Towards a 10-fold improved measurement of the antiproton magnetic moment

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Institutes: **MPIK, GSI, RIKEN**

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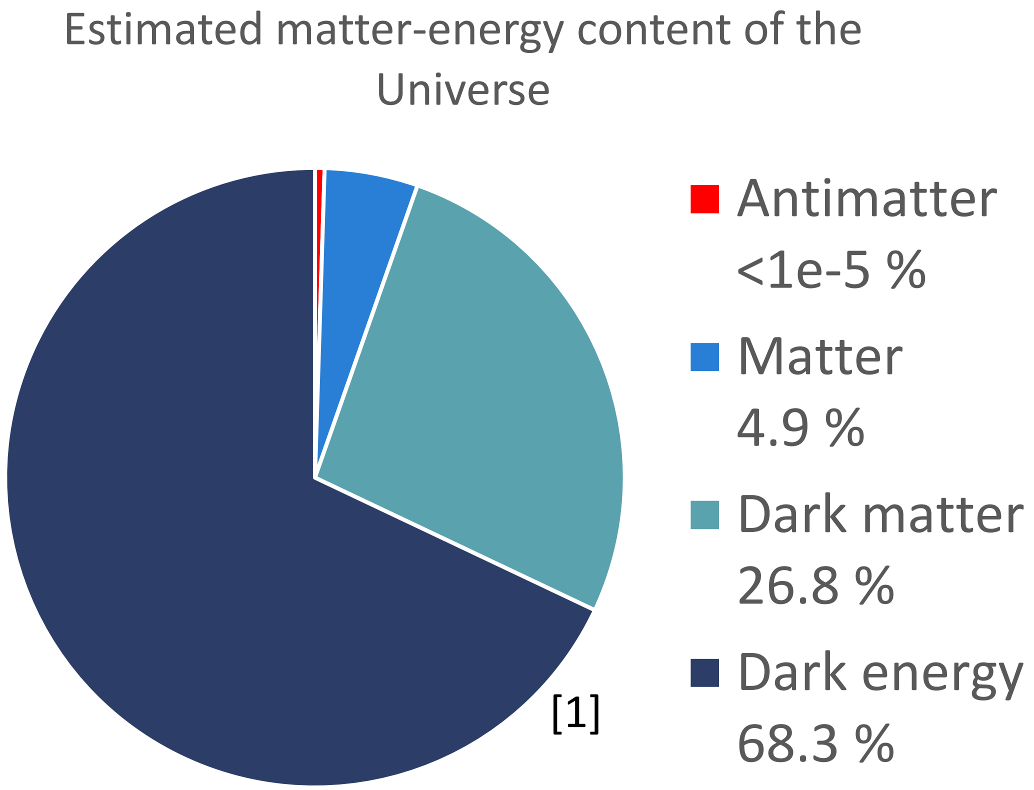
Matter-Antimatter Asymmetry



Sakharov conditions

1.) B-violation (plausible)
2.) CP-violation (observed / too small)
3.) Arrow of time (less motivated)

[2]

Alternative Source: CPT violation – adjusts matter/antimatter asymmetry by natural inversion given the effective chemical potential.

Naive Expectation	
Baryon/Photon Ratio	10^{-18}
Baryon/Antibaryon Ratio	1

Observation	
Baryon/Photon Ratio	$0.6 * 10^{-9}$
Baryon/Antibaryon Ratio	10 000

[1] Peplow, Mark. "Planck telescope peers into primordial Universe." *Nature* (2013).
[2] Charlton, Michael, Stefan Eriksson, and Graham M. Shore. *Antihydrogen and fundamental physics*. Cham: Springer, 2020.

Charge-to-mass Ratio

Direct measurement via invariance theorem

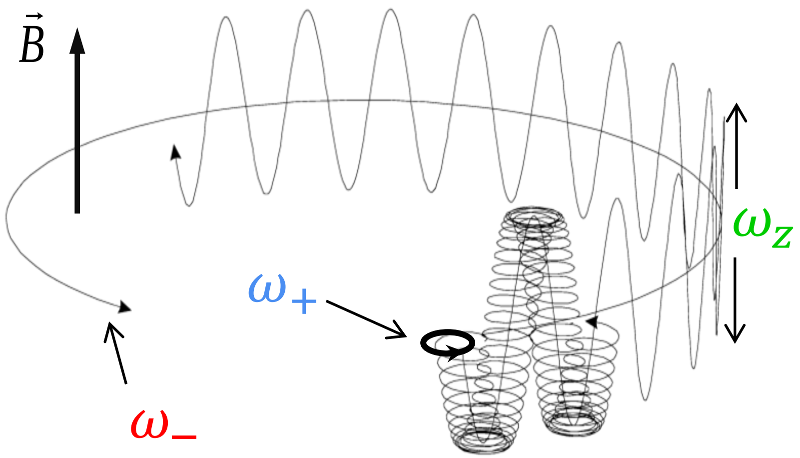
$$\omega_c = \sqrt{\omega_+^2 + \omega_-^2 + \omega_z^2} = \frac{qB}{m}$$

Compare protons and antiprotons

$$\frac{\omega_{c,\bar{p}}}{\omega_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

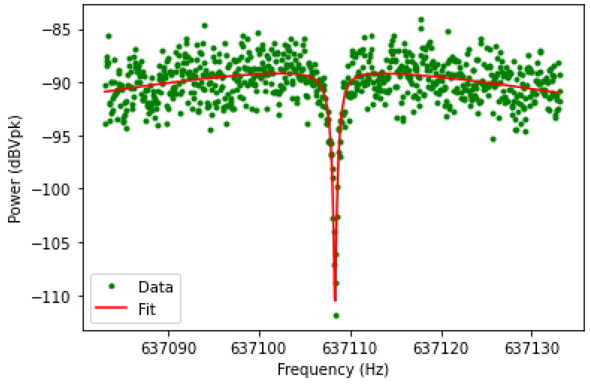
$$\frac{(q/m)_{\bar{\mathrm{p}}}}{(q/m)_{\mathrm{p}}} + 1 = -3(16) \times 10^{-12}$$ **16ppt** [3]

Particle in a Penning trap

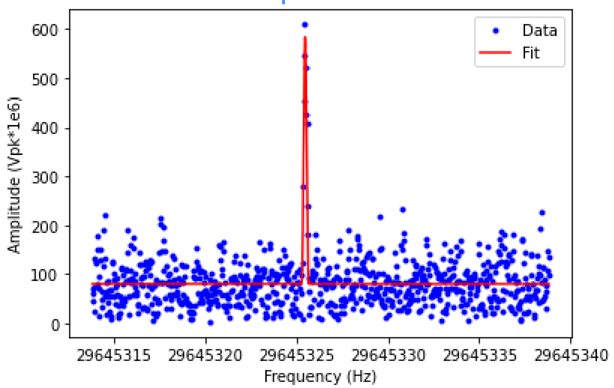


ω_c via image current detection

Dip at ω_z



Peak at ω_+



3 Ulmer, Stefan, et al. "High-precision comparison of the antiproton-to-proton charge-to-mass ratio." *Nature* 524.7564 (2015): 196-199.

Magnetic Moment g

Cyclotron frequency

$$\omega_c = \frac{q}{2m_{\bar{p}}} B$$

Larmor frequency

$$\omega_L = g \frac{q}{2m_{\bar{p}}} B$$

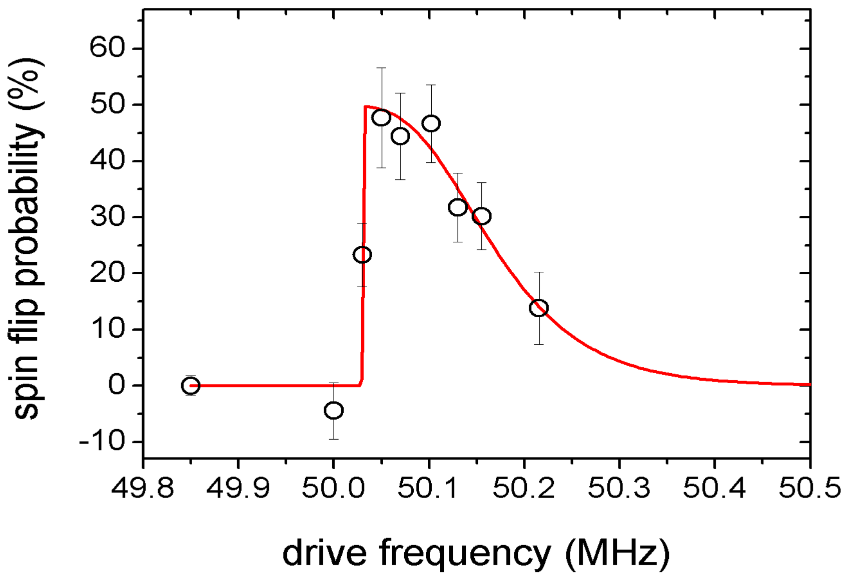
$$\frac{\omega_L}{\omega_c} = \frac{g}{2}$$

$$\left|\frac{g_p}{2}\right| = 2.792\,847\,344\,62(82)$$ **0.3ppb** [4]

$$\left|\frac{g_{\bar{p}}}{2}\right| = 2.792\,847\,344\,1(42)$$ **1.5ppb** [5]

No image current detection possible

Continuous Stern-Gerlach effect



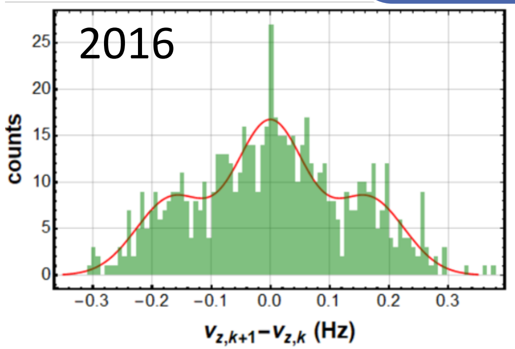
1. **Decoherent: random spin state (time independent, 50% sf)**
2. **Coherent: rabi oscillations (time dependent, 100% sf)**

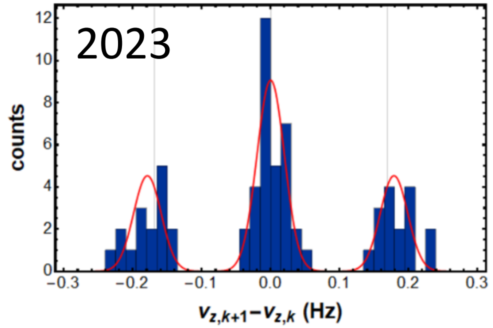
4 Schneider, Georg, et al. "Double-trap measurement of the proton magnetic moment at 0.3 parts per billion precision." *Science* 358.6366 (2017): 1081-1084.
5 Smorra, Ch, et al. "A parts-per-billion measurement of the antiproton magnetic moment." *Nature* 550.7676 (2017): 371-374.

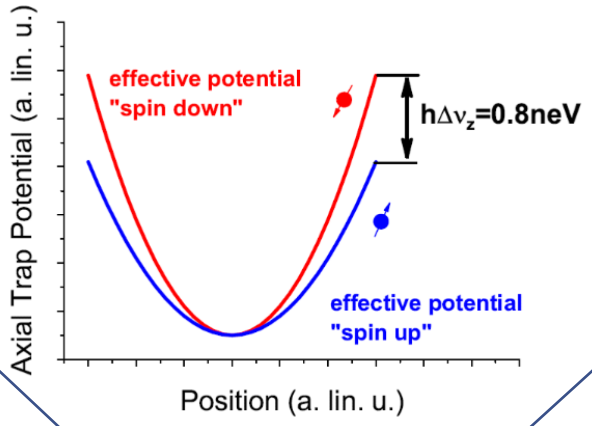
Challenges of Spin Flip determination

Small axial scatter

best reached under 30 mHz

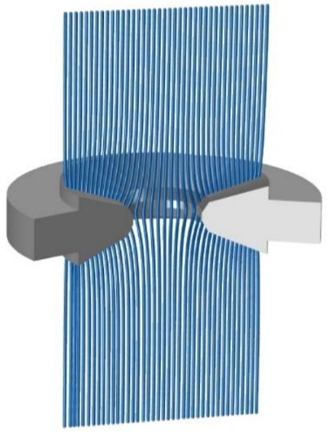






Strong magnetic bottle

$B_2 = 300000\ \frac{T}{m^2}$



Resolve spin shift

$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} \approx 170\ mHz$$

B-field expansion

$$B(z) = \int_{k=0}^{\infty} B_k z^k$$

Analog for potential

$$V(z) = V_0 \int_{k=0}^{\infty} C_k z^k$$

Requirement	Effect	Value
High B_2	Increased spin flip induced axial frequency shift	$\approx 300000\ \frac{T}{m^2}$
Low T_+, T_-	Decreased axial scatter	$< 200\ mK$

Challenges of Spin Flip determination

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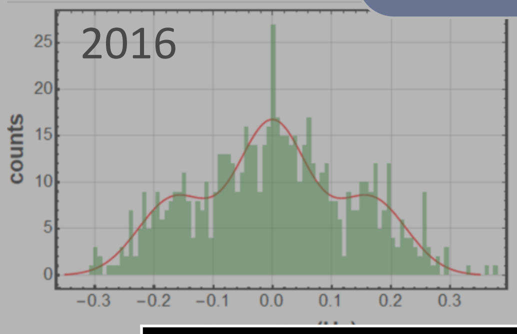
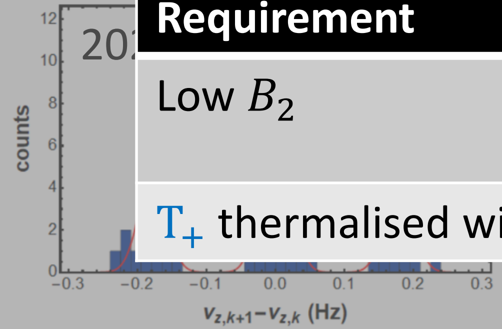
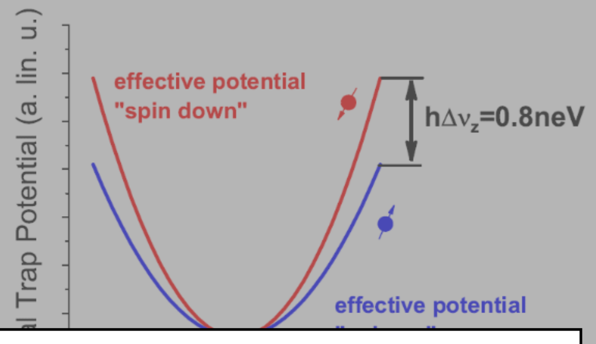
best reached under 30 mHz

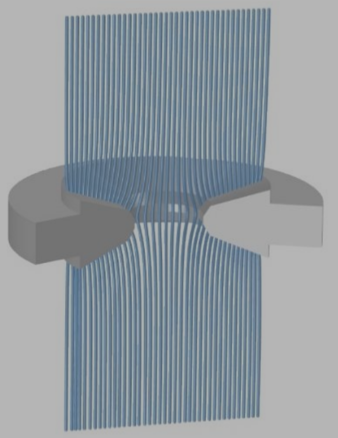






Strong magnetic bottle

$B_2 = 300000 \, \frac{T}{m^2}$



Requirements for ω_c

Requirement	Effect	Value
Low B_2	Decreased Systematics	$\approx 0 \, \frac{T}{m^2}$
T_+ thermalised with T_z	Measurement	$\approx 300 \, K$

Requirement	Effect	Value
High B_2	Increased spin flip induced axial frequency shift	$\approx 300000 \, \frac{T}{m^2}$
Low T_+, T_-	Decreased axial scatter	$< 200 \, mK$

B-field expansion

$$B(z) = \int_{k=0}^{\infty} B_k z^k$$

Analog for potential

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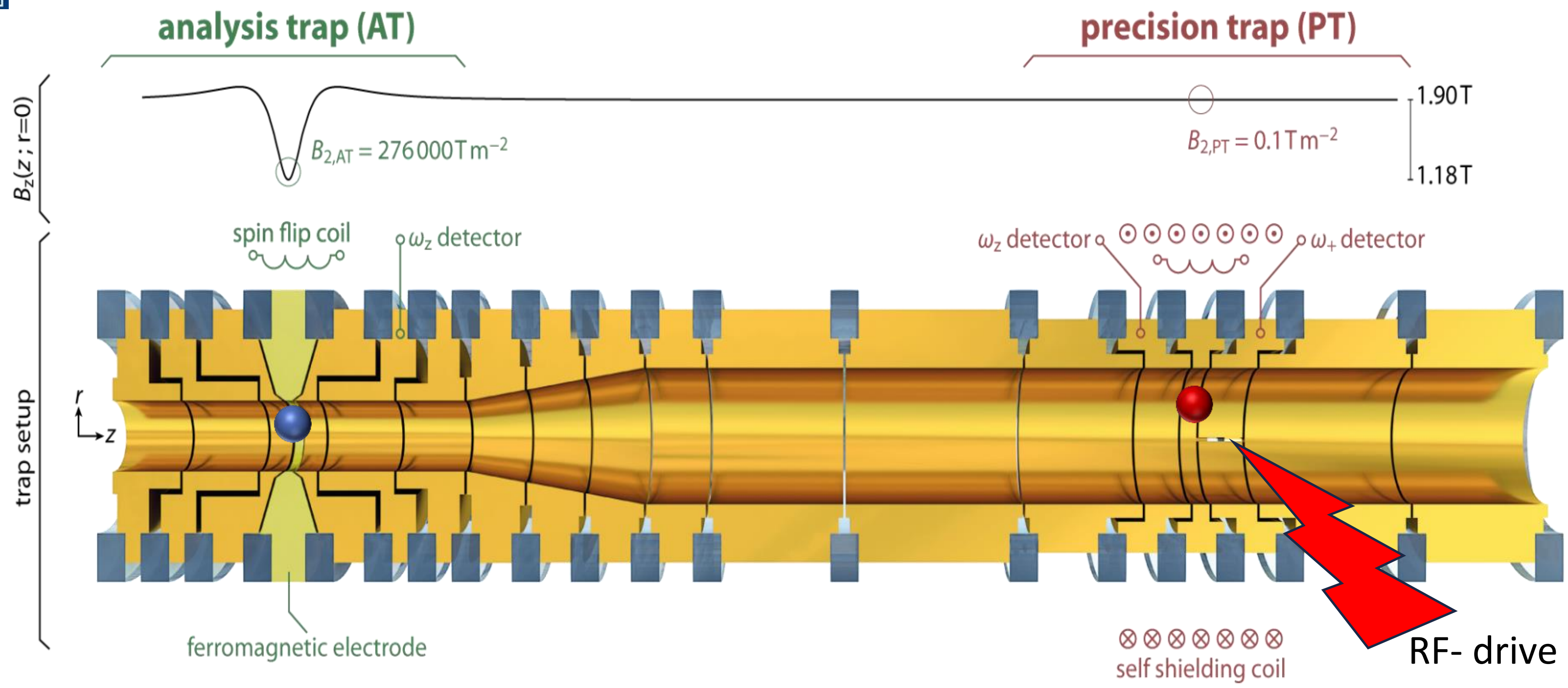
The Two-trap Method



1. Spin state is initialized (AT) // ω_c is measured (PT)
2. Transport
3. Larmor excitation
4. Transport
5. Spin state detection // ω_c measurement (PT)

Understanding Systematic Errors

Table 1 | Error budget of the antiproton magnetic moment measurement

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

[5]

Shift related to:

$$B_1 = 71.2(4)\ \frac{mT}{m^2}$$

Shift related to:

$$B_2 = 2740(220)\ \frac{mT}{m^2}$$

Dominant error contribution!

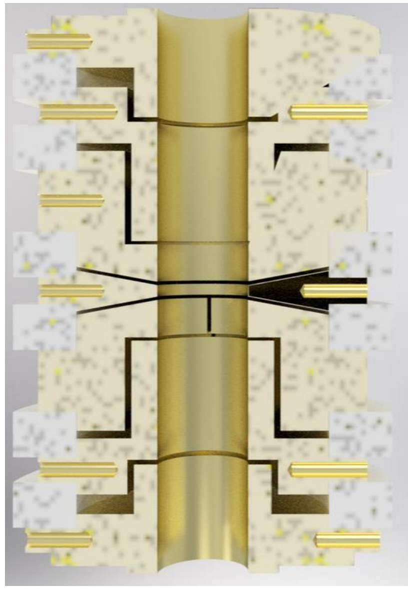
Decoherence due to line width parameter $\omega_c = \frac{q}{m} B_0 \left(1 + \frac{\boldsymbol{B_2} E_z}{\boldsymbol{B_0} m \omega_z^2}\right)$

5 Smorra, Ch, et al. "A parts-per-billion measurement of the antiproton magnetic moment." *Nature* 550.7676 (2017): 371-374.

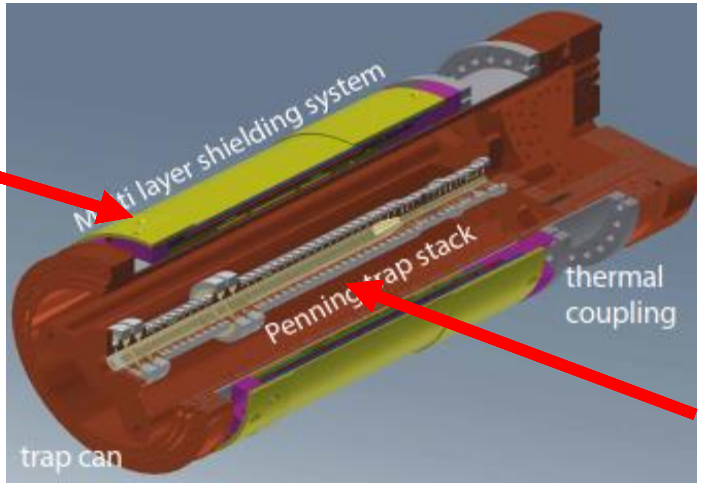
Hardware Upgrades

Upgrade	Effect	Reduction
Superconducting -shiming coils	Residual B2	1000 fold
Superconducting -shield coils	Magnetic field fluctuations	50-100 fold
New trap stack including a dedicated cooling trap	Measurement time	Cooling time reduced by a factor of 25
Phase sensitive ω_+ measurement	Decreased ω_+ scatter	Philip Geissler Poster

Cooling Trap



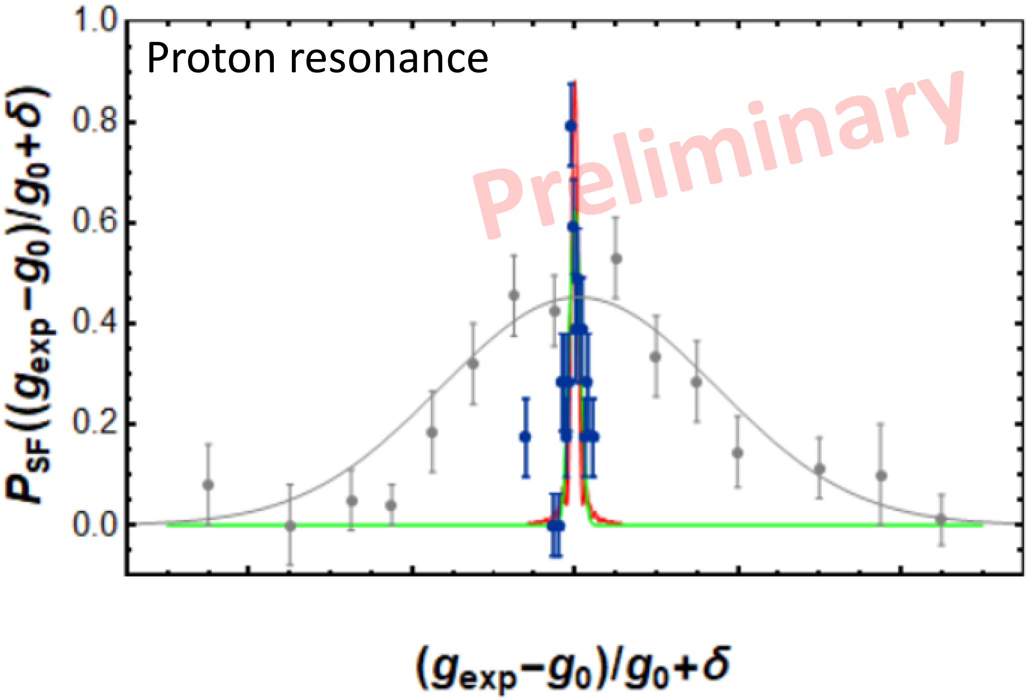
Outer layer:
Self shielding coils



Inner layer:
Shiming coils for B2 and B1

Reduction of the Resonance Linewidth

Thinner linwidth-> more systematics



Particles are not similar:

Larmor particle: low E_+, E_-

Cyclotron particle: high E_+, E_-

The shifts $\Delta\omega_z$, $\Delta\omega_+$, $\Delta\omega_c$ dominated by terms that scale with

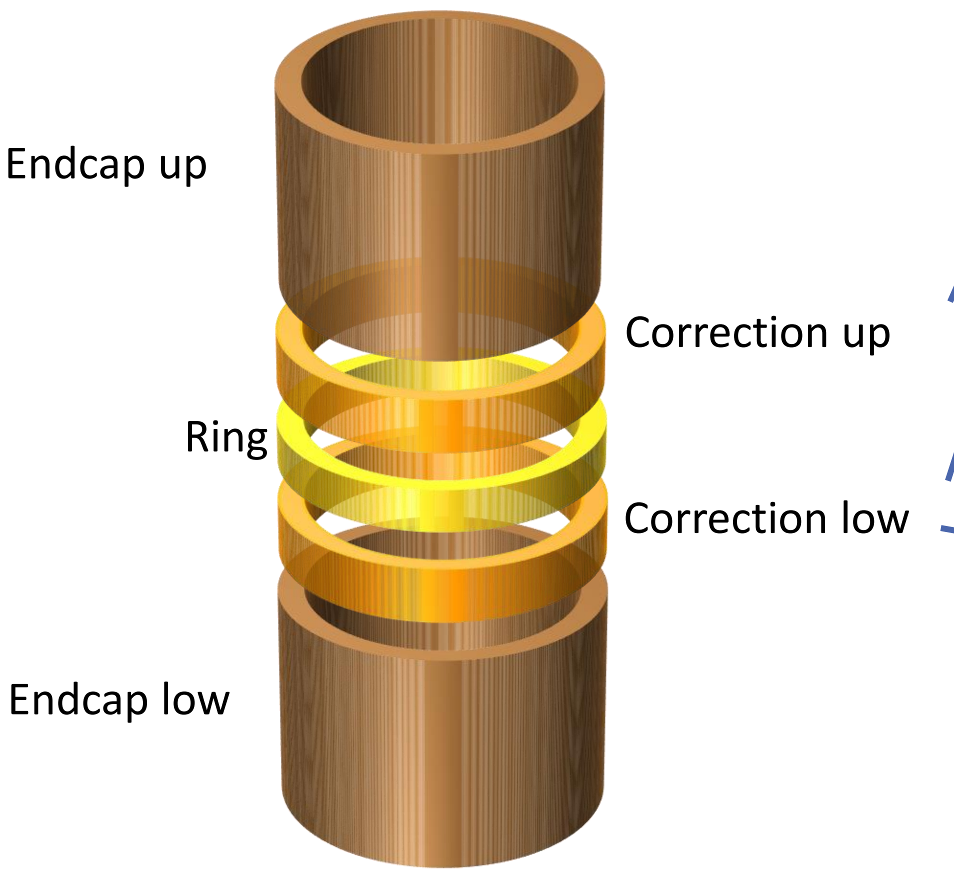
relativistic | **B-field contributions** | **Potential contributions** | **Mixing term** | **and more**

$$\nu_+(E_+) = \nu_+(0)\left\{1 + \left(-\frac{1}{mc^2} - \frac{1}{4\pi^2 m\nu_z^2}\left[\left(\frac{B_1}{B_0}\right)^2 + \left(\frac{\nu_z}{\nu_+}\right)^4\left(\frac{B_2}{B_0}\right)\right] + \frac{3}{4qV_0}\frac{C_4}{C_2^2}\left(\frac{\nu_z}{\nu_+}\right)^4 - \frac{9\nu_z^2}{16\pi^2 m\nu_+^4}\frac{C_3^2}{C_2^2} + \frac{3}{4qV_0}\frac{2C_3B_1}{C_2^2B_0}\left(\frac{\nu_z}{\nu_+}\right)^2\right)\ldots\right\}E_+$$

B_1, B_2 | C_4 | C_3 | B_1, C_3 asymmetric

Manipulate Potentials

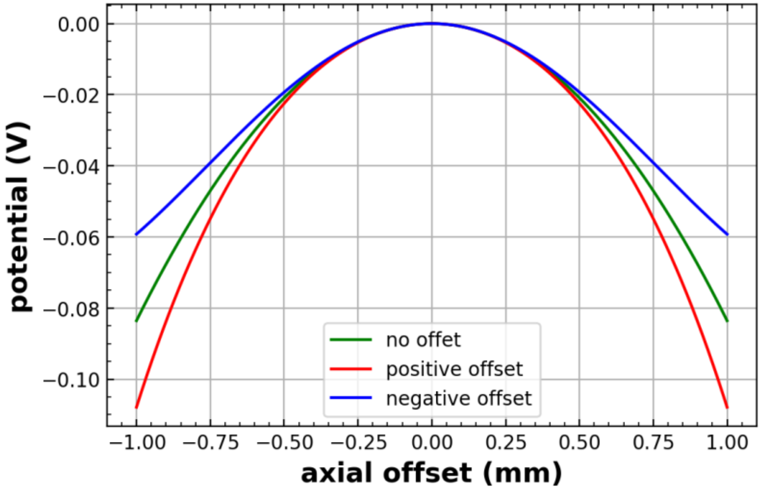
Open-endcap Penning trap



Vary correction electrodes

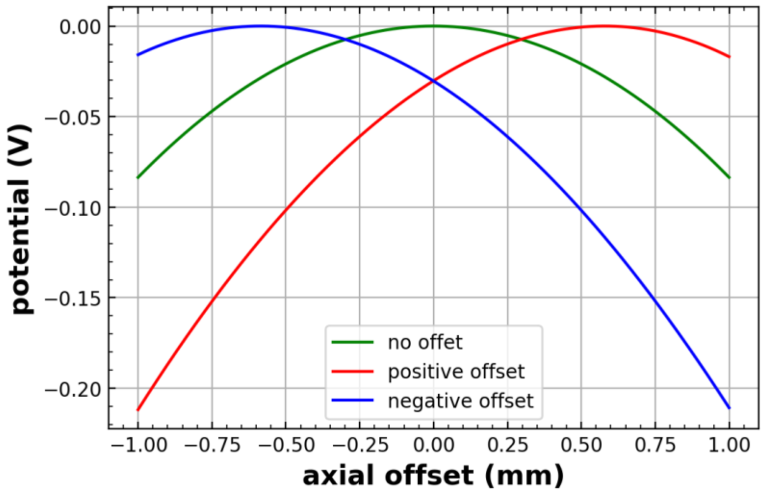
Both electrodes:

- changes C_4
- tuning ratio optimisation



One electrode:

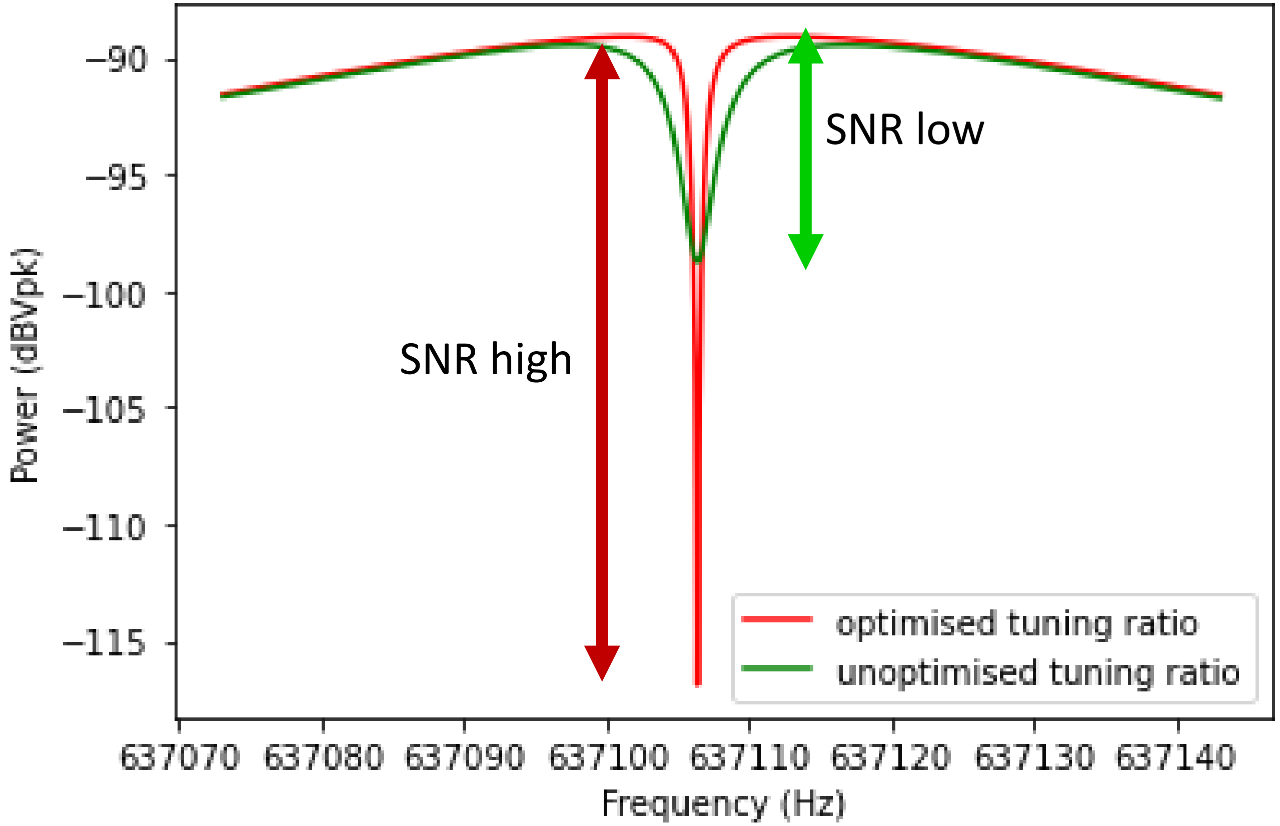
- changes C_3
- changes axial position



Tuning Ratio Optimisation

Axial frequency is energy dependent

$$\frac{\Delta \nu_z}{\nu_z} \propto \left(\frac{C_4}{C_2^2} - \frac{5}{4}\frac{C_3^2}{C_2^3} + \cdots \right) E_z \rightarrow 0$$



Not optimised:

Energy distribution smears out signal
→ low signal-to-noise ratio

Optimised:

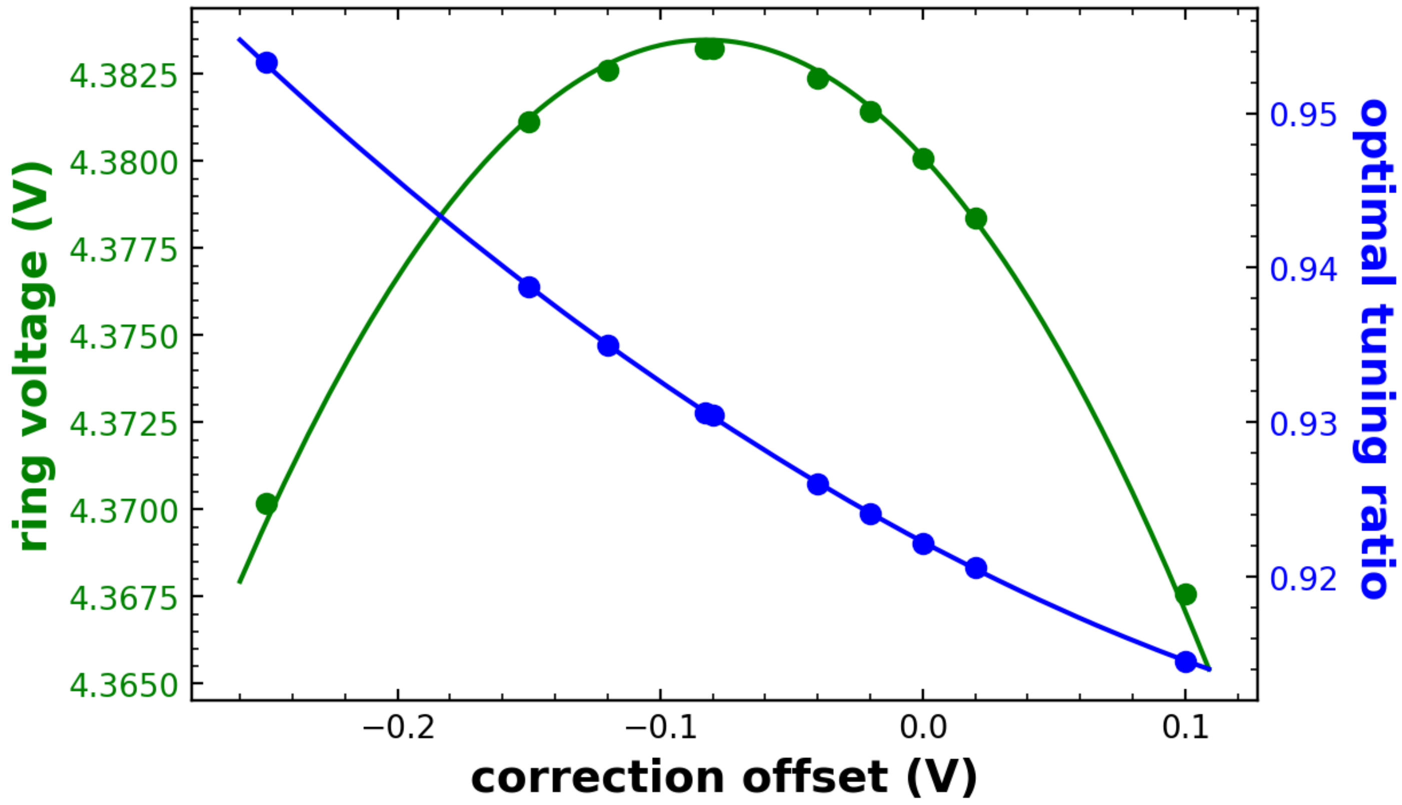
Frequency independent of E_z
→ high signal-to-noise ratio

Centering the Particle

1. Vary a correction electrode
2. Optimise tuning ratio
3. Find the trap center at ring voltage maximum

But: This does not get rid of C_3!

Simulate and fit different endcap offset to the data:



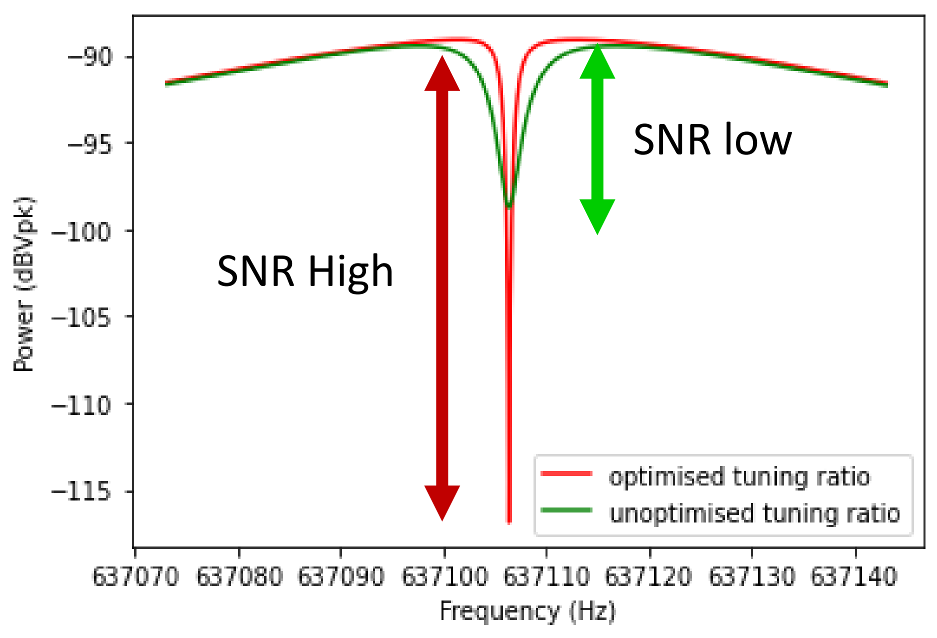
$$C_3 \text{ simulation} = 22900 \pm 2500 \ \frac{V}{m^3}$$

Direct Measurement of C3

Recall: E_z axial shift optimisation:

Vary tuning ratio→

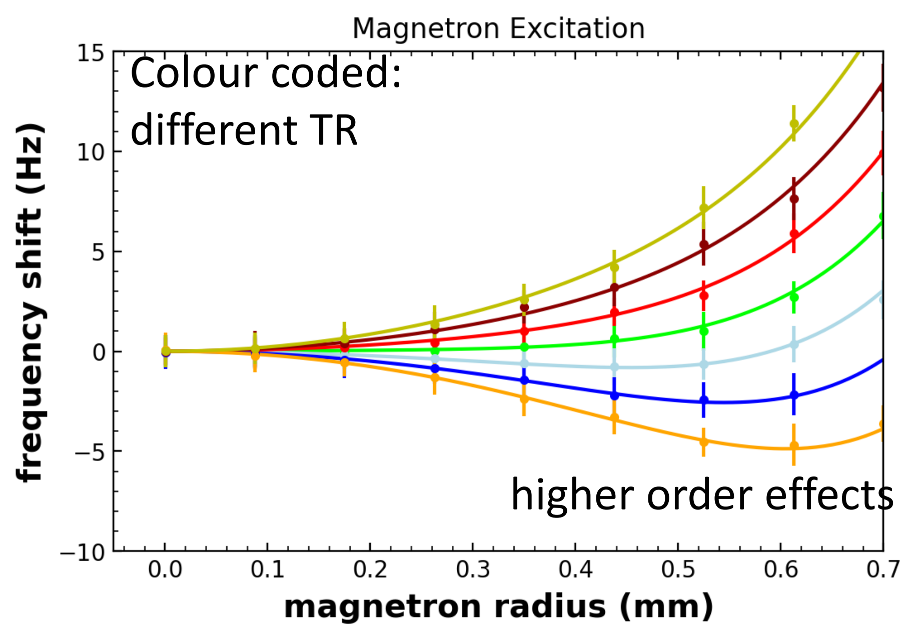
Optimise the SNR



E_- axial shift optimisation:

Excite magnetron mode externally →

Measure energy dependent shift $\Delta \nu_z$



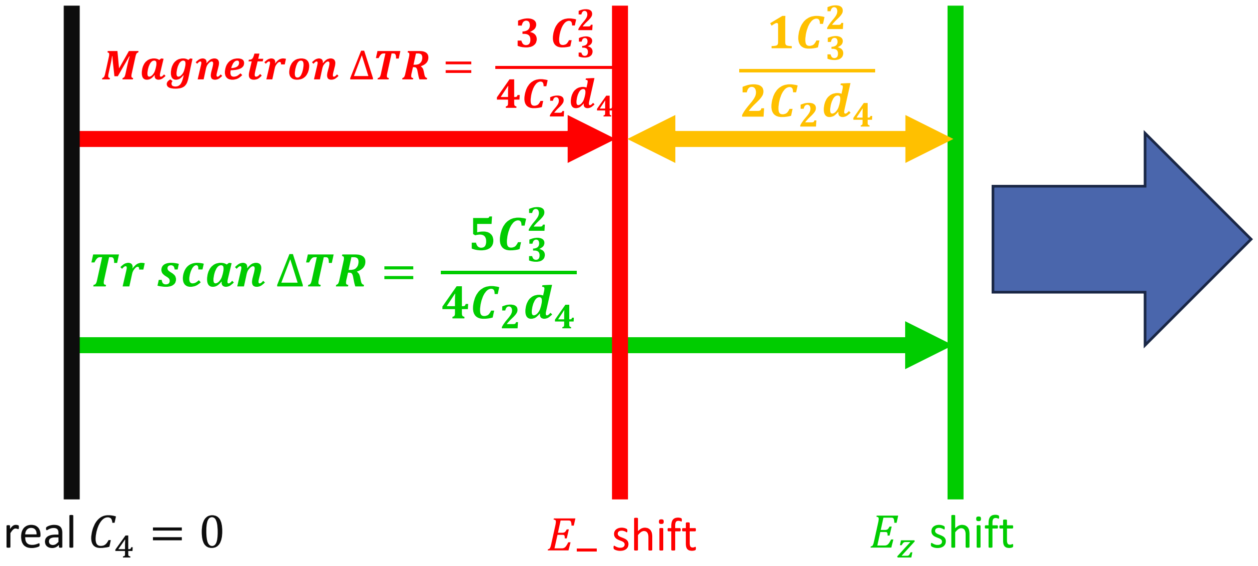
Both measurements cannot cannot distinguish between C_3 and C_4

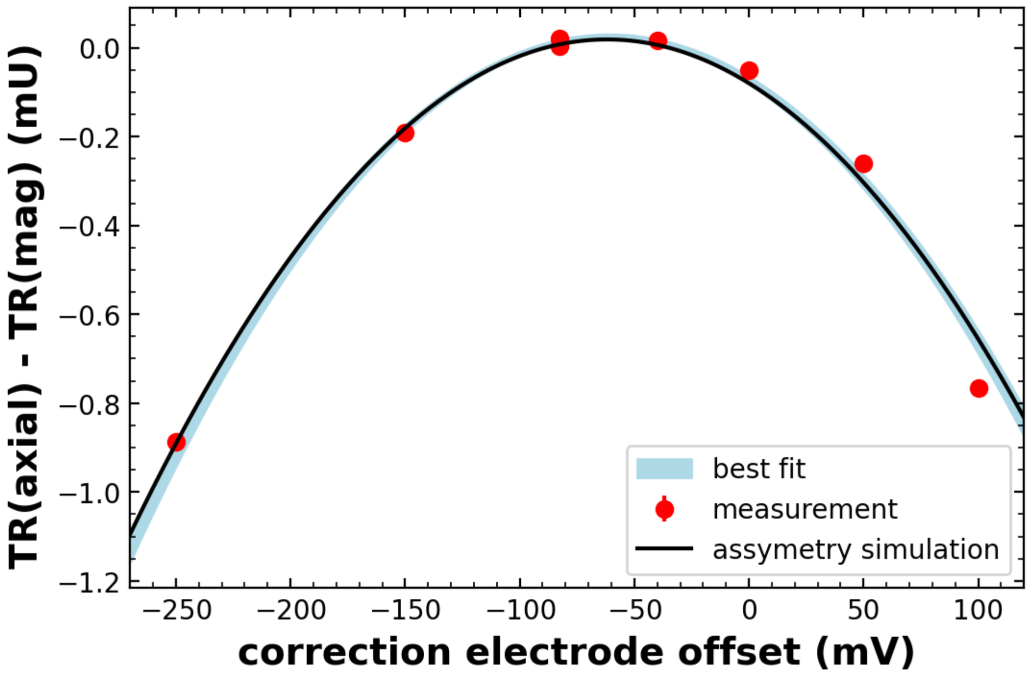
$$\frac{\Delta \nu_z}{\nu_z} \propto \left(\frac{C_4}{C_2^2} - \frac{5}{4} \frac{C_3^2}{C_2^3} + \cdots \right) E_z \to 0$$

$$\frac{\Delta \nu_z}{\nu_z} \propto \left(\frac{C_4}{C_2^2} - \frac{3}{4} \frac{C_3^2}{C_2^3} + \cdots \right) E_- \to 0$$

Combined C_3

Combine measurements to get C_3 independent of C_4





Resulting offset C_3 in the Base 2024 g-factor run: $22500 \pm 2200\, V/m^3$

Systematic Errors

C_3 leads to:

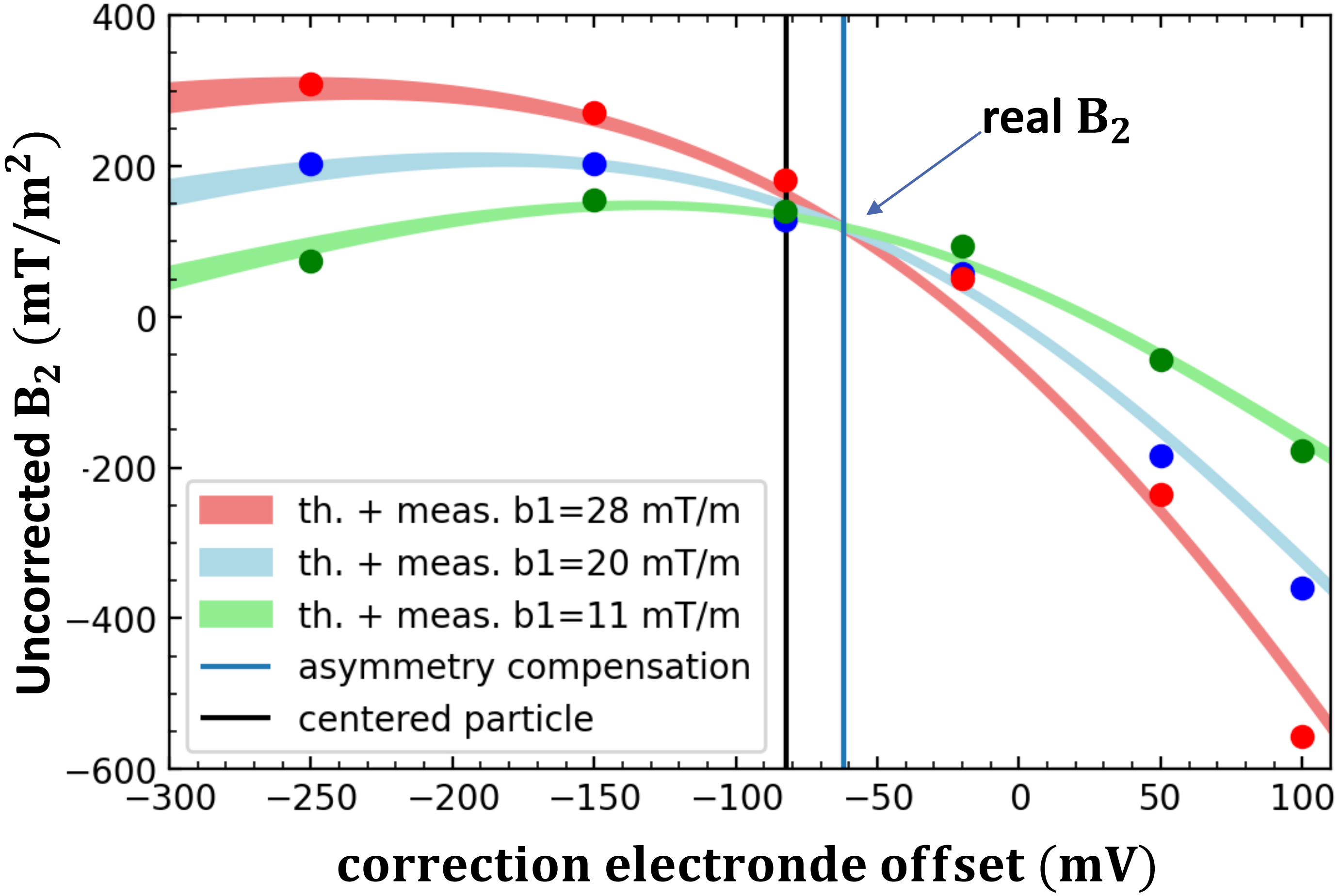
- Direct systematic shifts
- Increase residual C_4
- Increased ν_z, ν_+ scatter

Small effects <10 ppt error

BUT

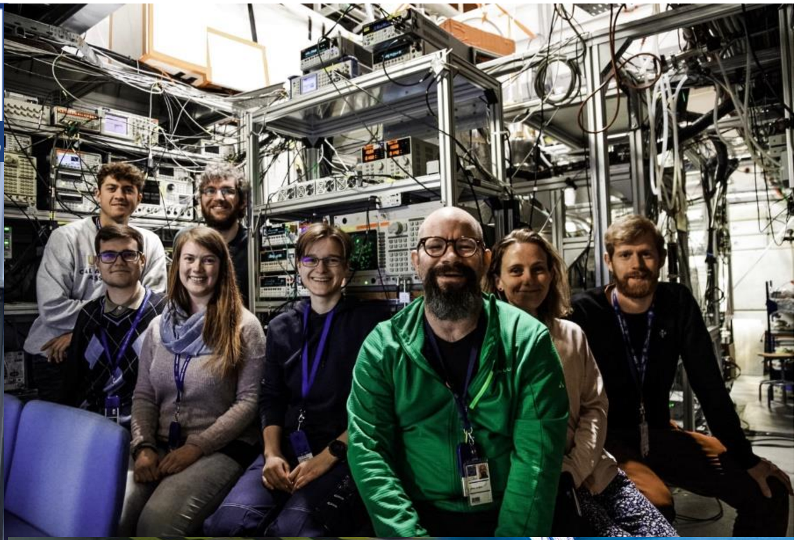
Faulty B_2 evaluation

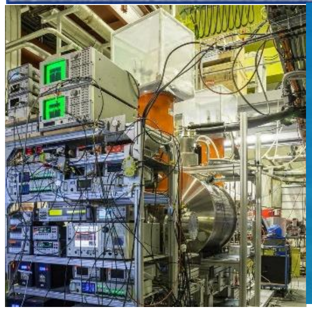
→reduced coherence time

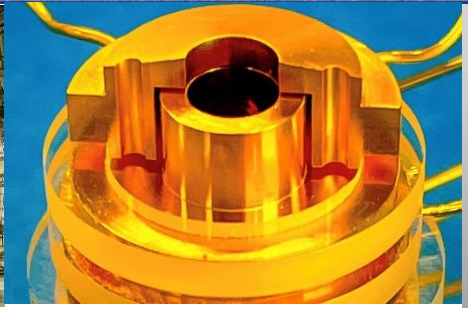


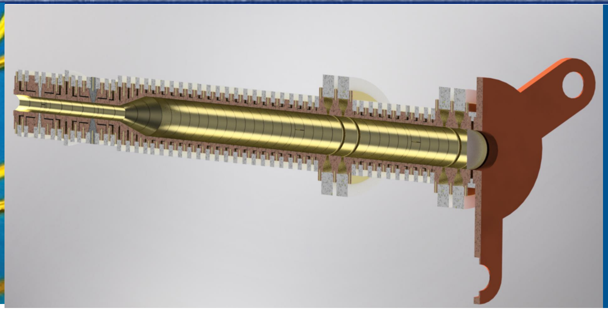
Controlling assymetry is crucial to perform sub 100 ppt g-factor experiments!

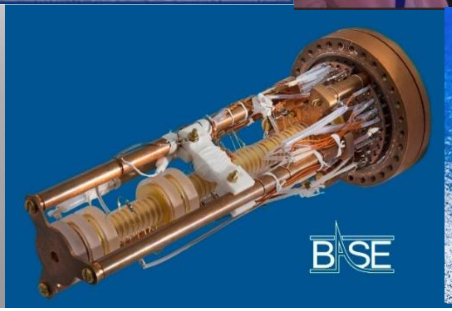
Thanks for your attention

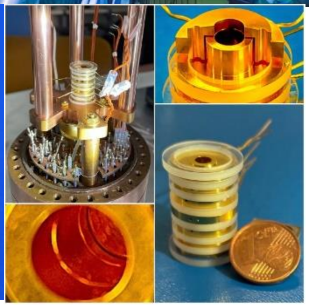








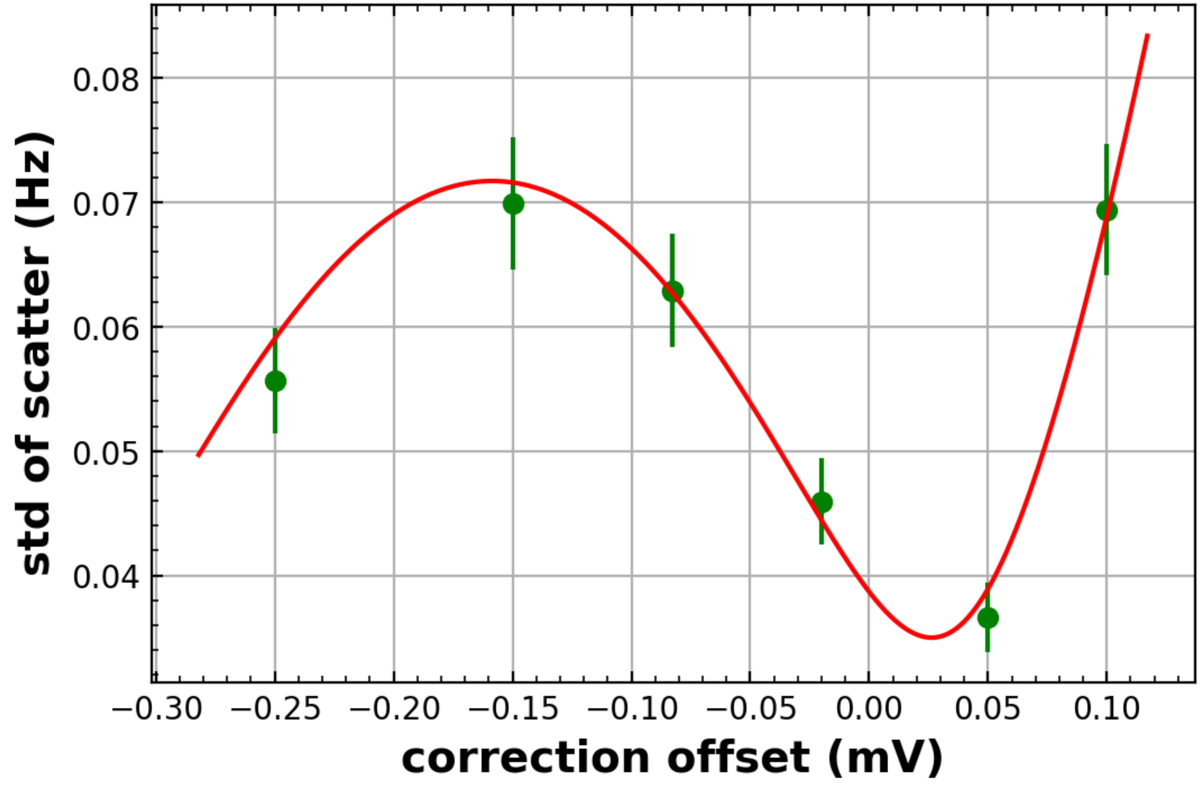




Axial scatter from E_+

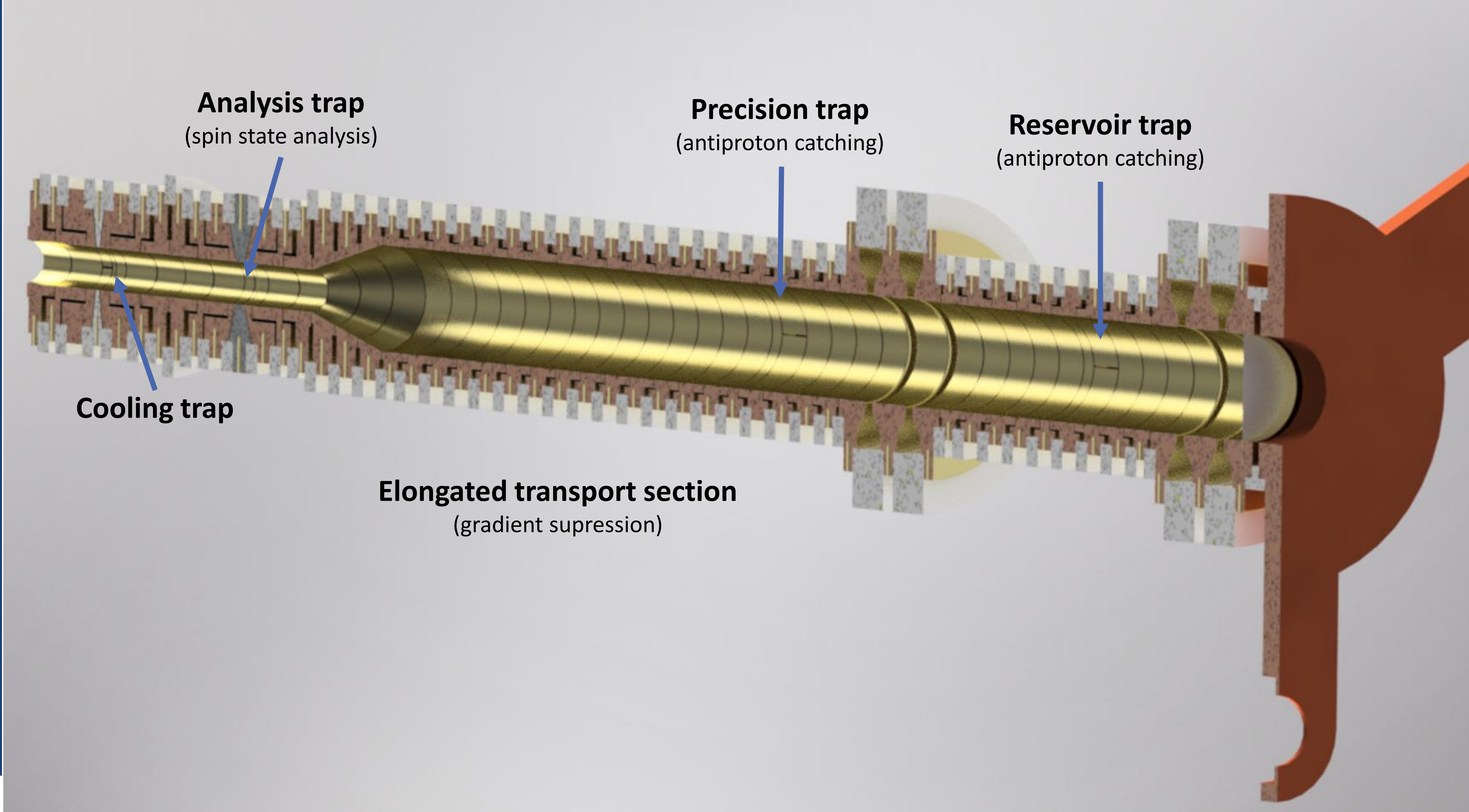
Std. scatter= $\left|X_0(B_2) + X_1(B1)c_3 + X_3 c_3^2\right|$

Background gaussian scatter axial : 33.5 mHz
Resonator temperature: 48 K



$$\nu_z(E_+) = \nu_z(0) * \left\{1 + \left(-\frac{1}{2mc^2} + \frac{1}{4\pi^2 m\nu_z^2}\frac{b_2}{b_0} + \frac{3}{4qV_0}\left[-\frac{c_4}{c_2^2}\left(\frac{\nu_z}{\nu_+}\right)^2 + \frac{3}{2}\frac{c_3^2}{c_2^3}\left(\frac{\nu_z}{\nu_+}\right)^2 - \frac{c_3 b_1}{c_2^2 b_0}\right]\right)\dots\right\} E_+$$

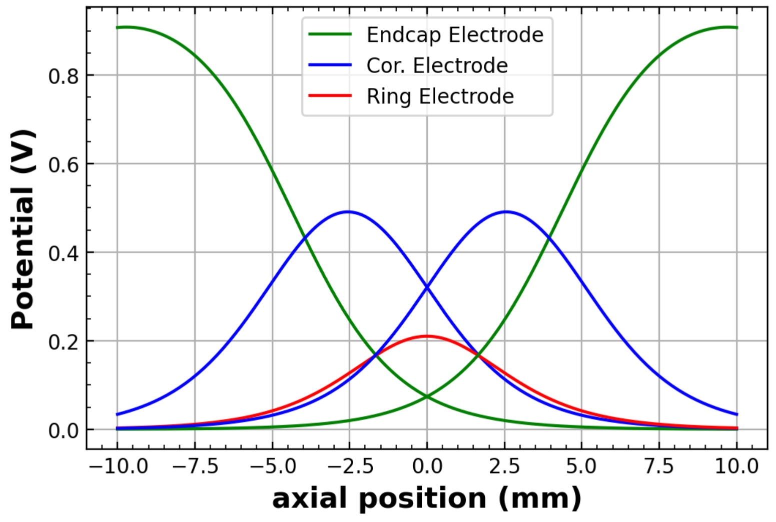
Full BASE trap stack



Potential simulation

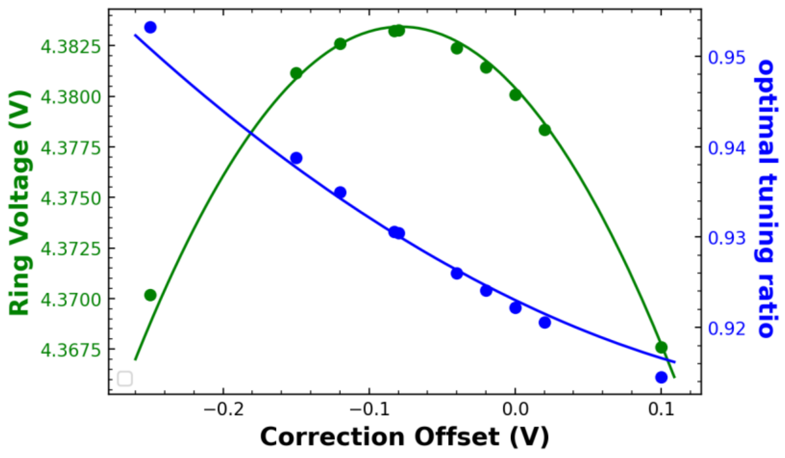
1. Solve Laplace with given geometry [1]

$$\Delta\phi(\rho,z) = \frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial}{\partial\rho}\phi(\rho,z)\right) + \frac{\partial^2}{\partial z^2}\phi(\rho,z) = 0$$

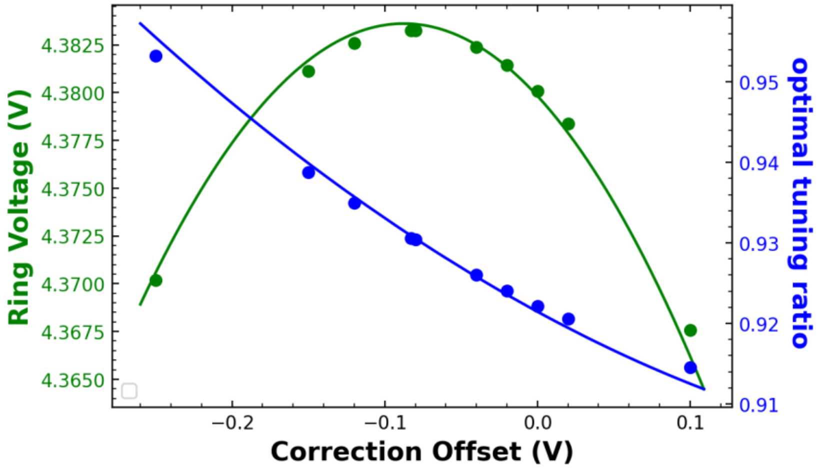


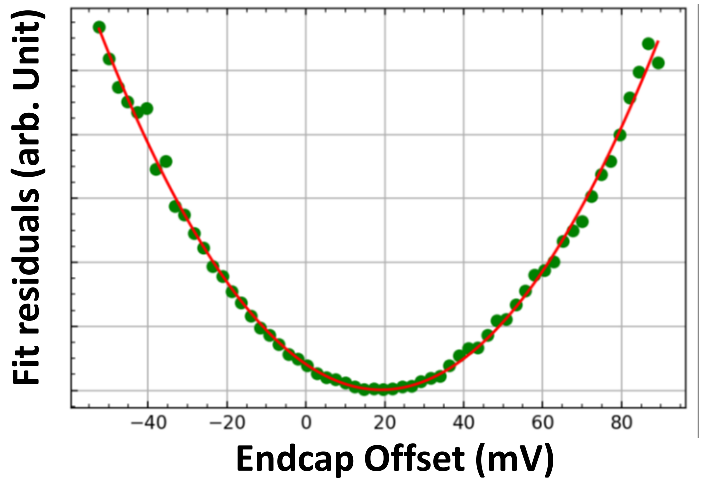
2. Calculate potential coefficient of each electrode
3. Optimise for different endcap offsets

Positive lower endcap offset



Negative lower endcap offset





[1] Ulmer, Stefan. *First observation of spin flips with a single proton stored in a cryogenic Penning trap*. Diss. Ruprecht-Karls-Universität Heidelberg, Germany, 2011.

To do mayor

- Update plots
- First slide money hierarchy
- Physics scope
- Align presentation: capital letters/slide nr etc
- Additional slides