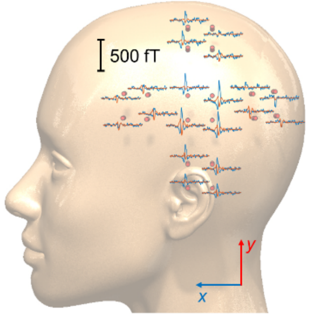
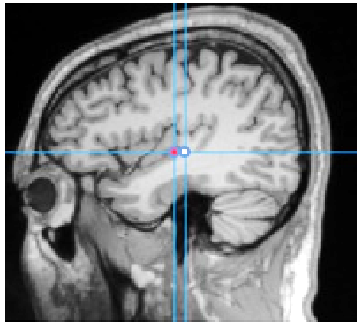
SAND2024-15474C

Introduction to Optically Pumped Magnetometers (OPMs)

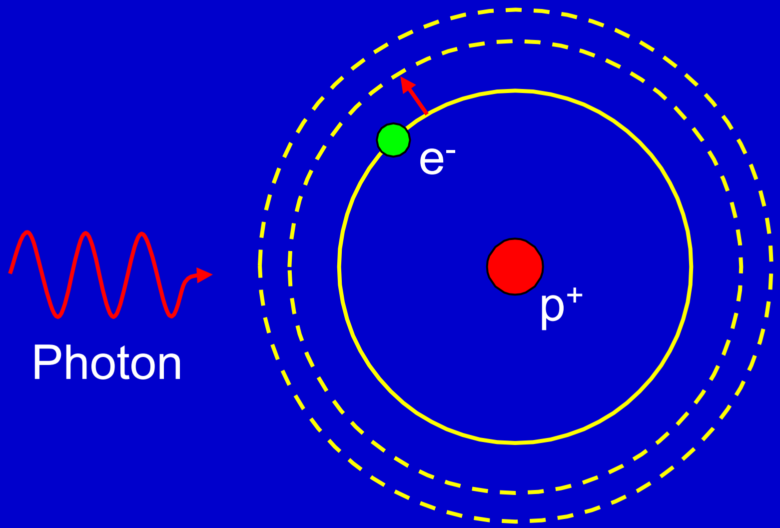


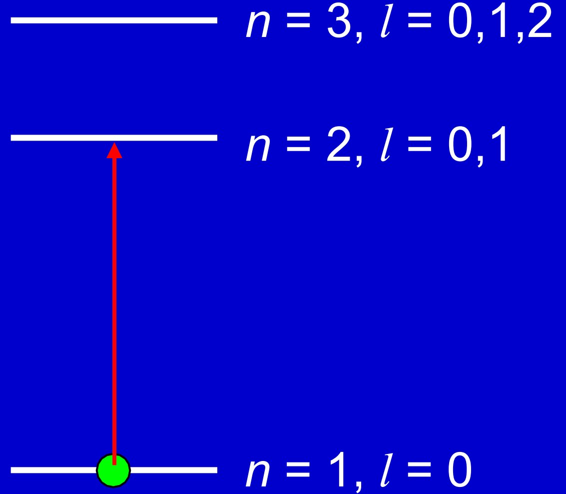


Peter D. D. Schwindt

Properties of a Neutral Atoms

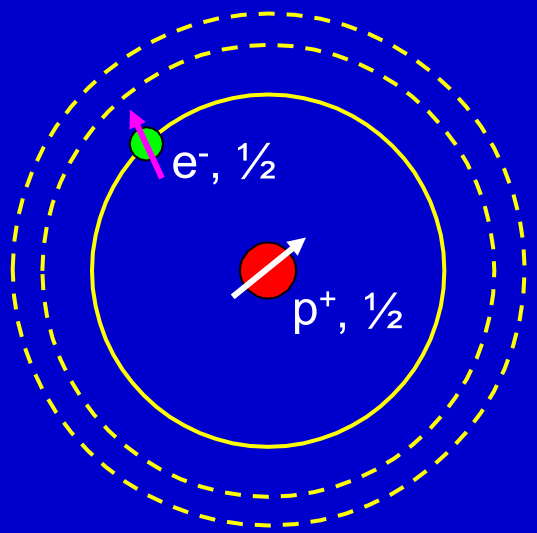
- Quantized energy levels

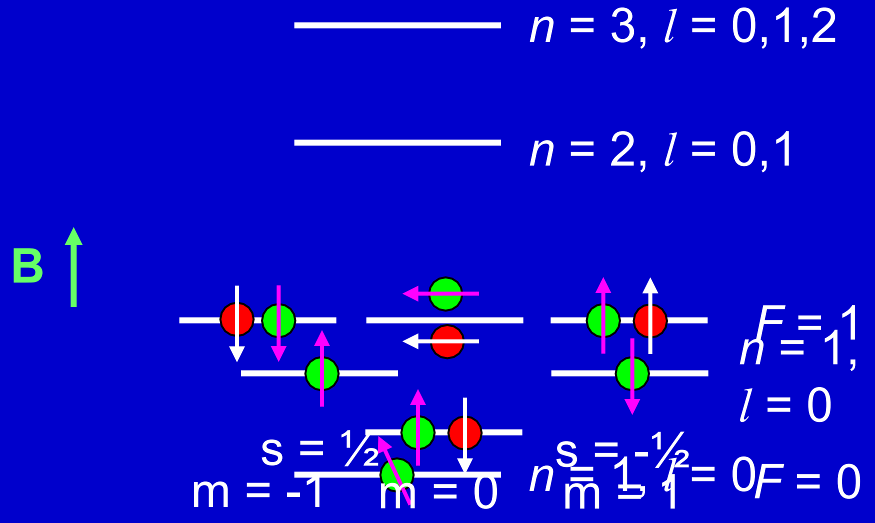




Properties of a Neutral Atoms

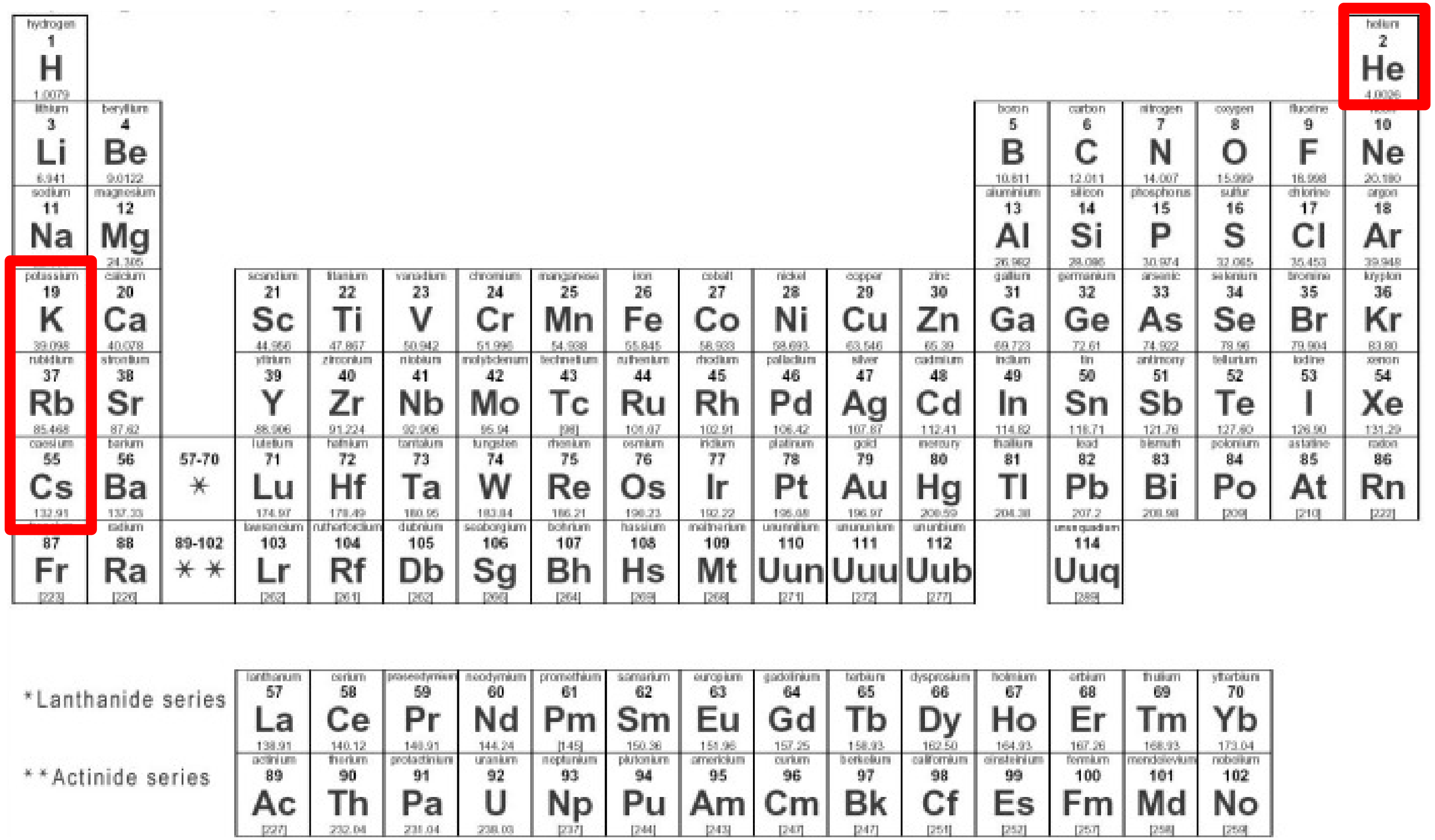
- Spin and magnetic moment
  - Electron spin
  - Nuclear spin



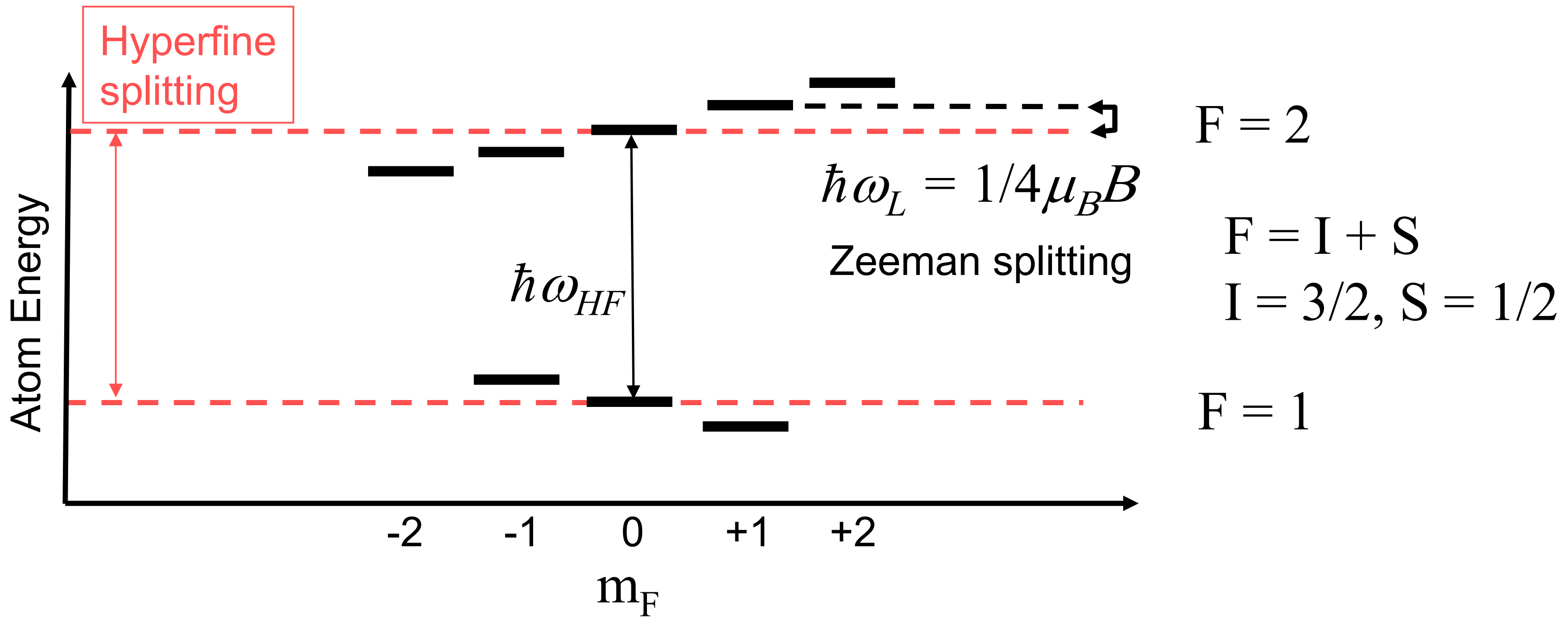


Zeeman effect

Atoms Used in OPMs



The Rubidium-87 Ground State



Clock—measure hyperfine frequency

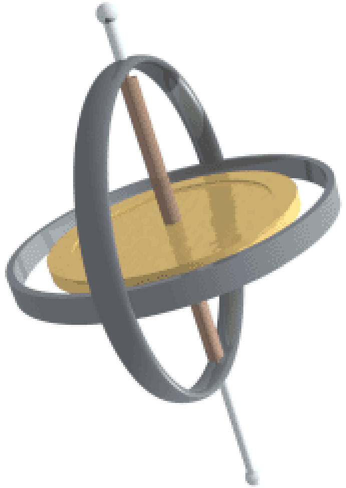
Magnetometer—measure Zeeman splitting

Gyromagnetic Ratio = 2π 7 Hz / nT

Bloch Equations for an OPM

$$\frac{d\mathbf{P}}{dt} = D\nabla^2\mathbf{P} + \gamma\mathbf{P}\times\mathbf{B} + R_{OP}(\mathbf{s}-\mathbf{P}) - \frac{\mathbf{P}}{T_1,T_2} - R_{PR}\mathbf{P}$$

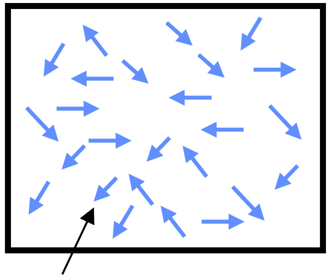
1. Atoms diffuse through inert buffer gas (limits atom-wall depolarization)
2. Atoms precess under influence of magnetic field $\mathbf{B}$ at rate given by the gyro magnetic ratio $\gamma = \frac{g_F\mu_B}{\hbar}$
3. Electrons are oriented along circularly polarized pump beam (photon spin $\mathbf{s}$) via optical pumping at rate R_{OP}
4. Optical pumping causes depolarization of the collective magnetic moment
5. Collisions cause atomic depolarization (T_1) and decoherence (T_2)
6. Probing the atoms causes depolarization of the collective magnetic moment at a rate R_{PR}



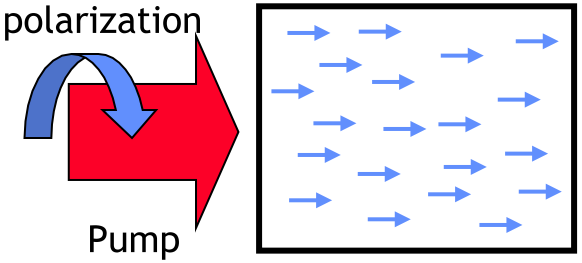
By Lucas Vieira - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=1528090

Zero-Field/SERF Magnetometer (Vector)

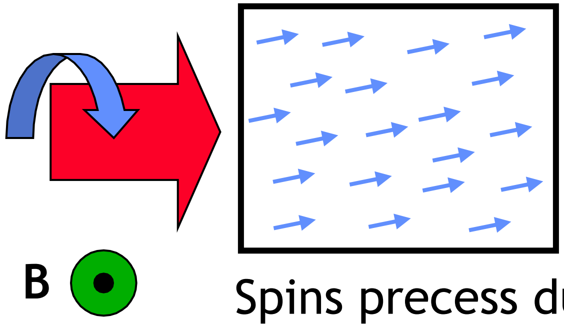
Alkali Vapor Cell



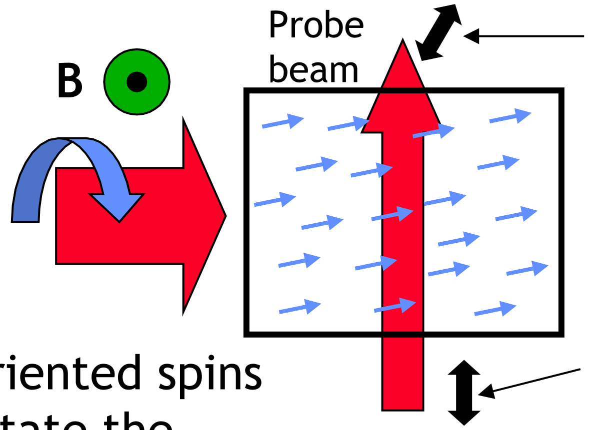
Optical pumping



Apply Small Magnetic Field



Detect with probe beam



Signals to Detect

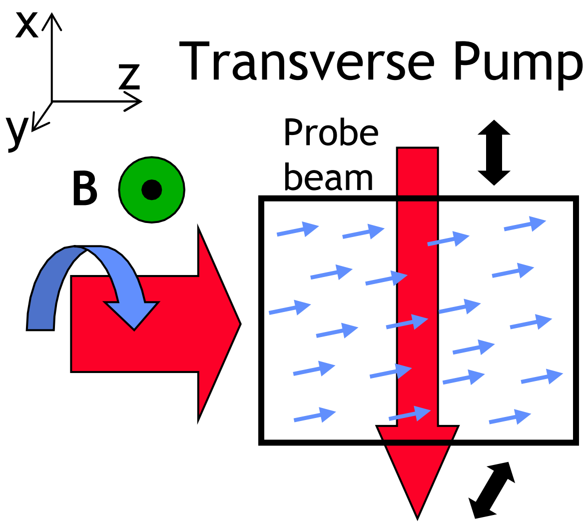
Spin Polarization Bloch Equation

$$\frac{d\mathbf{P}}{dt} = D\nabla^2\mathbf{P} + \frac{1}{Q(P)}\left(\gamma\mathbf{P}\times\mathbf{B} + R(\mathbf{s}-\mathbf{P}) - \frac{\mathbf{P}}{T_2}\right)$$

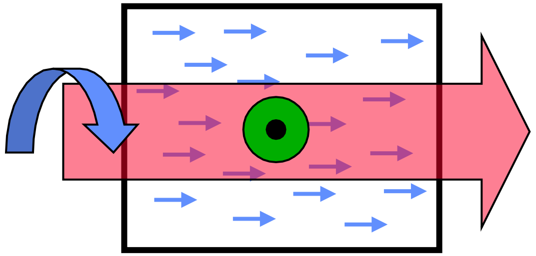
Bx = Bz = 0 Steady State Solution

$$P_x = \frac{\gamma B_y s R}{\gamma^2 B_y^2 + \left(R + T_2^{-1}\right)^2} \qquad P_z = \frac{sR\left(R+T_2^{-1}\right)}{\gamma^2 B_y^2 + \left(R+T_2^{-1}\right)^2}$$

Transverse Pump

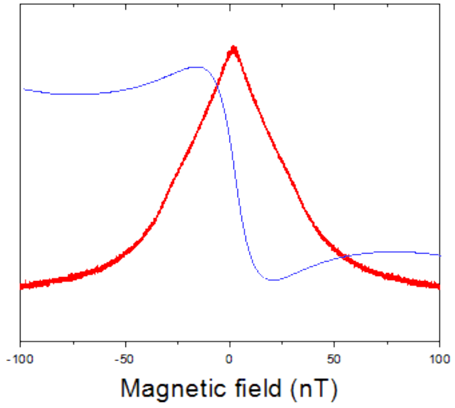


Detect the Pump

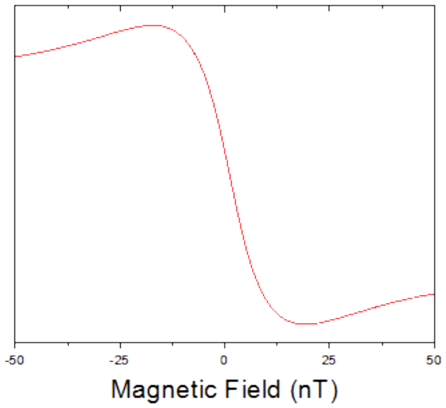


$B_0+B_1\sin(\omega t)$

Atomic Polarization, P_z
Pump Transmission



Atomic Polarization, P_x
or Angle of Light Polarization



Measuring field strength with an optically pumped magnetometer

PML
PHYSICAL MEASUREMENT LABORATORY

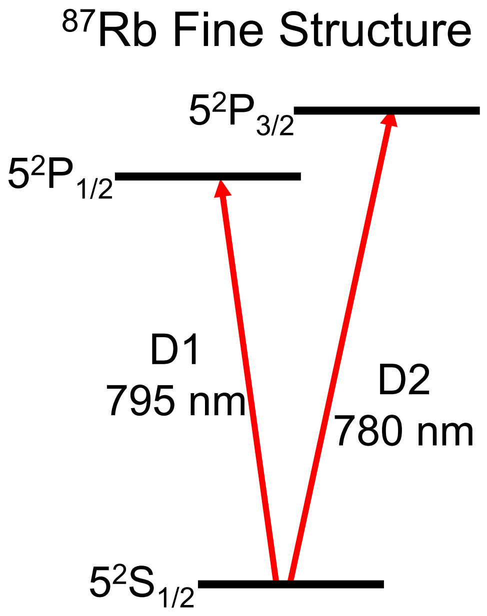
NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Two-color pump/probe scheme

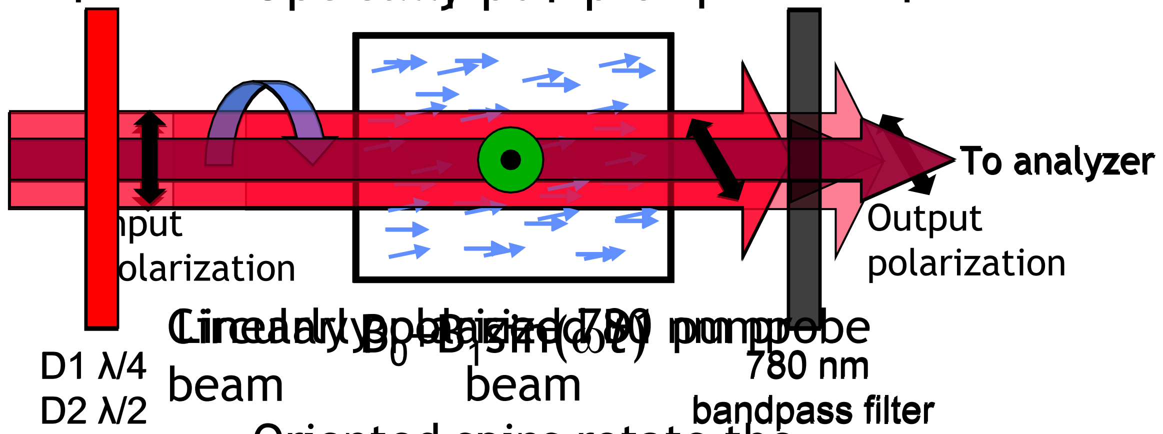
Two optical resonances in Rubidium (fine structure)

- Use D1 for optical pumping and D2 for probing

Based on: V. Shah and M. V. Romalis, PRA 80, 013416 (2009)

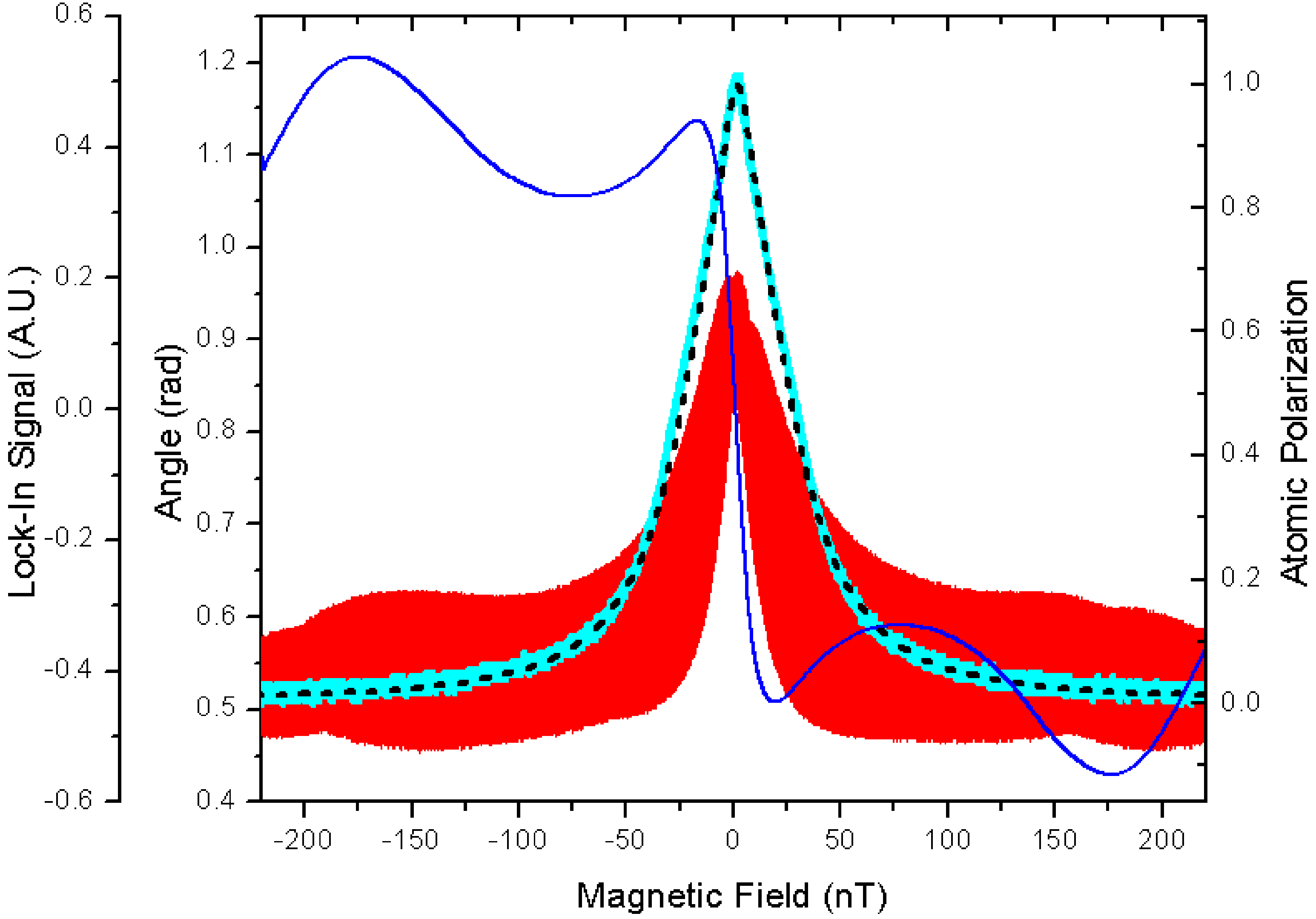


Field modulation/phase sensitive detection required to extract dispersive lineshape



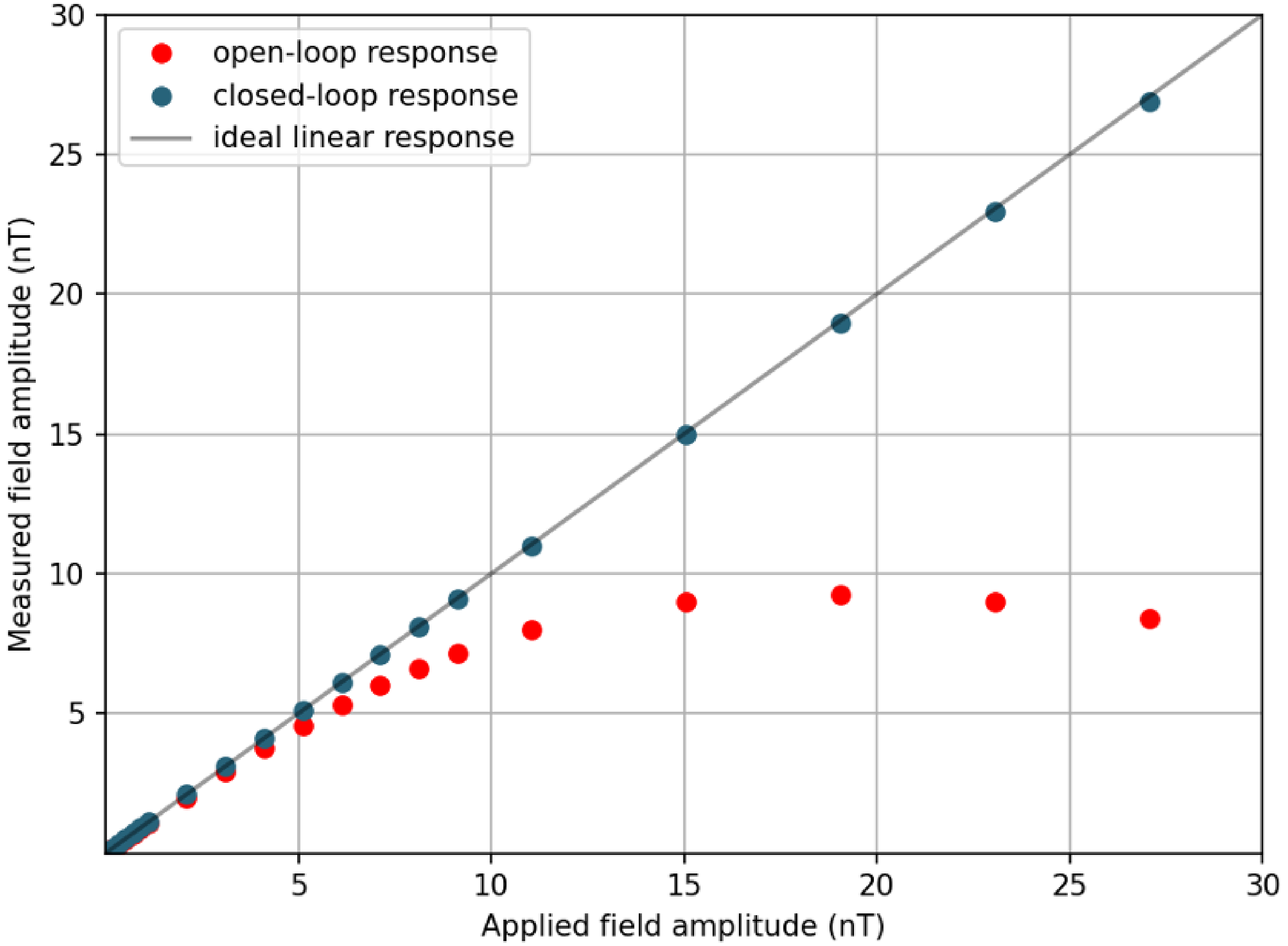
Oriented spins rotate the polarization

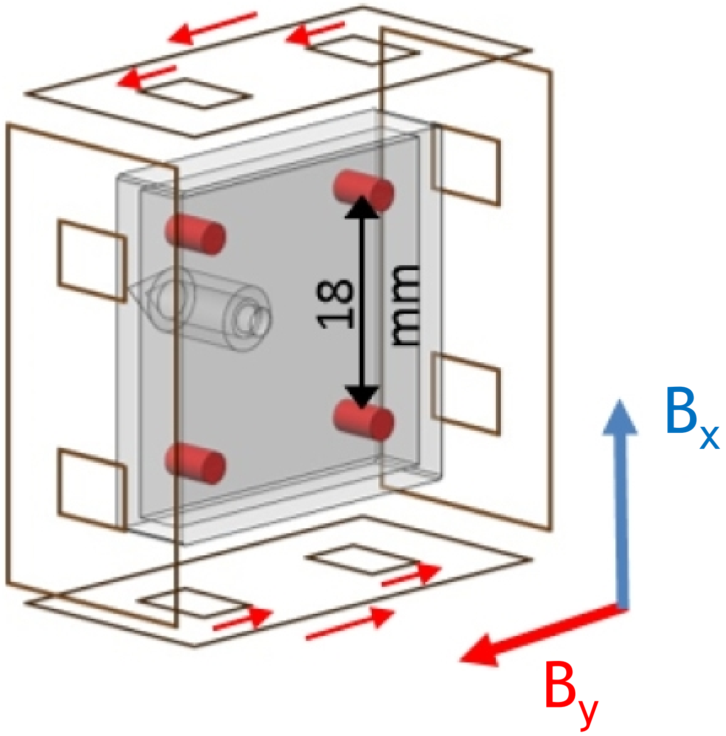
Magnetometer Signals



Blue trace: Magnetometer (lock-in) signal

Linearity of OPMs





From Svenja Knappe

What is SERF?
Spin Exchange Relaxation Free

T_2 often limited by spin exchange collisions.

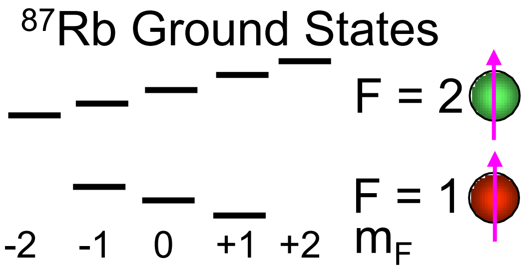
Near zero field and at high density, spin exchange rate >> spin precession frequency

- More F = 2 states, so on average atoms precess in F = 2 direction
- Precession rate is slowed down by nuclear spin and incomplete optical pumping

Record sensitivity: 160 aT / Hz$^{1/2}$ $\omega_0 = \frac{g_s \mu_B B}{Q\hbar}$

- Atom shot noise: ~0.1 fT / Hz$^{1/2}$

SERF in a ~6 mm^3 scale cell: 5 fT / Hz$^{1/2}$



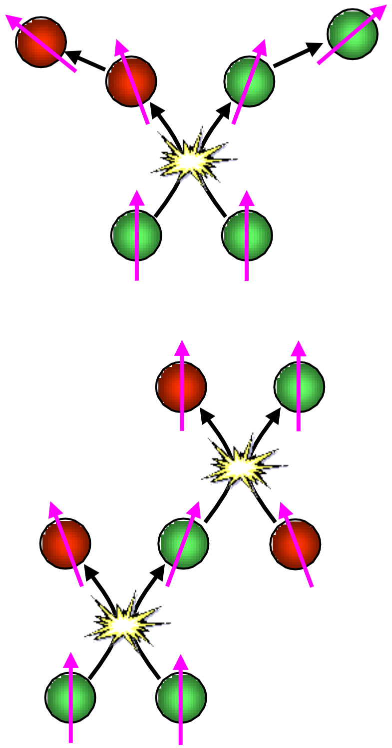
$$\delta B = \frac{1}{\gamma\sqrt{NT_2\tau}}$$

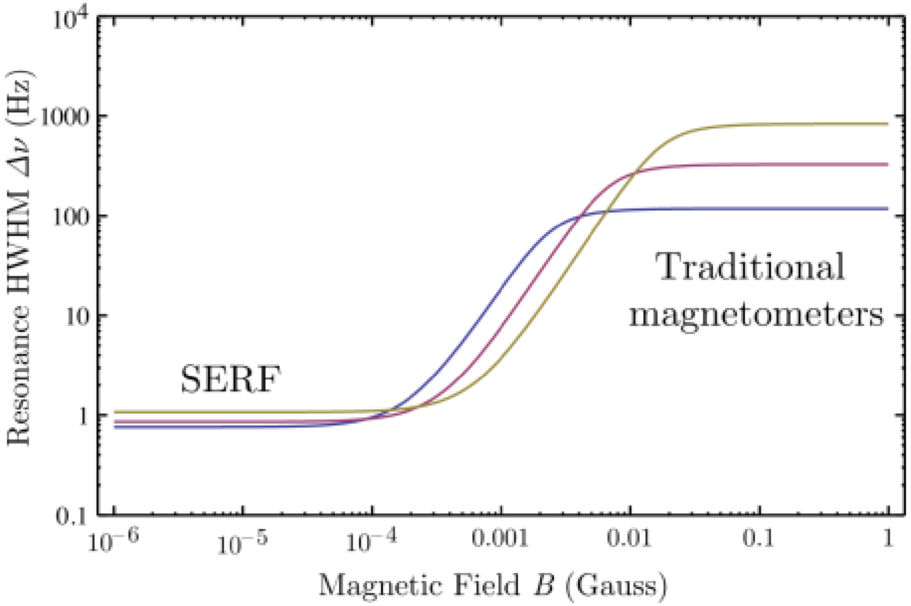
γ = gyromagnetic ratio

$T_2 = \frac{1}{\pi\,\Delta\nu}$ = transverse coherence time

N = number of atoms

τ = measurement time



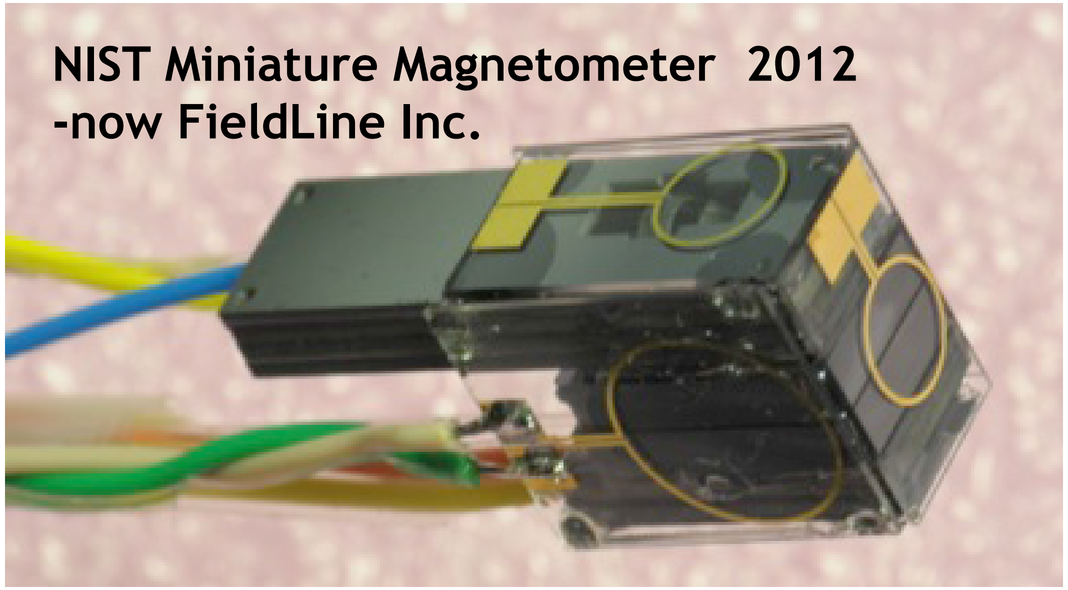


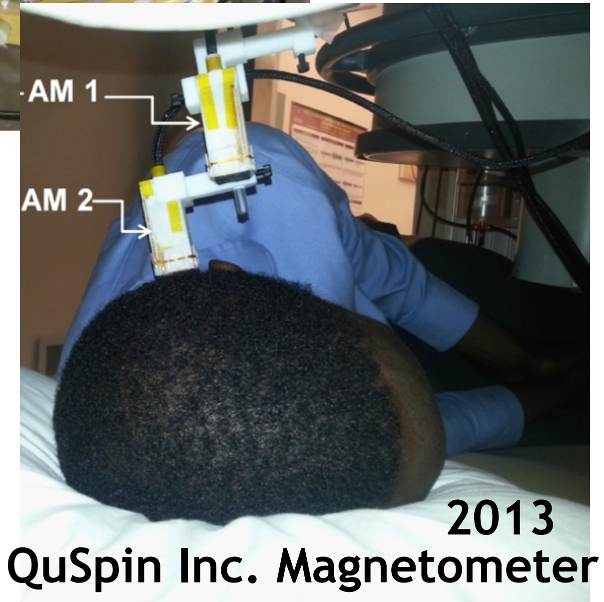
Rubidium relaxation cross sections

σ_{SE} = 2 x 10^{-14} cm^2
σ_{SD} = 9 x 10^{-18} cm^2

H. D. Dang, A. C. Maloof, M. V. Romalis, *Applied Physics Letters* **97**, 151110 (2010)
W. C. Griffith, S. Knappe, and J. Kitching, *Optics Express*, **18**, 27167-27172 (2010).

OPMs for MEG: Early work was all SERF





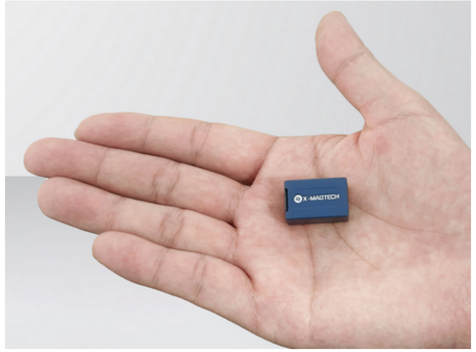
Emerging Companies Using Zero-Field/SERF OPM

QUSPIN
AN ATOMIC DEVICES COMPANY

cerca
Magnetics Limited

FieldLine

未磁科技 *
X-MAGTECH™

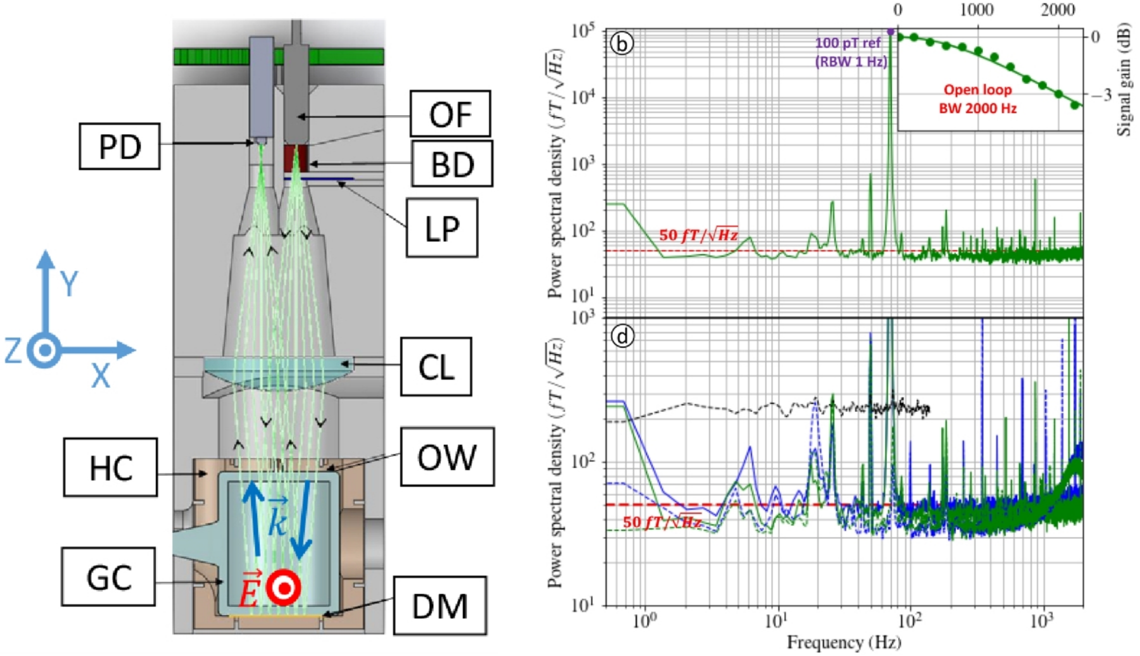


*Assuming this is a zero-field/SERF OPM

Other types of OPM

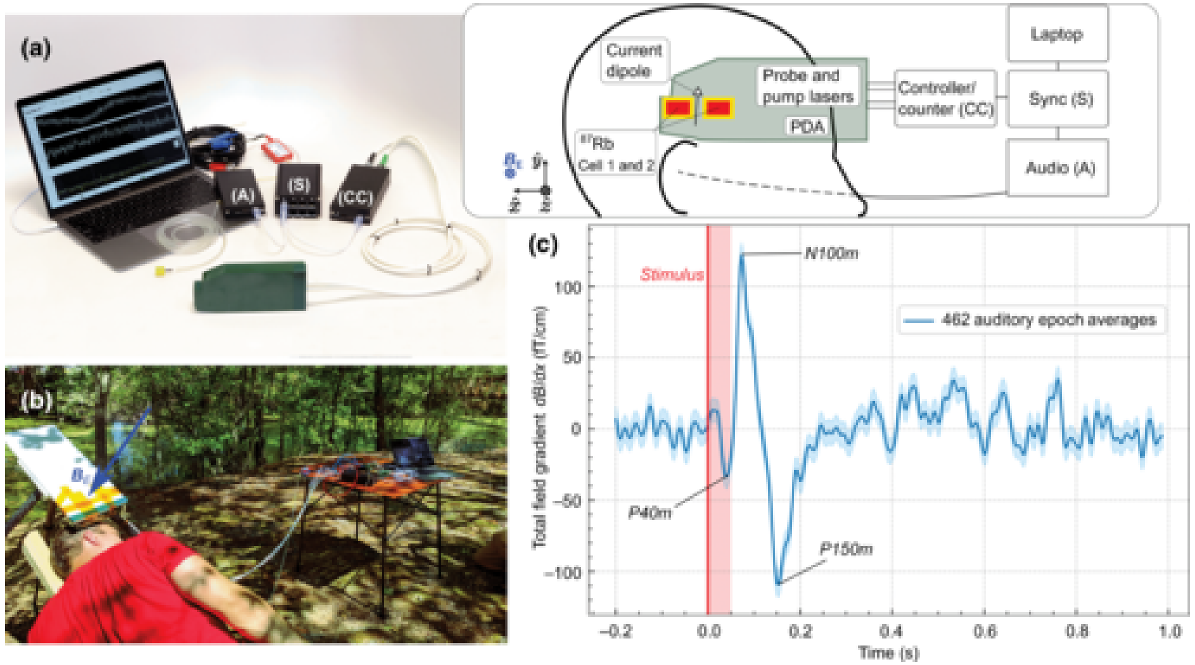
Helium-4 OPM

Sensitivity: 50 fT/rt-Hz
Closed-loop, triaxial operation
No cell heating: 10 mW RF discharge



Unshielded MEG using scalar OPM

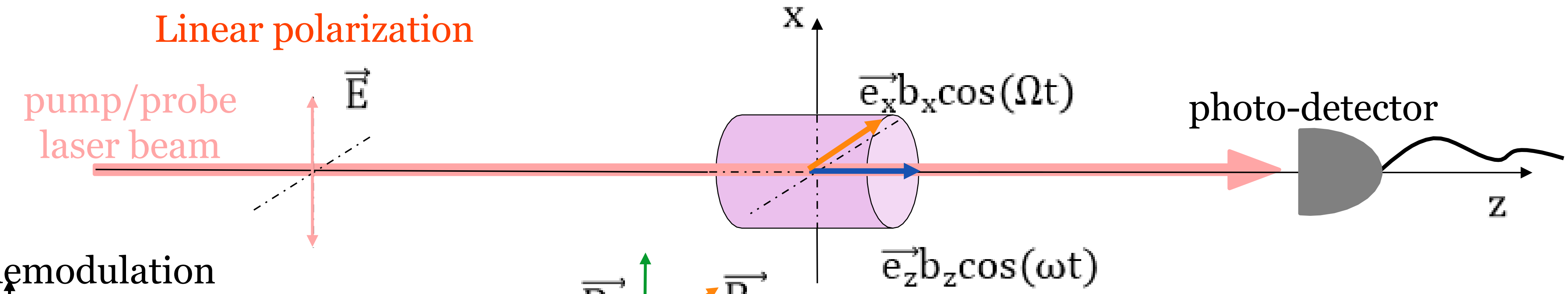
Gradiometric Sensitivity: 15 fT/cm/rt-Hz
Measure field component parallel to ambient field
No crosstalk / magnetically silent

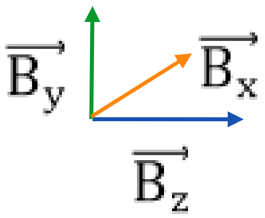


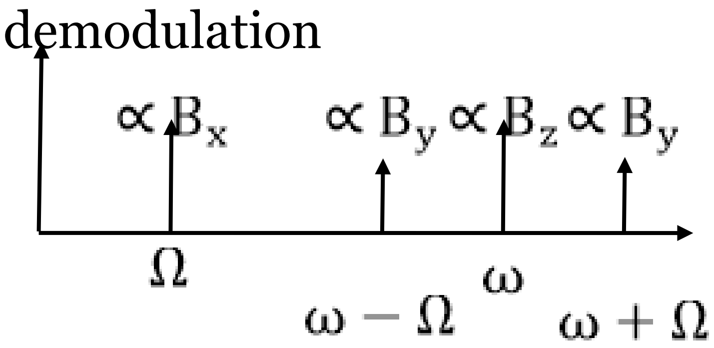
William Fourcault, et al., *Opt. Express* **29**, 14467-14475 (2021)

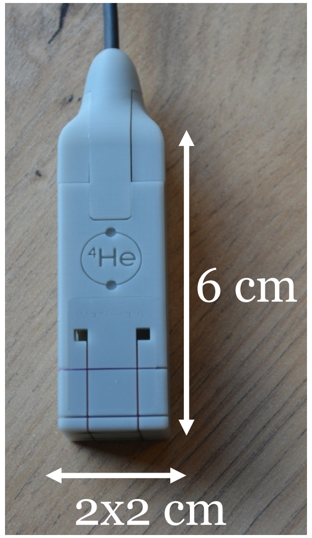
Limes, M.E., et al., *Phys. Rev. Appl.* **14**, 011002 (2020)

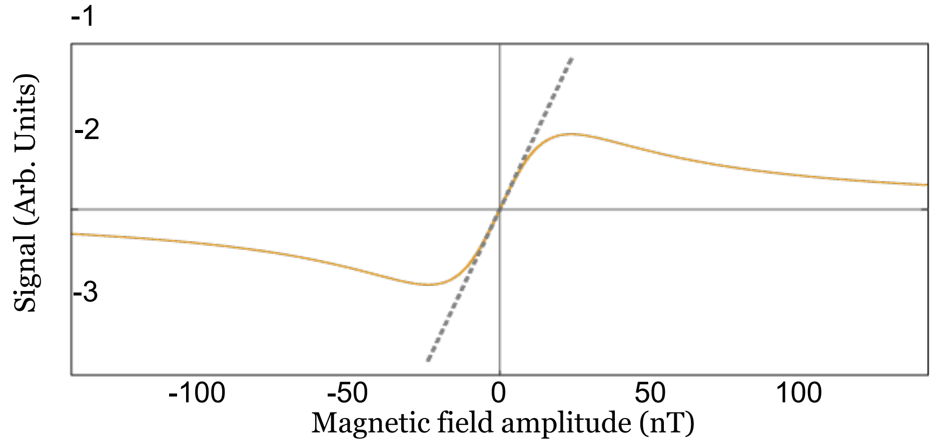
Helium-4 OPM - principle









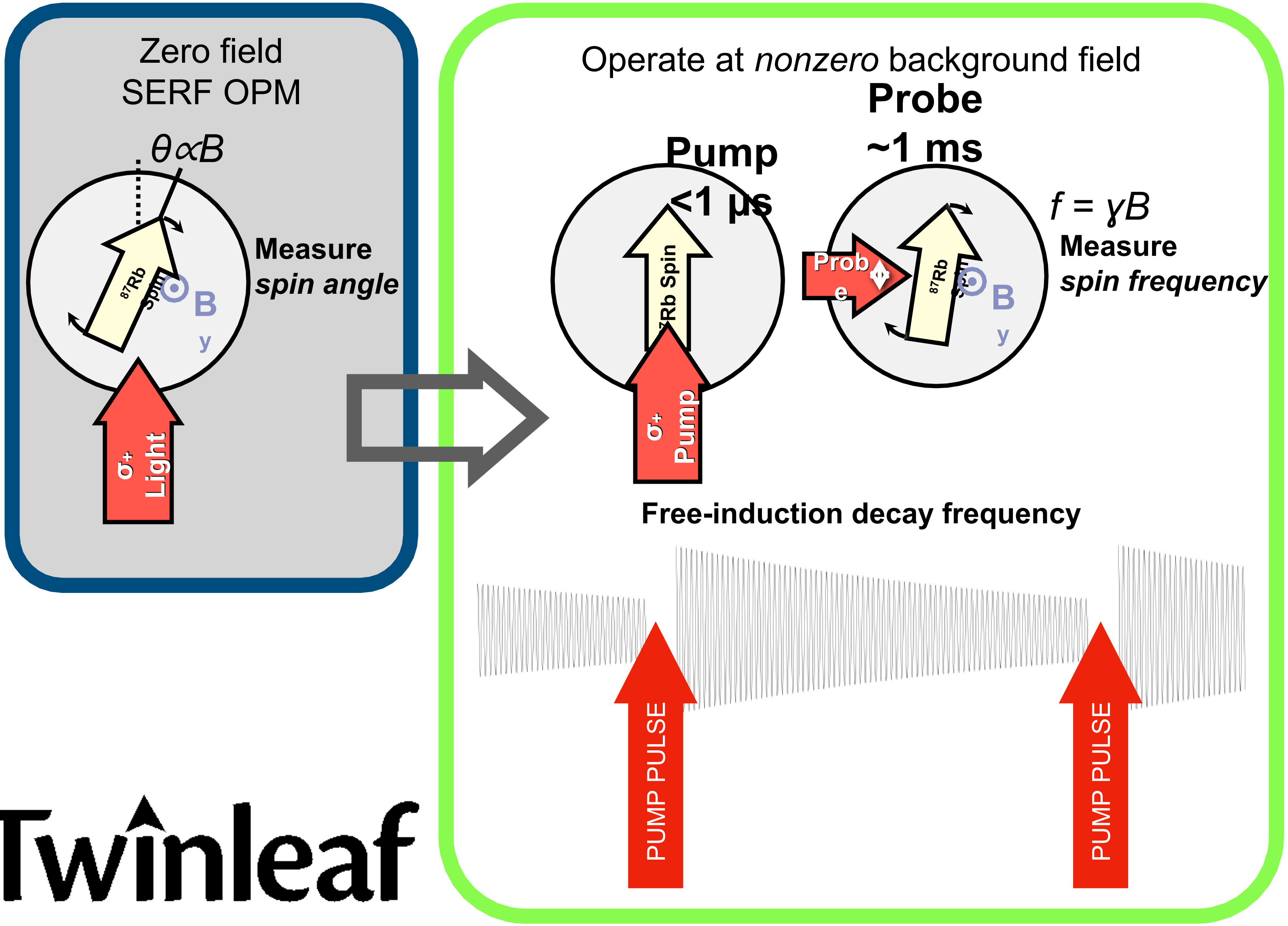


Parametric resonances along each direction with 2 rf fields and 1 laser beam → Magnetic ALIGNED state

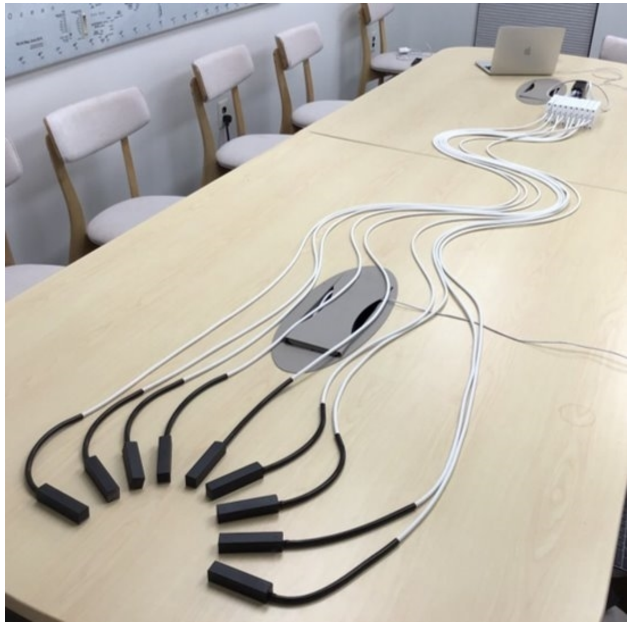
MAG⁴Health

F. Beato et al. Phys. Rev. A **98**, 053431 (2018)

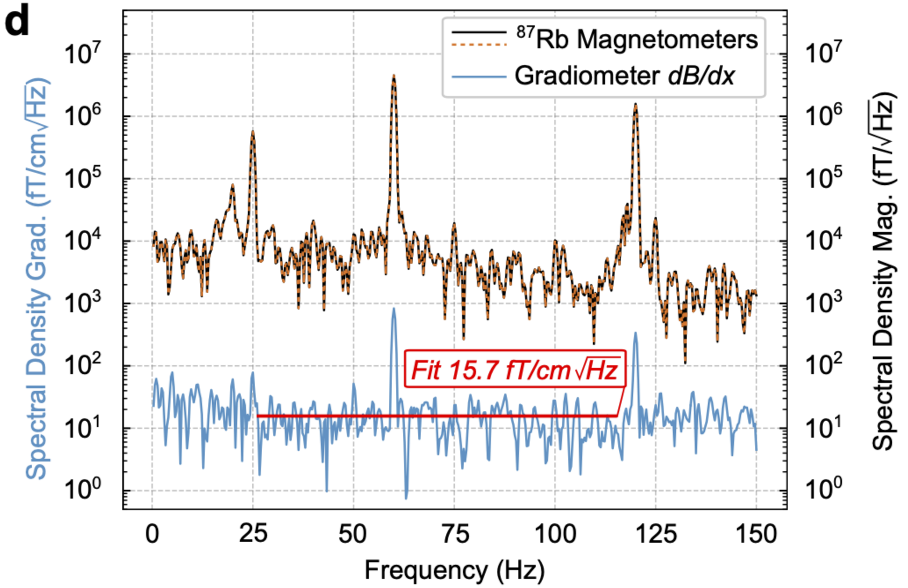
Pulsed Pump Magnetometer



High performance Optical Magnetic Gradiometers

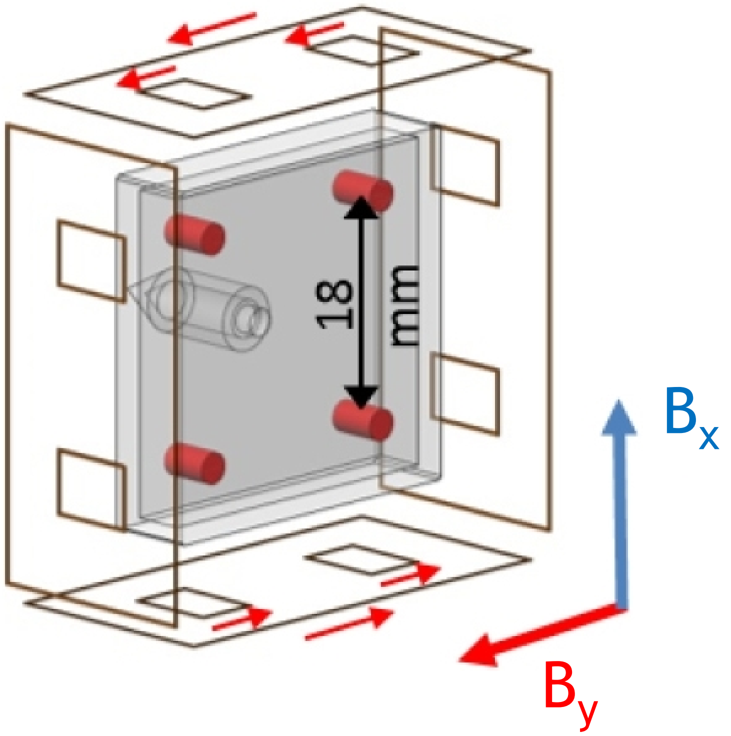


Extraordinary sensitivity without magnetic shielding



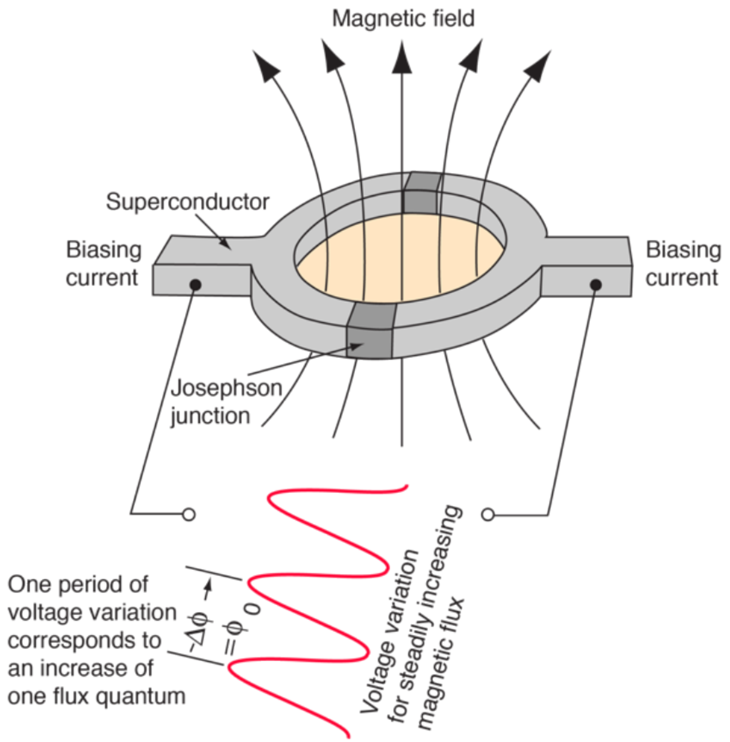
SQUID vs OPM

SERF OPM



- Integrates over volume of laser beam
- Sensitive axis determined by field modulation (Some SERF designs use laser beam geometry to define sensitivity axis.)

SQUID



http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/Squid.html

- Integrates over the area of pickup loop
- Sensitive axis determined by loop geometry

SQUID vs OPM

	Sensitivity	Bandwidth	Sensitive axis	Dynamic range (Max field)
Zero field, SERF OPM	5-20 fT/rt-Hz	80-150 Hz (open loop) 350 Hz (closed loop)**	1, 2, or 3 axis (3rd axis from 2nd OPM)	±2 nT (80 nT) open loop* ±150 nT (150 nT) closed loop**
He OPM	50 fT/rt-Hz	2 kHz (open loop) 1.35 kHz (closed loop)	3 axis (3rd axis 6x worse sensitivity)	±300 nT (unknown)
Scalar OPM gradio-meter—Unshielded	15 fT/cm/rt-Hz	300 Samples/s (adjustable)	Parallel to am-bient bias field	Unknown (Earth's field)
SQUID	2-3 fT/rt-Hz	1–5 kS/s (adjustable)	Normal to pickup loop	±20 nT (Unshielded operation possible)

*Quspin Neuro-1: Neuro-1 flyer

Fieldline: Alem O, et al., *Front. Neurosci*. **17, 1190310 (2023)

Unknown = Unknown to this author

SERF OPMs: Formulating Gain/Sense-Angle Error

C. Cohen-Tannoudji, J. Dupont-Roc, S. Haroche, F. Laloë. Diverses résonances de croisement de niveaux sur des atomes pompés optiquement en champ nul. I. Théorie. Revue de Physique Appliquee, 1970, 5 (1), pp.95-101. 10.1051/rphysap:019700050109500 . jpa-00243381

$$B_x = \widehat{B_{xs}}(t) + B_m \sin(\omega_m t)$$

$$P_z \approx \underbrace{\frac{R_{op}}{R_{op}+R_{rel}} J_0\left(\frac{\gamma B_m}{q\omega_m}\right) J_1\left(\frac{\gamma B_m}{q\omega_m}\right)\sin(\omega_m t)\left[\frac{\frac{\gamma\widehat{B_{xs}}(t)}{(R_{op}+R_{rel})}}{1+\left(\frac{\gamma\widehat{B_{xs}}(t)}{(R_{op}+R_{rel})}\right)^2}\right.}_{G_{OPM}} - J_0{}^2\left(\frac{\gamma B_m}{q\omega_m}\right)\left\{\underbrace{\frac{\frac{\gamma^2 B_y B_z}{(R_{op}+R_{rel})^2}}{1+\left(\frac{\gamma\widehat{B_{xs}}(t)}{(R_{op}+R_{rel})}\right)^2}}_{G_2} + \underbrace{\frac{\frac{\gamma\widehat{B_{xs}}(t)}{(R_{op}+R_{rel})}}{\left(1+\left(\frac{\gamma\widehat{B_{xs}}(t)}{(R_{op}+R_{rel})}\right)^2\right)^2}\left(\left(\frac{\gamma B_y}{(R_{op}+R_{rel})}\right)^2+\left(\frac{\gamma B_z}{(R_{op}+R_{rel})}\right)^2\right)}_{G_3}\right\}\Bigg]$$

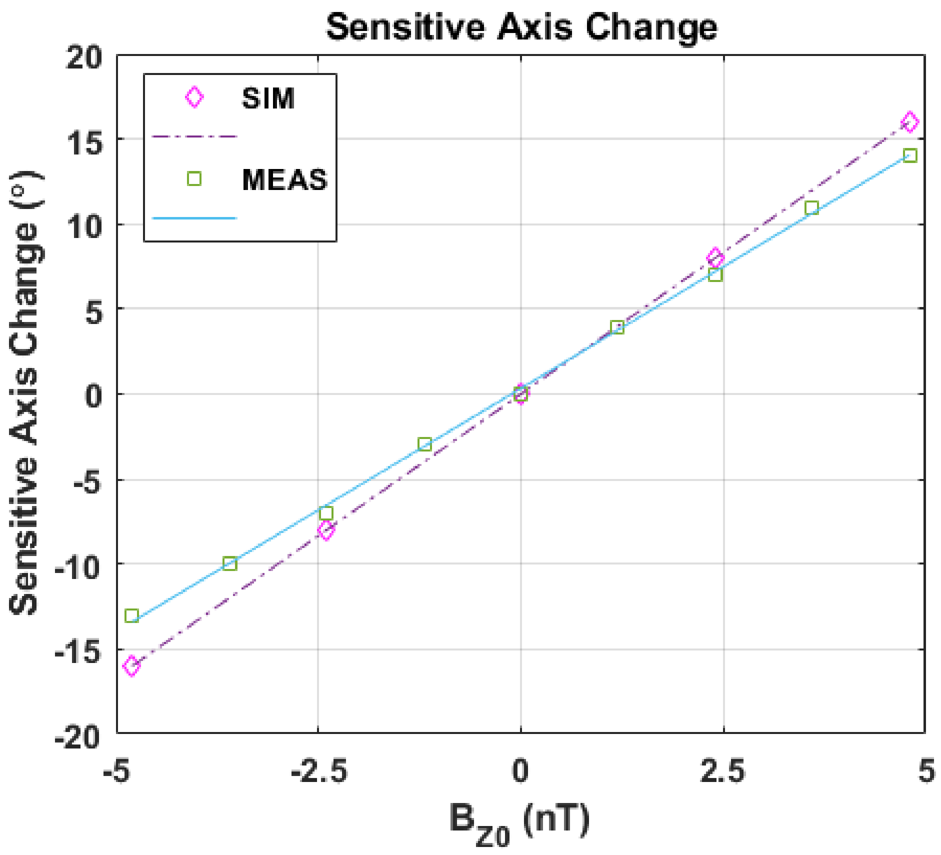
Cross Axis Projection Error (CAPE) Effects

$$\begin{cases} \varphi_i \approx \arctan\left(\frac{-G_2 B_i}{G_{OPM}}\right), i = y \text{ or } z \rightarrow \text{Rotation of the sensitive axis} \\ G_\varphi \approx \left(G_{OPM} - G_3\left(B_y{}^2 + B_z{}^2\right)\right) \rightarrow \text{Reduction of gain} \end{cases}$$

Phase errors

Amir Borna, Joonas Iivanainen, Tony R. Carter, Jim McKay, Samu Taulu, Julia Stephen, Peter D.D. Schwindt, "Cross-Axis projection error in optically pumped magnetometers and its implication for magnetoencephalography systems," *NeuroImage*, **247**, 118818 (2022).

Sensitive Axis Rotation: Simulation vs. Measurement



$$\varphi_z \approx \arctan\left(\frac{-G_2 B_z}{G_{OPM}}\right)$$

- CAPE rotates the sensitive axis by 2.86 °/nT (measured) and 3.33 °/nT (simulated).
- The slight difference between the two is attributed to different relaxation rates.

Mitigation of CAPE

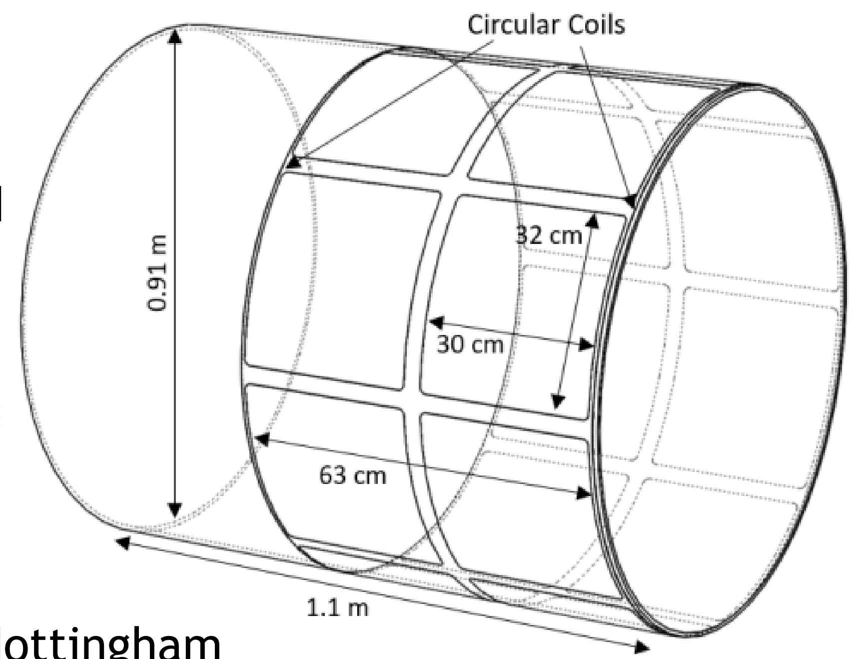
Zero the fields (easier)

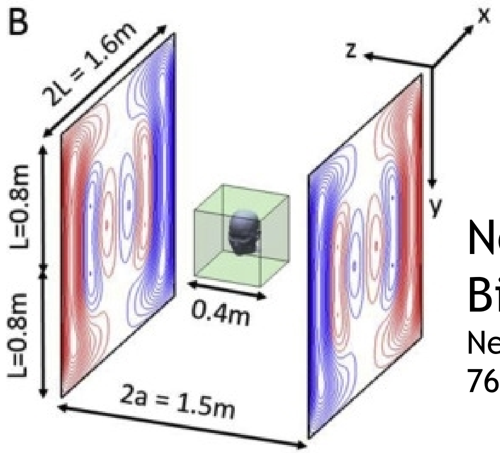
- Zero the field at each sensor (< nT)
- Zero the field in the shield

Closed-loop, 3-axis OPM (harder)

- Upside: It's a 3-axis measurement!
  - Can we maintain good sensitivity?
- Upside: Fixed gain. Sensors are always calibrated.
- Downside: cross-talk between sensors.

Sandia Person-Sized Shield Coils





Nottingham Biplanar Coils
NeuroImage, **181**, 760-774 (2018)

QuSpin Gen 3 QZFM
Triax Variant: <23 fT/√Hz in 3-100 Hz band (typical 15 fT/√Hz all axis simultaneous)

Uses 2 perpendicular beams

NeuroImage, **236**, 118025 (2021)
NeuroImage, **252**, 119027 (2022)

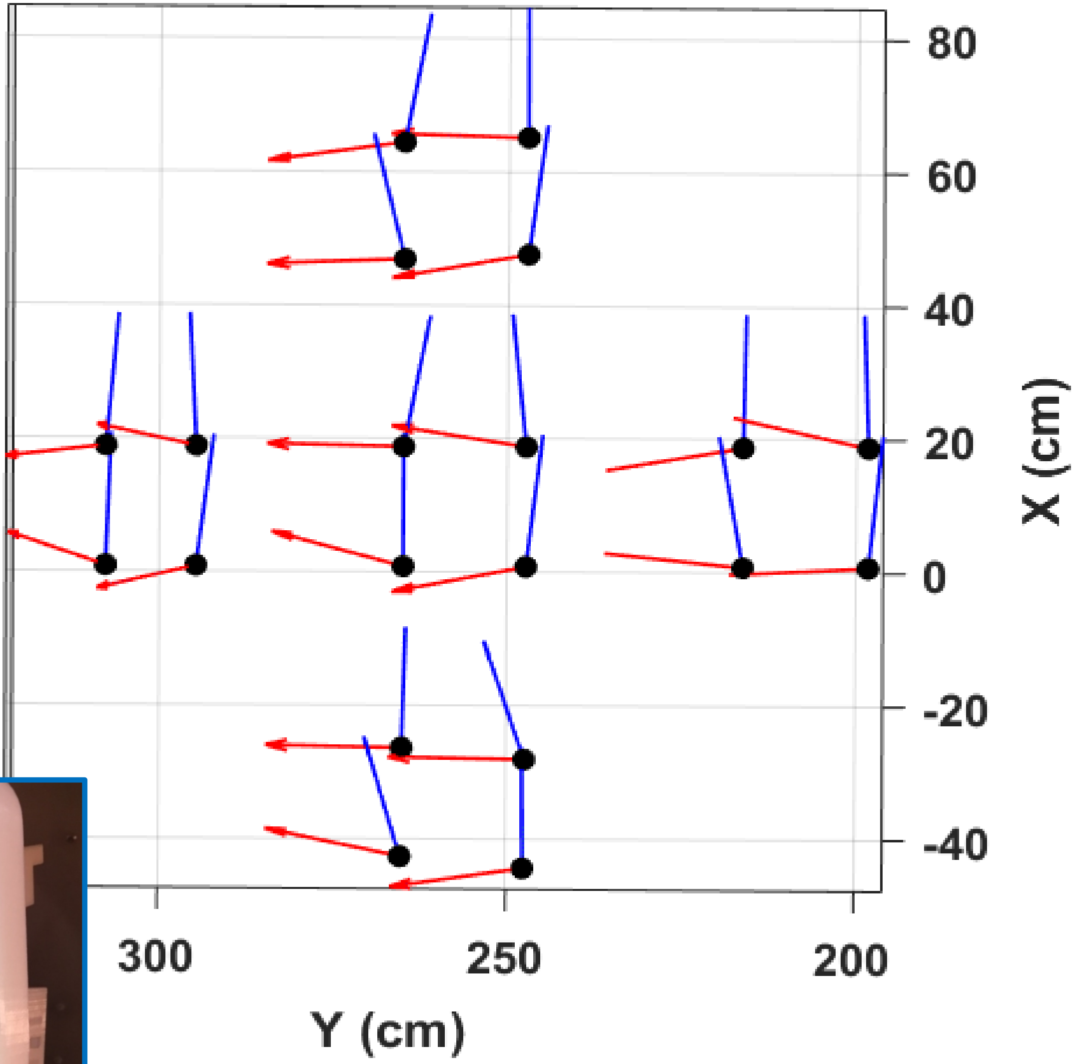
Interference and crosstalk

Interference

- Leakage of the modulation field from one sensor to another
- Can easily be ameliorated through sensor calibration

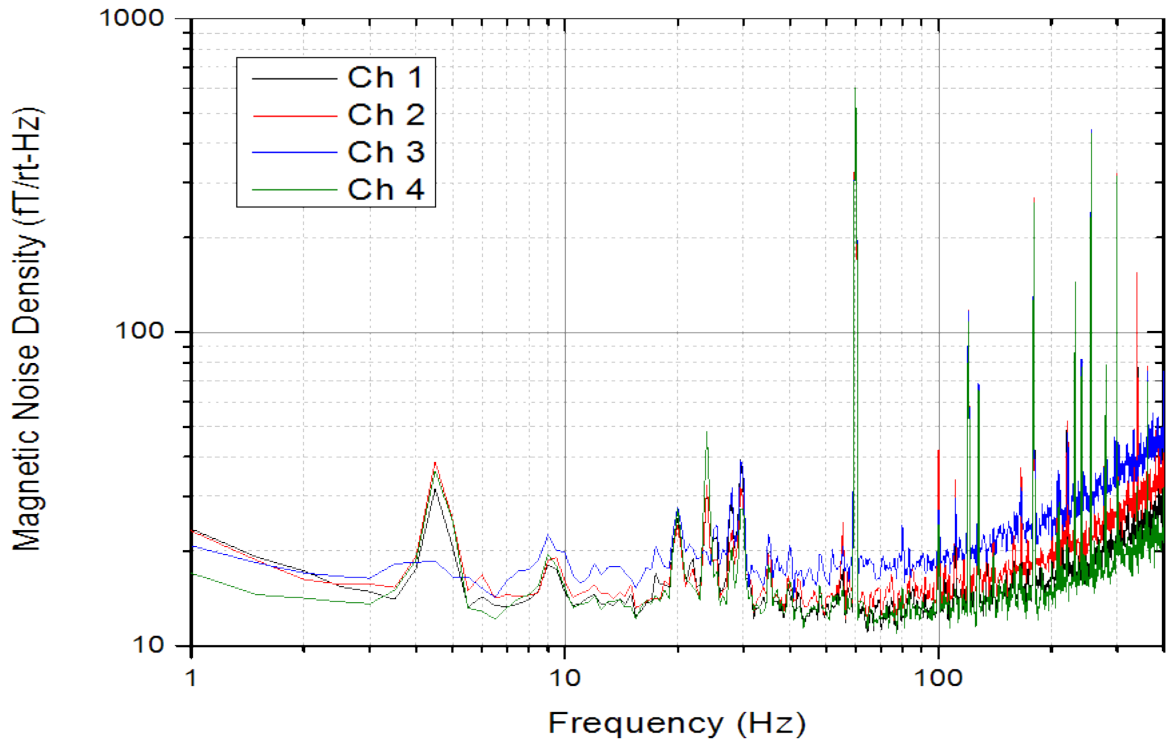
Crosstalk in closed loop system

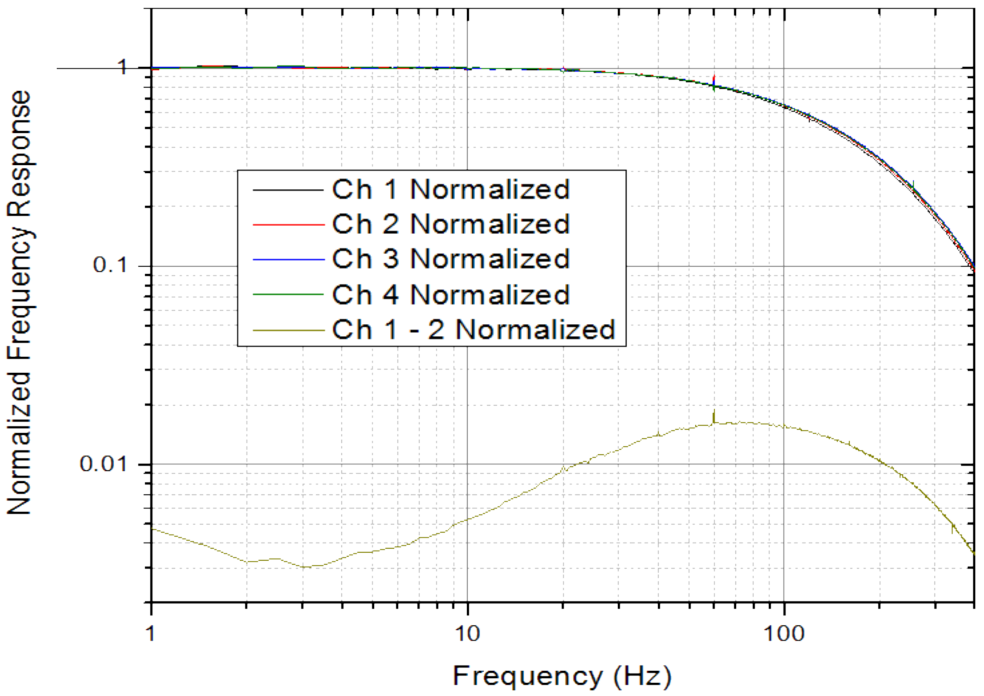
- Cancelling field at one sensor is sensed by another sensor
- Mitigation: Design feedback coils that minimize cross talk.
- Mitigation: A cross-talk matrix may need to be measured for each sensor configuration.



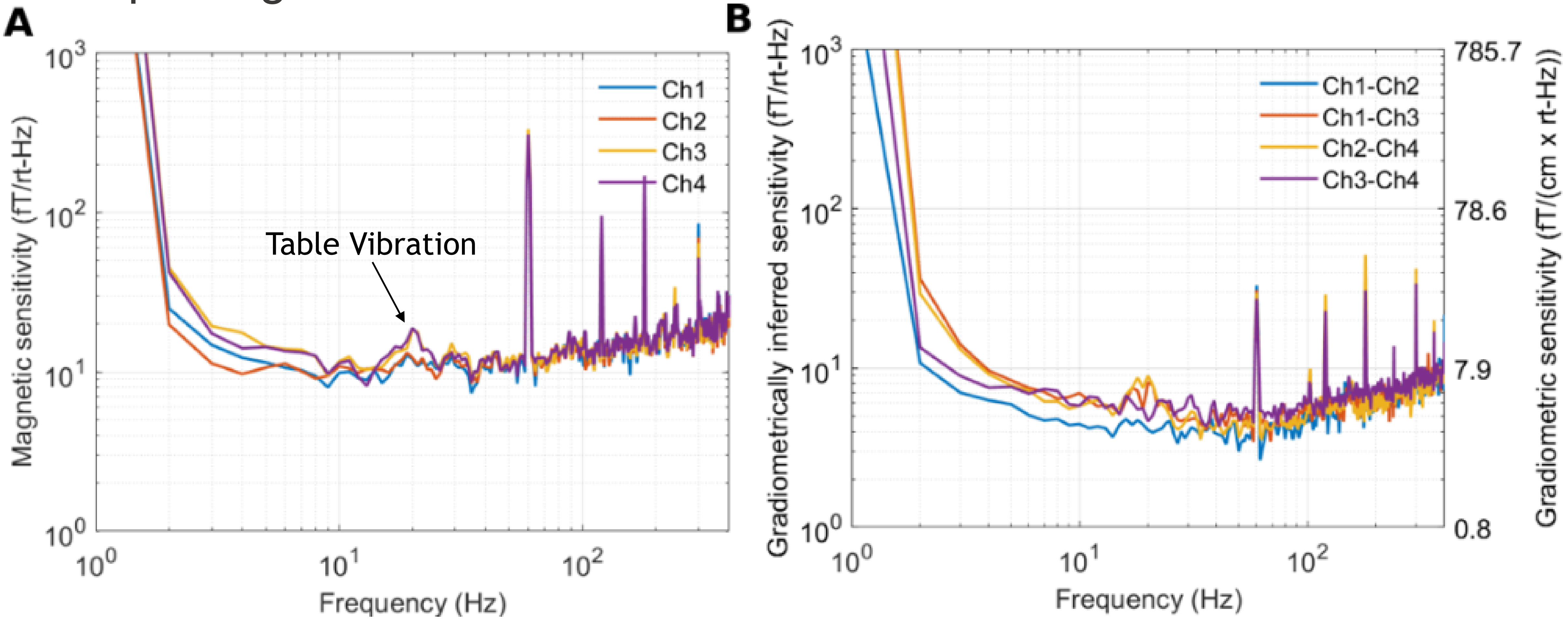
Reporting results

Sensitivity results should be normalized by the bandwidth.





Reporting results



Gradiometrically inferred sensitivity = (Ch1 – Ch2)/$\sqrt{2}$
Gradiometer sensitivity = (Ch1 – Ch2)/1.8 cm
1.8 cm = gradiometer baseline

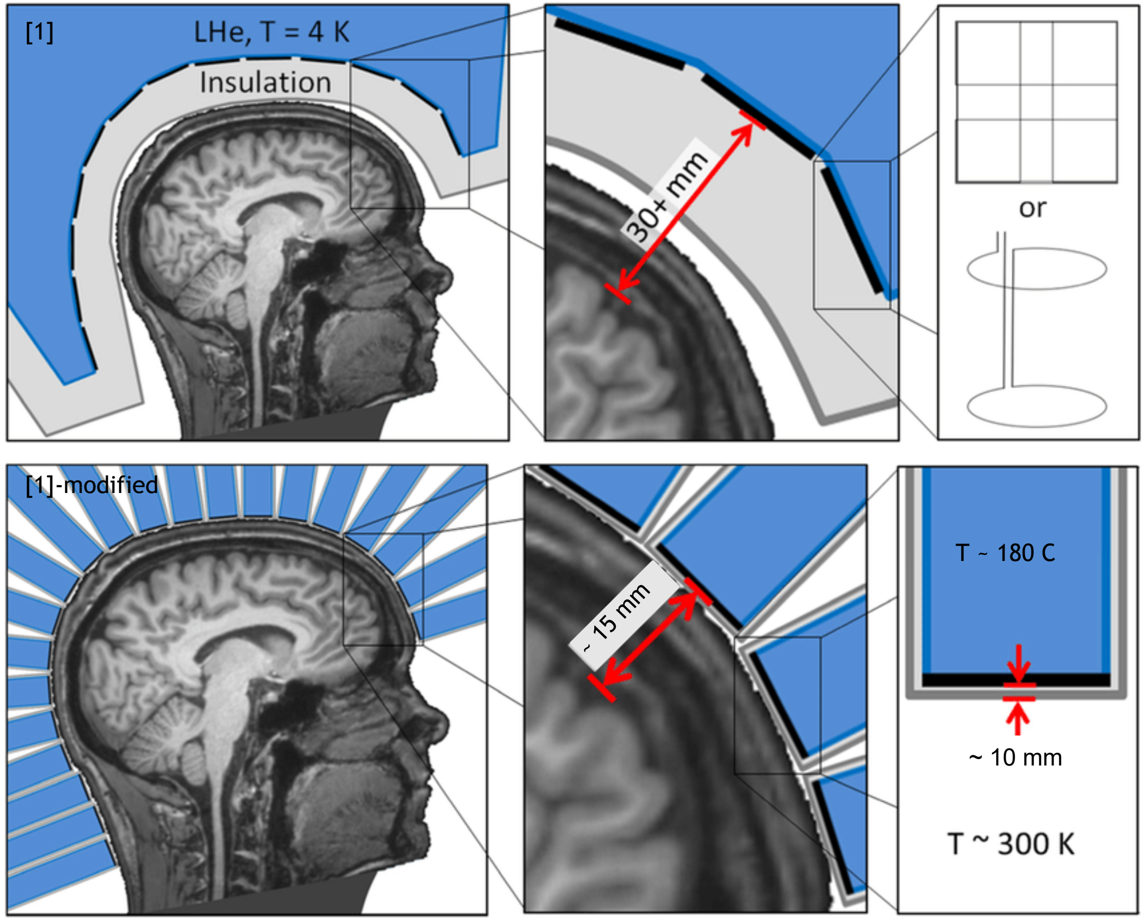
Conclusions

OPMs are fundamentally different than SQUID sensors

- OPMs integrate field over a volume, not an area
- Bandwidth reduced compared to SQUID, at least for SERF OPMs
- Sensitivity of today's OPM are reduced compared to SQUIDs
  - Mitigated by being closer to the head
  - Prospects for better OPM sensitivity: Best OPM 0.16 fT/rt-Hz
- OPM respond to all components of the field
  - "Vectorization" methods needed to read out specific field components
  - Three-axis detection possible
  - Systematic errors arise from offset field

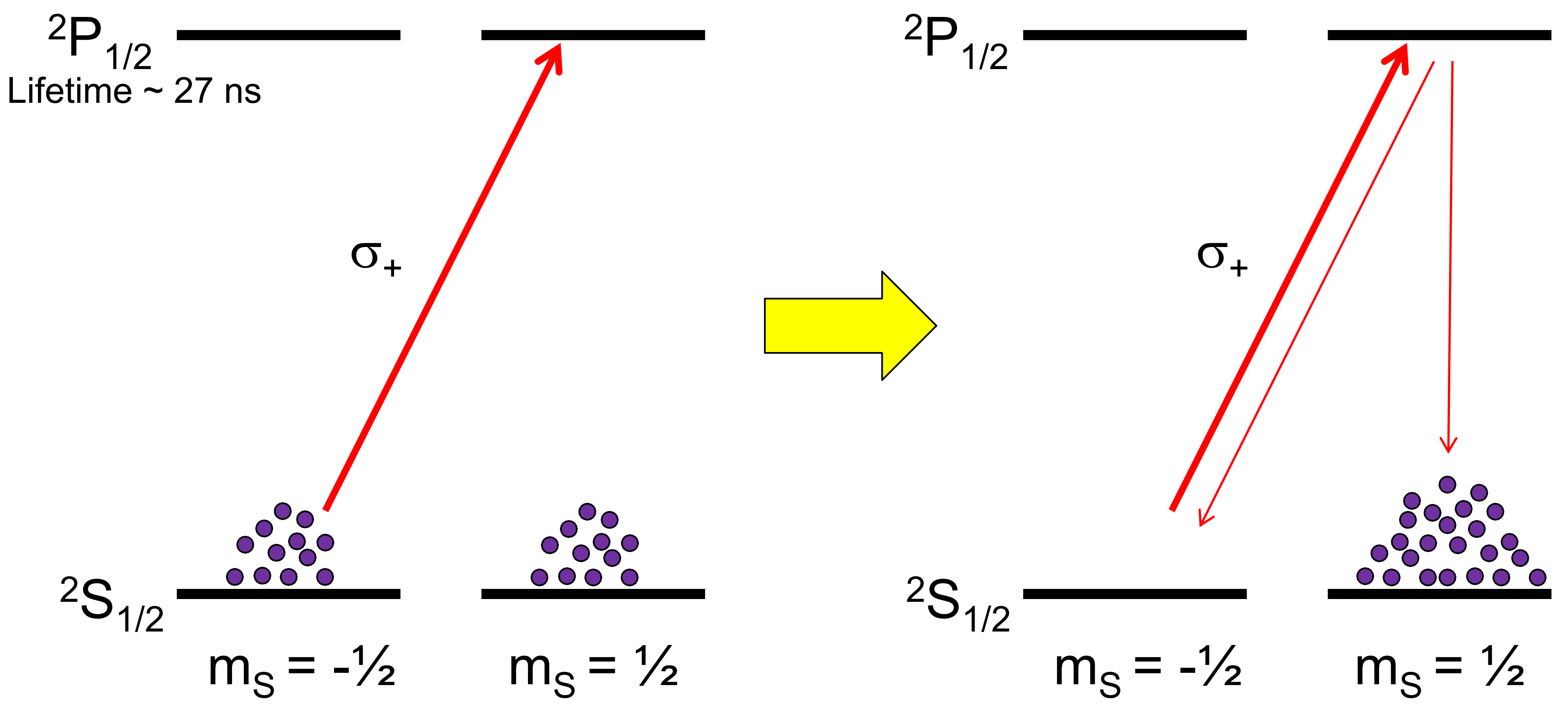
SERF and He OPM need a low-field environment

Scalar gradiometer operates in Earth's field



Back up slides

Optical Pumping



Hyperfine Ground State

Ground State Hamiltonian:

- Spin angular momentum $\mathbf{S}$
- Nuclear angular momentum $\mathbf{I}$
- Total angular momentum $\mathbf{F} = \mathbf{S} + \mathbf{I}$
- $H_{HF} = \mu_B g_S \mathbf{S} \cdot \mathbf{B} + \mu_B g_I \mathbf{I} \cdot \mathbf{B} + A_{HF} \mathbf{I} \cdot \mathbf{S}$
- $g_S = 2.002$, $g_I = -0.000995$ (^{87}Rb), -0.000399 (^{133}Cs)
- $E_{HF} = \frac{1}{2} A_{HF}\big(F(F+1) - I(I+1) - S(S+1)\big)$
- ^{87}Rb : $\Delta E_{HF}/h = 6.835$ GHz, $I = 3/2$
- ^{133}Cs: $\Delta E_{HF}/h = 9.192$ GHz, $I = 7/2$

At low field the nuclear and electron spins are combined,

- $H_B = \mu_B g_F \mathbf{F} \cdot \mathbf{B}$, $\Delta E_{mF} = g_F m_F \mu_B B$
- $g_F \approx \pm \frac{1}{2F_{max}}, -F \leq m_F \leq F$
- $\frac{g_s \mu_B}{h} = 2.8$ MHz/G or 28 Hz/nT (gyromagnetic ratio)
- ^{87}Rb: $g_F = \pm \frac{1}{4}$, $\frac{g_F \mu_B}{h} = 700$ kHz/G or 7 Hz/nT
- ^{133}Cs: $g_F = \pm \frac{1}{8}$, $\frac{g_F \mu_B}{h} = 350$ kHz/G or 3.5 Hz/nT

Sensitivity Limits

Magnetic Sensitivity $$\delta B = \frac{S_{noise}}{dS/dB}$$

Atom shot noise limit

$$\delta B = \frac{1}{\gamma\sqrt{NT_2\tau}}$$

γ = gyromagnetic ratio
T_2 = transverse coherence time
N = number of atoms
τ = measurement time

Decoherence limits noise to $1/N^{1/2}$ scaling

Sensitivity improved by increasing T_2 or N

Most AMs do not operate at this limit.

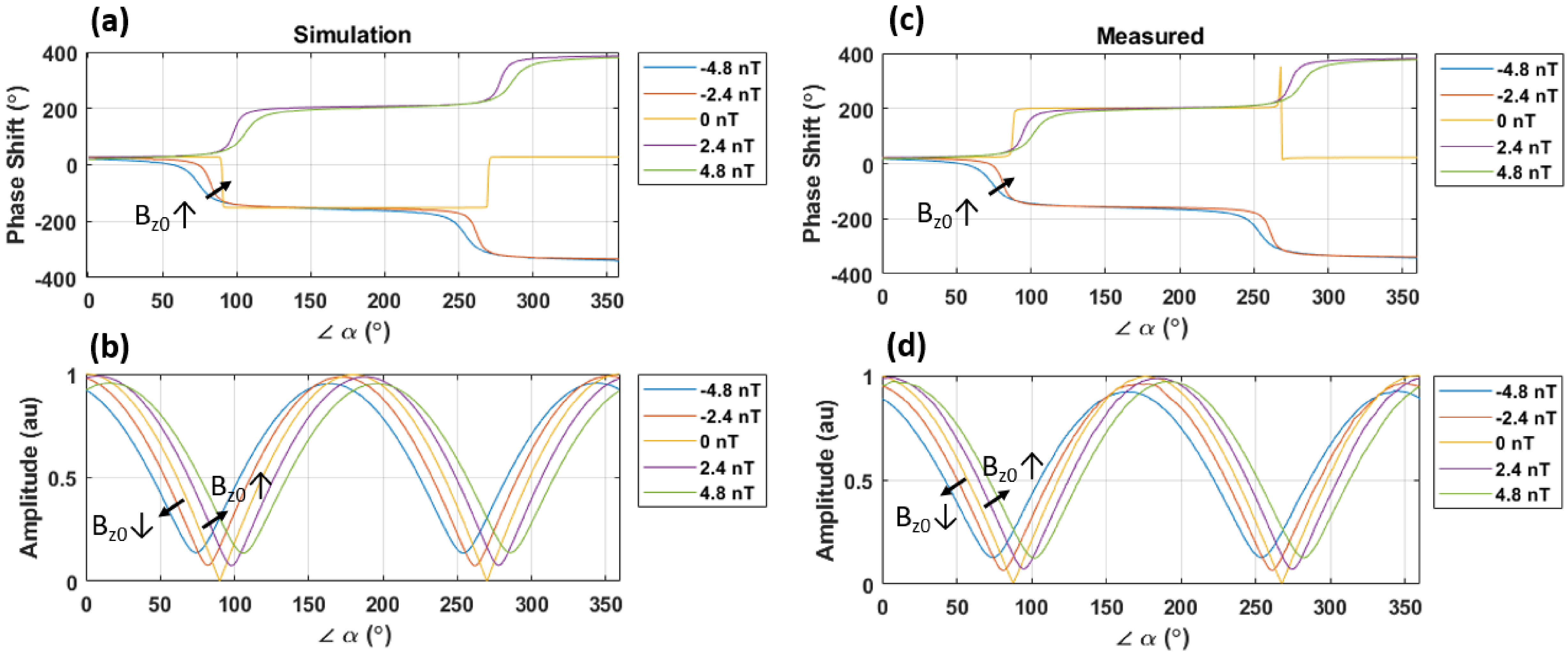
Photon shot noise limit

$$\delta B = \frac{\sqrt{2N_{ph}}}{dS(N_{ph})/dB} \propto \frac{1}{\sqrt{N_{ph}}}$$

Most AMs operate at or near the photon shot noise limit

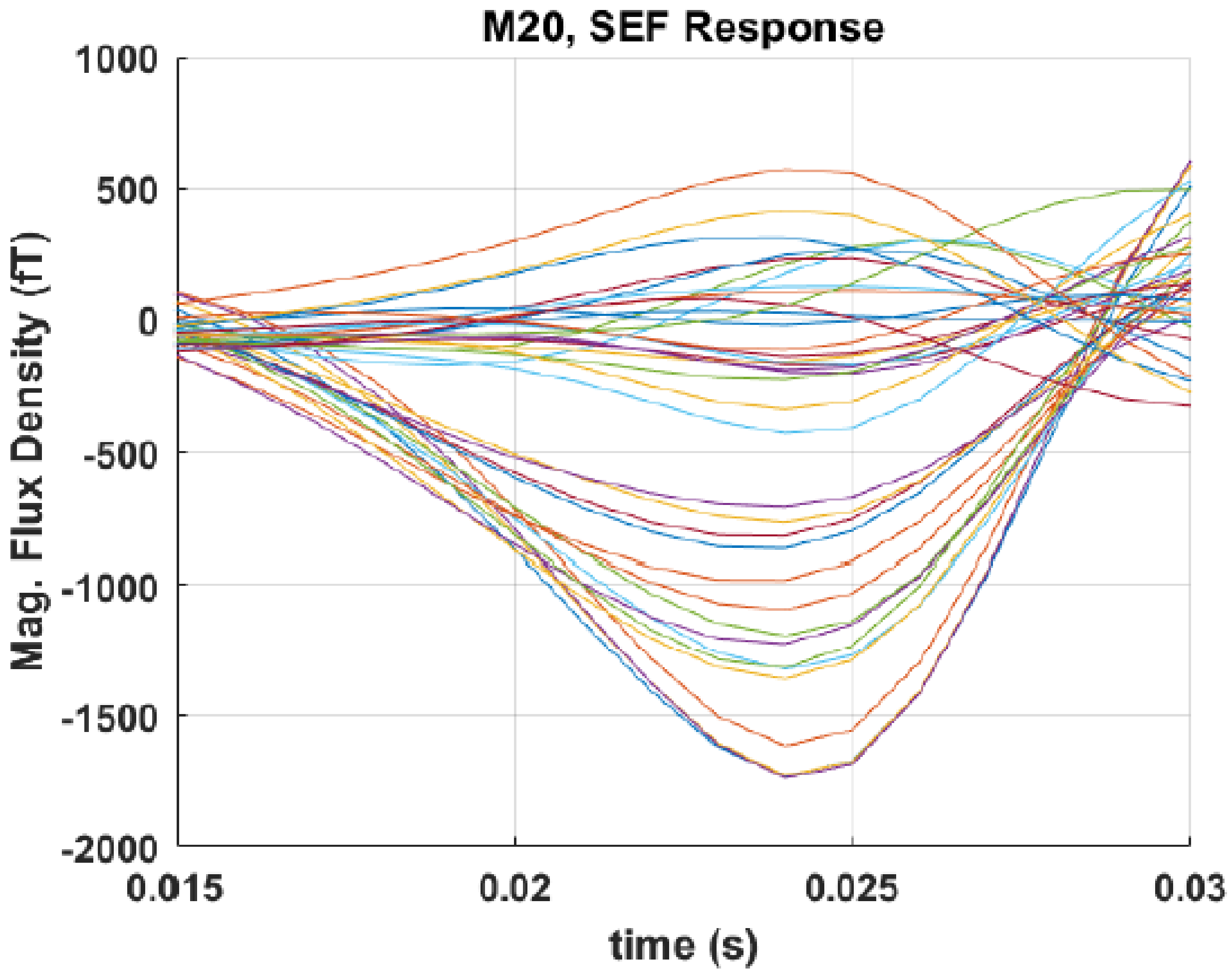
Probe intensity contributes to T_2 so N_{ph} cannot be made arbitrarily high.

Simulation vs. Measurement, CAPE



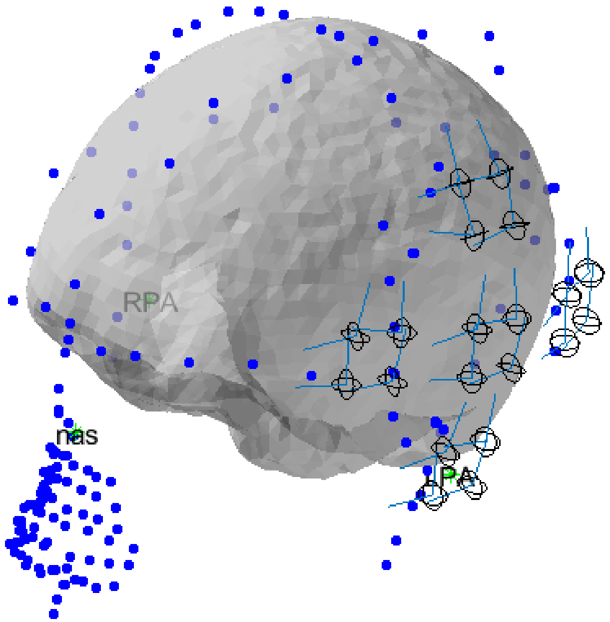
OPM's cross-axis projection error for a 25 Hz, sinusoidal signal with an amplitude of 0.33 nT.

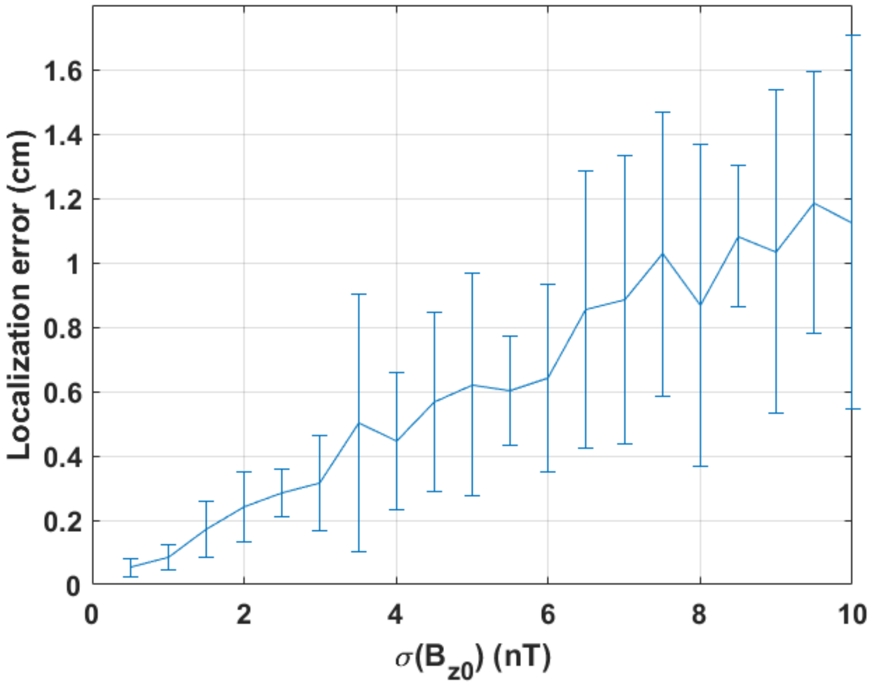
Impact of CAPE on MEG Signals: M20 Median Nerve Response



Wide bandwidth of SEF response at 20 ms (M20) reveals possible effects of CAPE.

Impact of CAPE on OPM-MEG Systems' Localization Capability





Poster Number: IM-29
Amir Borna

The mean and standard deviation (bars) for source localization error; the *x*-axis is the standard deviation of the remnant static magnetic field on the laser propagation axis selected from a normal gaussian distribution.

On-Sensor coils for the Gen 2 Sensor

Designed by Joonas Iivanainen with *bfieldtools*

Coils:

- X: 2 coils
- Y: 2 coils
- Z: 4 coils