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Progress toward a multi-channel magnetoencephalography system using optically pumped atomic magnetometers

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Sandia National Laboratories

August 26th, 2014

Outline

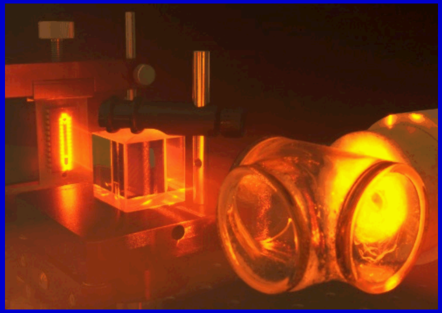
- Introduction
- First sensor design
  - Performance
  - MEG measurements with one and two sensors
- Scaling up to a larger array
  - Second sensor design
- System considerations
  - Simulations of detecting MEG signals with our AM array
- Conclusion

Motivation

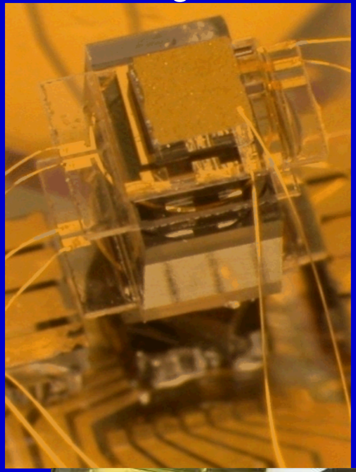
- Early 2000's, high sensitivity demonstrated with atomic magnetometers (AMs)
  - 0.5 fT/Hz$^{1/2}$
  - I. K. Kominis, T. W. Kornack, J. C. Allred, and M. V. Romalis. Nature **422**, 596 (2003).
- Chip-scale atomic magnetometers demonstrated.
  - Small size and low power
  - 70 fT/Hz$^{1/2}$
  - V. Shah, S. Knappe, P.D. Schwindt, and J. Kitching, *Nature Photonics* **1**, 649-652 (2007).

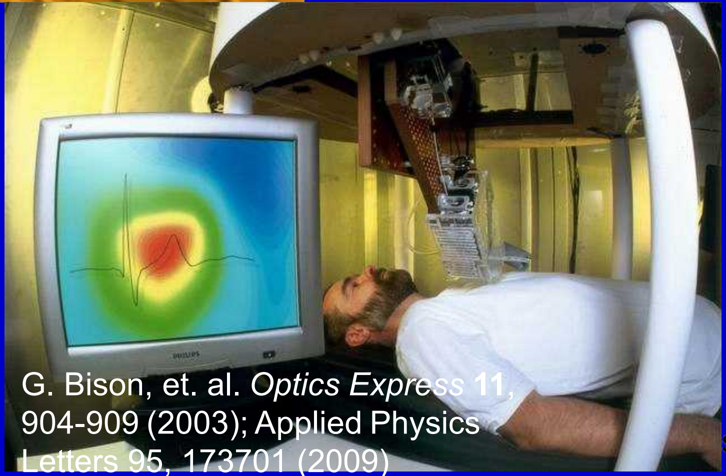
- What should we do with these new high sensitivity magnetometer?
- Biomagnetic applications
  - Magnetocardiography
  - Magnetoencephalography
  - Magnetic Nanoparticles
- Geomagnetism
  - Rock magnetometer

Princeton SERF magnetometer



NIST Chip-Scale Atomic Magnetometer





G. Bison, et. al. *Optics Express* **11**, 904-909 (2003); Applied Physics Letters 95, 173701 (2009)

Current Technology

Superconducting Quantum Interference Devices (SQUIDs)

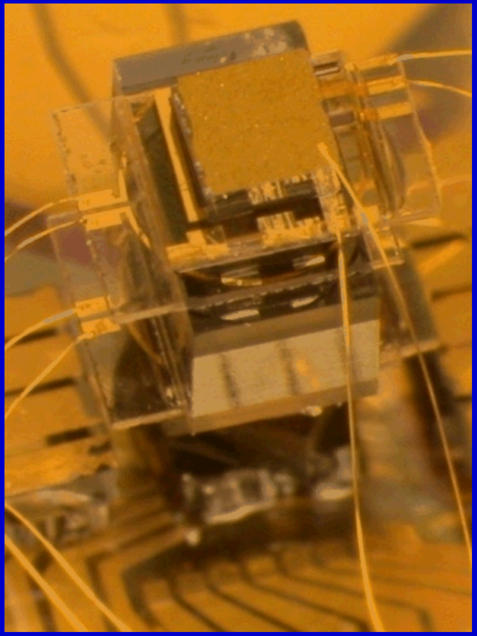
- Mature technology
  - Highly sensitive, 2-3 fT / Hz$^{1/2}$
  - High bandwidth
  - Whole head coverage (> 300 channels)

- Disadvantages
  - Require cryogenic cooling
    - Helium is expensive, sources unreliable
  - Large, requires an expensive shielded
  - Helmet size is fixed to accommodate largest head size

Atomic Magnetometers for MEG

Potential Improvements for MEG

- No cryogenic cooling
  - AM needs to be heated
- Much smaller sensor array size
  - Leads to a smaller magnetic shield
  - Transportable system
- Reconfigurable array is possible
  - Small sensor size
  - Accommodate head sizes ranging from infants to adults
  - Reconfigure for other applications: MCG



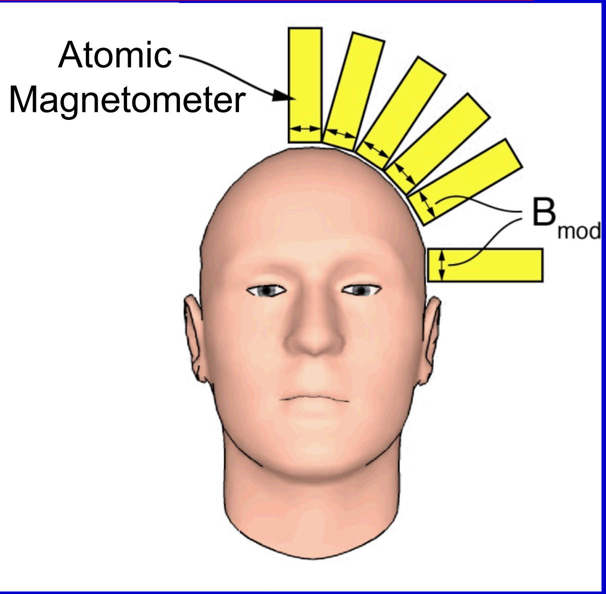
Potential drawbacks

- Trade-off between bandwidth and sensitivity
- Opposite thermal problem
  - Need to heat the cell to 150 C and maintain close sensor-to-head distance
- Sensor position and sensitive axis is not fixed
  - Source localization relies on knowing the location and orientation of the magnetic sensor
- Sensor gain varies from sensor to sensor and it can drift

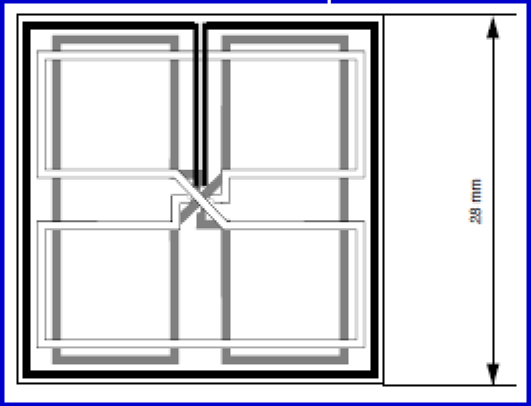
Sandia MEG Goals

Mimic SQUID MEG sensor

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



Elekta Triple Sensor Chip



Collaboration:

- Wright State University, Candoo Systems, Cleveland Clinic, UNM School of Medicine, MRN
- Design input from neuroscientists
- Strengthen ties to ultimate user community

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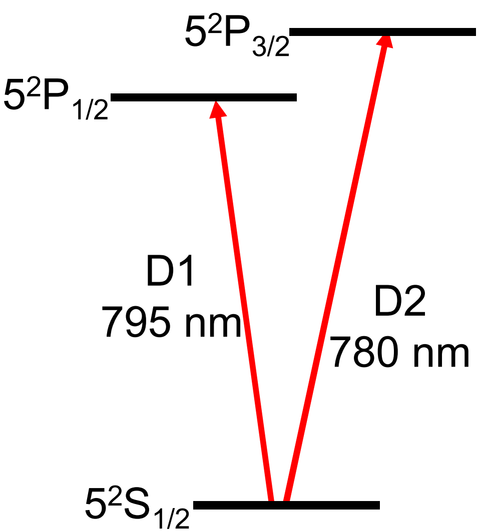
Two-color pump/probe scheme

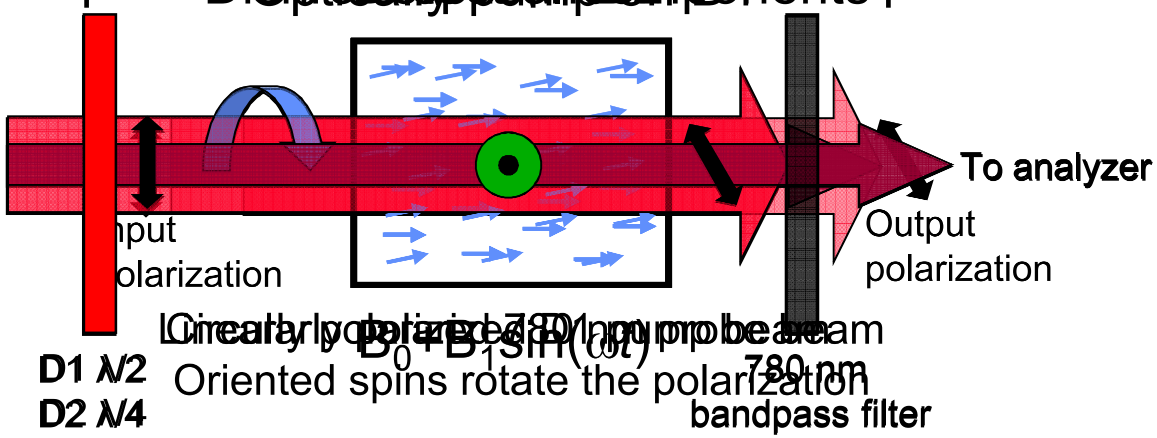
Separate pumping and probing functions into two separate beams

- Circular polarization pumps, linear polarization for probing
- Both beams are co-propagating
  - Utilize rubidium fine structure
- Modification of an elliptically polarized scheme: V. Shah and M. V. Romalis, PRA 80, 013416 (2009)

^{87}Rb Fine Structure

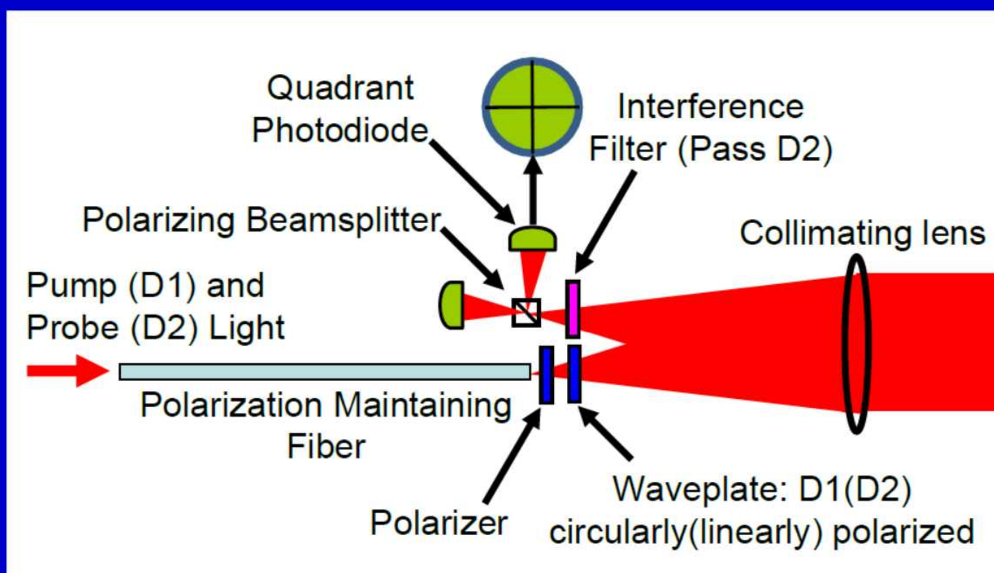


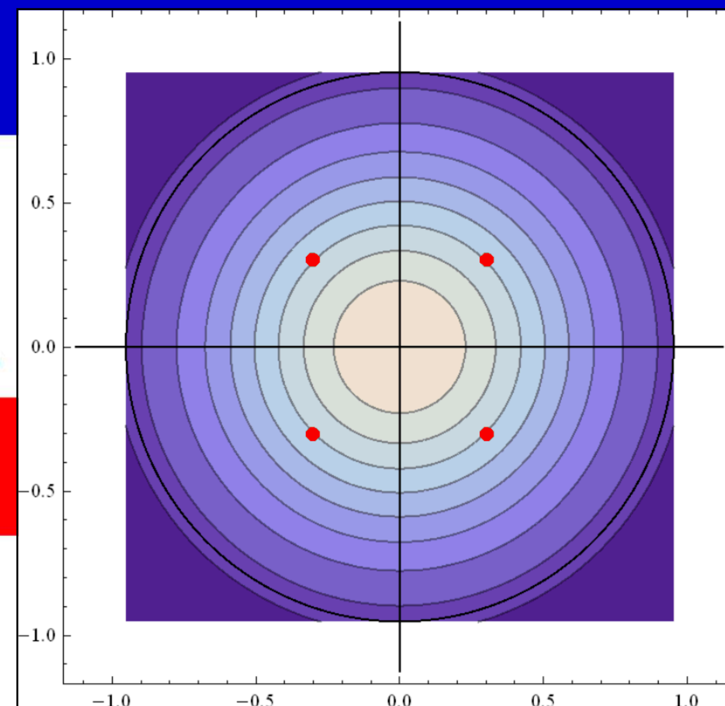
Field modulation/phase sensitive detection required to extract dispersive lineshape



1st Generation Sensor Design

- Single optical axis: compact, single fiber for pump/probe
  - Use ^{87}Rb (D1 795 nm, D2 780 nm)
- Retroreflecting mirror minimizes vapor-cell-to-head distance
- Modulate Bx/By for lock-in detection (choose sensitive axis)
- Gradiometry performed with quadrant photodiode
  - $1/e^2$ diameter of 20 mm: give a gradiometer baseline of ~4-5 mm





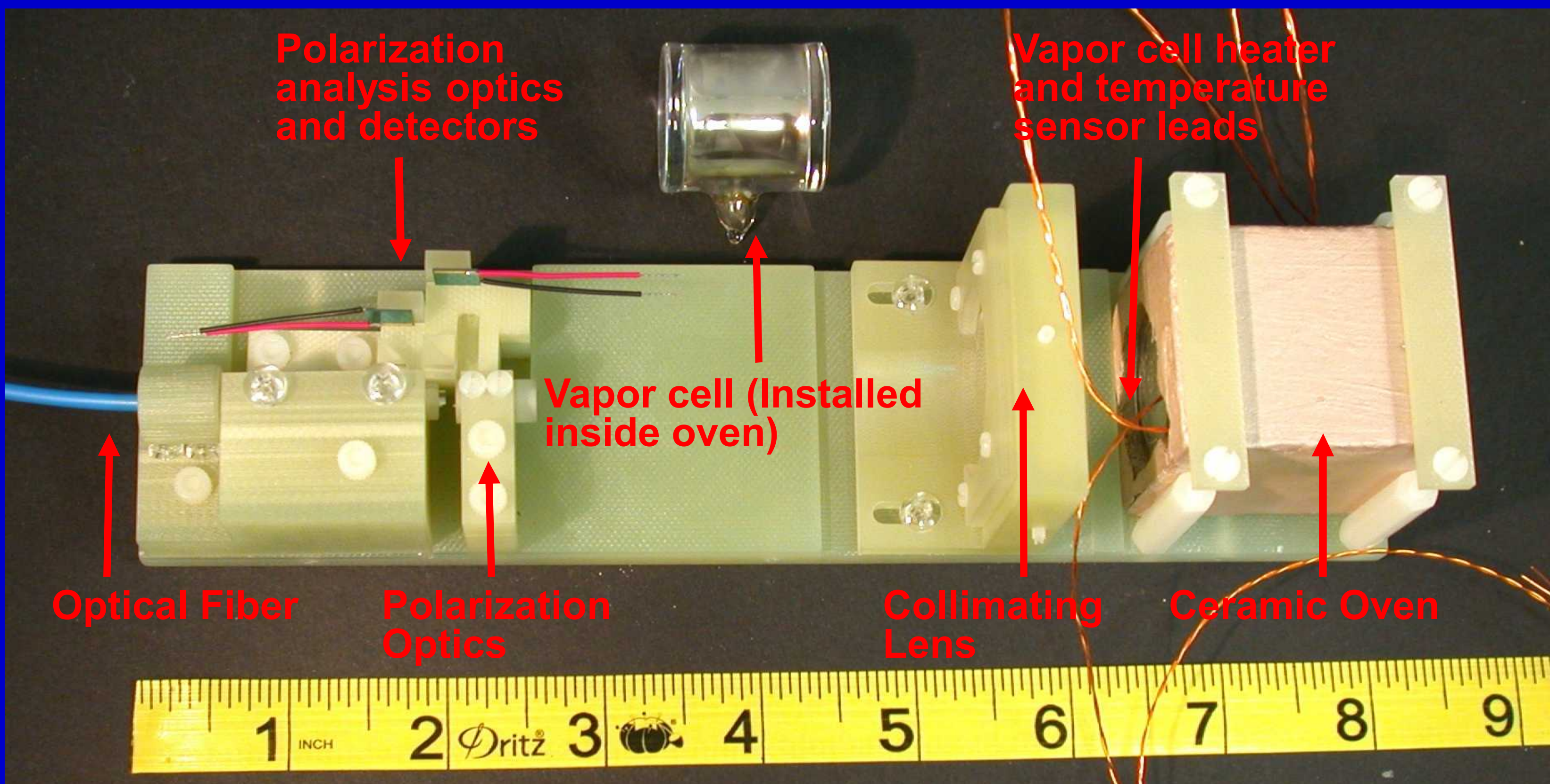
Distance between vapor cell center and head: ~3 cm

insulation

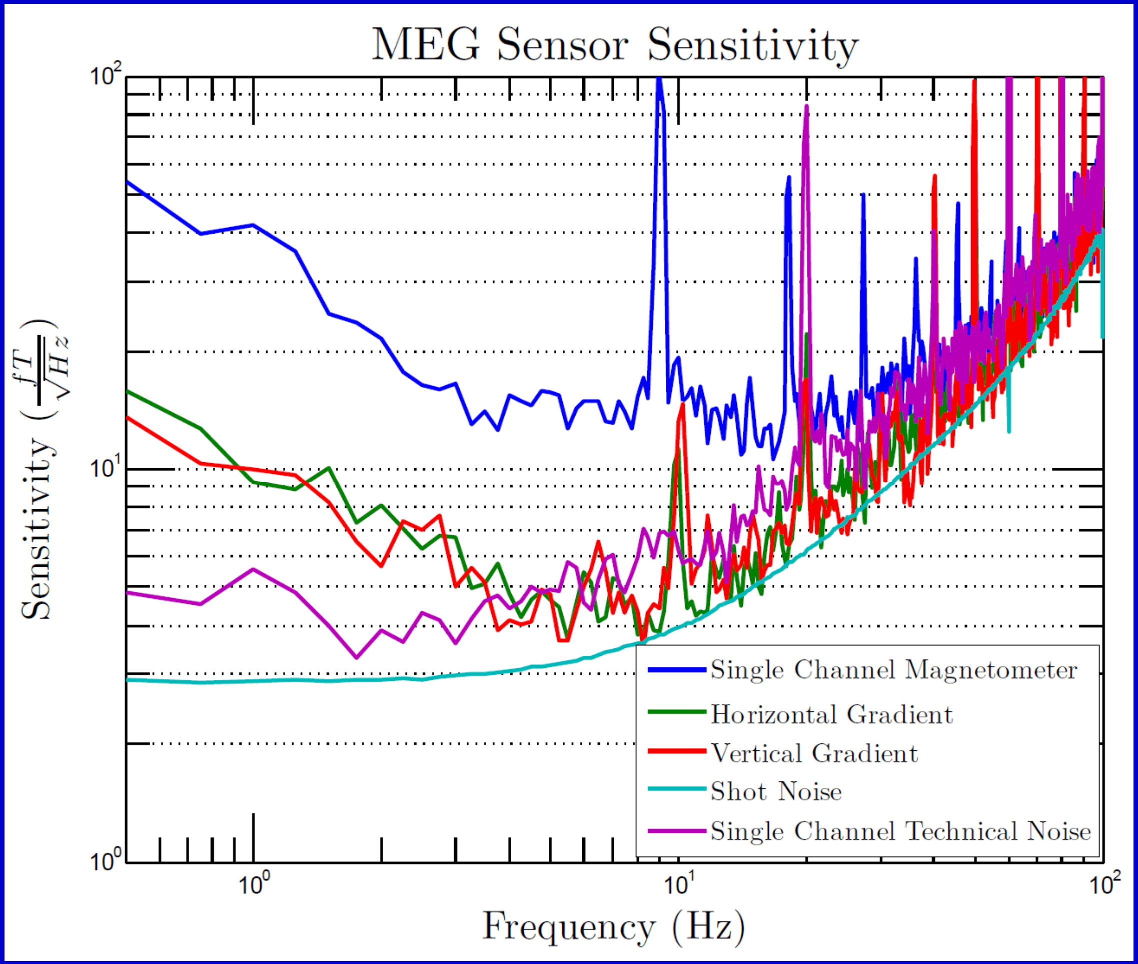
gap

Magnetometer Hardware

- Vapor cell
  - ~600 Torr He, 30 Torr N2
  - Interior size: L = ¾” x ϕ = ¾”
- Insulation: Microporous ceramic oven, vacuum enclosure
- Non-metallic materials: G-10 fiberglass, custom phototdiode mounts
- 1/*f* noise reduced by using optical fibers and a vacuum enclosure



Magnetometer Performance



- Gradient measures intrinsic sensitivity
- <5 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 fT/Hz$^{1/2}$ at 1 Hz
- Sufficient for initial MEG demonstration

Installation in the shielded room

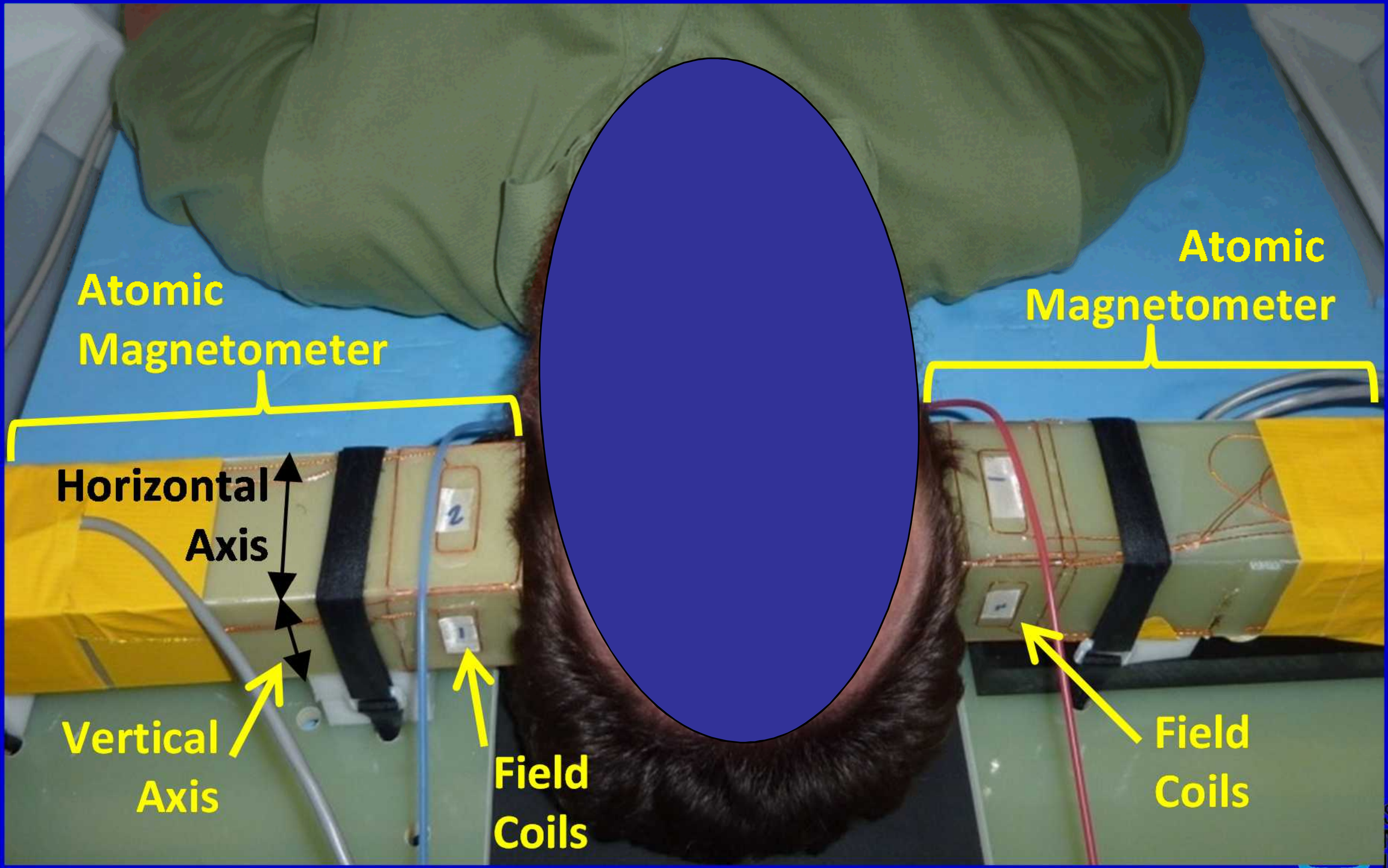
18-coil field cancellation system for reducing the field from ~100 nT to < 1 nT

Median nerve stimulator: 8 mA for 100 μs

SQUID MEG machine

Two Sensor MEG Measurements

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



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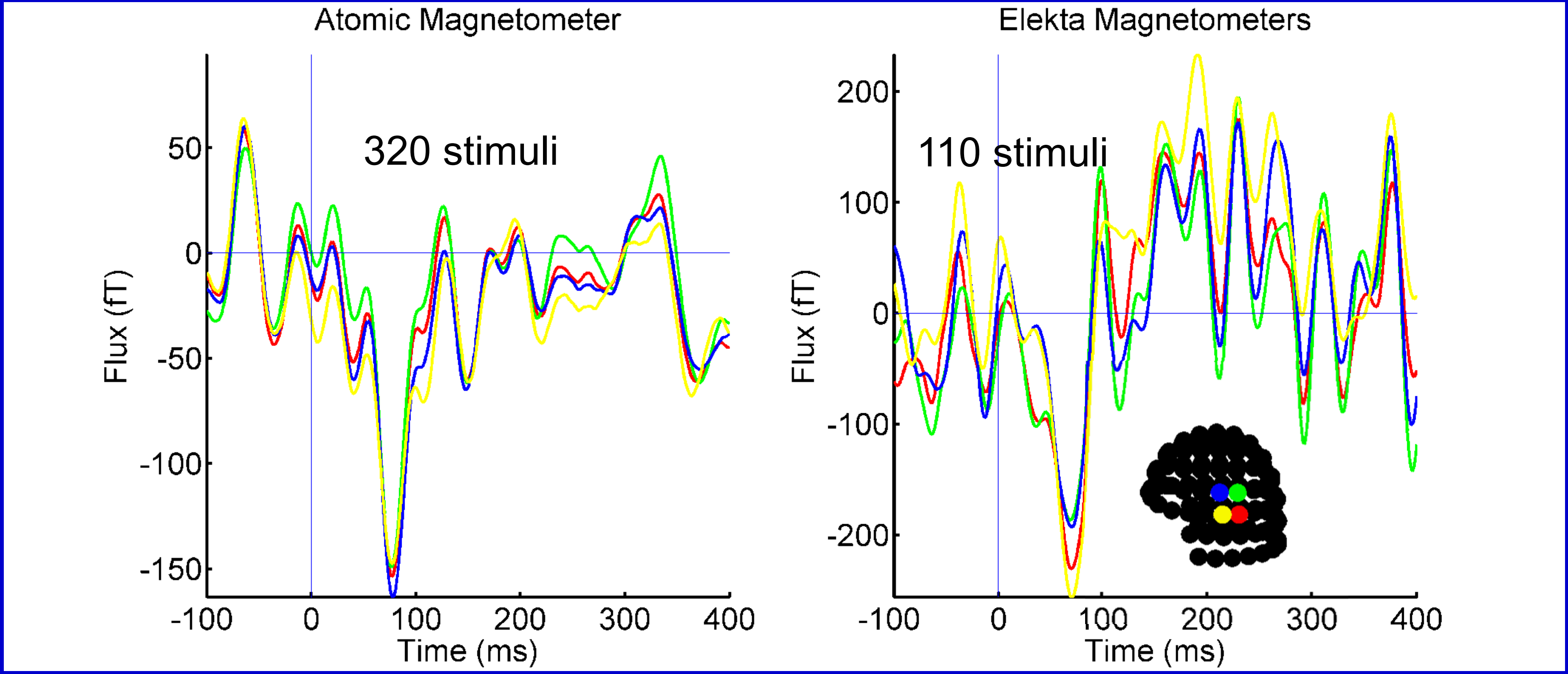
Comparison of a Single 4-Channel Atomic Magnetometer to the SQUIDs

Auditory Stimulation



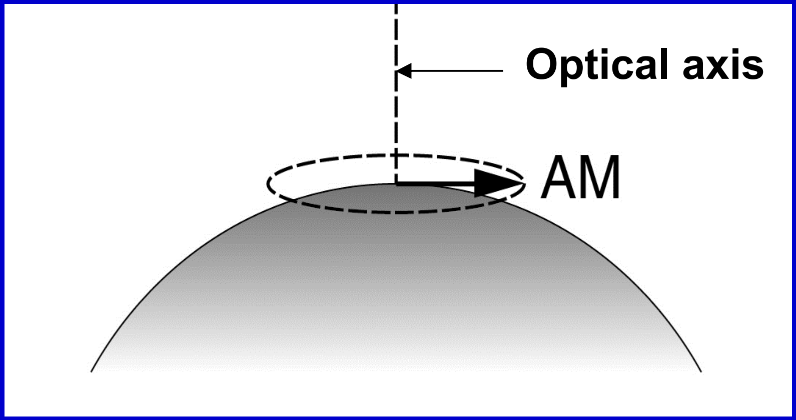
- Present 1000 Hz tones in both ears, measure evoked response in auditory cortex
- Expected signal at ~100 ms is present in AM and SQUID data

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

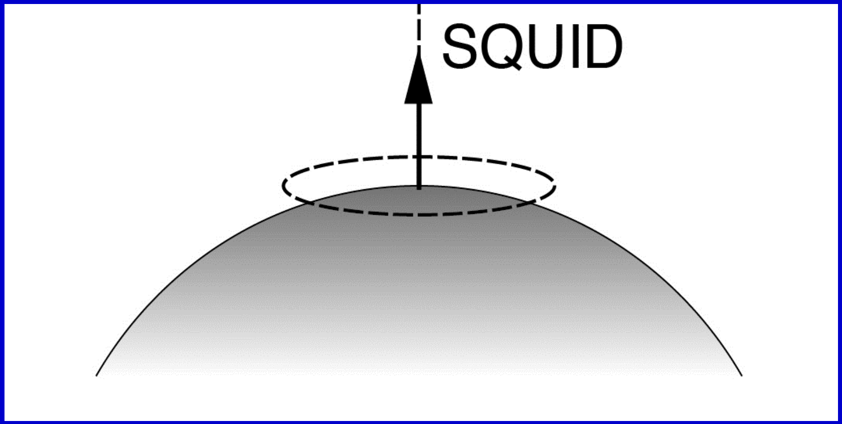
AM vs SQUID

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)

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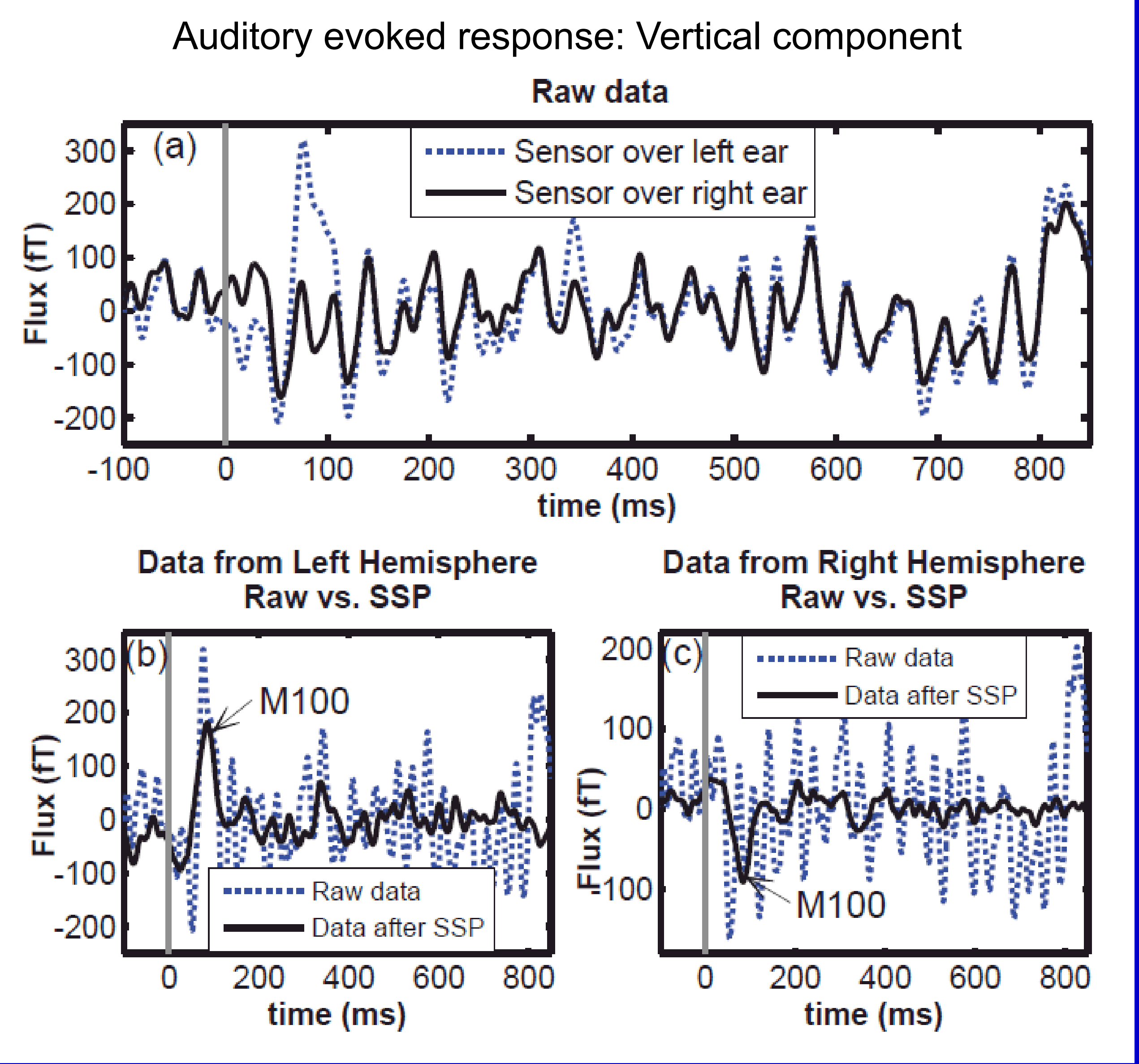
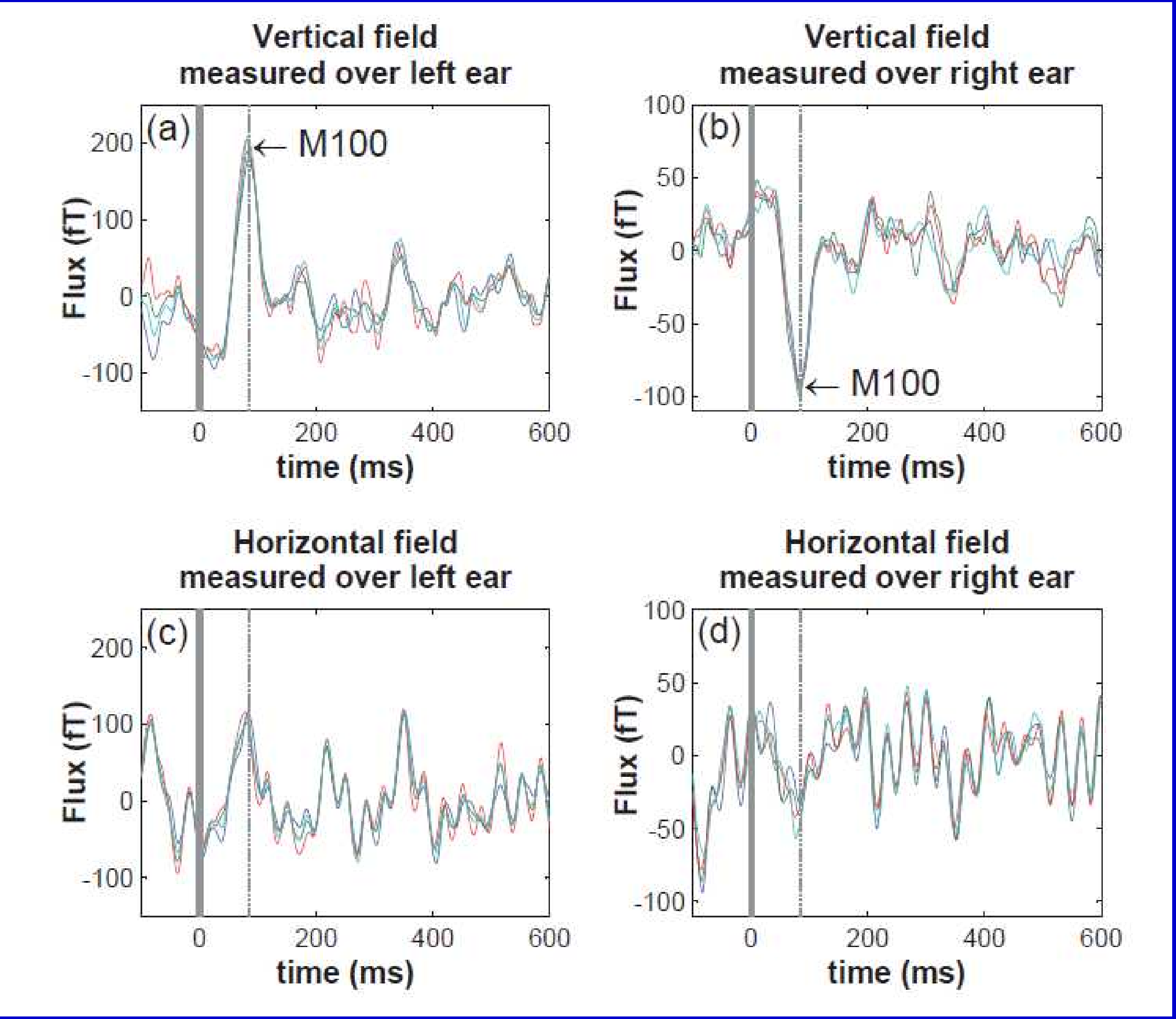
Noise Cancellation

- 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.

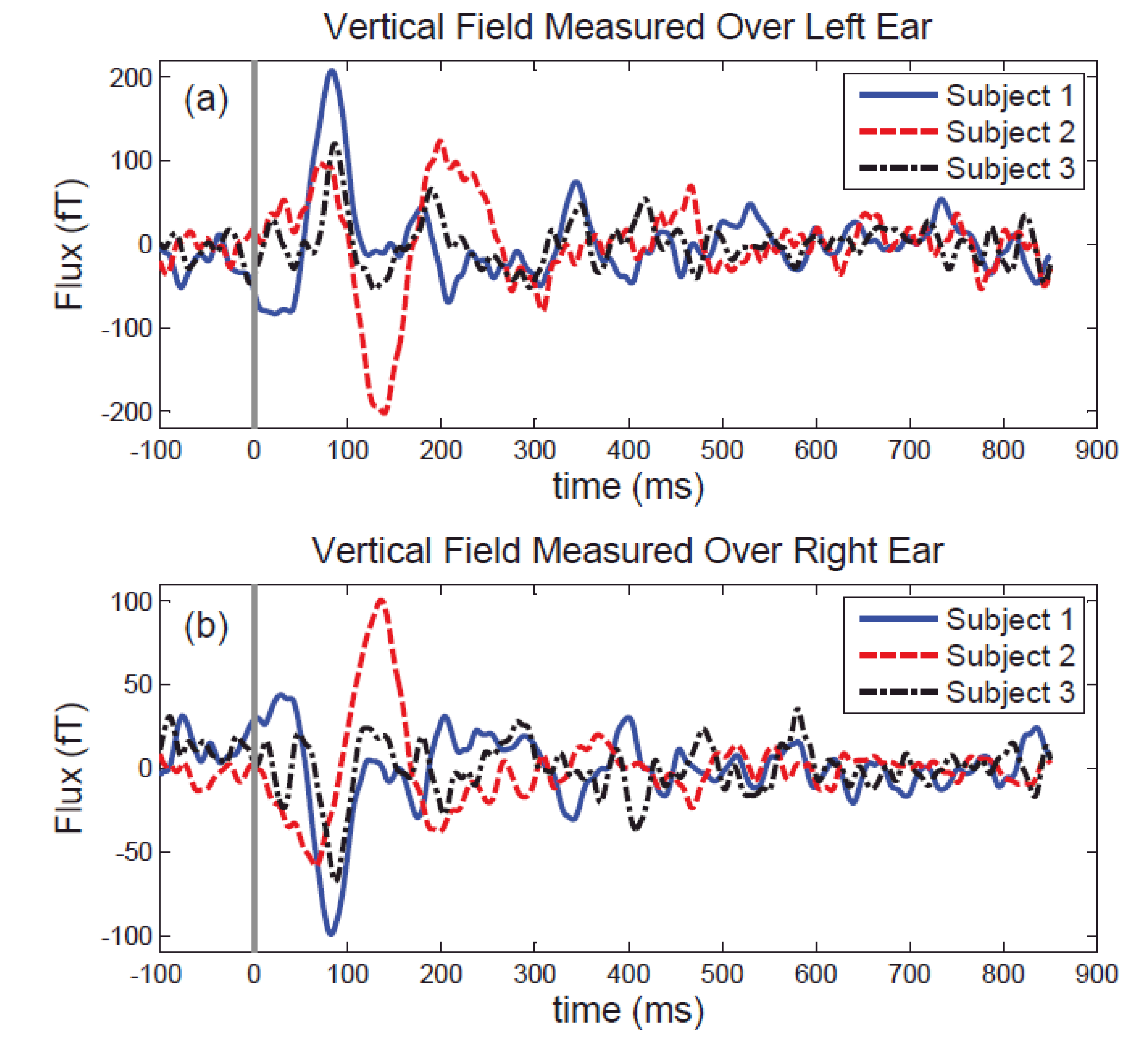


Auditory Stimuli with Two Field Components Measured

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



Auditory Stimuli Multiple Subjects



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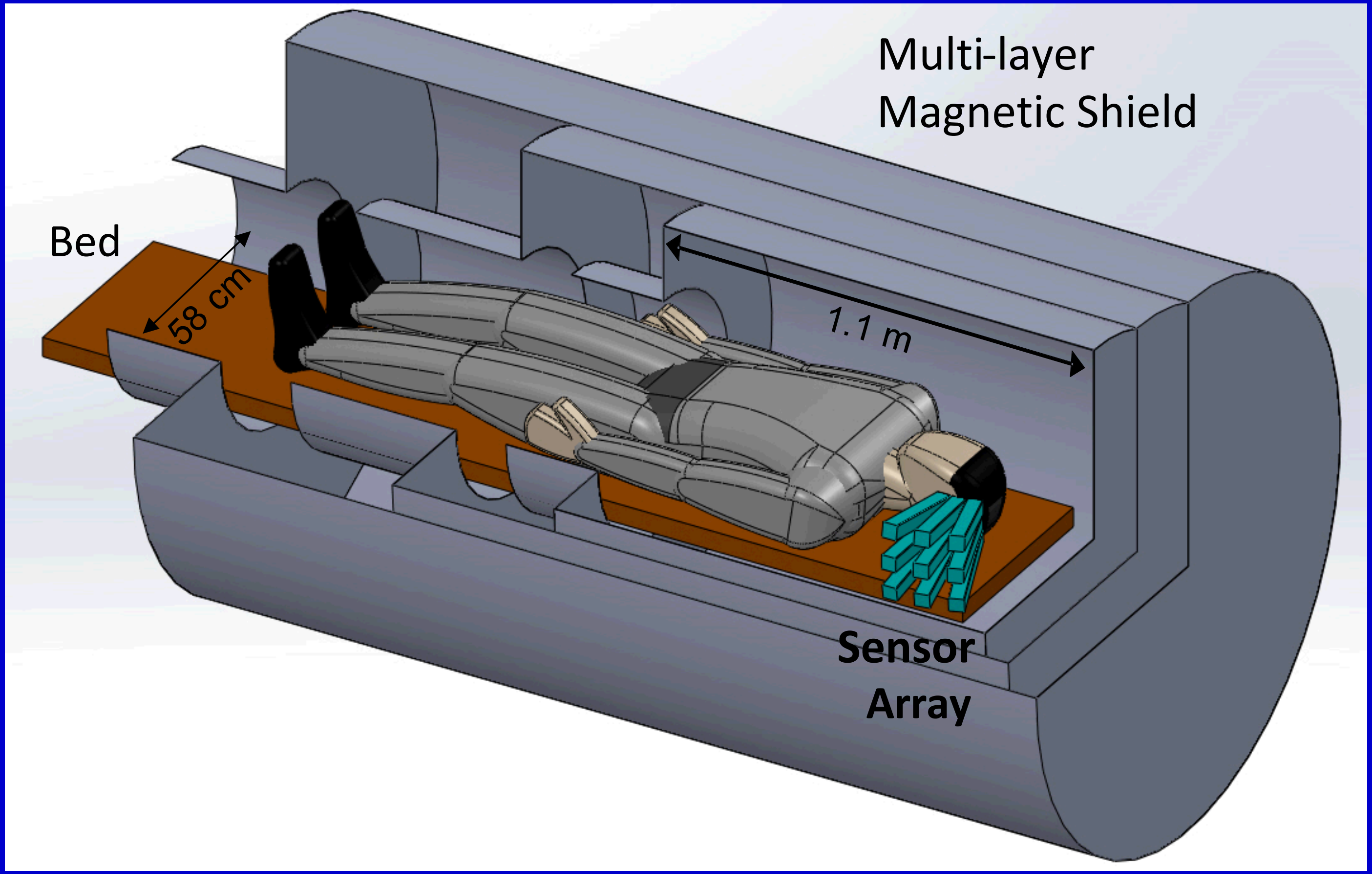
Towards a Complete MEG System

- 36 channel AM array, reconfigurable (position, head size)
- Human-sized shield, cheaper/smaller installation
- Compare AM and SQUID recordings of human subjects



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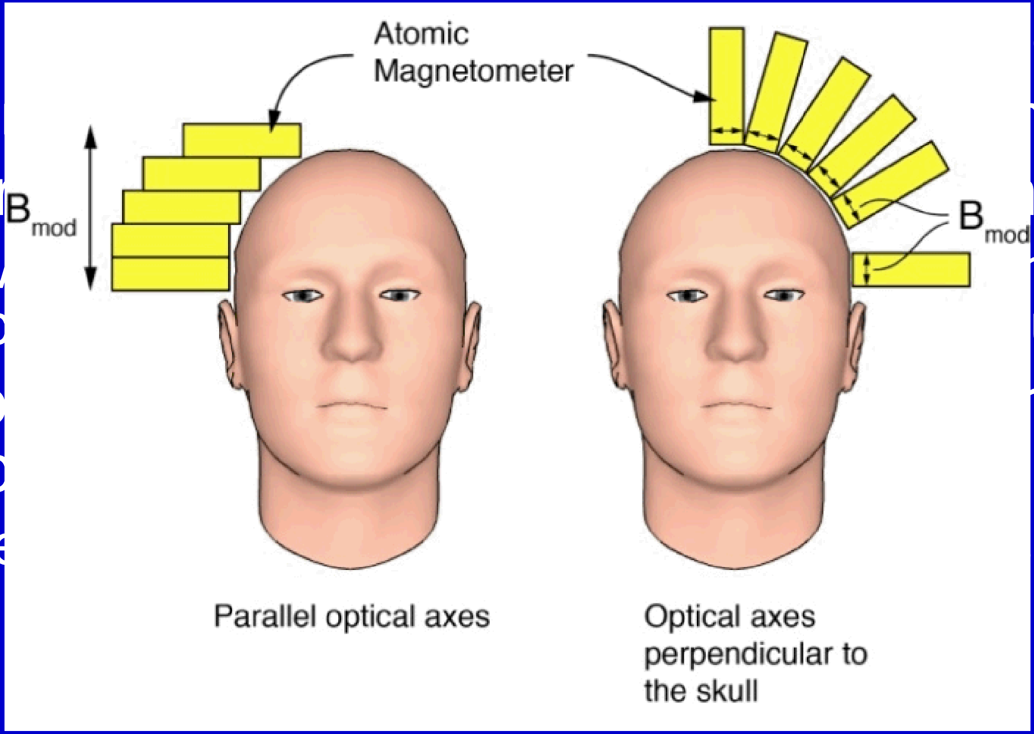
NIH Project: Major Tasks

1. Redesign, miniaturize sensor (4 cm X 4 cm)
   - <10 fT/Hz$^{1/2}$, >100 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 geometry
   - Brai modeling
5. Constr phantom
   - How nd know
     pred ured?
6. Audito human
   subjec
   - Core on



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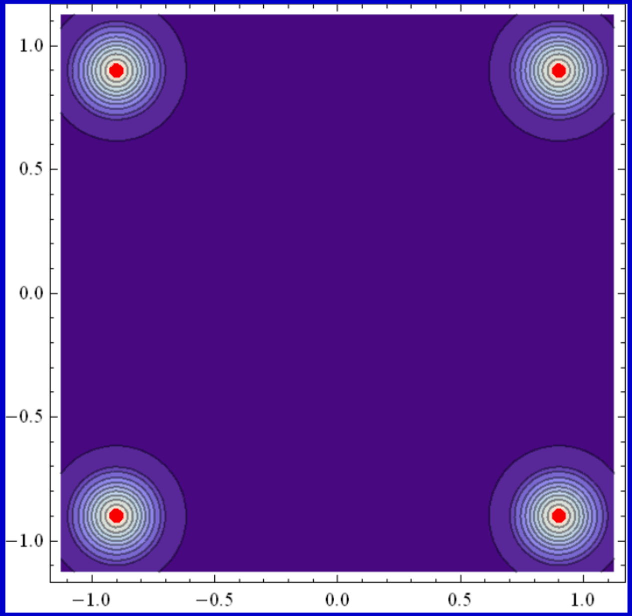
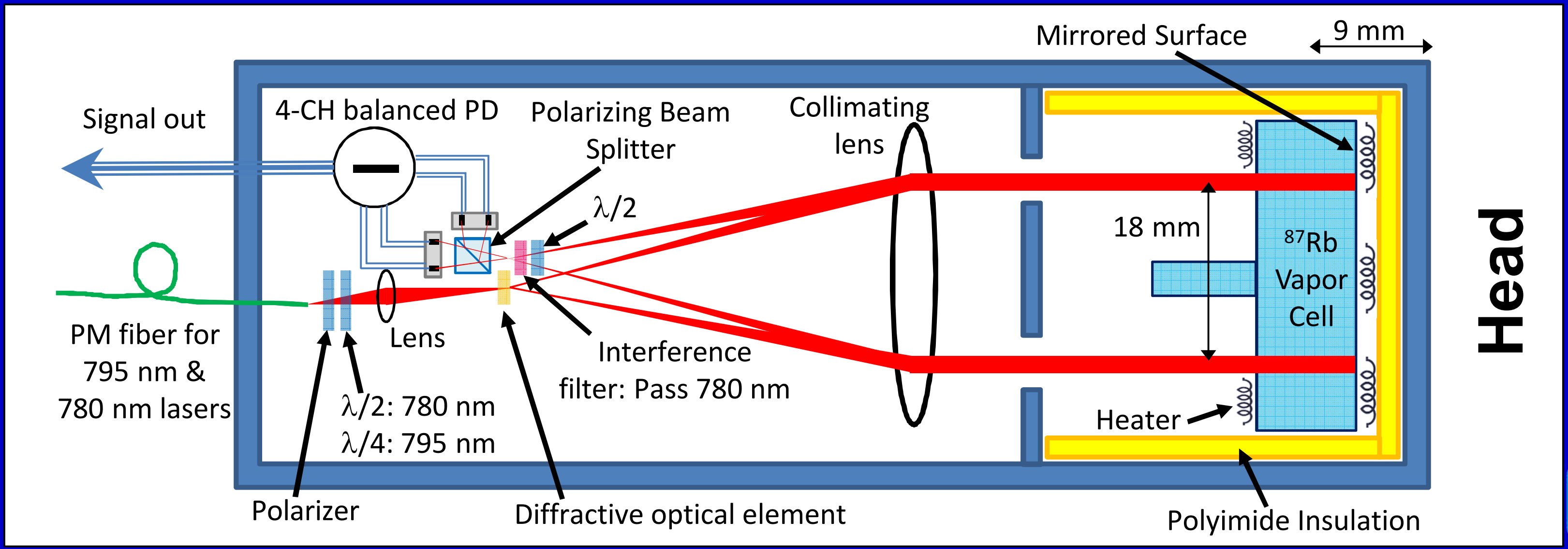
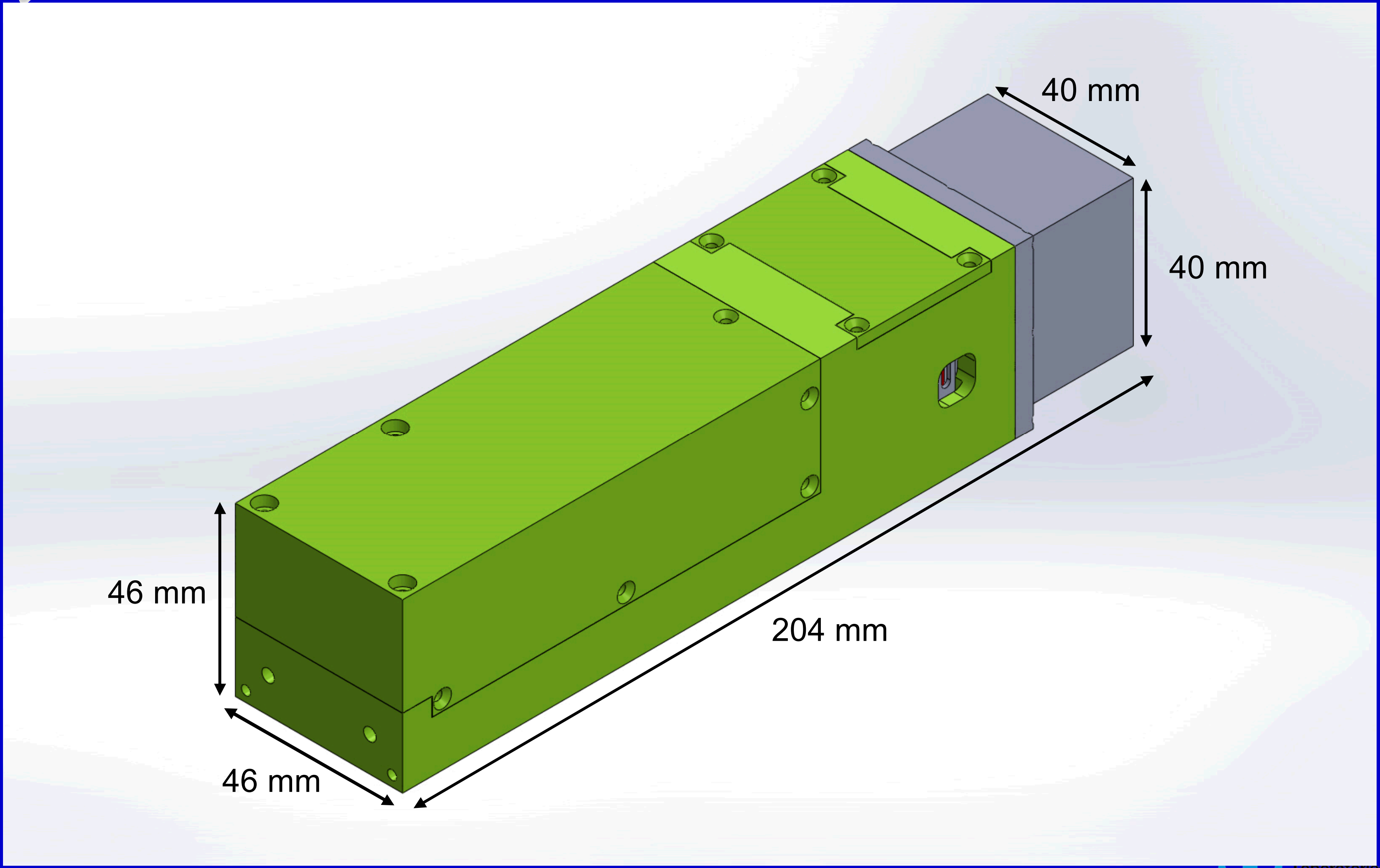
2^{nd} Generation Sensor Design

- Previous single-beam design was very difficult to align and had a short gradiometer baseline, ~5 mm
- Switch to four beams, 18 mm baseline, 2.5 mm FWHM beam diameter
- Vapor cell:
  - Previous: 10 mm long, 600 Torr He, 30 Torr N_2
  - Current: 4 mm long, 600 Torr N_2
- Minimize distance from the head to the vapor cell: 9 mm

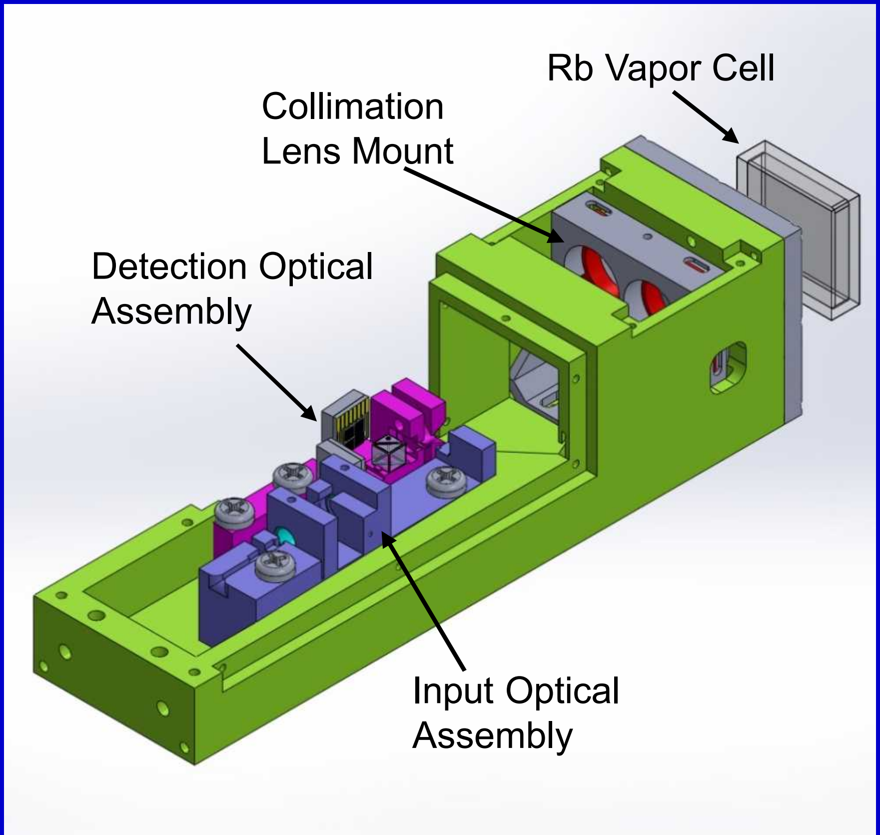


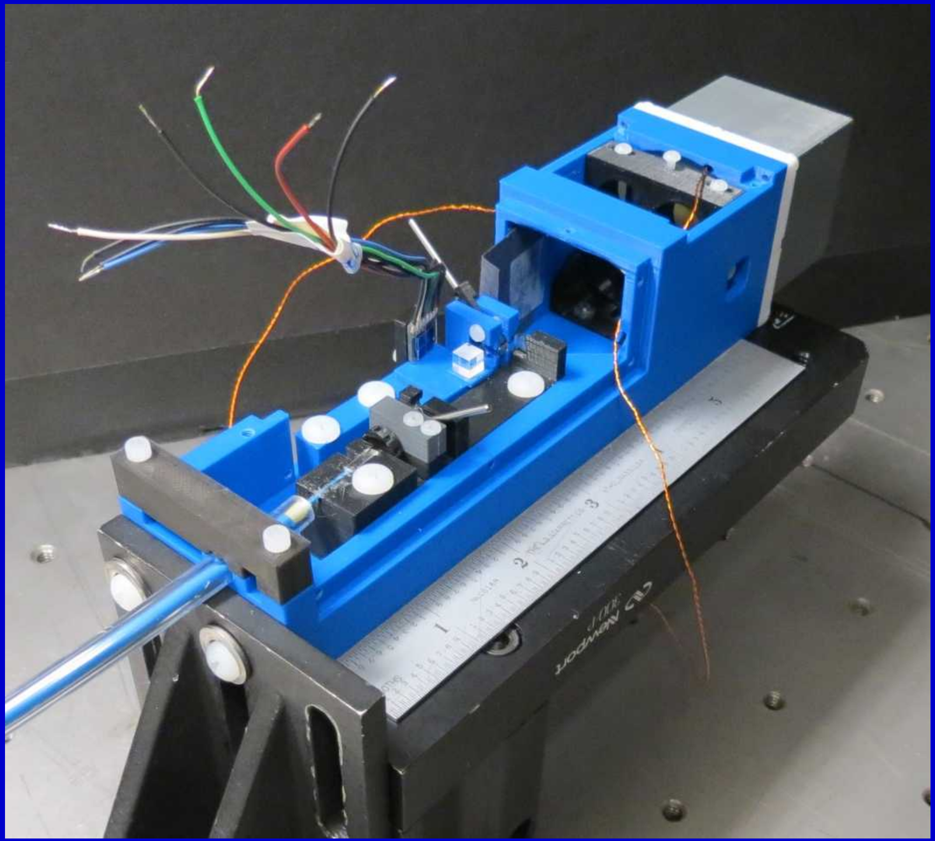


2nd Generation Sensor Design

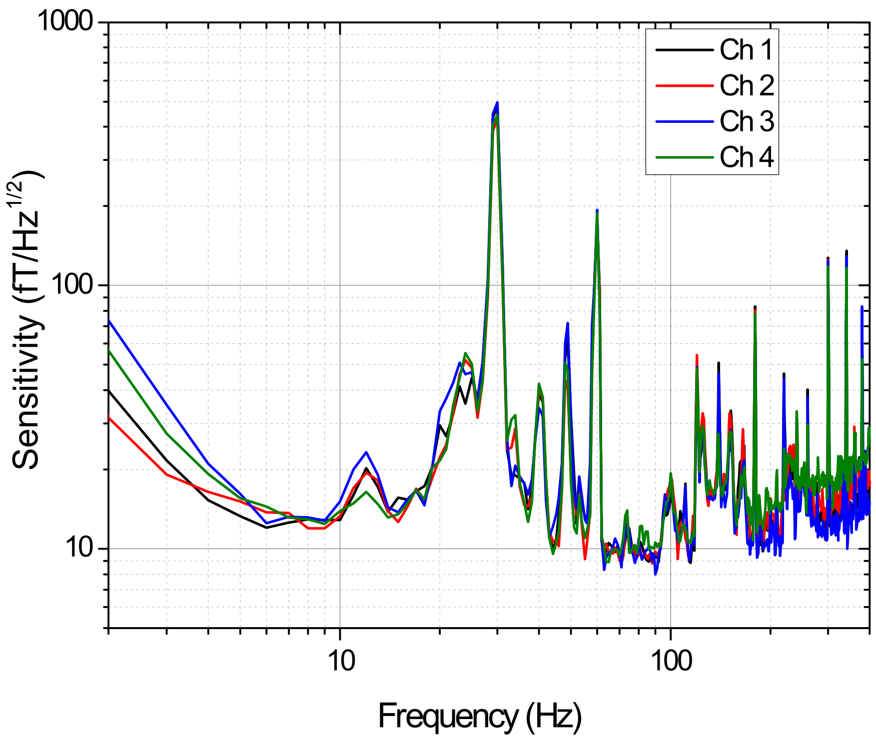


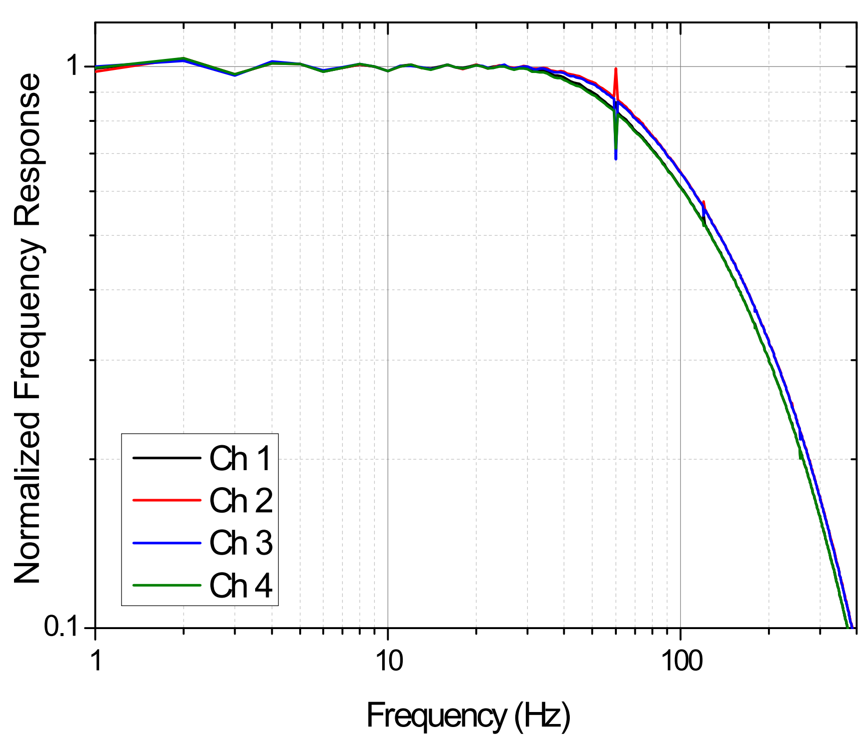
2nd Generation Sensor Design





Prototype Performance: 4 Channels





- Current sensitivity: 10–20 fT/Hz$^{1/2}$ over 5–200 Hz
- Limited by noise in the shield and technical laser noise

	Ch 1	**Ch 2**	**Ch 3**	**Ch 4**
DC Gain	19.5 V/nT	18.0 V/nT	18.7 V/nT	19.7 V/nT
3 dB Bandwidth	81 Hz	88 Hz	88 Hz	80 Hz

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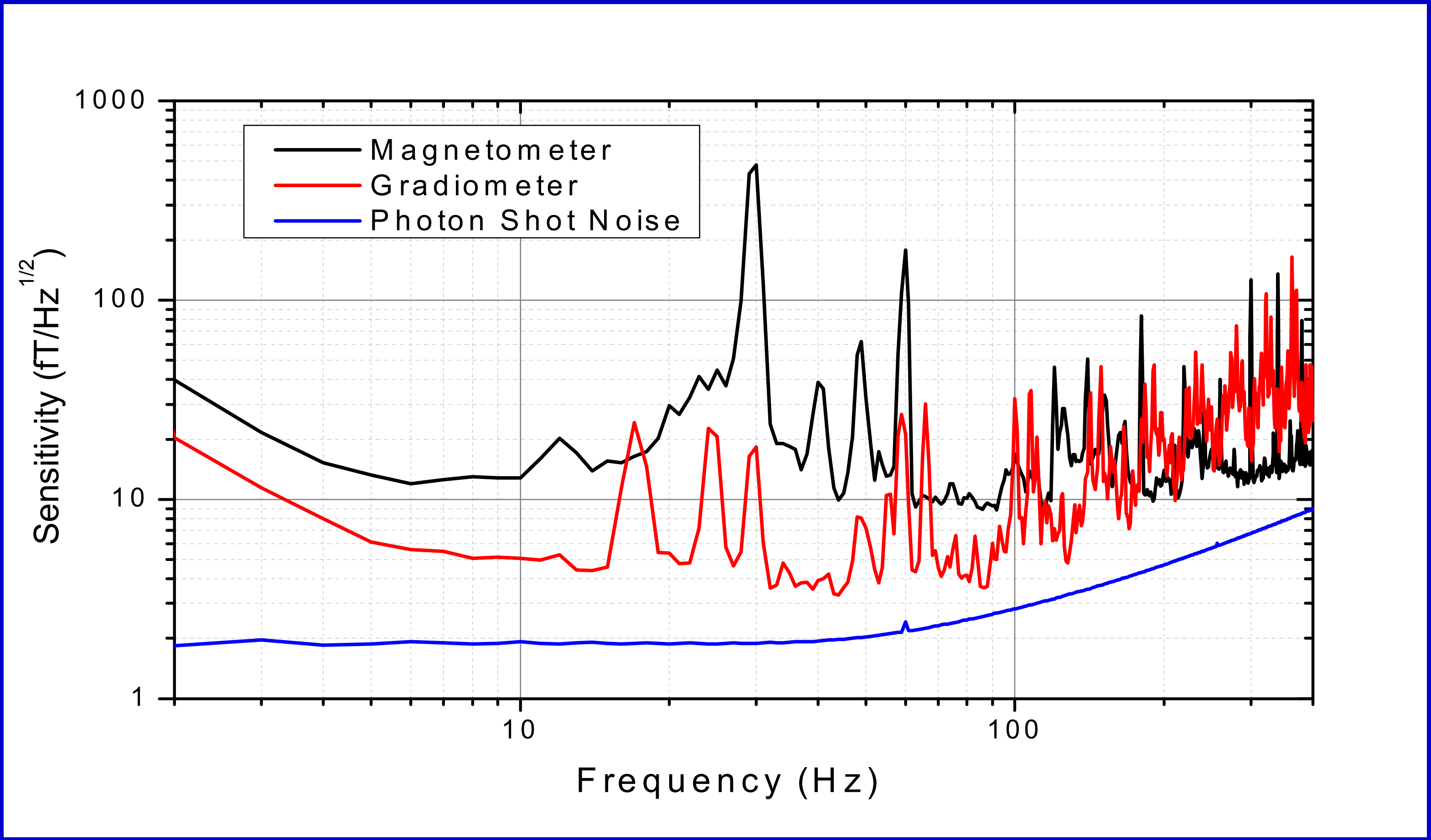
Gradiometer Performance



- Gradiometer: Channel 1 – Channel 3
- Noise floor below 10 fT/Hz$^{1/2}$ from 5-100 Hz
- Need to work on the technical noise sources

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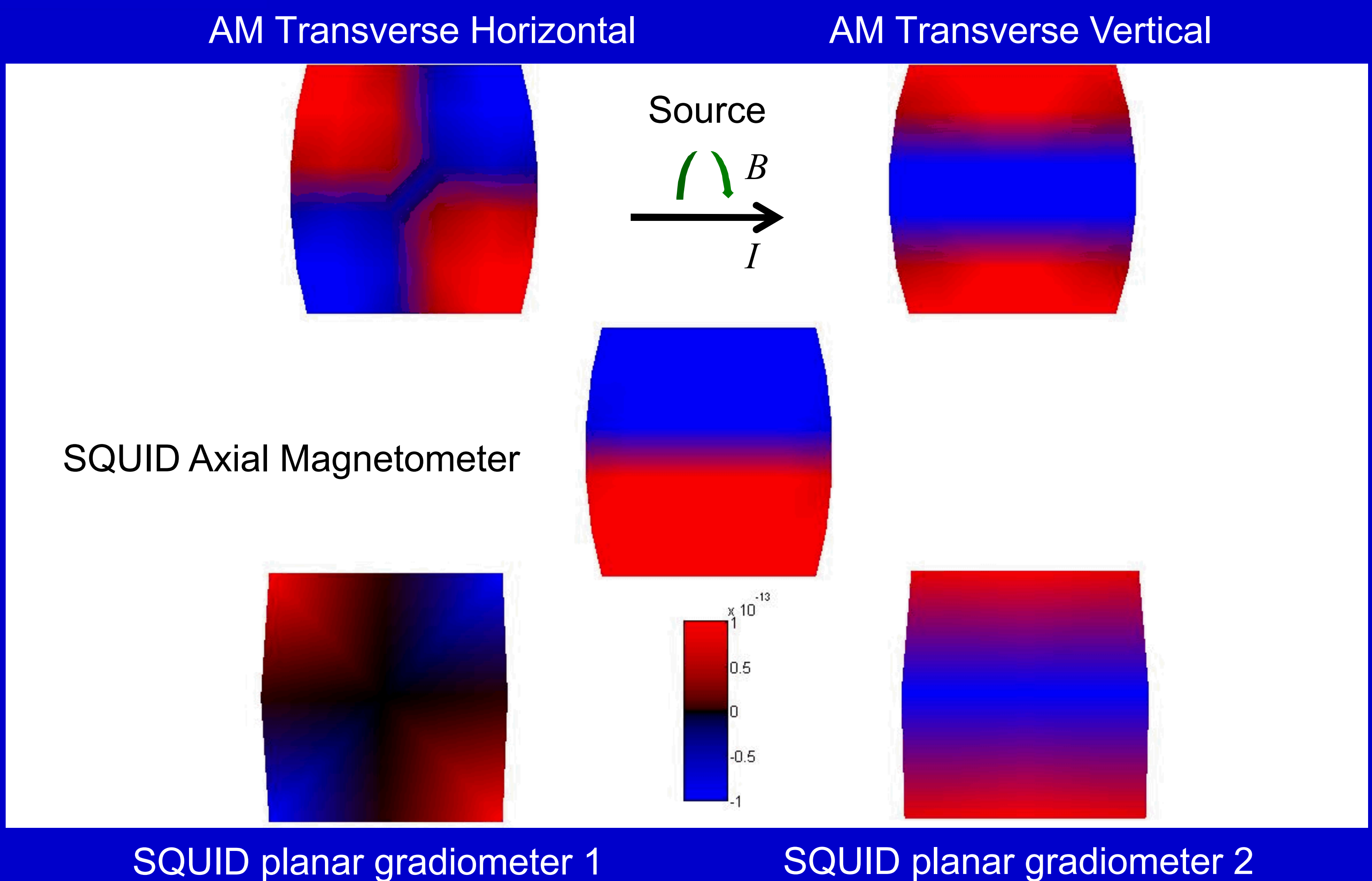
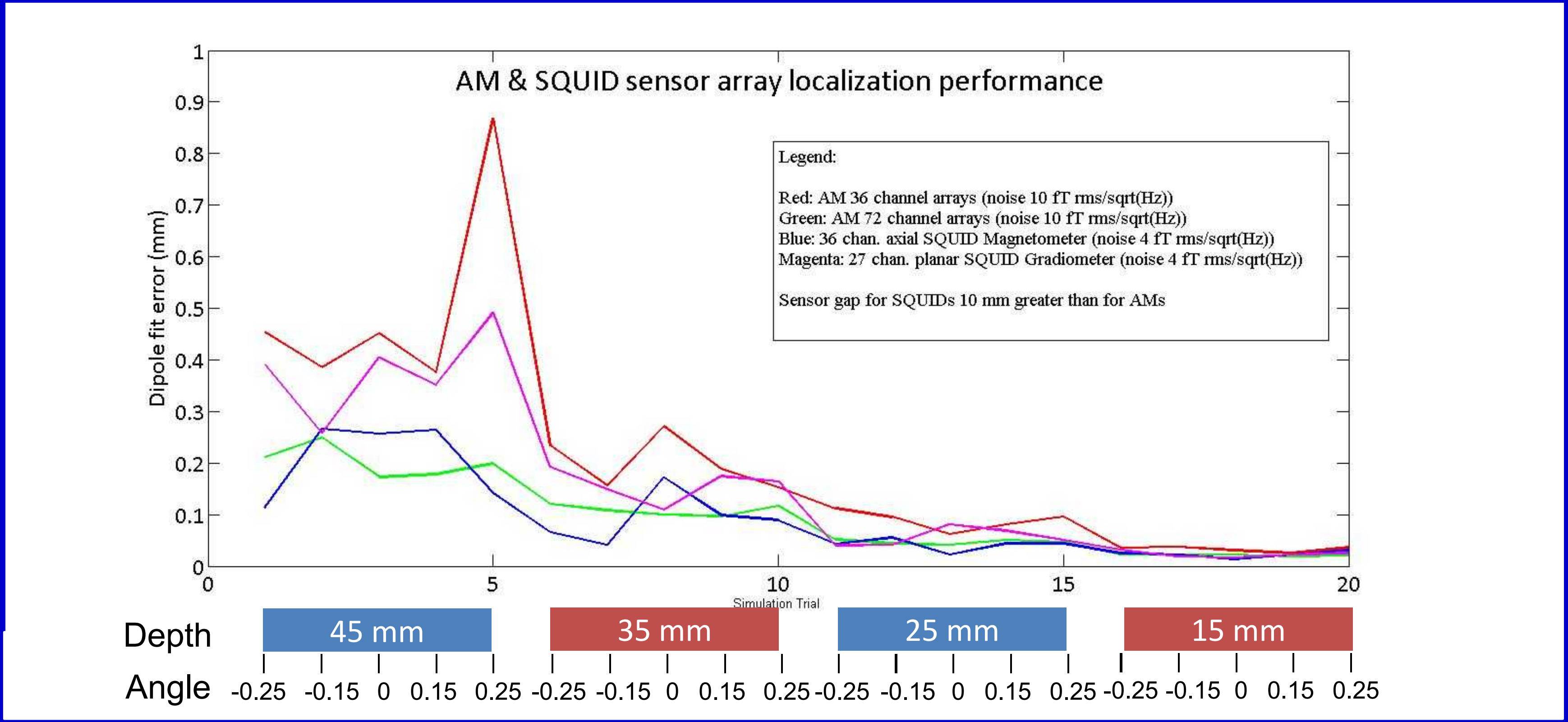
Sensor field maps



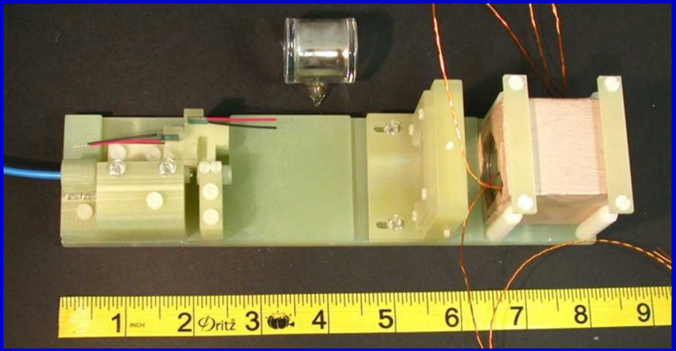
AM Localization Performance Similar to SQUID sensors

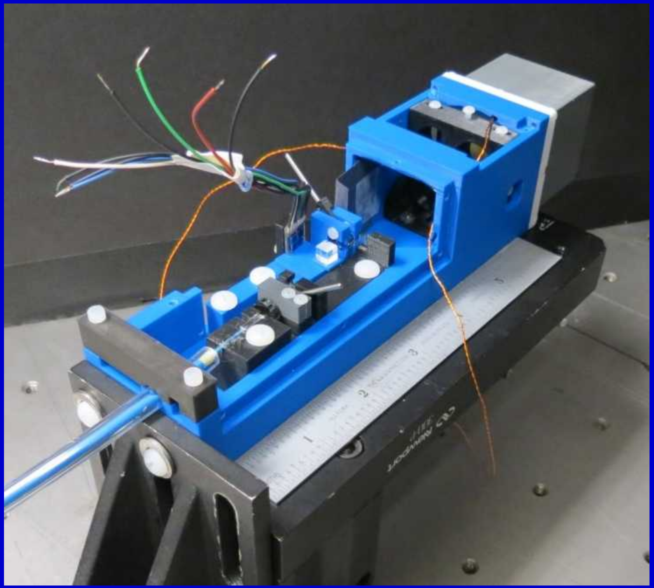


Each point is an average of the 4 source orientations at 1 sensor array position

Conclusion

- 1st generation 4-channel sensor
  - <5 $fT/Hz^{1/2}$ sensitivity
- Successfully measured MEG signals using transverse fields and multiple sensors
- Constructed our first 2nd generation sensor
  - 18 mm channel separation
  - <5 $fT/Hz^{1/2}$ sensitivity
- Three-layer shield design
- Work toward building up the 36-channel array





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Acknowledgements

- Sandia MEG Team: Peter Schwindt, Anthony Colombo, Yuan-Yu Jau, Tony Carter, Amber Young, Christopher Berry
  - Former Team Members: Cort Johnson, George Burns, Jon Bryan, Grant Biedermann, Michael Pack, Aaron Hankin
- Collaborators: Mike Weisend (MRN), Jim McKay (Candoo Systems), John Mosher (Cleveland Clinic), Bruce Fisch (UNM School of Medicine)
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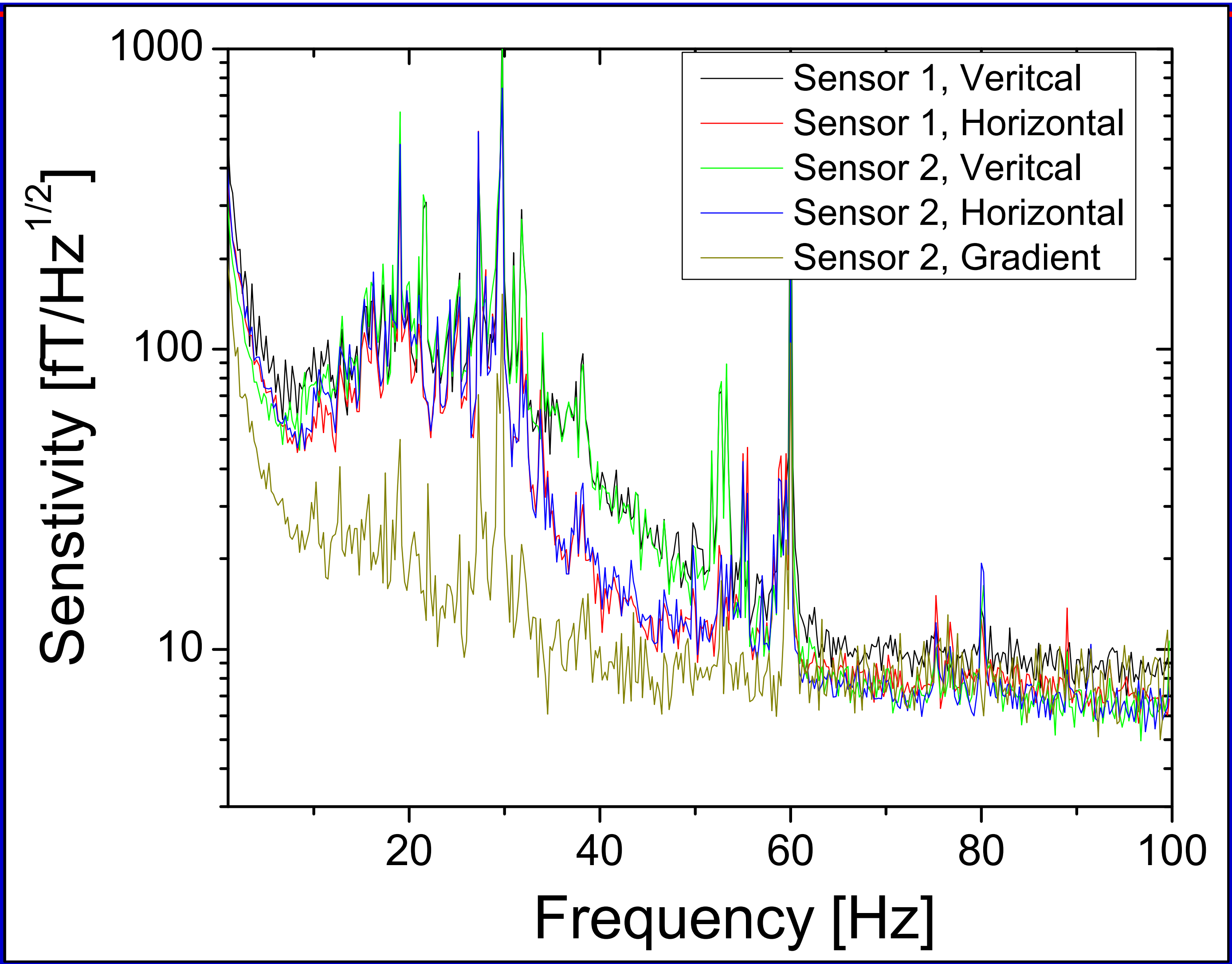
Backup

Noise in the Shielded Room



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

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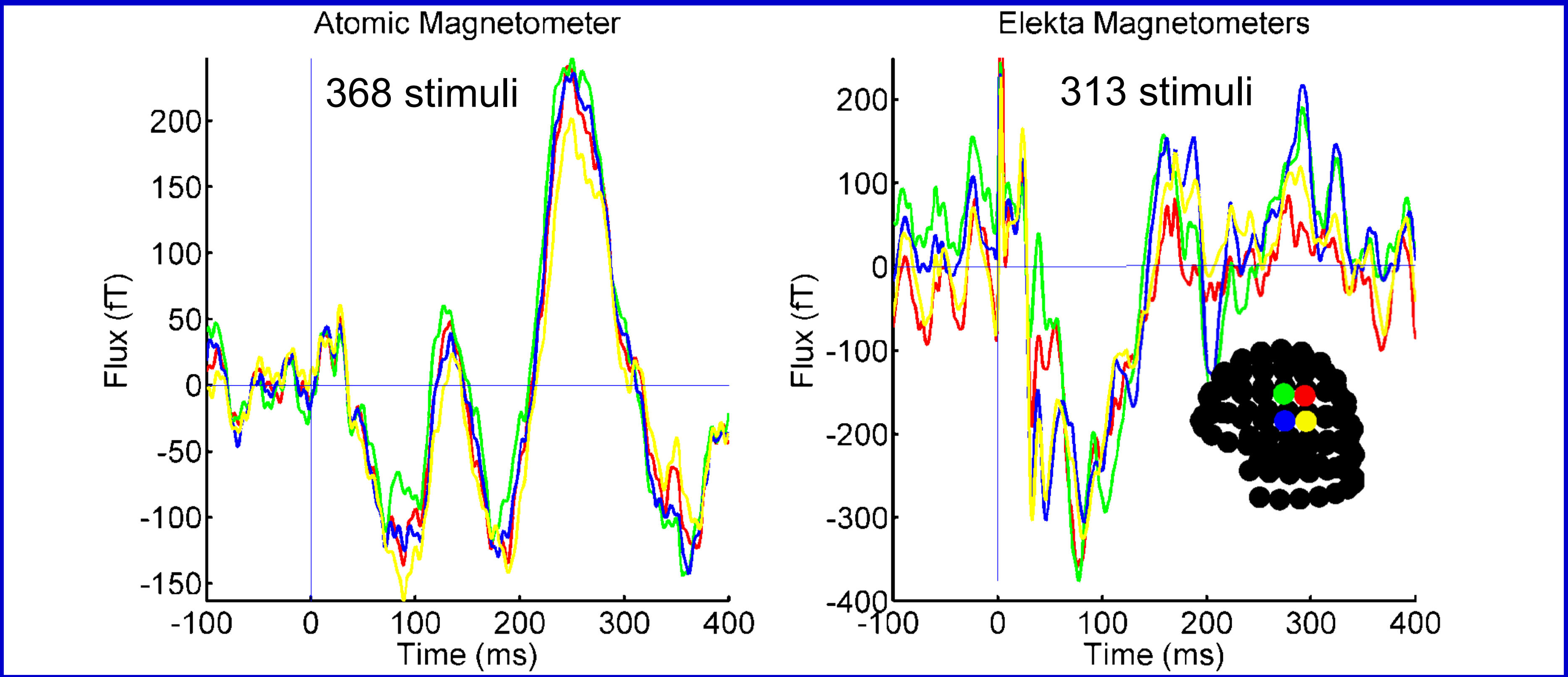
Comparison of the Atomic Magnetometer to the SQUIDs

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)

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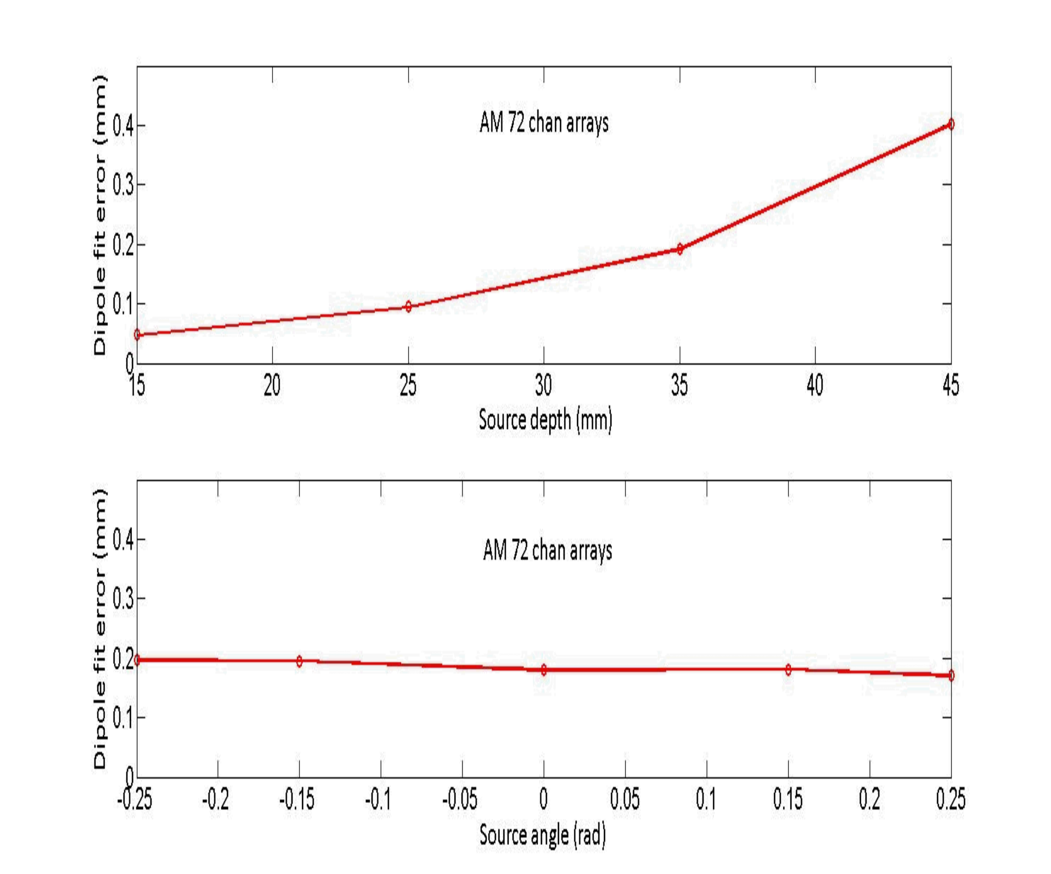
AM Localization Performance vs Source Depth and Array Offset



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

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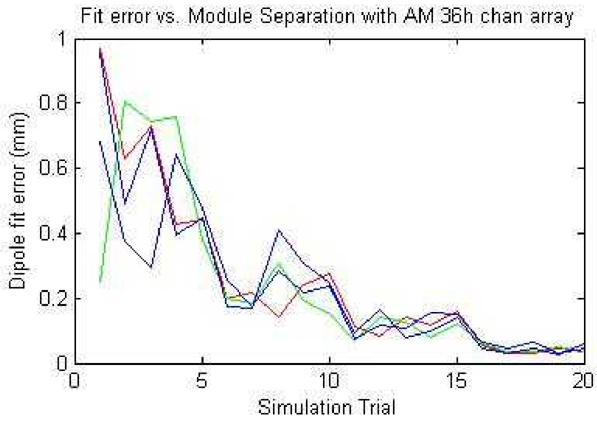
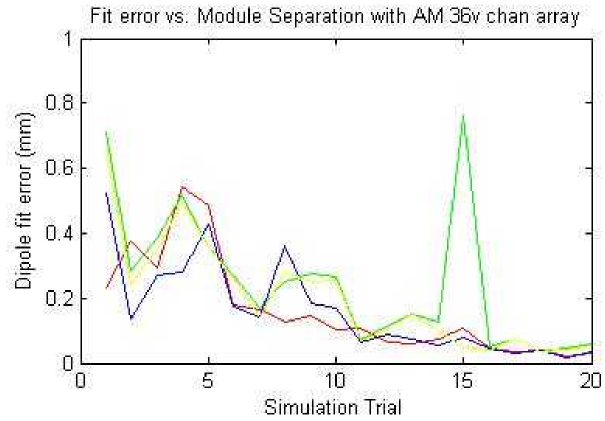
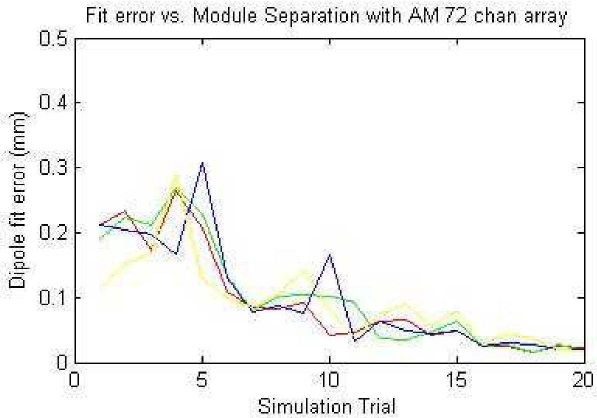
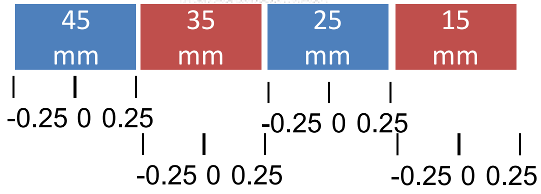
AM Sensor module separation does not change localization error much









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

For 20 mm sensor separation

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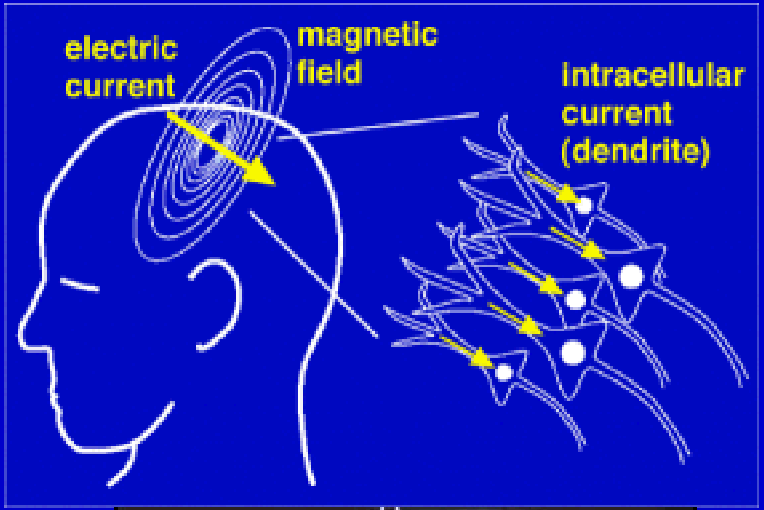
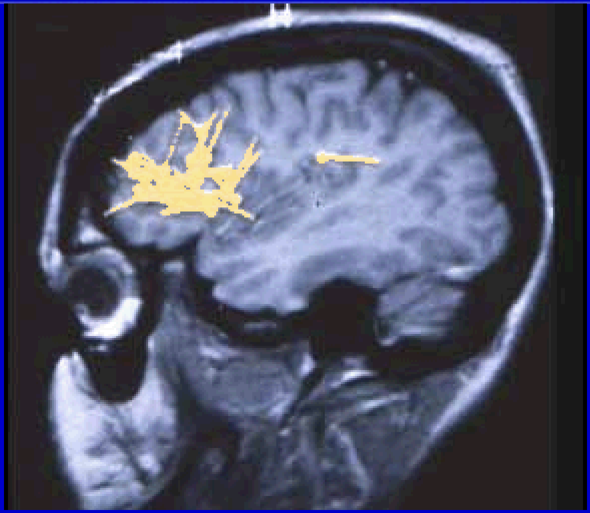
Magnetoencephalography (MEG)

- 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





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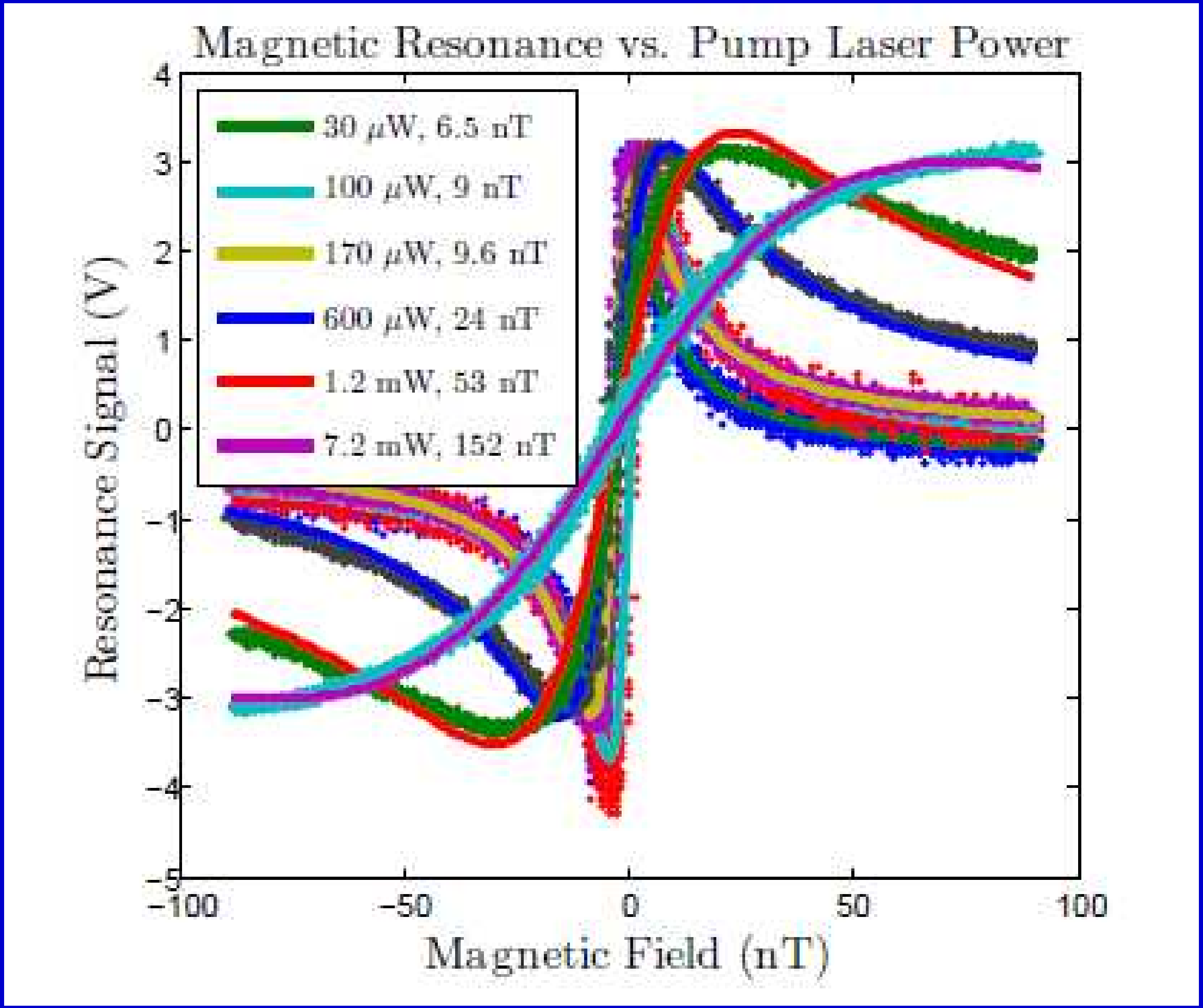
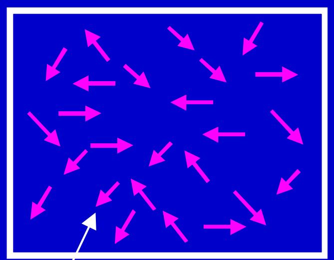
Typical Faraday Rotation Signal



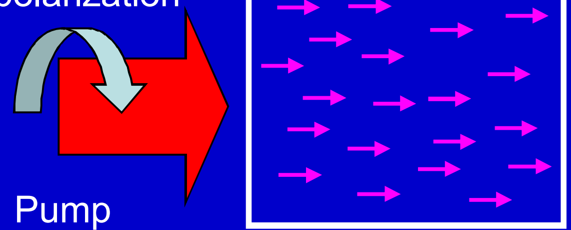
Atomic Magnetometer Basics

Alkali Vapor Cell



Randomly oriented atomic spins

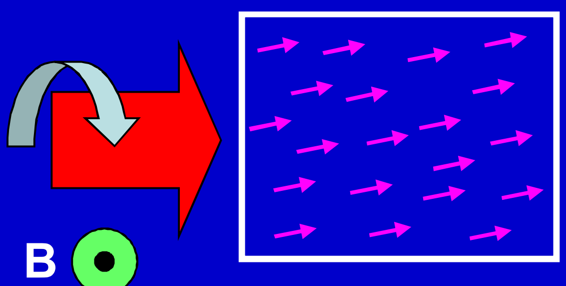
Optical pumping



Spins align with the pump beam

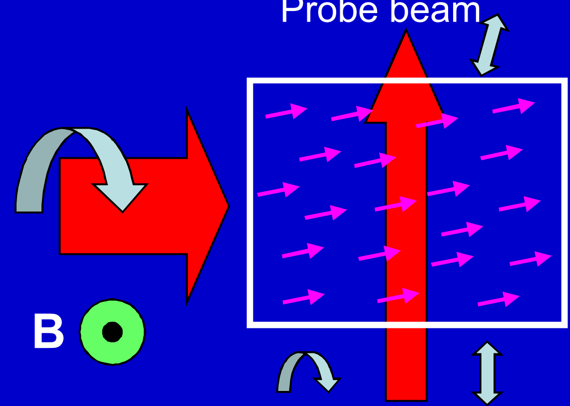
*D. Budker, *et al. Phys. Rev. A* **62**, 043403 (2000).

Apply Small Magnetic Field

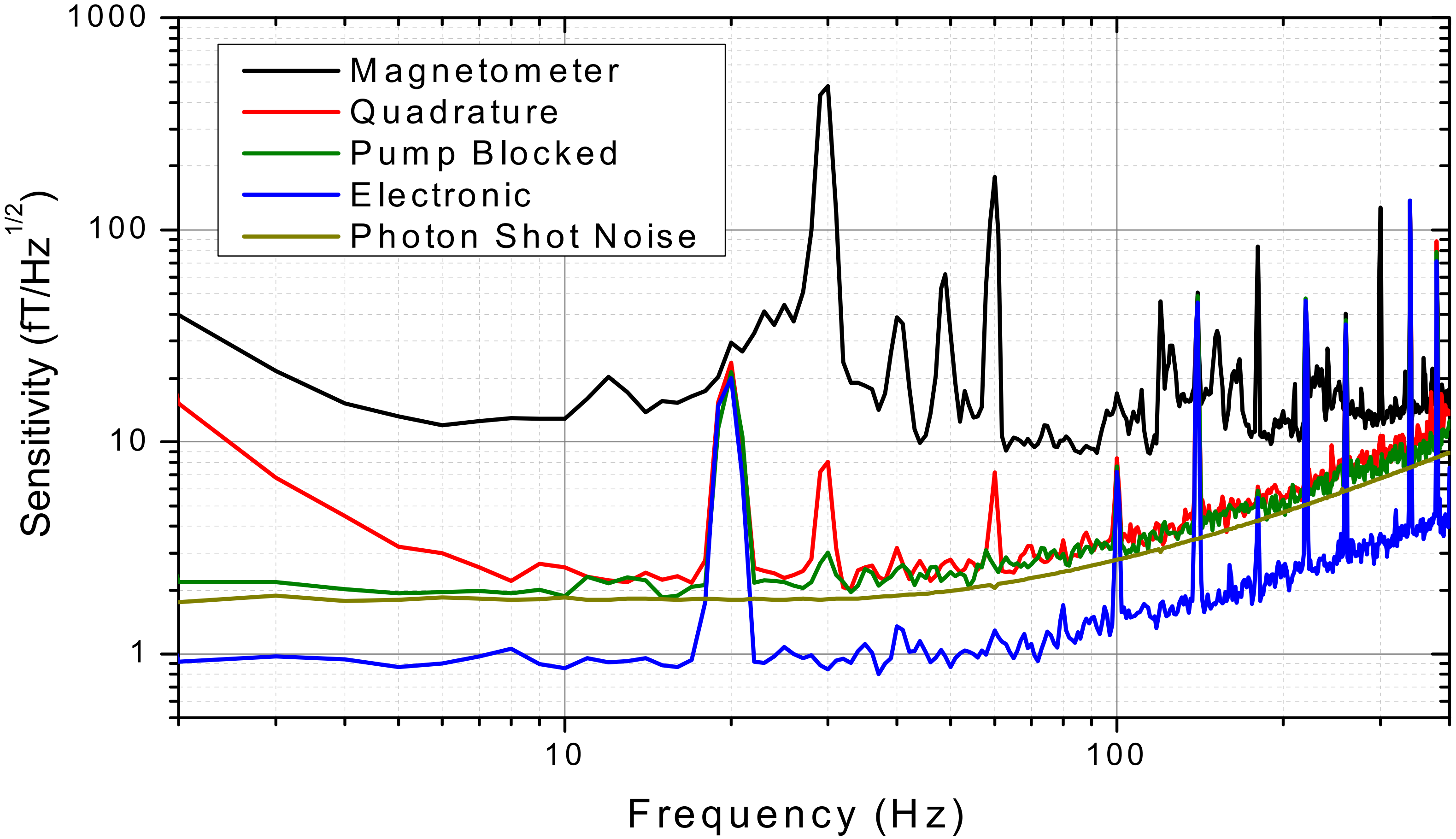


Spins precess due to magnetic field

Detect with probe beam



Channel 1 Performance



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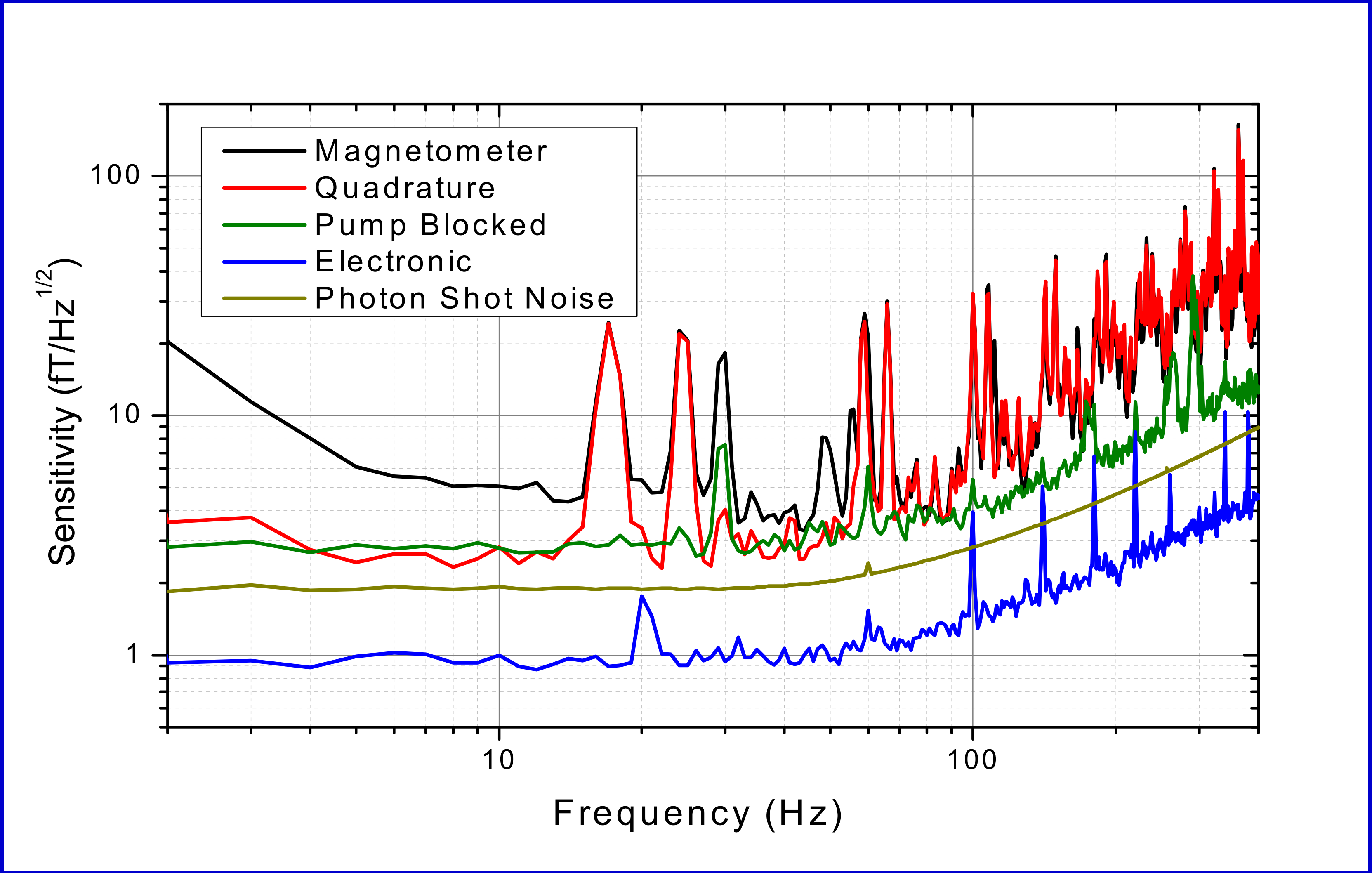
Gradiometer: Channel 1 – Channel 3



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