Low Field NMR of Liquid ^{129}Xe: Progress Towards a Search for a Permanent EDM

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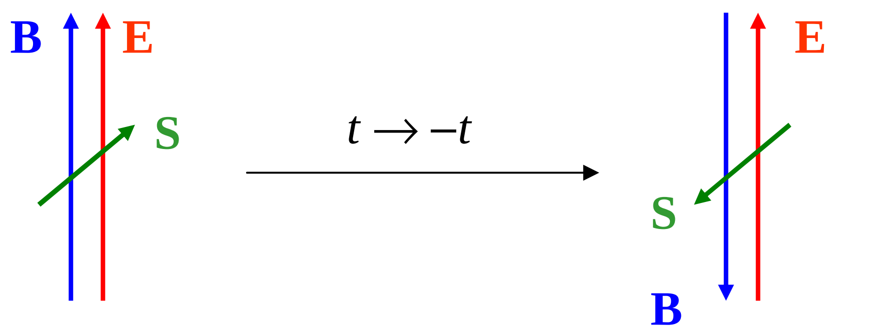
Motivations

A nonzero EDM violates time reversal invariance and is an unambiguous signal for new physics

$H = d\mathbf{S}\cdot\mathbf{E} + \mu\mathbf{S}\cdot\mathbf{B}$ $\qquad$ $H = -d\mathbf{S}\cdot\mathbf{E} + \mu\mathbf{S}\cdot\mathbf{B}$



Extra sources of CP violation are necessary to account for the observed matter/antimatter asymmetry.

Supersymmetry naturally predicts large EDMs and fixes other problems in the Standard Model such as the electroweak hierarchy problem.

Why Liquid Xenon?

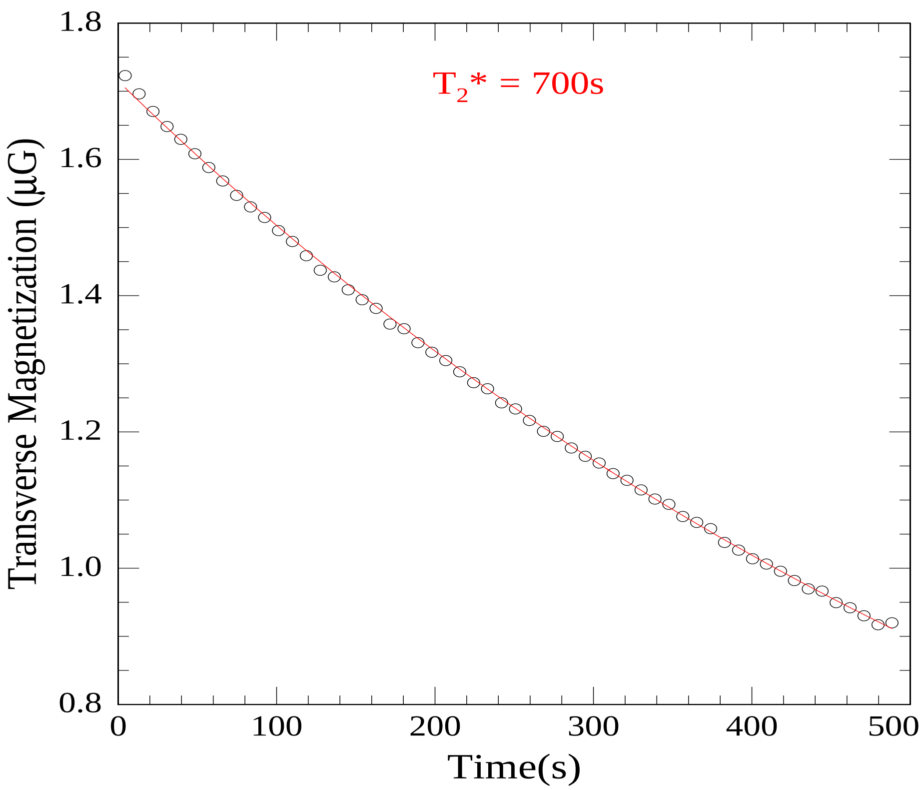
High Density: ~10^{22} atoms
Long transverse relaxation time: ~1300s [1]
Large electric field breakdown: ~400kV/cm

$$\hbar\delta\omega = 2dE$$

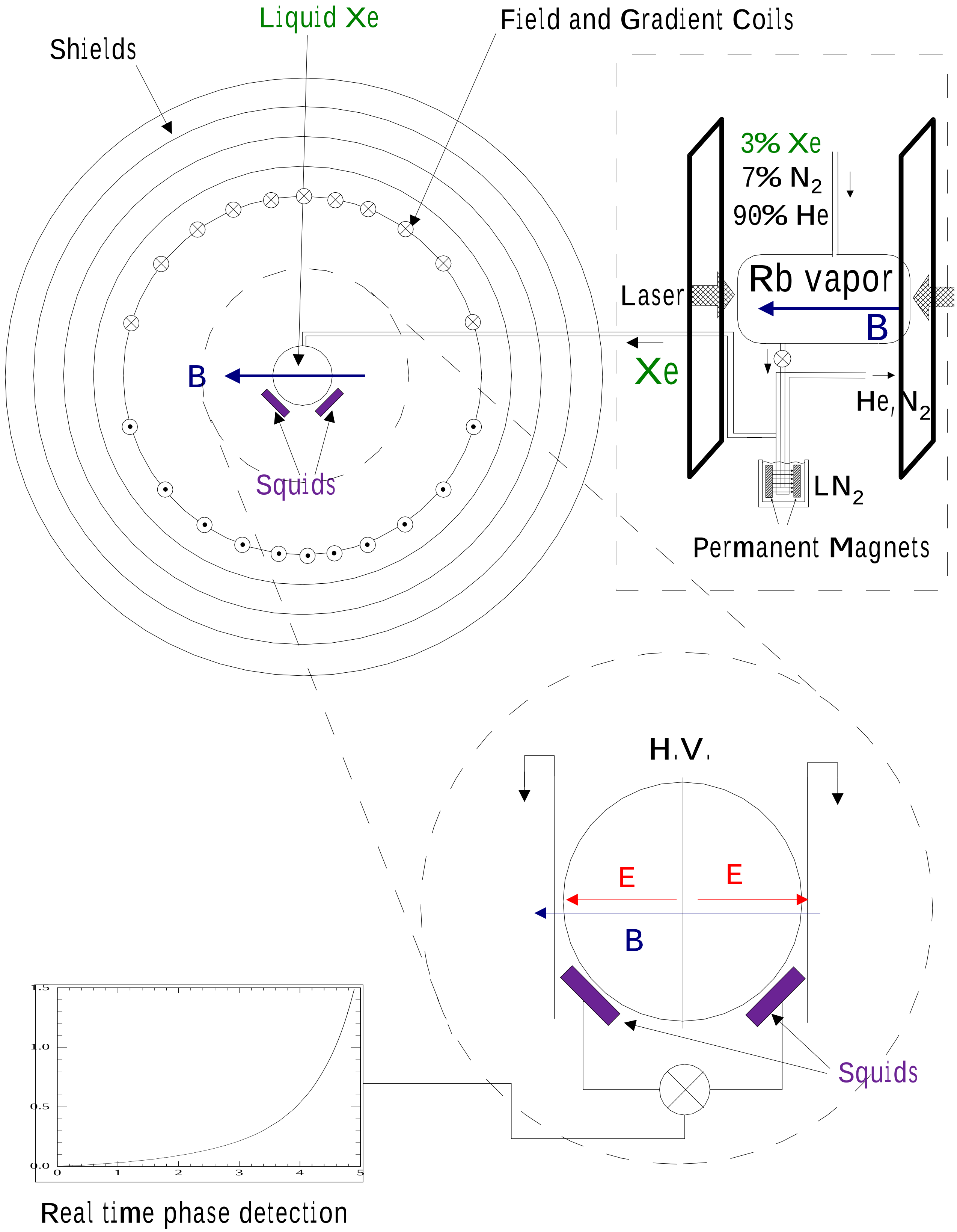
$$\delta\omega = 1/\sqrt{2NT_2t}$$

Shot noise limit: ~$5*10^{-37}$ *e* cm in one day!

Conservative limit: ~10^{-31}-10^{-32} *e* cm



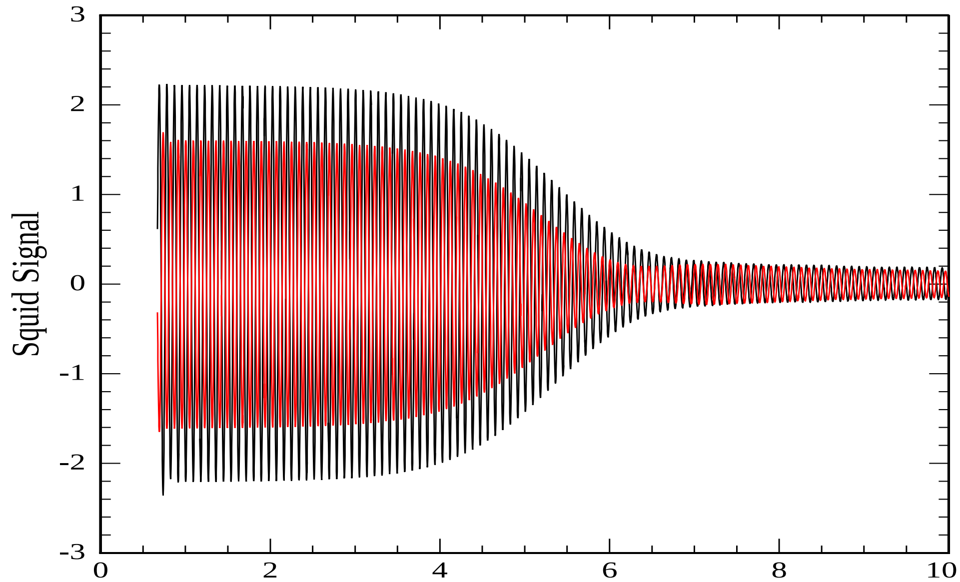
[1] M.V. Romalis and M.P. Ledbetter Phys. Rev. Lett. **87**, 67601 (2001)

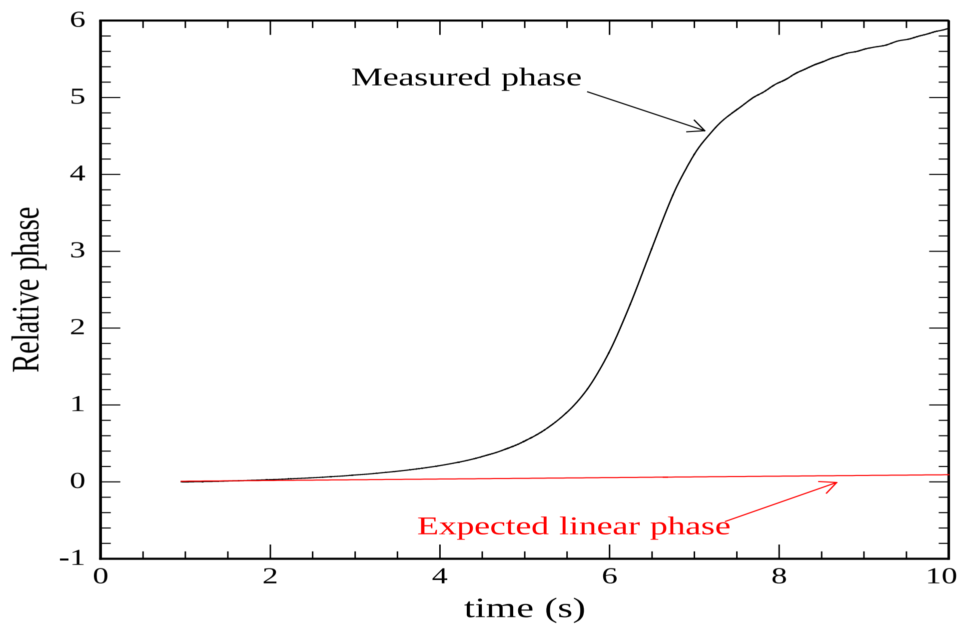


Liquid Xe
Field and Gradient Coils
Shields
3% Xe
7% N_2
90% He
Rb vapor
Laser
B
Xe
He, N_2
LN_2
Permanent Magnets
B
Squids
H.V.
E
E
B
Squids
0.0
0.5
1.0
1.5
0
1
2
3
4
5
Real time phase detection

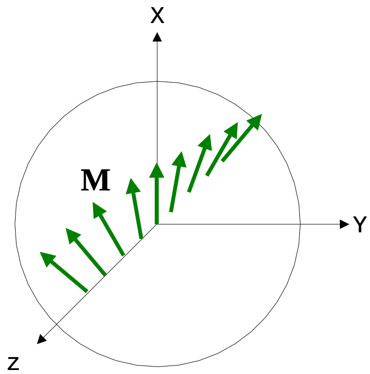
An interesting twist

Highly nonlinear behavior in the presence of an applied magnetic field gradient due to dipolar fields and slow diffusion.





Neglecting self interactions: simple helical configuration, pitch grows linearly with time



$$M_x = M_0$$

$$M_y = m_y(t) z$$

$$m_y(t) = M_0 g \gamma t$$

Boring….

Things get interesting if we include the dipolar fields:

$$M_y = m_y(t) z / R \quad \longrightarrow \quad B_y = \frac{8\pi}{15} m_y(t) z / R$$

$$M_x$$

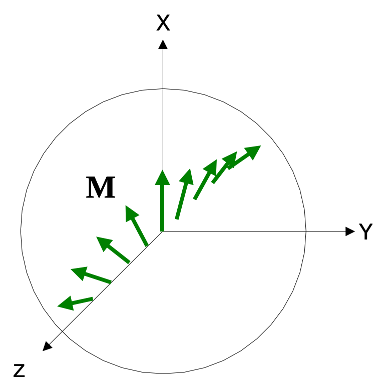
$$M_z = m_z(t) z / R \quad \longrightarrow \quad B_z = \frac{16\pi}{15} m_z(t) z / R + gz$$

The solution to the Bloch equations yield an exponentially growing gradient of the magnetization!!

$$m_y(t) = \frac{-\gamma M_0 g R \sin\alpha \sinh(\beta t)}{\beta}$$

$$\beta = \frac{8\pi}{15} M_0 \gamma \kappa \sqrt{\frac{1 - 3\cos(2\alpha)}{2}}$$

$$\kappa = \begin{cases} 1 & \parallel \text{ gradients} \\ 1/2 & \perp \text{ gradients} \end{cases}$$



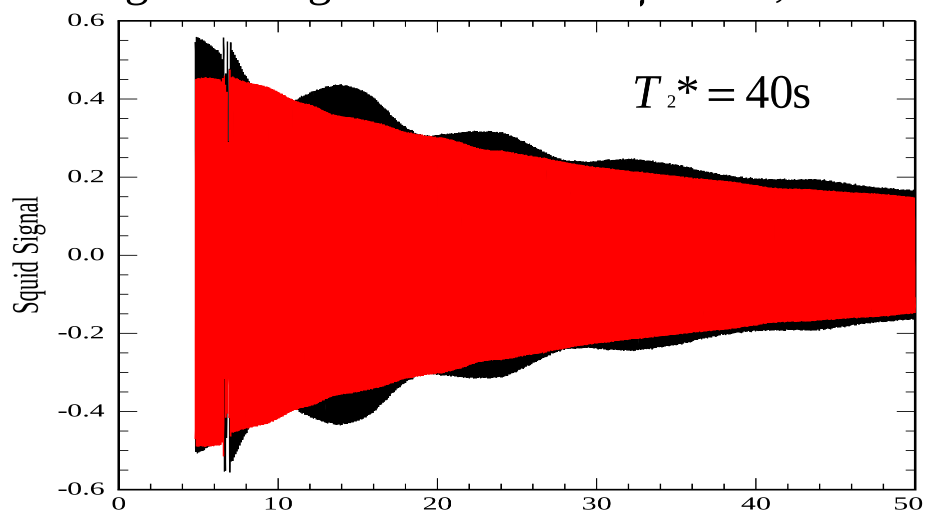
Initially shallow helical pitch due to a nonzero EDM is amplified exponentially

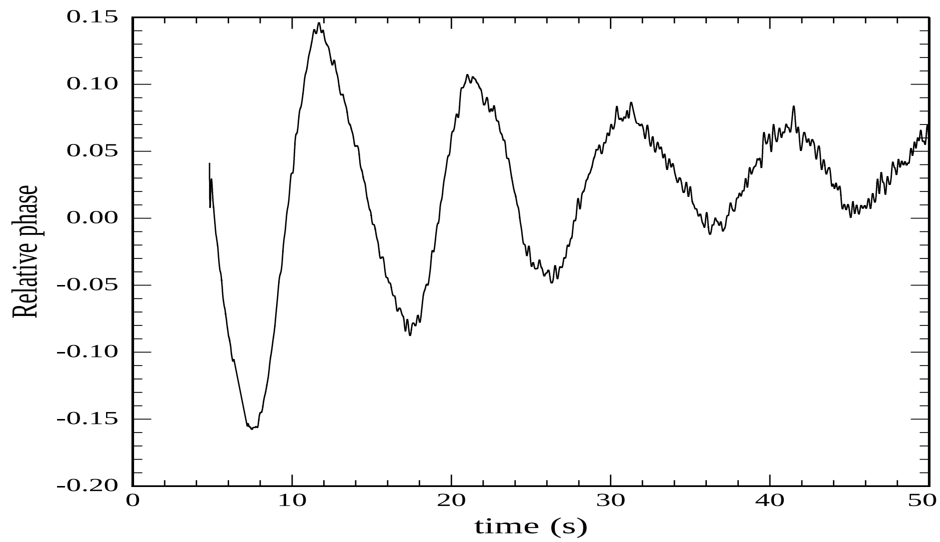
Two qualitatively different regimes:

$$\beta = \frac{8\pi}{15} M_0 \gamma \kappa \sqrt{\frac{1-3\cos(2\alpha)}{2}} = \begin{cases} \text{imaginary} & \alpha < 35° \\ \text{real} & \alpha > 35° \end{cases}$$

For small tip angles, large scale phase growth is suppressed and replaced by oscillations

Applied longitudinal gradient of $\sim 56\mu\text{G/cm}, \alpha = 17°$

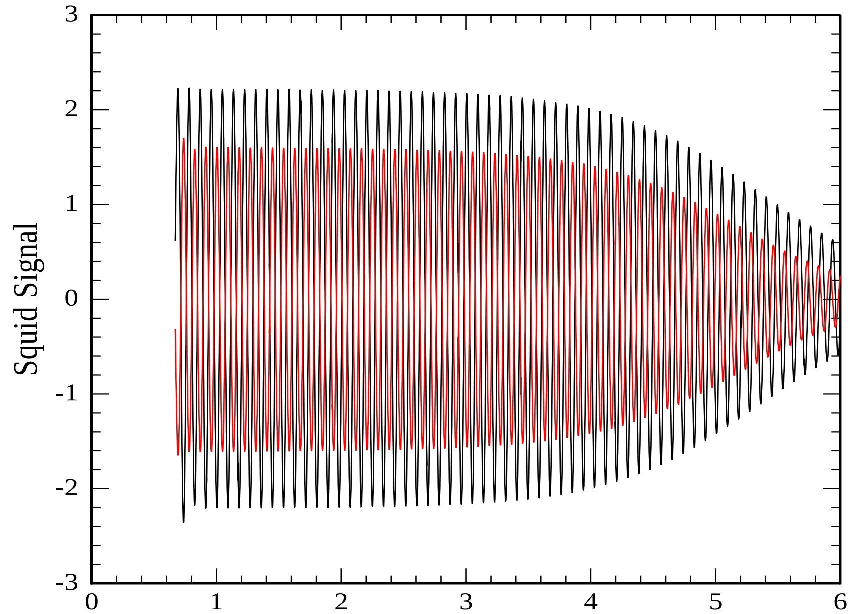


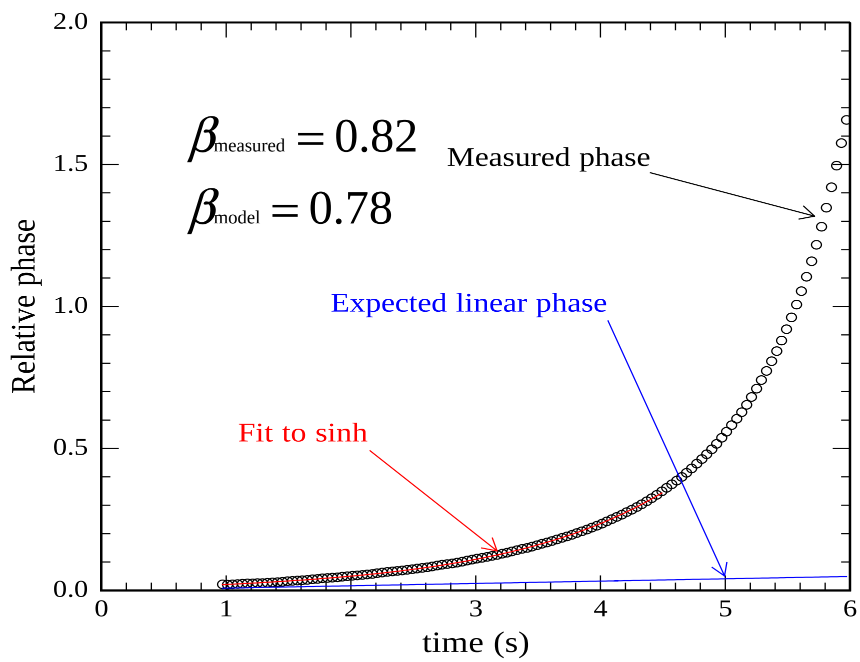


Expectations for non self-interacting system: $\begin{cases} T_2{}^* \approx 5s \\ \varphi \approx 30 \text{ rad at } 40\text{s} \end{cases}$

Large tip angles, exponential phase growth:

Applied longitudinal gradient of $\sim 5\mu\text{G/cm}, \alpha = 90°$





$$gain = \frac{\phi_{interacting}}{\phi_{lin}} = \frac{\sinh(\beta t)}{\beta t} \xrightarrow[t \to 1000]{} \approx 10^{431}$$

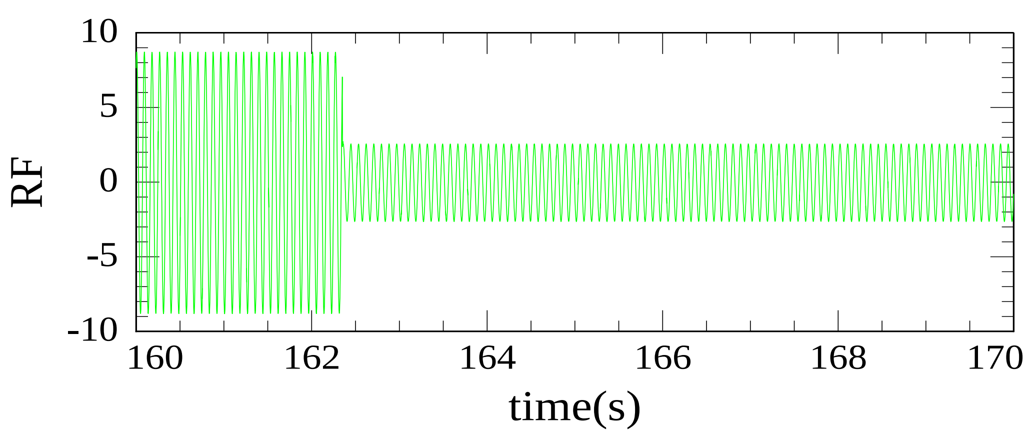
Transverse Gradients?

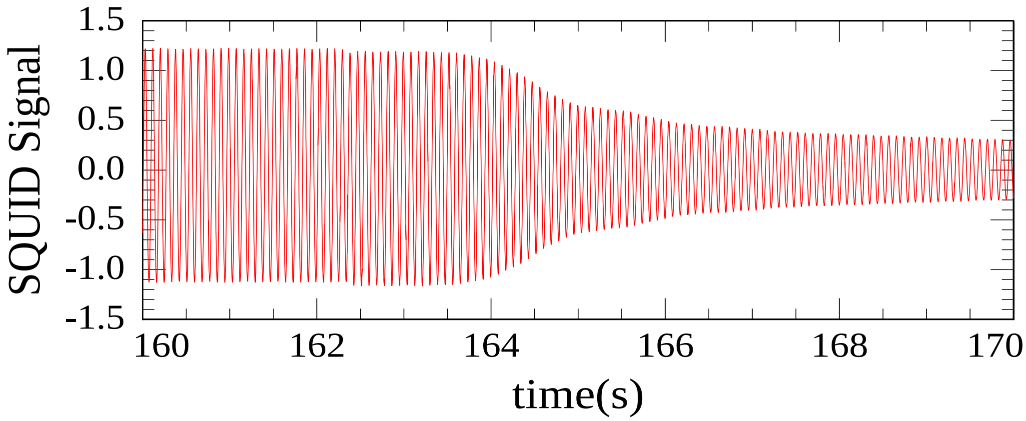
Squids are sensitive to dephasing only in the longitudinal direction

Reduce sensitivity of the spin system to transverse gradients by applying a small magnetic field in the rotating frame.

$$\beta = \sqrt{\left[\left(\frac{16\pi}{15}\kappa^2\gamma M_0 - \gamma B_{rot}\right)\left(\frac{8\pi}{15}\gamma M_0 + \gamma B_{rot}\right)\right]}$$

$$= \begin{cases} \text{imaginary if} & \gamma B_{rot} > \frac{16\pi}{15}\kappa^2\gamma M_0 \\ \text{real} \quad \text{if} & \gamma B_{rot} < \frac{16\pi}{15}\kappa^2\gamma M_0 \end{cases} \qquad \begin{matrix} \kappa_\perp = 1/2 \\ \kappa_\parallel = 1 \end{matrix}$$





Summary

- First experimental study of nonlinear effects in a spherical cell with detailed phase information.
- Suppression of dephasing due to applied field gradients for small angle pulses.
- Exponential enhancement of phase shift for large angle pulses.
- With low sensitivity high T_c SQUID detectors we may perform an EDM search that approaches the shot noise limit relatively easily.