SAND2015-2686C

Development of an Optically Pumped Atomic Magnetometer Array for Magnetoencephalography (MEG)

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Outline

- Introduction
- First generation optically pumped magnetometer (OPM) design
  - Optically pump magnetometer = Atomic magnetometer
  - MEG measurements with two sensors
- Complete MEG system
  - Second generation OPM design
  - Scaling up to a larger array
  - Person-sized magnetic shield
- Conclusion

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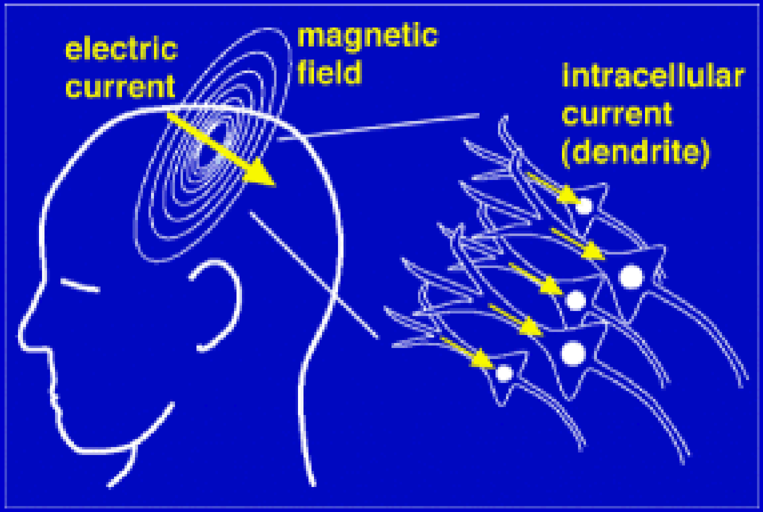
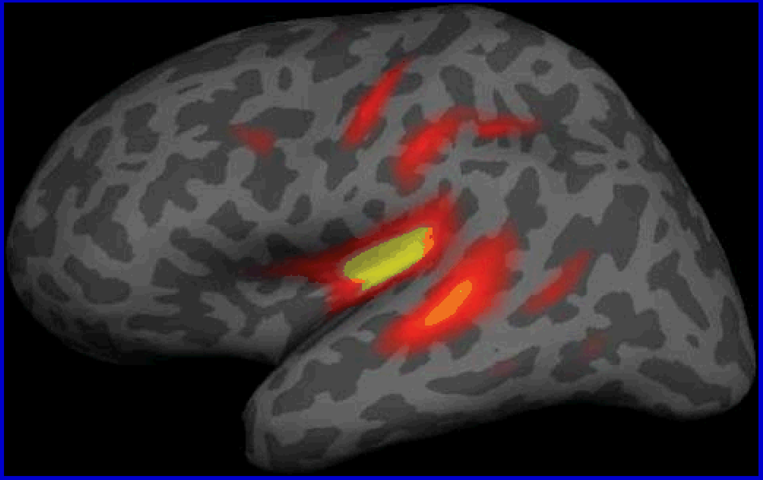
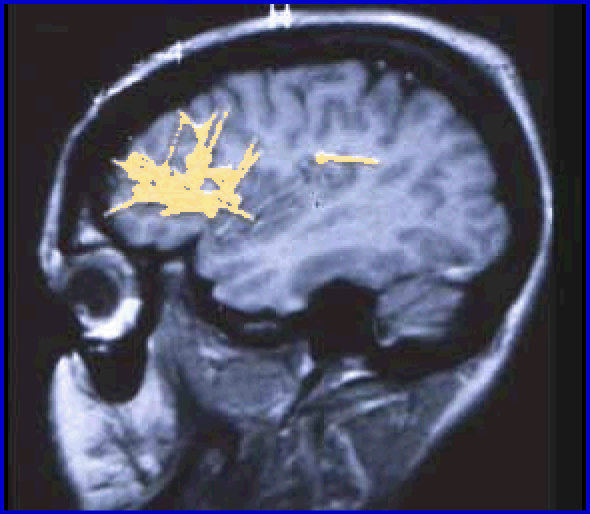
What is MEG?

- Detect magnetic fields produced by neural currents.
  - > 10,000 neurons
  - < 10^{-13} T or 100 fT
- Localize the brain activity.
- Measure noninvasively.







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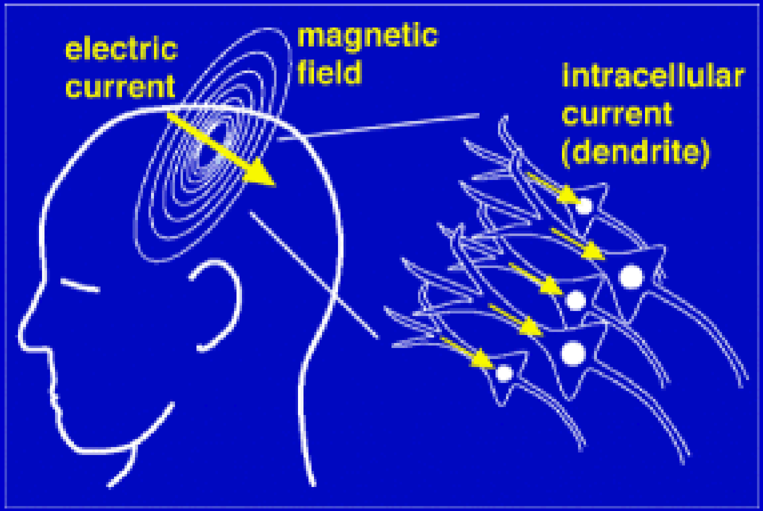
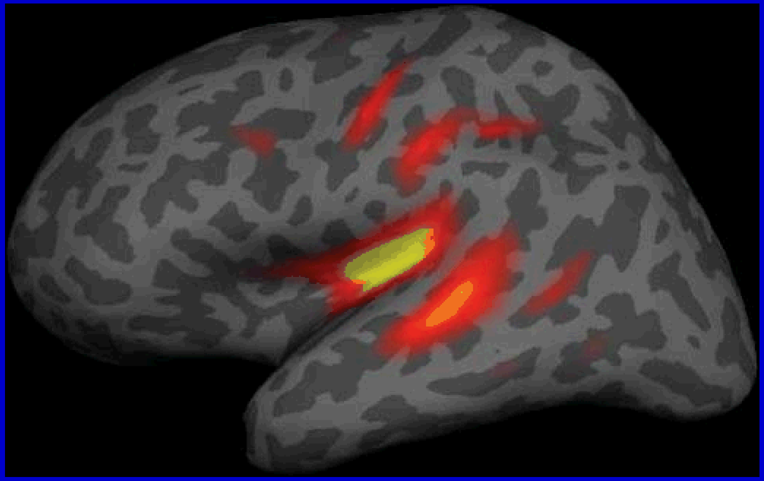
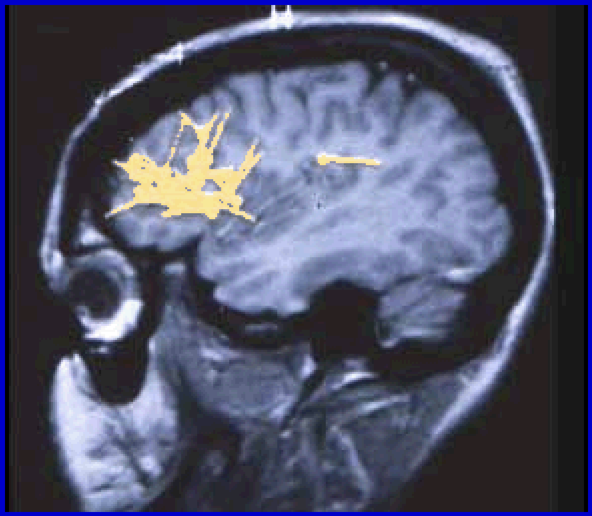
What is MEG?

- Uses
  - Understand spatial/temporal brain function.
  - Study psychological/neurological disorders.
  - Localize a pathology (e.g. epilepsy).







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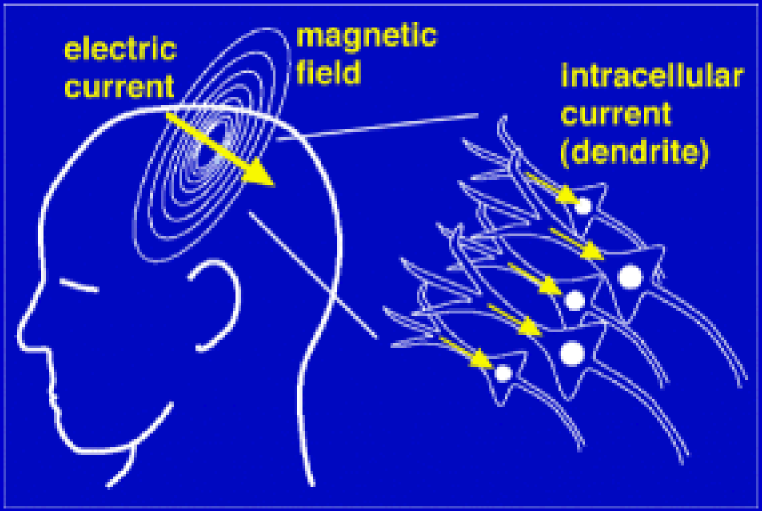
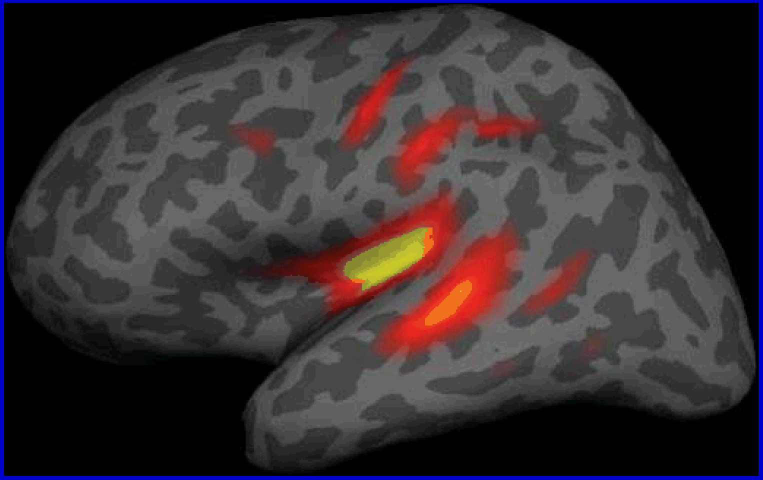
MEG is inherently hard.

- Signal frequencies < 100 Hz
- Signal strength ~100 fT (Earth's field ~50 μT)
- Requirements:
  - Magnetic shielding
  - Ultra-sensitive magnetometers





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Current instruments are large and expensive.

- Superconducting Quantum Interference Devices (SQUIDs):
  - High sensitivity: 2-3 $fT/Hz^{1/2}$
  - High bandwidth (~kHz)
  - Whole head coverage (> 300 channels)
- Disadvantages: Need for liquid helium.
  - Large instrument
    - Requires a magnetically shielded *room* (~$1M).
    - Not portable.
  - Liquid helium is expensive (>$50k per year)…
  - …and sources are unreliable.
  - Helmet is fixed.
    - Design to fit large heads; lose signal for smaller heads.

Elekta Neuromag®.
(Million-dollar shielded room sold separately.)

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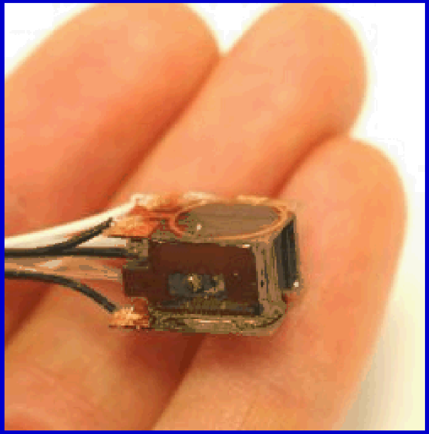
The potential of MEG has not been fully realized.

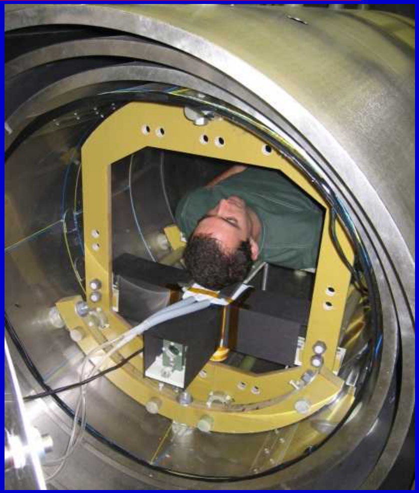
Optically Pumped Magnetometers are sensitive enough for MEG.

OPM advantages:

- No cryogens
  - Smaller
  - Closer to head
  - Cheaper shield
  - Portable or wearable?
- Reconfigurable arrays are possible
  - Fit any head size, e.g. infants
  - Larger signals
  - Adaptable, e.g. for magnetocardiography



NIST Miniature Magnetometer



Princeton OPM MEG System

QuSpin Inc. OPM

Challenges:

- Reaching high enough sensitivity…
- …with acceptable bandwidth (100 Hz).
- Must cancel residual fields.
- Sensor position and sensitive axis are not fixed.
- Need 150 °C vapor cell close to the head.
- Sensor gains may vary and drift.

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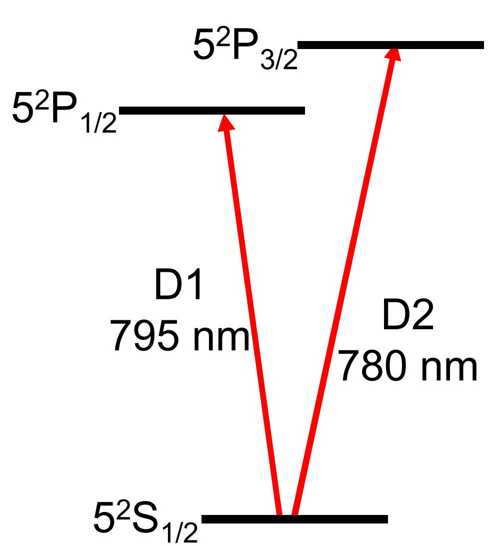
Two-color pump/probe scheme

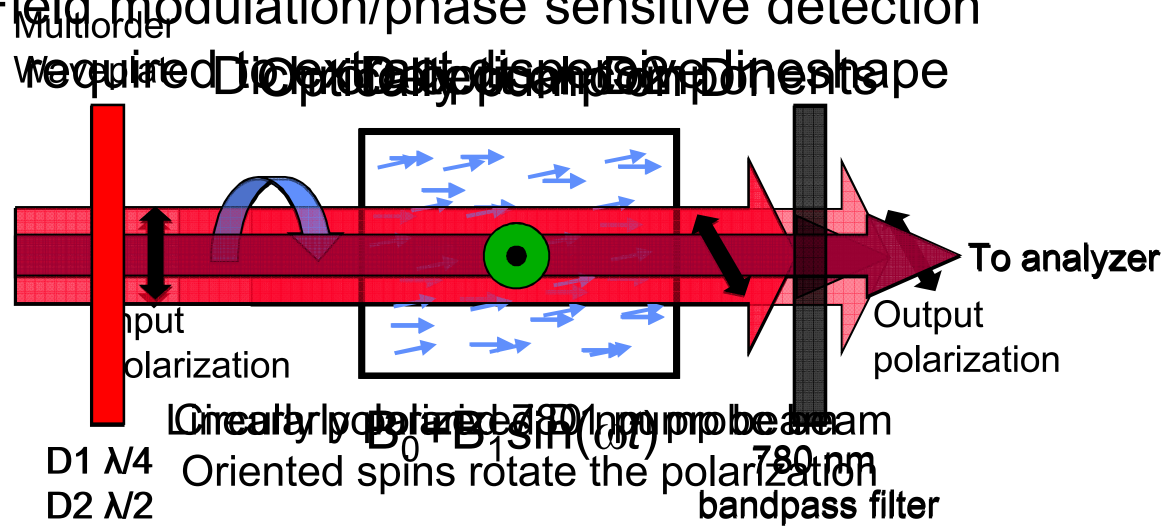
Single beam laser design but pumping and probing functions are separated into two different beams

- 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

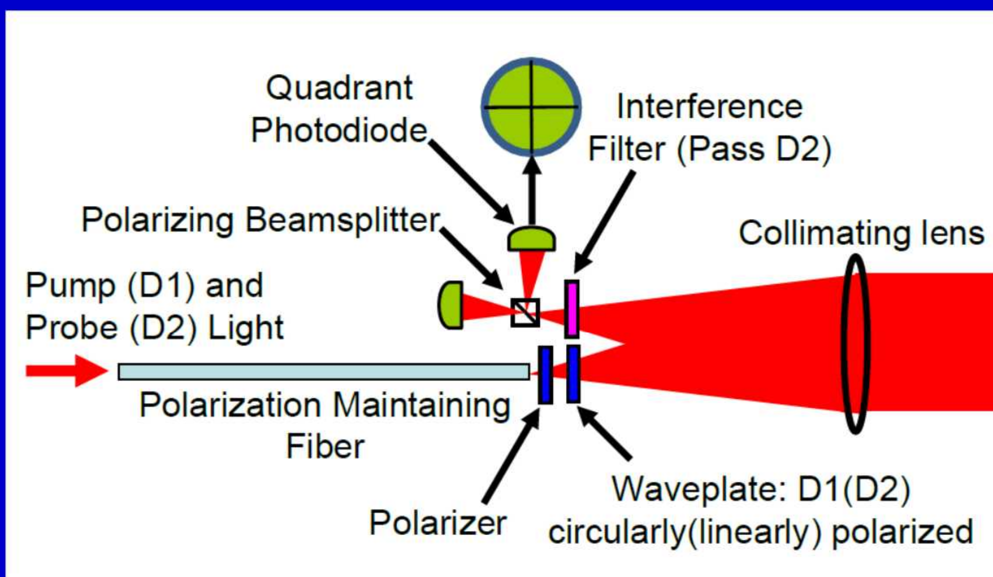


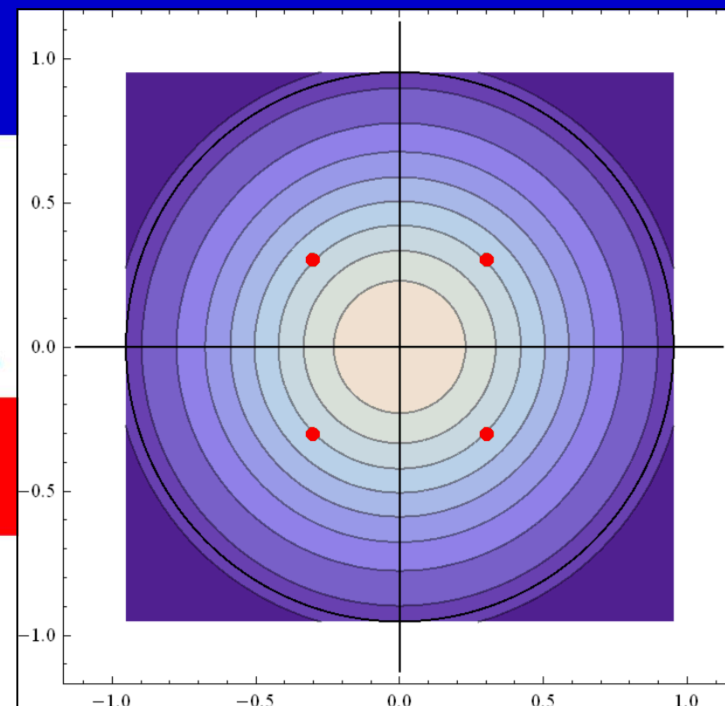
Field modulation/phase sensitive detection required to extract dispersive lineshape



1^{st} 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

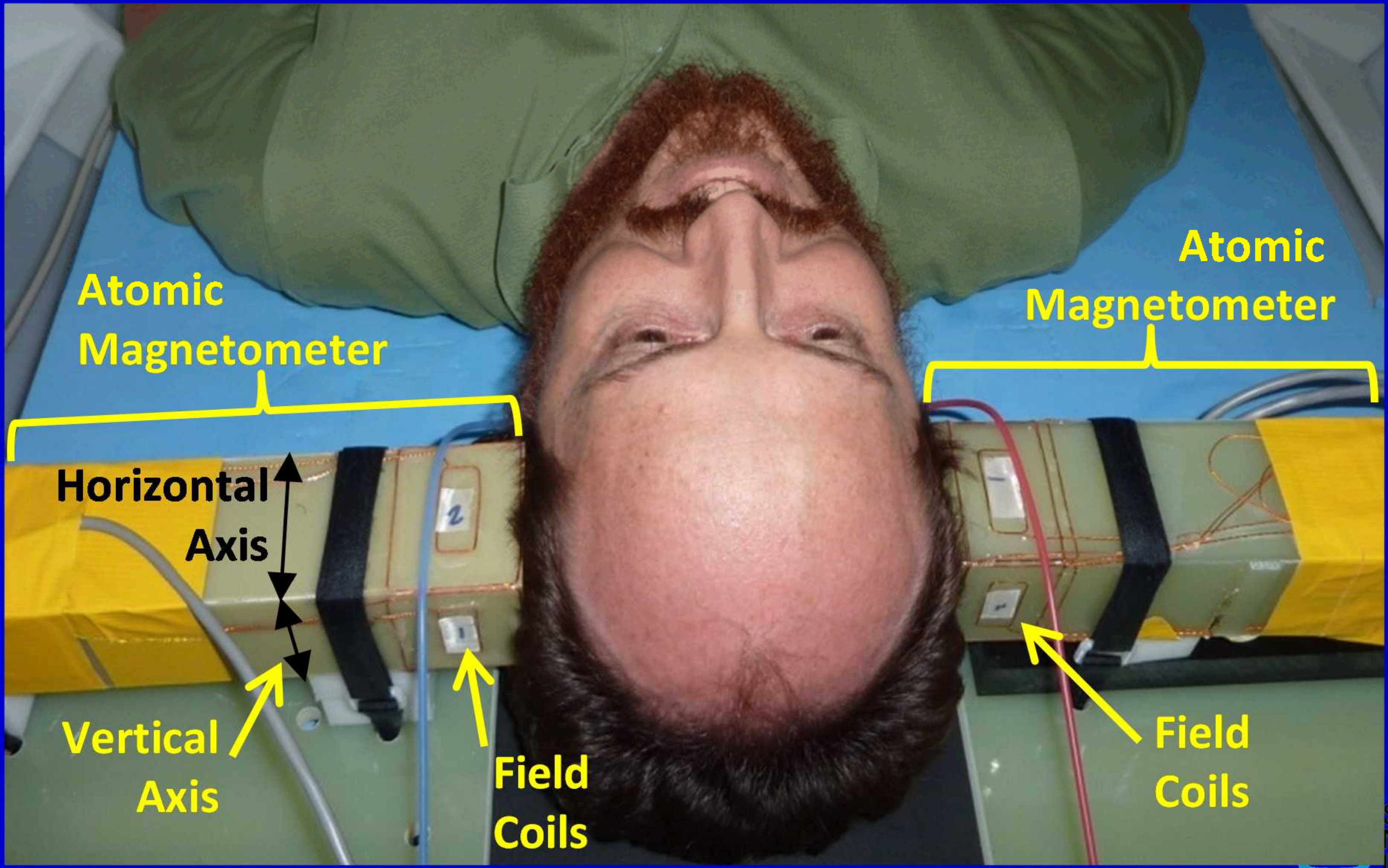




Distance between vapor cell center and head: ~3 cm

Two Sensor MEG Measurements

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



Installation in the shielded room at MRN

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

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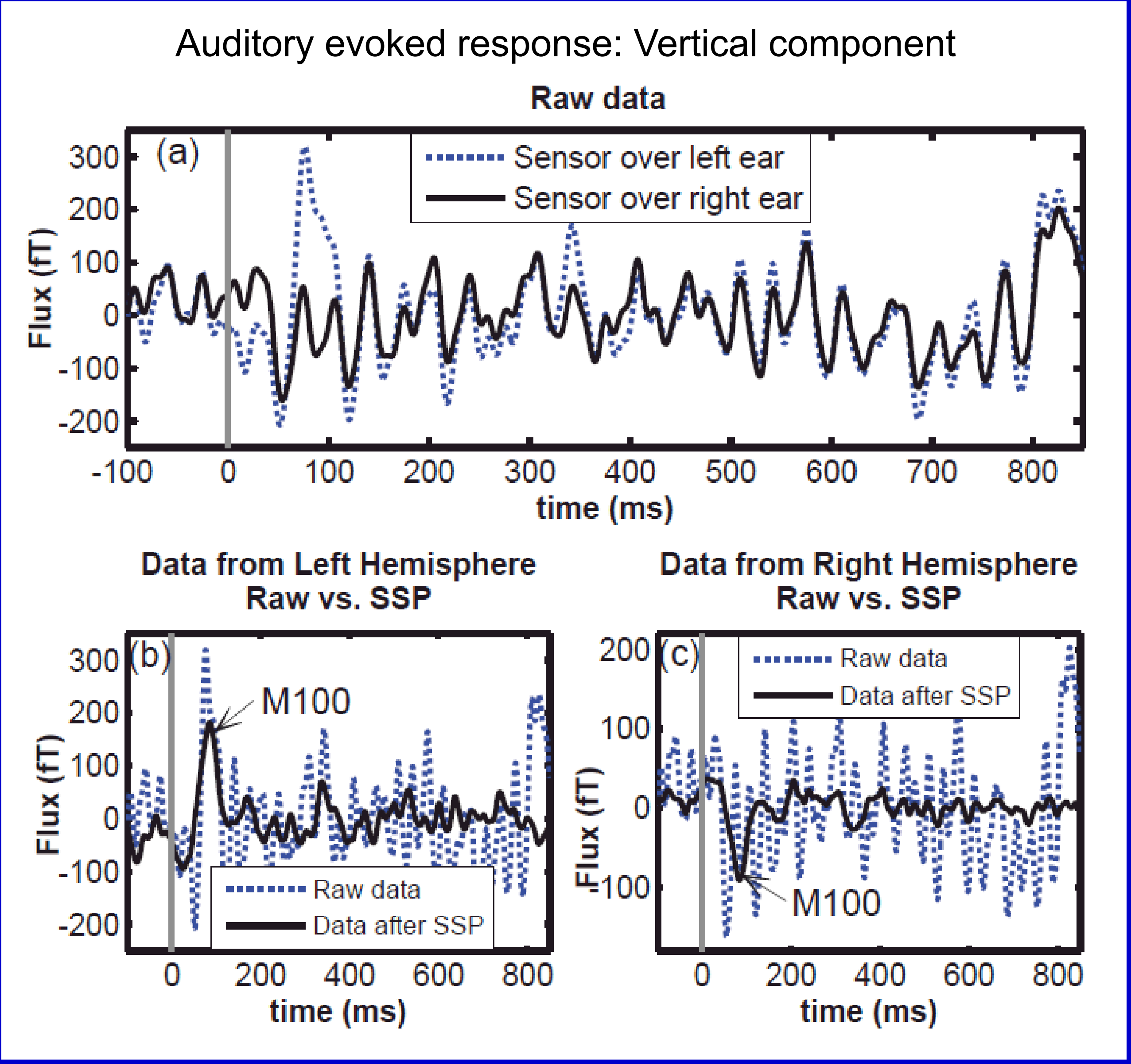
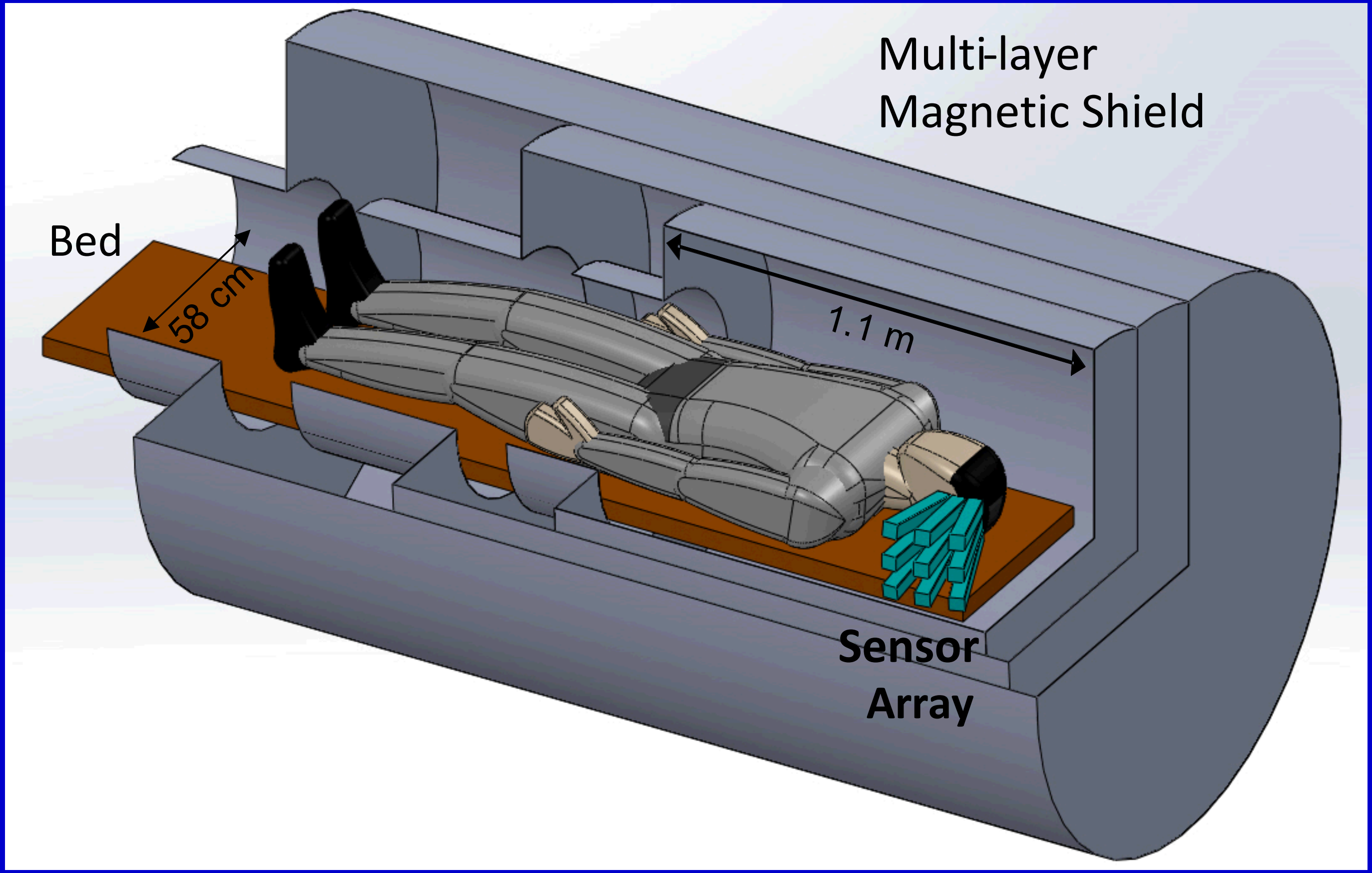
Two Sensors: Noise Cancellation

- 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.
- C.N. Johnson, P.D.D. Schwindt, and M. Weisend, *Phys. Med. Biol.* **58** 6065 (2013).



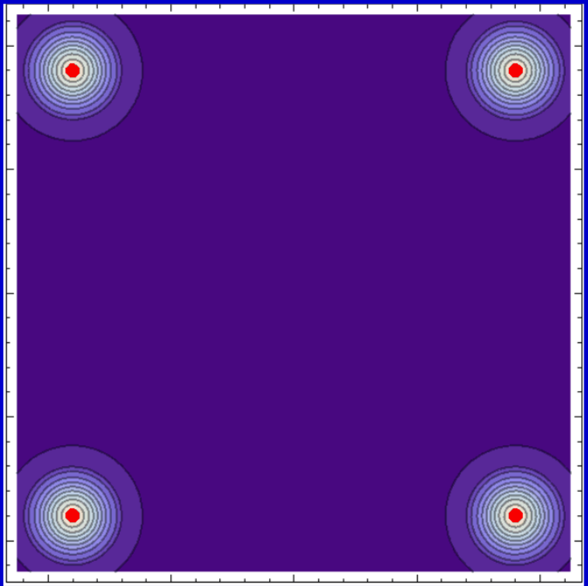
Towards a Complete MEG System

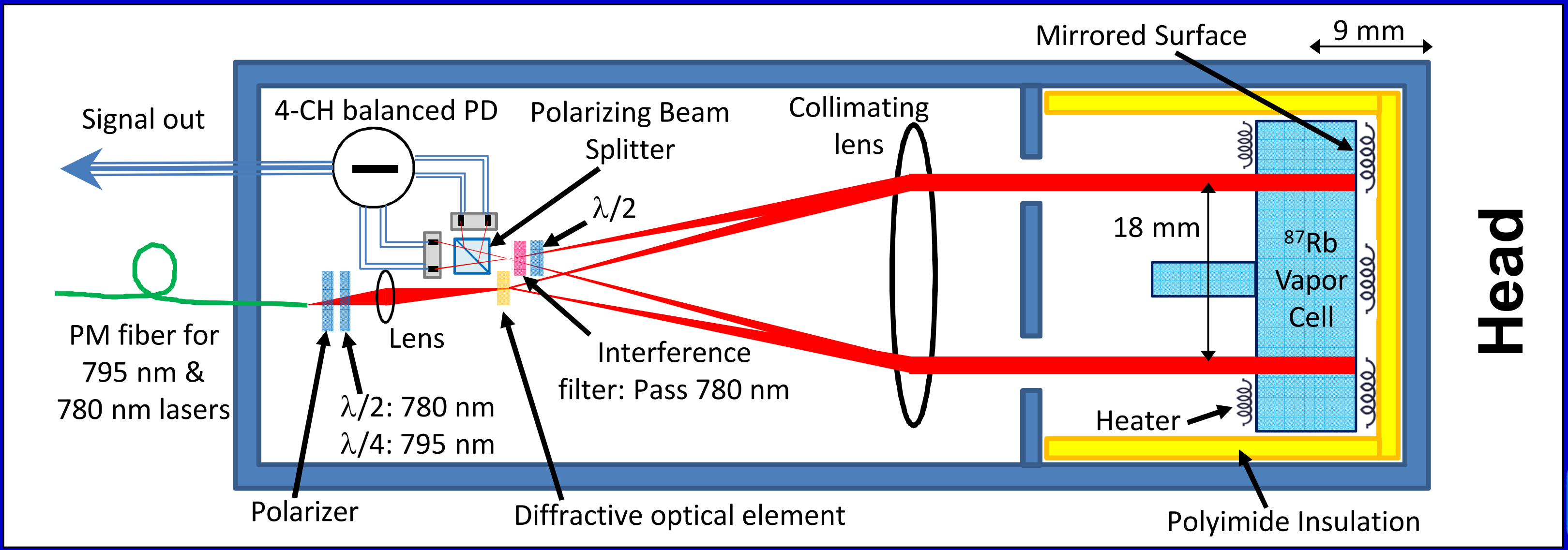
- 36 channel OPM array, reconfigurable (position, head size)
- Human-sized shield, cheaper/smaller installation (expected shielding factor > 16,000)
- Compare OPM and SQUID recordings of human subjects



2nd 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: 19 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





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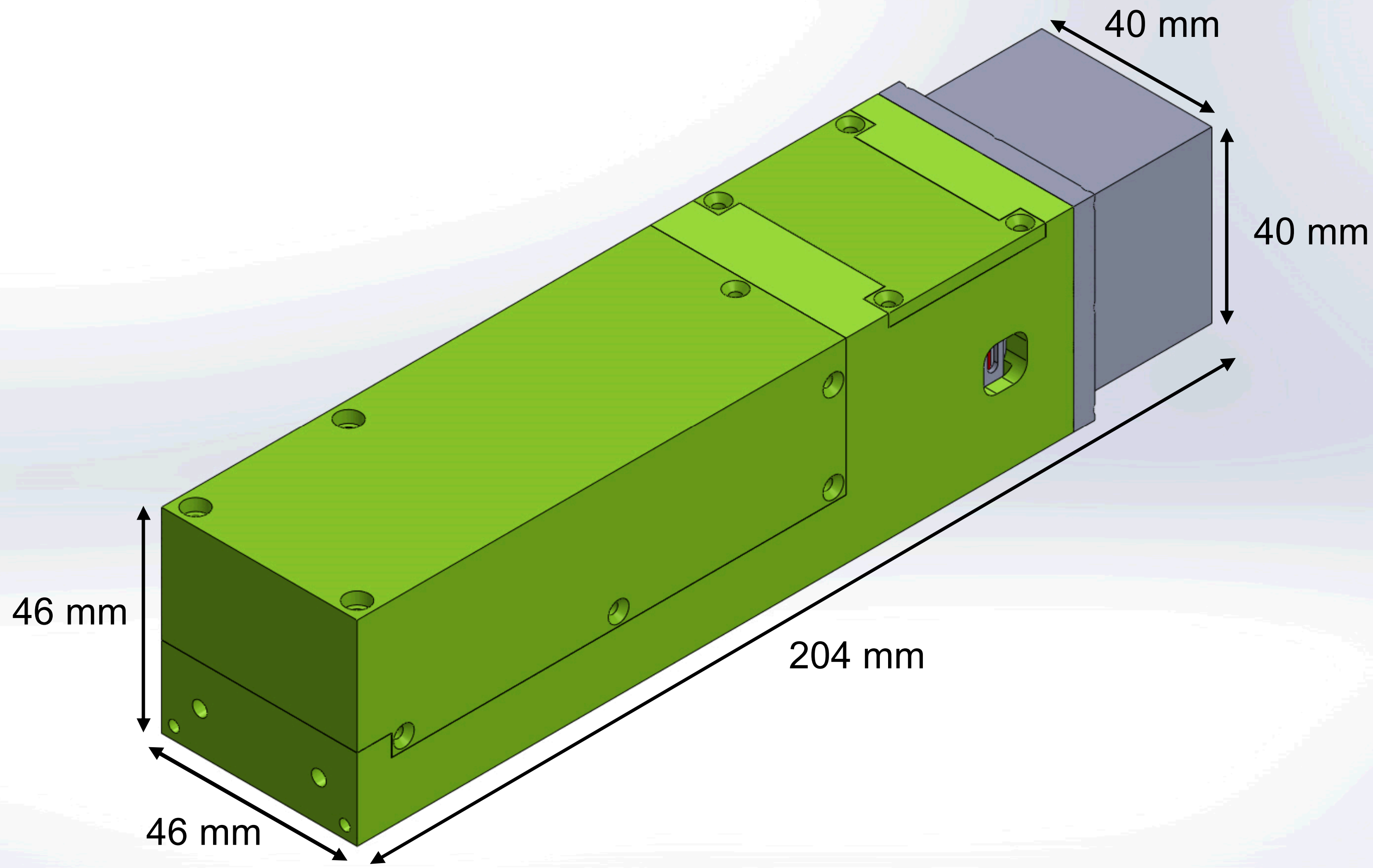
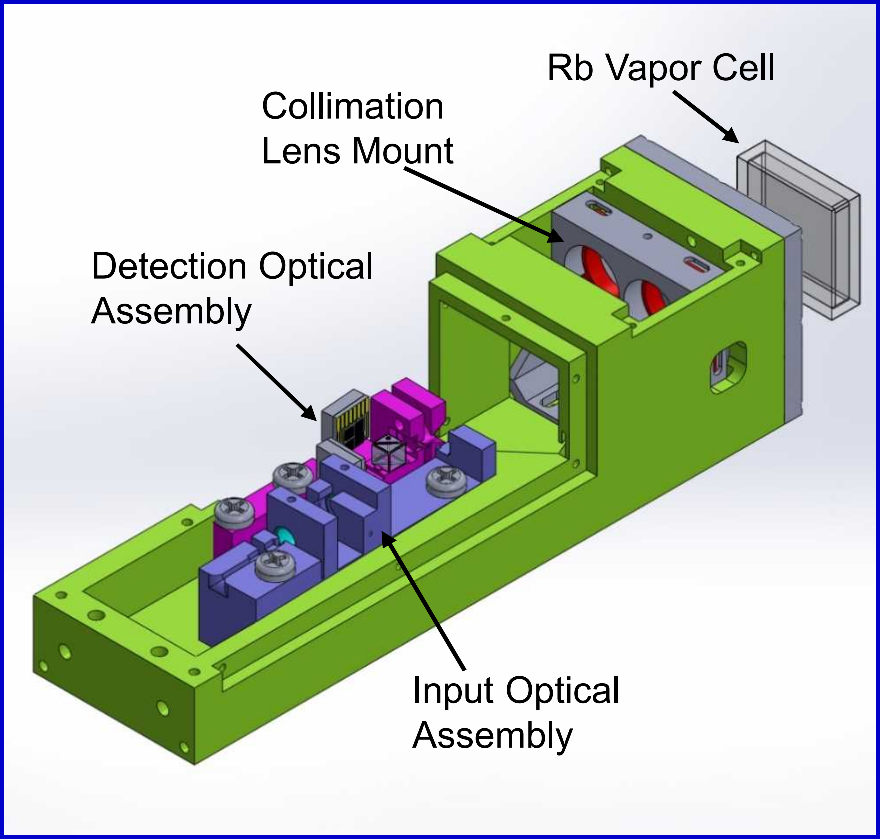
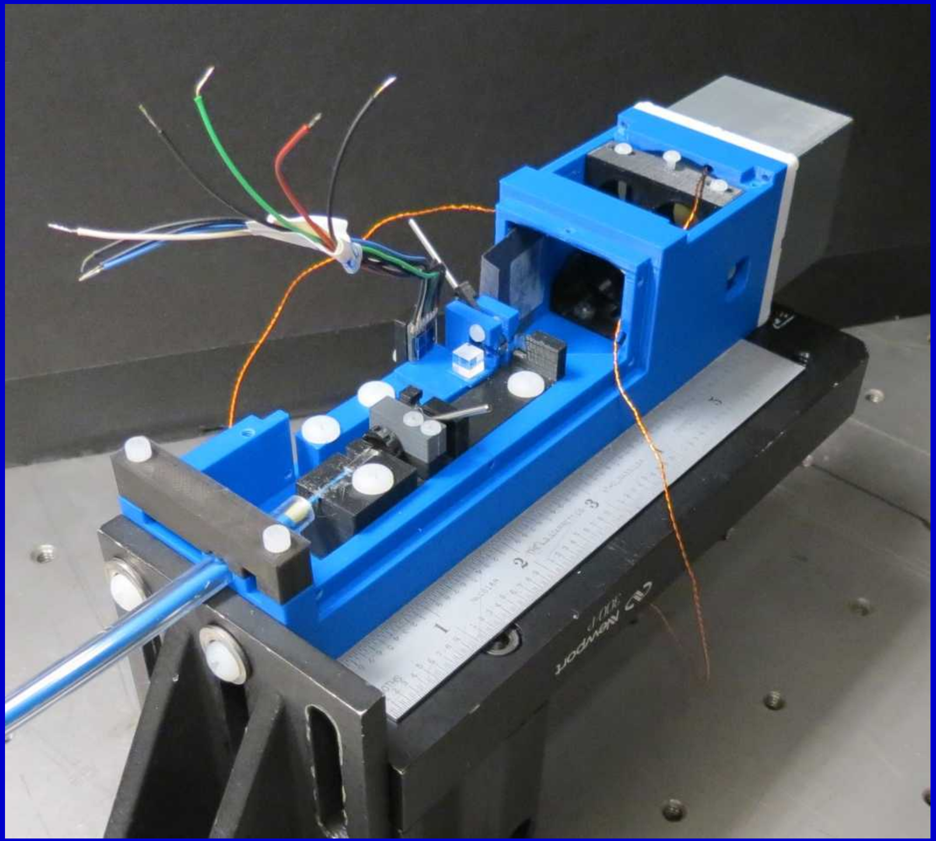
2nd Generation Sensor Design



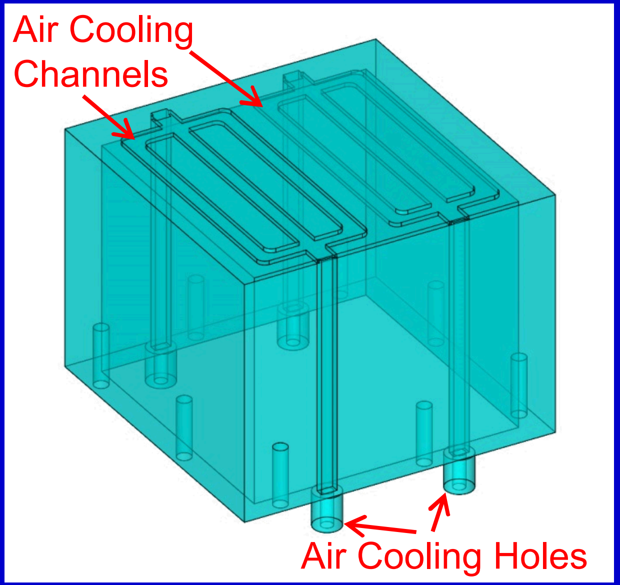
2nd Generation Sensor Design

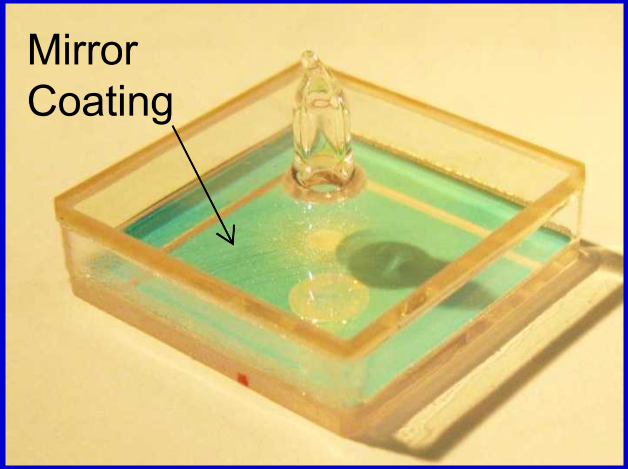


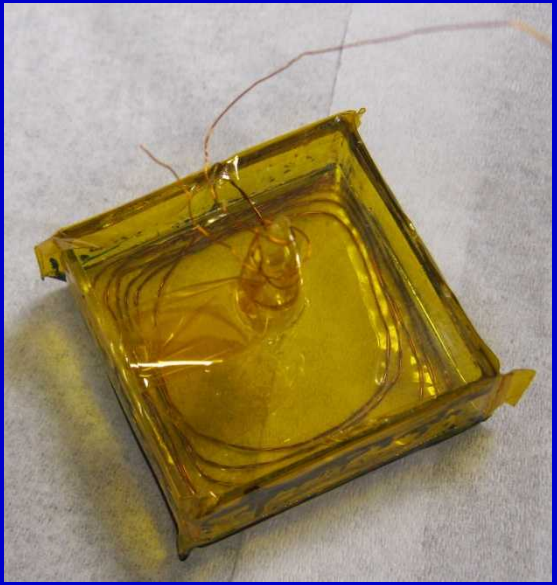


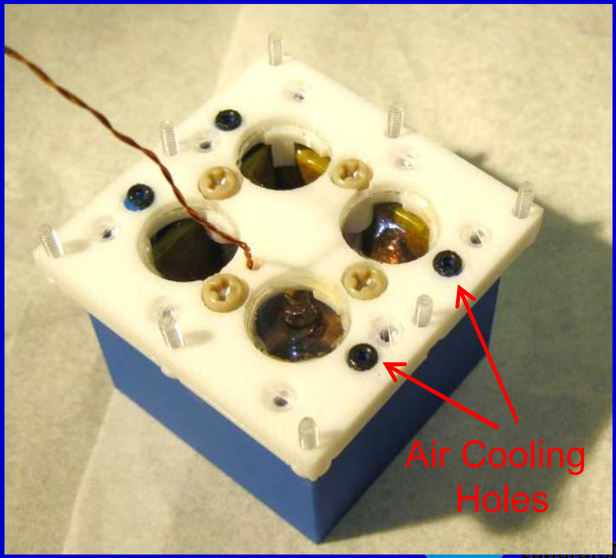
Vapor Cell and Oven

- Vapor cell inner dimensions: 4 mm x 25 mm x 25 mm
- Cell material: Fused silica fails. Try Pyrex.
- Heater: twisted pair of phosphor-bronze wire
- Oven: 3D-printed ABS and polycarbonate plastic

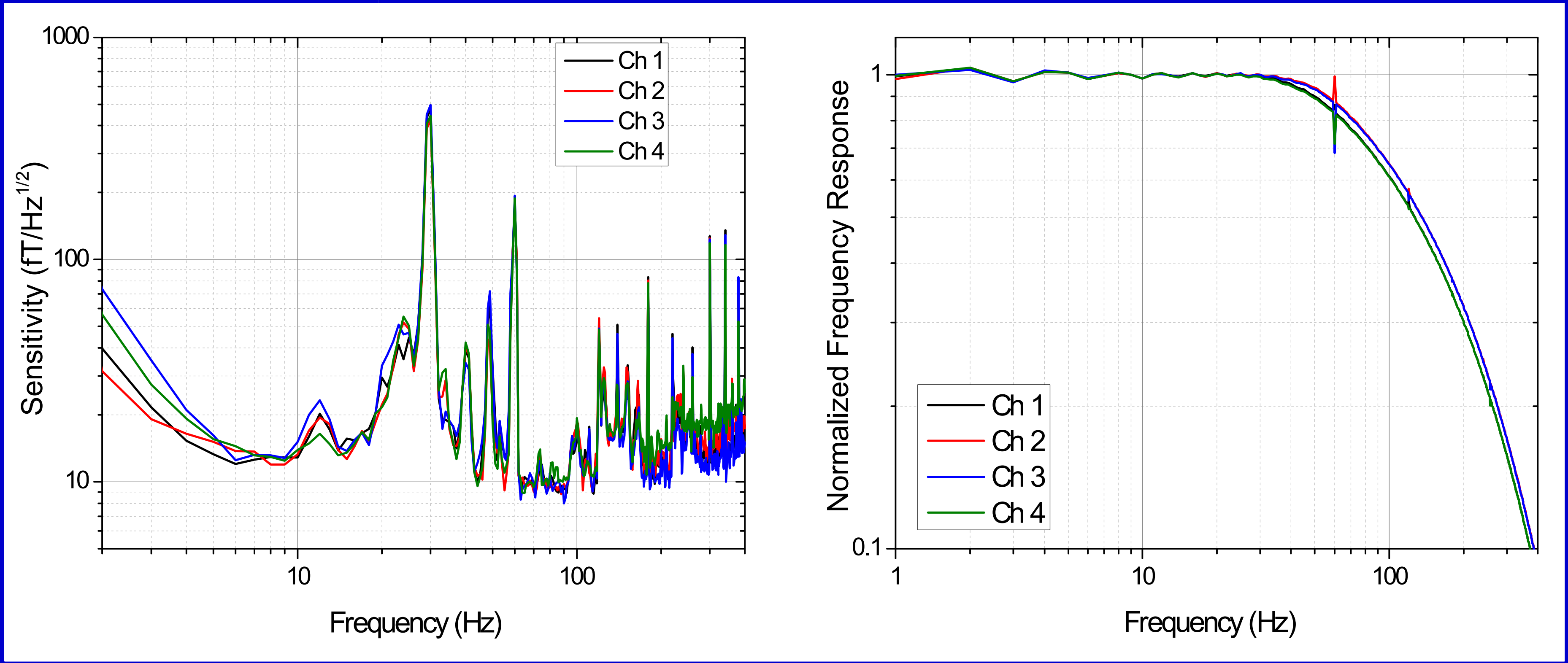








Prototype Performance: 4 Channels



- 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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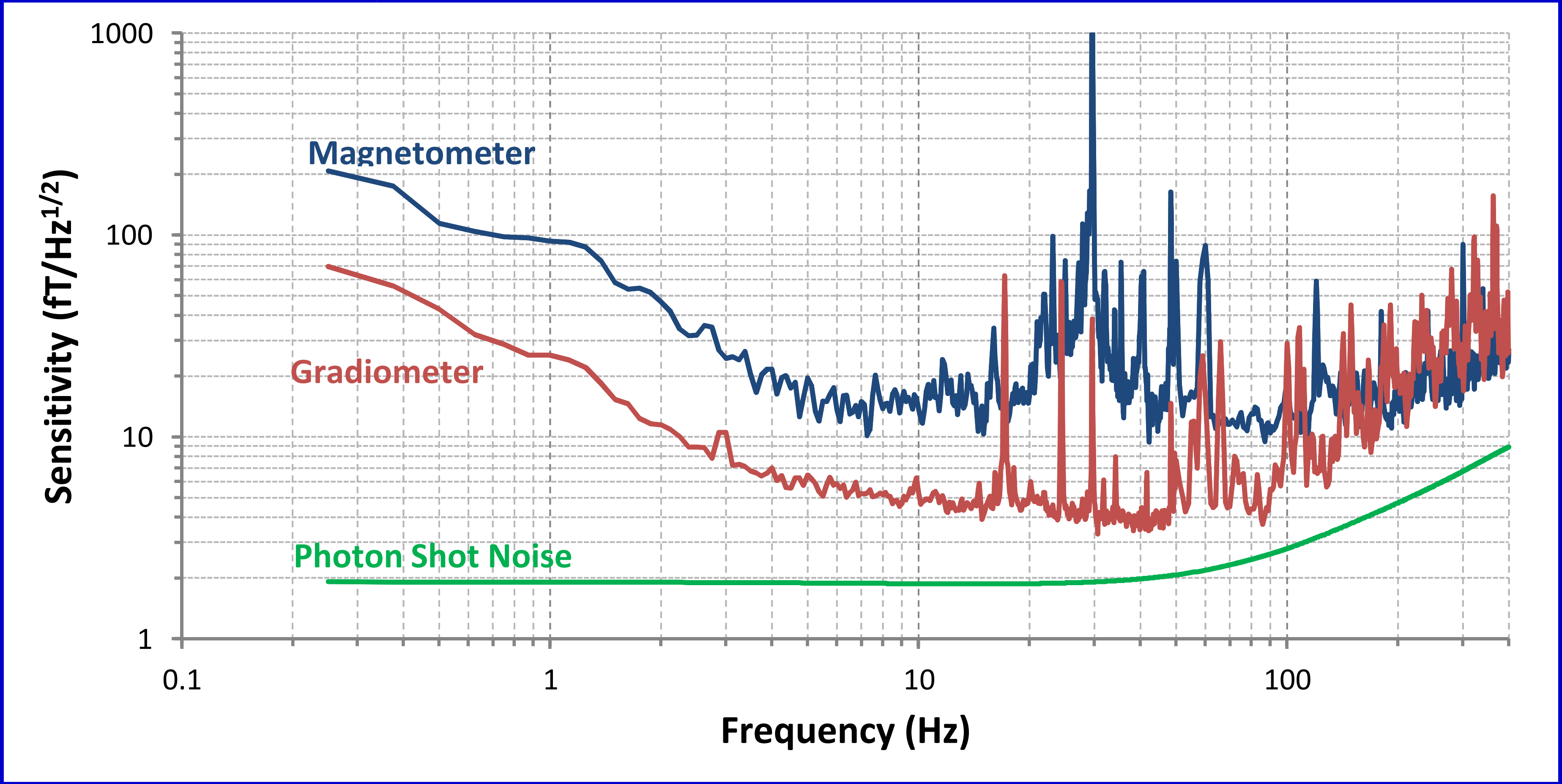
Gradiometer Performance



- 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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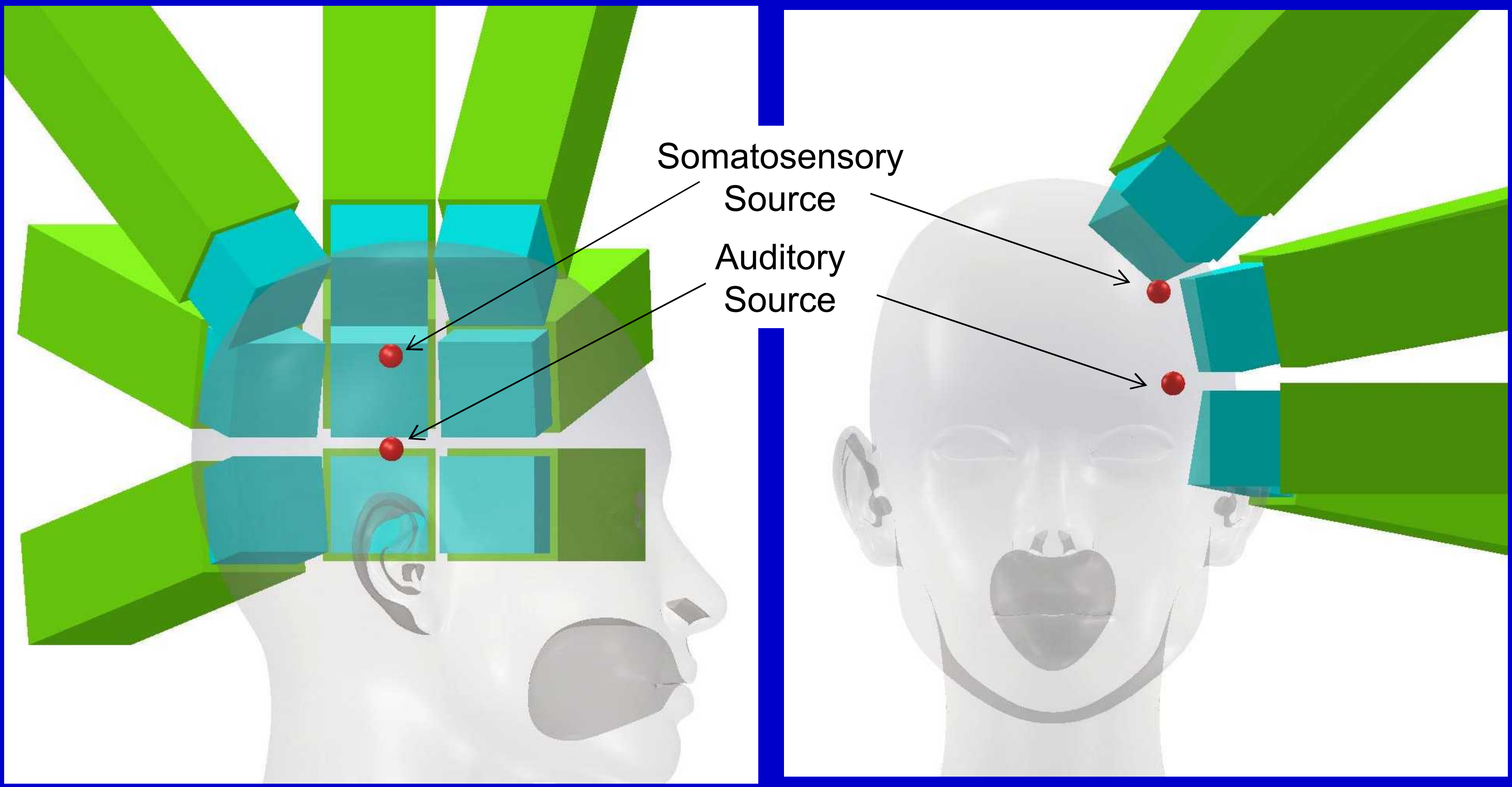
36-Channel Array on the Head



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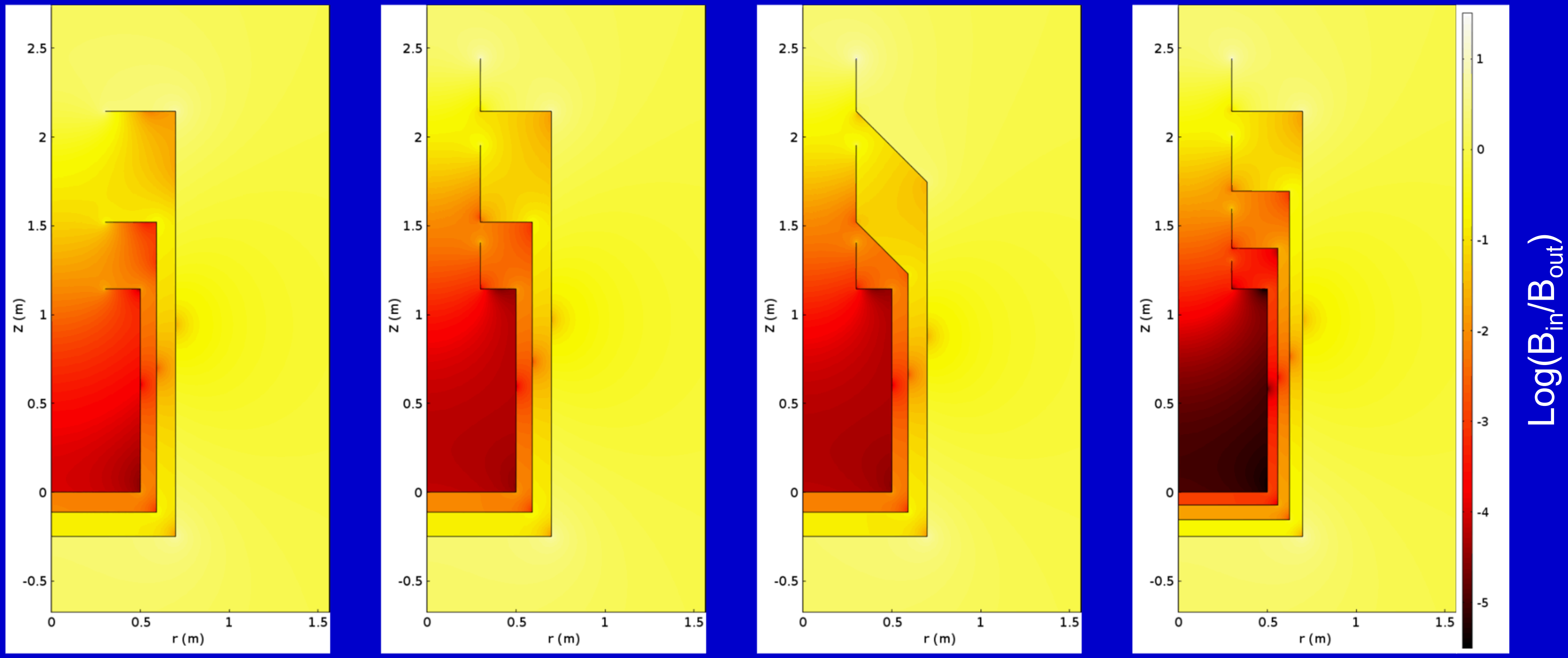
Magnetic Shield Modeling

3-Layer Cylinder | 3-Layer Cylinder with tubes | 3-Layer Cylinder with Chamfer | 4-Layer Cylinder with tubes



- Focused mainly on longitudinal shielding (transverse shielding much better)
- Asymmetric shield design with tubes leads to larger area of uniform field

- Permeability = 40,000
- Thickness = 1/16”

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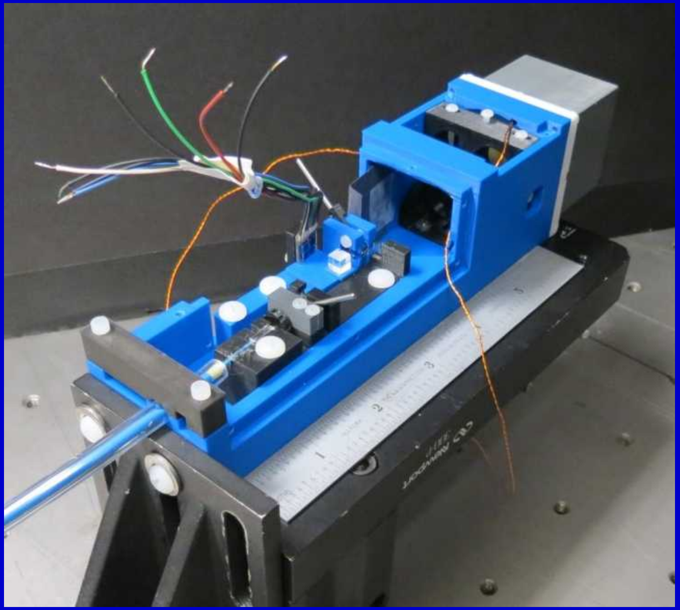
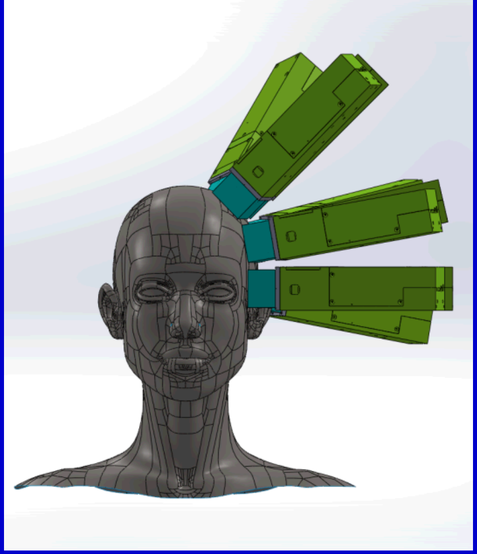
Conclusion

- Successfully measured MEG signals
  - Two 4-channel sensors
- Constructed our first 2^{nd} generation sensor
  - 18 mm channel separation
  - <5 $fT/Hz^{1/2}$ sensitivity
- Three-layer shield designed and installed
- Working 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 (Wright State Research Institute), Jim McKay (Candoo Systems), John Mosher (Cleveland Clinic), Bruce Fisch (UNM School of Medicine), Mind Research Network
- Funding:

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

NATIONAL INSTITUTES OF HEALTH

NIBIB National Institute of Biomedical Imaging and Bioengineering

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Backup

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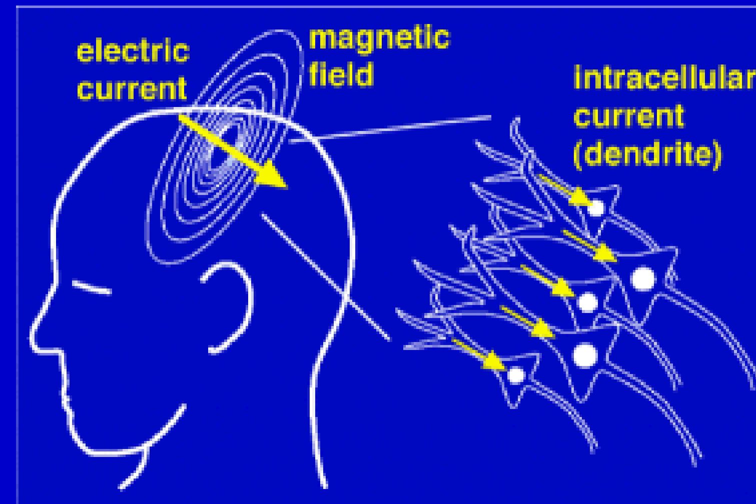
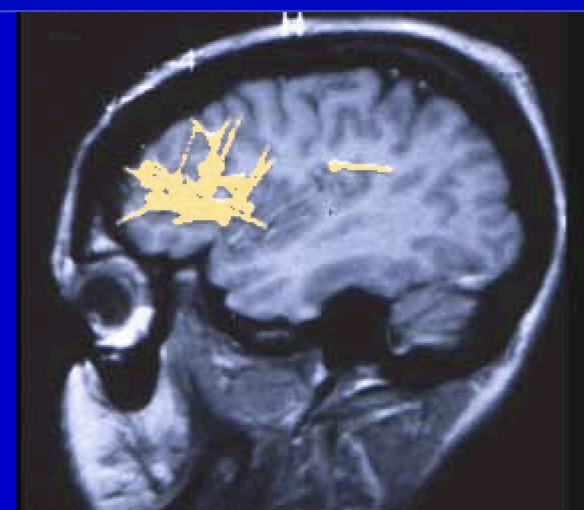
Magnetoencephalography (MEG)

- Detects magnetic fields produced by neural currents in the brain.
  - Non-invasive
  - 100 fT signals, <100 Hz
- Sub-centimeter spatial and millisecond 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 DOE 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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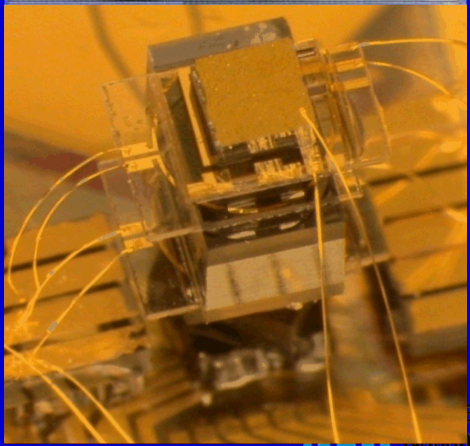
Current Technology

Superconducting Quantum Interference Devices (SQUIDs)

- Mature technology
  - Highly sensitive, 2-3 fT / $Hz^{1/2}$
  - Whole head coverage (> 300 channels)
- Disadvantages
  - Require cryogenic cooling
  - Large and power hungry
  - $$$ → ~150systems worldwide
  - Fixed head size



Atomic Magnetometer Potential

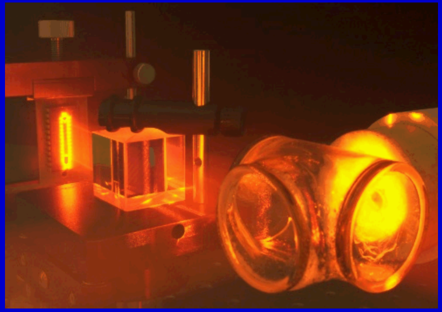
- Record sensitivity of 160 aT / $Hz^{1/2}$ (Romalis, Princeton) **arXiv:0910.2206v1 [physics.atom-ph] 12 Oct 2009**
- Vast improvement in size and portability.
- Sensor closer to the source

Motivation

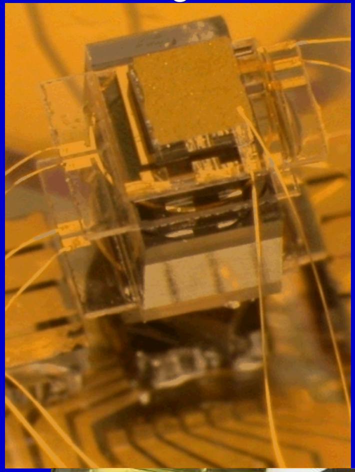
- Early 2000's, high sensitivity demonstrated with atomic magnetometers (AMs)
  - 0.5 $fT/Hz^{1/2}$
  - I. K. Kominis, T. W. Kornack, J. C. Allred, and M. V. Romalis. Nature **422**, 596 (2003).
- Chip-scale atomic magnetometers demonstrated.
  - Small size and low power
  - 70 $fT/Hz^{1/2}$
  - V. Shah,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

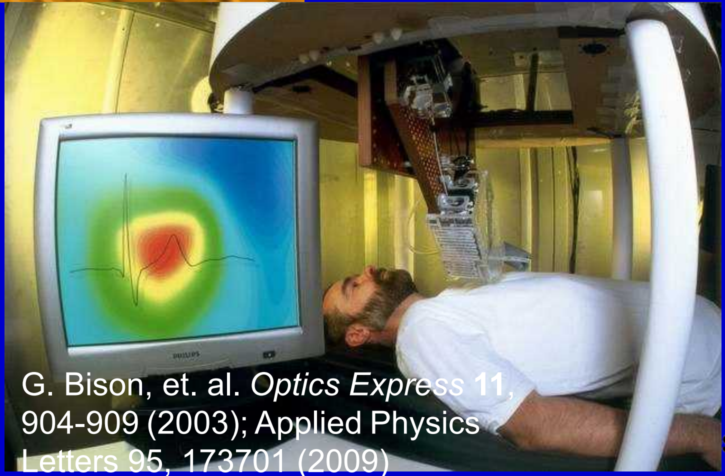
- What should we do with these new high sensitivity magnetometer?
- Biomagnetic applications
  - Magnetocariography
  - Magnetoencephalography
  - Magnetic Nanoparticles
- Geomagnetism
  - Rock magnetometer

Princeton SERF magnetometer



NIST Chip-Scale Atomic Magnetometer





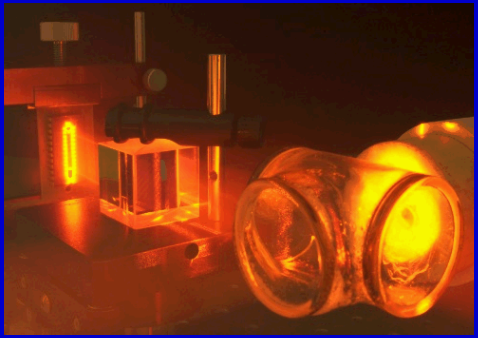
G. Bison, et. al. *Optics Express* **11**, 904-909 (2003); Applied Physics Letters 95, 173701 (2009)

Optically Pumped Magnetometers for MEG

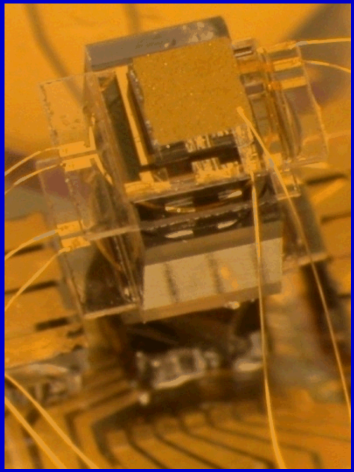
Potential Improvements for MEG
- No cryogenic cooling
  - OPM needs to be heated
- Much smaller instrument size
  - Leads to a smaller magnetic shield
  - Transportable system
- Reconfigurable array is possible
  - Small sensor size
  - Accommodate head sizes ranging from infants to adults
  - Reconfigure 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

Princeton SERF magnetometer* 0.5 $fT/Hz^{1/2}$



NIST Chip-Scale Atomic Magnetometer** 70 $fT/Hz^{1/2}$



*I. K. Kominis, T. W. Kornack, J. C. Allred, and M. V. Romalis. Nature **422**, 596 (2003).
V. Shah, S. Knappe, P.D. Schwindt, and J. Kitching, *Nature Photonics* **1, 649-652 (2007).

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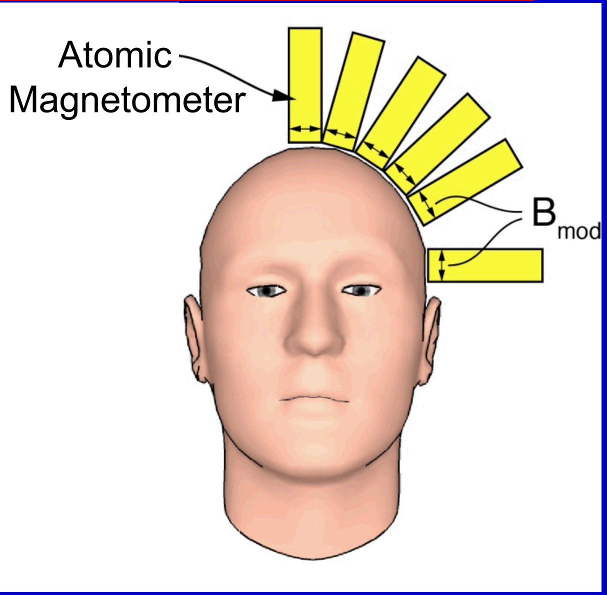
Sandia MEG Goals

Mimic SQUID MEG sensor

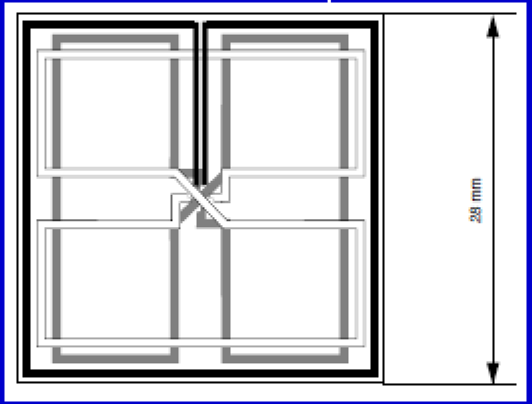
- Whole-head coverage: tailor sensor design for arrays
- Adequate sensitivity/bandwidth (<10 fT/Hz$^{1/2}$/100 Hz)
- Small footprint
- Eliminate free space laser beams (fiber coupled sensors)
- Gradiometric 2D output



Collaboration:

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

Elekta Triple Sensor Chip



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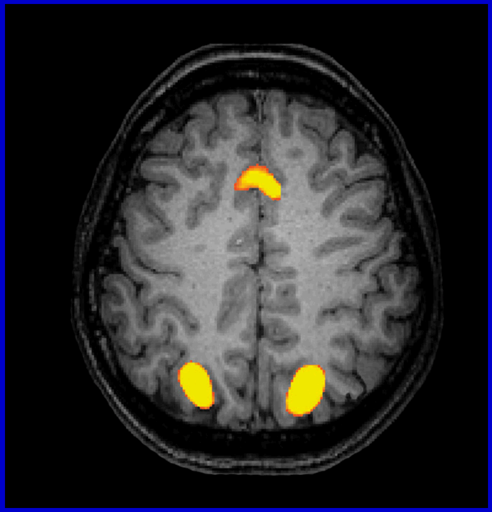
MEG offers excellent spatial and temporal resolution.

	EEG	MEG	fMRI
Spatial Resolution	**Poor** (~cm)	**Great** (~mm)	**Great** (~mm)
Temporal Resolution	**Great** (~ms)	**Great** (~ms)	**Poor** (~s)



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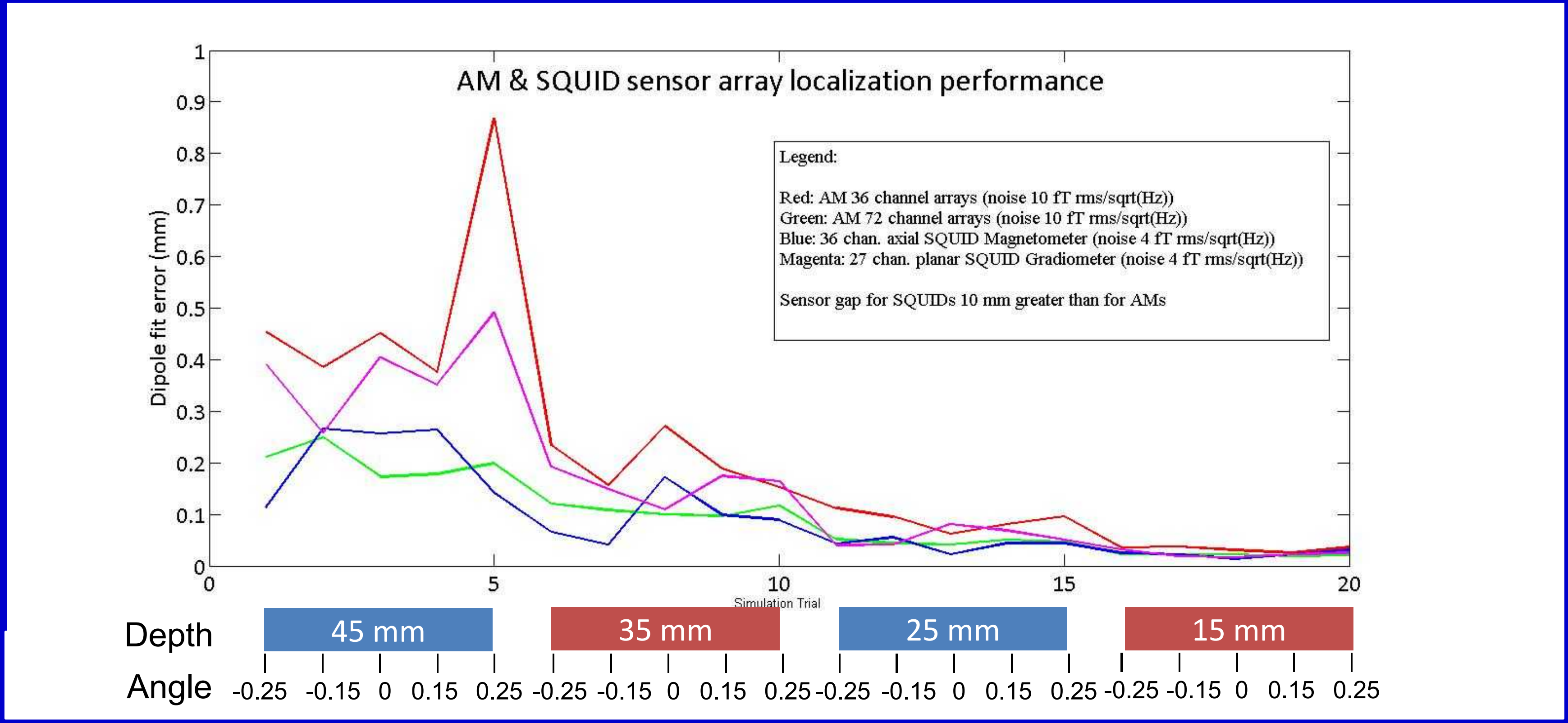
OPM Localization Performance Similar to SQUID sensors



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

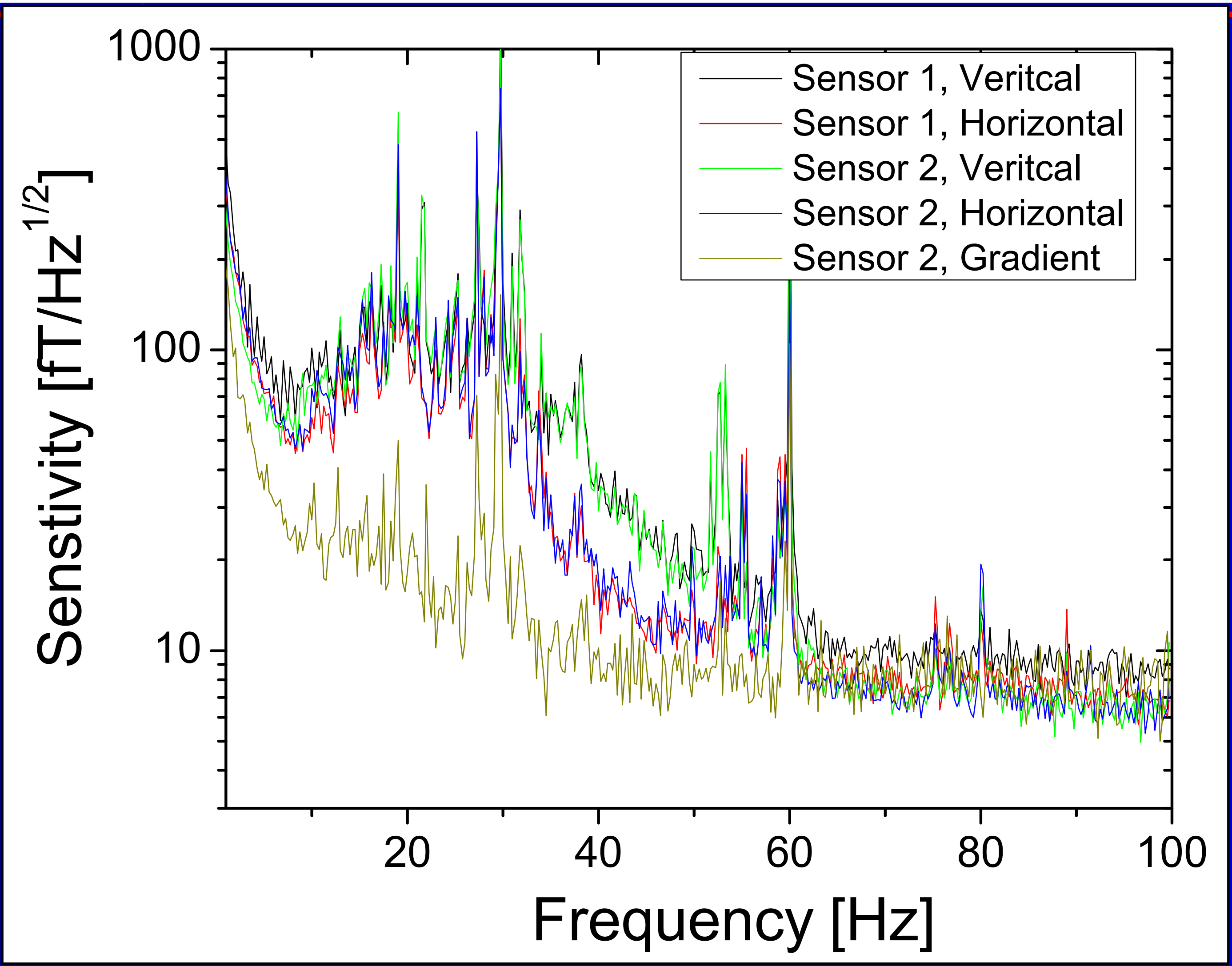
Current Technology

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

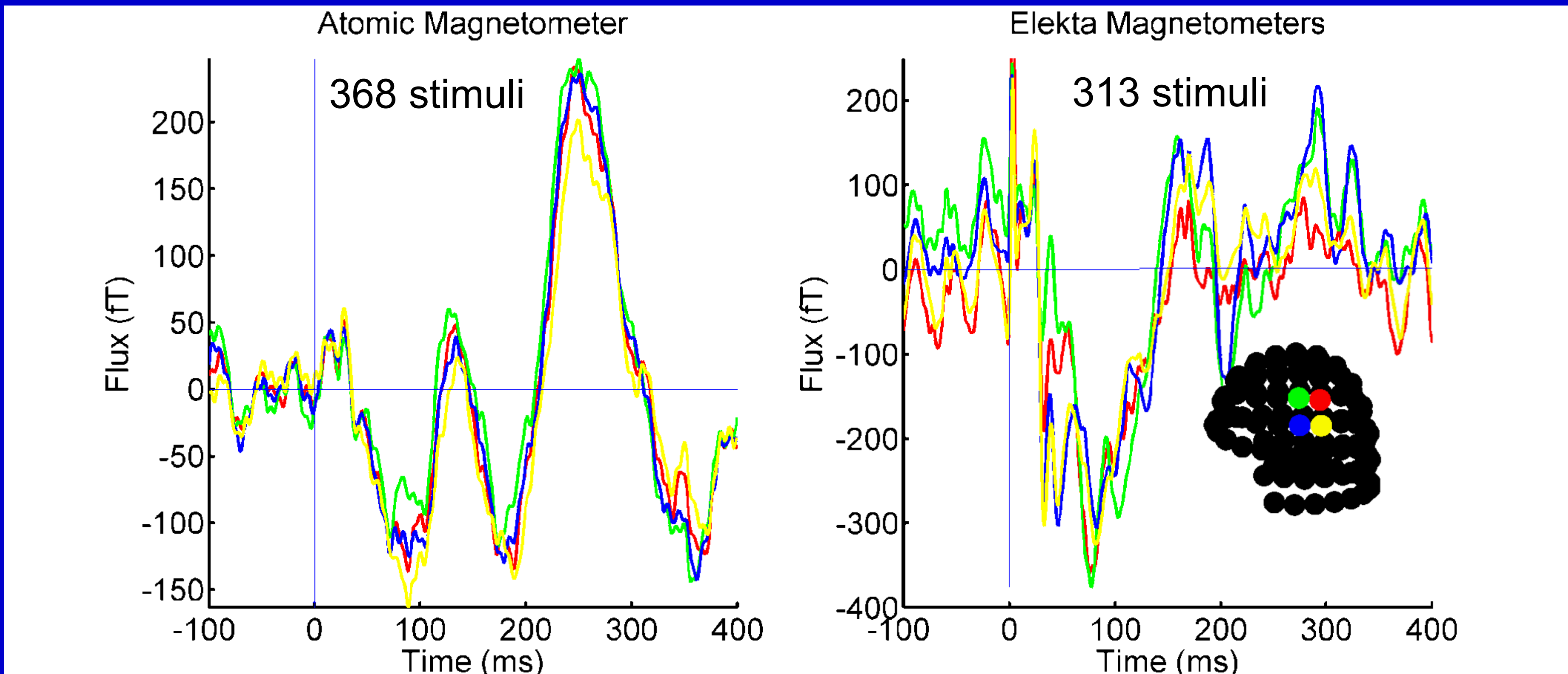
Noise in the Shielded Room



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

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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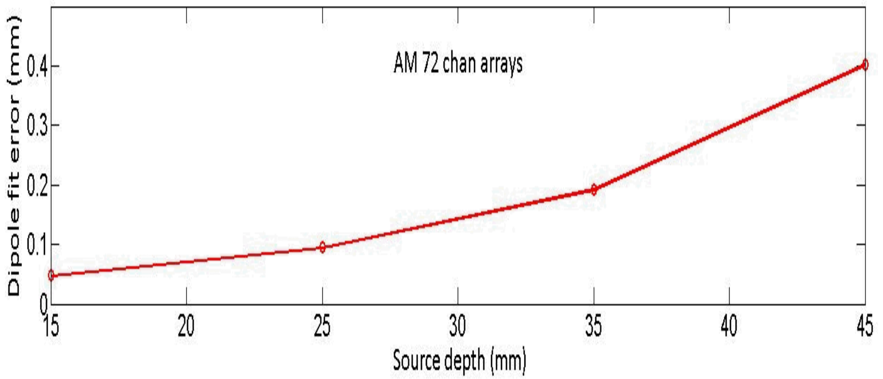
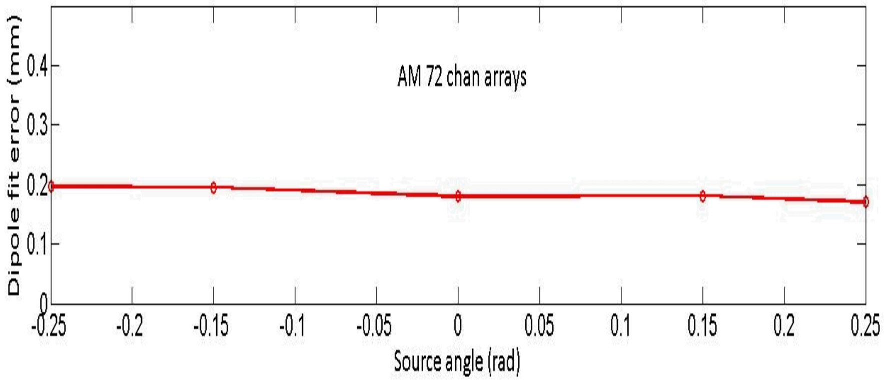
AM Localization Performance vs Source Depth and Array Offset



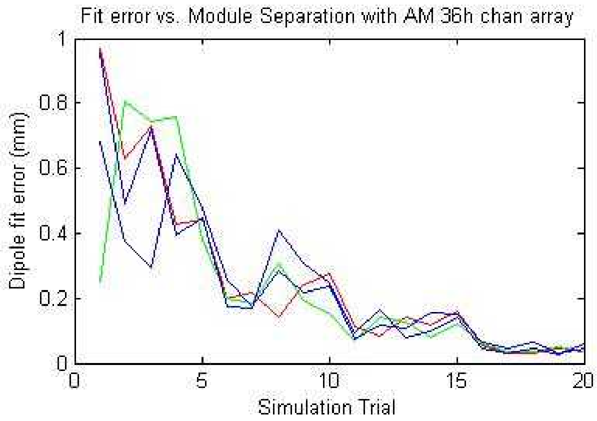
Error proportional to d^(2-3)

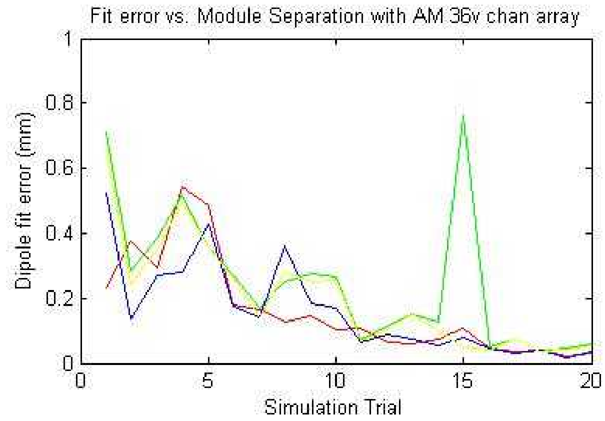
Average of 20 mm & 14 mm sensor spacing options, 20 source locations, and 4 sensor gaps

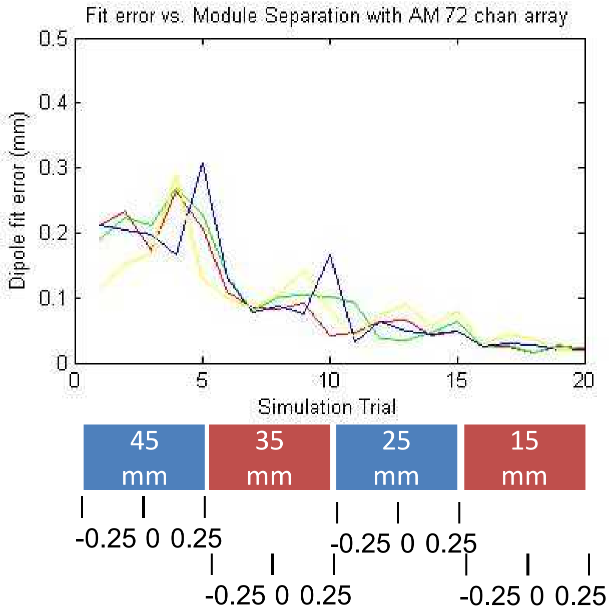


Error indep. of source elevation angle in this range, but convergence rate decreases sharply at >0.25 rad

AM Sensor module separation does not change localization error much



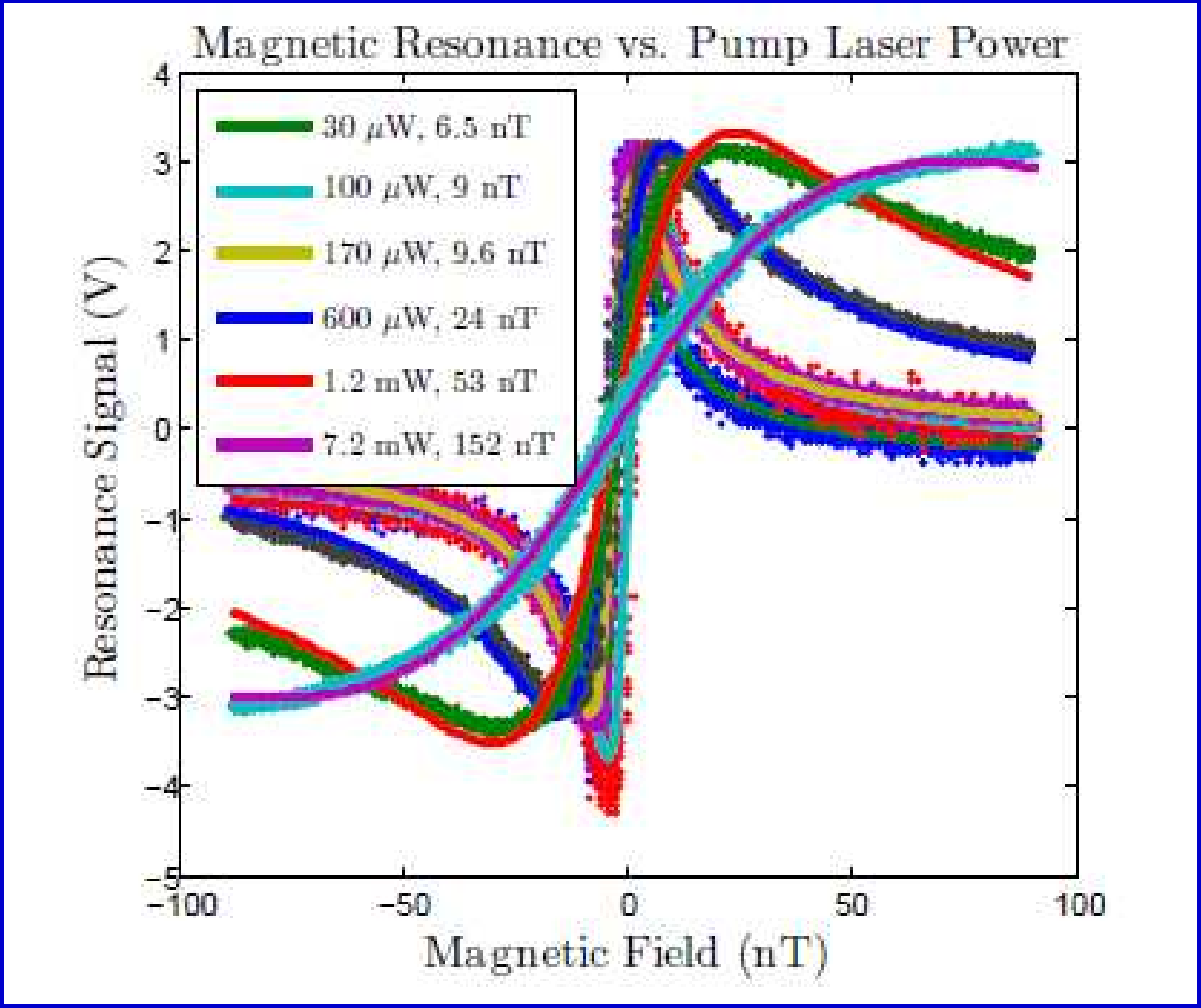




4 sensor module separations:
Red: 45 mm (closest possible)
Green: 49 mm
Blue: 53 mm
Yellow: 63 mm

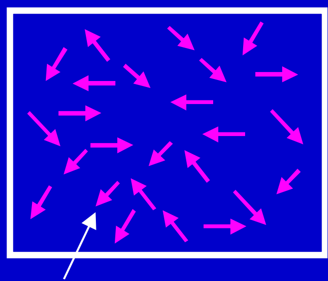
For 20 mm sensor separation

Typical Faraday Rotation Signal



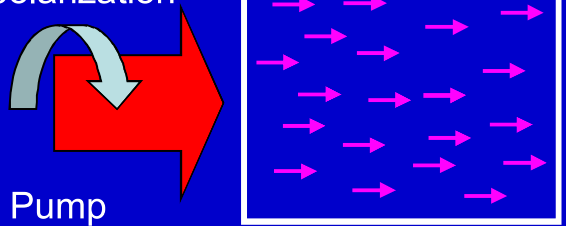
Atomic Magnetometer Basics

Alkali Vapor Cell



Randomly oriented atomic spins

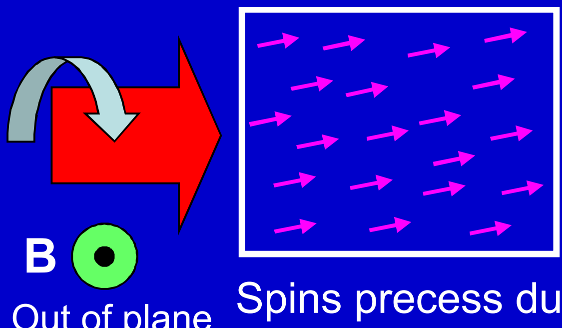
Optical pumping



Spins align with the pump beam

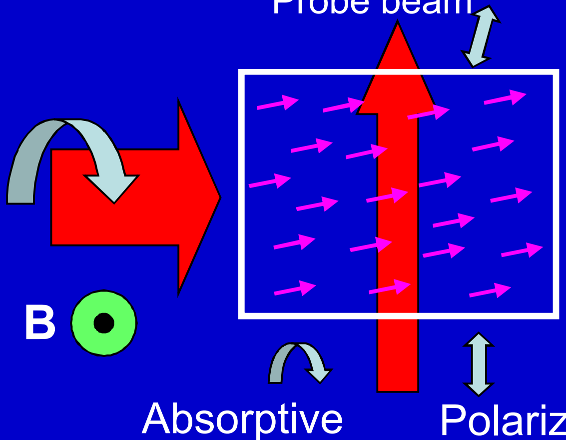
*D. Budker, *et al. Phys. Rev. A* **62**, 043403 (2000).

Apply Small Magnetic Field



Spins precess due to magnetic field

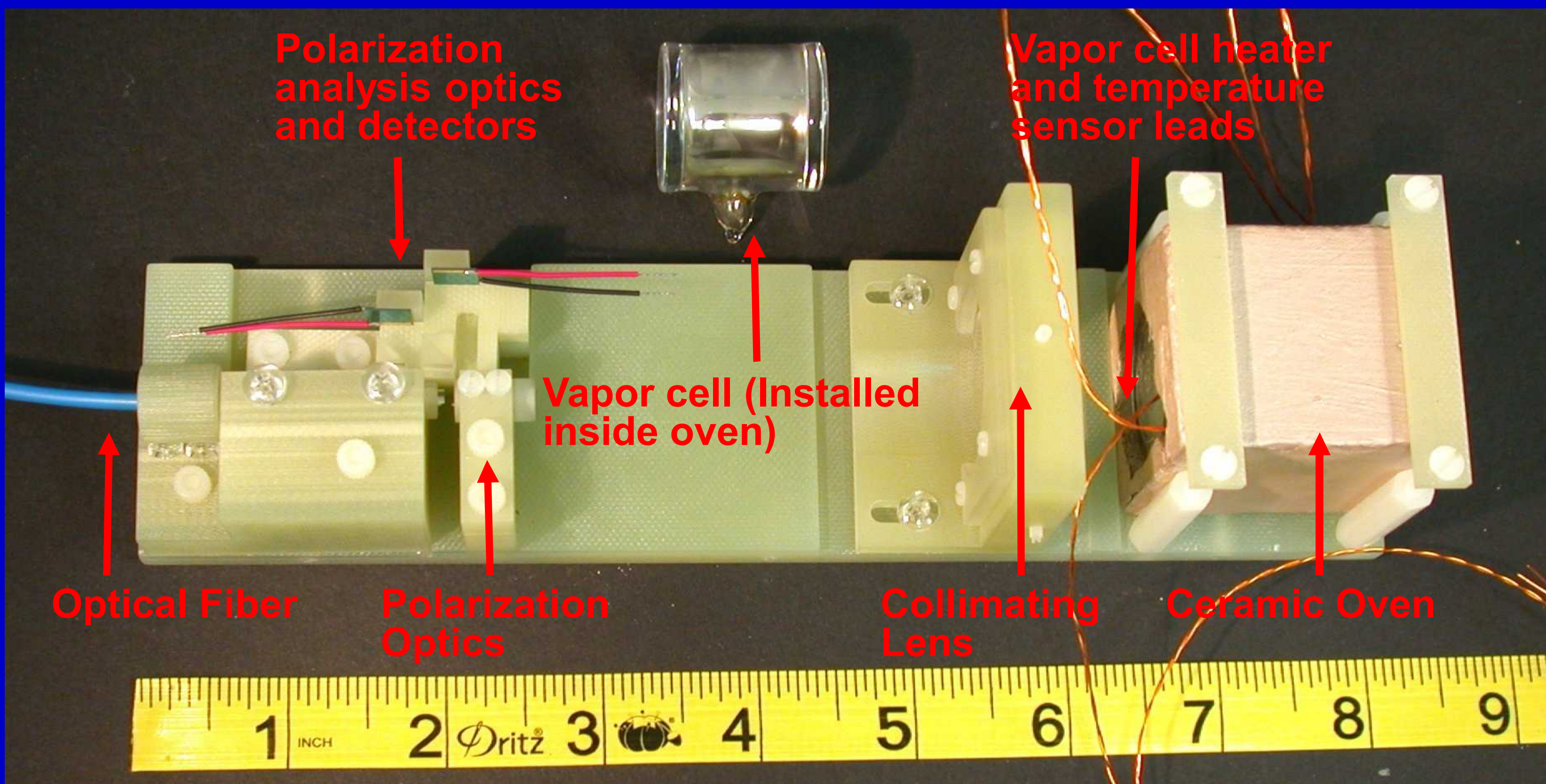
Detect with probe beam



Magnetometer Hardware

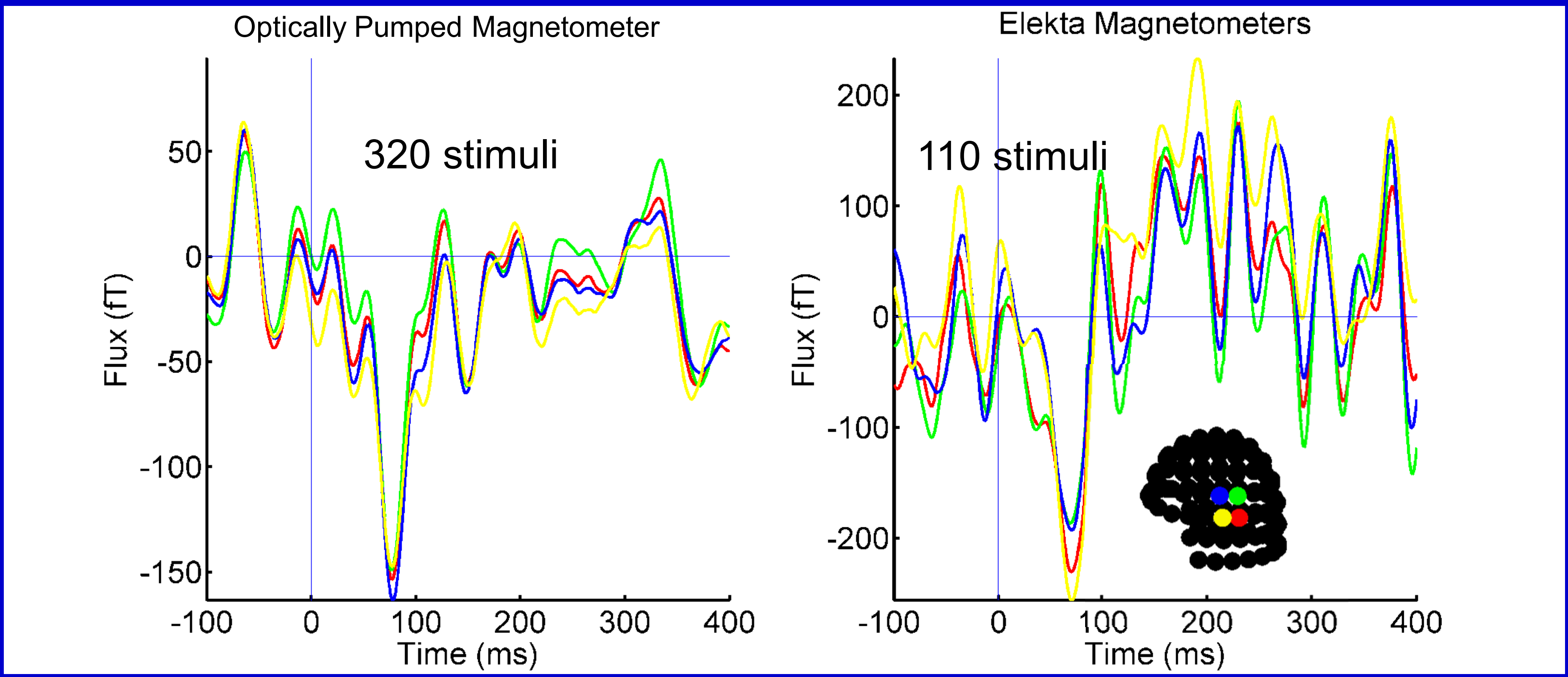
- Insulation: Microporous ceramic oven, vacuum enclosure
- Non-metallic materials: G-10 fiberglass, custom photodiode mounts

- Vapor cell
  - ~600 Torr He, 30 Torr N_2
  - Interior size: L = ¾” x ϕ = ¾”



Comparison of a Single 4-Channel OPM to the SQUIDs

Auditory Stimulation

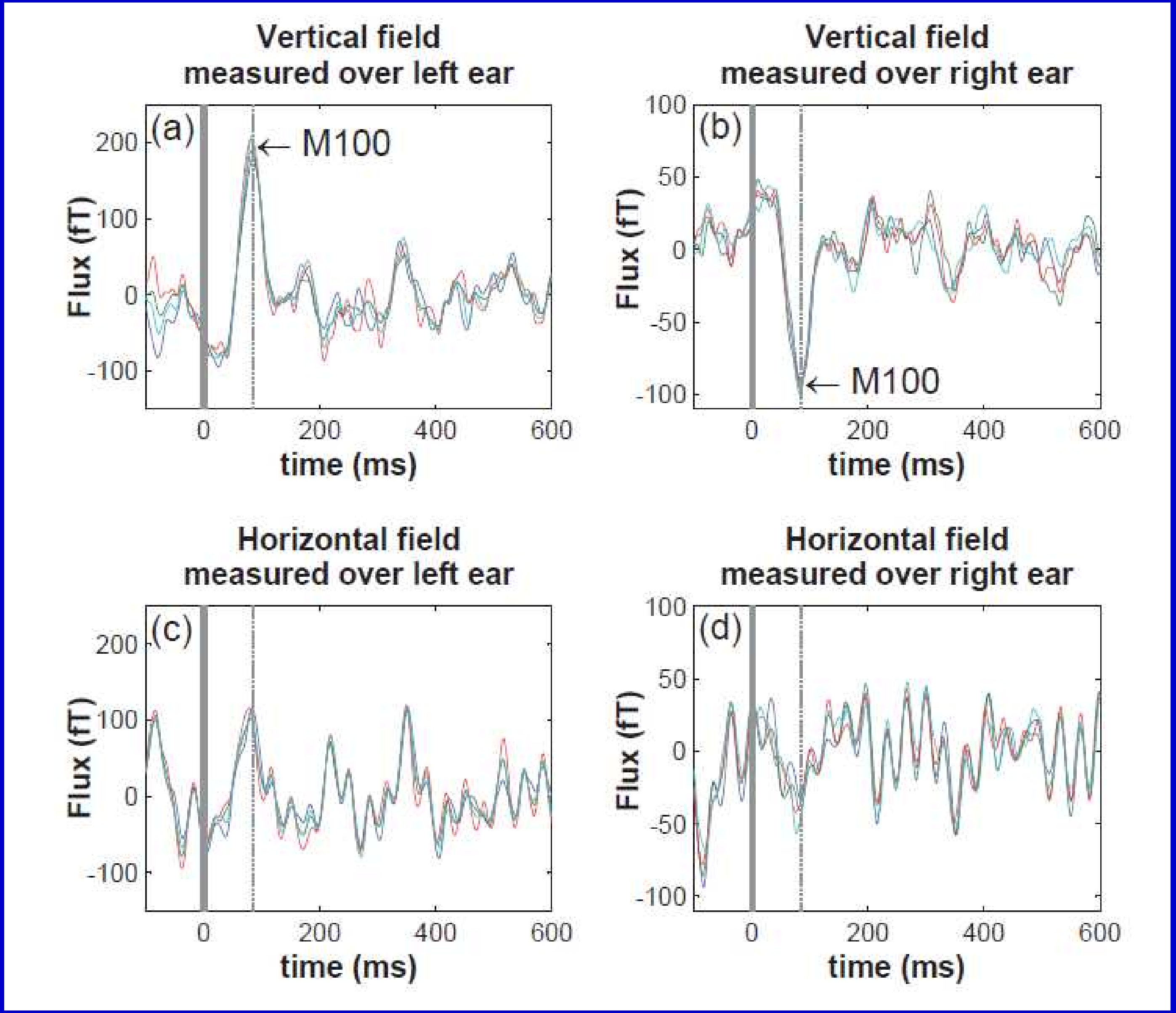


- Present 1000 Hz tones in both ears, measure evoked response in auditory cortex
- Expected signal at ~100 ms is present in OPM and SQUID data

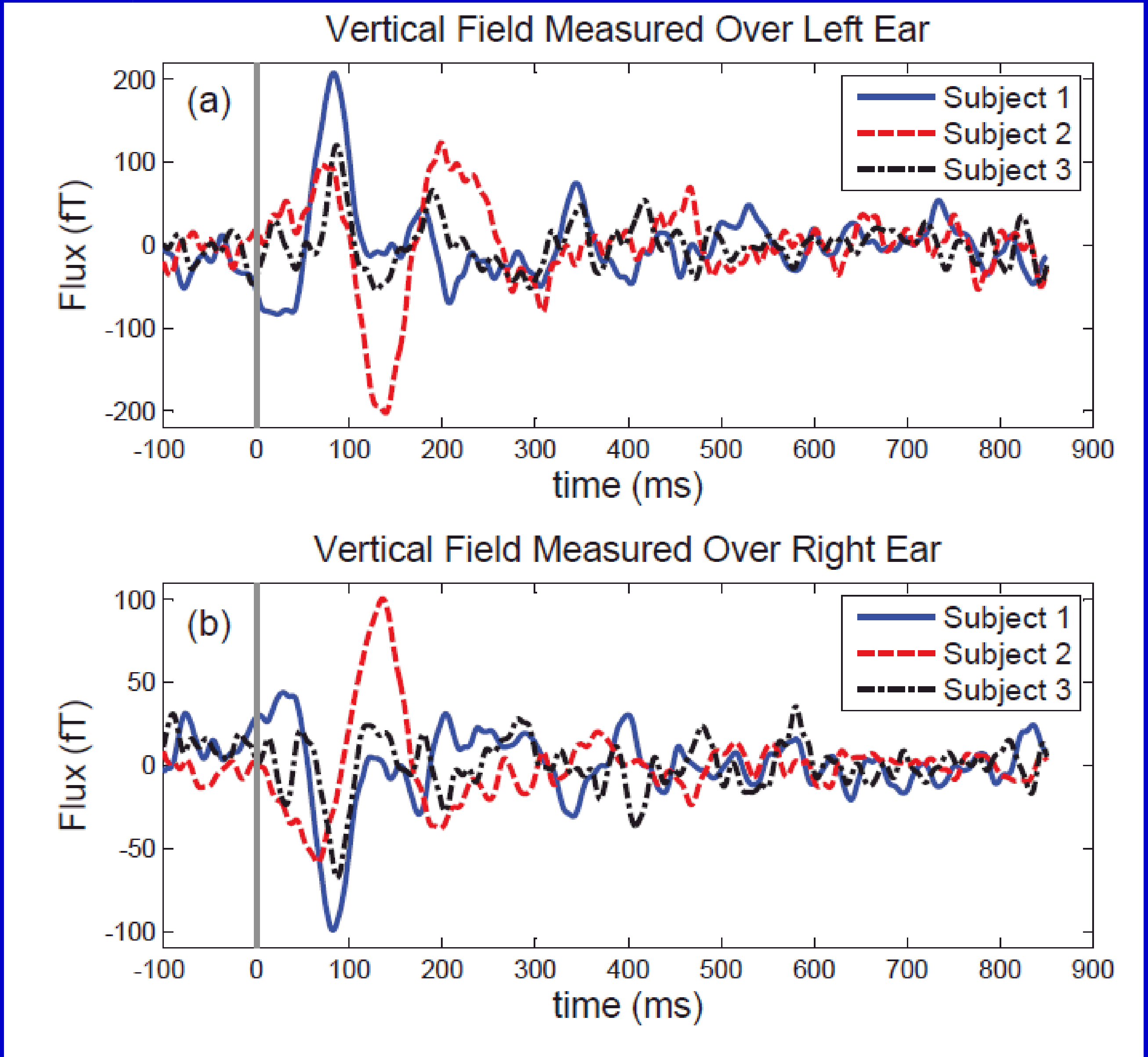
Cort Johnson, Peter D. D. Schwindt, and Michael Weisend, Appl. Phys. Lett. 97, 243703 (2010)

Auditory Stimuli with Two Field Components Measured

- Recordings of vertical/horizontal axes measured subsequently
- M100 peak clearly visible on both sensors, vertical axis
- C.N. Johnson, P.D.D. Schwindt, and M. Weisend, *Phys. Med. Biol.* **58** 6065 (2013).



Auditory Stimuli Multiple Subjects



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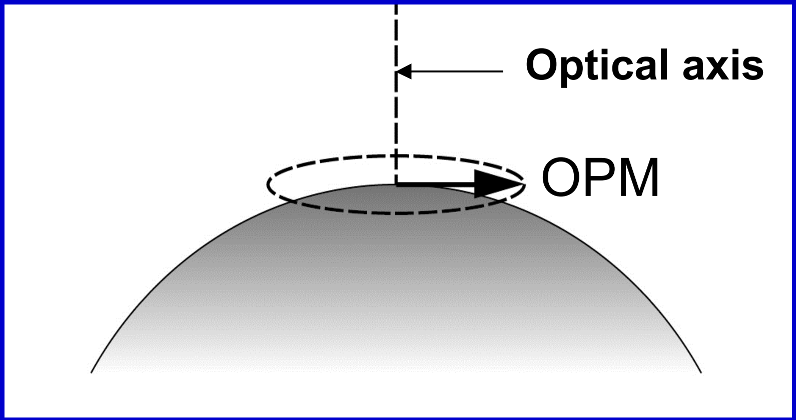
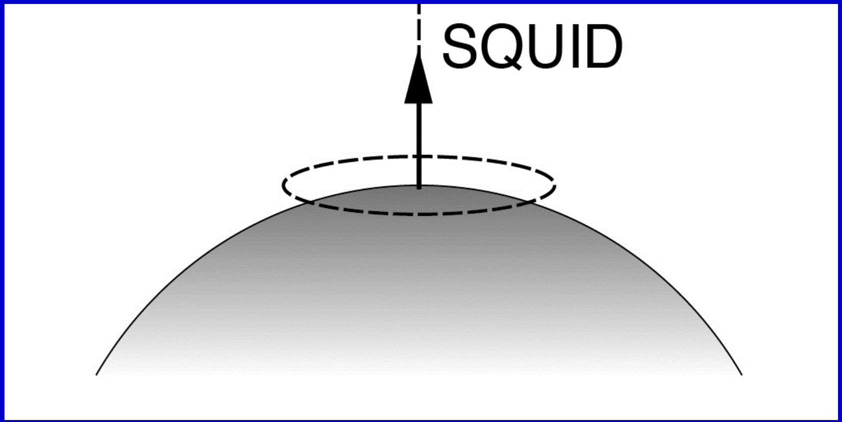
OPM vs. SQUID

SQUID and OPM signals are not identical. Why?

Our OPMs measure fields parallel to scalp (optical axis perpendicular to scalp)



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



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

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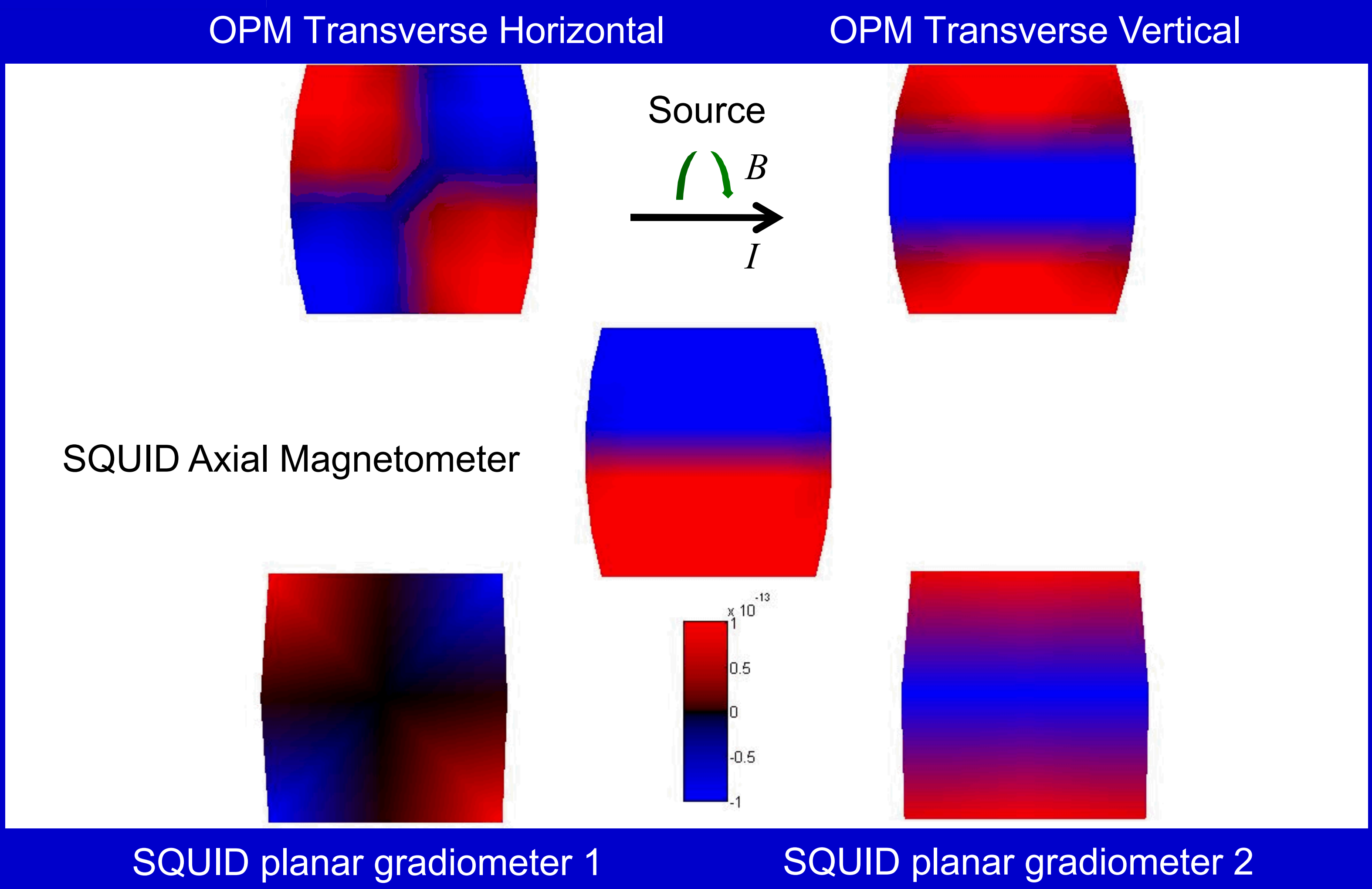
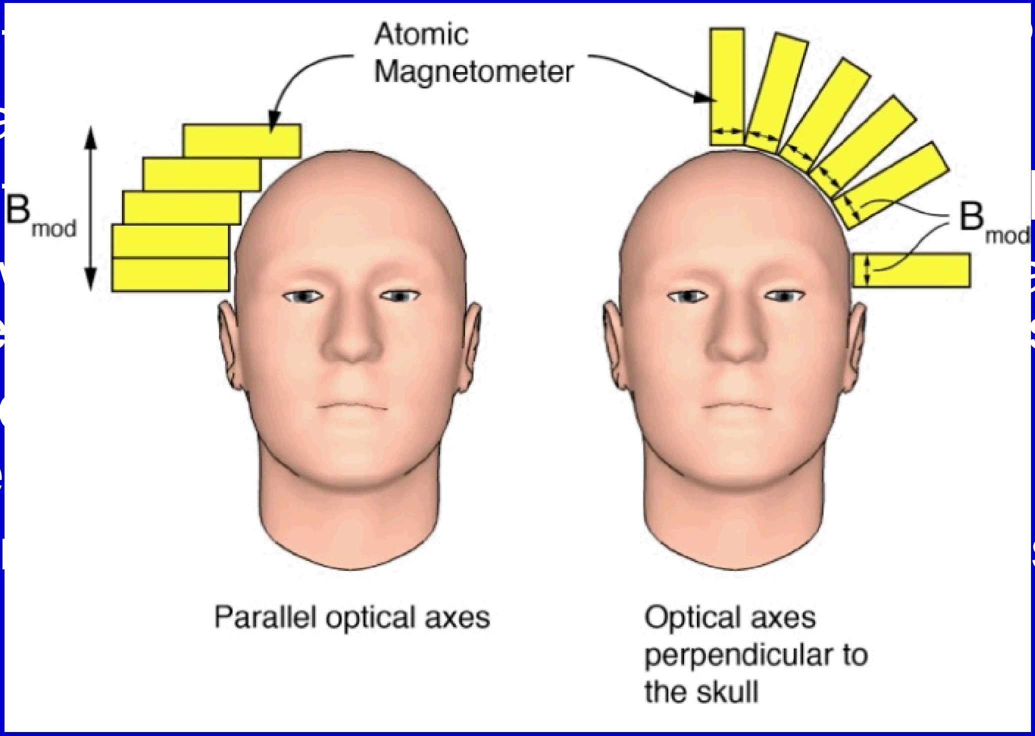
Sensor field maps



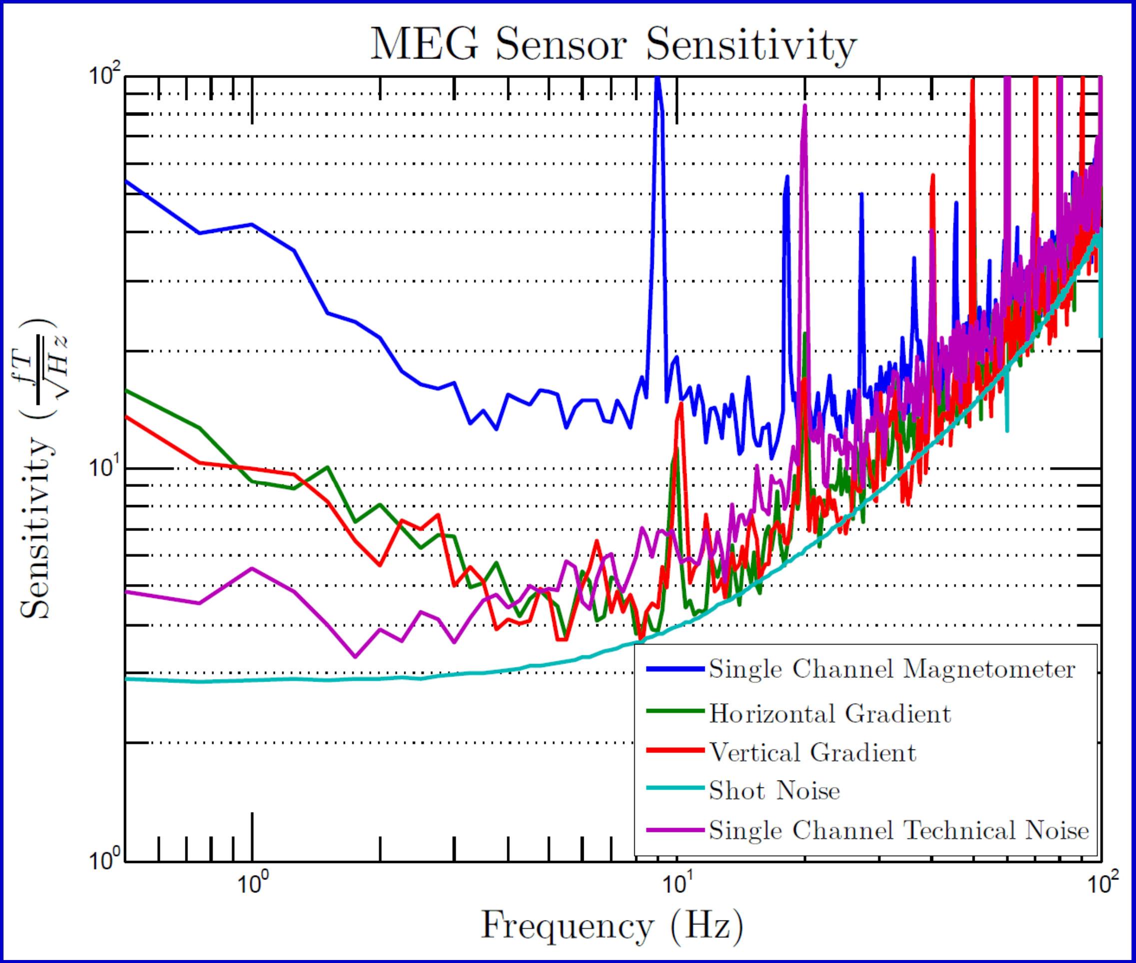
Major Tasks

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 M geometry
   - Bra
5. Cons h phantom
   - Ho and know pre sured?
6. Audit human subje
   - Co son



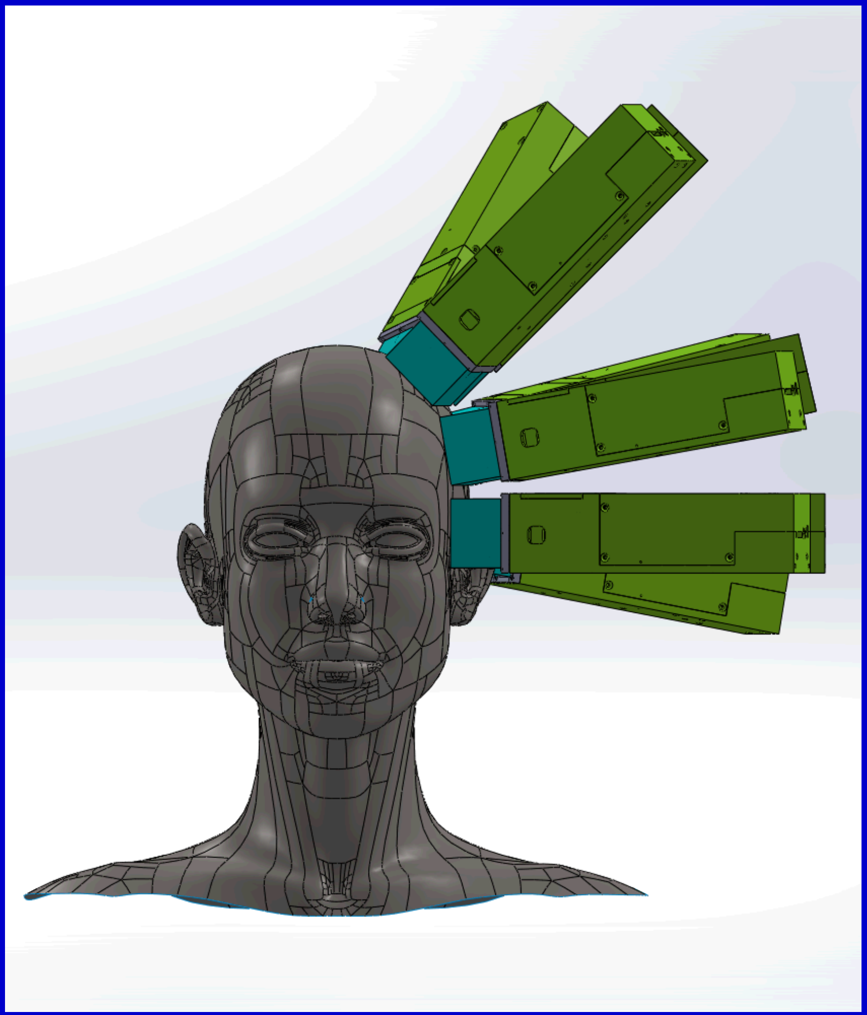
Parallel optical axes
Optical axes perpendicular to the skull

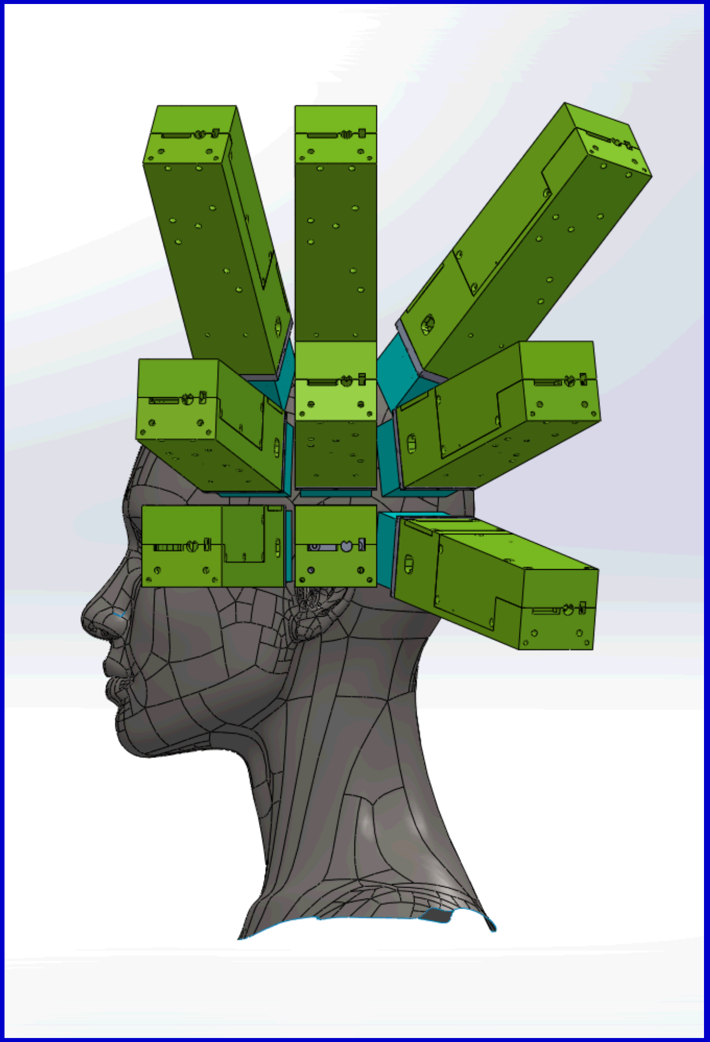
Magnetometer Performance



- Gradient measures intrinsic sensitivity
- <5 fT/Hz$^{1/2}$ at 10 Hz
- Noise floor consistent with magnetic shield noise
- Bandwidth = 17 Hz;

36-Channel Array on the Head





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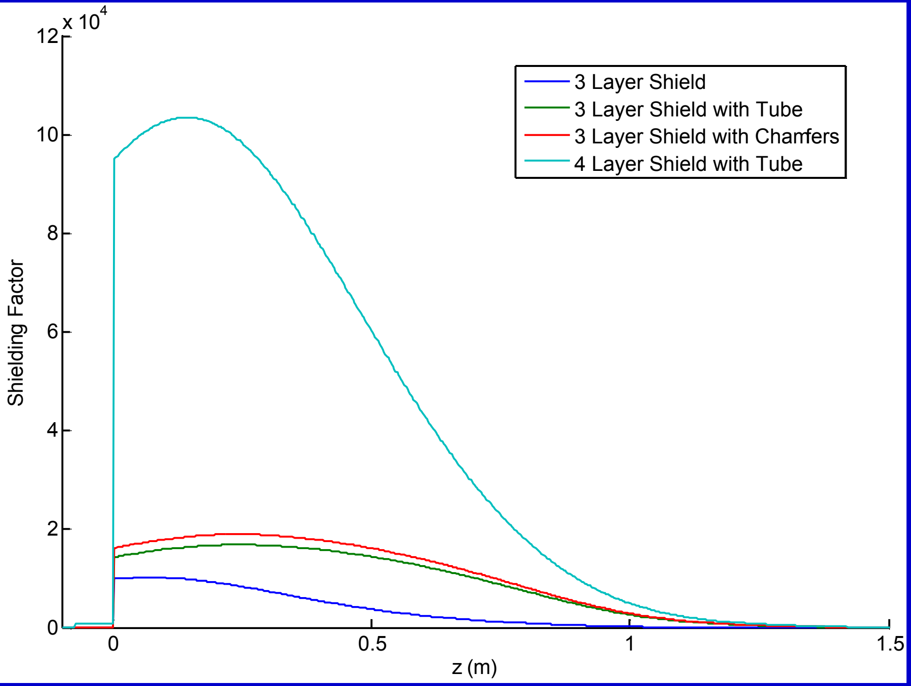
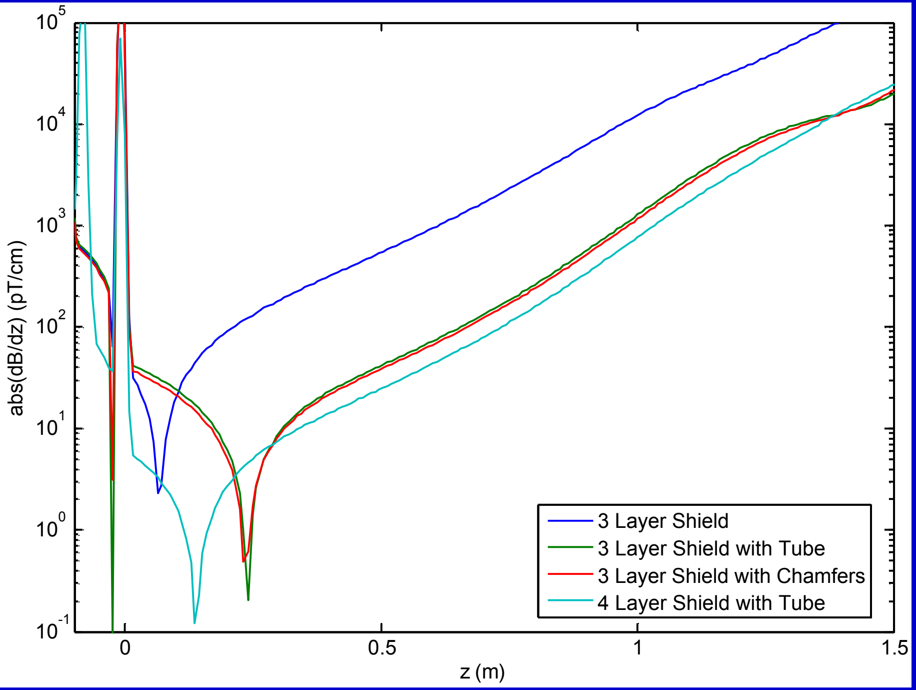
Longitudinal Field

Longitudinal Field



Longitudinal Field Gradient



- 4-layer performs better
- Gradient minimum closer to the center of the shield with 3-layer
- 3-layer is about $20k cheaper

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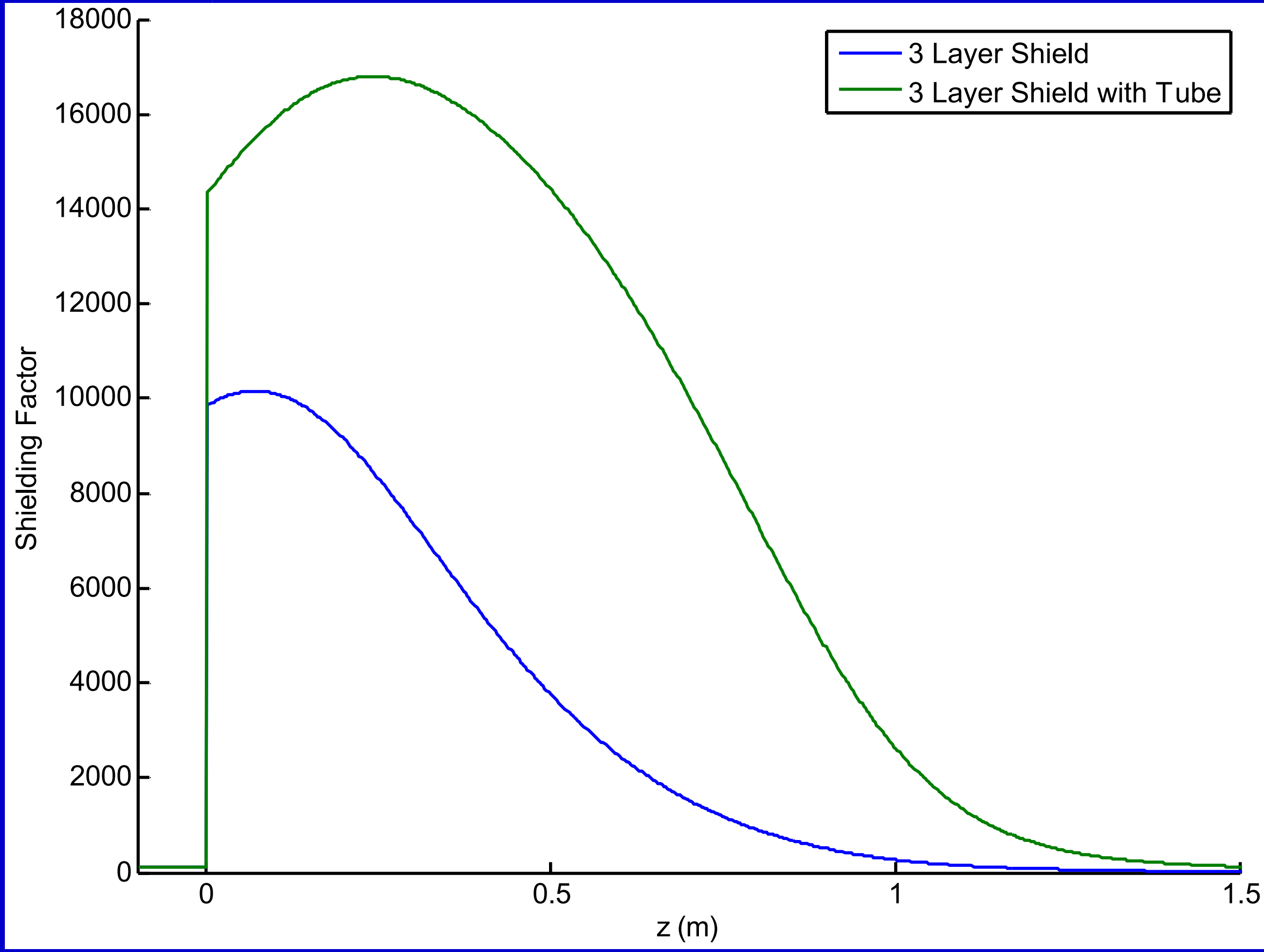
3-Layer Shields



- 3-layer shield with tube shielding factor = 17,000

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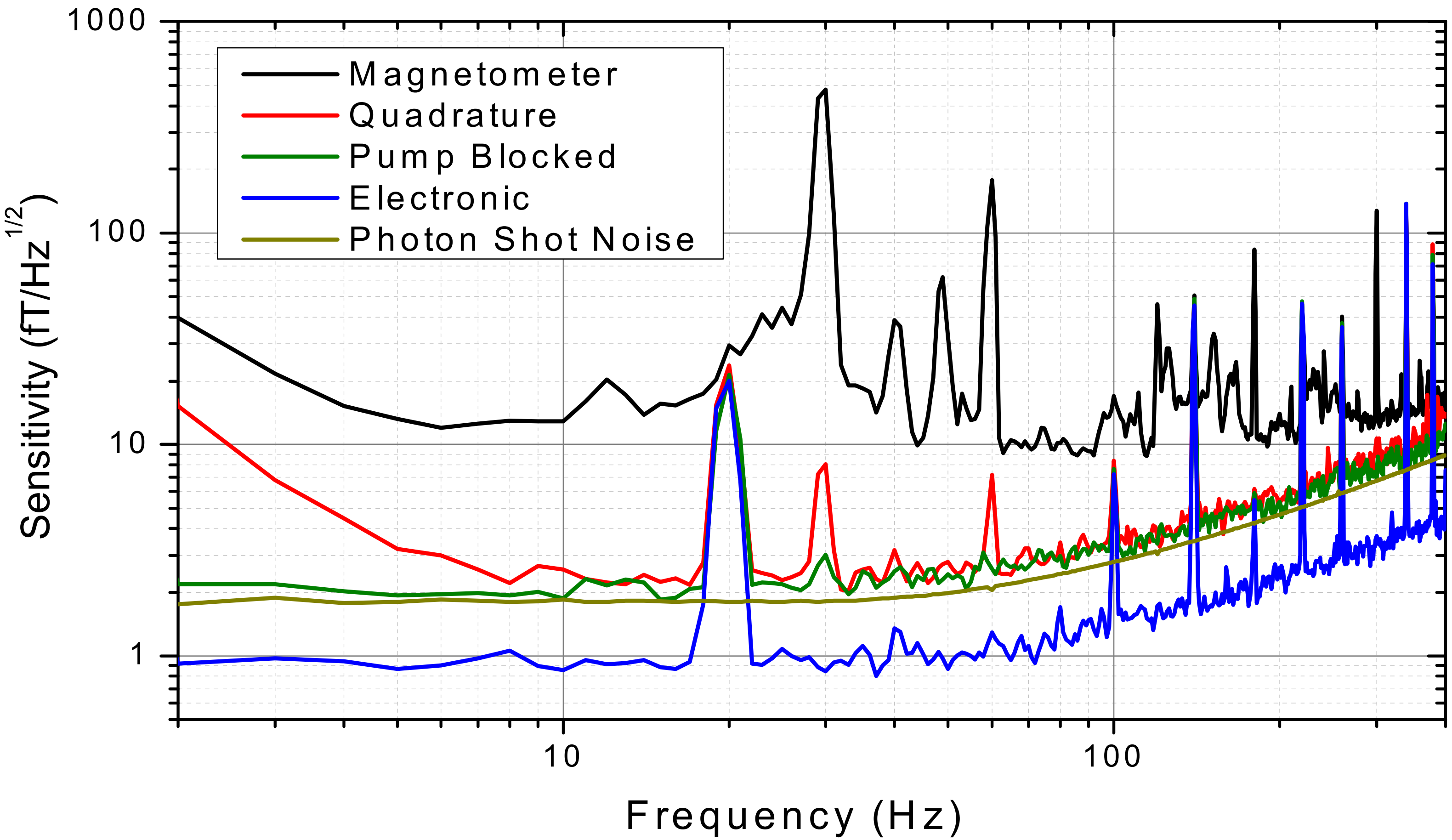
Channel 1 Performance



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Gradiometer: Channel 1 – Channel 3