Atomic Magnetometry for neutron EDM experiment

J. Martin, W. Klassen, C. Cerasani,
R. Mammei, M. Lang, T. Andalib,
D. Ostapchuk, and C. Bidinosti

The University of Winnipeg

Need for Precision Magnetometry

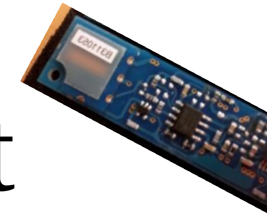
$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

- The EDM (*d*) term violates CP.
- New sources of CP violation required in e.g. electroweak baryogenesis.

$$h\nu = 2\mu B \pm 2dE$$

- Precision goal $\delta d_{stat} = 10^{-25}$ e-cm / 100 s.
- Requires *average B* known to $\delta B < 16$ fT, operating field $B = 1\ \mu$T.

Magnetometers on the Market



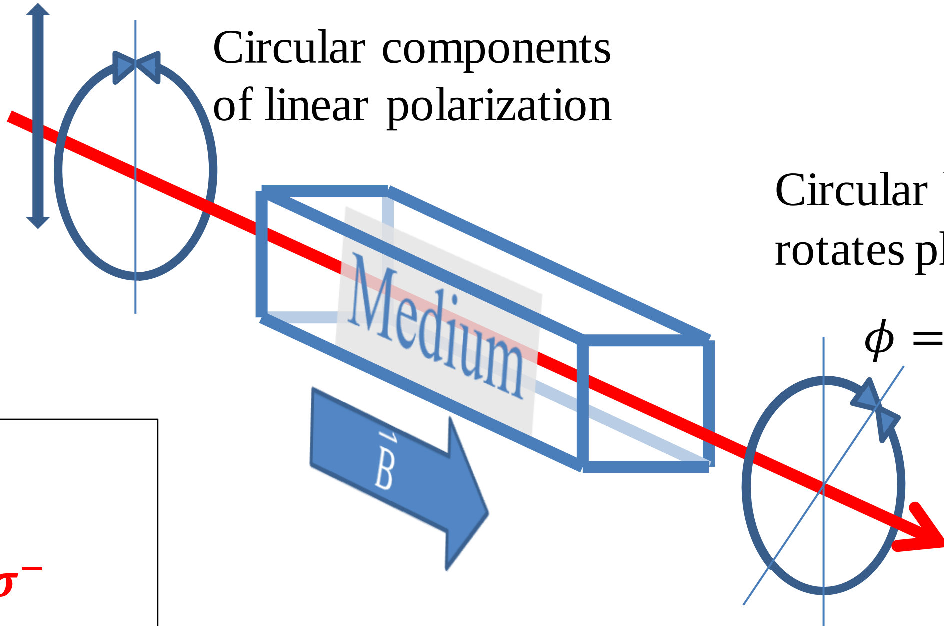
• Hg-199, Xe-129	10 fT in 100 s	
• Fluxgates	10 pT/rtHz	magnetic
• GMI	10 pT/rtHz	
• SQUID	1 fT/rtHz	cryogenic

Alkali Atom Magnetometers

• Ls OPM (Mx)	~10 fT/rtHz	RF
• NMOR	2 fT/rtHz	all-optical
• SERF	160 aT/rtHz	$B = 0$

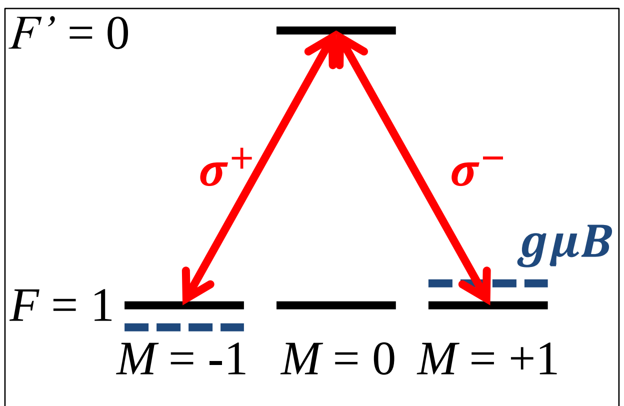
We have been studying NMOR-based magnetometers at U. Winnipeg
(as well as Xe-129, Fluxgates, GMI, and SQUID's but that's not in this talk)

Magneto-optical rotation (Faraday rotation)



Circular birefringence ($n_{\pm}$) rotates plane of polarization

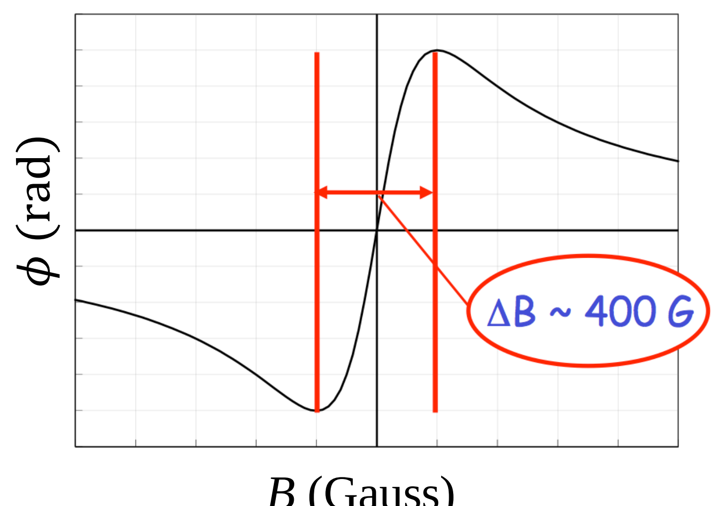
$$\phi = \pi(n_{+} - n_{-})\frac{l}{\lambda}$$



Linear effect from Zeeman splitting

$$\phi = \frac{2g\mu B/\hbar\Gamma}{1 + (2g\mu B/\hbar\Gamma)^2}\frac{l}{l_0}$$

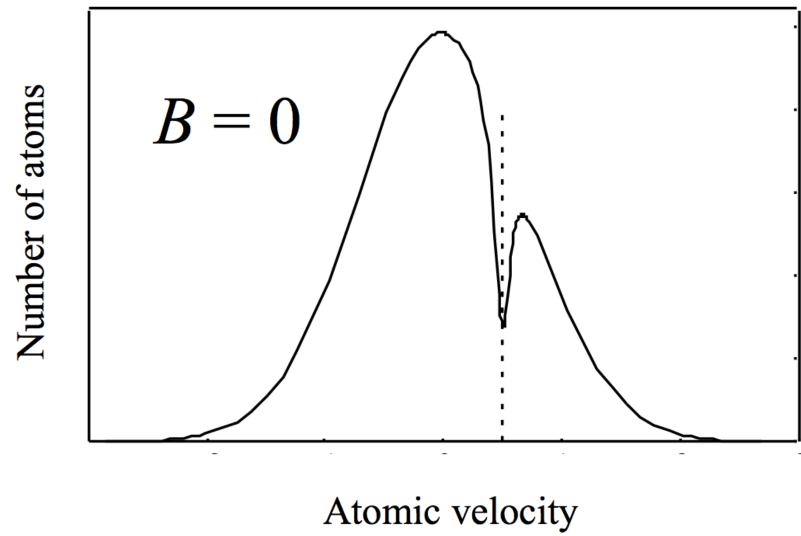
Doppler width Γ ~ GHz



Nonlinear Magneto-Optical Rotation (NMOR)

Nonlinear = light modifies the medium

1. <u>Hole burning</u>:
   Light depletes ground-state velocity distribution.
2. <u>Coherent dark state</u>:
   Linearly polarized light $\Delta M = \pm 1$ selection rule creates coherent dark state.

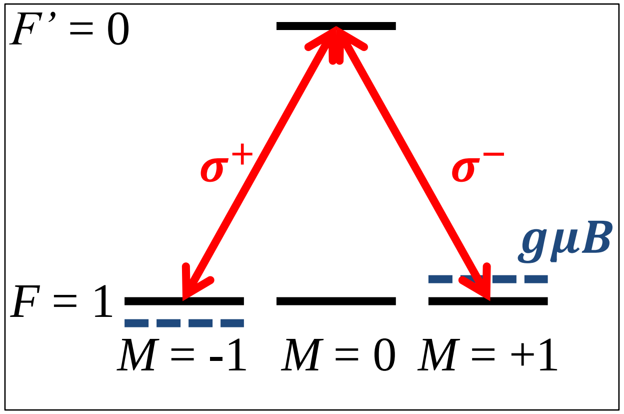


burned

$$\frac{1}{\sqrt{2}}(|M = 1\rangle + |M = -1\rangle)$$

$$|M = 0\rangle$$

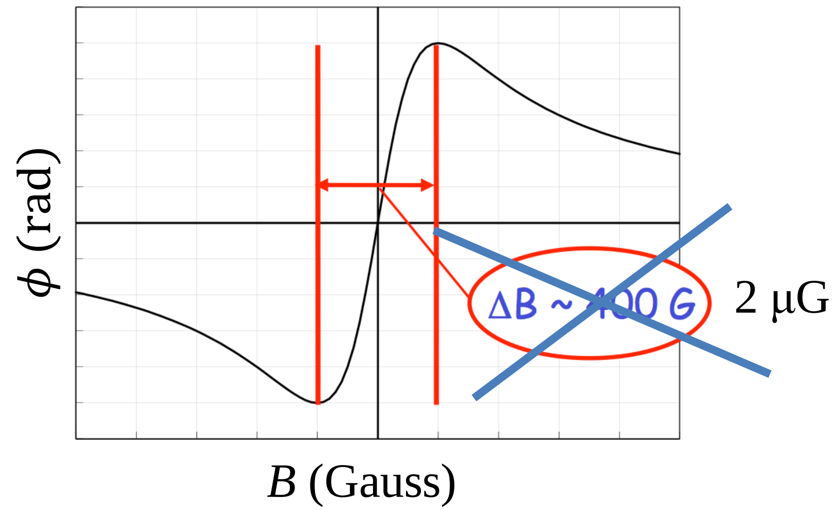
$$\frac{1}{\sqrt{2}}(|M = 1\rangle - |M = -1\rangle)$$



NMOR

- Medium becomes linearly dichroic
- Axis of alignment rotates by Larmor precession in the magnetic field
- Net result: again, circular birefringence.

$$\phi = \frac{2g\mu B/\hbar\gamma_{rel}}{1+(2g\mu B/\hbar\gamma_{rel})^2}\frac{l}{l_0}$$



$\Gamma \to \gamma_{rel}$

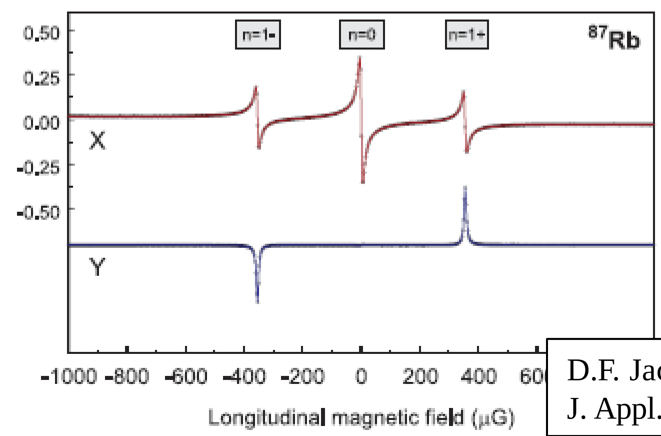
GHz → Hz

400 G → 2 μG

40 mT → 200 pT

Removing Limitation on the Dynamic Range: AM/FM NMOR

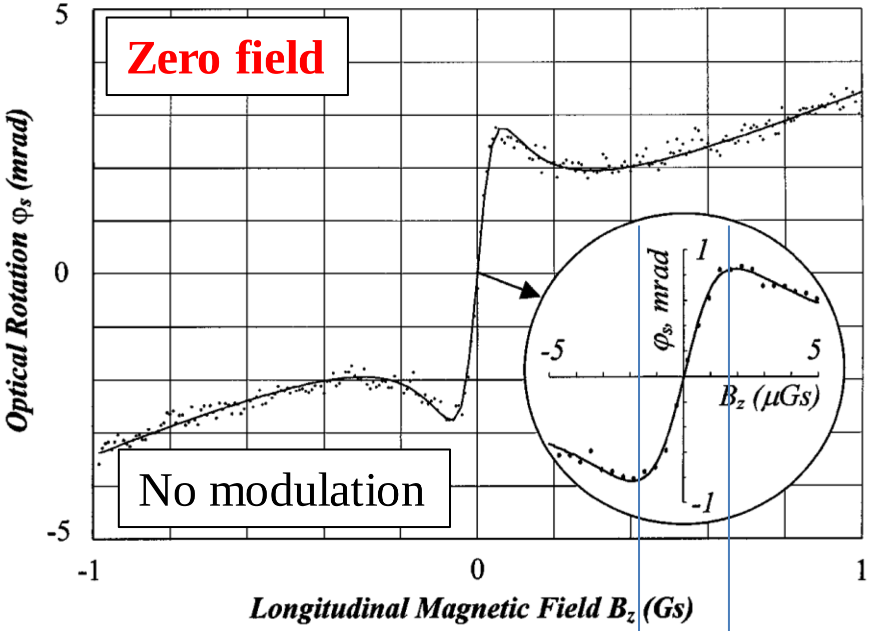
- Axis of alignment in the vapour rotates at $\omega_L = \gamma B$,
  γ = 4.7 kHz/μT (^{85}Rb)
- Stroboscopic effect: flash the laser light at $2\omega_L$
- Displaces the resonance from zero field to B.

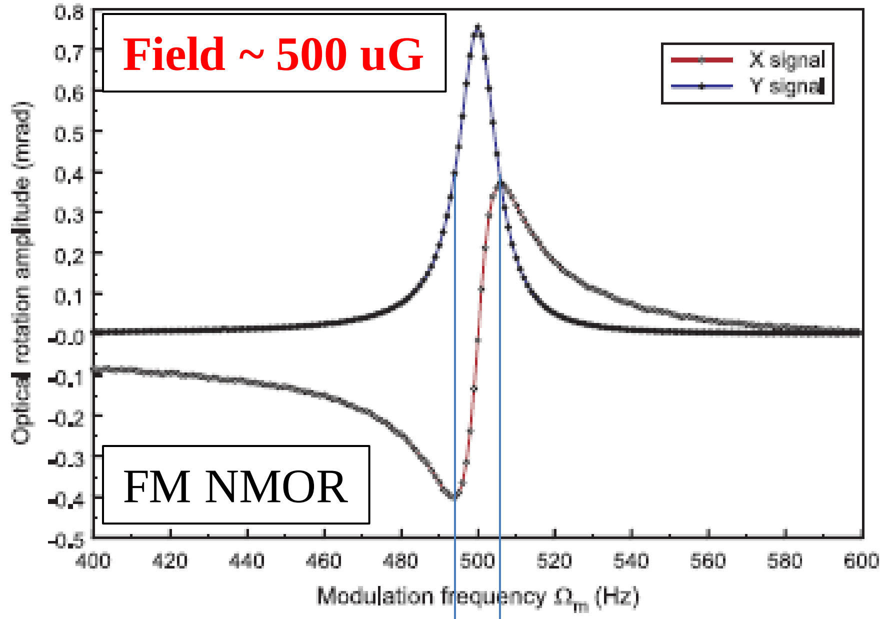


FM NMOR
@ 500 Hz
Rb-87

D.F. Jackson-Kimball, et al.,
J. Appl. Phys. **106**, 063113 (2009)

Previous Work of Others





2.8 μG=
280 pT

15 μG=
1.5 nT

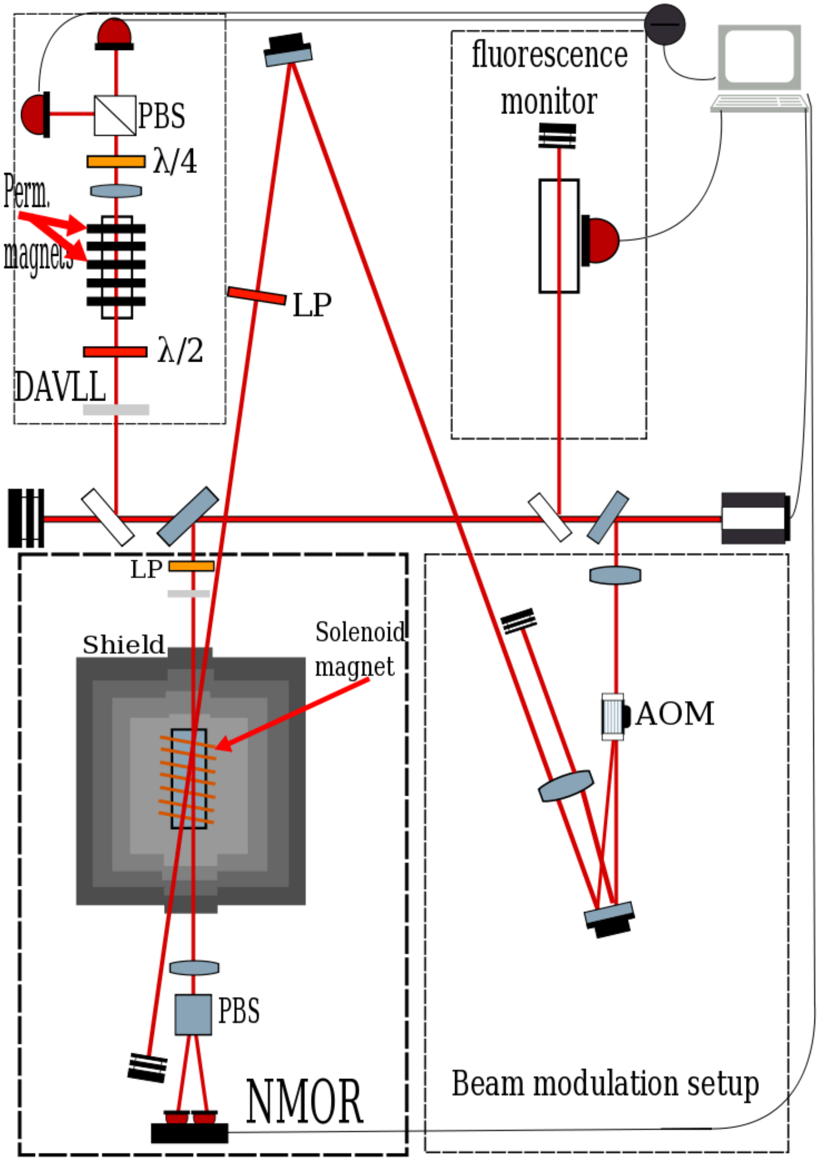
$$\delta B_{\mathrm{SNL}} \approx \frac{1}{g_F \mu_0} \sqrt{\frac{\gamma_{\mathrm{rel}}}{N\tau}}$$

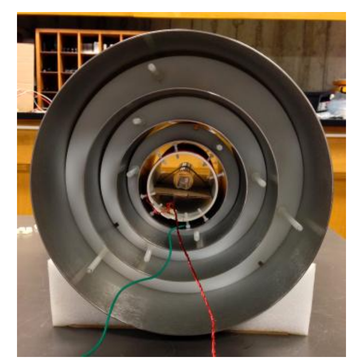
=2 fT/rtHz
(T=35^{o}C)

D. Budker, et al.,
PRL **81**, 5788 (1998)

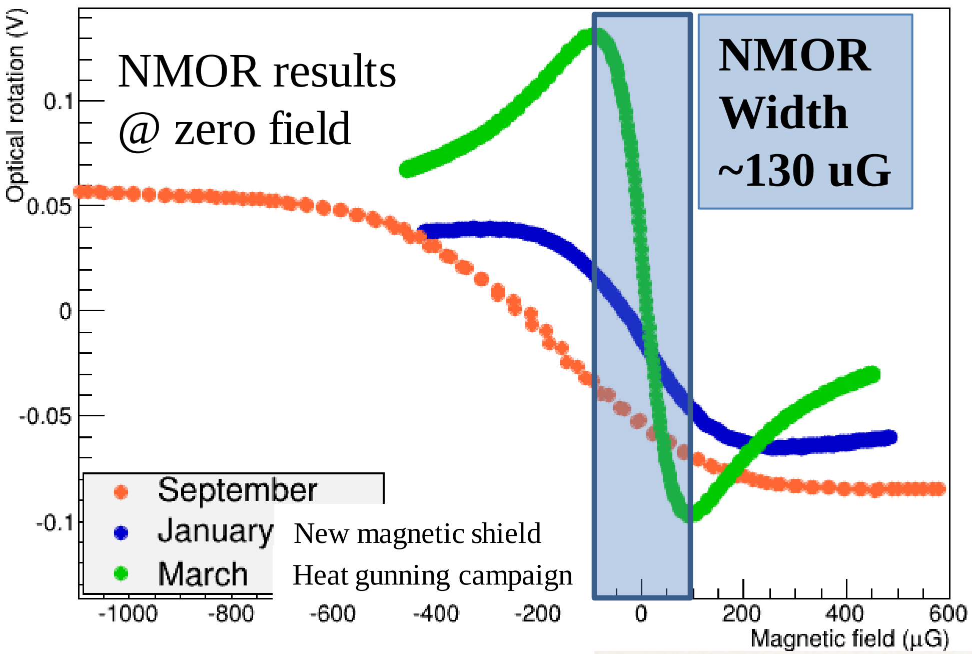
D.F. Jackson-Kimball, et al.,
J. Appl. Phys. **106**, 063113 (2009)

Our Work - Apparatus





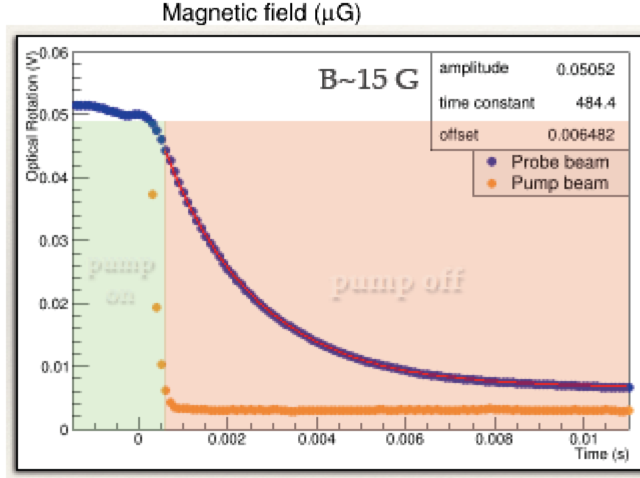
Results from 2013-14 school year



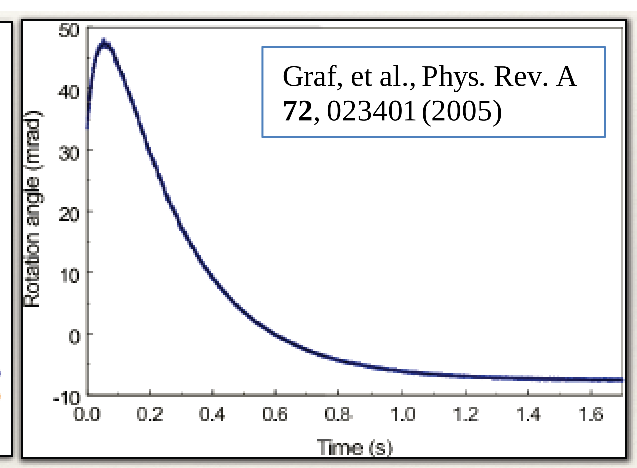
C. Cerasani, Hons. Thesis (2014).

Direct Measurement of Relaxation of Axis of Alignment

Clear indicator of issues with cell/coating quality (paraffin)

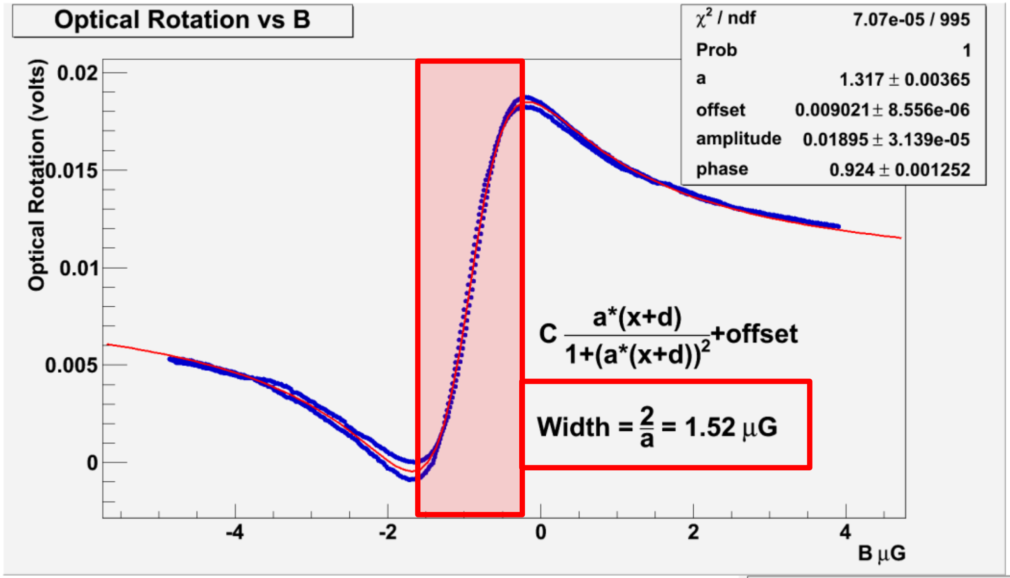


Us: $\tau = 2.1$ ms $= 1/\gamma_{rel}$



Graf: $\tau = 0.4$ s $= 1/\gamma_{rel}$

New Cell (borrowed from D. Budker)

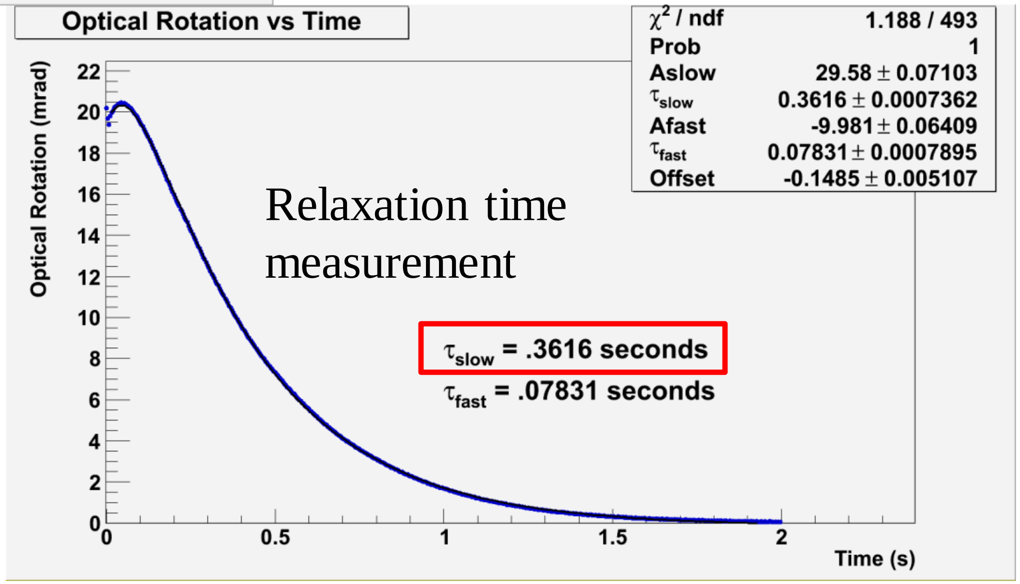


- NMOR width ~ 1.5 μG = 150 pT
- γ_{rel} ~ 1/0.36 s = 2.8 Hz

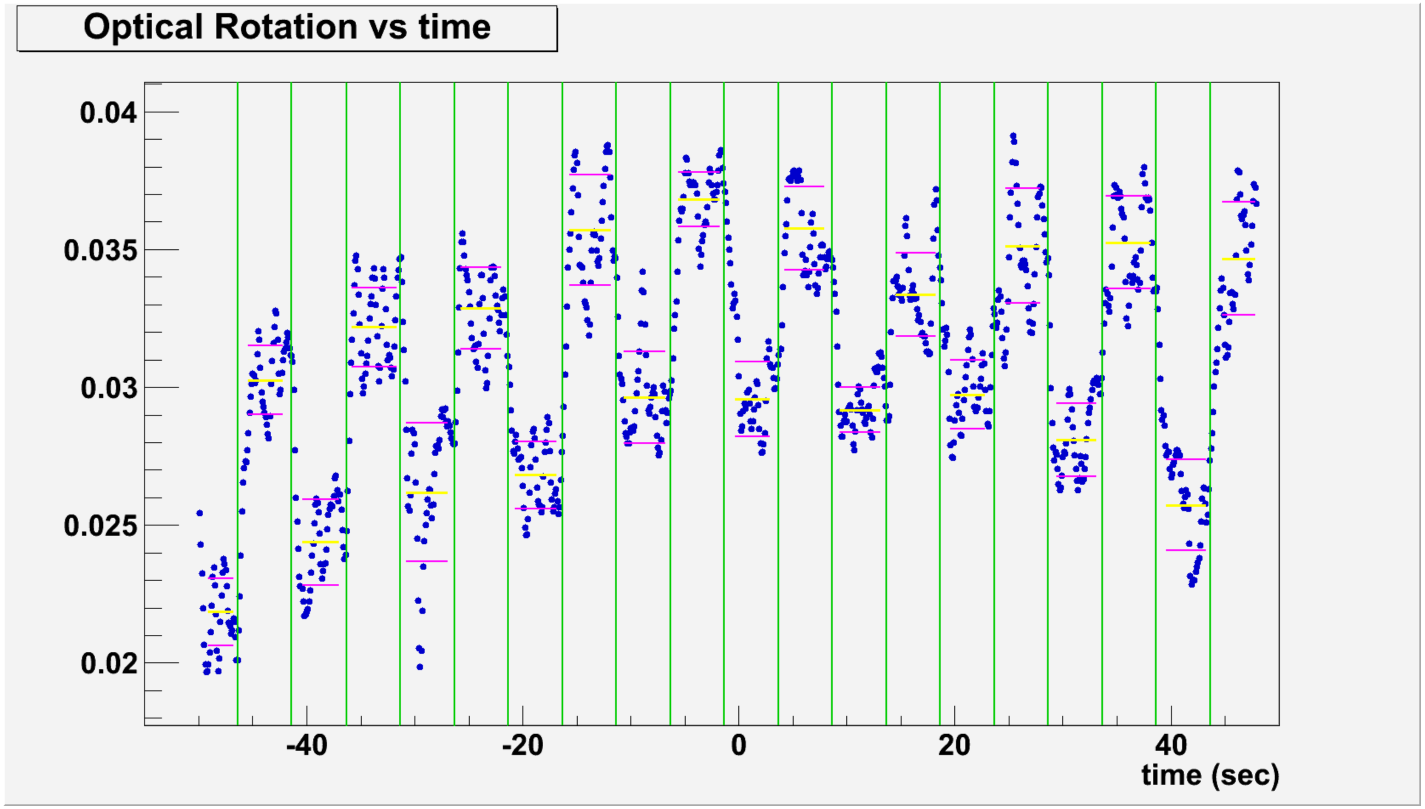
Consistent with Budker's best results!

"Dear Dima and Brian,
Your cell works great!"

New cells from Balabas expected.

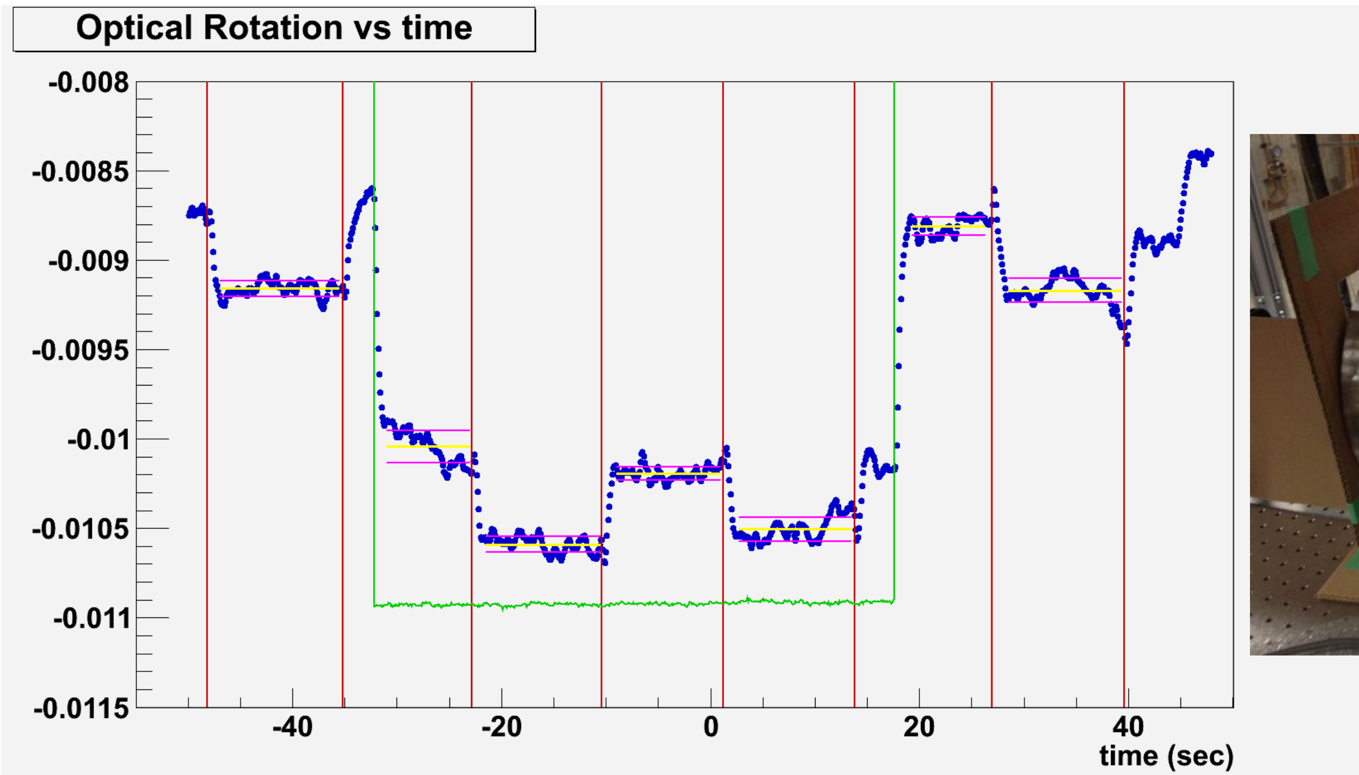


Measuring small fields



± 46 fT steps in applied magnetic field.
1 Hz filter applied to optical rotation signal.
Probe power 13 uW.

Application: Measurement of very large magnetic shielding factors

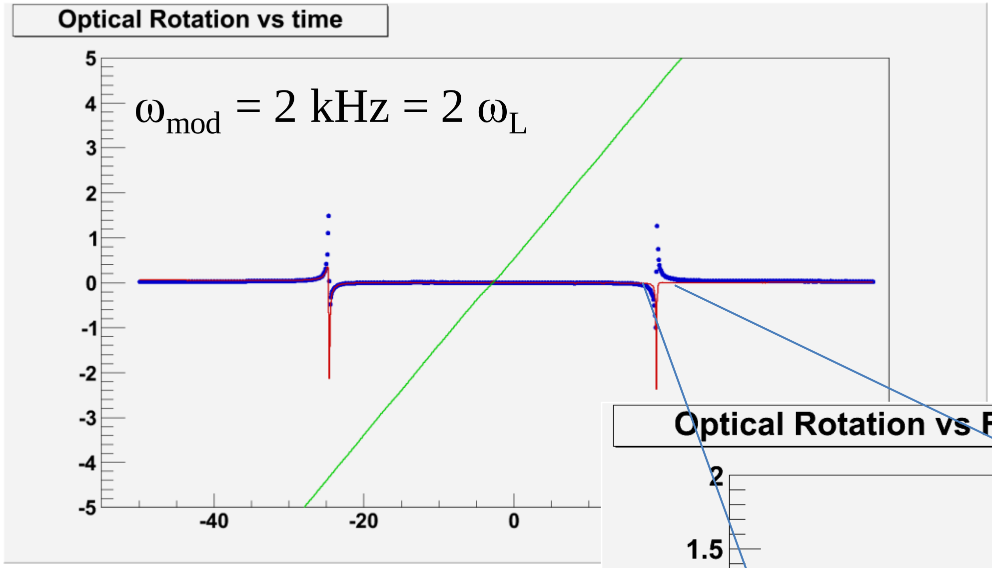


Green: internal field (calibration, ±500 fT)

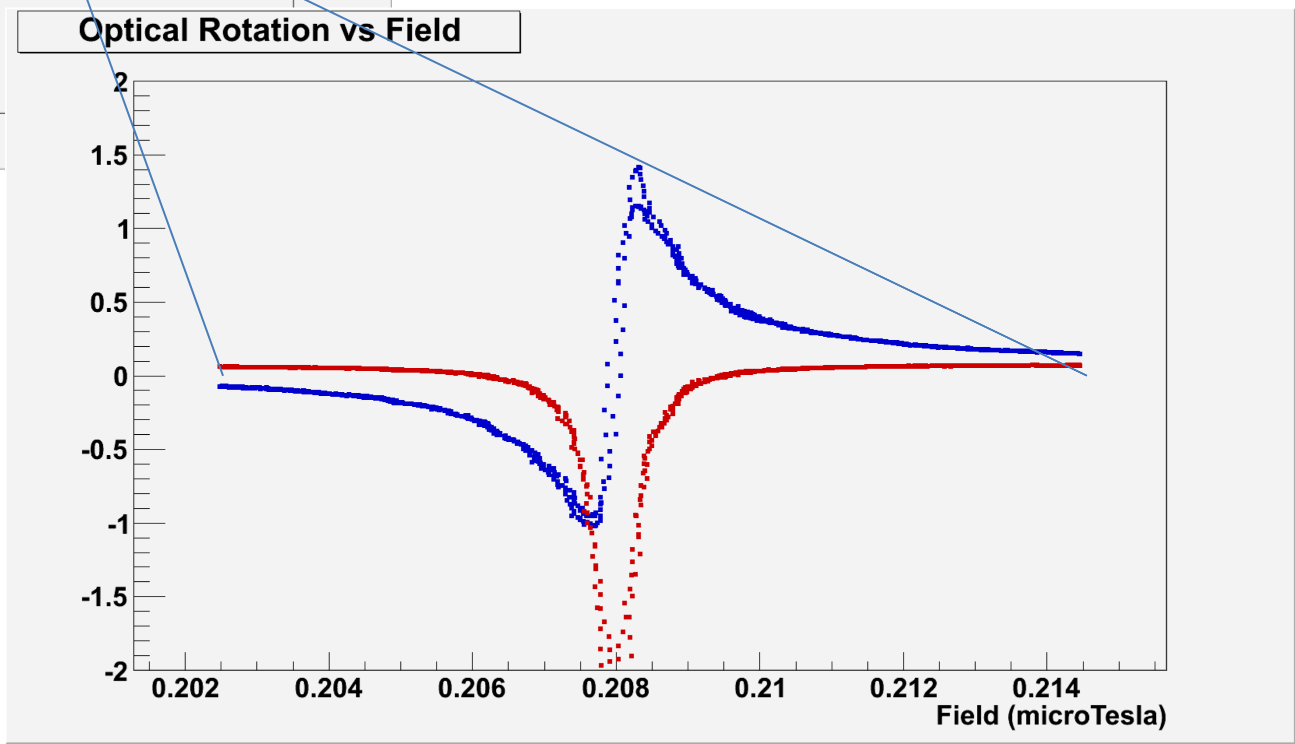
Red: external field (applied ±2 μT, unknown shielding factor)

Conclusion: The shielding factor is 1.5 x 10^7, couldn't have been measured otherwise.

AM NMOR



- Width ~ 1 nT Consistent with Jackson-Kimball.
- Larmor frequency consistent with fluxgate calibration 0.21 μT



- Noise ~ pT
- Still working to make it better.
- Room temperature.
- Quantifying existing magnetic noise, field quality.

Conclusions

- Precision magnetometry below 1 pT is critical for nEDM measurement.
- AM NMOR is studied as a solution for fT-level magnetometry.
- System developed at U. Winnipeg approaches this goal
    - NMOR widths consistent with best published values.
    - ~30 fT/rtHz noise @ 1 Hz for zero field
    - ~pT/rtHz noise @ 1 Hz for 0.22 uT applied field – we are working hard to understand and make it better.
- Method already applied to measurements of very large axial magnetic shielding factors with very small applied fields.

Future

- Make the best magnetometer we can based on this system and use it to study magnetic shielding, generation of magnetic fields.
- Using this system will make us experts capable of employing a Cs-based fiberized system for the eventual nEDM experiment.
- New: B. Patton et al "All-Optical Vector Atomic Magnetometer" arXiv:1403.7545!!!
- Developing collaboration with Budker, Balabas.
A big thank you to D. Budker, B. Patton, and M. Solarz for the use of their cell.

Thanks NSERC, CRC, CFI, MRIF.