



Ultrasensitive Atomic Magnetometers



Faculty

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Principles and Sensitivity of Atomic Magnetometry

Application to Biomagnetism

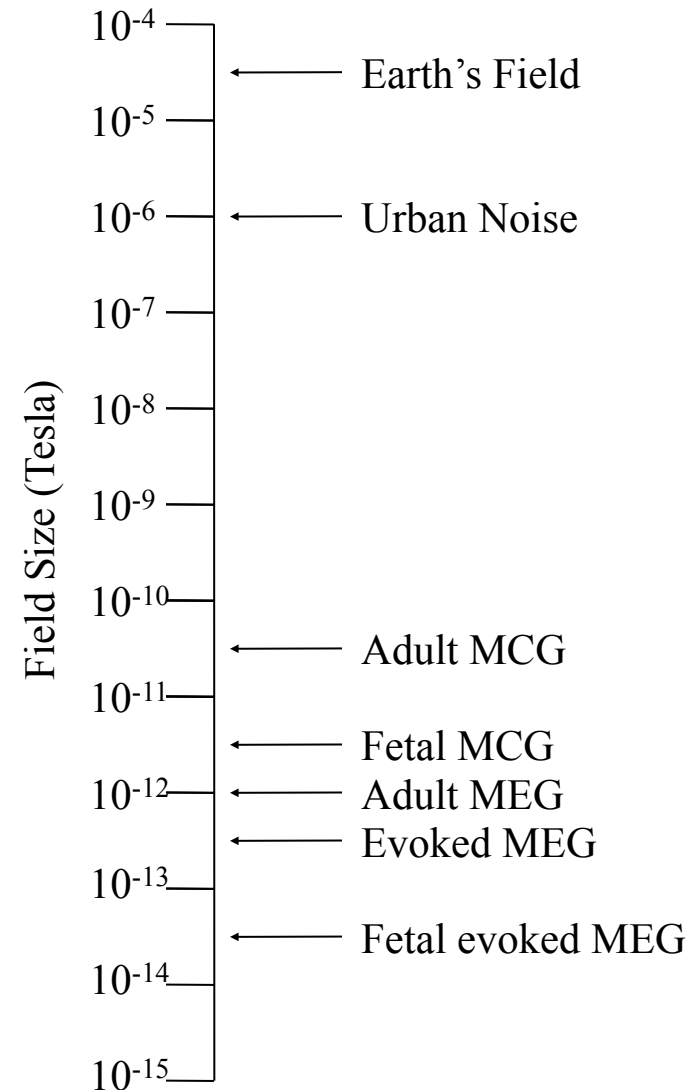
UW Portable Biomagnetometer





Biomagnetism Scales

- Fetal MCG
- Puts requirements on magnetometer:
 - Sensitivity $\sim 10\text{fT/Hz}^{1/2}$
 - Bandwidth $\sim 100\text{Hz}$



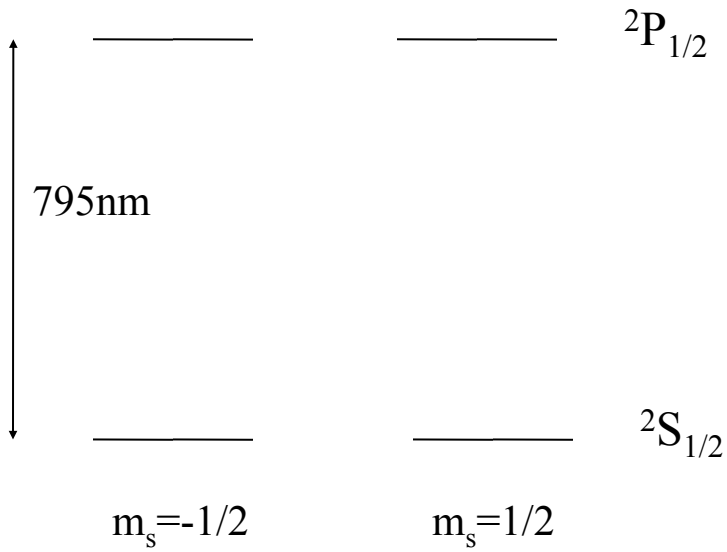
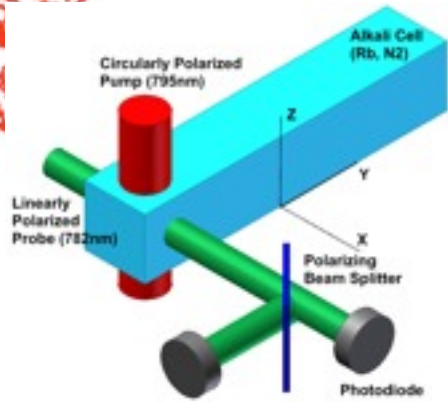


Highly Sensitive Magnetometers

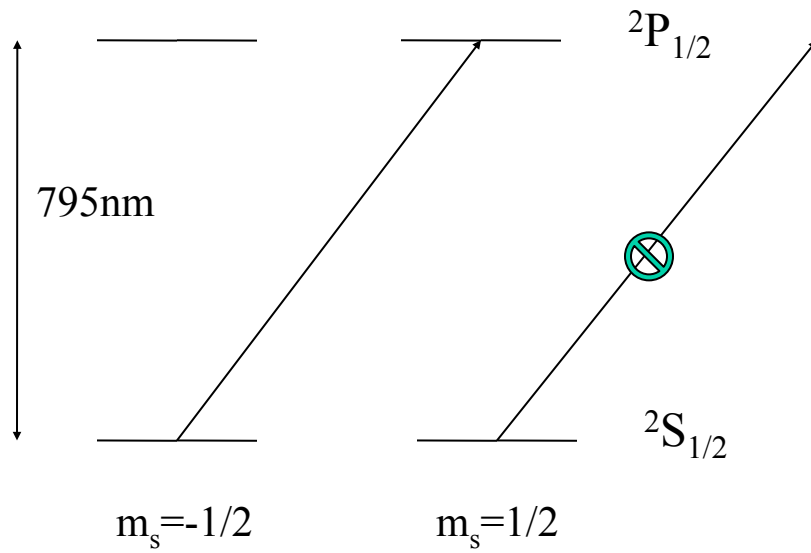
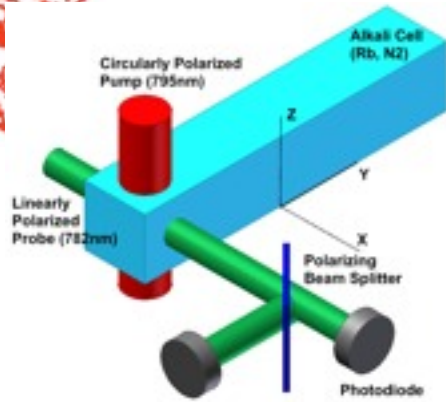
SQUID	Cryogenics Expensive	Can operate in large fields	Sensitivity $\sim 1 \text{ fT/Hz}^{1/2}$	High bandwidth (up to microwave frequencies)
Atomic Magnetometer	Portable Inexpensive	Fully sensitive when in fields $< 10 \text{ nT}$	Sensitivity $< 1 \text{ fT/Hz}^{1/2}$, shot noise limit $< 10 \text{ aT/Hz}^{1/2}$	Limited bandwidth



Optical Pumping

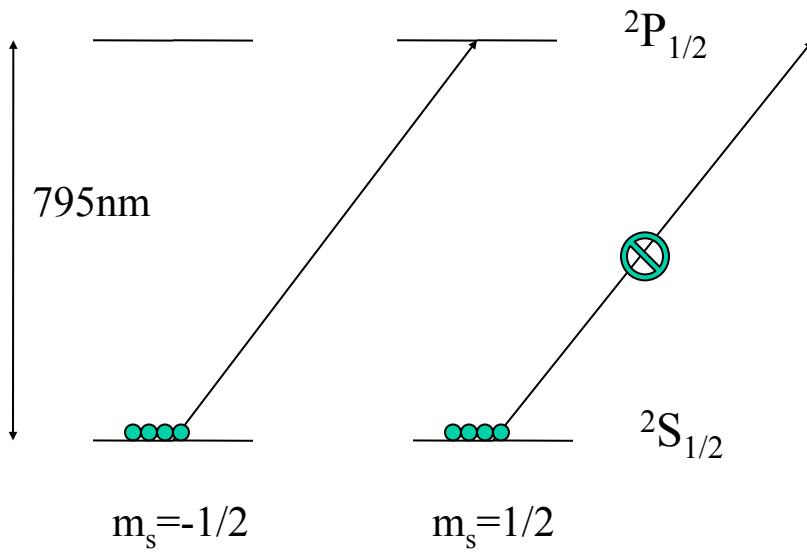
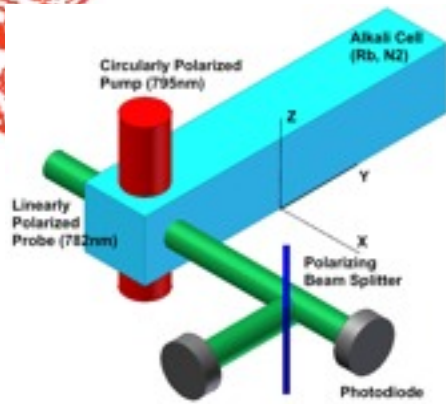


Optical Pumping



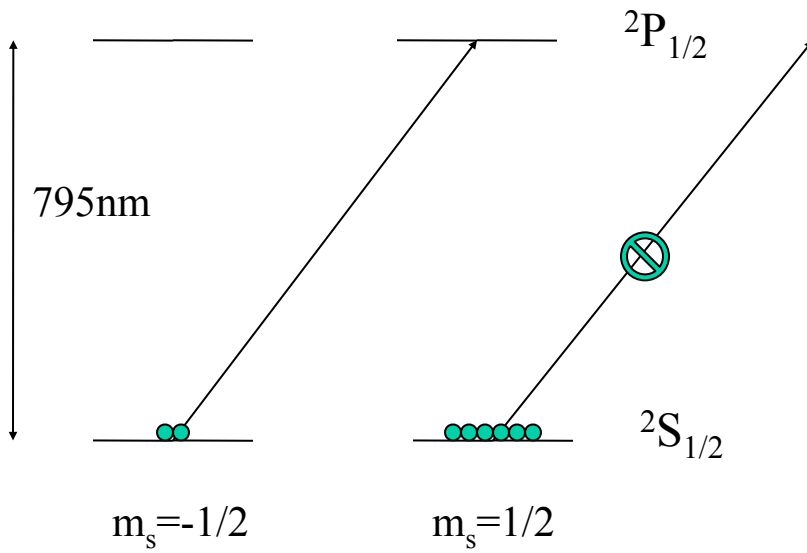
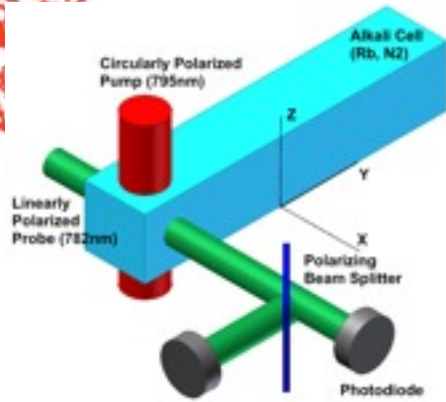
Circularly Polarized light carries +1 ang. Momentum in propagation (z) direction

Optical Pumping



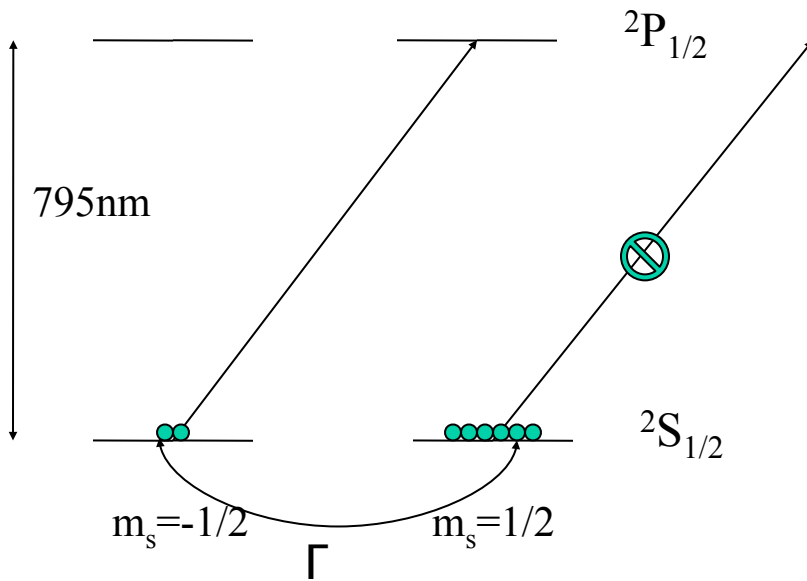
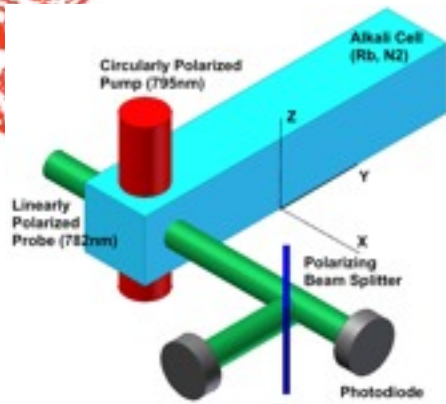
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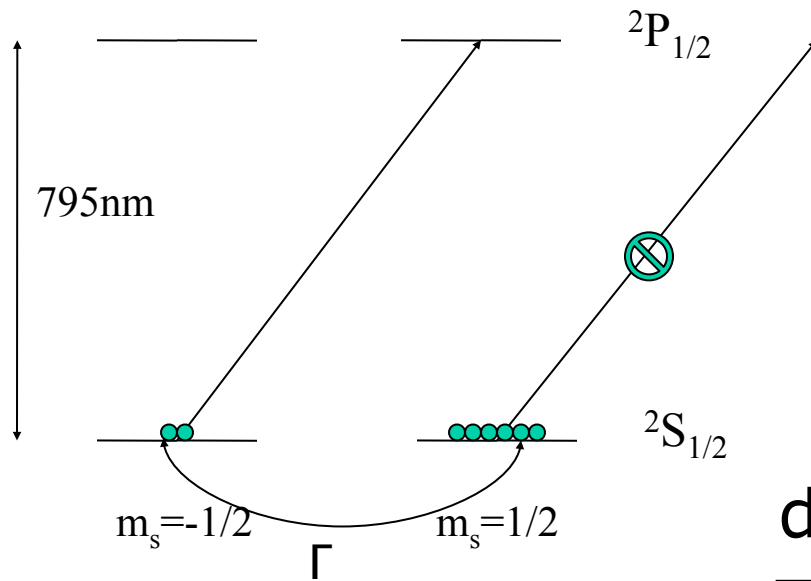
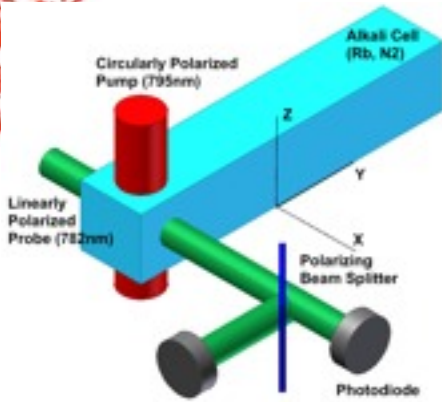
Circularly Polarized light carries +1 ang. Momentum in propagation (z) direction

Optical Pumping



Circularly Polarized light carries +1 ang. Momentum in propagation (z) direction

Optical Pumping



Circularly Polarized light carries +1 ang. Momentum in propagation (z) direction

$$\frac{d\langle \vec{F} \rangle}{dt} = R \left(\frac{\vec{S}}{2} - \langle \vec{S} \rangle \right) - \Gamma \langle \vec{S} \rangle$$

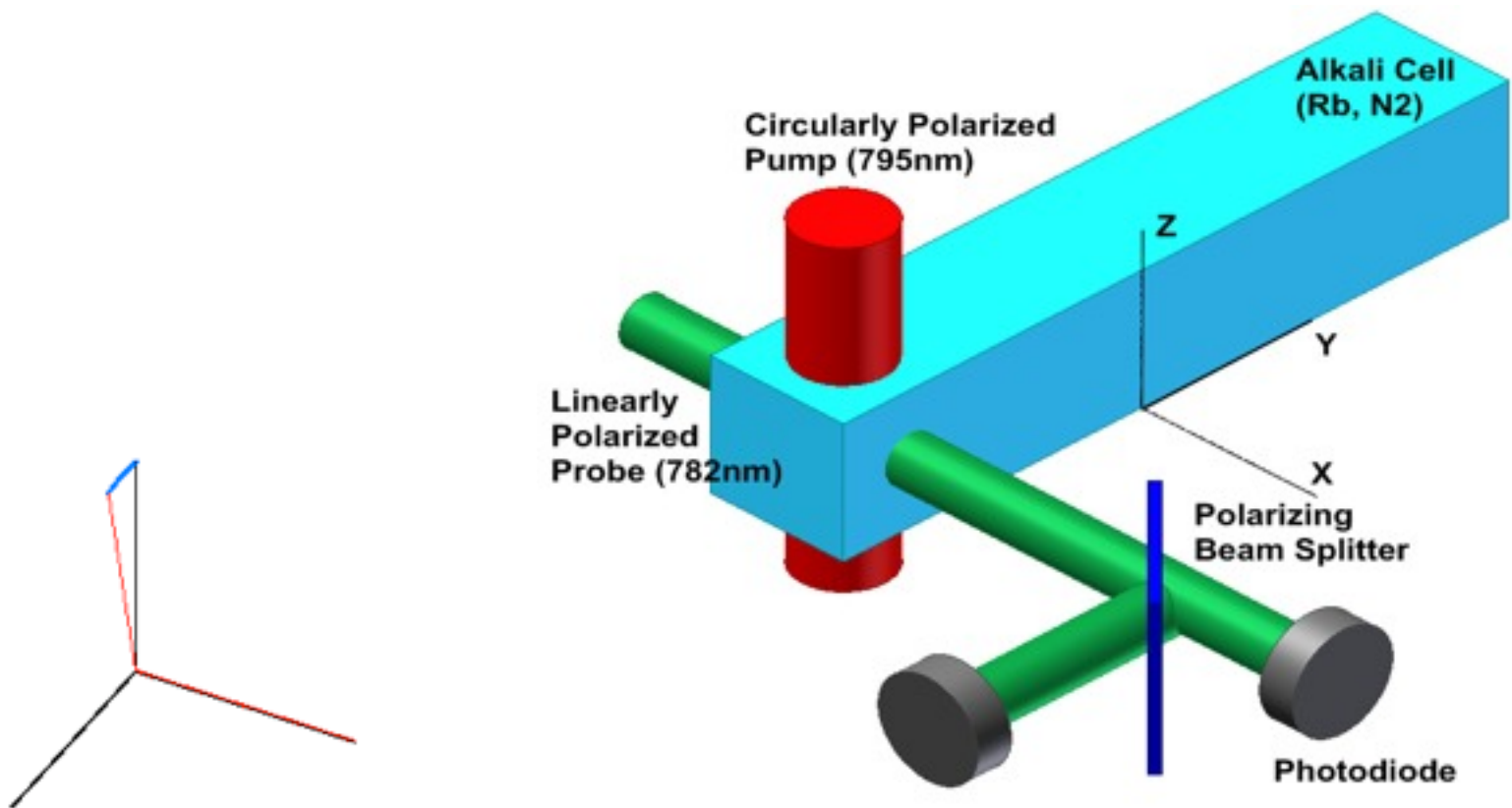


Atomic Magnetometer



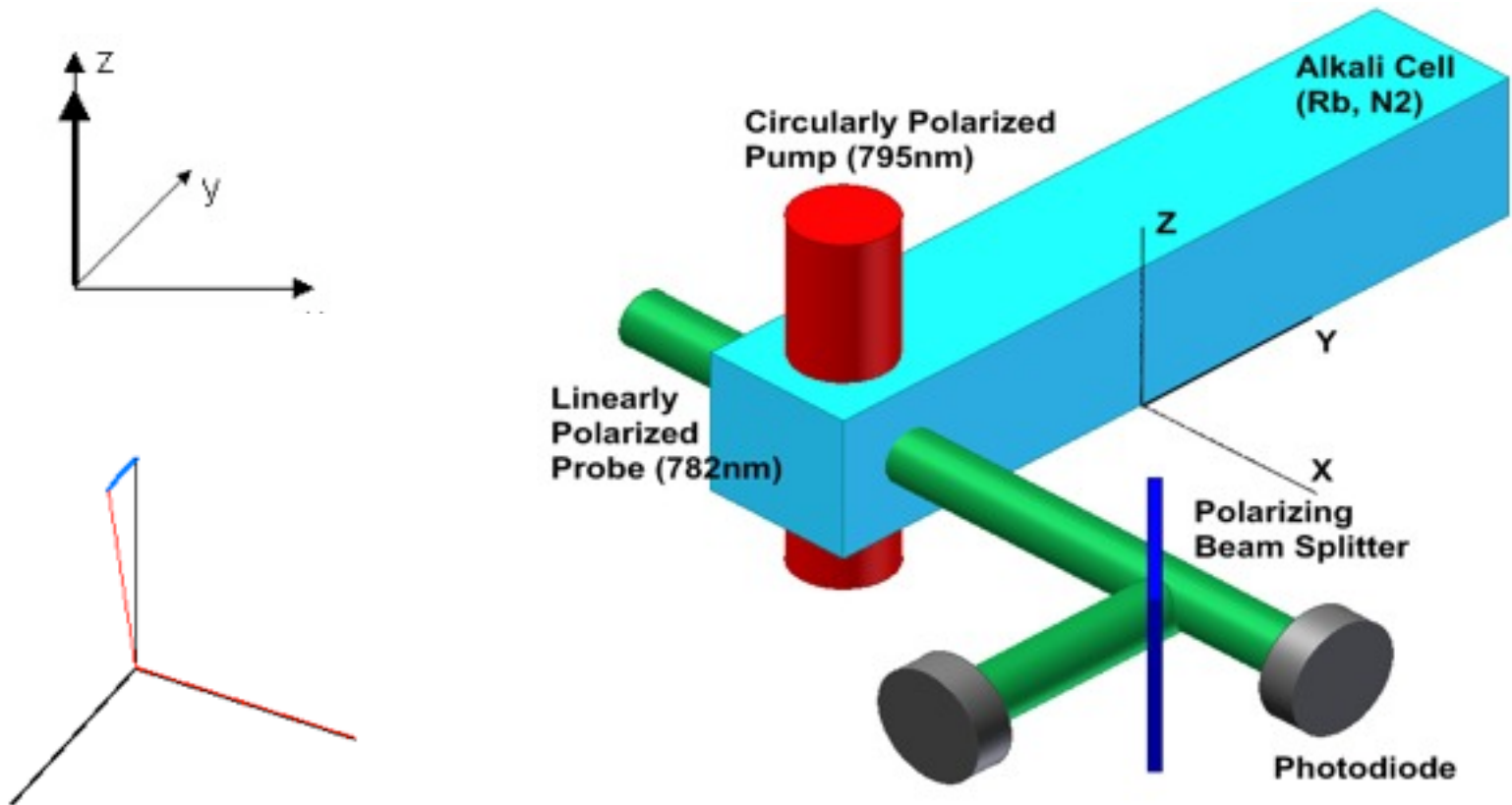


Atomic Magnetometer



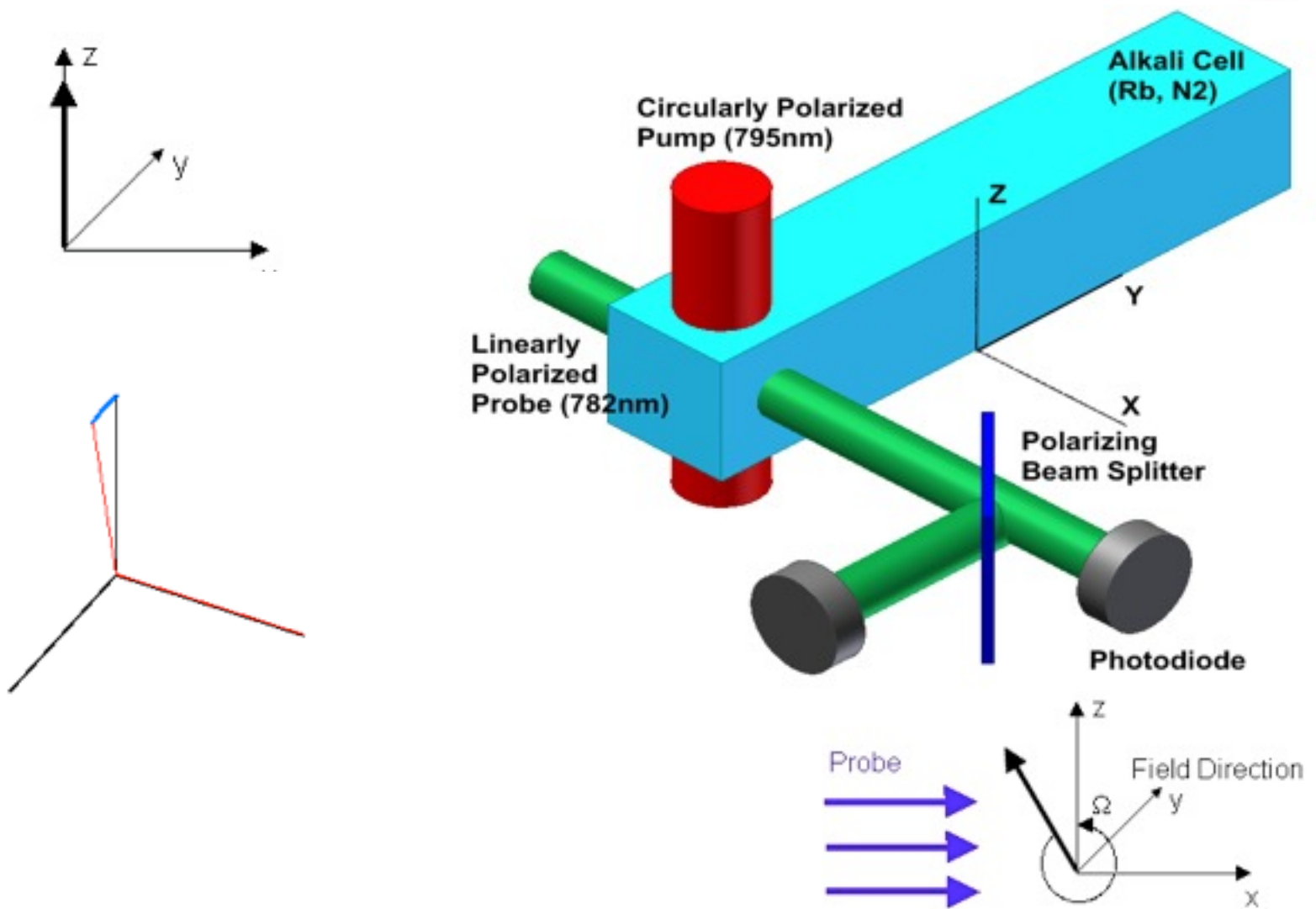


Atomic Magnetometer





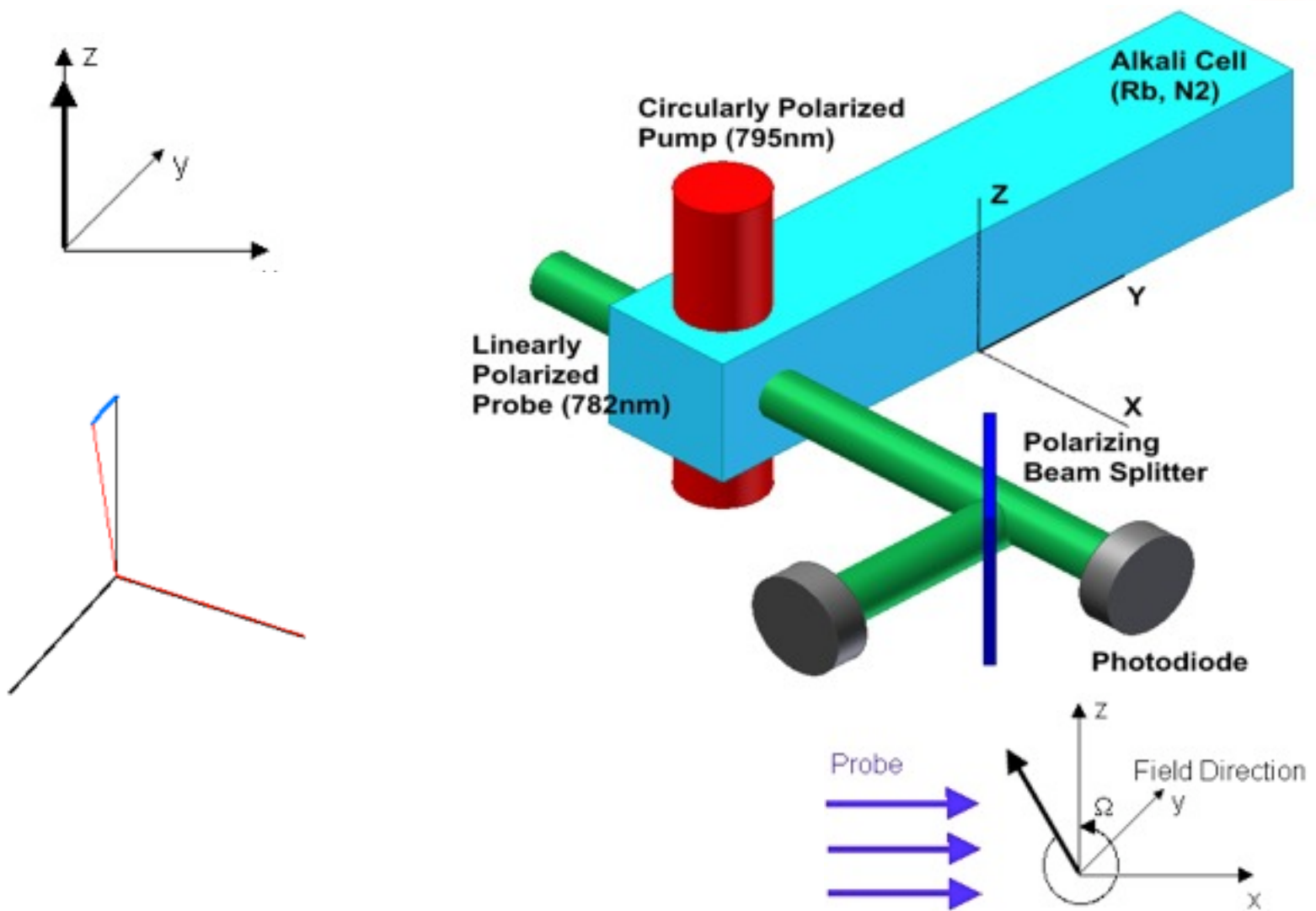
Atomic Magnetometer



Faraday rotation of probe beam is $\sim \langle S_x \rangle$



Atomic Magnetometer



Faraday rotation of probe beam is $\sim \langle S_x \rangle$



Optically Pumped Magnetometers

$$\mathbf{F} = \mathbf{I} + \mathbf{S}$$

Diagram showing the components of the total spin vector \mathbf{F} :

- \mathbf{F} is connected to **Total Spin** (orange text).
- \mathbf{I} is connected to **Nuclear Spin** (blue text).
- \mathbf{S} is connected to **Electron Spin** (red text).

$$\frac{d\mathbf{F}}{dt} = \boldsymbol{\Omega} \times \mathbf{S} - \Gamma \mathbf{S} + R \left(\frac{\hat{z}}{2} - \mathbf{S} \right)$$

Diagram showing the components of the Bloch equation:

- $\frac{d\mathbf{F}}{dt}$ is connected to **Magnetic precession** (red text).
- $\boldsymbol{\Omega} \times \mathbf{S}$ is connected to **Magnetic precession** (red text).
- $\Gamma \mathbf{S}$ is connected to **Spin-Relaxation** (blue text).
- $R \left(\frac{\hat{z}}{2} - \mathbf{S} \right)$ is connected to **Optical Pumping** (green text).

DC Response:

$$S_x = S_z \frac{\Omega_y}{\Gamma + R}$$



Sensitivity

$$\delta B \approx \frac{\hbar}{g_s \mu_B} \sqrt{\frac{\Gamma}{nVT}}$$

n = density; V = volume

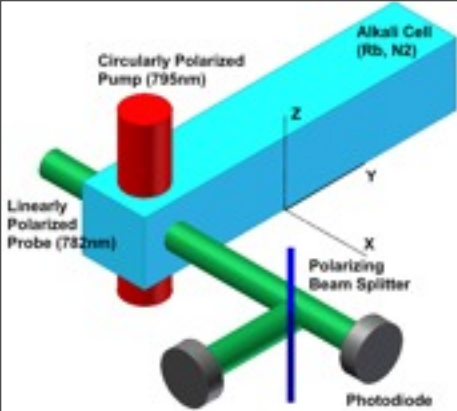
T \equiv Measurement Time

Spin-Exchange Collisions: $\Gamma = n\sigma_{SE}\bar{V}$

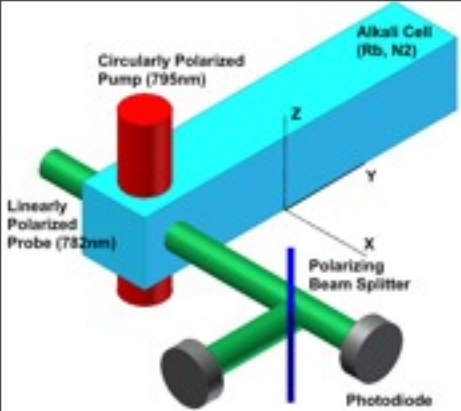
Limits on traditional AM sensitivity:

- Traditional AM's had coherence times that were limited by Alkali-Alkali spin-exchange.
- When density is turned up, the rate of these collisions increases, and $\Gamma / n \rightarrow \text{const.}$
- Shot noise limit $\sim 10 \text{ fT}/\sqrt{\text{Hz}}$

Spin-Exchange Collisions

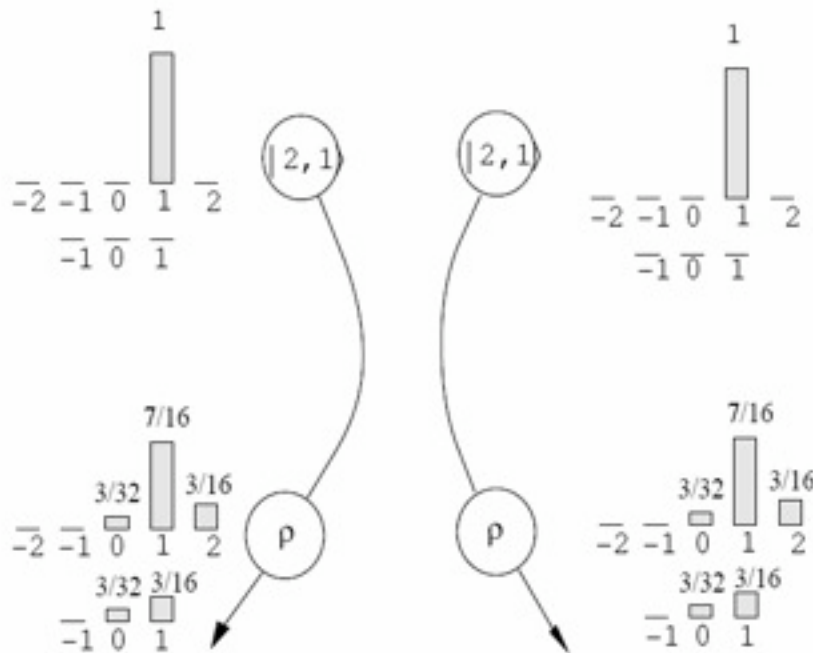
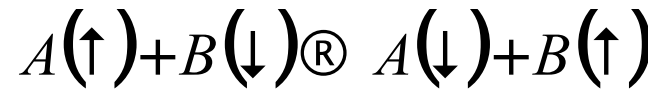


Conserves **F**
but redistributes
between **S** and **I**



Spin-Exchange Collisions

Spin-Exchange Collisions

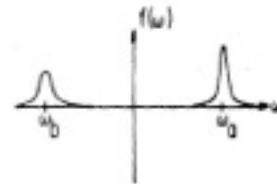


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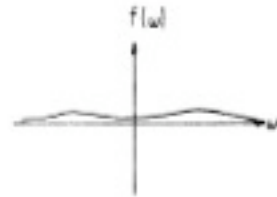
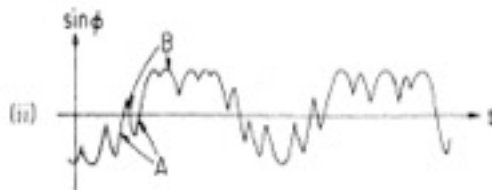


Spin-Exchange Relaxation Free (SERF) Regime

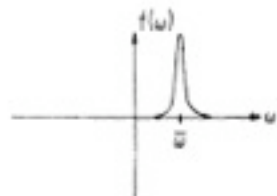
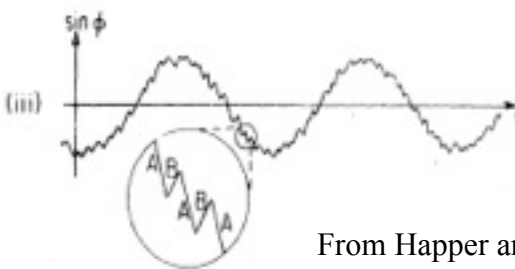
$$\text{Larmor Frequency: } \bar{\omega}_{\bar{F}=\bar{I} \pm \frac{1}{2}} = \pm \frac{g_J \mu_B \bar{B}}{(2I + 1)\hbar}$$



$$\omega \gg \frac{1}{T_{SE}}$$



$$\omega \approx \frac{1}{T_{SE}}$$



$$\omega \ll \frac{1}{T_{SE}} \quad (\text{SERF regime})$$

$$B_{SERF} \ll 1 \mu T$$

Depends on alkali density

From Happer and Tam, PRA **16**, 1877 (1977)

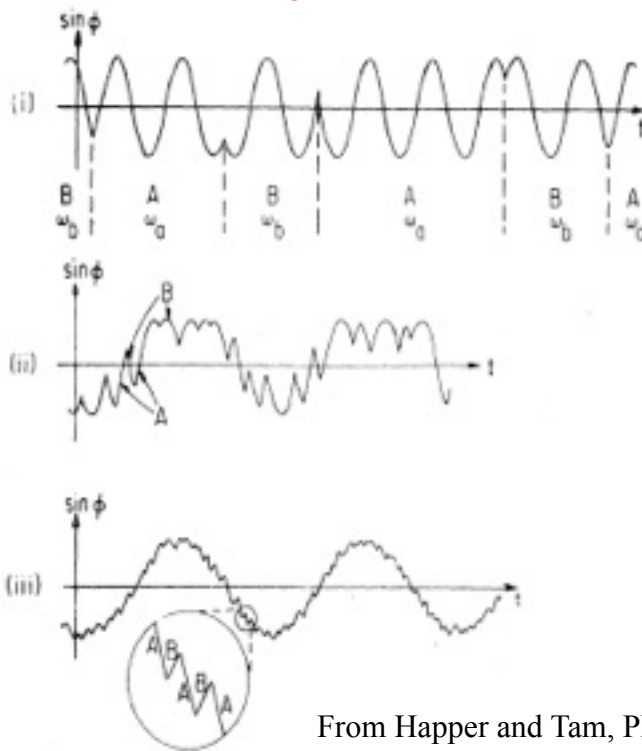
- Operation in SERF regime allows the magnetometer sensitivity to depend on much weaker collisions with other atoms, hence several orders of magnitude greater sensitivity



Spin-Exchange Relaxation Free (SERF) Regime

$$\delta B \approx \frac{\hbar}{g_s \mu_B} \sqrt{\frac{\Gamma}{nVT}}$$

Larmor Frequency: $\bar{\omega}_{\vec{F}=\vec{I} \pm \frac{1}{2}} = \pm \frac{g_J \mu_B \bar{B}}{(2I + 1)\hbar}$



From Happer and Tam, PRA **16**, 1877 (1977)

$$\omega \gg \frac{1}{T_{SE}}$$

$$\omega \approx \frac{1}{T_{SE}}$$

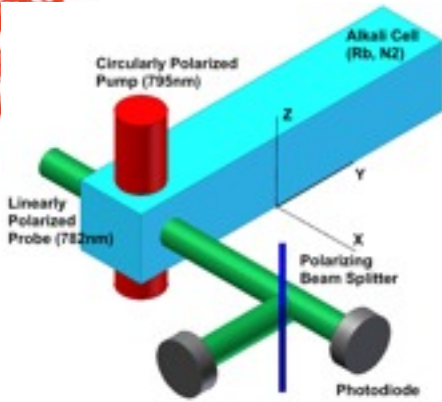
$$\omega \ll \frac{1}{T_{SE}} \text{ (SERF regime)}$$

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SERF Magnetometer

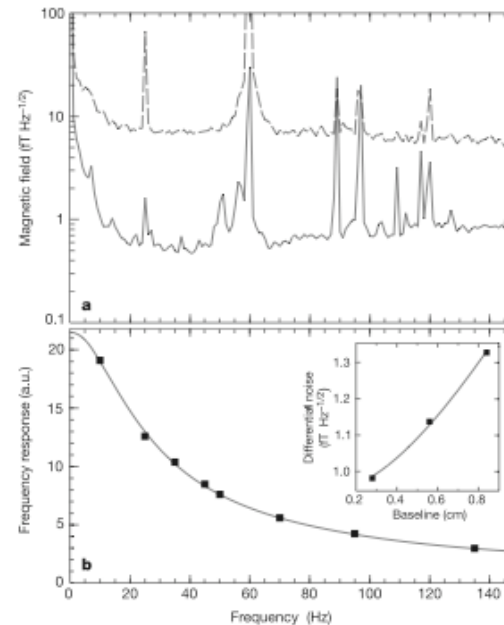
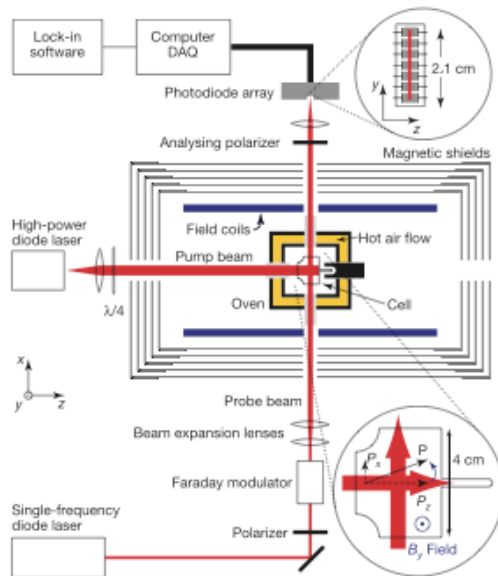


Rapid spin-exchange compared to the precession frequency leads to the spin-temperature distribution.

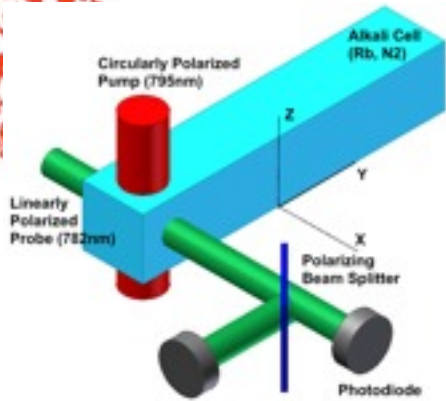
Links total spin to electron spin through “slowing down” factor. $\langle \mathbf{F} \rangle = q \langle \bar{\mathbf{S}} \rangle \quad 4 < q < 6$

$$q \frac{d\mathbf{S}}{dt} = \boldsymbol{\Omega} \times \mathbf{S} - \Gamma \mathbf{S} + R \left(\frac{\hat{z}}{2} - \mathbf{S} \right)$$

Spin-exchange
does not contribute
to Γ !



Kominis et. al.
Nature 422, 596 (2003)

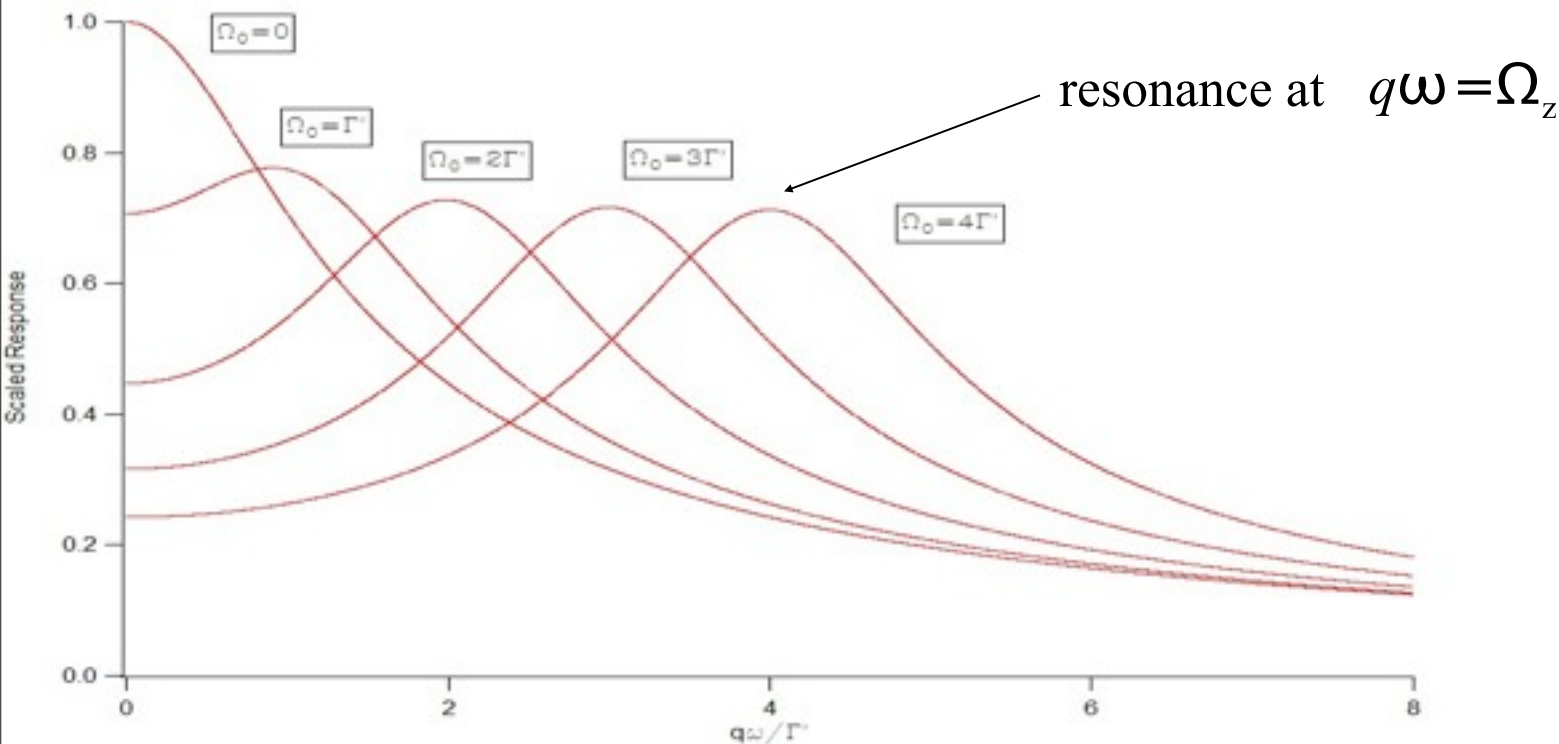


Frequency Response

If we apply a small oscillating field $\vec{\Omega}_1 = \Omega_1 \cos \omega t \hat{y}$

in the presence of a larger DC field $\vec{\Omega}_0 = \Omega_0 \hat{z}$

$$|S_{1x}| = S_z \sqrt{\frac{\Omega_{1y}^2 (\Gamma'^2 + q\omega^2) + \Omega_{1x}^2 \Omega_0}{\Gamma'^4 + (\Omega_0^2 - q^2 \omega^2)^2 + 2\Gamma'^2 (\Omega_0^2 + q^2 \omega^2)}} \quad |S_{1x}|_{\Omega_0 \rightarrow 0} = S_z \frac{\Omega_{1y}}{\sqrt{\Gamma'^2 + q^2 \omega^2}}$$





DC Field Cancellation

SERF limit is about $1 \mu\text{T}$, but to get full sensitivity in our (DC) operation mode,

$$\omega_B \ll \frac{\Gamma_{\text{SD}}}{q(P)} \text{ gives } \vec{B} \ll 30\text{nT}$$

Residual field in our 4-layer shield is $\sim 10\text{s nT}$, so this requires further cancellation using triaxial Helmholtz coils. Automation of this process should be straightforward.

$$S_x = -S_z \frac{\Omega_y \Gamma' - \Omega_x \Omega_z}{\Omega^2 + \Gamma'^2}$$

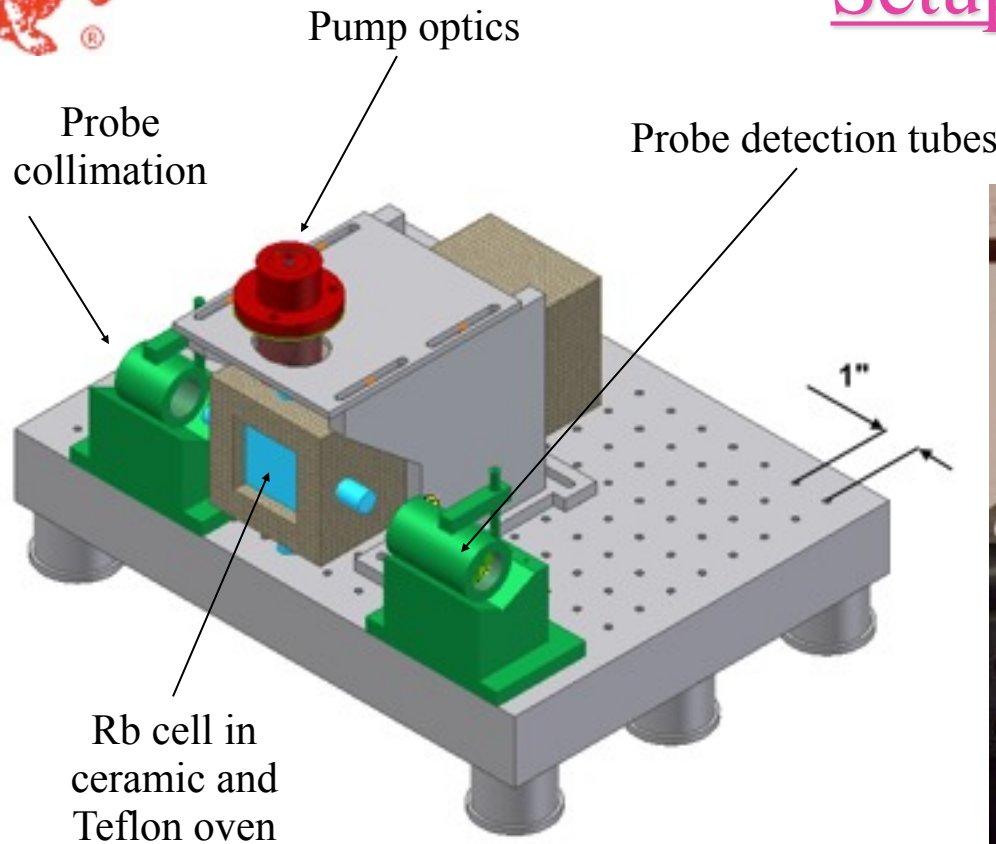
$$\Gamma' = R + \Gamma_{\text{SD}}$$

Shot-noise limit $20 \text{ aT}/\sqrt{\text{Hz}}$
w/ 100 Hz bandwidth

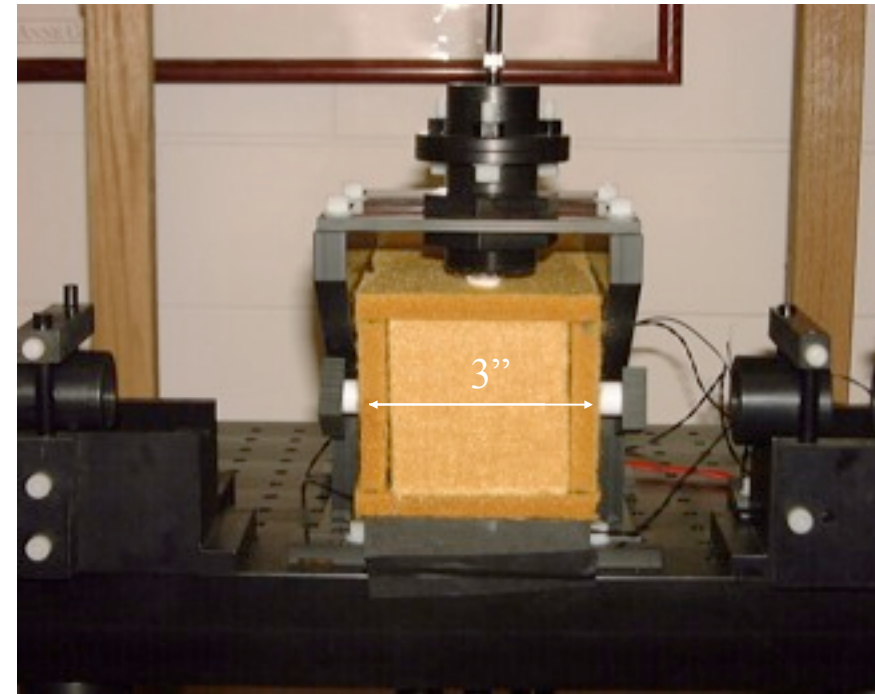
Allows easy residual
field canceling



Setup



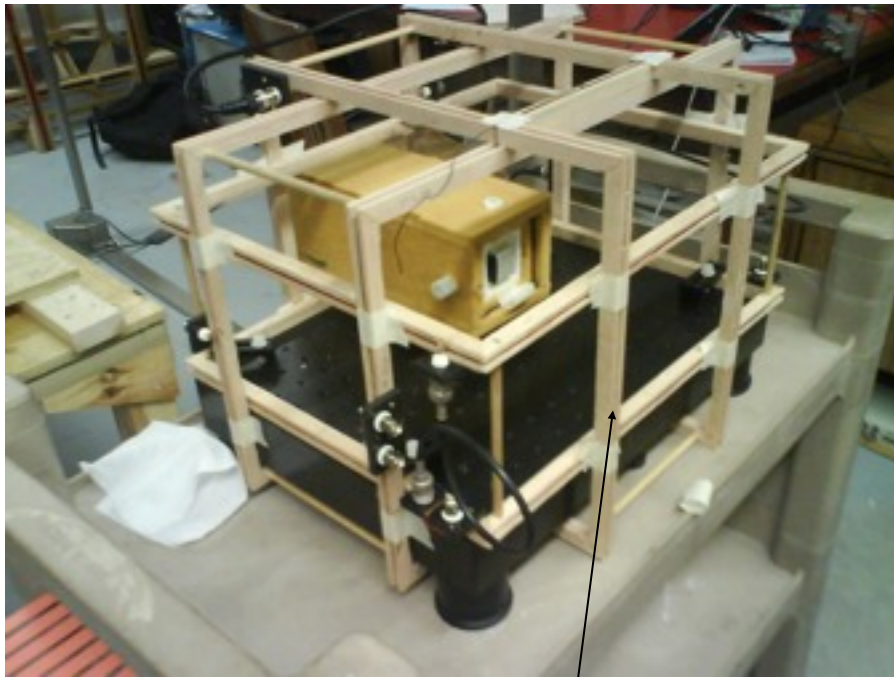
- Rb 87 with N₂ (100T) buffer gases
- Circularly polarized pump at 795nm
- Linearly polarized probe at ~780nm
- Cell heated to 180 C
- All lasers fiber coupled



- Apparatus inside 4-layer mu-metal shield in lab
- Clinical use is in 3-layer shielded room



Some More Pictures



Tri-axial Helmholtz coils

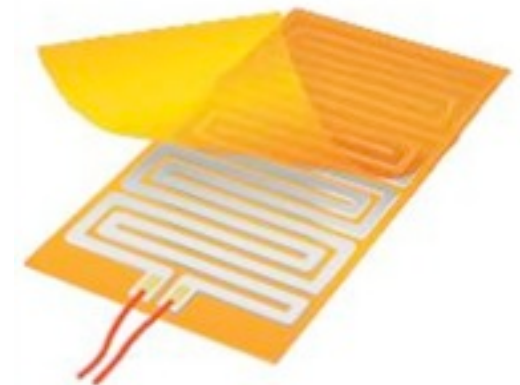
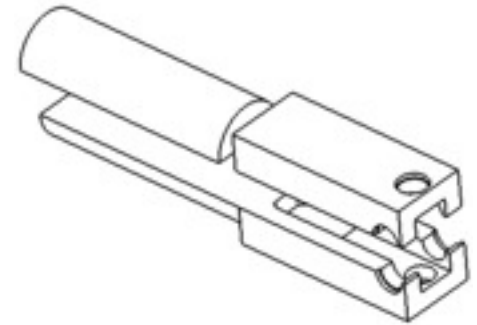
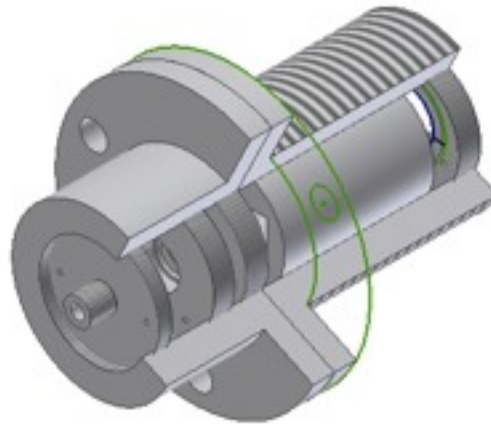
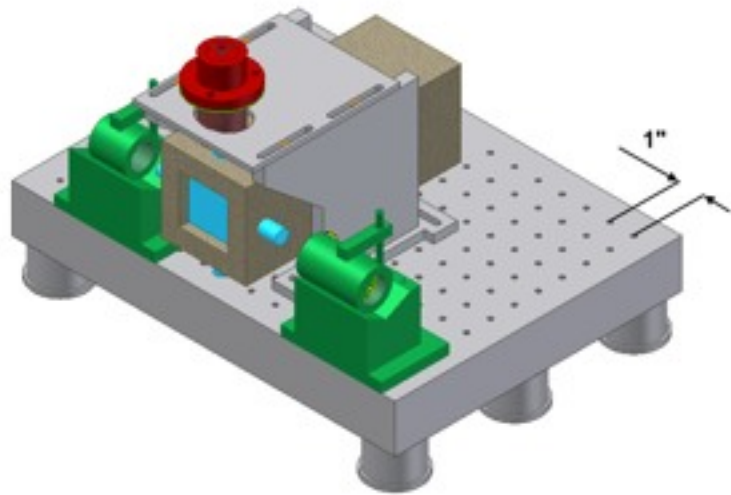


4-layer mu-metal shield



Technical Considerations

- Plastic, ceramic, and Teflon parts reduce Johnson noise
- Electric heating: dipole/quadrupole suppressed resistive film heater sandwich heats w/ small residual field ($\sim 100\text{pT}$)
- Insulation allows subject to be 1cm away from Rb cell
- Simple 1-cm baseline gradiometer with pump tube
- Commercial $1\text{ cm} \times 1\text{ cm} \times 6\text{ cm}$ vapor cell





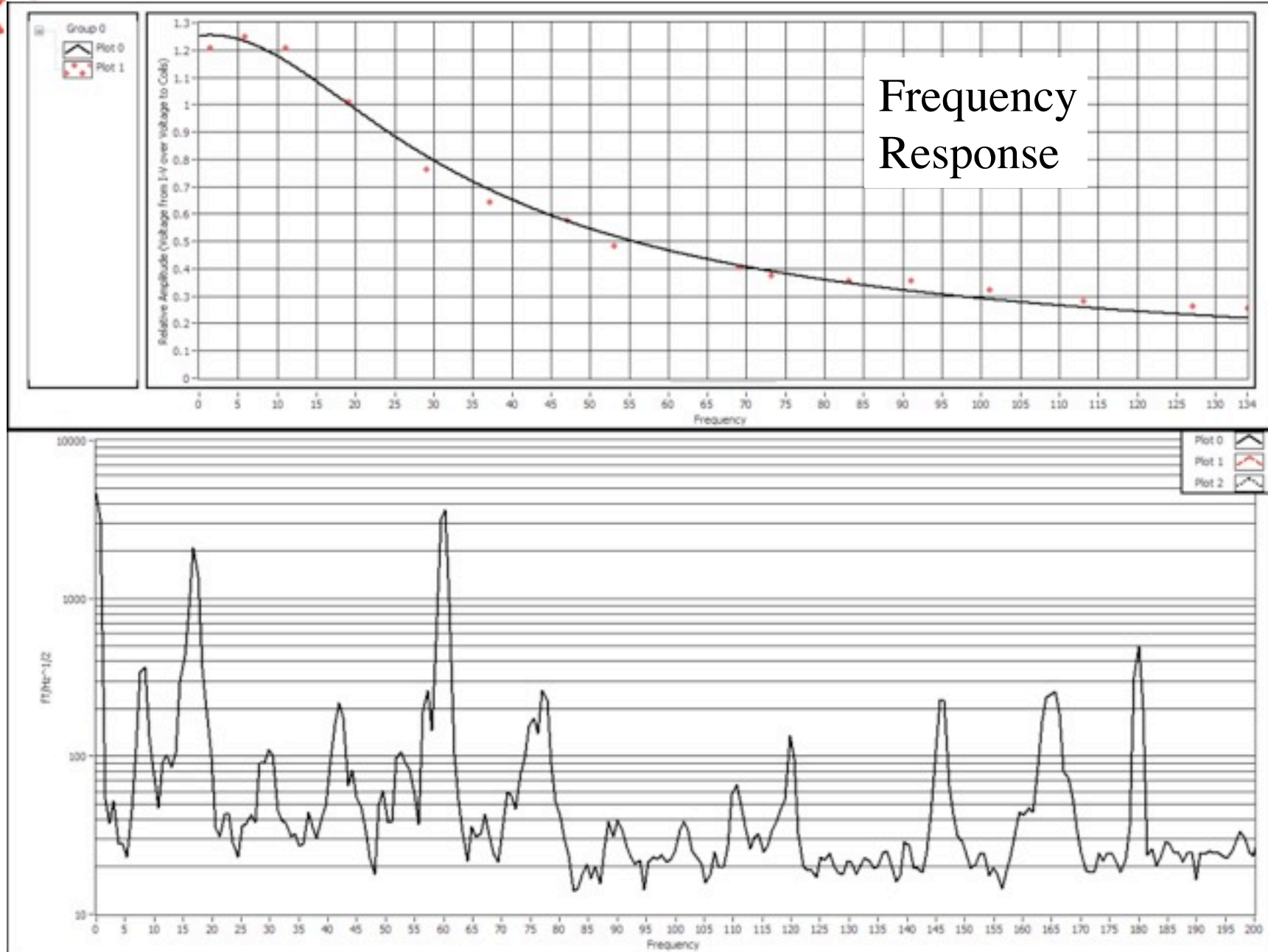
Portability



• Bob Wyllie

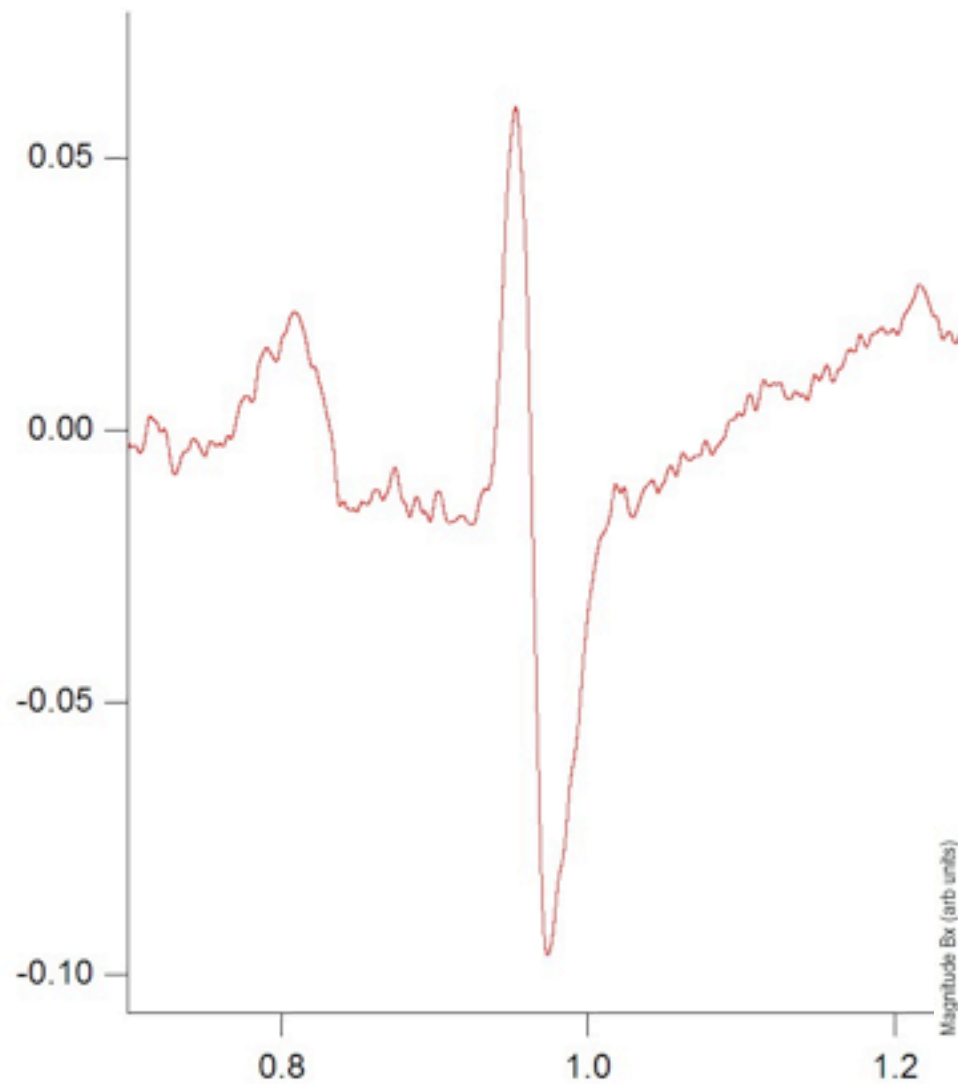


Results

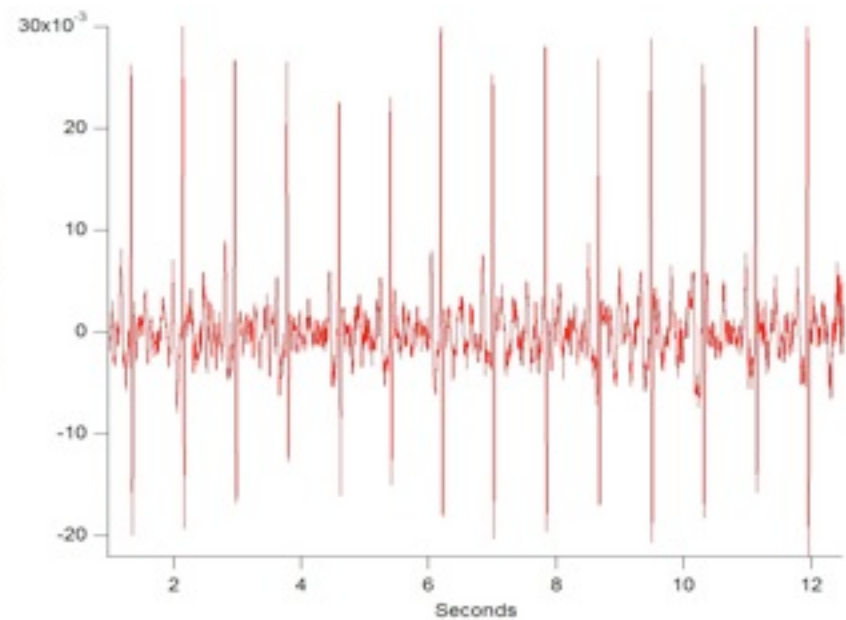




Heart Signals



Average of 4 beats





Z-Mode

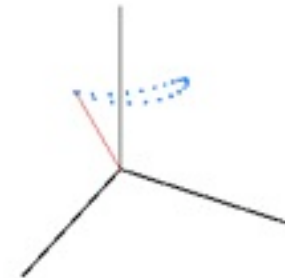
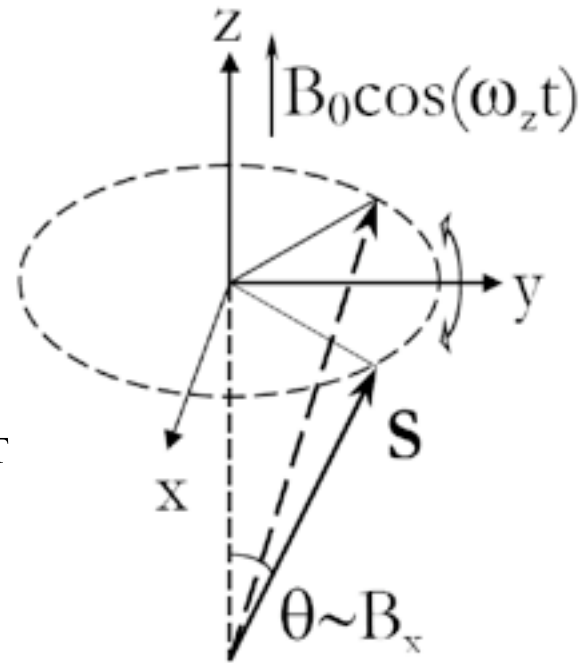
Z Li, R T Wakai, and T G Walker,
Appl. Phys. Lett. 89, 134105 (2006)

For best sensitivity, z-field Larmor
frequency \sim parametric frequency, sets $B_z \approx 430 \text{ nT}$

Allows us to run the magnetometer as a 2-
component vector magnetometer

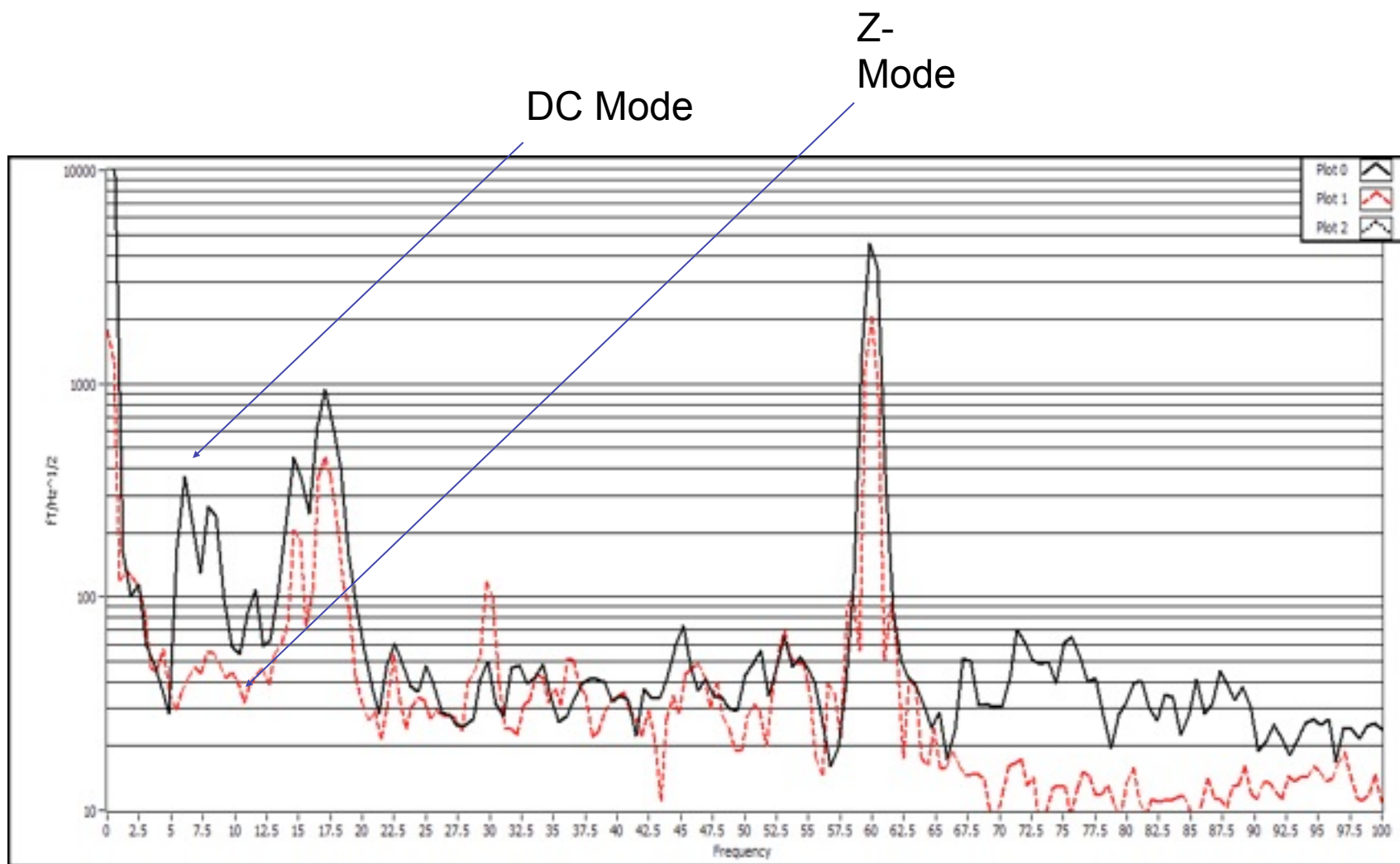
- Z1, S_x signal oscillates at ω_z for B_x
- Z2, S_x signal oscillates at $2\omega_z$ for B_y

Future: lock ω_z to Ω_z to measure
changes in z-field



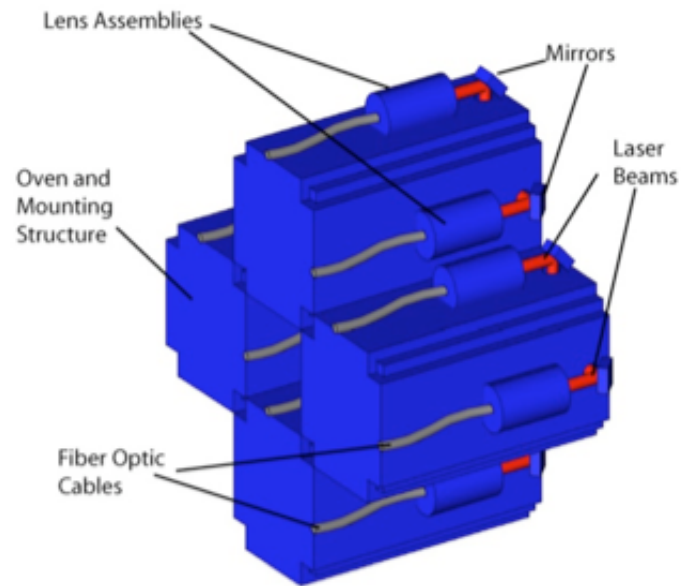


Technical Noise Reduction





Multichannel FMCG

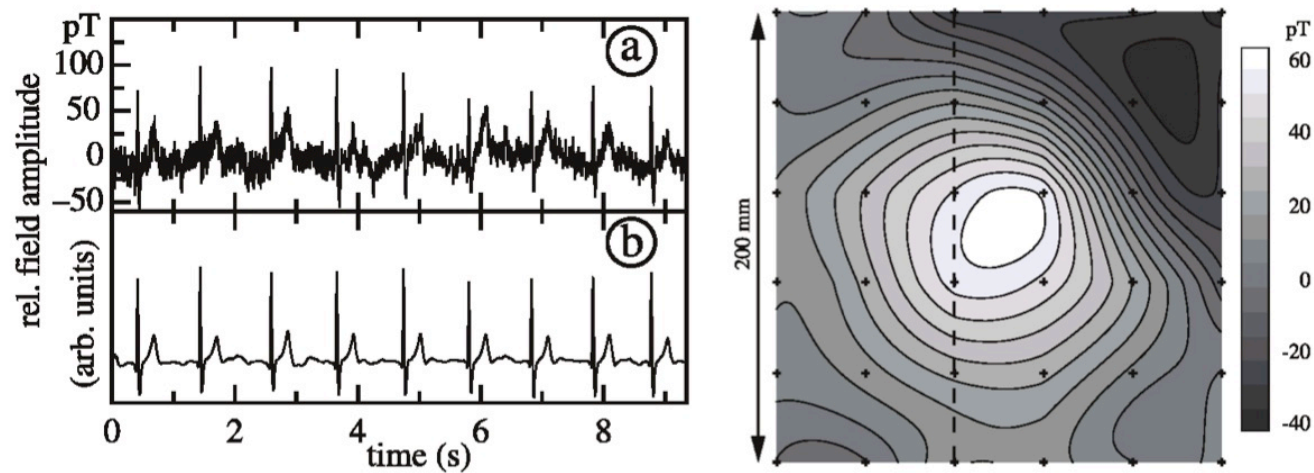


Should be easily miniaturized to a few cm/channel



Other AM MCG results

Shot-noise limited M_x non-SERF magnetometer



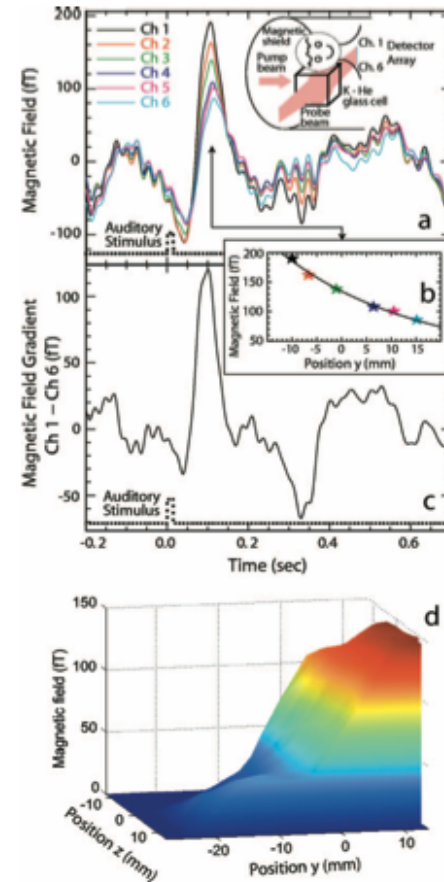
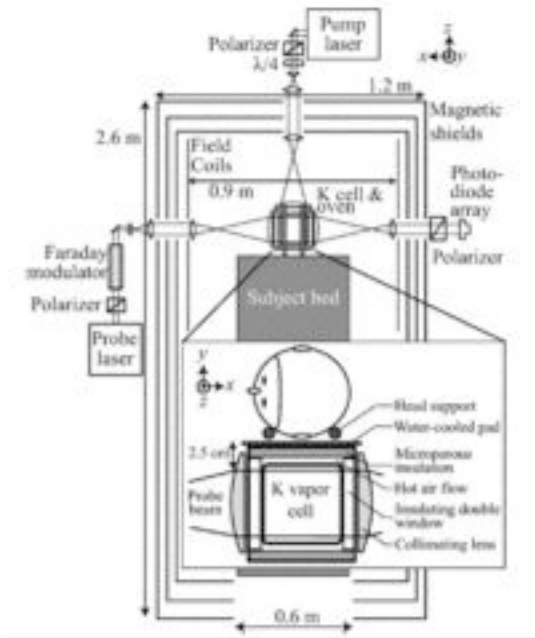
Bison et al., OPTICS EXPRESS 11, 904 (2003)

Poster 10-33

Measurement of Biomagnetic Fields in Small Animals by use of an
Optical Pumping Atomic Magnetometer S. Taue et. al



Evoked MEG



XIA et al, APPLIED PHYSICS LETTERS 89, 211104

10-24 Development of a Wide-coverage Atomic Brain
Magnetometer System (K. Kim, H. Xia, S. Lee, M.V. Romalis)



Summary

- Atomic magnetometers are performance-competitive with SQUIDs.
- Potentially substantially less expensive to build and operate
- Developed a portable, highly sensitive atomic magnetometer suited for fetal MCG measurements.
 - Sensitivity $\sim 40 \text{ fT/Hz}^{1/2}$
 - Bandwidth $\sim 40 \text{ Hz}$
- Z-mode technical noise suppression and the ability to simultaneously detect two components of the magnetic field simultaneously.