

# Towards a Multi-Channel Atomic Magnetometer Array for MEG

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Sandia National Laboratories

Workshop on Atomic Magnetometry

June 16, 2012



# Outline

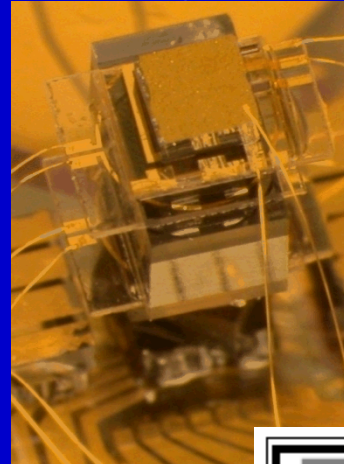
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- Introduction
- First sensor design
  - Performance
  - MEG measurements with one and two sensors
- Scaling up to larger array
  - Second sensor design
- System considerations
  - Simulations of detecting MEG signals with our AM array
- Conclusion

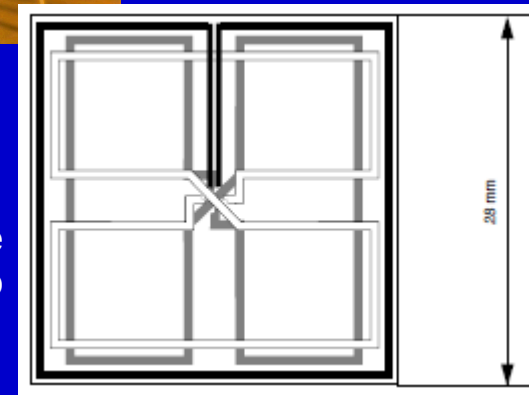
# Introduction

- Two projects focusing on developing atomic magnetometers (AMs) for MEG
  - Internal funding from Sandia, 2008-2010
  - NIH funding, 2012-present
- Looking to develop a scalable sensor design
  - Toward whole head coverage
- Took inspiration from the Elekta sensor design
  - Adequate sensitivity/bandwidth ( $<10 \text{ fT/Hz}^{1/2}/100 \text{ Hz}$ )
  - Small footprint  $\sim 30 \text{ mm square}$
  - Fiber coupled design
  - Gradiometric 2D output
- Collaboration: The Mind Research Network
  - Design input from neuroscientists
  - Strengthen ties to ultimate user community
  - Use magnetically shielded room

NIST Chip-Scale Atomic Magnetometer



Princeton AM MEG System



Elekta Triple Sensor Chip

# Engineering Challenges

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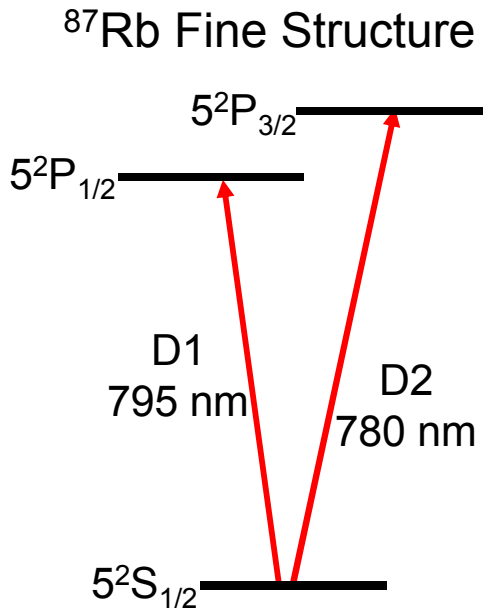
1. Earth's field  $\sim 10^{-4}$  T, brain's field  $\sim 10^{-13}$  T
  - Use the shielded room at the Mind Research Network (ABQ, NM)
  - Characterize shielded room, add needed passive or active shielding
  - Use gradiometry to remove common mode field noise.
2. Minimize distance between  $\sim 200$  °C cell and the head?
  - Compact optical design
  - Use a vacuum gap or micro porous insulations (aerogels)
  - Active cooling of subject (water cooled pad)
3. Interrogate atoms inside shielded room: Fiber optic delivery
  - Maintain polarimetry capability; use PM fiber
    - Polarization modulation cannot be done pre-fiber; other modulation technique needed to produce dispersive signal
    - Polarization rotation of probe measured inside magnetic shield?
4. No magnetic materials allowed

# Two-color pump/probe scheme

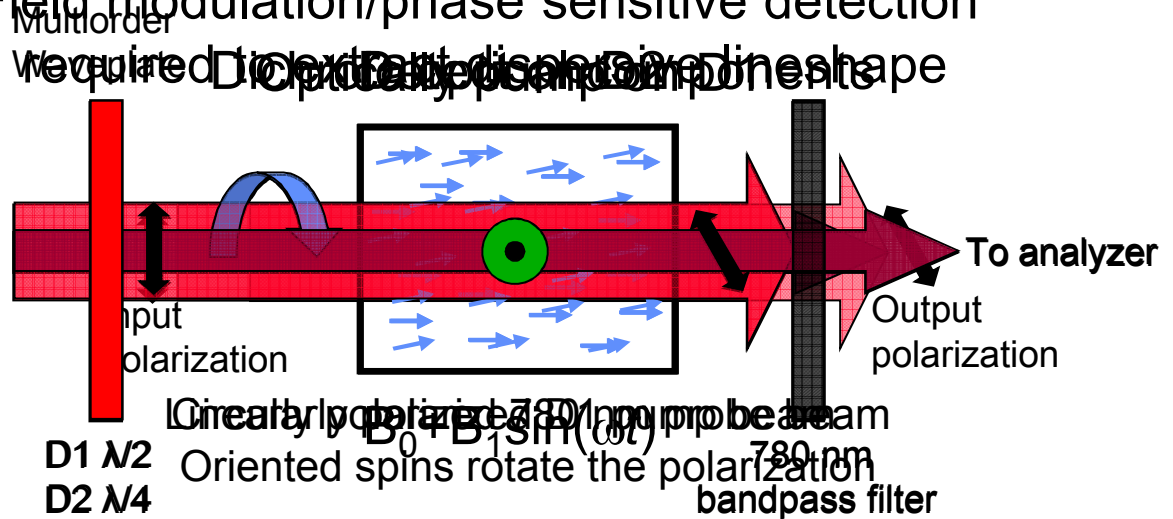
## Single axis, elliptically polarized pump/probe scheme

- Circular component pumps, linear component probes
- $7 \text{ fT/Hz}^{1/2}$ , 150 Hz bandwidth V. Shah and M. V. Romalis, PRA 80, 013416 (2009)
- Pump beam adds noise to detector, pump/probe not independent

## Alternate scheme: utilize rubidium fine structure



## Field modulation/phase sensitive detection



# Relevant Atomic Processes

## Spin Polarization Bloch Equation

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

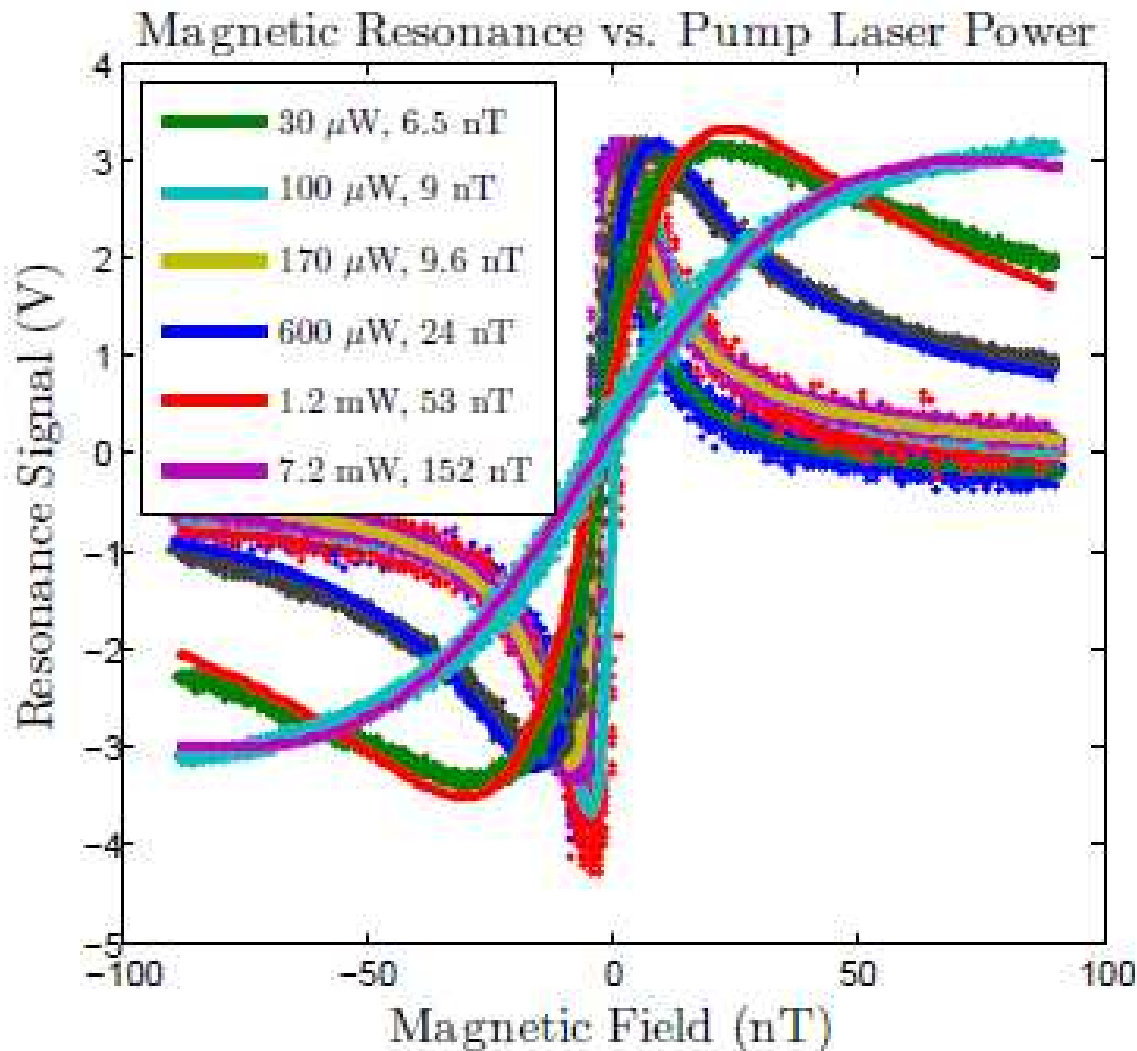
Relevant processes: diffusion through buffer gas, precession in magnetic field, optical pumping, collisions

## $B_x = B_z = 0$ Steady State Solution

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

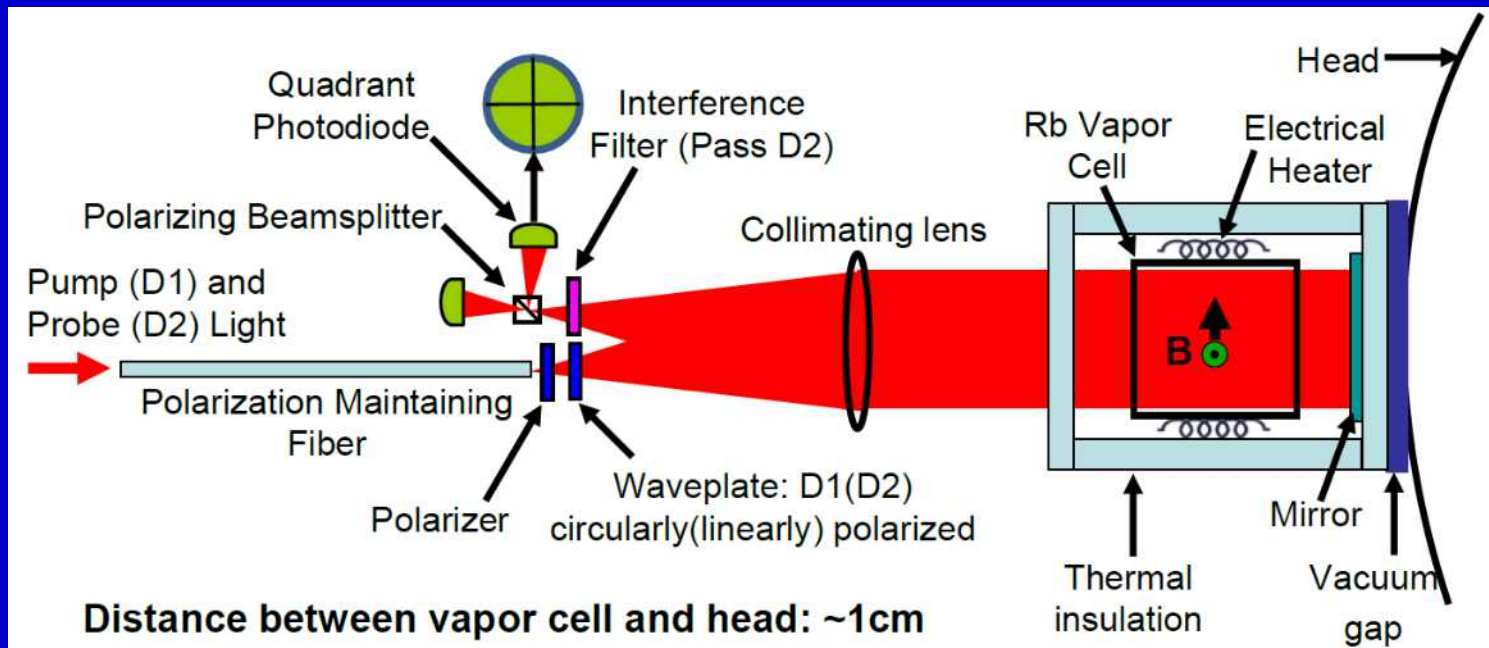
- Probe  $P_x$  or  $P_z$  to measure  $B_y$  magnetic field
  - $P_x, P_z$  affect optical absorption/polarization
- Sensitivity limited by atomic decoherence

# Typical Faraday Rotation Signal



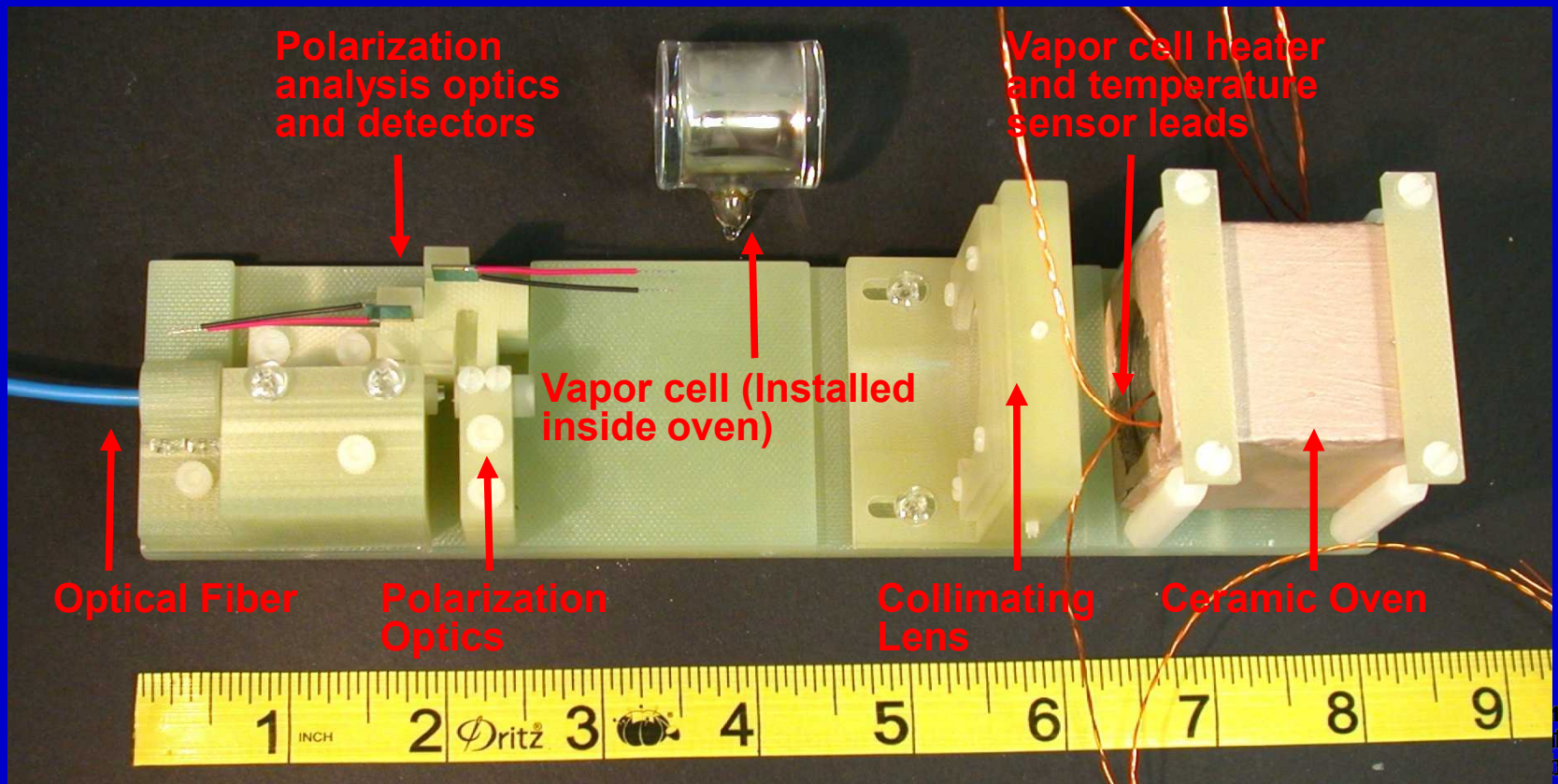
# Sensor Design

- Single optical axis: compact, single fiber for pump/probe
- Use  $^{87}\text{Rb}$  (D1 795 nm, D2 780 nm)
  - Higher vapor pressure = stronger optical rotation, more signal
  - Higher collision rates = more bandwidth
- Retroreflecting mirror minimizes vapor-cell-to-head distance
- Modulate  $B_x/B_y$  for lock-in detection (choose sensitive axis)

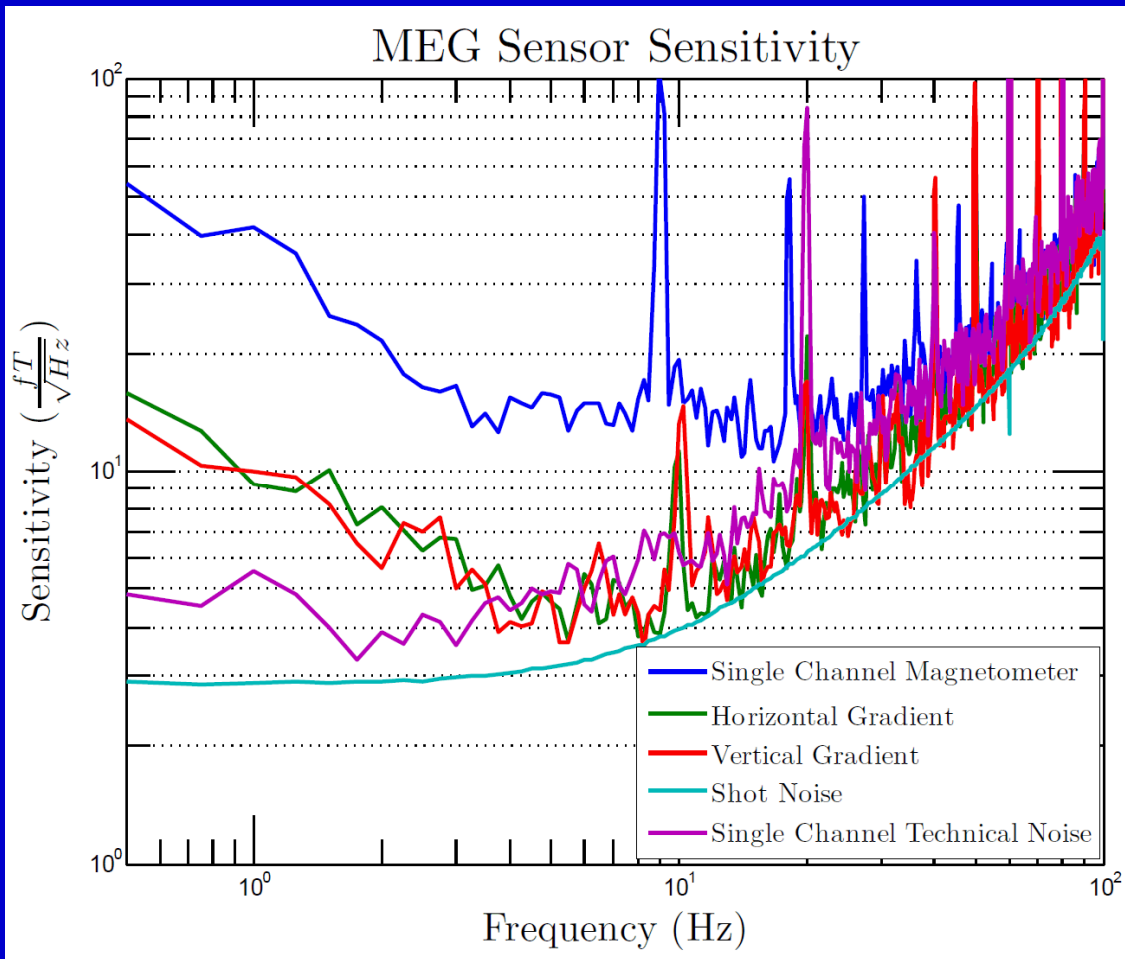


# Magnetometer Hardware

- One inch vapor cell and quadrant photodiode for gradient detection
- Non-metallic G-10 fiberglass
- Microporous ceramic oven
- $1/f$  noise reduced by using optical fibers and a vacuum enclosure
- Improve bandwidth ( $> 100$  Hz) by using a very high alkali density
  - Heat Rb to  $\sim 200$  °C



# Magnetometer Performance



- Gradient measures intrinsic sensitivity
- $<5 \text{ fT/Hz}^{1/2}$  at 10 Hz
- Noise floor consistent with magnetic shield noise
- Bandwidth = 17 Hz; further temperature increase damages mirror
- Shot noise limited above 10 Hz; can be improved with more probe power
- Further work needed to identify low frequency noise source, but already below  $10 \text{ fT/Hz}^{1/2}$  at 1 Hz
- Sufficient for initial MEG demonstration

# Installation in the shielded room



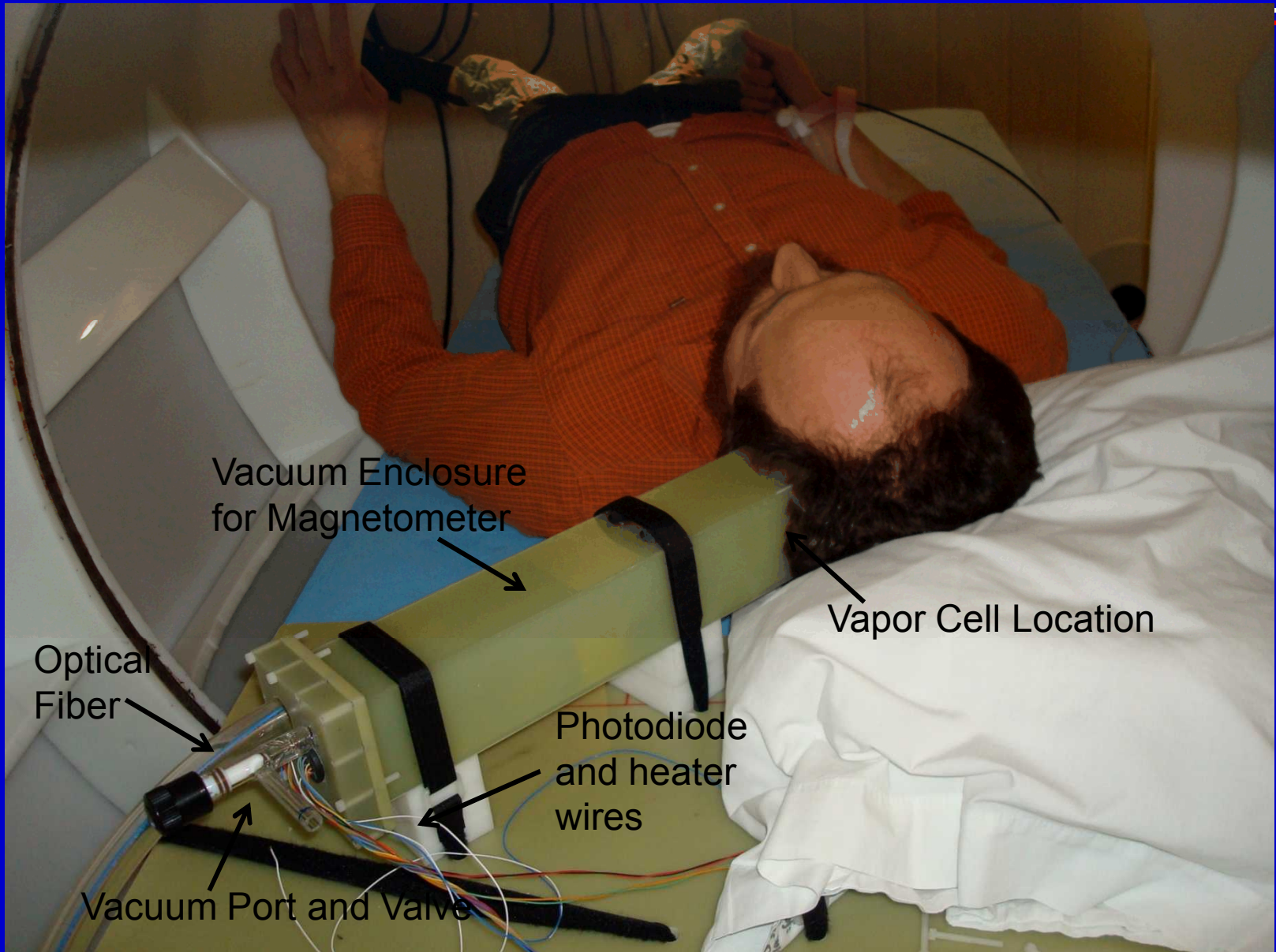
18-coil field cancellation system for reducing the field from  $\sim 100$  nT to  $< 1$  nT



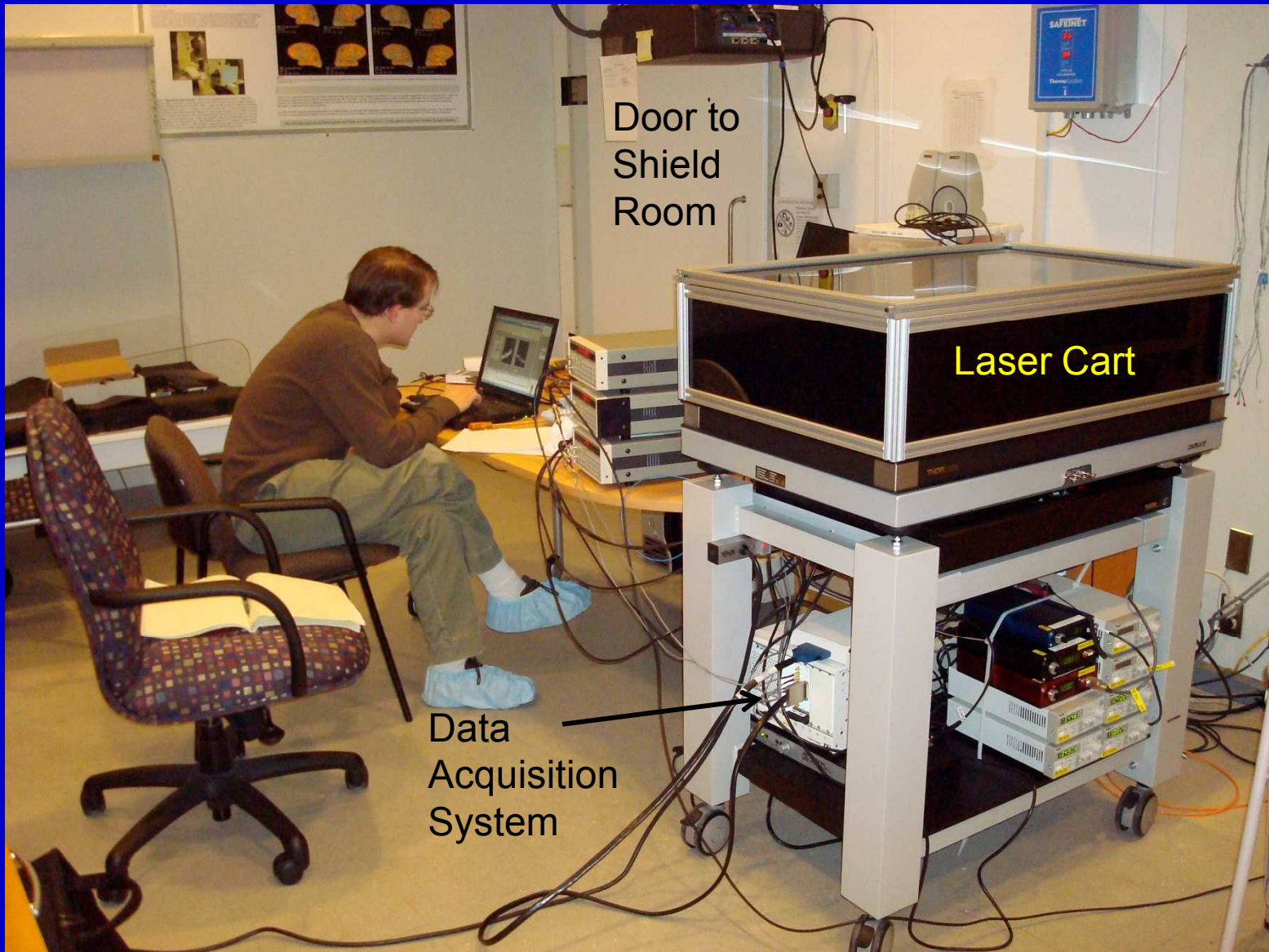
Median nerve stimulator: 8 mA for 100  $\mu$ s

SQUID MEG machine

# Installation in the shielded room

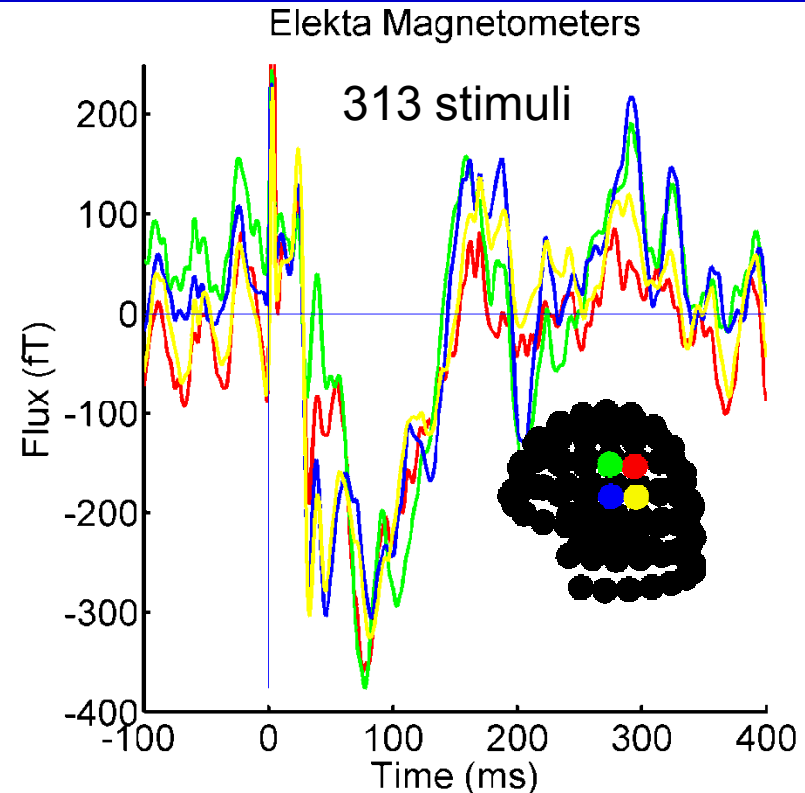
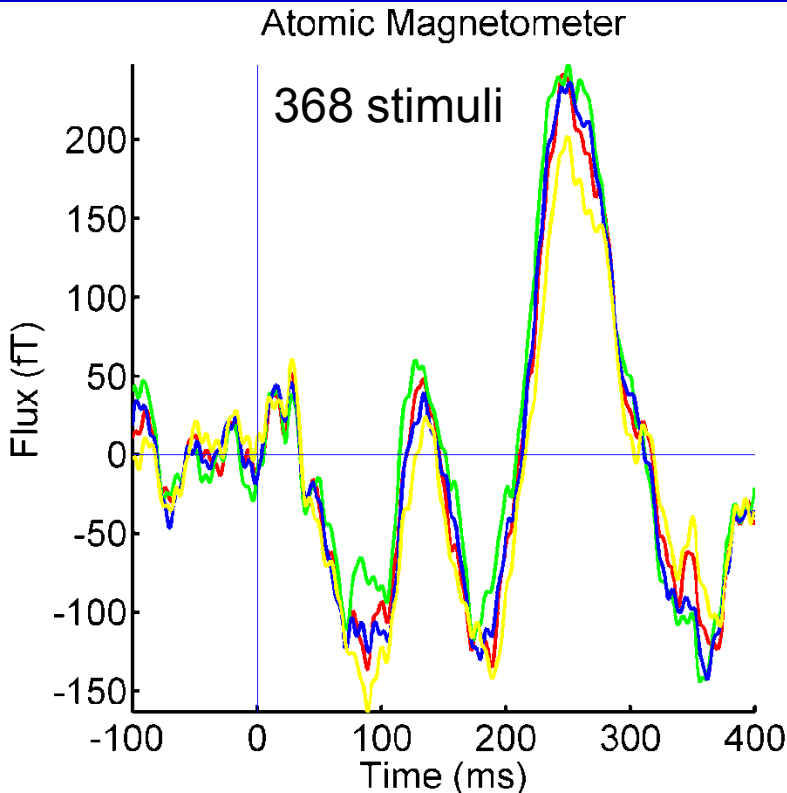


# Lasers and Data Acquisition



# Comparison of the Atomic Magnetometer to the SQUIDs

## Median Nerve Stimulation

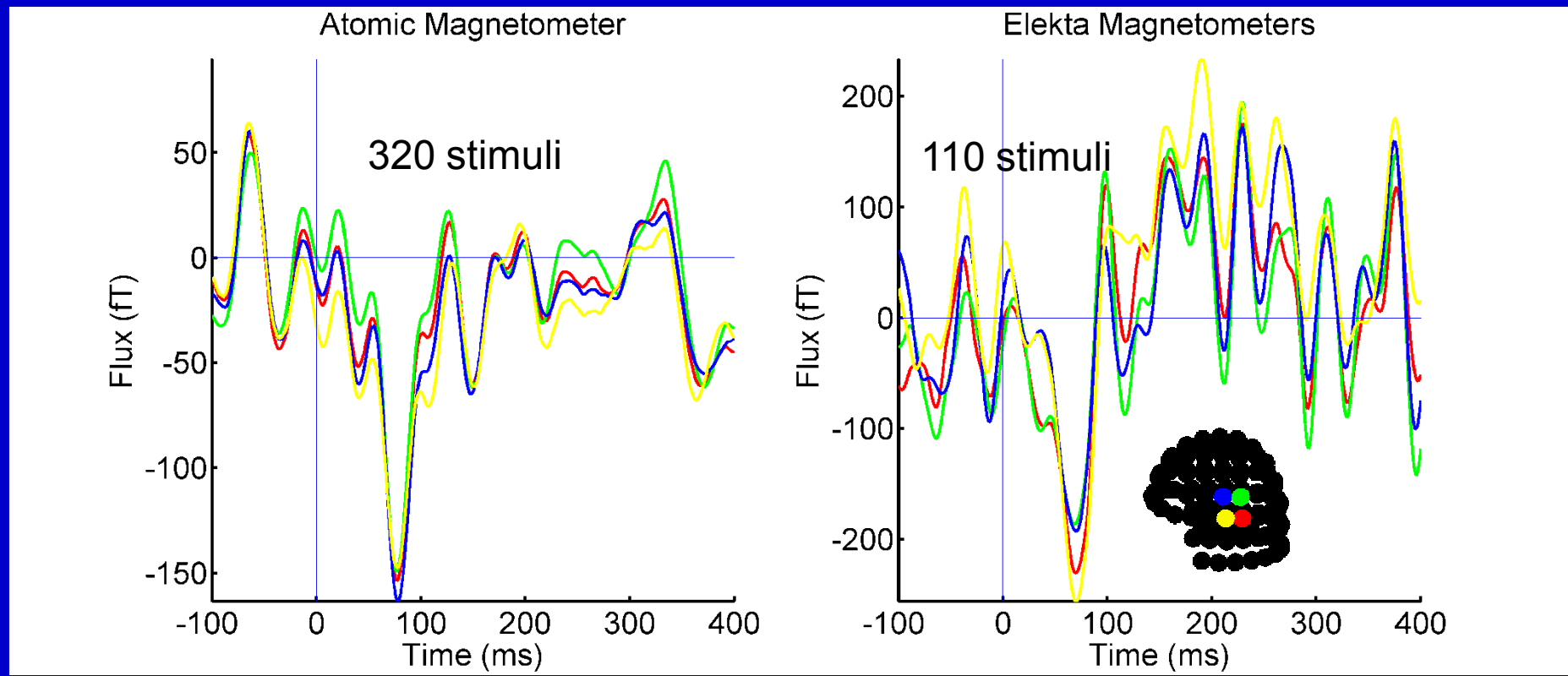


Stimulate Median Nerve, measure evoked response in somatosensory cortex

Cort Johnson, Peter D. D. Schwindt, and Michael Weisend,  
Appl. Phys. Lett. 97, 243703 (2010)

# Comparison of the Atomic Magnetometer to the SQUIDs

## Auditory Stimulation

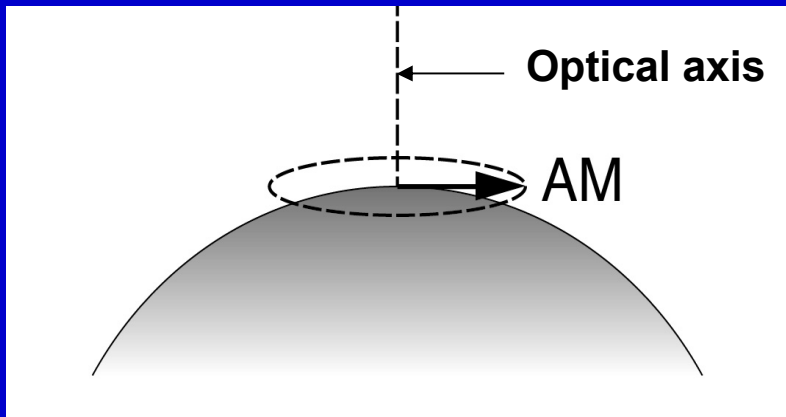


- Present 1000 Hz tones in both ears, measure evoked response in auditory cortex
- Expected signal at ~100 ms is present in AM and SQUID data

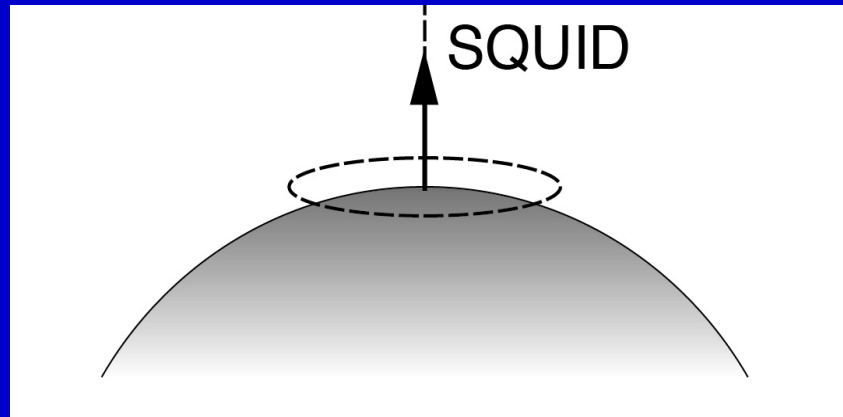
# AM vs SQUID

SQUID and AM signals are not identical. Why?

AMs measure fields parallel to scalp  
(optical axis perpendicular to scalp)



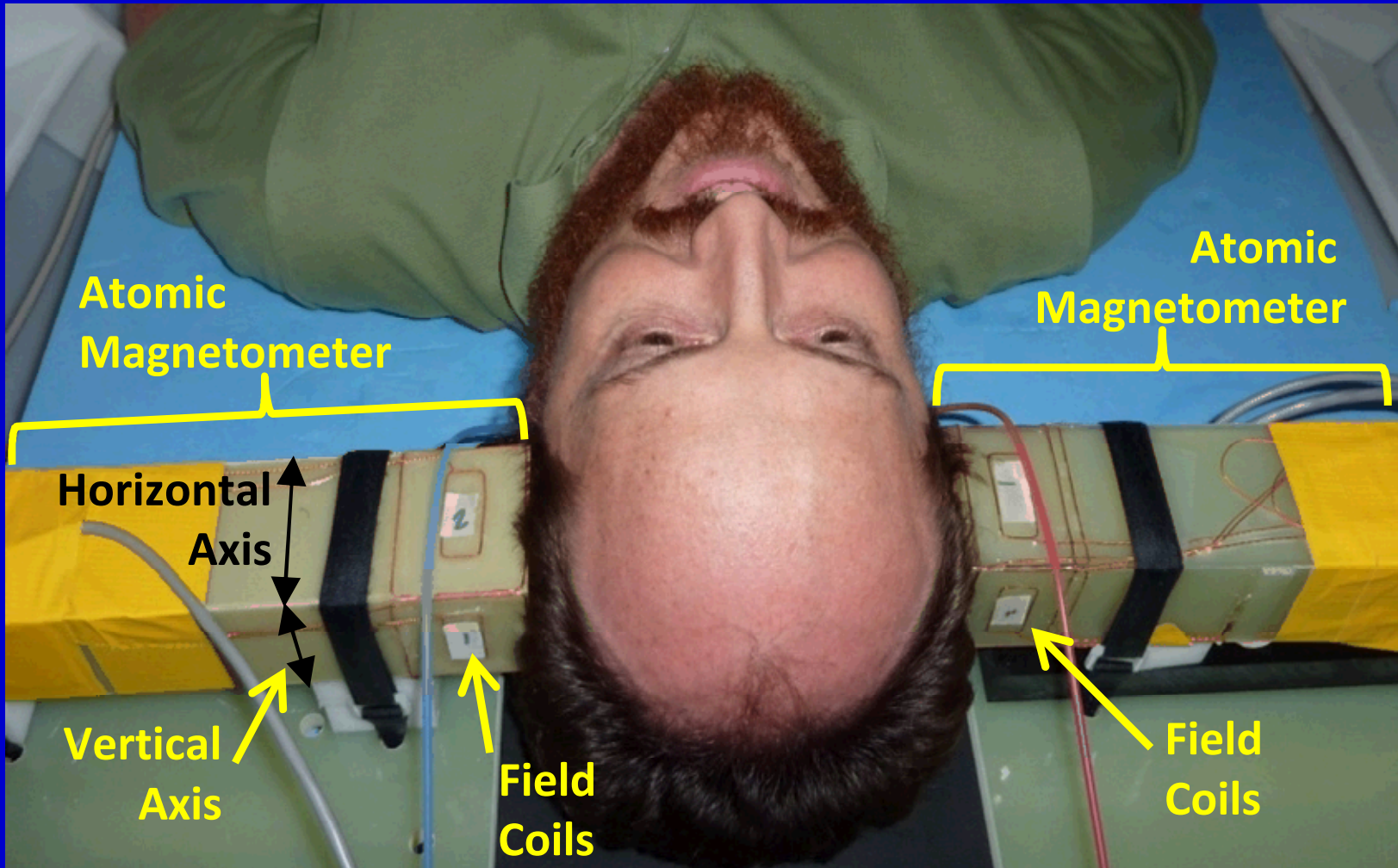
SQUIDs measure fields perpendicular to scalp  
(coils are parallel to scalp)



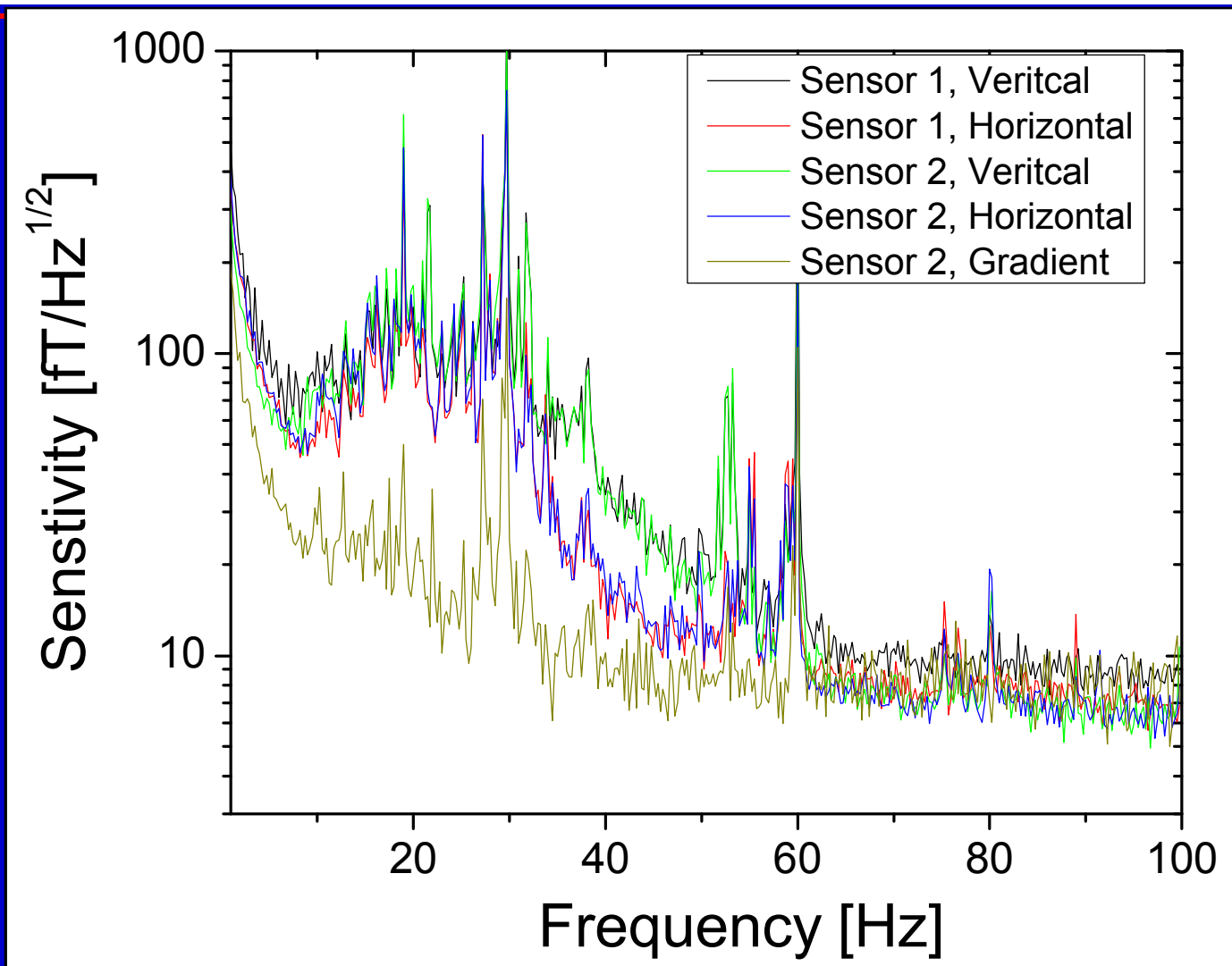
- Magnetometer channel separation: ~5mm
- SQUID channel separation: ~30 mm
- Different bandwidth (AM: ~20 Hz, SQUID: ~ kHz)

# Two Sensor MEG Measurements

- Three subjects measured with auditory stimuli
- Two subjects measured with somatosensory stimuli



# Noise in the Shielded Room

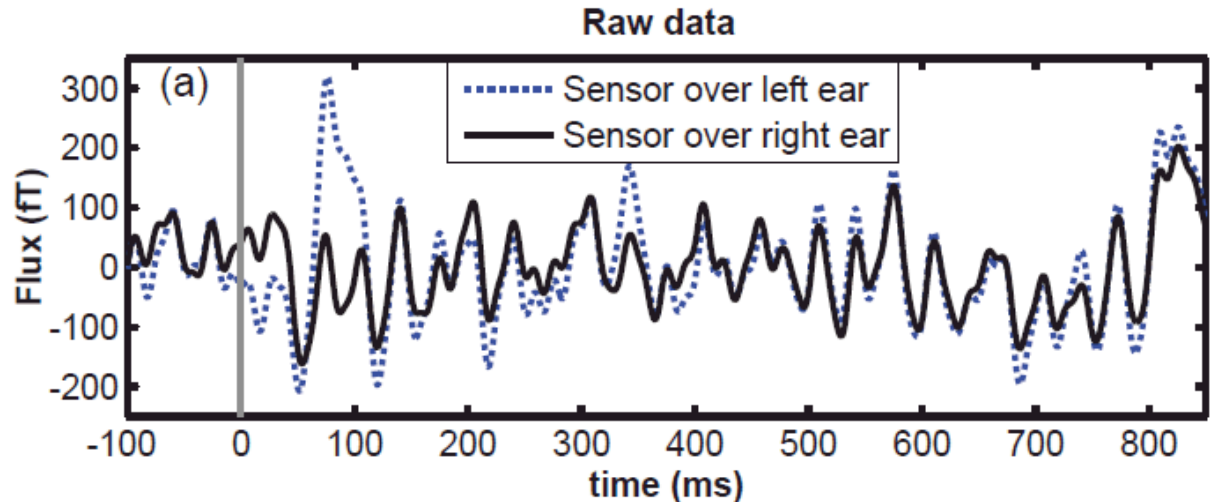


- Both sensors measure same noise spectra
- Vertical/Horizontal sensitivities now quite similar

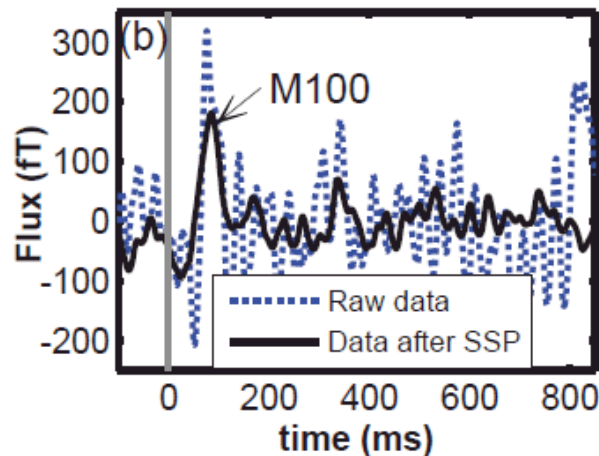
# Noise Cancellation

- 1000 Hz auditory stimulus applied to both ears
- Recordings from left/right sensors measured simultaneously
- Recordings of vertical component
- Bandpass filter: 2-55 Hz, Trials averaged: 330
- Use a signal space projection technique to cancel noise.
- With noise projected out, a clear M100 response is observed.

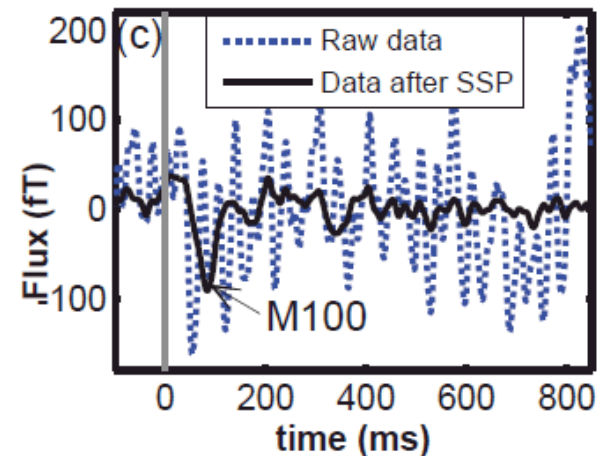
Auditory evoked response: Vertical component



Data from Left Hemisphere  
Raw vs. SSP

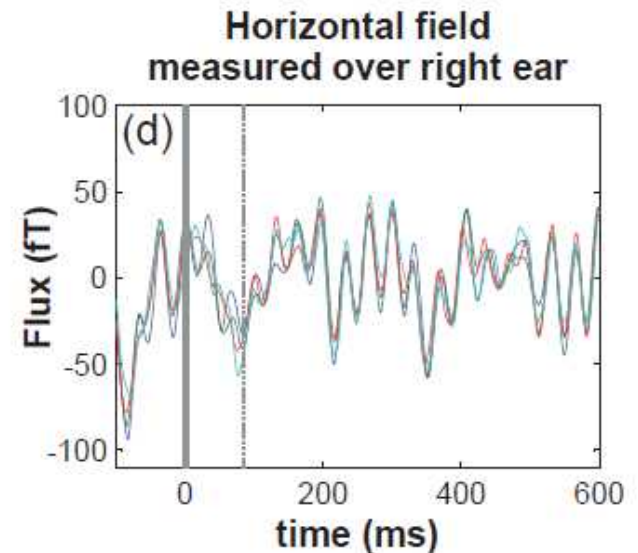
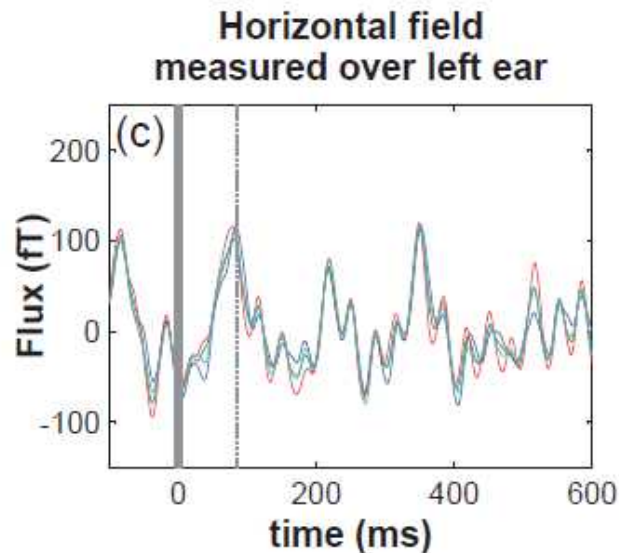
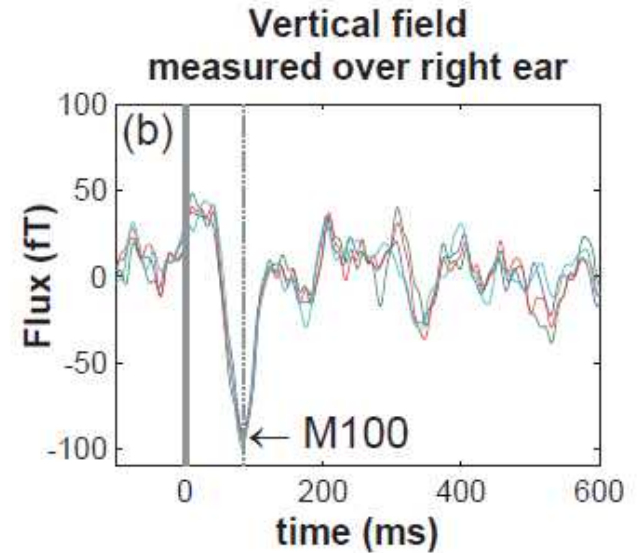
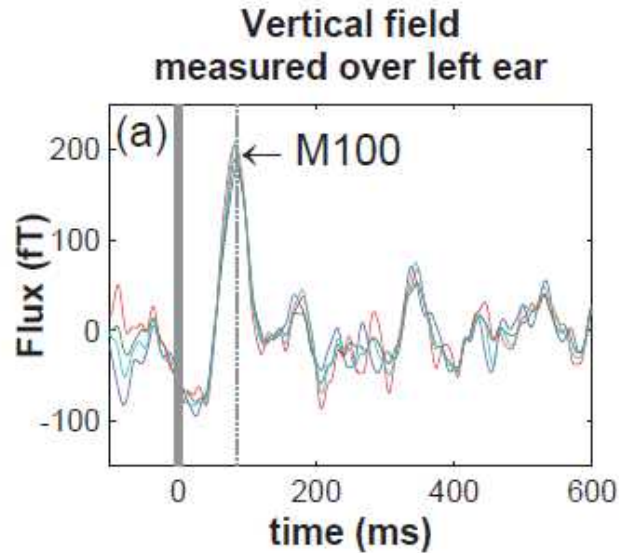


Data from Right Hemisphere  
Raw vs. SSP

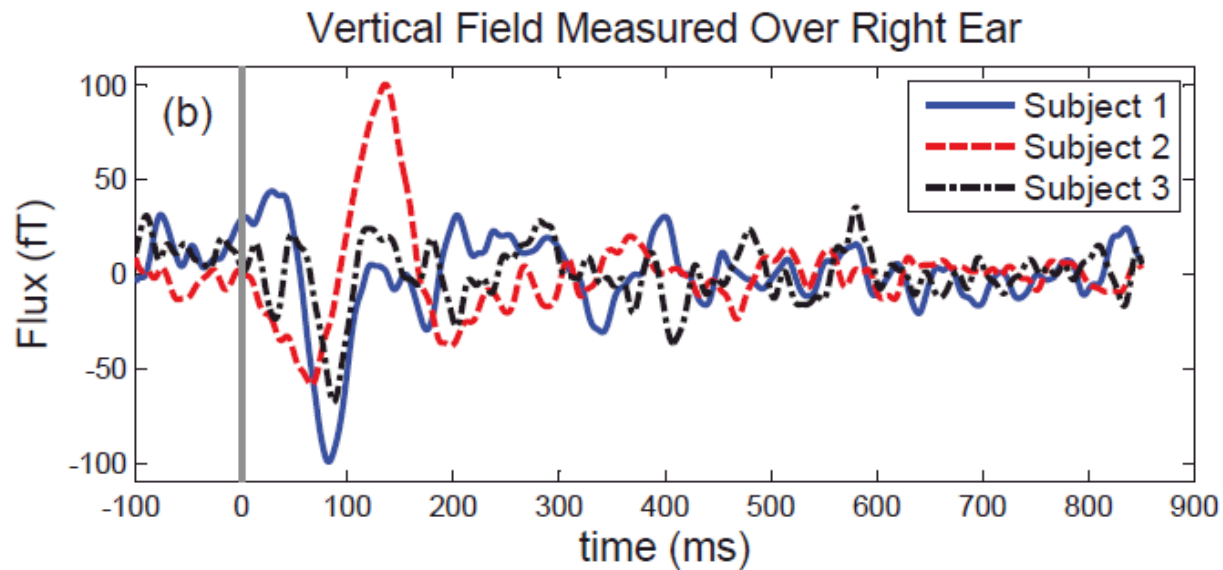
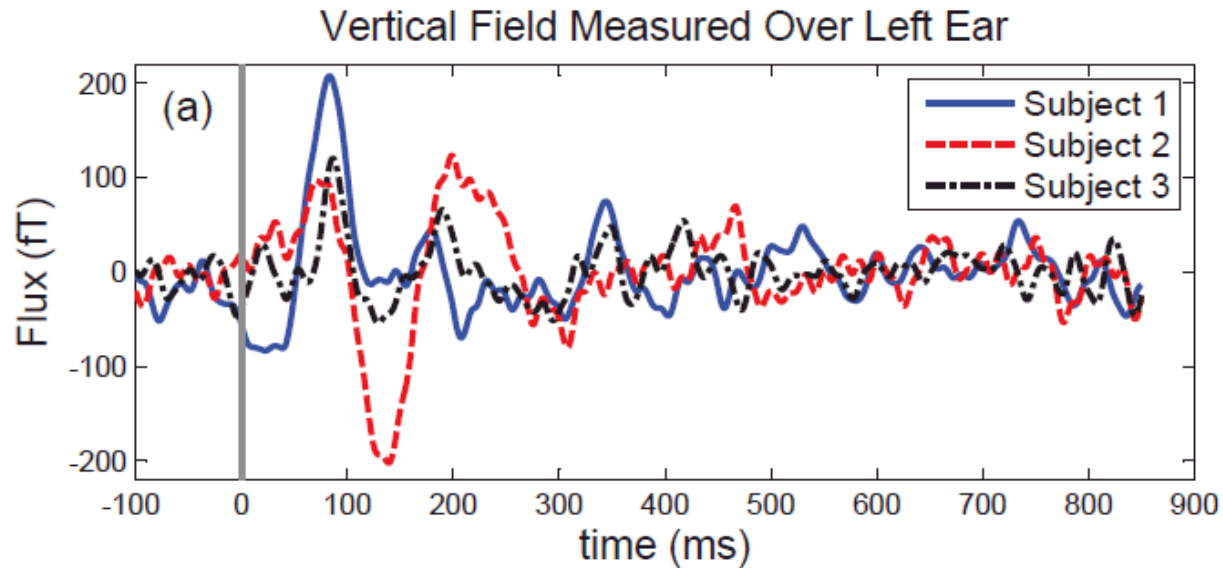


# Auditory Stimuli with Two Field Components Measured

- Recordings of vertical/horizontal axes measured subsequently
- M100 peak clearly visible on both sensors, vertical axis

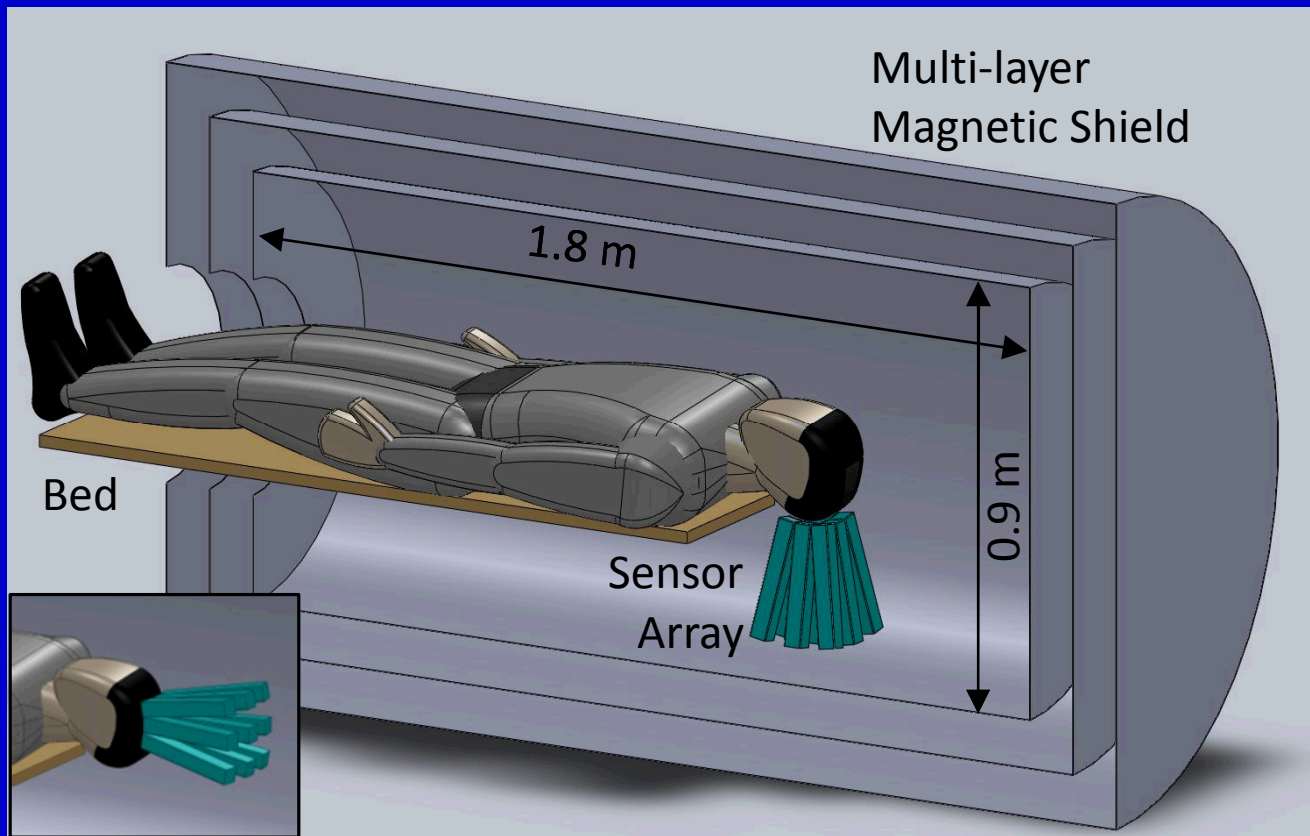


# Auditory Stimuli Multiple Subjects



# NIH Project: Build a System

- 36 channel AM array, reconfigurable (position, head size)
- Human-sized shield, cheaper/smaller installation
- Compare AM and SQUID recordings of human subjects
- Collaboration with MRN, UNM hospital, Candoo Systems



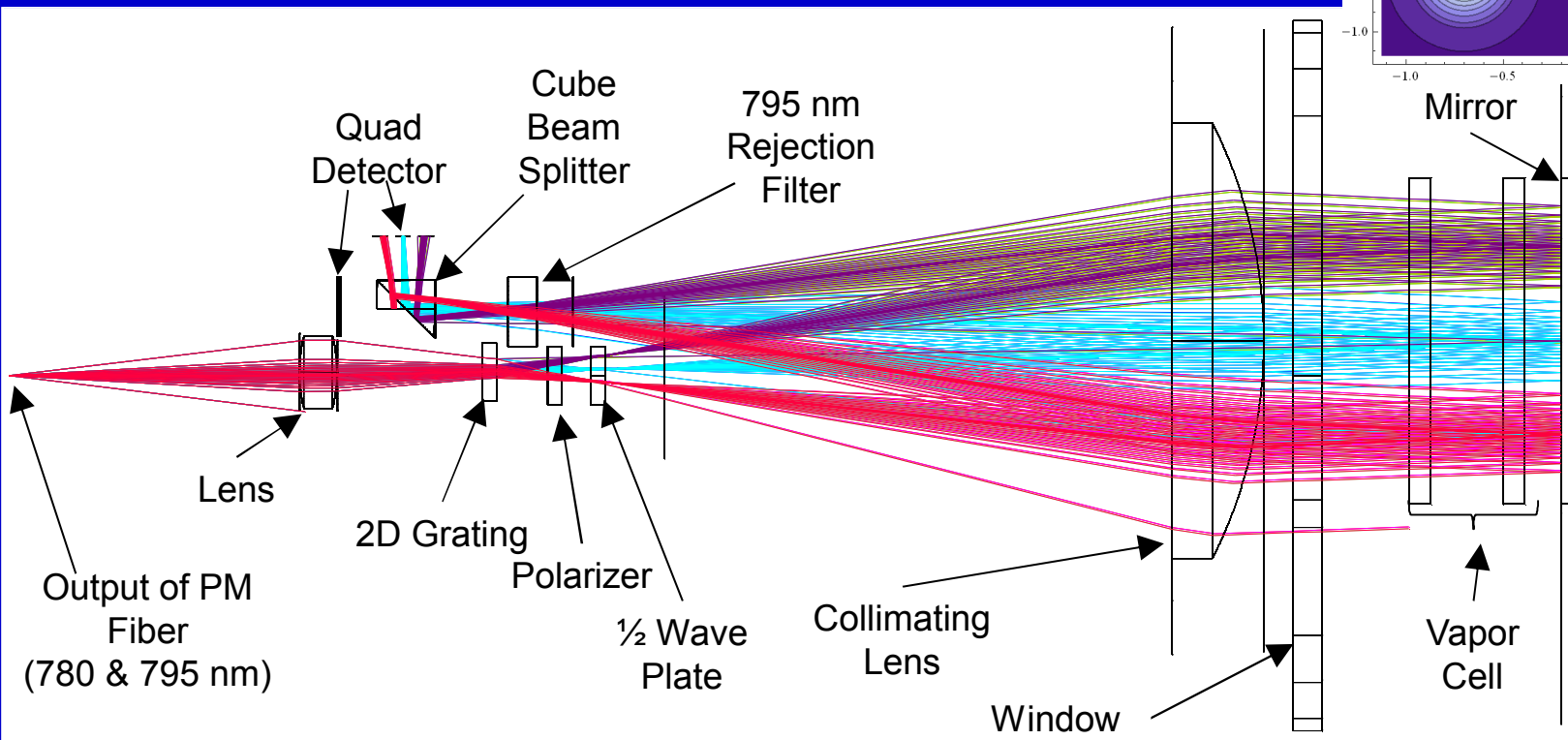
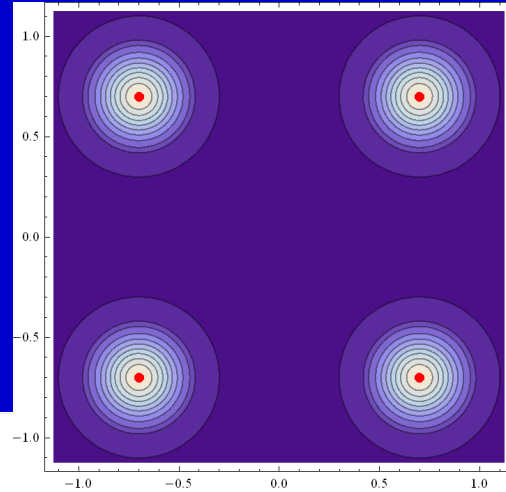
# NIH Project: Major Tasks

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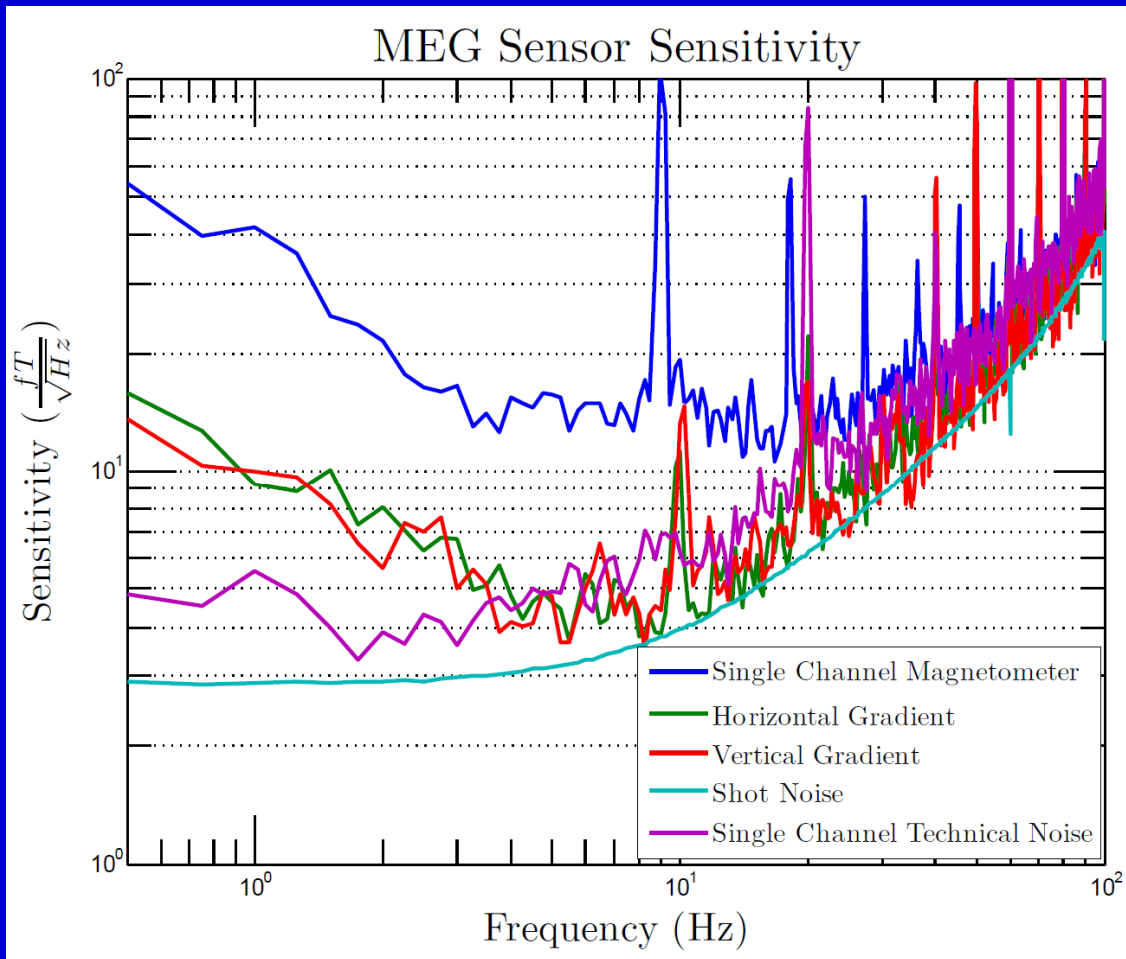
1. Redesign, miniaturize sensor (4 cm X 4 cm)
  - $<10 \text{ fT/Hz}^{1/2}$ ,  $>100 \text{ Hz}$  bandwidth
2. Carefully model human-sized shield performance
3. Design/model array for minimum interference
  - Modulation coil fields are seen by neighboring sensors
4. Adapt source localization codes for AM geometry
  - Brainstorm for localization and Fieldtrip for modeling
5. Construct array; source localization with phantom
6. Auditory/somatosensory recordings on human subjects with AM/SQUID systems
  - Coregistration, source localization comparison

# Sensor Redesign


- Previous design was very difficult to align and had a short gradiometer baseline, ~5 mm
- Switch to four beams, ~15 mm baseline
- Vapor cell: Previous: 1 cm long, 600 Torr He, 30 Torr N<sub>2</sub>  
Current: 2-5 mm long, 600 Torr N<sub>2</sub>
- Minimize distance from the head to the vapor cell.



# 5 mm Vapor Cell Performance



- ~2 mm beam size



# AM Sensor Simulation Presentation for WAM

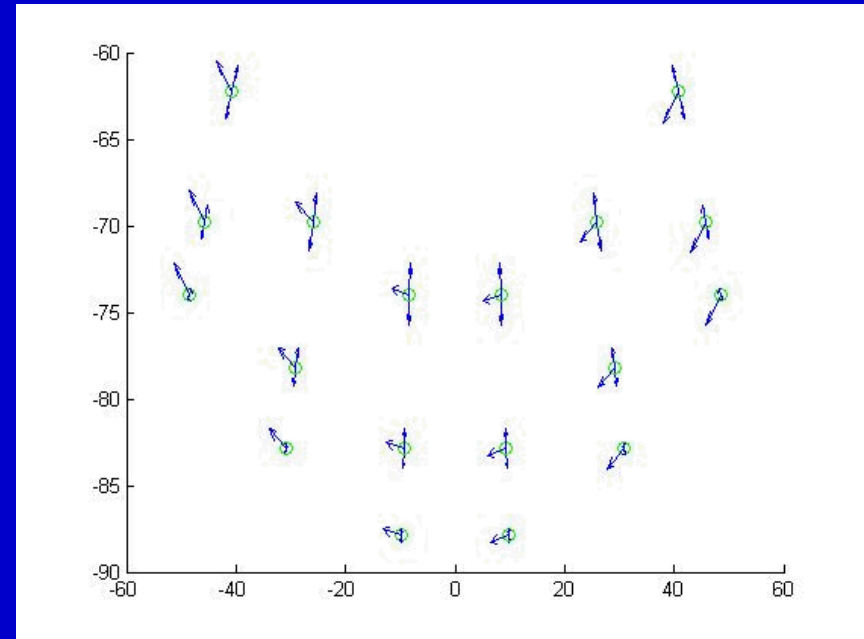
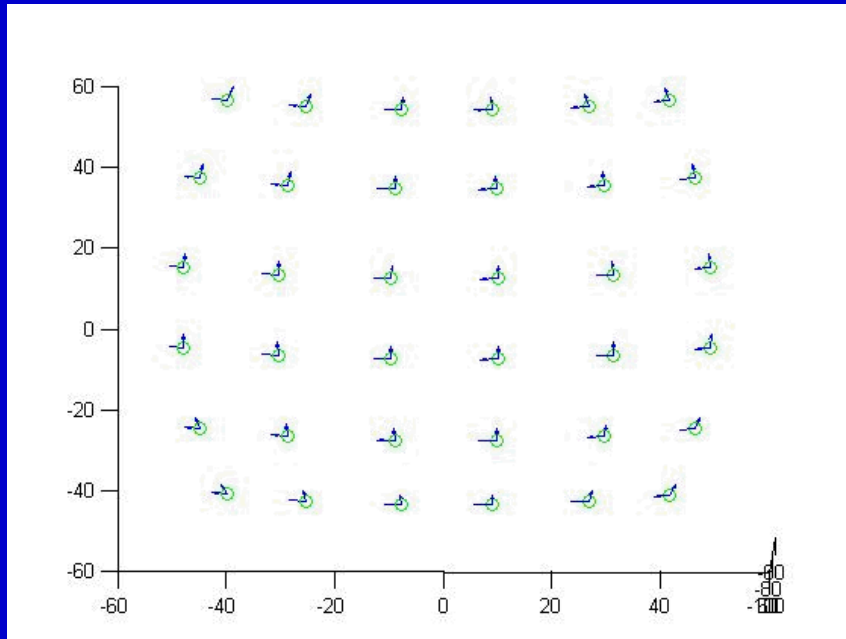
Jim McKay  
10 June 2013

# Simulation Methods/Goals

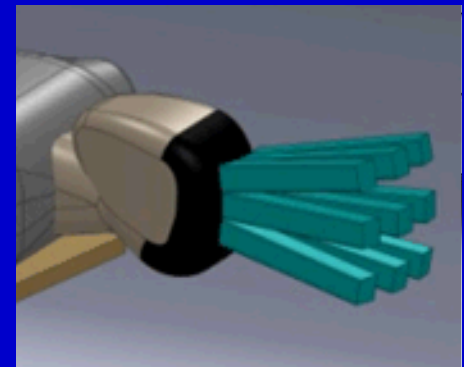
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- Fieldtrip MEG modeling:  
<http://fieldtrip.fcdonders.nl>
- Enter simulation parameters and load head model and head shape (single sphere)
- Perform forward solution and inverse solution calculations for different source strengths and positions and sensor array geometries
- Determine efficacy of AM array compared to SQUID arrays
  - Evaluate source localization in the presence of sensor noise.

# AM Sensor Array Design

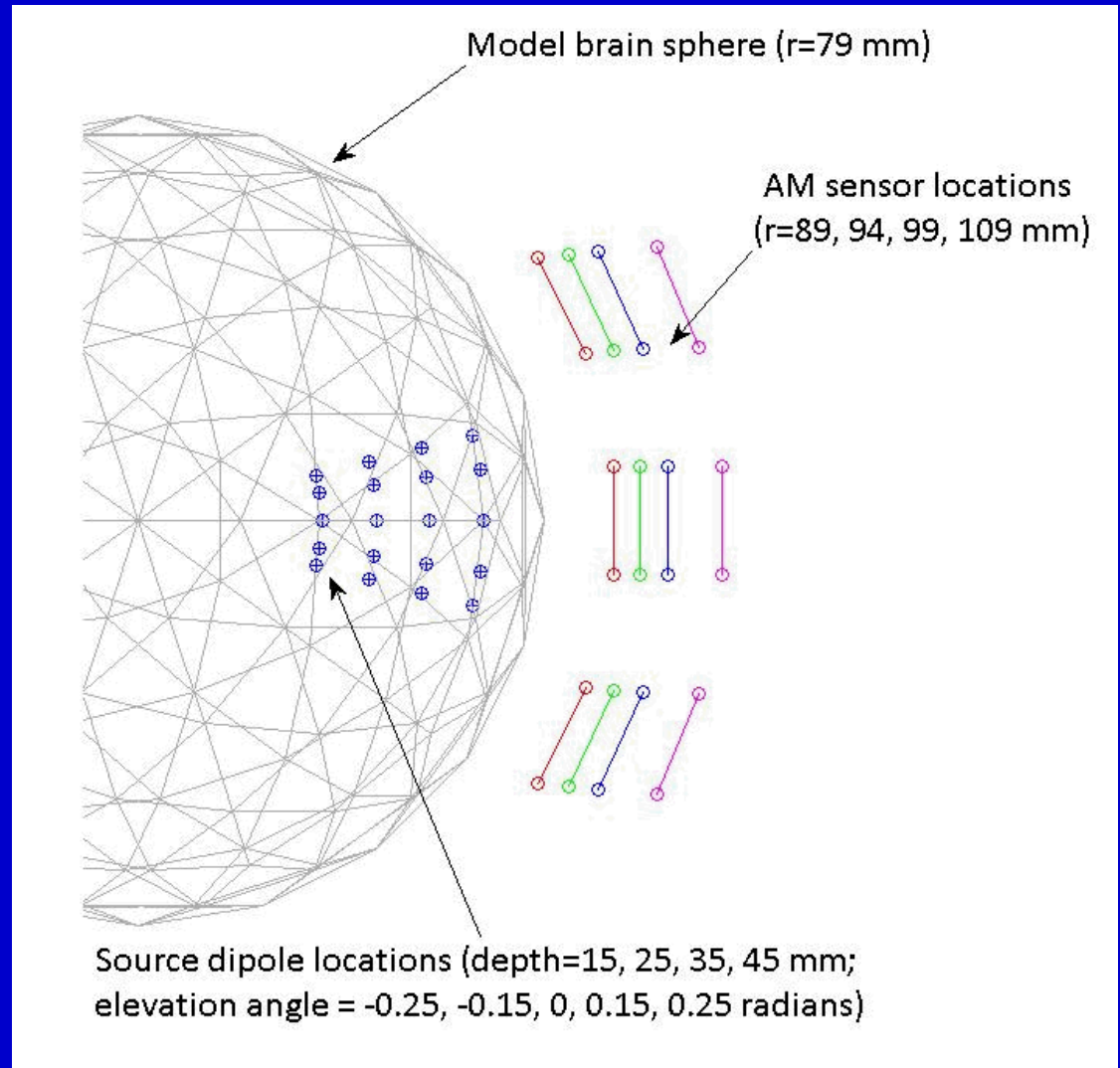


- 36 sensor sites, 1 or 2 transverse AMs at each site
- Spherical sensor surface with 9 modules, each with 4 sites
- Figures show 20 mm sensor separation and 45 mm module separation



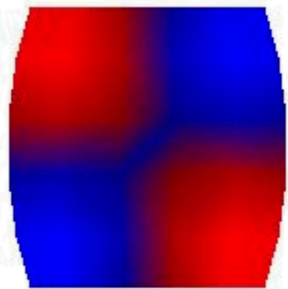
# Source & Sensor Locations

In Fieldtrip dipole strength does not have units, has been set to give realistic signal strengths of 200-1000 fT p-p depending on source depth

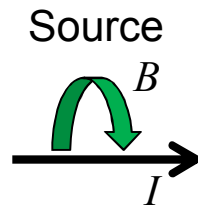
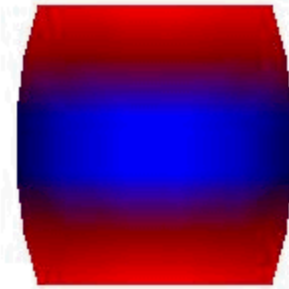


# Sensor field maps

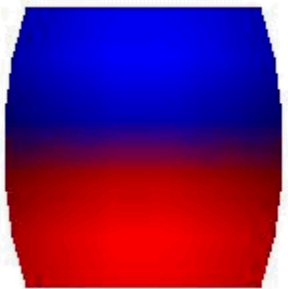
AM Transverse horizontal



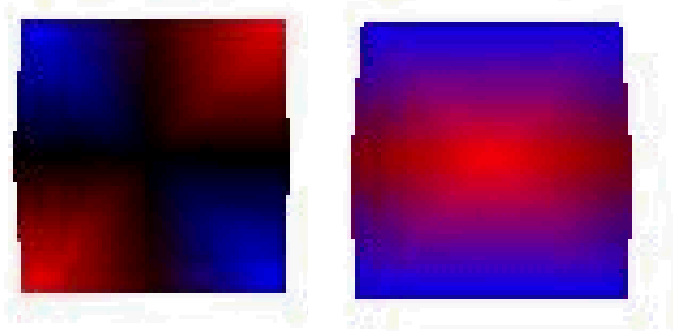
AM Transverse vertical



SQUID Axial Magnetometer

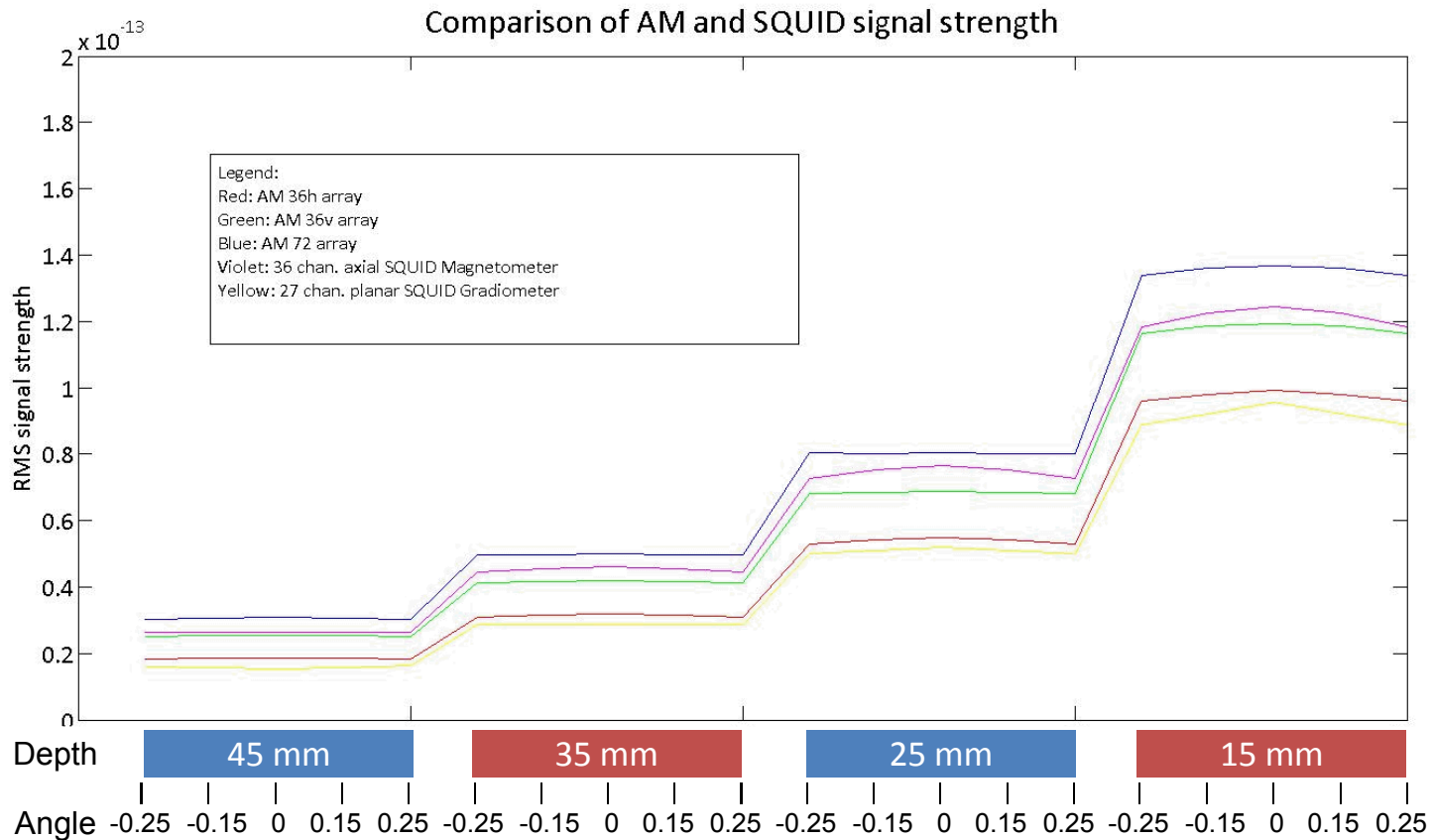


SQUID Planar gradiometers



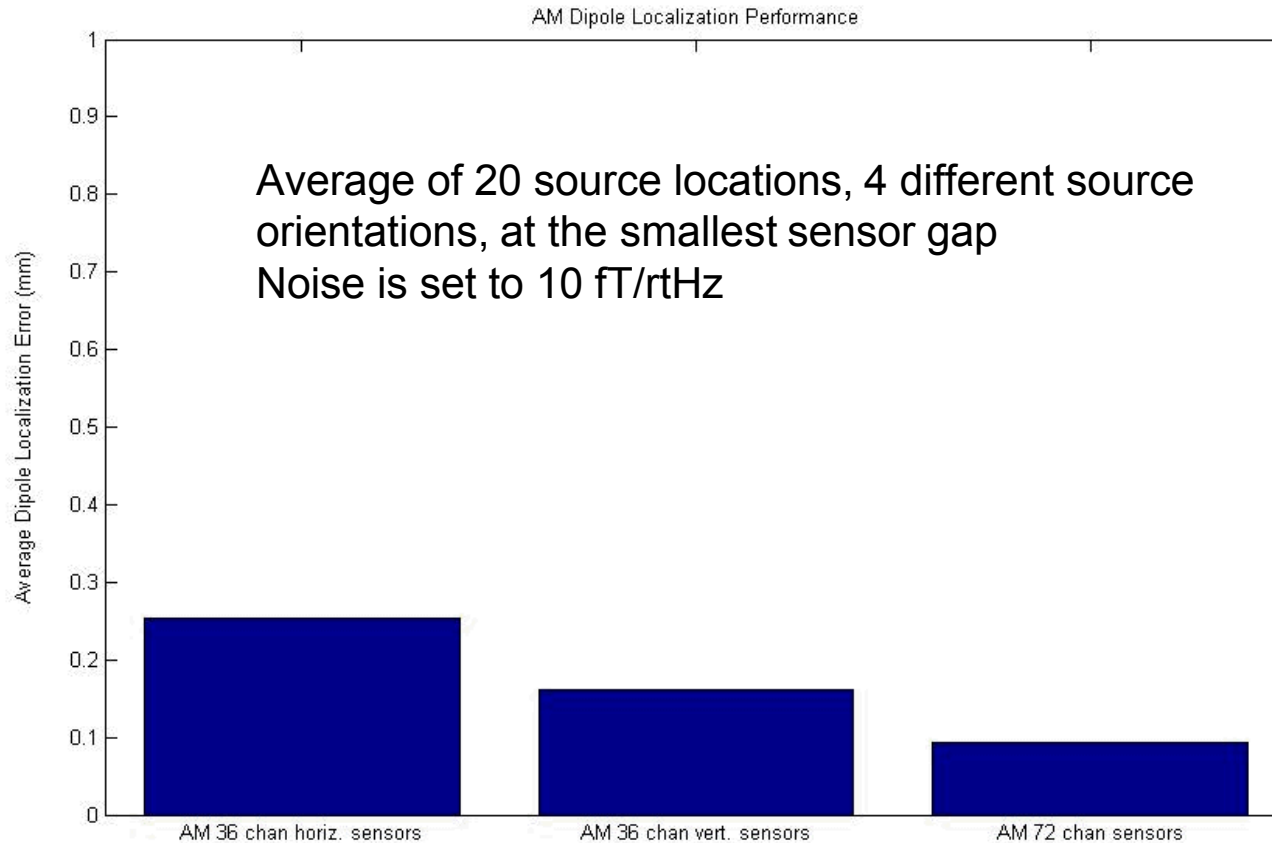
Note: Maps not on same scale. Source is horizontally oriented current dipole.

# AM Signal Strength is similar to SQUID sensors

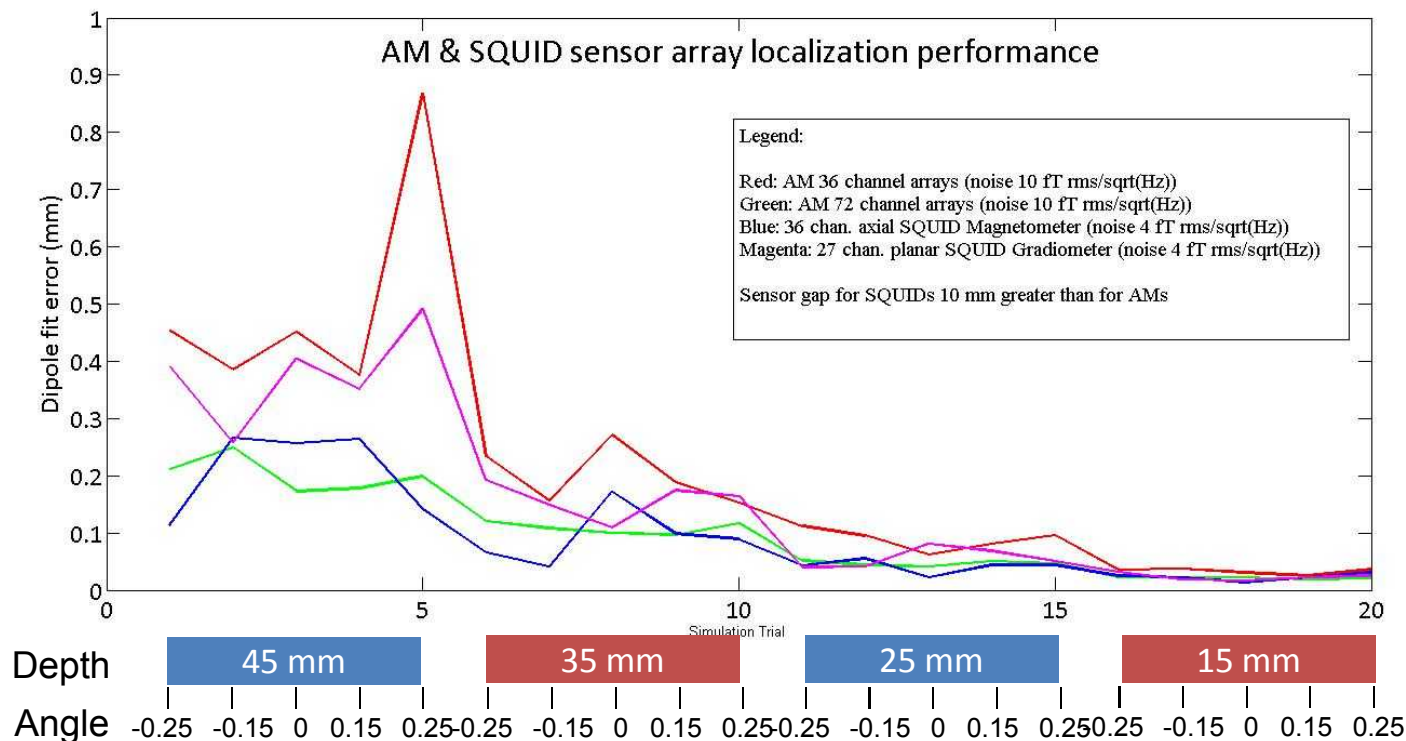


These are for a single source orientation, and the shortest sensor gap (SQUID arrays have 10 mm more gap).

# AM Sensors provide good localization performance

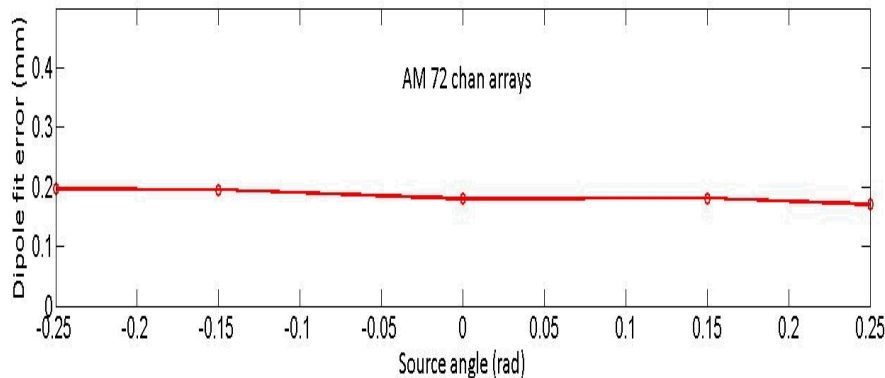
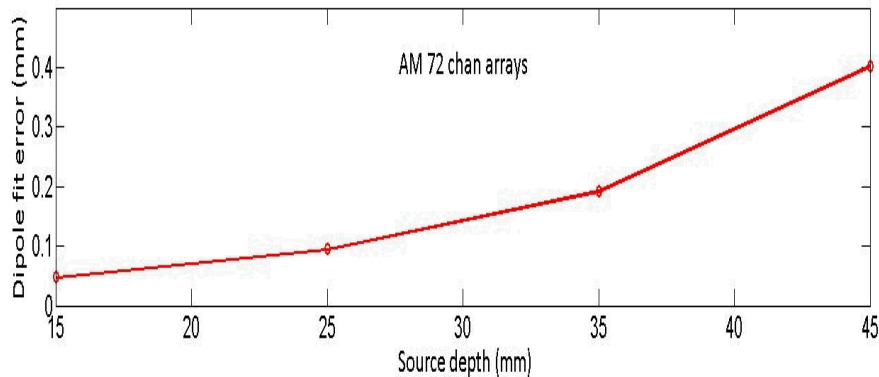


# AM Localization Performance is similar to SQUID sensors



Each point is an average of the 4 source orientations at 1 sensor array position

# AM Localization Performance vs Source Depth and Array Offset

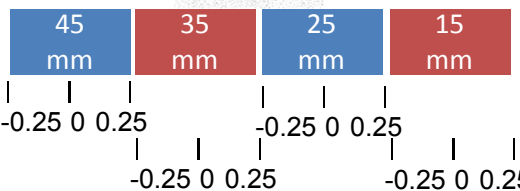
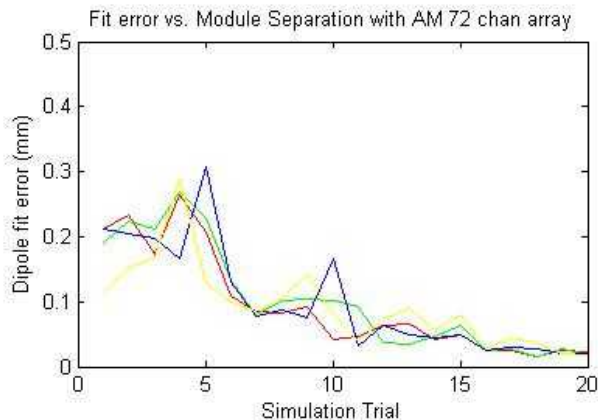
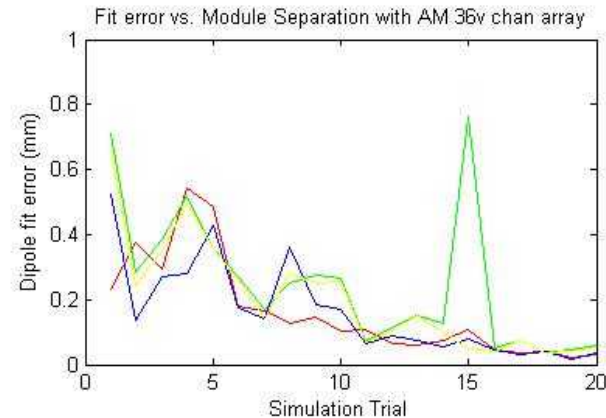
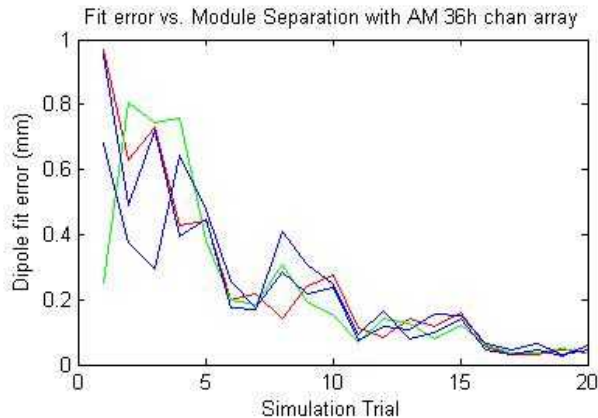


Error proportional to  $d^{(2-3)}$

Average of 20 mm & 14 mm sensor spacing options, 20 source locations, and 4 sensor gaps

Error indep. of source elevation angle in this range, but convergence rate decreases sharply at  $>0.25$  rad

# AM Sensor module separation does not change localization error much

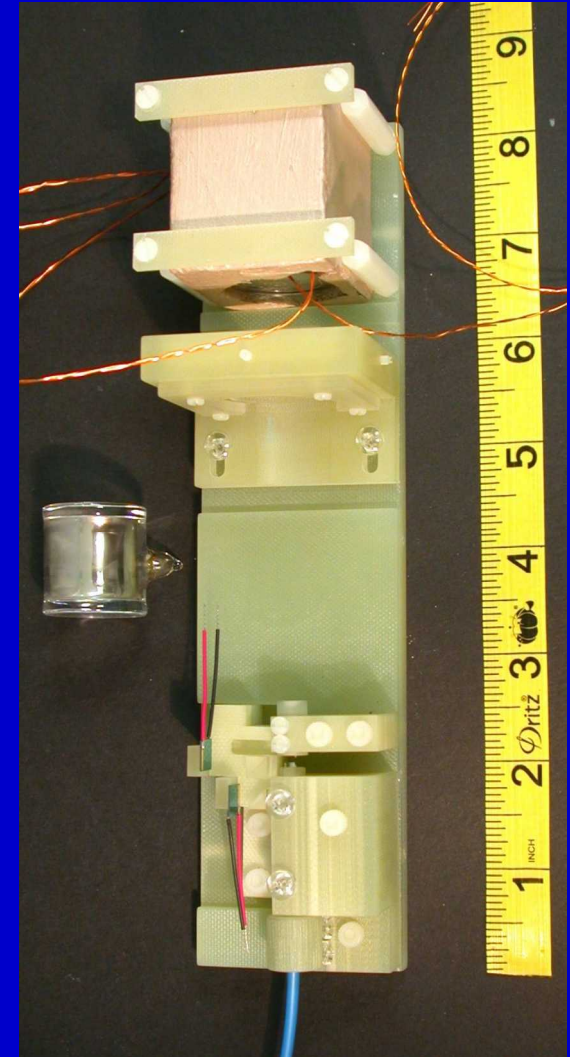


4 sensor module separations:  
Red: 45 mm (closest possible)  
Green: 49 mm  
Blue: 53 mm  
Yellow: 63 mm

For 20 mm sensor separation

# Conclusion

- Compact, single axis sensor design
  - $<5 \text{ fT/Hz}^{1/2}$  sensitivity
- Successfully measured MEG signals using transverse fields and multiple sensors
- Future: NIH Project - build AM array, perform source localization
  - Working to redesign sensor
  - Simulations show measuring transverse field gives similar source localization performance.



# Acknowledgements

- Sandia MEG Team: Peter Schwindt, Yuan-Yu Jau, Tony Carter
  - Former Team Members: Cort Johnson, George Burns, Jon Bryan, Grant Biedermann, Michael Pack, Aaron Hankin
- Collaborators: Mike Weisend (MRN), Jim McKay (Candoo Systems)
- Funding:



# Backup

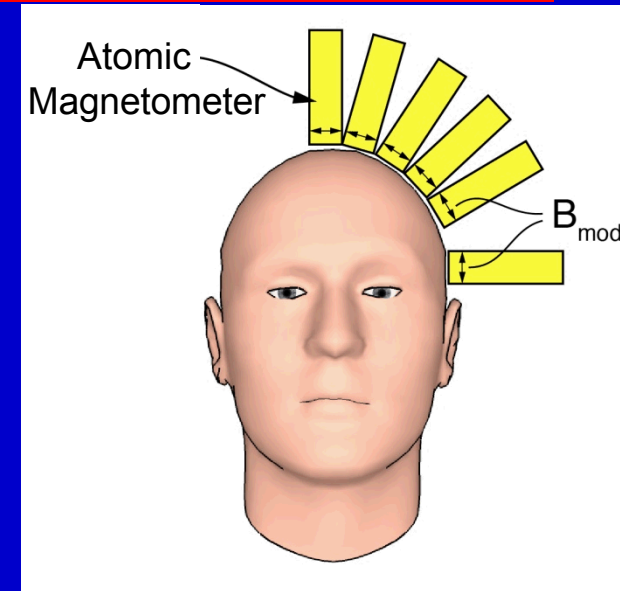
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# Sandia MEG Goals

## Mimic SQUID MEG sensor

- Whole-head coverage: tailor sensor design for arrays
- Adequate sensitivity/bandwidth ( $<10$  fT/Hz<sup>1/2</sup>/100 Hz)
- Small footprint  $\sim 30$  mm square
- Eliminate free space beams (fiber coupled sensors)
- Gradiometric 2D output

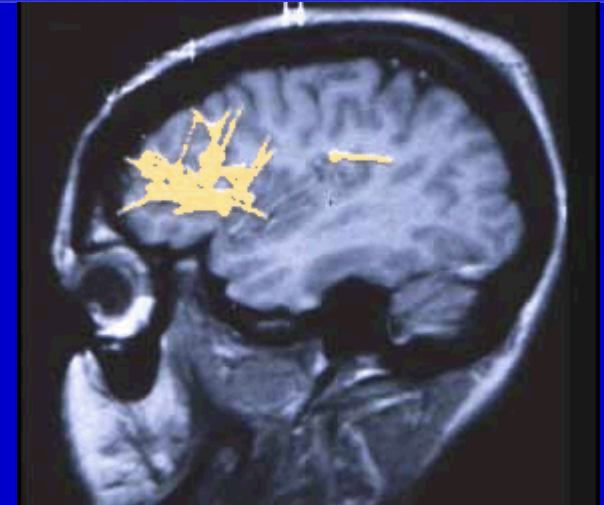
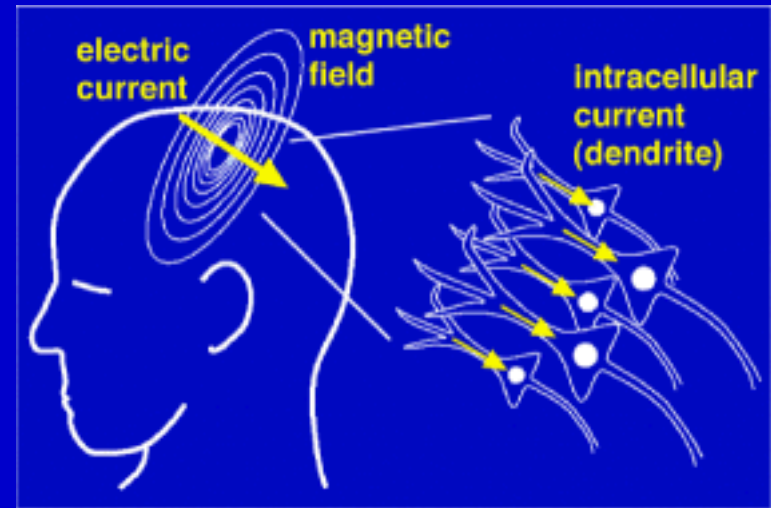


## Collaboration: The Mind Research Network

- Design input from neuroscientists
- Strengthen ties to ultimate user community
- Use magnetically shielded room

# Magnetoencephalography (MEG)

- Detects magnetic fields produced by neural currents in the brain.
  - Non-invasive
  - 100 fT signals, <100 Hz
- Sub-cm spatial; msec temporal resolution
  - Functional MRI (poor temporal resolution)
  - EEG (poor spatial resolution)
- Uses:
  - Localize a pathology (epilepsy)
  - Understand spatial/temporal brain function.
  - Study psychological/neurological disorders
- Potential applications
  - Study/monitor behavior in high stress environments
  - Augment human data processing
  - Improved human-machine interfaces
  - Diagnose traumatic brain injury/PTSD



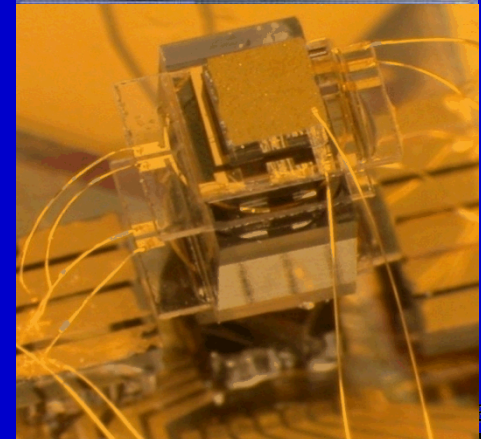
# Current Technology

## Superconducting Quantum Interference Devices (SQUIDs)

- Mature technology
  - Highly sensitive,  $2\text{-}3 \text{ fT} / \text{Hz}^{1/2}$
  - Whole head coverage ( $> 300$  channels)
- Disadvantages
  - Requires cryogenic cooling
  - Large and power hungry
  - \$\$\$  $\rightarrow$  100 systems worldwide

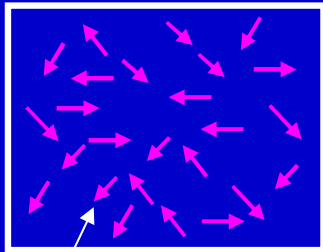
## Atomic Magnetometer Potential

- Record sensitivity of  $160 \text{ aT} / \text{Hz}^{1/2}$   
(Romalis, Princeton) Dang, et al. APL 97, 151110 (2010)
- Vast improvement in size, power consumption, and portability.



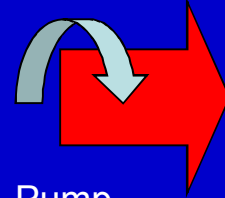
# Atomic Magnetometer Basics

## Alkali Vapor Cell



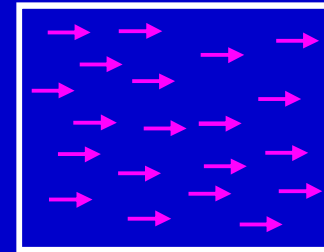
Randomly oriented atomic spins

Circular (or linear\*) polarization



Pump beam

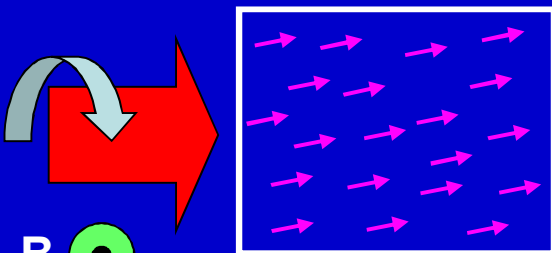
## Optical pumping



Spins align with the pump beam

\*D. Budker, *et al. Phys. Rev. A* 62, 043403 (2000).

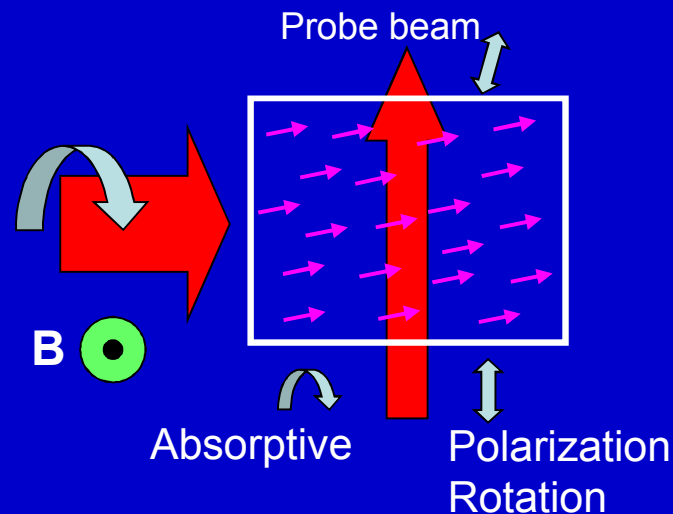
## Apply Small Magnetic Field



**B**  
Out of plane

Spins precess due to magnetic field

## Detect with probe beam



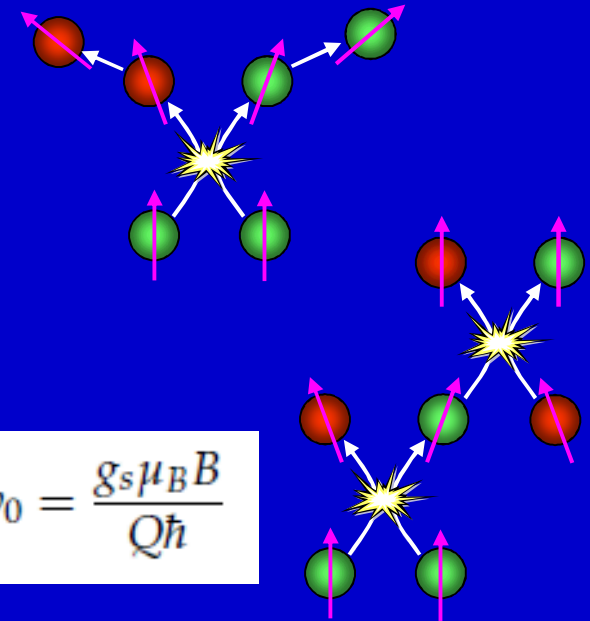
Probe beam

Absorptive

Polarization Rotation

# Spin Exchange Relaxation Free (SERF) Magnetometer

- $T_2$  often limited by spin exchange collisions.
  - Spin exchange collisions preserve total  $m_f$  but not  $F$
  - $F = 1, F = 2$  precess in opposite directions
- Near zero field and at high density, spin exchange rate  $\gg$  spin precession frequency
  - Many hops from  $F = 1$  to  $F = 2$  in infinitesimal rotation
  - More  $F = 2$  states, so on average atoms precesses in  $F = 2$  direction
  - Precession rate is slowed down by nuclear spin and incomplete optical pumping



$$\omega_0 = \frac{g_s \mu_B B}{Q \hbar}$$

- Record sensitivity: 160 aT / Hz<sup>1/2</sup>

H. D. Dang, A. C. Maloof, M. V. Romalis, *APL* **97**, 151110 (2010)

- SERF in a  $\sim 6 \text{ mm}^3$  cell : 5 fT / Hz<sup>1/2</sup>

W.C. Griffith, S. Knappe, and J. Kitching, *Opt. Express* **18**, 27167 (2010).

- MEG with free-space beam SERF

H. Xia, A. Ben-Amar Baranga, D. Hoffman, and M. V. Romalis, *Appl. Phys. Lett.* **89**, 211104 (2006).

Rubidium  
cross sections

$$\sigma_{SE} = 2 \times 10^{-14} \text{ cm}^2$$

$$\sigma_{SD} = 9 \times 10^{-18} \text{ cm}^2$$

# References

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- Robert Oostenveld, Pascal Fries, Eric Maris, and Jan-Mathijs Schoffelen, **“FieldTrip: Open Source Software for Advanced Analysis of MEG, EEG, and Invasive Electrophysiological Data,”** Computational Intelligence and Neuroscience, vol. 2011, Article ID 156869, 9 pages, 2011.  
doi:10.1155/2011/156869