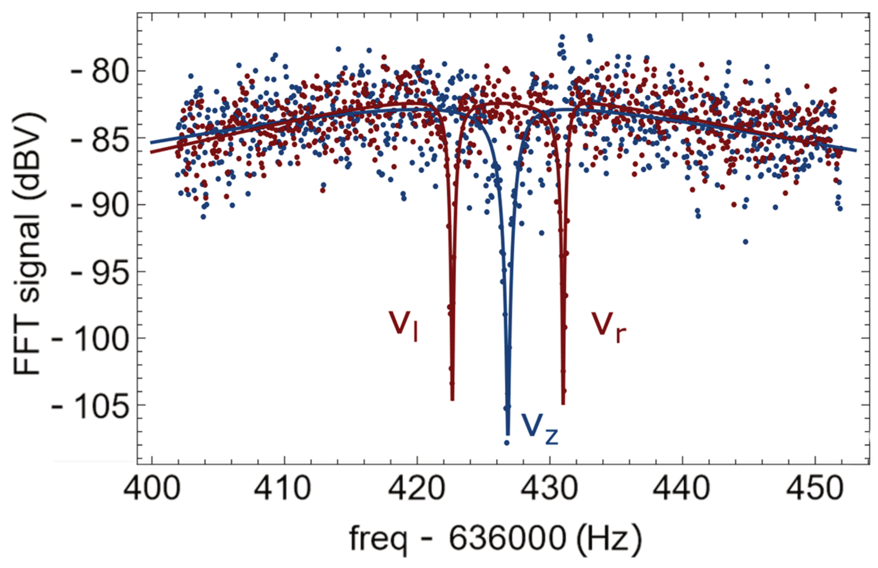


- $\omega_c = \sqrt{\omega_+{}^2 + \omega_z{}^2 + \omega_-{}^2}$, $\omega_+ \gg \omega_z \gg \omega_-$
- Custom built high-Q resonators allow precise determination of ω_z and sidebands of ω_- and ω_+
- resonators at ω_+ only at much lower Q
- ω_- sufficiently precisely measured with SB method

$\sigma(\omega_c) \approx \sigma(\omega_+)$!

Sideband Method ω_+

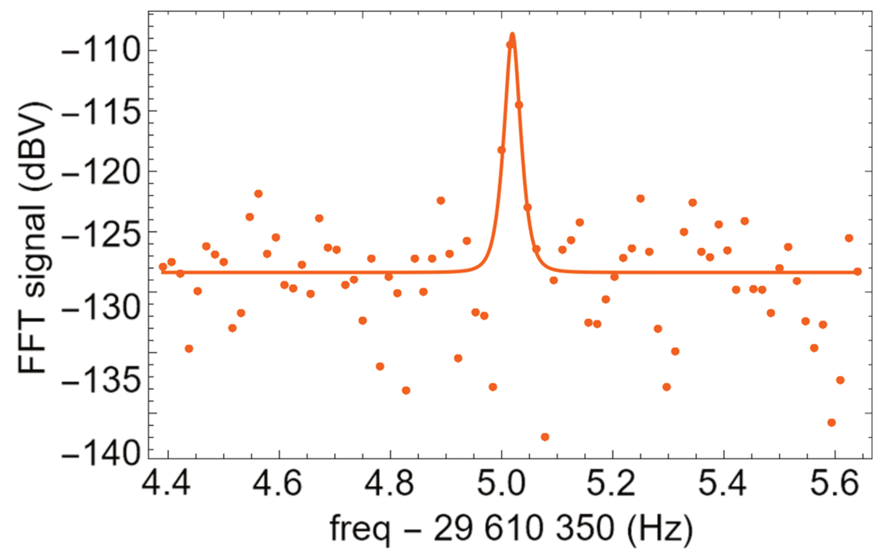
- Single Dip
  - low energy particle thermally coupled to a parallel RCL resonator
  - Johnson noise in resonator causes LSD $\sim \sqrt{4k_BT\,\mathrm{Re}[Z(\omega)]}$ noise
  - around the particles axial resonance frequency ω_z, the particle shorts the noise, acting as a serial RCL resonator with a greater Q
  - no energy transfer due to random phase, but thermalization
- Double Dip
  - using prior knowledge of $\omega_{+/-}$, radiating $\omega_{RF} \approx \omega_{+/-} \mp \omega_z$ Rabi-couples axial with other mode
  - then $\omega_{+/-}$ can be determined via $\omega_{+/-} = \omega_{RF} \pm \omega_l \pm \omega_r \mp \omega_z$



(optimal conditions) $\sigma_{+,SB} \approx$ **1.46 ppb** $\sim 1/\sqrt{T}$ (avg)
@ 180 s

Peak Method ω_+

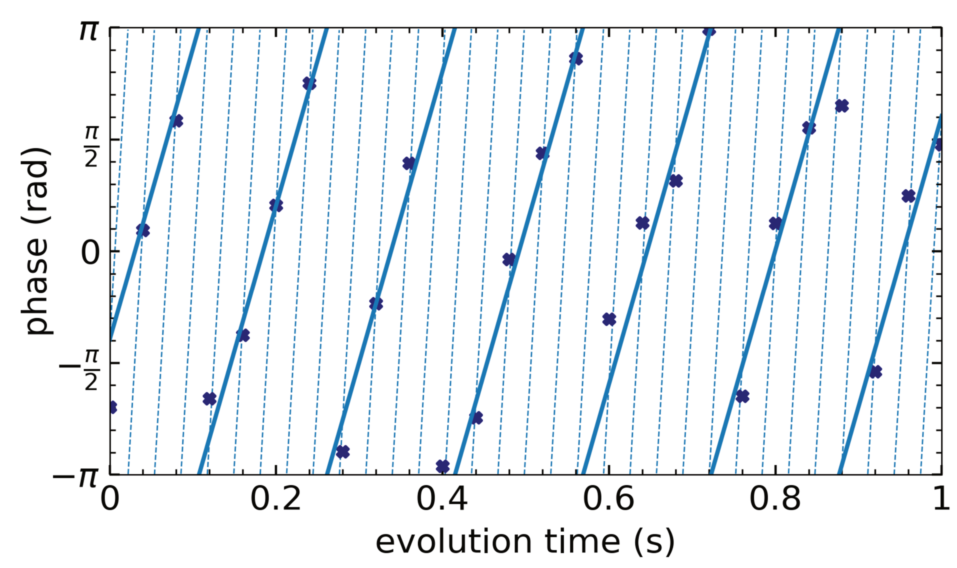
- Cyclotron resonator limited in Q-value, potential dip too thin to detect at $\Delta\omega_{+,\mathrm{dip}} \sim 20$ mHz, and SNR lower (10 dB) than axial (20 dB)
- Induce peak in LSD by exciting particle on ω_+ resonator
  - $U_{\mathrm{Res}} = RI_{\bar{p}}$ → stronger signal at resonator resonance frequency
  - advantage: direct measurement
  - problem: inhomogeneous $\vec{B}(\vec{r})$
    - high E_+ → high r_+ → systematic shifts in ω_+
    - high E_+ → high $\sigma(E_+)$ → high $\sigma(r_+)$ → increased scatter in ω_+
  - recording requires particle energy loss (energy decay exponential)
    - upper limit in single shot FFT timespan



(optimal conditions) $\sigma_{+,PK} \approx$ **0.5 ppb** $\sim 1/\sqrt{T}$ (avg.)
@ 60 s

Phase Method [8] ω_+

- $\Delta\phi = \omega_+\Delta t$, allowing frequency fit of ω_+ from $\Delta\phi$ information
- Excite particle with from ω_+ *detuned* resonator, knowing inital phase
- Rabi coupling for $\frac{1}{2}T_{\mathrm{Rabi}} \sim \sqrt{P_{\mathrm{RF}}}$ imprints ω_+ phase onto ω_z phase
- Axial phases are able to be determined via FFT of decaying axial peak
- Advantages: method allows long particle evolution at constant E_+
- Problems / limits:
  - inital phase scatter from cyclotron excitation procedure
  - systematic frequency shifts from high energy cyclotron mode
  - frequency drifts due to magnetic field drift
  - frequency aliasing due to limited sampling frequency span f_S

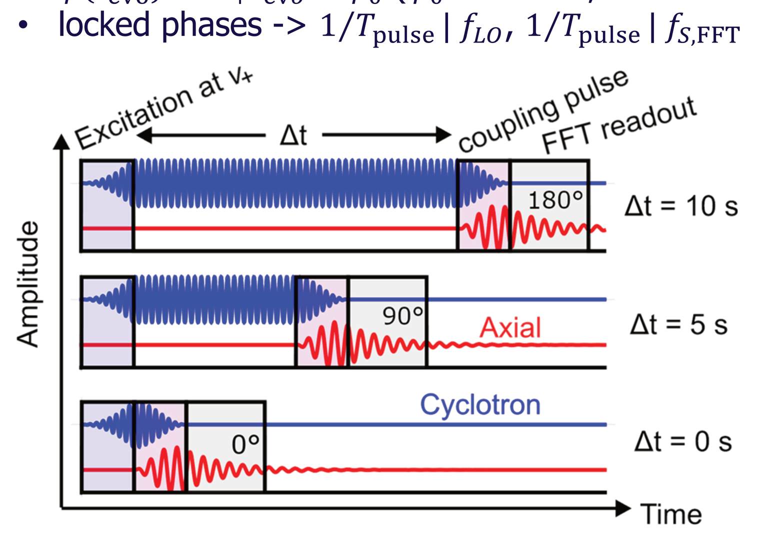


(optimal conditions) $\sigma_{+,PK} \approx$ **0.24 ppb** $\sim 1/T$ (evolve) [6]
(current progress) $\sigma_{+,PK} \approx$ **3 ppb** (AD limited)

Considerations in Phase Method Implementation

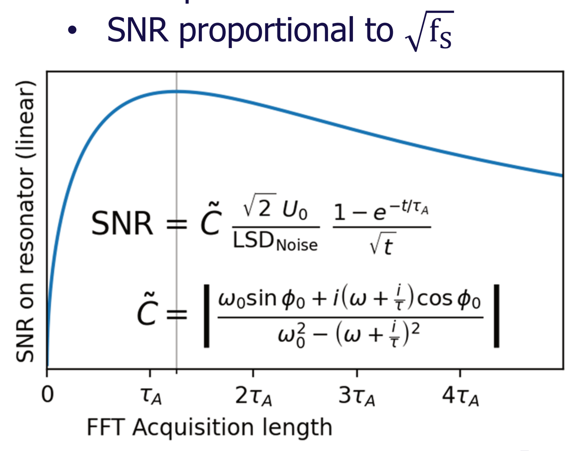
Timing Sequence

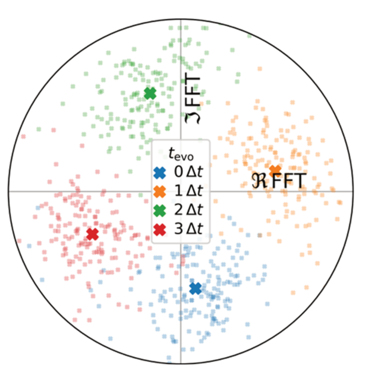
- excite ω_+, *evolve,* couple at $\omega_+ - \omega_z$, acquire, cool
- $\phi(t_{\mathrm{evo}}) = \omega_+ t_{\mathrm{evo}} + \phi_0$ (ϕ_0 unknown, but constant)
- locked phases -> $1/T_{\mathrm{pulse}} \mid f_{LO}$, $1/T_{\mathrm{pulse}} \mid f_{S,\mathrm{FFT}}$



FFT Acquisition

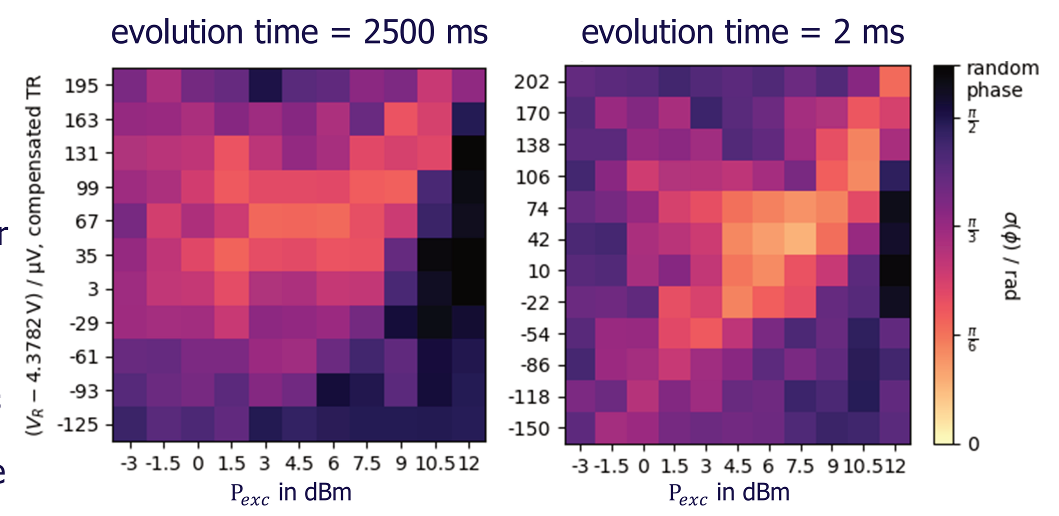
- axial signal decays exponentially, noise const.
  - $\tau_A = 180$ ms → $t_{\mathrm{opt}} = 225$ ms ≈ 256 ms
  - expected maximum SNR of approximately 5
- unwindowed FFT minimzes NENBW
- axial peak centered in one bin for maximum SNR
- SNR proportional to $\sqrt{f_S}$





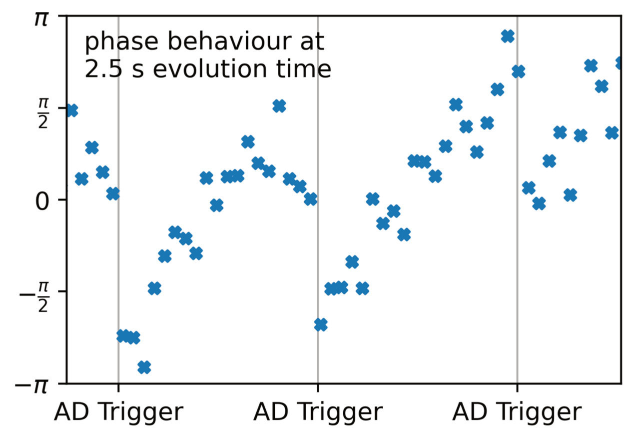
Optimizations

- in optimized 5-pole penning trap, TR determined in advance and $V_r = V_r(f_{z,\mathrm{resonator}}, \mathrm{TR})$
  - scan TR around canonical point to minimize phase scatter
- $X(z) = X_0 + X_1 z + X_2 z^2 + X_3 z^3 \ldots$ compensated $B_1, B_2, \ldots$ and $\Phi_1, \Phi_3, \Phi_4, \ldots$ minimizes phase scatter
- FFT acquisition start, length and f_S
- decreasing particle cool drive time increases phase measurement rate



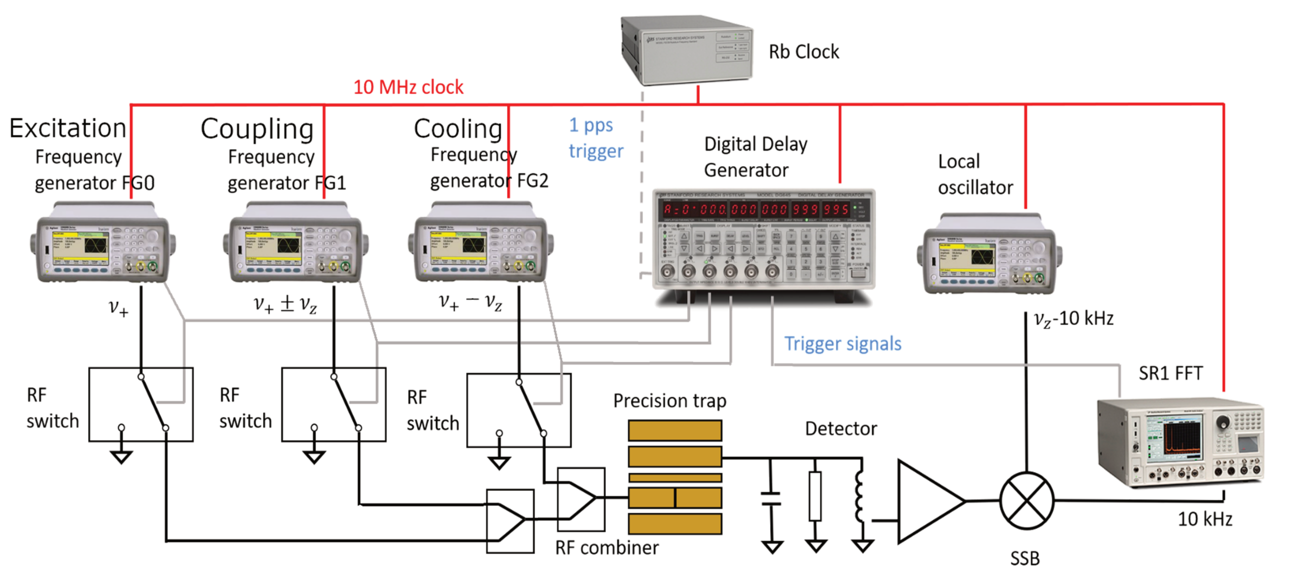
Limits

- systematic ω_+ shifts from $B_1, B_2, \ldots \neq 0$
  - increases at higher E_+
- phase scatter after excitation $\sigma(E_+) \approx \sqrt{2E_{+,0}E_{+,\mathrm{exc}}}$
  - increases with initial T_+ and $B_1, B_2, \ldots \neq 0$
- acquisition noise phase scatter
  - decreases at higher E_+ and increases for $\Phi_1, \Phi_3, \Phi_4, \ldots \neq 0$ due to axial peak broadening
- Magnetic Field Drift ~ 40 ppb/day
- AD magnet ramping ~ 400 ppb/min when on!
  - repeating variations in measured phase currently limiting phase meas. to ≈ 3 ppb



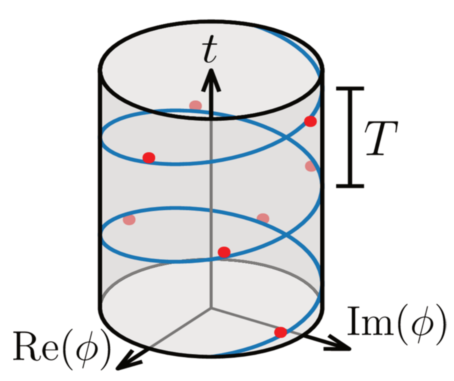
Implementation Diagram

- all instruments referenced to high precision Rb clock to avoid phase drifts
- drive outputs both gated *and* externally switched, minimizing crosstalk



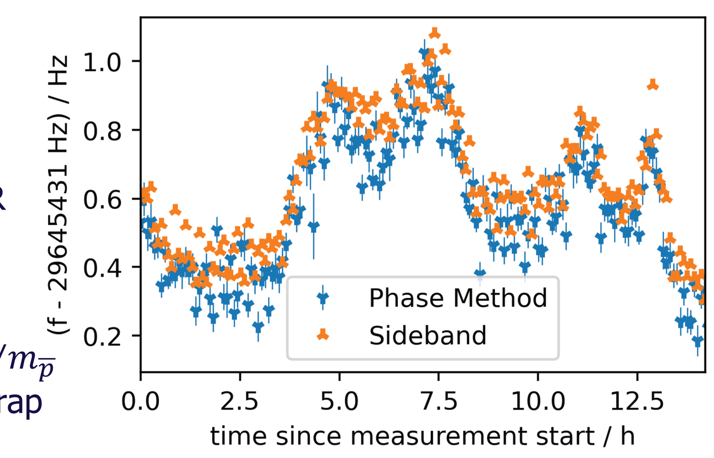
Phase Unwrapping

- $\phi \in \mathbb{R}/2\pi\mathbb{Z} \ncong \mathbb{R}$ → phase jumps
- remove jumps by *unwrapping*
  - unstable at low phase SNR
- Solution: treat phases in $\mathbb{C}$
- Direct helix fit is susceptible to convergence into local minima
  - FFT for init. ω_+ estimation



Outlook

- upper SB coupling at $\omega_+ + \omega_z$ for increased SNR at the cost of even larger systematics (PnA [7])
- systematic corrections to reach consistency with sideband and peak methods
- subsequent improved measurements of g & $q_{\bar{p}}/m_{\bar{p}}$
- direct axial phase methods in high-B_2 analysis trap



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